# Chapter 6

# Discussion

In this chapter, the data and analyses are discussed with respect to the hypotheses outlined in Chapter 1. First is a spatial comparison of the MS and IRB study areas in terms of sedimentary features and sediment properties, using side-scan, sedimentary data, and box core data analyses. Second, evidence of sedimentary movement over seasonal/annual time scales is addressed by examining GIS analyses of the time series of side-scan sonar images, as well as hydrologic data and, to a lesser extent, sedimentary and box core data. Evidence of sediment movement over a shorter time frame is then examined for the southwestern sub-study area of the IRB region, using data collected before and after the passage of a cold front in November 1998. Finally, the relationship between sedimentary properties and side-scan backscatter intensity is considered.

## Spatial Comparison of the IRB and MS Study Areas

One goal of this study was to ascertain whether sedimentary features observed in the IRB study area were present in deeper water environments farther west on the WFS. Comparisons of the features in each area in terms of size, shape, sedimentary characteristics, and hydrologic environments are discussed, based on side-scan, sedimentary, box core, and current meter data analyses.

*Sedimentary Features.* Although the orientations of the large sand bodies were the same in the MS and IRB areas (northwest-southeast trending), the sizes of the features differed. Sand ridges from Harrison's (1996) study area were found to be composed of overlapping sand waves (Figure 4). These sand waves combined to form ridges that had spacing ranging from 200-1500 m, thicknesses of 2-4 m, and lengths up to 2 km. Harrison (1996) found that these features, in general, became larger, thicker, and spaced further apart with distance from shore and increasing water depth.

Sand ridges in the IRB area (Figures 23 and 25) varied in width from ~50 m to more than 300 m. Spacing ranged from ~100 m to 500 m. In the eastern portion of the IRB study area, ridges were narrower in width, spaced more closely, and exhibited narrow areas of high backscatter (coarse sediments) in the troughs between the low backscatter (fine sediments) ridges. Sand ridge width and spacing increased in the western portion of the study area, as did the widths of the troughs separating the features. In contrast, the features in the MS study area (Figure 13) were wider, measuring as much as 2000 m across. Where two discrete features were visible, the trough separating them was nearly 2000 m across as well. Sediment thickness across one sand body (Figure 85, Appendix F) was up to 3.5 m. It was difficult to determine the full extent (length) of these features from the MS96M side-scan sonar mosaic (Figure 13); however, it is reasonable to assume the features extended in length beyond the mosaic boundaries to the southeast and northwest. Together these observed dimensions imply that the features in the MS area are an order of magnitude larger in areal extent than the features in the IRB area.

Bedforms superimposed upon the IRB area sand ridges were visible in the data. High backscatter, linear features transverse to the ridge axes (Figures 23 and 25) were present. Spaced tens of meters apart, these bedforms were observed by divers to be narrow (< 5 m in width) linear depressions, filled with coarse sedimentary material and molluscan shells. High backscatter bedforms were largely absent over the features in both the MS96M and MS98JL side-scan sonar surveys (Figures 13 and 14) and were not observed by divers. Consistently observed by divers (and sometimes in the side-scan sonar record) were bedforms in the coarse trough materials between sand bodies. These ripples were oriented primarily north-south and had wavelengths of 1 m and amplitudes of ~10 cm. Smaller ripple features, with wavelengths of ~10-15 cm and amplitudes of a few centimeters, were observed by divers in the fine sands of the sand bodies in both the IRB and MS areas. These features were not visible in any of the side-scan imagery.

The sedimentary features observed in both the MS and IRB study areas were similar in orientation and had smaller bedforms superimposed upon the larger features. The trend toward larger sand bodies, spaced farther apart, with increasing distance from shore, appeared to continue through the IRB area and out into the MS study area. The MS area features do not appear to be sand ridges like those in the IRB area, but resemble large lenses of sediment. The absence of the linear transverse bedforms of coarse material in the MS area was also a significant difference (besides overall scale) in sedimentary features between the two areas.

The presence of the sand bodies in deeper waters on the WFS begs the question of their origins. Several models have been proposed for the formation of sand ridges in shelf environments, and range from ebb tidal deltas, spits and barrier islands stranded during transgression (Stubblefield et al., 1984; McBride and Moslow, 1991) to features formed *in situ* by hydrologic processes (Huthnance, 1982a and 1982b). On the WFS, the origins of the linear sand ridges and ridges in the IRB area have been hypothesized by Harrison (1996) and Edwards (1998) to be transgressive features which had been migrating shoreward but were subsequently stranded by sea level rise. Similar features have been found south of the IRB area, south of the mouth of Tampa Bay (Figure 3) near Sarasota, Florida (Twichell et al., 1996). Are the sand bodies in the MS area also stranded transgressive features? They are similar in thickness (Figure 85, Appendix F) to those in the IRB area, but are larger in areal extent. Sediment input and availability may have been greater at the time sea level was lower and these were shallow water features. Or sediments may have been moved offshore during some Holocene (or earlier) regression, only to be stranded there during a rapid transgression.

One dissimilarity between the MS and IRB sand bodies was the absence of the high backscatter, linear, transverse bedforms in the MS area which were present in the IRB area. Differences in sedimentary properties between the two areas, discussed below, may partially explain their absence in the MS area.

*Sedimentary Properties.* The differences in sedimentary properties between the IRB and MS areas revealed that processes, either in the geologic past and/or currently in operation, have created sedimentary features in each area which differ in grain size, sorting, and mineralogic composition. Sediment grain size distributions differed between the two sites (Figures 49, 51, 53, and 55). The MS96M and MS98JL sediment samples taken directly from the sand bodies were all similar in grain size distribution and showed little spatial variation across the sand features. Only MS98JL samples 06 and 10 showed any tendency towards a coarser distribution (Figure 51). The grain size distributions of the IRB97N and IRB98JL sediment samples were more varied. The T2 (middle transects across the sand ridge) samples exhibited some spatial variation in distribution across the sand ridge. The T1 and T3 samples were more dissimilar and showed marked spatial variation across the sand ridges, implying some transport and sorting mechanisms. The changes in sedimentary character corresponded with high and low backscatter variations on the sand ridges (Figures 24 and 26). The presence of more and varying coarse sediments in the IRB area made possible the formation of these coarse bedforms on the sand ridges. The lack of such materials in the MS sand body sediments may have precluded the formation of the coarse bedforms there.

