

## **Chapter 5**

### **Results: Observations and Analyses**

First order observations and characterizations from side-scan sonar, box cores, sediment samples, and current meter data are presented in this chapter, along with the results of analyses which were completed using these four data sets. First, sedimentary features are identified in the processed side-scan sonar images from each survey, and GIS analyses of boundary position changes based on the time series of sonar images are presented. Next, images of box core peels are displayed and the features within each core are identified. This is followed by presentation of physical sedimentary properties from collected samples and comparisons between the IRB and MS areas, including sedimentary properties of box core subsamples. The relationships between sedimentary properties and the side-scan sonar signal are also analyzed. Finally, the S4<sup>®</sup> current meter data are presented, compared between the IRB and MS areas, and also utilized along with sedimentary data to determine threshold values related to the initiation of sediment movement.

#### **Side-Scan Sonar**

Side-scan sonar images were processed using Elics DelphSonar and DelphMap software packages. Images were enhanced by manipulating time variable gain (TVG), signal amplitude, and other display variables in order to produce the clearest picture of the data for qualitative comparison. All images utilized the same gray scale pallet, progressing from an artificially designated, darkest pixel value of 255 (highest return) to the lightest

pixel value of 0 (lowest return). In all side-scan images, the following convention is followed:

- high backscatter (low signal attenuation) surfaces, are generally coarse sediments and/or exposed rock or other hardbottom material, represented by dark grays.
- low backscatter (high signal attenuation) surfaces, are generally fine sediments, represented by light grays.

Images are presented first for the MS study area, including GIS analyses, followed by the same for the IRB study area.

*MS Study Area Mosaics.* The 100 kHz side-scan sonar mosaic from the MS96M survey is presented in Figure 13 (see Figure 3 for location). Pixel resolution was 1 m x 1 m. The major morphologic feature in this mosaic, located between 27° 57' N and 27° 56' N and east of 83° 6' W, is a northwest-southeast trending sand body, with vertical relief of 1.5-4.5 m; the overall depth range is 15-20 m (Figure 85, Appendix F) (Hafen et al., 1997). The feature to the southwest of this sand body may be the southeastern terminus of another sand body. The low backscatter areas to the northeast are possibly part of a third sand body structure.

Smaller features also imaged include several high backscatter troughs within the main sand bodies, such as the one on the main sand feature beginning east of 83° 5' W and trending to the northwest (Figure 13). Most of these linear troughs trend with the axes of the sand bodies. Within the high backscatter trough features and near the edges of the sand bodies are ovate, low backscatter features, which are patches of fine sand with little vertical relief.

Subsequent diver observations in this area have noted the presence of smaller bedforms, predominantly ripples, within the fine sands of the sand bodies. These have frequencies of < 0.5 m, amplitudes ≤ 10 cm, and trend either north-south or perpendicular to the ridge axes. These features were not visible in the 100 kHz side-scan imagery (Figure

Figure 13

13). North-south trending bedforms in the coarse sediments of the troughs, which were also observed by divers and appeared in higher frequency side-scan images, are also not visible in the 100 kHz data.

500 kHz side-scan sonar from the MS98JL survey (Figure 14) is a subsection of the MS96M area (Figure 13), and focuses on a portion of the main sand body observed in the 1996 data. Even at this higher frequency and pixel resolution (0.2 m x 0.2 m), the low backscatter returns over the fine sands of the main sand ridge appear homogeneous; few features or bedforms are visible. Along the northeastern boundary of the sand ridge, several linear bedforms, perpendicular to the ridge axis, show a high backscatter return indicative of coarse sediment and/or exposed bedrock. The largest of these features is found near 27° 56' 40" N between 83° 05' 20" W and 83° 05' 25" W (Figure 14) and is visible on the MS96M 100 kHz image as well (Figures 13).

Parallel to the northeastern edge of the ridge are large features which exhibit a low backscatter return and have little vertical relief. Diver observations and sampling revealed these features to be thin veneers of sands of varying size and composition, overlying limestone bedrock (Figure 85, Appendix F) (Hafen et al., 1997 and 1998b). The distinct linear, high backscatter feature that appears to divide the largest of these sand patches (near 27° 57' 10" N and 83° 05' 35" W) is visible in the MS96M survey (Figure 13). The small, scattered sand patches on the northeast side of the main sand body are also visible on the MS96M image and do not appear to have changed in the two years separating the two surveys (Figures 13 and 14).

*MS Study Area GIS Analysis.* Seven sub-study areas (A-G) were analyzed in the MS area (Figure 6), comparing the digitized boundaries between high and low backscatter features from the MS96M and MS98JL side-scan images. Qualitatively, in MS sub-area A (Figure 15) the boundary shifts in the high/low backscatter boundary between the 1996 and

Figure 14

Figure 15

Figure 15

1998 surveys were not consistent. Some portions of the boundary shifted to the north and east (n/e) and some to the south and west (s/w). One area of change, 110.9 m<sup>2</sup> in the n/e direction (Table 3), exceeded the error tolerance buffers. Here, the border appeared to retreat toward the sand body between the 1996 and 1998 side-scan surveys. This was the only significant boundary movement in this sub-area (Figure 15).

**Table 3. Areas of polygons representing movement of fine sediments between 1996 and 1998 along sand body boundaries in the MS area. Movement to the north and east (n/e) are positive numbers; movement to the south and west (s/w) are negative numbers. See Figure 6 for locations of sub-areas A-G.**

	Area A	Σ Areas B, C, D	Area E	Area F	Area G	Totals
<b>Δ to n/e (+m<sup>2</sup>)</b>	+110.9	+953.1	0	0	0	+1064.0
<b>Δ to s/w (-m<sup>2</sup>)</b>	0	-692.4	0	-120.4	-263.3	-1076.1
<b>Net Δ (±m<sup>2</sup>)</b>	+110.9	+260.7	0	-120.4	-263.3	-12.1
<b>Boundary length (m)</b>	1171	3367	645	1020	2911	9114
<b>Δ m<sup>2</sup>/m of boundary</b>	+0.095	+0.077	0	-0.118	-0.090	-0.001

Along the northern border of the MS sand body, represented by sub-areas B, C, and D (Figure 6), boundary shifts were not consistently in one direction (Figure 16). Two areas of significant movement occurred. The first, in sub-area B, was the larger of the two and totaled 953.1 m<sup>2</sup> to the n/e (Table 3). The second, in sub-area C, totaled 692.4 m<sup>2</sup> to the s/w (Table 3). Net transport, then, was in the n/e direction, but there was nearly as much transport in the s/w directions as in the n/e (Table 3). The net change per meter of boundary in sub-area A (0.095 m<sup>2</sup>/m) and sub-areas B, C, and D (0.077 m<sup>2</sup>/m) were of the same order of magnitude and nearly identical. The distance across the sand body, separating these two boundaries, ranged from 1100-1600 m.

Boundary shifts from 1996 to 1998 in sub-area E (Figure 6) were mixed but were predominantly to the s/w (Figure 17); however, none exceeded the error tolerance buffers

Figure 16

Figure 16

Figure 17

Figure 17

(Table 3). Sub-area F contains a low backscatter feature surrounded on three sides by high sonar backscatter on side-scan imagery (Figure 6). Most of the northern and southern boundaries of this feature shifted to the s/w between 1996 and 1998, while the eastern boundaries shifted to the n/e (Figure 18). Two significant areas of change to the s/w occurred along the northern boundary, totalling 120.4 m<sup>2</sup>, or 0.118 m<sup>2</sup>/m of boundary, similar in magnitude to sub-areas A and B, C, and D (Table 3). The distances between the boundaries in sub-areas B, C, and D and those of E and F ranged from 200-920 m (Figure 6).

Sub-area G contained two low backscatter features in the trough north of the main sand body in the MS area (Figure 6). Border shifts from 1996 to 1998 were mixed, but showed consistency over long stretches of the boundaries (Figure 19). For example, almost all of the northern boundary and half of the southern boundary of the right (eastern) feature shifted to the s/w, while the eastern half of the southern boundary shifted to the n/e (Figure 19). Border shifts along the western feature were more mixed. Overall, significant change, beyond the error tolerance buffers, of 263.3 m<sup>2</sup> occurred to the s/w (Table 3) in two areas, one along the eastern feature and one along the western feature (Figure 19). The amount of change per meter of border (0.090 m<sup>2</sup>/m, Table 3) was consistent in magnitude with net change measured in the other sub-areas. Attached to the west end of the eastern feature, a small patch of low backscatter material, that was not present in the MS96M mosaic (Figure 13), appeared in the MS98JL mosaic (Figure 14) and accounts for most of the significant change measured (Figure 19). On the southern border of the western feature, a small patch of low backscatter, that was digitized as part of the whole feature in the MS96M mosaic, appeared as a detached and separate feature adjacent to the southern border in the MS98JL mosaic. The movement of this feature was not significant in relation to the error tolerance buffers.

Figure 18

Figure 18

Figure 19

Figure 19

*IRB Study Area Mosaics.* The quality of the IRB96M 500 kHz side-scan sonar mosaic from May 1996 (Figure 20) is poor, due primarily to inconsistent acquisition parameters. In addition, the individual lines were collected in conjunction with a multibeam bathymetric survey that required a very large number of closely spaced lines collected for the narrow bathymetry swath. The multibeam line spacing created excessive overlap of side-scan in some places and data gaps in other areas, where data collection was aborted due to malfunctions of the multibeam computer. Nevertheless, most features are discernable in the survey and can be compared to data from later surveys.

A series of northwest-southeast trending sand ridges, composed primarily of medium to fine sands were recently surveyed by Harrison (1996). These ridges are visible as low backscatter returns, separated by high backscatter, linear troughs of coarse sediments and exposed bedrock (Figure 20). The width of the troughs between the ridges increases from east to west with increasing water depth. Also visible are narrow, linear, transverse bedforms, that appear as high backscatter features, perpendicular to the ridge axes. Diver observations and sediment sampling in the southwest sub-study area (Figure 21) determined these to be shallow troughs filled with sediments coarser than those of the surrounding ridge, including whole and partial mollusk shells.

A partial 500 kHz survey of the IRB area was conducted in October 1997 (Figure 22). This survey included only the lower half of the full IRB study area. However, the observed features were consistent with those of Harrison (1996) and the IRB96M survey (Figure 20).

A full 500 kHz survey of the area was conducted in November 1997 (IRB97N), less than one month after IRB97O (Figure 23). The side-scan imagery shows the presence of all the major features identified in the IRB96M survey (Figure 23). Sediment sampling and diver observations were conducted on sand ridges in the southwestern portion of this area (Figure 24).

Figure 20

Figure 21

Figure 22

Figure 23

Figure 24

Data for the IRB98JL 500 kHz mosaic were collected in July 1998 (Figure 25). Sediment samples, box cores, and current meter data were collected on sand ridges in the southwestern sub-study area of this mosaic (Figure 26).