Comparison of the four sedimentary properties (mean grain size, sorting, carbonate content, and fine materials) showed measurable differences in overall sedimentary characteristics between the two areas (Table 22). Besides the differences in properties, the MS area samples were also more homogeneous than those from the IRB area. The difference in homogeneity between the two areas is probably a function of sediment reworking. In their discussion of relict sediments on continental shelves, Swift et al. (1971) stated:

> "Reworking of the Holocene transgressive facies in the Gulf of Mexico is better described as the mixing of previously better sorted, homogeneous sediments rather than unmixing."

In other words, Holocene transgression of sediments has, in places, mixed together sediments with differing properties. Since different energy regimes result in different extent of reworking (Swift et al., 1971), the sedimentary properties and morphologies of the MS and IRB areas have developed differently as well. Sources of larger grained particles have made the sediments in the IRB area coarser and more poorly sorted. There are strong significant correlations between increasing grain size and percent carbonate in the IRB sediments (Tables 15, 17, 19, 21), but not so in the MS sediments (Tables 11 and 13), indicating that the difference in sediment carbonate content between the two areas explains the difference in overall mean grain size (Table 22). Exposed limestones and biogenic sources in the shallow IRB waters are a source of these larger carbonate sediments. Large carbonate grains have not been reworked as extensively into the fine-grained MS sediments.

Overall sedimentary characteristics in the two areas differed. Sediments were finer grained, better sorted, with less carbonate in the MS area, and coarser grained, not as well sorted, and contained more carbonate in the IRB area. In addition there was more spatial variability in the sedimentary characteristics over the IRB area than in the MS area, with MS sediments overall being more homogeneous in character, probably due to more extensive reworking of the IRB sediments.

The differences in sedimentary characteristics and relationships between the IRB and MS areas were further borne out by the sedimentary characteristics and structures observed below the sediment-water interface in the embedded box core peels.

*Sub-Surface Sedimentary Structures.* The box core peels and sediment subsamples from the MS area displayed a vertical homogeneity in terms of sedimentary structures and sediment grain size (Table 7; Figures 40, 41, and 42). Aside from some buried shells and some infilled burrow structures, there were no visible sedimentary structures indicative of depositional processes, such as parallel laminations or storm/armored layers, within the top 20-25 cm of sediments. This homogeneity was consistent at all three core locations across the main sand body in the MS area.

In contrast, the box core peels from the IRB area preserved biological structures, parallel laminations, storm/armored layers, and changes in sedimentary character downcore (Tables 8 and 9; Figures 43-48). Sediment grain size fined upwards in subsamples from cores in locations IRB02 and IRB03. Sedimentary structures were visible in cores from all locations, but showed spatial variability across the sand ridge from which they were taken. For example, cores IRB01-A and -B exhibited shallow angle (from horizontal) bedding planes, while those from IRB02-A and -B were more steeply dipping (Figures 43 and 44). Those from IRB02-C and -D showed fine scale parallel laminations in the upper few centimeters (Figure 45) as did those from IRB04-A and -B (Figure 48).

Sedimentary structures in the MS area sand bodies, if they exist, may occur deeper than 25 cm or they may be lacking altogether. Changes in sedimentary characteristics, such as mean grain size, may also occur deeper than 25 cm. The lack of structures in the upper 25 cm may be due to bioturbation during long periods between the events which suspend and redeposit the sediments, whereas the sediments in the IRB area, in shallower (~8 m) water, are affected more frequently by storm wave activity. In addition, the homogeneous nature of the sediments in the MS area (consistent mean grain size, carbonate content, and higher degree of sorting) may mask subtle depositional structures, as preferential sorting or deposition by size or composition would be difficult to ascertain. In contrast, the heterogeneous nature of the sediments in the IRB area tend to make depositional structures more visible, with more variety in grain size and composition and the opportunity for preferential sorting by hydrologic mechanisms.

The MS area is also highly disturbed by commercial shrimping operations, which may have affected the upper 25 cm of the sediments. According to personal communications with the commercial shrimper who dredged up the S4® current meter that was deployed in the MS area, the sand ridges of that area are extensively disturbed by his and other shrimp-boat operators on a seasonal basis. The IRB area is too shallow to be fished by commercial shrimpers (personal communication, John Williams, commercial shrimper, Tarpon Springs, Florida). It is difficult to ascertain the extent to which this trawling activity may have affected the downcore character of the sediments in this area, but it must be considered as a possible factor in what is observed in the MS box core peels and why they differ so markedly from those in the IRB area.

The commercial shrimping aspect notwithstanding, the spatial variations between the cores in the MS and IRB areas indicate that differing hydrologic forcing mechanisms are one factor affecting the observed features in the two areas. The presence of fine scale parallel laminations and low angle bedding in cores IRB01-A (Figure 43), IRB02-A (Figure 44), IRB02-C and IRB02-D (Figure 45), and IRB04-B (Figure 48) indicate periods of wave action dominance, whereas the high angle bedding seen in the lower portions of IRB02-A and IRB02-B (Figure 44), and IRB04-A (Figure 48) indicate tidal current dominance or combined flow (Snedden and Nummedal, 1991; van de Meene et al., 1996). The lack of most such structures (except some fine scale parallel laminations) in the MS cores can be attributed to the absence of both the heterogeneous sediments and the hydrologic forcing necessary to produce them.

Further comparison of the hydrologic conditions in each area, as interpreted from near-bottom current meter data, is presented below to examine the variation between the MS and IRB areas.

*Hydrologic Conditions.* The small data set of mean current velocities from the MS area (Figure 68) makes comparison to the IRB data set difficult, but possible. Mean currents were strongest in the same directions (NE-SW) in both area. Mean currents reached higher speeds in MS compared to IRB, but the amount of time the highest speeds were reached in both areas was proportionately very small. The majority of the time, mean currents were 10 cm/s or less in both areas (Figure 72).

The along-shore and cross-shore components in both areas (*u* and *v*, respectively) were asymmetrically skewed (Table 23). In the MS area, the maximum values in the positive directions (east and north) were less than those in the negative directions (west and south). The mean and median cross-shore values were positive (eastward) while the mean and median along-shore components were both negative (southward). In the IRB area, the maximum *u* and *v* were both larger in the westward and southward directions, and both mean and median values for the along-shore and cross-shore components were negative, indicating a dominance to the west and south. However, the magnitudes of the central tendency values in both data sets were near zero, indicating the magnitudes of the velocity asymmetries were not great.

The mean current ellipses for both areas (Figures 69 and 71) show tidal current vectors were dominant in the northeast and southwest directions, perpendicular to the ridge axes. These currents flow almost parallel, but slightly oblique, to the barrier island shoreline of Sand Key directly to the east (Figure 3). The magnitudes of the mean currents were similar, indicating that tidal current velocities in the MS and IRB areas differed little. However, the short duration of the MS98S4 data set leaves the question open for now.

More data, especially from the MS area, are needed to determine whether the mean currents near the seafloor are significantly different between the two areas. What is similar in both areas is that the dominant mean current velocities flow nearly perpendicular to the axes of the sand ridges. What may be different is the magnitude of those velocities, as the overall MS area velocities are somewhat higher than those in the IRB area for the limited data sets collected.

*Comparison Summaries.* Comparison of the MS and IRB areas in terms of hydrology and sedimentary features and properties, indicates that there are measurable differences between the two areas. These differences may be the results of their geologic history, present-day hydrologic regimes, or a combination of these and other factors.

The increase in size and spacing of sand body features in the MS area compared to the IRB area continues the trend first identified by Harrison (1996) and is consistent with other models of morphology of these features (Swift and Field, 1981; McBride and Moslow, 1991; Thorne et al., 1991). Relationships between sedimentary properties differed between the two areas, with less spatial variability in the MS area compared to the IRB area. Spatial variability in sedimentary properties correlated with differences in the features of the two areas (e.g., fewer secondary bedforms superimposed on the sand ridges in the MS area compared to the IRB area).

Hydrologic conditions appeared similar in that the dominant mean current forcing along the seafloor was perpendicular to the sand body axes in each area. In addition the periods of maximum current velocities were small in both areas. However, the magnitude of mean current forcing may be stronger in the MS area. A more extensive data set in the MS area is necessary to test this hypothesis.

The variations observed between the MS and IRB areas, 15-20 km apart, adds to the variation already observed on this portion of the WFS in terms of sedimentary features. To the south of the IRB area, approaching the mouth of Tampa Bay, the linear sand ridges give way to a variety of other morphologic features (Donahue, 1999). To the south of the Tampa Bay ebb tidal delta, there area linear sand ridges oriented 90º opposite to those observed in the IRB area (Twichell et al., 1996). Their extent offshore is not clear. The effects of transgressive processes on shelf sedimentary features thus appear to vary spatially both cross-shore and along-shore. Modeling or generalizing the hydrology and sedimentology of the nearshore to midshelf region of the WFS from only one of these study areas would prove erroneous.

## Sediment Transport Over Seasonal/Annual Temporal Scales

Time series analyses addressing sediment movement/transport show changes in the positions of boundaries between high and low backscatter areas in side-scan imagery. These boundary changes were interpreted to represent movement of fine sediments. Analyses of bottom currents showed mean current velocities were sometimes sufficient to initiate movement of fine-grained sediments. Sedimentary structures seen in embedded box core peels provide evidence of past transport and depositional events. The significance of these data in interpreting sediment movement and transport over seasonal and annual time scales is discussed first for the MS area and then for the IRB area.

*MS Area.* Data from the GIS analysis of the MS area side-scan mosaics (MS96M and MS98JL) showed evidence of sediment movement in multiple directions. Results were similar to those found by Davis et al. (1996), in that the sharp contrast between high and low backscattering strength, or the transition zone, retained its acoustic signature over time, but not its exact position. Sub-areas A, and B (Figure 6) showed significant border shifts.

to the north and east from May 1996 to July 1998 (Figures 15 and 16). Sub-areas D, F and G (Figure 6) showed significant change to the south and west. Key observations were that the net direction and magnitude of movements varied between areas; the total amount of movement in each direction in each area (normalized to the length of each border) also varied without exhibiting a consistent pattern; and, over the entire MS sub-study area, the total measured amounts of movement in each direction were nearly equal (Table 3).

That border movements in both directions were exhibited in all areas is indicative of either a variety of forcing mechanisms (e.g., mean currents, wave orbital velocities) acting over annual/seasonal time frames, or mechanisms (tidal currents) which act locally or over small spatial scales. The significant border changes observed provide evidence that forcing mechanisms, acting over distance scales of 10's to 100's of meters have been responsible for movement of sediment. Since sedimentary characteristics of this area are so homogeneous (Table 12), it is unlikely that variations in sedimentary properties are largely or solely responsible for the patterns of movement observed in the GIS analyses. However, it may be that, due to the 3D geometry of the sand bodies, sediments in certain portions of the feature are more susceptible to movement. For example, currents of a given magnitude are more likely to initiate movement of sediments on a steep slope than those on a flatter slope.

The variations in magnitude and direction of transport along individual borders (for example, the border represented by sub-areas B, C, and D (Figure 6)) and between borders, separated in most instances by less than 1500 m, indicate that there was not a unified hydrologic forcing mechanism acting in this area between 1996 and 1998. Localized mechanisms may have dominated sediment transport at times in these areas. Tide dominated mean current velocities as high as 30 cm/s were recorded during the deployment of the S4 current meter in the MS area. Values of $U \geq 20.0$ cm/s, in combination with smaller grain sizes, were capable of initiating sediment movement (Figure 76). Mean current velocities of this magnitude occurred < 10% of the time during the period bottom current velocities were measured (Figure 72). This points to periodic forcing mechanisms other than tide-dominated mean currents along the bottom as the cause of patterns of sediment movement observed.