Despite use of the same acquisition parameters as the IRB97N survey, the IRB98JL image differs from IRB97N in terms of backscatter intensity contrast when first processed (Figures 23 and 25). This will be analyzed further in a later section of this chapter; however, different conditions in the water column (affecting signal attenuation, volume scattering, etc.) and variations in acquisition parameters (Table 2) contributed to the difference in image quality. The major features -- sand ridges, troughs, and superimposed bedforms -- are visible, and at first observation, appear to have changed little from the previous survey. The extent to which actual change has taken place is examined in the GIS analyses in the next section.

*IRB Study Area GIS Analysis.* Seven sub-study areas (A-G) were analyzed in the IRB area (Figure 7), comparing the digitized boundaries between high and low backscatter features from the MS96M and MS98JL side-scan images. Sub-areas A, B, and C, were similar in morphology as sand ridge-trough boundaries; sub-areas D, E, F, and G appeared similar as discrete high backscatter features that paralleled low backscatter ridge features (Figure 7).

Qualitatively, the boundary shifts in the high/low backscatter boundary in IRB sub-area A between 1996 and 1997 were not consistently in one direction (Figure 27), and none were significant enough to exceed the error tolerance buffers (Table 4). Some portions of the boundary shifted to the north and east (n/e) and some to the south and west (s/w). However, between 1996 and 1998, a significant area of movement of 168.6 m<sup>2</sup> to the n/e was observed (Table 4), and boundary shifts, though mixed, were found more frequently in the n/e direction.

Figure 25

Figure 26

Figure 27

Figure 27

**Table 4. Areas of polygons representing movement of fine sediments between 1996 and 1998 along sand ridge boundaries in IRB sub-areas A-C (Figure 7). Movements to the north and east (n/e) are positive numbers; movements to the south and west (s/w) are negative numbers.**

	Area A		Area B		Area C		$\Sigma$ (A, B, C)	
	1996-1997	1996-1998	1996-1997	1996-1998	1996-1997	1996-1998	1996-1997	1996-1998
$\Delta$ to n/e (+m <sup>2</sup> )	0	+168.6	0	0	+278.3	+539.3	+278.3	+707.9
$\Delta$ to s/w (-m <sup>2</sup> )	0	0	0	0	0	0	0	0
<b>Net <math>\Delta</math> (<math>\pm</math>m<sup>2</sup>)</b>	0	+168.6	0	0	+278.3	+539.3	+278.3	+707.9
<b>Boundary length (m)</b>	1498		717		1,153		3,368	
<b><math>\Delta</math> m<sup>2</sup>/m of boundary</b>	0	+0.113	0	0	+0.241	+0.468	+0.083	+0.210

The boundary in sub-area B was located along the southwestern flank of a ridge feature (Figure 7). The boundary shifts observed from 1996 to 1997 were mixed in direction (Figure 28) and not significant enough to exceed the error tolerance buffers (Table 4). However, the movements of two small low backscatter features near the ridge-trough boundary were to the south and east (Figure 28). These two features were both located near the southwestern boundary of a sand ridge (Figure 28) and were separated by a distance of ~150 m. From 1996 to 1998, boundary movements were still mixed, but the two small features again showed consistent movement to the south and east (Figure 28). The eastern (cross-shore) component of these movements correlated with those found in sub-area A (Figure 27).

The boundary in sub-area C was also located along the southwestern flank of a ridge feature (Figure 7) and was greater than 1000 m in length. All movement measured along this boundary from 1996 to 1997 (278.3 m<sup>2</sup>) and from 1996 to 1998 (539.3 m<sup>2</sup>) was to the n/e (Table 4). More than half the total movement measured from 1996 to 1998 occurred between 1996 and 1997. Boundary shifts observed were consistently to the n/e in

Figure 28

Figure 28

all the analyses (Figure 29). In addition, the polygons of significant change occurred at the same locations in both the 1996-1997 and 1996-1998 analyses (Figure 29).

Qualitatively and quantitatively, evidence of magnitude and direction of sediment movement was more consistent in sub-area C than in sub-areas A or B (Figures 27, 28 and 29; Table 4). Overall, measurable, significant movement in these three sub-areas was to the n/e from 1996 to 1998 (Table 4).

Sub-areas D, E, F, and G appeared as discrete, high backscatter features within the sand ridges of the eastern portion of the IRB study area (Figure 7). Sub-area D was located ~100 m to the east of the sand ridge boundary analyzed in sub-area C (Figure 7). All movement measured in sub-area D was to the s/w, with a small amount (5.2 m<sup>2</sup>) occurring from 1996 and 1997 and much more (900.5 m<sup>2</sup>) from 1996 to 1998 (Table 5). Boundary

**Table 5. Areas (in m<sup>2</sup>) of polygons representing movement of fine sediments between 1996 and 1998 along boundaries between high and low backscatter features in IRB sub-areas D-G (Figure 7). Movements to the north and east (n/e) are positive numbers; movements to the south and west (s/w) are negative numbers.**

	Area D		Area E		Area F		Area G		$\Sigma$ (D, E, F, G)	
	1996-1997	1996-1998	1996-1997	1996-1998	1996-1997	1996-1998	1996-1997	1996-1998	1996-1997	1996-1998
$\Delta$ to n/e (+m <sup>2</sup> )	0	0	+494.0	+2164.1	0	+112.0	+875.6	+76.3	+1369.6	+2352.4
$\Delta$ to s/w (-m <sup>2</sup> )	-5.2	-900.5	-554.5	-1469.5	0	0	0	-1.8	-559.7	-2371.8
Net $\Delta$ ( $\pm$ m <sup>2</sup> )	-5.2	-900.5	-60.5	+694.6	0	+112.0	+875.6	+74.5	+809.9	-19.4
Boundary length (m)	1849		3372		1259		1108		7588	
$\Delta$ m <sup>2</sup> /m of boundary	-0.003	-0.487	-0.018	+0.206	0	+0.089	+0.790	+0.067	+0.107	-0.003

Figure 29

Figure 29

shifts from 1996 to 1997 were not consistently in one direction, although movement to the s/w was evident on the western side of the feature (Figure 30). The boundary shifts observed from 1996 to 1998 were also mixed with some to the n/e and some to the s/w. Significant change was measured to the s/w, and the net effect was that the feature appeared to have expanded overall in total size, either by deposition of high backscatter materials or, more likely, the removal of low backscatter fine sands.

Sub-area E, located east of sub-area D, was the largest of the four discrete high backscatter features analyzed (Figure 7). Boundary shifts from 1996 to 1997 were mixed and indicated an overall expansion of the feature (Figure 31). Significant movement during this period was also mixed, with polygons totaling 494.0 m<sup>2</sup> to the n/e and 554.5 m<sup>2</sup> to the s/w (Table 5). Measured movement from 1996 to 1998 was more dominantly in the n/e direction, with 2164.1 m<sup>2</sup> to the n/e compared to 1469.5 m<sup>2</sup> to the s/w (Table 5). Observed boundary shifts were mixed overall, but again the feature appeared to expand overall as the measured movement to the s/w occurred on the west side of the feature and to the n/e on the east side (Figure 31).

The least amount of measured movement occurred in sub-area F (Figure 7). No significant movement occurred between 1996 and 1997; polygons totaling 112.0 m<sup>2</sup> to the n/e were measured from 1996 to 1998 (Table 5). Overall boundary shifts from 1996 to 1997 and 1996 to 1998 were not consistent in direction and the feature did not appear to expand in size (Figure 32) as did those in sub-areas D and E (Figure 30 and 31).

The smallest of the four high backscatter features, in sub-area G (Figure 7), showed the greatest amount of significant movement in the 1996 to 1997 period, with movement of 875.6 m<sup>2</sup> to the n/e, an average of 0.790 m<sup>2</sup>/m of boundary (Table 5). Boundary shifts during this period were consistently to the n/e (Figure 33). From 1996 to 1998, measured movement was much less at 76.3 m<sup>2</sup>, though still to the n/e (Table 5). The areas of measured movement for the latter period were consistent in location with those from the

Figure 30

Figure 30

Figure 31

Figure 31

Figure 32

Figure 32

Figure 33

Figure 33

1996 to 1997 period, but not in direction of movement. (Figure 33). Boundary shifts from 1996 to 1998 were more frequently to the n/e overall.

The summation of the observed changes in sub-areas D, E, F, and G indicates dominant movement to n/e during the 1996 to 1997 period, but almost equal movement in each set of directions during the 1996 to 1998 period (Table 5). Magnitude and direction of changes were inconsistent. Boundary shifts were mixed, but in three of the four features an overall expansion was indicated.

*IRB Sub-study Region Mosaics.* Side-scan surveys were completed in November 1998 in the southwest sub-study area of the IRB region where sediment samples, box cores, and current meter data had been collected in November 1997 and July 1998 (Figures 24 and 26). The two November 1998 side-scan and sediment sampling surveys were collected before (IRB98N1) and after (IRB98N2) the passage of a cold front (Figures 34 and 35). Current meter data were collected on one sand ridge between the two surveys (Figure 34).

Additional sedimentary features of interest in this subsection are:

- two sand wave termini, centered near 27° 56' 10" N and 82° 54' 30" W, which appeared to be offsetting and somewhat overlapping, as observed by Harrison (1996).
- oval sedimentary bedforms, similar in shape to "hummocks" identified in other studies (Ramsay et al., 1996; van de Meene et al., 1996; Vogt, 1997).
- linear, north-south trending bedforms, with ~1 m frequencies, in the coarse trough sediments.
- biologically active hardbottom, observed by Harrison (1996) and visible in the side-scan imagery, centered near 27° 56' 20" N and 82° 54' 36" W.

*IRB Sub-study Region GIS Analysis.* In the southwest sub-study region investigated in November 1998 (Figure 10), four sub-study areas were delineated for GIS analysis of the extent of movement along ridge-trough borders between 11/9/98 and 11/25/98 (Figure

Figure 34

Figure 35

8). Sub-area A was located on the northeastern flank of the main sand ridge in the IRB southwest sub-study region (Figure 8); movement along a boundary of 327 m was analyzed (Table 6). No movement exceeding the error tolerance buffers was measured in this area. Boundary shifts on side-scan data observed between the two surveys were mainly to the south and west along the southern portion of the high/low backscatter boundary, and mixed in the northern portion of the boundary (Figure 36).

**Table 6. Length of boundaries analyzed in side-scan images from November 9 (IRB98N1, Figure 34) and November 25, 1998 (IRB98N2, Figure 35). See Figure 8 for locations of sub-areas A, B, C, and D.**

	Area A	Area B	Area C	Area D	$\Sigma$ (A, B, C, D)
<b>Boundary length (m)</b>	327	798	2133	681	3939

Sub-area B was located on the southwestern flank of the same sand ridge as sub-area A, but contained a longer (798 m) boundary (Table 6). These two areas were approximately 300 m apart at the widest part of the sand ridge (Figure 8). No significant movement was measured along the boundary, and boundary shifts observed were not consistently in one direction (Figure 37). Sub-area B also contained the same two small, low backscatter features observed in the 1996-1998 analysis of IRB sub-area B (Figure 28). Consistent with the 1996-1998 observations, these two features appeared to move to the south and east during the period of the November 1998 experiments (Figure 37). In fact, by the final side-scan data collection on November 25, 1998 (Figure 35), the smaller of the two features in this area had moved enough that it was not distinguishable as a separate feature from the adjacent sand ridge (Figure 37).