Sustained episodes of sediment transport were not supported by box core evidence. Sedimentary structures that could be interpreted as having resulted from sediment transport events, such as laminations, cross bedding, or armored layers (Snedden and Nummedal, 1991; van de Meene et al., 1996) were lacking in the MS box cores (Figures 40-42). However, absence of evidence is not evidence of absence. Sediment transport events may have occurred and produced underlying structures, such as parallel laminations from wave-suspended sediment deposition, that were then bioturbated and re-worked during fair weather, as observed by Amos et al. (1996). Long time periods separating such events may have allowed biological forces to eradicate traces of sedimentary structures. The fact that the only structures visible in the midshelf area cores were related to shells and burrows (Figures 40-42) supports this idea. The lack of coarse material in the sand body sediments in this area, and the well-sorted nature of the sediments, was also not conducive to the formation of sedimentary structures. Even if current velocities had been sufficient to mobilize sediments on a large scale, no preferential sorting evidence would have been visible.

In addition, biological factors such as the presence of algal mats and/or near-surface bioturbation may have inhibited sediment entrainment. Only two dives were completed in this area (both in summer 1998) and no algal mats were observed. However, based on evidence from the IRB area, algal mats appear to form seasonally (observed in fall and winter in the IRB area) and may play a part in affecting sediment entrainment in the MS area. Divers did observe small (less than 10 cm spacing) current ripples on the sand body near the current meter deployment area, indicating some bottom current action on the fine sands in this area.

Sediment movement did occur in the MS study area from 1996 to 1998, based on the evidence from side-scan, current meter, sedimentary, and box core data. However, data are insufficient to determine the mechanisms responsible for this movement. Measured mean current velocities, most of the time, were insufficient to initiate sediment movement. In addition, velocities strong enough to initiate movement were of short duration and likely would not have sustained mass transport. A more comprehensive set of current velocity data are needed to determine if mean currents are ever great enough and sustained long enough to cause sustained large scale sediment movement, or if storm related bottom currents and combined flow events are the primary hydrologic mechanism affecting sediment transport. The differences in sediment movement (direction and quantity) over the study area indicate that the movement of sediment observed may be tied to localized forcing events. The significant movement of sediments does not appear to be large scale, general transport, but rather limited to small scale ($10^1$ - $10^2$ m) areas with the proper combination of sedimentary characteristics and current flow such that transport can occur. Further, the mixed qualitative boundary shifts observed could also be indicative of localized sediment movement in the MS area.

*IRB Area*. Data from the GIS analysis of the IRB area side-scan mosaics showed evidence of sediment movement from 1996 to 1997 and overall from 1996 to 1998 (Figures 27-33). The implied sediment transport in sub-areas A, B, and C was uniform in comparison with that observed in the MS area. From May 1996 to November 1997, significant movement in sub-area C was consistently to the north and east (Table 4; Figure 29). From May 1996 to July 1998, significant movement in sub-areas A and C was consistently to the north and east (Table 4; Figures 27 and 29). Overall boundary shifts in sub-area C were also to the north and east. No significant movement occurred in sub-area

B, but two small low backscatter features moved consistently toward the south and east, parallel to oblique to the sand ridge-trough boundary (Figure 28).

The direction of significant movement in sub-areas A and C, and the observed boundary shifts in sub-areas A, B, and C, correlate with the direction of winds (and wind waves) associated with seasonal fronts that move through the area (Hine and Belknap, 1986; Davis et al., 1992). Waves, generated by southwesterly and northwesterly winds associated with weather fronts, suspend and move sediments toward the east.

The spatial relationships among sub-areas A, C, and C may account for the lack of significant movement observed in sub-area B compared to A and C. The boundaries analyzed in sub-areas A, B, and C were located primarily on the southwestern flanks of sand ridges (Figure 7). These spatial relationships place these ridge-trough boundaries on stoss slopes in the face of wave-dominated bottom currents. Further, the boundaries of sub-areas A and C are located on the eastern side of a trough feature that is up to 500 m wide, whereas sub-area B is in a more shielded location (Figure 7).

Changes in shape and size of the features represented in IRB sub-areas D, E, F, and G are the result of the removal of low backscatter materials (fine sands), leaving high backscatter coarse sediments and/or exposed hardbottoms. The implied sediment transport from the results of the analyses of sub-areas D, E, F, and G was mixed compared to sub-areas A, B, and C. From 1996 to 1997, sub-areas E and G showed significant movement to the north and east (Table 5; Figures 31 and 33). During the same period, sub-areas D and E showed significant movement to the south and west, with net movement in sub-area E to the south and west (Table 5; Figures 30 and 31). Net movement over all four areas was to the north and east from 1996 to 1997, by a ratio of 2.4:1 (Table 5). Between 1996 and 1998, sub-areas E, F, and G showed significant movement to the north and east; sub-areas D, E, and G showed significant movement to the south and west (Figures 30-33). Net significant movement in sub-areas E and G was to the north and east; net significant movement over all four areas was close to 0 (Table 5).

Boundary shifts and measured movements in sub-areas D and E were to the north and east on the eastern side of these features and to the south and west on the western sides. The net effect was an expansion in size overall of the high backscatter features in sub-areas D and E (Figures 30 and 31). Boundary shifts in sub-area F were inconsistent in direction, but the significant movement to the north and east was on the eastern side of the feature (Figure 32). Boundary shifts and net significant movement in sub-area G were to the north and east, although the significant movement occurred on the western side of the feature (Figure 33).

The total length of boundaries examined in sub-areas D-G was more than twice that examined in sub-areas A-C (Tables 4 and 5). The total quantity of significant movement in either direction in sub-areas D-G was greater than in sub-areas A-C by factors from 2 to 6, implying a greater amount of sediment movement in sub-areas D-G (Tables 4 and 5). The difference in implied sediment movement may be explained in terms of bathymetry. High backscatter areas in the eastern portion of the IRB area are located in troughs between ridges (Figure 7). These troughs are about 1 m shallower than the troughs in the western portion of the study area (Figure 86, Appendix F). The effects of bottom current velocities generated by wind waves are greater at shallower depths, generating more suspended sediments assuming velocities are sufficient to initiate sediment movement (Wright, 1995). Suspended sediments are then transported by wave orbital and mean current flow, or combined flow (Green et al., 1988). The same wind waves that affected sediment transport in sub-areas A, B, and C would have had a greater impact at the shallower depths of sub-areas D-G, moving more sediment.