The boundary in sub-area C (Figure 8) was the longest (2133 m) analyzed in this area (Table 6). The trough separating sub-areas B and C varied in width from 50-200 m (Figure 8). Both the northeastern and southwestern flanks of a sand body were included in sub-area C. Boundary shifts between the two surveys showed no consistent change or

Figure 36

Figure 36

Figure 37

Figure 37

patterns (Figure 38). No significant movement exceeding the error tolerances was measured in sub-area C.

Sub-area D encompassed the northeastern flank of a sand body, separated from sub-area C by a trough ~50-100 m wide (Figure 8). Boundary shifts along the 681 m high/low backscatter border (Table 6) were mixed, no discernable patterns were observed, and no significant movement was measured (Figure 39).

Overall, no measurable movement was observed during the period of the November 1998 analysis. The only consistent qualitative changes observed were the movements of the small low backscatter features in sub-area B (Figure 37).

*Summary.* Side-scan data and GIS analyses for the MS and IRB study areas revealed evidence of sediment movement over seasonal/annual time scales, though not always consistent in direction or magnitude. Sediment movement on the shorter time scale experiment in the IRB sub-study area was not indicated.

### Box Cores

Box cores were retrieved in both the MS and IRB study areas. Scanned images of the box core peels and the properties of sediment subsamples from the cores are presented and described in this section.

*MS Study Area.* Sediment samples taken from the MS01 box cores (Figure 40) had mean grain sizes in the fine sand range (Table 7). The standard deviation values about these means (Table 7) indicate moderate to poor sorting (Folk, 1980; Carranza-Edwards et al., 1998; Livingstone et al., 1999). Descriptions made of the cores before embedding noted a darker sediment color below 2 cm, a higher abundance of shell material below 15 cm, and a sulphur smell emanating from both cores.

Figure 38

Figure 38

Figure 39

Figure 39

Figure 40

**Table 7. Mean grain size and sorting (standard deviation,  $\sigma$ ) for MS box core sediment subsamples. Locations of the box cores are shown in Figure 14.**

Box Core	0-2 cm depth in core		13-15 cm depth in core	
	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	Mean $\phi$	$\pm\sigma$ ( $\phi$ )
MS01-A	2.630	1.210	2.839	0.764
MS01-B	2.559	1.366	2.590	1.113
MS02-A	2.836	0.638	2.857	0.626
MS02-B	2.837	0.669	2.834	0.635
MS03-A	2.672	0.714	2.637	0.754
MS03-B	2.580	0.753	2.585	0.889

From the sediment-water interface to a depth of approximately 25 cm, there are few visible sedimentary structures in either of the MS01 cores (Figure 40), which were taken from the southwest flank of the sand body in the MS study area (Figure 14). Some very fine-scale laminations may be present in the two cores; however, it was difficult to determine if these linear beddings are genuine or an artifact of the embedding process. Sediments appear homogeneous throughout the core in MS01-A. Some change in grain size is evident in the lower 5 cm of MS01-B (Figure 40). A thin, shelly bedding plane separates slightly different sediment (color, texture) in the lower 5 cm of the core in MS01-B. This horizon is not visible in MS01-A. Preserved biomatter in both cores consists primarily of small shells and foraminifera tests, except for two large shells at 18-20 cm in MS01-B (Figure 40). These large shells are part of a layered assemblage of shells infilling a burrow or some other structure that is ~5 cm wide at its base and extends from 16 cm to at least the base of the core (Figure 40).

Box core peels from site MS02 (Figure 41) were recovered near the center of the main sand body in the MS area, near the location of the S4<sup>®</sup> current meter deployment (Figure 14). In both cores, the mean grain sizes at the 0-2 cm and 13-15 cm sampling depths were in the fine sand range, with standard deviations indicating moderate sorting

Figure 41

(Table 7). In descriptions of the cores made prior to embedding, foraminifera tests were noted in the sediments to a depth of 15 cm in MS02-A. Also noted was a change in sediment color/texture at ~5 cm depth in both cores, and again at 20 cm depth surrounding the area where a large shell (6 cm in length) is preserved.

As with the MS01 cores, there is an absence of bedding structures in either of the MS02 cores; the many parallel gaps visible in MS02-B were likely a processing artifact, although they may be related to fine-scale bedding planes (Beavers, 1999). Some small shell fragments are visible between 11 and 12 cm depth in MS02-A. A large shell is preserved between 18 and 22 cm depth in MS02-A, with some surrounding sediment discoloration visible in this core and in MS02-B at the same depth (Figure 41). Except for the sediments surrounding this preserved shell, the sediments throughout the cores are homogeneous in color and texture.

The MS03 cores (Figure 42) were taken from the northeast edge of the main sand ridge of the study area (Figure 14). Sediments were very fine, moderately sorted sands (Table 7). It should be noted that the top 0.5 cm of the sediment in peel MS03-A was lost in processing.

Consistent with the other cores from this area, no bedding structures are visible in this set of cores. A concentration of small shells and fragments was noted at 10 cm depth in peel MS03-A (Figure 42). A large shell is buried in MS03-B between 12 and 14 cm depth, the outline of which is visible in the peel (the shell itself did not remain attached to the peel) (Figure 42). Some alteration of the sediment color is visible near where the shell was located. Overall, few differences were evident in the sediments between this set of cores and those from the other two sites in the MS area.

Figure 42

*IRB Study Area.* A total of ten box cores were retrieved from four sites in the IRB southwestern sub-study region. Eight cores (two per site) were collected from the four sites in July 1998 (Figure 26), and two more were collected from one of the sites in November 1998 (Figure 34).

The IRB01 box cores were taken from the northeast edge of the main sand ridge in the IRB sub-study region, near the northeast terminus of sediment sampling Transect 2 (Figure 26). Mean grain sizes at 0-2 cm and 13-15 cm were in the range of medium sand and were moderately sorted (Folk, 1980) (Table 8).

**Table 8. Mean grain size and standard deviation for IRB July 1998 box core sediment subsamples. Locations of box cores are shown in Figure 26.**

Box Core	0-2 cm depth in core		13-15 cm depth in core	
	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	Mean $\phi$	$\pm\sigma$ ( $\phi$ )
IRB01-A	1.377	0.971	1.455	0.853
IRB01-B	1.445	0.935	1.565	0.736
IRB02-A	2.229	0.748	1.496	1.027
IRB02-B	2.294	0.693	1.637	0.996
IRB03-A	2.230	1.477	1.862	1.421
IRB03-B	2.252	1.347	-0.311	2.262
IRB04-A	2.185	1.227	2.025	1.322
IRB04-B	2.310	1.005	2.328	0.937

Unlike the cores in the MS study area, those in the IRB area all exhibit bedding structures at various depths in the cores. IRB01-A and IRB01-B both show corresponding bedding planes at depths of 10-12 cm and 16-18 cm (Figure 43). Evidence of bioturbation (clusters of shell material, possible infilled burrows) exists throughout both cores. From 6-11 cm in IRB01-B, laminations parallel to a bedding plane at 12 cm are found. Likewise, laminations parallel to a deeper bedding plane are seen from 16-18 cm. These are not evident in IRB01-A, which was taken parallel to the ridge axis and perpendicular to IRB01-B. The lower bedding plane from both cores dips at a low angle, as do the parallel laminations above it and above the upper bedding plane.

Figure 43

IRB02-A and IRB02-B (Figure 44), were recovered in July 1998 from the center of the main sand ridge in the IRB sub-study region, near the site of the current meter deployments (Figure 26). It was noted in the core descriptions made prior to embedding that sediments became coarser with depth and contained more shell materials. Surface subsamples have mean grain sizes in the fine sand range and are moderately sorted; those from 13-15 cm were medium sands, moderately to poorly sorted (Table 8).

Two bedding planes were identified from peels IRB02-A and IRB02-B, one between 6 and 10 cm depth in both cores, and another between 16 and 21 cm in IRB02-A and between 19 and 25 cm in IRB02-B (Figure 44). The sediments above 6-10 cm in both cores appear to be heavily bioturbated with no visible sedimentary structures. A narrow infilled burrow extends from 3 to 16 cm depth in IRB02-A. In IRB02-A, the sediments below each of the bedding planes are laminated and parallel to the planes. Shell material and other larger sedimentary particles are more evident in the lowest portions of both cores, reflected in the mean grain sizes at the 13-15 cm intervals of 1.496  $\phi$  for IRB02-A and 1.637  $\phi$  for IRB02-B (Table 8).

Box cores IRB02-C and IRB02-D were recovered in November 1998 (Figure 34) from the same location as IRB02-A and IRB02-B (Figure 26), but at different angles relative to the ridge axis, facing southwest and southeast, respectively (Figure 45). Pre-embedding core descriptions noted an increase in large shells and shell hash with depth in both cores, as well as a transition from a lighter, yellow-gray sand in the upper 6 cm to a darker gray sand below 6 cm. Analyses of sediment subsamples taken every 2 cm from these cores revealed moderately sorted fine sands except at two intervals. Shelly bedding planes at 6 cm and below 16 cm in both cores contained poorly sorted, medium sands reflecting the increased amount of shell materials at these depths (Figure 46; Table 9).

Two horizontal bedding planes are visible in IRB02-C and IRB02-D at ~6 cm depth and again at 16-18 cm depth (Figure 45), similar in location to those of IRB02-A and

Figure 44

Figure 45

Figure 46

**Table 9. Mean grain size and standard deviation for IRB November 1998 box core sediment subsamples. Box cores locations are shown in Figure 34.**

Depth (cm)	IRB02-C		IRB02-D	
	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	Mean $\phi$	$\pm\sigma$ ( $\phi$ )
0-2	2.287	0.601	2.056	0.791
2-4	2.221	0.712	1.968	1.049
4-6	1.992	1.232	1.926	0.950
6-8	1.717	1.684	1.931	1.031
8-10	2.179	0.888	2.178	0.765
10-12	2.181	0.748	2.134	0.652
12-14	2.082	0.967	2.269	0.758
14-16	2.141	0.867	2.068	0.908
16-18	1.822	1.110	1.977	1.096
18-20	1.693	1.181	1.417	1.426

IRB02-B (Figure 44). Sediments above the 6 cm plane exhibit low angle parallel laminations and contain a small number of shells and large shell fragments. Sediments below each of the bedding planes contain increasingly larger shells and fragments, but do not exhibit any laminated or cross-bedding structures.

Cores IRB03-A and IRB03-B (Figure 47) were taken from the southwest edge of the main sand ridge in the IRB sub-study region, near the southwest terminus of sediment sampling Transect 2 (Figure 26). Core descriptions prior to embedding noted several changes in color and texture of sediments with depth in the cores, with a notable increase in whole shell materials below 15 cm. In addition to shell materials, a small sponge was recovered from IRB03-A at 10 cm depth. The grain size and sorting of sediment samples from 0-2 cm 13-15 cm are remarkably different (Table 8). The surface samples are poorly sorted, fine sands in both cores, but the deeper samples are poorly sorted medium sands for IRB03-A and a very poorly sorted, very coarse sands for IRB03-B.

Figure 47

Three bedding planes were observed in the IRB03 core peels (Figure 47). The first occurs at 3-4 cm depth in both cores. The fine sands above this flat surface contain a few large shells and exhibit no lamination or other structures. The second bedding plane occurs between 6 and 10 cm, and appears as an irregular surface. In IRB03-A, this plane separates a darker gray sand with few shells from a lighter gray sand with more small shells and fragments (Figure 47). In IRB03-B, the second bedding plane is more marked, consisting of a thin layer of coarse shell material separating sands with varying shell material content above and below. The third bedding plane occurs at ~14 cm depth in both IRB03 cores. The sediments below this plane are mainly whole shells and shell hash material, similar in composition to the shell materials, ~20 cm thick, in the trough on the southwest side of the IRB sub-study region sand ridge (Figure 26). In IRB03-A, within the lower shelly layer, is a sandy feature, devoid of shells, protruding upwards from the core base to 19 cm depth (Figure 47). It is unclear if this represents any significant change in the composition of the sediments at this depth, although it could be a buried bedform such as a sand ripple.

Cores IRB04-A and IRB04-B (Figure 48) were taken from an oval patch of sand located near the southwestern edge of the sand ridge in the IRB sub-study region (Figure 26). This feature appears as an area of low acoustic backscatter on every side-scan sonar image in this study (e.g., Figures 25 and 26) and has been present since the initial survey by Harrison (1996). Core descriptions prior to embedding noted few features other than mottling of sediment color, an indicator of biochemical alteration (Lewis and McConchie, 1994b). Mean grain size is in the fine sand range, poorly sorted, for both cores at 0-2 cm; subsamples at 13-15 cm were also fine sands, moderately to poorly sorted (Table 8).

Two bedding planes were identified in the upper half of each of the IRB04 cores (Figure 48). The first occurs ~5 cm depth in IRB04-A and ~3 cm depth in IRB04-B. The sediments above this horizon exhibit some laminations and contain numerous small shells and fragments. Below this bedding plane in IRB04-A, sediments appear finer than those

Figure 48

above the bedding plane, but contain larger shells which were distributed laterally, resembling a single laminated structure. In IRB04-B, however, almost no shell material is included with the finer sands. Very fine-scale, parallel laminations are evident, just above the next bedding plane at 8-10 cm depth; the correlated plane in IRB04-A occurs at 7-9 cm depth.

Below the second bedding planes in both IRB04 cores are evidence of biological alteration and bioturbation. From 8-12 cm depth in IRB04-A is an area which spreads 8 cm laterally and is filled with very small shells and sand in a pattern of vertical, crescent-shaped laminations, as if it had been infilled from the side (Figure 48). At 16 cm depth is a 2 cm, barnacle-covered shell with some surrounding discoloration of the sediment. In IRB04-B, what appears to be a ~2 cm wide, infilled burrow structure extends from 10-16 cm depth. Isolated parallel structures below 16 cm in IRB04-B do not appear to be depositional laminations but may be lateral burrow structures.

*Summary of Box Core Results.* Overall, the IRB area box cores exhibited more evidence of depositional activity, in the form of bedding planes, parallel laminations, and changes in sedimentary properties, than the MS area cores, which showed little change with depth. The properties of sediment subsamples differed between the two areas. Those from the MS area were finer, overall, and more consistent in grain size across the MS sand ridge and with depth in each core than those from the IRB area. Sorting at the MS02 and MS03 sites was better (moderate) than any of the IRB sites. The subsamples from the IRB cores exhibited some spatial variations in grain size and sorting, both across the sand ridge and with depth, reflecting the presence of bedding structures and shell/hash layers downcore, as well as variations across the sand ridge surface.

## Sediment Samples

In this section, data from the time series of surface sediment samples are presented. Two sets of sediment grab samples were obtained from the MS study area, in May 1996 (MS96M) and July 1998 (MS98JL). Four sets of samples were collected in the IRB area, one in November 1997 (IRB97N), one in July 1998 (IRB98JL), and two in November 1998, before (IRB98N1) and after (IRB98N2) the passage of a cold front. Sedimentary properties measured include cumulative grain size distribution, mean grain size and sorting (standard deviation), percent carbonate content, and percent silt and clay (Appendix A). The results of statistical tests to determine spatial and temporal variations between and within study areas are presented. The relationship between sedimentary properties and the side-scan sonar signal using multiple regression is modeled.

*MS96M.* Sample sites 01-07 were located on an east-west transect across the main sand ridge in the study area; sample site 08 was located south of the main sand body (Figure 13). Due to losses which occurred in processing, no data for sample MS96-04B are presented.

With the exception of samples 08A and 08B, sedimentary properties across the sand body showed remarkable similarity (Figures 49 and 50). Samples from sites 01-07 all showed the greatest percentage of their grains concentrated in the 3.0-4.0  $\phi$  class sizes. The mean grain sizes of the sediment samples from sites 01-07 were primarily fine sands; two samples (MS96-01A and -05B) were very fine sands. Most were moderately well sorted, with the exception of site 07, where samples MS96-07A and -07B showed only moderate sorting (Folk, 1980). Spatial variations in carbonate content and in silt and clay content were not discernable in the main sand body samples, except for those from site 07. Those from site 07 showed a higher percentage of carbonate content in the sand-sized fraction, and a higher percentage of silt and clay in the total sample, than those from the other sand body

Figure 49

Figure 50

transect sites (Table 10). The overall lack of variation in sedimentary characteristics across the ridge correlated well with the homogeneous backscatter seen in the side-scan imagery from this area (Figure 13).

**Table 10. MS96M sediment sample data (Figure 13). Mean grain size and degree of sorting were calculated for the coarse fraction (larger than 4  $\phi$ ); carbonate content was determined from the sand fraction only (-1  $\phi$  through 4  $\phi$ ); and percent silt and clay was determined from the total sample.**

Sample	Mean $\phi$ (in $\geq 4 \phi$ )	$\pm\sigma$ ( $\phi$ ) (in $\geq 4 \phi$ )	% Carbonate (in -1 $\phi$ through 4 $\phi$ )	% silt & clay (in total sample)
MS96-01A	3.222	0.666	11.72%	1.84%
MS96-01B	2.439	0.449	15.53%	2.49%
MS96-02A	2.486	0.583	14.42%	2.51%
MS96-02B	2.432	0.497	18.87%	1.95%
MS96-03A	2.434	0.637	22.81%	2.32%
MS96-03B	2.365	0.600	19.70%	2.54%
MS96-04A	2.566	0.576	19.20%	2.42%
MS96-05A	2.461	0.513	17.85%	2.28%
MS96-05B	3.034	0.705	17.76%	2.43%
MS96-06A	2.619	0.613	21.45%	3.64%
MS96-06B	2.474	0.512	24.85%	3.88%
MS96-07A	2.529	0.901	30.03%	8.54%
MS96-07B	2.678	0.849	27.48%	9.14%
MS96-08A	1.318	0.881	70.17%	0.99%
MS96-08B	1.352	1.420	58.60%	1.57%

In contrast to the sand ridge samples, sediments from MS96-08A and -08B were medium sands, poorly to moderately sorted, with a high carbonate content and the lowest silt and clay fraction of any of the sites. Nearly 80% of their grains from these sites were concentrated between -3  $\phi$  and 2  $\phi$ , which was reflected in the high backscatter side-scan signal observed over these trough sediments compared to those from sites 01-07 on the sand body (Figure 13).

Correlation coefficients between all four sedimentary properties (Table 11) were calculated first for all samples, then for samples from sites 01-07 (on the sand body) only. A separate set of correlations was calculated for samples from sites 01-06, excluding those

from site 07, which had a higher carbonate content, a higher percentage of fine materials, and were more poorly sorted than the remaining sand ridge samples (Figure 50).

Significance tests were derived from Rohlf and Sokal (1981).

**Table 11. Correlation coefficients among mean grain size, sorting, percent carbonate, and percent fine fraction for MS96M sediment samples (Table 10). Coefficients were calculated first for all samples; absolute values exceeding 0.514 are significant ( $\alpha = .05$ , for  $\nu = 13$ ). Coefficients were then calculated for samples from sites 01-07, which were collected from the sand body (Figure 13); absolute values exceeding 0.754 are significant ( $\alpha = .05$ , for  $\nu = 5$ ). Finally, coefficients were calculated for samples 01-06, which were all similar in their distribution of values in each property (Table 10); no values exceeded the significant value of 0.811 ( $\alpha = .05$ , for  $\nu = 4$ ).**

All Samples	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.5784	1		
% CaCO <sub>3</sub>	-0.8851	0.7486	1	
% Silt and Clay	0.2773	0.1428	-0.0972	1
Samples 01-07	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	0.3649	1		
% CaCO <sub>3</sub>	-0.3397	0.5875	1	
% Silt and Clay	-0.0398	0.7942	0.8174	1
Samples 01-06	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	0.6816	1		
% CaCO <sub>3</sub>	-0.5123	-0.1196	1	
% Silt and Clay	-0.2537	-0.1362	0.6626	1

For all MS96M sediment samples, the relationship between the percentage of fine material and the other properties was virtually non-existent. The strongest (statistically significant) relationships were between mean grain size and percent carbonate and between sorting and percent carbonate. Grain size coarsened (mean  $\phi$  decreased) as the percent carbonate increased. This relationship was expected, as larger grain sizes consisted of

molluscan shell fragments and carbonate lithoclasts. Likewise, sorting became poorer ( $\sigma$  increased) as percent carbonate increased, due to the number of various sized shell fragments and other larger particles. A weaker but still significant relationship was exhibited between mean grain size and sorting ( $r = -0.5784$ ), with poorer sorting associated with coarser grain size. This relationship reversed and was not significant when the coarse trough samples were excluded (Table 11), that is, a weak positive relationship between poorer sorting and finer grain size was present.

For the sand body-only samples (sites 01-07), the strongest and only significant correlations were between the amount of fine material and the amount of carbonate ( $r = 0.8174$ ) and between fine material and sorting ( $r = 0.7942$ ). The elimination of the trough samples, which had little fine material but very high carbonate contents, revealed a stronger correlation between these properties in the sand body sediments, which had more (and variable) fine material to compare to carbonates (Table 10). The strength of the relationship between sorting and percent carbonate was weaker and not significant for the sand body-only samples ( $r = 0.5875$ ) compared to that for all samples ( $r = 0.7846$ ). All other relationships between properties for the ridge samples were weak and not significant (Table 11).

A third set of correlation coefficients was calculated, eliminating samples from site 07, which differed from all other sand ridge samples in carbonate content, amount of fine material, and sorting. With these samples eliminated, the remaining sand ridge samples showed a positive correlation between carbonate content and fine materials ( $r = 0.6626$ ) that was not significant. The relationship between poorer sorting and finer grain sizes was stronger ( $r = 0.6816$ ) than when the site 07 samples were included ( $r = 0.3649$ ), but was still not statistically significant (Table 11). Likewise the relationship between mean grain size and carbonate content ( $r = -0.5123$ ) was more pronounced, but also not significant at this small sample size (Table 11).