Predictions of the initiation of sediment movement over the range of grain sizes and mean current velocities for the IRB area were limited to the finer materials and highest velocities (Figure 77). Mean current speeds greater than 20 cm/s, strong enough to initiate movement in finer sands, occurred < 5% of the time (Figure 72). Currents measured during a frontal passage in November 1998 (outside this seasonal/annual study period) reached maximum velocities just over 30 cm/s (Figure 73). However, even these speeds were predicted to initiate movement only in sediments with mean grain sizes of 1.127 ϕ (0.458 mm) and finer (Figure 77). Current speeds greater than those measured thus far (and which probably have occurred during times of greater storm wave conditions) would have been required to have moved coarse sediments into the trough areas, while those same currents would also have been strong enough to have moved fine sediments out as well. Thus the transport of fine sediments from the troughs in sub-areas D, E, F, and G is the more likely reason for the increase in size of these high backscatter areas. What is unclear is where these transported fine sediments were deposited. They may have been deposited on the sand ridges adjacent to the troughs, or removed from the IRB study area entirely. More data (e.g., more comprehensive current profiles, measurements of suspended sediment concentrations, as well as time series of bathymetry) would be necessary to investigate this.

Subsurface sedimentary structures visible in the IRB box cores indicated sedimentary transport events have occurred on the sand ridges (Figures 43-48). The number of box cores collected, and spacing between them, does not lend itself to general interpretations for the entire sand ridge, let alone the IRB study area. However, several observations can be discussed regarding the sedimentary bedding features contained in the cores. Besides biological/bioturbation features, three types of structures were most commonly visible in the box core peels (Figures 43-48): parallel laminations, high angle bedding, and low angle bedding.

Parallel to sub-parallel laminations in the upper portions of cores IRB01-B (Figure 43), IRB02-C and IRB02-D (Figure 45), and IRB04-B (Figure 48) indicate that wave-suspended sediment deposition occurred (Amos et al., 1996; Beavers, 1999). These surficial laminae were generally composed of fine sediments.  Since coarse sediments require stronger wave-induced currents than the finer sediments for suspension, it can be hypothesized that there is a progressive fining upwards of sediments after a period of strong wave-induced suspension.  The process results in the formation of an armored layer of coarse sediments, above which the finer sediments are often reworked by milder storm waves until an event which can resuspend the coarse sediments (Chiew, 1991).  Sediments fining upward and an armored bedding plane, visible in cores IRB02-C and IRB02-D (Figures 45 and 46), and also evident in sedimentary data from cores IRB02-A, IRB02-B, IRB03-A, and IRB03-B (Table 8), provide evidence of past storm-induced suspension of sediments, leaving coarser sediments behind while finer sediments above were reworked.

The parallel laminations and high angle bedding planes seen in cores from the IRB04 site represent evidence of the migration of the feature in IRB sub-area B that was observed between May 1996 and November 1998 (Figure 28).  The IRB04 cores were taken off the main sand ridge, on the migrating feature in IRB sub-area B (Figure 28) and did not contain much coarse sediment even at depth. High angle bedding planes, indicative of tidal current dominance during combined flow sediment deposition events (van de Meene et al., 1996), were visible in cores IRB04-A and IRB04-B at 8-10 cm depth (Figure 48).

Evidence that the fine sediments of the sand ridge had been transported and deposited over the coarse trough sediments was seen in cores IRB03-A and IRB03-B (Figure 47).  Low angle bedding planes, indicative of wave action dominance during sediment deposition events (van de Meene et al., 1996), were visible in these cores, taken between adjacent lobes of sand bodies (Figure 26).  Sediments in the IRB03 cores were coarse and contained significant shell material, especially with depth in the cores.  No parallel laminae were visible above the bedding planes.  Finer sediments in the upper half of each core were deposited atop shells and shell hash in the lower half of the cores.  These shelly sediments are similar to those found in the trough adjacent to and between the flanks of the sand bodies (Figure 26), implying one or both as the source of the fine sediments. Since other sediment movement inferred near this area (sub-area B, Figure 28) was to the south and east, the westernmost of the sand bodies was the likely source.

*Summary.* The maintenance over time of the sharp contrast between high and low backscatter regions in the side-scan images of the MS and IRB areas is indicative of maintenance by long-term hydrologic processes (Davis et al., 1996). Variations in the direction and amount of sediment movement along the ridge-trough borders in the MS and IRB areas point to spatially localized forcing mechanisms as the agents of sediment transport. These may be periods of short duration during which bottom currents are sufficient to entrain sediments, combined with localized sedimentary characteristics that may facilitate movement. Large-scale morphology may also influence the effect that bottom currents can have on a particular area of sediment, for example by providing a shielding effect (Huthnance, 1973), and determine whether or not sediment transport takes place. These findings are consistent with those of Twichell (1983), who reported on the movement of sand waves in a higher energy environment (Little Georges Bank) and found that a spatial coherence in the direction of movement from sand wave crest to crest suggested extremely local variations in the hydraulic regime.

Bottom currents generated by wind waves from tropical storms and extra-tropical storms may generate the only hydrologic forcing strong enough to transport quantities of sediments great enough to cause measurable changes in large scale morphology in either the MS or the IRB areas. Based on the observations from 1996 to 1998, a period in which no tropical storms occurred proximal to the study areas, there does not appear to have been any change in the size and shape of the sand bodies in either the IRB or MS areas. Evidence of some movement/redistribution of fine sediments was provided by the movement of sand body-trough borders in both study areas and by the growth in size of some of the high backscatter trough features in the eastern portion of the IRB area. Tidal forcing (mean currents) was not sufficient to suspend sediments, or entrain and transport them along the bottom, and thus no large-scale changes in the size and shape of sand bodies can be expected strictly from tidal current forcing. Non-storm related wind waves did not appear to affect bottom current velocities enough to entrain sediments, and even the passage of a weak cold front did not generate an effect on bottom currents that was significantly beyond tidal current velocities. In more energetic settings, such as the Great Barrier Reef coast of northeastern Australia, waves and wind-driven currents associated with prevailing winds are, with time, able to rework the deposits of intense cyclones (Woolfe et al., 1998), leaving little record of the depositional history in subsurface structures.