*MS98JL*. Sediment samples were collected at thirteen sites in the MS study area in conjunction with the July 1998 side-scan sonar survey and box core collection (Figure 14). Sample sites 01-10 were located on a roughly southwest-northeast trending transect across the main sand ridge in the study area. Site 11 was a successful test grab on the southern edge of the main sand ridge and these data were included in the results for this area. Data were also included from sample sites 29 and 30, which were located in an area of thin sedimentary cover north of the main sand ridge and were collected by divers during box coring operations.

Samples 01-11 were similar in their grain size distributions, with samples 06 and 10 exhibiting a somewhat higher proportion of grains coarser than  $2\phi$  (Figure 51; Table 24, Appendix A). The *MS98JL* sand ridge samples were primarily moderately well sorted, fine sands, except at locations 06 and 10, which had mean grain sizes in the medium sand range, and at locations 03 and 08, which were well sorted (Table 12). No spatial patterns of variations in grain size, sorting, carbonate content, or silt and clay content were discernable across the main sand body (Figure 52). Carbonate content increased slightly across the transect from the southern (01) to the northern (10) sand ridge samples, from less than 20% to near 25% (Table 12; Figure 52). However, this increase did not correspond with changes in grain size, sorting, or amount of fine material across the sand body. The overall homogeneity of the sedimentary characteristics was consistent with the low backscatter signal across the main sand body seen in the side-scan imagery of the *MS98JL* survey (Figure 14).

Figure 51

Figure 52

**Table 12. MS98JL sediment sample data (Figure 14). Mean grain size and degree of sorting were calculated for the coarse fraction (larger than 4  $\phi$ ); carbonate content was determined from the sand fraction only (-1  $\phi$  through 4  $\phi$ ); and percent silt and clay was determined from the total sample.**

<b>Sample</b>	<b>Mean <math>\phi</math> (in <math>\geq 4 \phi</math>)</b>	<b><math>\pm\sigma</math> (<math>\phi</math>) (in <math>\geq 4 \phi</math>)</b>	<b>% Carbonate (in -1 <math>\phi</math> through 4 <math>\phi</math>)</b>	<b>% silt &amp; clay (in total sample)</b>
MS98-01	2.236	0.544	17.86%	4.01%
MS98-02	2.213	0.553	20.53%	8.70%
MS98-03	2.288	0.455	15.44%	5.26%
MS98-04	2.264	0.595	16.18%	5.37%
MS98-05	2.236	0.614	18.99%	4.43%
MS98-06	1.840	0.587	18.86%	4.36%
MS98-07	2.188	0.629	22.93%	5.17%
MS98-08	2.307	0.453	20.46%	6.34%
MS98-09	2.206	0.513	23.87%	7.50%
MS98-10	1.884	0.574	25.53%	3.25%
MS98-11	2.308	0.597	25.42%	7.09%
MS98-29	2.583	0.687	49.32%	15.20%
MS98-30	0.471	0.709	37.41%	4.21%

Sample 29 sediments, from the area north of the sand body, displayed similar grain size and sorting characteristics to those on the sand bodies and exhibited an even higher proportion of finer sands than the sand body samples (Figure 51). Site 30 sediments were moderately well sorted coarse sands with nearly 90% of grains 1  $\phi$  or coarser. Samples 29 and 30 exhibited higher carbonate content, and a 2-3 fold increase in the silt and clay content at site 29, compared to sites 01-11 (Table 12, Figure 52). Samples 29 and 30 were taken ~2 m apart, in an area of thin (~20 cm) sedimentary cover near an active hardbottom community, which may account for the higher carbonate content in these samples. Divers observed a sharply-defined boundary between coarse and finer materials, represented in the side-scan imagery by a sharp transition from a high to a low backscatter return (Figure 14).

Correlation coefficients were calculated first for all samples, then for samples from sites 01-11 (on the sand ridge) only, excluding those from sites 29 and 30 (off the sand body) (Table 13). Significance tests were derived from Rohlf and Sokal (1981).

**Table 13. Correlation coefficients among mean grain size, sorting, percent carbonate, and percent fine fraction for MS98JL sediment samples (Table 12). Coefficients were calculated first for all samples; absolute values exceeding 0.553 are significant ( $\alpha = .05$ , for  $v = 11$ ). Coefficients were then calculated for samples from sites 01-11 only, which were collected from the sand body (Figure 14); none of the correlations for samples 01-11 are significant (absolute values exceeding 0.602,  $\alpha = .05$ , for  $v = 9$ ).**

All Samples	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.4403	1		
% CaCO <sub>3</sub>	-0.2371	0.6817	1	
% Silt and Clay	0.4350	0.2204	0.6673	1
Samples 01-11	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.3024	1		
% CaCO <sub>3</sub>	-0.2360	0.2710	1	
% Silt and Clay	0.5014	-0.2413	0.2012	1

In the entire sample set, the strongest correlations, and the only statistically significant ones, were between sorting and carbonate content ( $r = 0.6817$ ) and percent fine material and carbonate content ( $r = 0.6673$ ). As carbonate content increased, sorting became poorer because of the increased number of shell fragments and other large carbonate grains. At the same time, the amount of fine material increased. These relationships were influenced by samples 29 and 30. When these samples were removed, the correlations dropped to  $r = 0.2710$  and  $r = 0.2012$ , respectively (Table 13), and were not significant. A moderate (though not significant) correlation over the entire sample set was exhibited between mean phi and sorting ( $r = -0.4403$ ), with sorting becoming poorer as mean grain size became coarser (mean  $\phi$  decreased). This relationship also became weaker ( $r = -0.3024$ ) when samples 29 and 30 were excluded, and was not significant. The relationship between mean grain size and carbonate content remained the same between the entire sample set and the removal of samples 29 and 30, though consistently weak and not

significant. Sorting became poorer as the amount of fine material increased for the complete data set ( $r = 0.2204$ ). This relationship was reversed ( $r = -0.2413$ ) for the sand body-only samples, as sorting improved with increased percentage of fine material; however, the correlation was not statistically significant.

*IRB97N*. The first side-scan sonar survey in the IRB study area for which sedimentary data were collected occurred in November 1997. Divers retrieved surface sediment samples along three transects across the ridges in the IRB sub-study region (Figure 24). Ten samples, planned ~24 m apart, were collected along Transect 1 (T1); eleven samples, ~30 m apart, were collected along Transect 2 (T2); and eleven samples, ~20 m apart, were collected along Transect 3 (T3).

The grain size distributions for the IRB97N-T1 samples (Figure 53; Table 26, Appendix A) were less uniform than those from the sediments from either of the MS area surveys (Figures 49 and 51). The IRB97N-T1 transect extended over an area of oval-shaped, hummocky structures, where two dune termini overlapped, providing alternating areas of fine and coarse sediments (Figure 24). Variations in mean grain size, from very poorly sorted coarse sands (T1-01) to well sorted fine sands (T1-09), reflected the changes in morphology seen across this transect and correlated with the high and low backscatter side-scan signals recorded during the IRB97N survey (Figure 24). Carbonate values were not as variable as grain size or sorting across the transect, and no relationship among these variables was apparent (Figure 54). Silt and clay content varied from ~1% to ~2%, except at T1-01, which contained more than 5% fine materials (Table 14).

Figure 53

Figure 53

Figure 53

Figure 54

**Table 14. IRB97N sediment sample data (Figure 24). Mean grain size and degree of sorting calculated for the coarse fraction (larger than 4  $\phi$ ); carbonate content was determined from the sand fraction only (-1  $\phi$  through 4  $\phi$ ); and percent silt and clay was determined from the total sample.**

<b>Sample</b>	<b>Mean <math>\phi</math> (in <math>\geq 4 \phi</math>)</b>	<b><math>\pm\sigma</math> (<math>\phi</math>) (in <math>\geq 4 \phi</math>)</b>	<b>% Carbonate (in -1 <math>\phi</math> through 4 <math>\phi</math>)</b>	<b>% silt &amp; clay (in total sample)</b>
T1-01	0.795	2.313	13.98%	5.18%
T1-02	2.495	0.705	7.15%	1.26%
T1-03	2.213	0.842	13.44%	1.20%
T1-05	1.827	0.855	13.51%	1.61%
T1-06	2.382	0.663	15.50%	1.78%
T1-07	1.193	0.804	15.27%	1.37%
T1-08	2.059	0.623	11.43%	0.91%
T1-09	2.365	0.496	13.20%	1.22%
T1-10	1.584	1.004	6.00%	1.87%
T1-11	1.028	1.034	26.09%	2.09%
<hr/>				
T2-01	-0.705	1.461	33.80%	2.04%
T2-02	2.176	0.542	6.92%	1.69%
T2-03	1.264	0.798	6.44%	1.86%
T2-04	1.287	0.721	11.48%	1.43%
T2-05	1.542	0.698	16.80%	1.58%
T2-06	1.604	0.660	21.57%	1.49%
T2-07	1.793	0.408	15.51%	1.22%
T2-08	1.593	0.490	2.78%	1.11%
T2-09	1.250	0.607	9.30%	1.65%
T2-10	1.289	0.708	7.89%	1.25%
T2-11	1.254	0.693	15.48%	1.30%
<hr/>				
T3-01	2.608	0.535	5.30%	1.42%
T3-02	2.497	0.507	12.81%	1.62%
T3-03	2.210	0.851	14.32%	1.70%
T3-04	2.230	0.534	6.02%	1.12%
T3-05	2.092	0.671	22.34%	1.55%
T3-06	1.145	0.747	30.38%	1.96%
T3-07	2.181	0.513	9.89%	1.48%
T3-08	1.524	0.633	8.65%	1.33%
T3-09	1.628	0.662	6.77%	1.68%
T3-10	0.757	0.990	9.97%	2.93%
T3-11	1.404	0.943	20.05%	2.17%

Samples from IRB97N-T2 were more consistent in character. They were collected on the central body of the sand ridge, where few bedforms or changes in morphology were visible in the side-scan imagery (Figure 24). With the exception of T2-01 just off the edge of the sand ridge (poorly sorted, very coarse sands) and T2-02 just on the sand ridge's edge (moderately well sorted, fine sands), the sediment samples all had mean  $\phi$  values in the range of medium sands, and were moderately, moderately well, or well sorted (Table 14). The overall distributions of grain sizes among samples 03-11 were similar, with 80-90% of their sediments  $\sim 2 \phi$  or coarser and  $\sim 40$ -50% concentrated between  $1 \phi$  and  $2 \phi$  (Figure 53). Carbonate content (Table 14) of the sediments varied from 2.78% to 21.57% across the body of the sand ridge, while silt and clay content varied between 1% and 2%, with no apparent spatial pattern or relationship among the four properties analyzed (Figure 54).

The grain size distributions for the IRB97N-T3 samples (Figure 53) appeared to be as variable as those from T1. However, samples 01-05 over the body of the sand ridge were similar: fine sands, moderately well sorted, with  $> 50\%$  of their grains concentrated between  $2 \phi$  and  $3 \phi$  (Table 14; Figure 53). Samples 06-09, on the northeastern flank of the sand ridge, were moderately well sorted, medium sands, reflected in the higher backscatter side-scan signal around these locations (Figure 24). Samples 10 and 11, off the sand ridge and near an isolated patch of sand, were moderately sorted, coarse and medium sands, respectively (Table 14). Carbonate content varied from 5-6% to 22% in the samples across the body of the sand ridge, and from  $< 7\%$  to 30% elsewhere. Silt and clay content, between 1% and 2%, was consistent at most sites (Figure 54).

Samples from all three transects had consistently low fractions of silt and clay, with the highest proportion only 5.18% at T1-01 and most of the remainder in the 1-2% range (Table 14). These percentages were lower than those from the MS96M or MS98JL samples (Tables 10 and 12). The differences may be real, but may also be due to the

different sampling methods employed, since the ship deployed grab samplers used in the MS area obtained larger samples overall and may have retained a larger portion of the fine material than the diver collected samples.

Correlation coefficients were calculated first for all samples, then for samples from each transect (Table 15). Significance tests were derived from Rohlf and Sokal (1981).

The relationships between mean grain size and sorting, carbonate content, and percent fine material were consistent and significant in the overall IRB97N sample set (Table 15). As mean grain size became coarser, sorting became poorer, carbonate content increased, and percent silt and clay increased. In the individual transect sets, the strength and direction (positive/negative) of the correlations were consistent with the overall samples set. However, the relationship between mean grain size and percent carbonate was not significant for samples in T1 and T3; and the relationship between mean grain size and percent fines was not significant for T2 (Table 15). T2, with primarily on-ridge samples, exhibited the highest correlations between mean grain size and sorting ( $r = -0.9443$ ) and between mean grain size and carbonate content ( $r = -0.7104$ ). The strongest correlations overall (all significant) were between sorting and percent silt and clay ( $r = 0.8760$ ), which showed a strong tendency for a higher percentage of fine materials with increasingly poor sorting. The relationship between sorting and carbonate content was not significant except for T2 samples ( $r = 0.7293$ ). Although the carbonate content of samples in T1 and T3 was generally less than 20% (Table 14), carbonate grain sizes were closer to the mean grain size in these samples. Variations in carbonate content were not the primary factor affecting sorting, as has been the case when increased carbonate content was directly associated with shell fragments and lithoclasts. The grain size distributions of both the T1 and T3 sample sets showed greater variability than those for T2 (Figure 53). Variations in carbonate content do not explain the greater variability in the sorting parameter in these samples.

**Table 15. Correlation coefficients among mean grain size, sorting, percent carbonate, and percent fine fraction for IRB97N sediment samples (Table 14). Coefficients were calculated first for all samples; absolute values exceeding 0.349 are significant ( $\alpha = .05$ , for  $\nu = 30$ ). Coefficients were then calculated for samples from each transect (Figure 24); absolute values exceeding 0.632 are significant for T1 ( $\alpha = .05$ , for  $\nu = 8$ ), and values exceeding 0.602 are significant for T2 and T3 ( $\alpha = .05$ , for  $\nu = 9$ ).**

All Samples	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.6044	1		
% CaCO <sub>3</sub>	-0.4911	0.3253	1	
% Silt and Clay	-0.4453	0.8760	0.1905	1
Transect 1	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.7354	1		
% CaCO <sub>3</sub>	-0.4528	0.1134	1	
% Silt and Clay	-0.6747	0.9707	0.1563	1
Transect 2	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.9443	1		
% CaCO <sub>3</sub>	-0.7104	0.7293	1	
% Silt and Clay	-0.5601	0.7175	0.4616	1
Transect 3	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.7395	1		
% CaCO <sub>3</sub>	-0.3466	0.3783	1	
% Silt and Clay	-0.7603	0.8381	0.2881	1

*IRB98JL*. In conjunction with the July 1998 side-scan sonar survey (*IRB98JL*), divers retrieved surface sediment samples along three transects across the sand ridges in the IRB sub-study region (Figure 26). Twelve samples, taken at eleven locations spaced ~24 m apart, were collected along Transect 1 (T1); eleven samples, ~30 m apart, were collected along Transect 2 (T2); and thirteen samples, collected at eleven locations spaced ~20 m

apart, were collected along Transect 3 (T3). Duplicate samples were taken at several locations along T1 and T3 because the sites were located in areas of transitioning sedimentary characteristics.

The size distributions for the samples across IRB98JL-T1 (Table 27, Appendix A) were coarser on the southwestern portion of the transect (samples 01-06) where the samples were taken across an area of varied hardbottom and patchy sand (Figure 55). Mean grain sizes were poorly to very poorly sorted coarse to very coarse sands, with high carbonate content (Table 16). Grain size distributions were finer on the northeastern portion (07-11) where the transect crossed hummocky bedforms approaching a transition area between dune termini (Figure 26). Mean grain sizes for these samples were moderately well to poorly sorted medium and fine sands. Samples 07 and 07A were taken 1 m apart and reflected a transition between fine and coarse sediments on a sandy hummocky structure. The lack of consistency in grain size distribution between samples was mirrored by variations in carbonate values for these samples, which ranged from ~13% at T1-07A to more than 80% at T1-02. Carbonate content values were lower across the transect where samples showed finer mean grain sizes and higher carbonate with coarser grains (Figure 56). Fine materials, ranging from ~2% in the fine sands of T1-08 and -09 to more than 6% in the overall coarsest sample (T1-04), showed no visible spatial trend (Figure 56).

The grain size distribution of samples from IRB98JL-T2 was more consistent than that from IRB98JL-T1 (Figure 55). Samples 05-09 reflected their locations on the fine sand of the central portion of the sand ridge, with moderately well to well sorted medium to fine sands. Likewise, samples 10 and 11 from the northeast edge of the sand ridge had coarser distributions, with nearly 60% of their grains at 0  $\phi$  or coarser (Figure 55). The sediments from these two samples were moderately to poorly sorted medium sands. These characteristics correlated with the higher backscatter return in the side-scan imagery at these locations (Figure 26). Samples 01-04, taken over an area that changed abruptly from low

Figure 55

Figure 55

Figure 55

**Table 16. IRB98JL sediment sample data (Figure 26). Mean grain size and degree of sorting calculated for the coarse fraction (larger than 4  $\phi$ ); carbonate content was determined from the sand fraction only (-1  $\phi$  through 4  $\phi$ ); and percent silt and clay was determined from the total sample.**

<b>Sample</b>	<b>Mean <math>\phi</math> (in <math>\geq 4 \phi</math>)</b>	<b><math>\pm\sigma</math> (<math>\phi</math>) (in <math>\geq 4 \phi</math>)</b>	<b>% Carbonate (in -1 <math>\phi</math> through 4 <math>\phi</math>)</b>	<b>% silt &amp; clay (in total sample)</b>
T1-01	-0.282	1.671	59.75%	3.34%
T1-02	-0.372	1.200	81.44%	3.93%
T1-03	0.532	1.488	58.10%	2.82%
T1-04	-1.006	2.017	51.48%	6.37%
T1-05	-0.296	0.983	60.04%	2.65%
T1-06	0.386	1.374	63.75%	4.52%
T1-07	2.545	0.631	20.00%	3.14%
T1-07A	1.127	1.081	13.27%	3.89%
T1-08	2.466	0.628	16.98%	2.02%
T1-09	2.234	0.697	32.62%	2.01%
T1-10	1.839	1.022	30.70%	2.37%
T1-11	1.180	1.311	66.12%	4.04%
T2-01	2.084	0.587	15.50%	1.37%
T2-02	2.191	0.591	20.87%	1.96%
T2-03	-0.004	1.389	62.44%	3.44%
T2-04	-0.218	1.369	64.49%	2.86%
T2-05	2.247	0.483	20.60%	1.70%
T2-06	1.871	0.852	36.35%	1.26%
T2-07	2.142	0.466	18.50%	2.39%
T2-08	2.087	0.527	24.80%	1.33%
T2-09	1.684	0.620	30.65%	1.04%
T2-10	1.225	1.091	40.58%	2.49%
T2-11	1.357	0.951	26.39%	1.57%
T3-01	2.688	0.564	14.92%	3.30%
T3-02	2.551	0.533	13.41%	3.17%
T3-03	2.059	0.732	38.02%	2.03%
T3-04	2.103	0.739	22.09%	2.17%
T3-05	1.210	1.127	52.68%	1.97%
T3-06	-1.212	1.426	75.50%	3.79%
T3-06B	0.296	1.160	50.85%	4.62%
T3-07	-0.479	1.459	39.56%	5.94%
T3-08	1.597	1.478	34.38%	2.17%
T3-09	1.572	0.993	31.18%	1.75%
T3-10D	-2.400	1.051	74.62%	8.55%
T3-10	1.972	0.913	58.49%	4.35%
T3-11	-0.866	1.274	61.50%	3.73%

Figure 56

to high backscatter on the side-scan imagery, also changed abruptly from moderately well sorted fine sands (01-02) to poorly sorted very coarse sands (03-04). Overall, samples from T2 with higher carbonate content also were the most poorly sorted and had coarser mean grain sizes (Figure 56). All samples contained fine materials which varied from ~1% to less than 4%.

The grain size distributions of the IRB98JL-T3 samples also varied (Figure 55) and correlated well with side-scan imagery (Figure 26). Samples 01-04, located on the main sand ridge, were moderately to moderately well sorted fine sands. Sample 05 at the sand ridge's northeastern edge exhibited a coarser distribution than 01-04 (Table 16). Sediments in samples 06-11 varied from poorly sorted (except 09) gravels (06 and 10D) to medium sands, as the sample locations of T3 traversed a trough of shell hash (higher backscatter) and some small features of sand (lower backscatter) (Figure 26). The differences in mean grain size and overall distribution between samples 06 and 06B and 10D and 10 reflected the transitions between finer and coarser materials at these sampling sites. The gravel samples at 06 and 10D also had the highest carbonate content (~75%). Silt and clay content varied from 1.75% at 09 to 8.55% at 10D (Table 16).

Correlation coefficients were calculated first for all samples, then for samples from each transect (Table 17). Significance tests were derived from Rohlf and Sokal (1981).

In the complete IRB98JL data set, correlations between mean grain size and sorting, carbonate content, and percent fine material were consistently strong and all significant, with coarsening of grain size corresponding to poorer sorting, increased carbonate content and an increase in the proportion of silt and clay (Table 17). These relationships varied little, and all remained significant, when examined among the individual transects. Samples from T2 exhibited the strongest significant correlations, with poorer sorting corresponding both to increased carbonate and to increased fine materials ( $r = 0.9327$  and  $0.7057$ , respectively).