A negative relationship exists between the proportion of fine grain sediments and amount of algal biomass (Cahoon et al., 1999). The sediments in the IRB area have a low proportion of fine sediments. Therefore the algal mats observed in the IRB area were consistent with that relationship. The algal mats may also have prevented sediment entrainment or formation of secondary bedforms, even during the brief periods where mean currents were sufficient to initiate sediment movement (Noffke, 1998).

### Sediment Transport Over A One-Week Temporal Scale Related to Frontal Passage

An analysis of a shorter temporal period was conducted in the IRB southwestern sub-study area (Figures 34 and 35), wherein side-scan, sedimentary, and current meter data were collected over a period from November 9-25, 1998. This study was designed to gather data before, during and after the passage of a cold front. The results were disappointing in that the front that passed through the study area was weak in terms of wind velocities (Figure 84, Appendix E). The current meter data recorded only a minor effect on bottom currents from waves due to averaging by the current meter software; mean (tidal) currents were by far the dominant forcing mechanism during this period.  However, there were still some insights gained from this experiment.

*Discussion*.  No significant movement of boundaries between high and low backscatter features was measured in sub-areas A, B, or C for this experiment, nor were any consistent boundary shifts were detected (Figures 36-38).  Sub-area B (Figure 37) corresponds to the same sub-area B in the 1996-1998 analyses (Figure 28), and contains the same two small low backscatter features in the trough adjacent to the sand ridge.  As in the 1996-1998 analysis, these features shifted to the south and east.  The smaller of the two shifted so far toward the sand ridge that, by the time of the last side-scan survey (Figure 35), the feature was no longer distinguishable a separate from the ridge (Figure 37).  Thus from the time of the first survey in May 1996 (Figure 21) until November 1998, this low backscatter feature, an accumulation of fine sands, has moved at least 30 m to the south and east from its original position.  This is the most consistent evidence of sediment movement in a localized area observed during the entire study.

As an indicator of sediment transport events, temporal variations in physical sedimentary properties can be compared between the IRB98N1 and IRB98N2 surveys. Grain size distributions were more variable across Transects 1 and 2 in the IRB98N2 survey compared to the IRB98N1 survey (Figures 57 and 59).  Grain size distributions across Transect 3 appeared about the same in both data sets, with a distinct partitioning between the first six samples taken (fine sands of the ridge) versus the last five (course trough materials). The difference in Transects 1 and 2 indicates some redistribution over the experiment period.  No significant difference was evident in the respective mean grain sizes between the two data sets, but significant differences in the variances of the distribution about those means, as well as significant differences in sorting, were evident (Tables 34 and 35, Appendix B).  The difference in sorting, however, was not enough to change the designation of "moderately sorted" for either data set (Folk, 1980). The overall lack of significant change in the sedimentary properties correlates with the lack of significant movement seen along the ridge-trough borders.

The current meter data over this study period (IRB98S4B), when separated into *u* (cross-shore) and *v* (along-shore) components, showed that these respective components were of equal speed most of the time. Where they differed, the cross-shore component dominated (Figures 74 and 75). In almost all cases where overall current speeds reached or exceeded 20 cm/s, the point at which initiation of sediment movement was predicted (Figure 77), a corresponding peak in the *u* velocity component occurred (Figure 73). Two exceptions occurred where both the *u* and *v* components were correspondingly strong and resulted in a strong overall current speed (Figure 73). Therefore it would appear that during this period, cross-shore hydrologic forcing was the more dominant factor in affecting the sediment movement that occurred. Most of the time, the peak values of *u* were positive, i.e., in an easterly direction. The only evidence of sediment movement corresponding with these peaks is the steady east/southeast migration of the small low backscatter features in sub-area B (Figure 37). Otherwise, no corresponding evidence of sediment movement -- either measurable or as consistent boundary shifts -- correlates with the speed and direction of bottom currents during the period of the experiment.

Diver observations during both of the sediment sampling surveys, and during the current meter deployments and recoveries, noted the presence of a patchy but widespread algal mat overlying bioturbated sediments. These features were observed both before and after the frontal passage, indicating that the mat was able to remain intact despite the bottom current velocities. The algal mat may have hindered fine sediment transport via alteration of (1) fluid momentum impinging on the bed, (2) particle exposure to the flow, (3) adhesion between particles, and (4) particle momentum (Jumars and Nowell, 1984). Velocities were not sufficient to remove the mat or to reorganize sediments into small-scale bedforms (e.g., current ripples), leaving the signs of bioturbation intact between surveys. The presence of these biological communities increases the critical threshold velocity for initiation of sediment movement (Jumars and Nowell, 1984), but to what extent is uncertain.

The presence of the algal mat and bioturbation features also provided evidence that areas which did not exhibit movement in the GIS analyses were not merely instances where sediments actually were moved in one direction, then back again, showing no net movement. In such a case the mat itself likely would no longer have been present and/or there would have been current ripples, or at least the removal of bioturbation features, indicating sediment had been transported.

*Summary*. Overall, the data from the November 1998 experiment provided mixed signals regarding movement of sediment. The GIS analyses of the side-scan images showed no consistent or measurable movement of sand ridge borders. The only evidence of movement observed involved the continued east/southeast migration of low backscatter features that has been observed over season/annual time scales since 1996. Bottom currents appeared to be influenced by storm wave activity, but were tidally dominated during this period. The front did not generate waves sufficient to affect mean bottom current velocities enough to predict large-scale initiation of sediment movement. This was supported by the scant changes shown in sedimentary properties between the two surveys.

Stubblefield et al. (1975) hypothesized three stages of bottom energy activity affecting sediment movement and redistribution of sedimentary properties:

> (1) fair weather circulation, with activity on sand ridges mainly biogenic;
>
> (2) storms which fail to entrain the complete water column due to insufficient velocities and/or water column stratification, with ridge crests undergoing winnowing of fine grained sands to the flanks and troughs by wave surge and the unidirectional component of storm flow; and
>
> (3) major storms where the entire water column is set in motion, where troughs undergo scour and sands are returned to the flanks and crests.