**Table 17. Correlation coefficients among mean grain size, sorting, percent carbonate, and percent fine fraction for IRB98JL sediment samples (Table 16). Coefficients were calculated first for all samples; absolute values exceeding 0.330 are significant ( $\alpha = .05$ ,  $\nu = 34$ ). Coefficients were then calculated for samples from each transect (Figure 26); significant absolute values are those exceeding 0.576 for T1 ( $\alpha = .05$ ,  $\nu = 10$ ), exceeding 0.602 for T2 ( $\alpha = .05$ ,  $\nu = 9$ ), and exceeding 0.553 for T3 ( $\alpha = .05$ ,  $\nu = 11$ ).**

All Samples	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.7511	1		
% CaCO <sub>3</sub>	-0.8113	0.6972	1	
% Silt and Clay	-0.7165	0.5332	0.5325	1
Transect 1	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.8241	1		
% CaCO <sub>3</sub>	-0.7438	0.5837	1	
% Silt and Clay	-0.6514	0.7617	0.3746	1
Transect 2	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.9516	1		
% CaCO <sub>3</sub>	-0.9533	0.9327	1	
% Silt and Clay	-0.7429	0.7057	0.7069	1
Transect 3	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.6542	1		
% CaCO <sub>3</sub>	-0.8178	0.5993	1	
% Silt and Clay	-0.7333	0.2336	0.5300	1

The relationship between sorting and carbonate was weaker but still significant for both the T1 and T3 samples sets ( $r = 0.5837$  and  $0.5993$ , respectively). The relationship between sorting and fine material for the T1 samples ( $r = 0.7617$ ) was comparable to that for T2; however it was not significant ( $r = 0.2336$ ) for the T3 samples. Correlation between carbonate and fine materials was not significant for T1 ( $r = 0.3746$ ) or T3 ( $r = 0.5300$ ), but was significant for T2 ( $r = 0.7069$ ). Overall, the samples from T2, most of which were

taken from the sand ridge, showed the greatest correlation among the four sedimentary properties. T1 and T3 samples, taken from sites with more variability in terms of morphology and sediment types (reflected in the side-scan imagery (Figure 26)), displayed more variation in the relationships between grain size, sorting, carbonate, and fine materials. The relationships in the IRB98JL samples were similar, overall, to those from the IRB97N samples.

*IRB98N1.* In conjunction with the first of two November 1998 side-scan sonar surveys (IRB98N1), divers retrieved surface sediment samples along three transects across the sand ridges in the IRB sub-study region (Figure 34). Eleven samples, taken at eleven locations spaced ~24 m apart, were collected along Transect 1 (T1); eleven samples, ~30 m apart, were collected along Transect 2 (T2); and eleven samples ~20 m apart, were collected along Transect 3 (T3).

It should be noted that during sample collection across all three transects, divers noted a reddish algal mat, prevalent over much of the sand ridge, along with evidence of extensive bioturbation. Although occasionally disturbed by other physical and biological activity, the algal mat was often continuous over large areas of the sand ridges and troughs.

With the exception of sites T1-02, T1-03, and T1-11, the sediments in the sample sites across IRB98N1-T1 were moderately to well sorted fine sands (Table 18). The cumulative grain size frequency curves (Figure 57) showed a 60-80% concentration in sizes between 2  $\phi$  and 3  $\phi$  for these samples. T1-02 contained moderately sorted coarse sands and T1-03 poorly sorted medium sands, both with high carbonate content, reflecting their locations in an exposed hardbottom area of high sonar backscatter on the southwest edge of the sand ridge (Figure 34). Although the transect crossed other areas of high and low backscatter on the sand ridge, sample sites 04-10 fell in areas of low backscatter (fine

**Table 18. IRB98N1 sediment sample data (Figure 34). Mean grain size and degree of sorting calculated for the coarse fraction (larger than 4  $\phi$ ); carbonate content was determined from the sand fraction only (-1  $\phi$  through 4  $\phi$ ); and percent silt and clay was determined from the total sample..**

<b>Sample</b>	<b>Mean <math>\phi</math> (in <math>\geq 4 \phi</math>)</b>	<b><math>\pm\sigma</math> (<math>\phi</math>) (in <math>\geq 4 \phi</math>)</b>	<b>% Carbonate (in -1 <math>\phi</math> through 4 <math>\phi</math>)</b>	<b>% silt &amp; clay (in total sample)</b>
T1-01	2.233	0.632	21.92%	2.28%
T1-02	0.585	0.956	61.69%	3.16%
T1-03	1.485	1.236	55.86%	2.74%
T1-04	2.345	0.929	29.43%	1.96%
T1-05	2.528	0.389	7.01%	1.89%
T1-06	2.133	0.637	29.73%	1.10%
T1-07	2.369	0.576	22.61%	1.61%
T1-08	2.294	0.391	12.46%	1.72%
T1-09	2.176	0.533	19.74%	2.21%
T1-10	2.126	0.670	25.55%	2.61%
T1-11	1.849	0.675	33.33%	2.73%
T2-01	2.496	0.734	26.10%	0.27%
T2-02	1.624	0.867	48.60%	2.84%
T2-03	2.026	0.600	35.57%	2.14%
T2-04	1.479	0.815	53.87%	1.74%
T2-05	1.596	0.949	49.42%	2.58%
T2-06	2.175	0.449	24.71%	1.63%
T2-07	2.073	0.447	23.50%	2.36%
T2-08	1.853	0.425	25.84%	1.54%
T2-09	1.814	0.515	29.75%	1.73%
T2-10	1.547	0.705	46.06%	2.99%
T2-11	2.170	1.241	27.26%	2.47%
T3-01	2.764	0.508	11.59%	1.32%
T3-02	2.578	0.508	15.84%	1.22%
T3-03	2.442	0.699	20.71%	2.10%
T3-04	0.705	0.921	74.15%	3.35%
T3-05	2.275	0.664	30.17%	1.96%
T3-06	2.227	0.501	18.89%	1.21%
T3-07	1.765	0.643	34.33%	2.40%
T3-08	1.043	1.141	54.20%	1.88%
T3-09	0.539	1.055	76.06%	2.98%
T3-10	0.149	1.058	77.15%	3.80%
T3-11	1.406	1.205	52.07%	2.39%

Figure 57

Figure 57

Figure 57

sands) with variable carbonate content (Table 18). T1-11 was located between patches of fine sand, in an area of medium sands. The generally high sonar backscatter in this area also revealed parallel bedforms, confirmed by diver observations during sampling. All sediments from T1 contained from ~1-3% silt and clay in the total sample. Mean grain size varied correspondingly with sorting and carbonate content (Figure 58).

Samples T2-01 through T2-07 were a mix of moderately to well sorted medium and fine sands, with the medium sands containing ~50% carbonate and the fine sands 20-35% carbonate (Table 18). This correlated with the mix of high and low backscatter sonar signals shown across the sand ridge (Figure 34). Samples 04 and 05, for example, were located in an area of higher backscatter, a larger bedform in which were smaller (~1 m spaced) bedforms in these coarser sands. On the northeast side of the sand ridge progressing into a trough area (which also contained the ~1 m bedforms), samples 08-10 contained more poorly sorted medium sands that contained a higher percentage of carbonate the further away from the sand ridge the sample was taken (Table 18). T2-11 was taken on an isolated patch of fine sands (low sonar backscatter), that, unlike most of the other samples with fine mean grain sizes, were poorly sorted. The variability in the grain size distributions and sorting characteristics for the T2 sediments, and the differences between samples 01-07 versus 08-10, were reflected in their cumulative grain size distributions (Figure 57). All samples contained between 0-3% silt and clay material. Variations among the four sediment properties did not correspond as well as they did in the T1 samples (Figure 58).

The first sample from IRB98N1-T3, across the northwest end of the sand ridge, was collected more than 50 m from the southwest edge of the sand ridge (Figure 34). Samples 01-03 and 05-06 reflected the fine sands (moderately well sorted) across this portion of the sand ridge, which appeared as low backscatter in sonar images and had correspondingly lower carbonate content and better sorting (Table 18; Figure 58). [Note: sample T3-04

Figure 58

contained moderately sorted coarse sands composed of ~74% carbonate. No corresponding area of high backscatter was reflected on the sonar image. However, a data gap appears between the lines in the mosaic where T3-04 was taken (Figure 34). A higher backscatter sonar return reflecting these sedimentary characteristics may have existed there.] Samples 07-11 were collected beginning on the northeast edge of the sand ridge and continuing into a trough area containing parallel bedforms. These were poorly sorted medium to coarse sands that contained a higher percentage of carbonate than the fine sand samples from the sand ridge body (Table 18). The contrast between samples 01-06 and 07-11 was reflected in the cumulative grain size distributions (Figure 57), with the grains of 01-06 (excluding 04) concentrated in the sizes between 2  $\phi$  and 3  $\phi$  and those of the last five samples spread over sizes smaller than 2  $\phi$ . Percentage of silt and clay in the samples ranged between 1-4%. The coarser grain sizes in samples 07-11 corresponded with poorer sorting and increased carbonate content and fine materials (Figure 58). Correlation coefficients were calculated first for all samples, then for samples from each transect (Table 19). Significance tests were derived from Rohlf and Sokal (1981).

In the overall data set (Table 19), correlations maintained their directions (positive/negative), and were all significant. The strongest correlation was between mean grain size and carbonate content ( $r = -0.9475$ ), with coarser sediments corresponding to increased carbonate. The correlation between sorting and carbonate content was also strong ( $r = 0.7461$ ), with poorer sorting associated with increased carbonate. The weakest relationship was between sorting and percentage of fine materials ( $r = 0.6899$ ). Among the individual transect sets, the T1 and T3 samples exhibited the strongest correlations between properties, with all T3 correlations significant and all but one significant for T1 (Table 19). The T2 samples had many weak relationships (in contrast to the analyses from the IRB97N and IRB98JL sample sets (Tables 15 and 17)). Based on past relationships, the T1 and T2

**Table 19. Correlation coefficients among mean grain size, sorting, percent carbonate, and percent fine fraction for IRB98N1 sediment samples (Table 18). Coefficients were calculated first for all samples; absolute values exceeding 0.344 are significant ( $\alpha = .05$ ,  $\nu = 31$ ). Coefficients were then calculated for samples from each transect (Figure 34); absolute values exceeding 0.602 are significant for T1, T2, and T3 ( $\alpha = .05$ ,  $\nu = 9$ ).**

All Samples	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.6291	1		
% CaCO <sub>3</sub>	-0.9475	0.7461	1	
% Silt and Clay	-0.7316	0.5167	0.6899	1
Transect 1	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.6505	1		
% CaCO <sub>3</sub>	-0.9091	0.8880	1	
% Silt and Clay	-0.7237	0.5444	0.6394	1
Transect 2	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.1256	1		
% CaCO <sub>3</sub>	-0.8354	0.4228	1	
% Silt and Clay	-0.6236	0.3195	0.4821	1
Transect 3	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.8256	1		
% CaCO <sub>3</sub>	-0.9828	0.8422	1	
% Silt and Clay	-0.8754	0.6685	0.8951	1

samples were expected to have the strongest correlations between properties, since they exhibited the least variability in grain size distributions among individual samples (Figure 57). However, the T2 samples showed a weak relationship ( $r = -0.1256$ ) between mean grain size and sorting; samples were both coarse but better sorted (e.g., samples 08 and 09) and also fine but more poorly sorted (e.g., sample 11) (Table 19). The T2 samples also had weak non-significant relationships between sorting and carbonates, sorting and fine

materials, and carbonates and fine materials, compared to the T1 and T3 samples. The IRB98N1-T2 samples were taken primarily from the central body of the sand ridge, but these samples lacked the homogeneity of the T2 samples of the IRB97N and IRB98JL surveys. Conversely, despite the IRB98N1-T1 and -T3 samples having been taken over the same areas as in previous surveys, the IRB98N1 samples exhibited stronger correlations among properties than in the previous surveys.