Overall the changes observed cannot be related strongly to the weather event encompassed by this experiment. The storm front which passed was too weak to have any substantial effect, falling into category (2), above, from Stubblefield et al. (1975). It follows that it takes an event stronger than this one to significantly move and redistribute sediments. Further, it also implies that a series of such strong events over the course of a season or year must be responsible for the net changes observed over long time scales, as mean current velocities are not sufficient most of the time to initiate sediment movement. Even when mean currents predict initiation of sediment movement, biological factors may add an additional hindrance to sediment transport. And still puzzling are the localized variations in movement that were observed over both long and short time scales, that imply that movement, in quantity and direction, is anything but consistent across even small spatial scales.

## Sedimentary Properties and Side-scan Backscatter Intensity

A simple multiple regression model was utilized to quantify the relationship between side-scan backscatter intensity and sedimentary properties, with the expectation that it would be incomplete in its explanation. However, such a model had potential usefulness as a rough estimator of sedimentary properties in a given depositional environment.

*Relationship of Sedimentary Properties*. Many of the relationships among the independent variables -- mean grain size, sorting, carbonate content, percent fine material, and gray scale standard deviation -- were consistent. For example, overall, increased carbonate content correlated with increased grain size and poorer sorting. However, the strength of these relationships varied spatially between the MS and IRB area samples and between transects within the respective IRB sample sets. Where there were more homogeneous sediments, that did not vary spatially in terms of grain size distribution (e.g., MS96M samples 01-06 (Table 11) or MS98JL sand body-only samples (Table 13)), the relationships between carbonate content and other factors broke down. However, when the trough or coarse sand body samples were included along with the homogeneous sand body samples, the relationships were stronger.

The relationship between mean grain size and sorting was consistent among the IRB98JL samples sets (Figure 61), owing to the heterogeneity of these samples and in direct contrast to the MS98JL samples, which showed little variation and no strong trend in the relationship between these properties.

Mean grain size and backscatter intensity (Figure 62), which vary directly (e.g., Goff et al., 2000), were not consistent in the strength of correlation between them, although all correlations were significant (Table 37, Appendix C). An argument could be made for three separate best fit lines of relationships between mean grain size and backscatter (Figure 62), one which would fit predominantly the IRB97N data, a second which would fit the MS96M and some of the IRB data, and a third which would fit the MS98JL and scattered IRB data. However, the paucity of data points in the IRB samples sets, and their locations all at the ends of transect lines, make it difficult to speculate how valid those individual trend lines would be. Most of the other sedimentary properties showed little relationship when plotted against backscatter intensity (Figures 63, 64, and 65), and correlations were inconsistent and sometimes not significant (Table 37, Appendix C). Thus it could be argued that, *individually*, the sedimentary properties each account for only a small portion of the variability in backscatter intensity. This raises the question as to whether one factor could be said to dominate or whether it is these factors acting in concert that produce the distribution of backscatter intensity observed in the side-scan images.

Separate from the sedimentary properties, the standard deviation of the gray scale distributions, $\sigma_G$, is a measure of how well the gray scale values are sorted, much as it is for sedimentary distributions. A strong trend toward higher values of $\sigma_G$ (poorer sorting) with increasing backscatter intensity is exhibited (Figure 66), supported by the strong, significant correlation coefficients between these variables (Table 37, Appendix C). It seems more likely that the former is the result of the latter and not *vice versa*. However, it could also be argued that the variability in the values of gray scale pixels was caused by factors in the sedimentary properties and therefore led to higher mean gray scale values. There is, in fact, a moderate and significant trend toward higher values of $\sigma_G$ with more poorly sorted sediments (Figure 67), especially when the MS samples are ignored (Table 37, Appendix C). The values of $\sigma_G$ may be reflecting some variation in one or more sedimentary properties.

Alternatively, the values of $\sigma_G$ may reflect other sedimentary characteristics which were not quantified but which may have an impact on backscatter return. For example, increased bottom roughness has been found to result in higher acoustic backscatter (Davis et al., 1996), and variability in that factor could be responsible for the variations in values of $\sigma_G$. Whatever the reason for the relationship, because of the strength of the correlation between backscatter intensity and $\sigma_G$, the latter parameter was considered an independent variable in the multiple regression.

*Multiple Regressions.* In the regression which considered the MS96M and MS98JL sample sets and all independent variables (Figure 77, Appendix C) the coefficient of multiple determination was very high (R Square = 0.9725). This was somewhat unexpected, given the homogeneity of the MS area sediment, the lack of consistent trends in the sedimentary data from this area, and the fact that data from both 100 kHz and 500 kHz side-scan were being grouped together. However, $\sigma_G$ was the only significant variable in that regression.

By ignoring $\sigma_G$ and regressing backscatter intensity with just the sedimentary properties for all the MS samples, mean grain size became one of the dominant factors, but the R Square dropped to 0.6945, meaning that variations in $\sigma_G$ explained almost 30% of the variability in backscatter intensity.

When analyzed separately, the MS96M and MS98JL data showed similar results, with higher R Square values as long $\sigma_G$ was part of the regression, and lower R Square values when $\sigma_G$ was excluded and only the sedimentary property variables were regressed. Interestingly, for the MS96M samples, exclusion of $\sigma_G$ resulted in none of the sedimentary variables being statistically significant in determining the variability in gray scale (Figure 77, Appendix C). However, for the MS98JL samples, exclusion of $\sigma_G$ meant mean grain size was the significant independent variable and the drop in R Square (from 0.8981 to 0.7851) was not as large as for MS96M regression (from 0.9826 to 0.8005). Thus $\sigma_G$ explained less of the variability in the MS98JL samples, when looked at individually, than in the MS96M samples. Still, $\sigma_G$ was the most significant factor in the MS area, which invites the question as to what $\sigma_G$ is actually reflecting: variation in some sedimentary or water column property(s) or merely a measure of the noisiness of the side-scan signal?

In the multiple regression of all variables for all IRB samples, R Square was lower (0.6527) than in the MS area regressions (Figure 77, Appendix C). Less of the variability in backscatter intensity was explained by variations in the five independent variables. However, $\sigma_G$ was still the only statistically significant factor (Figure 77, Appendix C). When $\sigma_G$ was excluded from the regression, carbonate content emerged as the significant factor; however the R Square decreased to 0.4407, with $\sigma_G$ thus accounting for ~21% of the variability in the first regression. The importance of $\sigma_G$ was not diminished in the IRB regression, but the overall ability of the five independent variables to explain variations in backscatter intensity was less in the IRB area compared to the MS area. The greater variation in grain size distribution, sorting, and carbonate content in the IRB area, and the inconsistencies in their relationships, reduced the ability of the regression to predict backscatter intensity.

When all 500 kHz data were combined (MS98JL and all IRB sample sites), the regression results were mixed. Regressing all variables, the resulting R Square was 0.6161, less than for the overall MS or overall IRB. But, both $\sigma_G$ and $\sigma_\phi$ (sediment sorting) were significant coefficients (Figure 77, Appendix C). A simple regression between mean grain size and backscatter intensity showed that mean $\phi$ was successful in explaining ~16% of the variation in backscatter intensity for all 500 kHz data, while a similar calculation for $\sigma_G$ showed it alone could explain ~46% (Figure 77, Appendix C).

The regression equation with all coefficients for the combined 500 kHz data is (Figure 78, Appendix C):

$$GS = 1.951\sigma_G + 2.305\phi - 33.266\sigma_\phi + 63.627X_{Ca} + 832.904X_\mu - 18.561 \qquad (3)$$

where: $GS$ = backscatter intensity as approximated by mean gray scale value
$\sigma_G$ = standard deviation of values about the mean gray scale value
$\phi$ = mean grain size in phi units
$\sigma_\phi$ = sediment sorting
$X_{Ca}$ = percent calcium carbonate
$X_\mu$ = percent fine material

In a cumulative plot of actual gray scale values vs. those predicted by the regression equation (Figure 78, Appendix C), the regression equation appears to overpredict mean gray scale in the lower to middle values, then underpredict the larger values. In the comparison of predicted to actual values the lower backscatter intensity values were mainly from IRB samples; the mid-level values from MS98JL; and the higher values, a mix of MS and IRB data (Figure 78, Appendix C). Thus the implications for over- or underprediction of backscatter intensity are not spatially consistent.

*Regression Effectiveness.* Multiple regression was only partially successful in modeling the relationship between sediment properties and acoustic backscatter, and would overall be unsuccessful as an algorithm for predicting backscatter intensity from sediment properties (or *vice versa*). Why was this not successful?

The correlations and relationships between sedimentary properties were inconsistent. There was also a degree of dependency among some of them (e.g., carbonate content and mean grain size) which may have affected the analysis. The way in which samples were collected (along transects, primarily on the fine sands of the sand bodies) may have impacted the distribution of the sediment properties. While samples from 50 sites were analyzed, a better sampling method (a systematic grid, rather than transects) might have yielded a more representative sedimentary data set. Likewise, the size of the buffer around each sampling site (10 m radius) added variability to the backscatter intensity data by including pixels of backscatter from sediments which may not have corresponded with the actual sediment sample locations. Better navigation and better ground truthing methods might yield better results. In addition, there were inconsistencies in the side-scan data itself that affected actual backscatter intensity, in terms of acquisition parameters, conditions during collection (e.g., water column), and navigation.

The insignificance of mean grain size in all the regressions is puzzling. There is ample evidence that mean grain size is the primary factor in acoustic backscatter, and while other factors may also contribute, it is the relationship between grain size and backscatter that has driven most other models and classification algorithms (LeBlanc et al., 1992, 1995; Panda et al., 1994; Ryan and Flood, 1996). Goff et al. (2000) found that grain size distributions that were not unimodal, or which contained more large grains in otherwise fine sands, were disproportionately affected in terms of backscatter strength. Davis et al. (1996) found that the variability of backscatter strength associated with fine sands was nearly twice that associated with medium and coarse sands, due possibly to the sporadic occurrence of lag shell material or bedforms in fine sand areas. These factors were not quantified directly in this analysis, but the effect of large grains in fine sands would be represented in higher values of $\sigma_\phi$, which regressed significantly in the all-500 kHz analysis (though not in any others).

Other factors which were not quantified here, such as bottom roughness (Davis et al., 1996; Goff et al., 2000), might also have contributed significantly to the regression equation, or have been a factor related to grain size which would help explain why mean $\phi$ was not the dominant property in predicting backscatter intensity. Measurements of bottom roughness have been taken in the IRB area (Stephens et al., 1997), but not in conjunction with the side-scan surveys conducted in this study. Water column conditions affect acoustic backscatter (Rajan and Frisk, 1992) and may have played a part in the variation in side-scan signature. Since mosaics were collected at different times of the year and under varying weather conditions, suspended sediments or biological factors in the water column may have affected signal strength and backscatter intensity.

Another factor which was not measured or determinable for existing data were the effects of side-scan tow fish position during data acquisition. Tow fish heave, roll, pitch, and yaw all determine which area of the seafloor is being ensonified, and at what angle, during side-scan data collection. These instrument positions during acquisition affect the sonar backscatter signal observed (Ryan and Flood, 1996; Blondel and Murton, 1997). The system utilized for data acquisition in this study (see Chapter 4, Methods) was not able to account for these factors. In addition, some of the sediment sampling locations analyzed fell on sections of the side-scan image which were near nadir or near the outer edge of a swath, where signal strength is distorted. It is unknown how side-scan backscatter is affected by biological organisms on the seabed, especially the algal mat that was present during IRB data collection during the IRB97N, IRB98N1, and IRB98N2 surveys. The mat was at most a few millimeters thick, but at 500 kHz frequencies could have significantly affected sonar return by either attenuating or reflecting the signal.

*Summary*. Multiple regression did not explain a great deal of the side-scan variation over the sediments in the MS and IRB areas. Variability in conditions during acquisition of data and in the relationships of sedimentary properties made this attempt to model variations in backscatter intensity from sedimentary properties unsuccessful. To better evaluate the effectiveness of this modeling technique for using backscatter as a proxy for sedimentological values, better sampling is necessary, with more samples and a smaller buffer around the location in which to measure the side-scan pixel values. In addition, better side-scan data is needed, both in terms of navigation/tolerance errors and signal calibration, so that pixel values are representative of sediment properties at particular locations. Side-scan sonar, as a quantitative tool for seafloor sedimentary analysis, needs further assessment before its usefulness can be determined.

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