*IRB98N2*. In conjunction with the second November 1998 side-scan sonar survey (IRB98N2), divers retrieved surface sediment samples along three transects across the sand ridges in the IRB sub-study region (Figure 35). Eleven samples, taken at eleven locations spaced ~24 m apart, were collected along Transect 1 (T1); eleven samples, ~30 m apart, were collected along Transect 2 (T2); and eleven samples ~20 m apart, were collected along Transect 3 (T3).

It should be noted that during this final sampling process, divers again observed an ubiquitous red algal mat over much of the sand ridges and troughs. The mat did not appear to have been significantly disturbed during the weather front passage that occurred between the IRB98N1 and IRB98N2 surveys. Bedforms (such as ripples) on the sand ridge and especially in the coarser materials in the troughs were present but showed various stages of bioturbation which indicated either a lack of disturbance during the frontal passage or rapid deterioration of the bedforms since their formation. The extent to which increased wind wave action may have affected bottom current velocities during the frontal passage is discussed in the Current Meter Data section of this chapter.

Sediment samples collected along IRB98N2-T1 were a mixture of fine and medium sands (Table 20), reflecting the composite of backscatter intensities recorded across this area over a variety of bedforms and sediment types (Figure 35). Samples 01 and 02 were collected near either side of an oval, hummocky structure on the southwest edge of the main

**Table 20. IRB98N2 sediment sample data (Figure 35). Mean grain size and degree of sorting were calculated for the coarse fraction (larger than 4  $\phi$ ); carbonate content was determined from the sand fraction only (-1  $\phi$  through 4  $\phi$ ); and percent silt and clay was determined from the total sample.**

<b>Sample</b>	<b>Mean <math>\phi</math> (in <math>\geq 4 \phi</math>)</b>	<b><math>\pm\sigma</math> (<math>\phi</math>) (in <math>\geq 4 \phi</math>)</b>	<b>% Carbonate (in -1 <math>\phi</math> through 4 <math>\phi</math>)</b>	<b>% silt &amp; clay (in total sample)</b>
T1-01	1.069	1.620	58.61%	4.10%
T1-02	1.574	1.534	46.23%	2.75%
T1-03	2.278	0.759	22.90%	2.07%
T1-04	1.831	1.007	39.37%	2.22%
T1-05	2.445	0.630	19.15%	2.26%
T1-06	1.583	1.036	55.57%	2.42%
T1-07	2.526	0.404	10.51%	1.66%
T1-08	2.600	0.381	10.54%	1.89%
T1-09	1.069	1.314	54.45%	3.13%
T1-10	2.428	0.622	19.20%	2.67%
T1-11	1.967	0.981	29.64%	2.49%
<hr/>				
T2-01	2.534	0.711	19.32%	2.85%
T2-02	2.101	0.696	32.49%	2.33%
T2-03	1.889	0.726	40.37%	2.21%
T2-04	1.476	0.911	55.11%	2.30%
T2-05	1.905	0.974	37.96%	3.19%
T2-06	2.214	0.403	16.50%	1.99%
T2-07	2.076	0.502	25.63%	2.18%
T2-08	1.859	0.569	31.39%	2.18%
T2-09	1.836	0.608	35.07%	2.30%
T2-10	1.307	1.055	53.21%	2.42%
T2-11	0.847	1.465	60.93%	3.54%
<hr/>				
T3-01	2.666	0.446	16.89%	3.40%
T3-02	2.641	0.511	19.97%	2.35%
T3-03	2.504	0.620	21.68%	1.64%
T3-04	2.278	0.647	28.88%	1.88%
T3-05	1.973	0.806	37.18%	2.05%
T3-06	1.449	0.878	57.25%	2.07%
T3-07	0.633	1.436	66.81%	2.53%
T3-08	0.807	1.641	60.55%	3.24%
T3-09	0.505	1.553	66.52%	3.18%
T3-10	0.362	1.547	65.44%	2.17%
T3-11	1.337	1.275	51.52%	2.17%

sand body. Samples 03-11 were taken across the main sand ridge and had a corresponding mixture of mean grain sizes in the fine and medium sand ranges (Table 20). All the samples in the medium sand range showed poor sorting (except 11, moderate sorting) and carbonate contents of ~40% or higher (except 11, ~30%). All the fine sands were moderately to well sorted, with lower carbonate components. Percent silt and clay ranged from less than 2% to slightly more than 4%. The cumulative grain size distributions (Figure 59) illustrate the poor sorting of the medium sand samples. Carbonate content, sorting, and to a lesser extent, mean grain size, varied correspondingly across T1 (Figure 60).

Sample collection on IRB98N2-T2 began near the southwest edge of the sand ridge in an area of low sonar backscatter (Figure 35). These sediments had mean grain sizes in the fine sand range and were moderately to moderately well sorted (Table 20), with more than 60% of their grains concentrated in the sizes between 2  $\phi$  and 3  $\phi$  (Figure 59). Sediments from sites 03-05, taken near an area showing a slightly darker sonar backscatter within the main sand ridge, were moderately sorted medium sands, that had carbonate contents between ~40% and 55%. Sediments from sites 06 and 07 were moderately well to well sorted fine sands (low backscatter in sonar imagery). Samples from sites 08-11 were taken on the northeastern edge of the sand ridge and into a trough area. Mean grain sizes became coarser, more poorly sorted, and contained higher percentages of carbonate as the site locations moved further from the edge of the sand ridge (lower sonar backscatter) into the trough (higher backscatter). This is reflected in the cumulative grain size distribution curves (Figure 59), which showed a progressive flattening of the curves (poorer sorting) and a larger percentage of grains in the coarser size classes from site 08 through site 11. Percent silt and clay for sediment samples from all sites ranged from ~2% to ~3.5%. Carbonate content and sorting in these samples varied together along with mean grain size (Figure 60).

Figure 59

Figure 59

Figure 59

Figure 60

The actual location of IRB98N2-T3 was significantly errant from its planned location. The first sample was collected near the center of the sand ridge's northwestern region and the remaining samples located to the east-northeast, off the sand ridge's northeastern edge and well into the high sonar backscatter trough area (Figure 35). Sediments from sites 01-04 were all fine sands, which changed in sorting from well sorted at T3-01 to moderately well sorted at T3-02 through -04. The calcium carbonate component also increased from site 01 to site 04, from ~17% to ~29% (Table 20). The sonar backscatter correlated well with these sediment characteristics over this portion of the transect, changing from a lower to a higher return from site 01 to site 04 at the edge of the sand ridge. Sediments from sites 05 and 06 (moderately sorted, medium sands) reflected the transition into the trough area, where carbonate content increased and the sonar return appeared darker on the side-scan images (Figure 35). In the trough area, the high sonar backscatter corresponded with the poorly sorted coarse sands that made up the samples from 07-10. These sediments all had carbonate components in excess of 60% (Table 20). Sediments from site 11 were taken near a lower backscatter area on the sonar record, and were poorly sorted medium sands with a slightly lower carbonate component. The silt and clay components again were ~3.5% or lower for all samples. The difference in grain size and sorting between sample sites 01-04 versus sites 07-10 was evident in the cumulative distribution curves (Figure 59). Mean grain size, sorting, and carbonate content varied correspondingly across the transect (Figure 60).

Correlation coefficients were calculated first for all samples, then for samples from each transect (Table 21). Significance tests were derived from Rohlf and Sokal (1981).

Correlations between mean grain size and sorting and mean grain size and carbonate content were significant and consistent in direction with samples from other surveys. Specifically, the relationship between mean  $\phi$  and sorting ( $r = -0.8964$ ) was stronger for the IRB98N2 samples, overall, than for IRB98N1. The strong relationship between mean grain

**Table 21. Correlation coefficients among mean grain size, sorting, percent carbonate, and percent fine fraction for IRB98N2 sediment samples (Table 20). Coefficients were calculated first for all samples; absolute values exceeding 0.344 are significant ( $\alpha = .05$ ,  $\nu = 31$ ). Coefficients were then calculated for samples from each transect (Figure 35); absolute values exceeding 0.602 are significant for T1, T2, and T3 ( $\alpha = .05$ ,  $\nu = 9$ ).**

All Samples	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.8964	1		
% CaCO <sub>3</sub>	-0.9557	0.8833	1	
% Silt and Clay	-0.4299	0.5883	0.4329	1
Transect 1	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.9329	1		
% CaCO <sub>3</sub>	-0.9681	0.9132	1	
% Silt and Clay	-0.8125	0.8258	0.7556	1
Transect 2	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.8182	1		
% CaCO <sub>3</sub>	-0.9334	0.8539	1	
% Silt and Clay	-0.4263	0.8124	0.4342	1
Transect 3	Mean $\phi$	$\pm\sigma$ ( $\phi$ )	% CaCO <sub>3</sub>	% Silt and Clay
Mean $\phi$	1			
$\pm\sigma$ ( $\phi$ )	-0.9686	1		
% CaCO <sub>3</sub>	-0.9798	0.9305	1	
% Silt and Clay	-0.2641	0.3216	0.2057	1

size and carbonate content in the IRB98N1 samples continued in the IRB98N2 correlations. However, there was a weaker but still significant correlation between mean grain size and percent fine materials in the latter survey ( $r = -0.4299$  for IRB98N2 compared to  $-0.7316$  for IRB98N1). The relationships between sorting and carbonate content and sorting and percent fine materials were as high or higher in the IRB98N2 samples compared to the IRB98N1 samples. The correlation between carbonate content and percent fine materials

was weaker, but still significant, showing only a marginal relationship ( $r = 0.4329$ ) between these variables compared to the IRB98N1 overall samples ( $r = 0.6899$ , Table 19).

IRB98N2-T1 samples exhibited strong correlations among all variables (Table 21), despite showing variability in the distribution of grain sizes among the samples (Figure 59). Correlations from the IRB98N2-T2 samples mirrored those from IRB98N1 (Table 19), except that the relationship between sorting and fine materials was higher for IRB98N2. The relationships between mean grain size, sorting, and carbonate content and percent fine materials were consistently weak for the T3 sample set. Considering the distinct partitioning of the IRB98N2-T3 samples (ridge vs. trough) based on grain size distribution (Figure 59), and the strength of the correlations among the variables in the IRB98N1 samples from the same transect (Table 19), stronger relationships were expected in the IRB98N2-T3 samples. However, the small range of values for percent fine material in all the time series of IRB samples contributed to the variability in the correlations with the other three variables.

*Spatial and Temporal Comparisons of Sedimentary Properties.* Sedimentary properties from surveys within each respective area were first compared to determine if there were significant temporal changes or spatial variations within the IRB and MS study areas. F-tests (comparison of variances of distributions) and t-tests (comparison of means of distributions) were performed comparing the MS96M and MS98JL sediment sample data (Tables 10 and 12), the IRB97N and IRB98JL data (Tables 14 and 16), and the IRB98N1 and IRB98N2 data (Tables 18 and 20). The statistics were generated to determine if the distributions of the mean grain sizes, sorting, and percentages of fine and carbonate materials were significantly different (Sokal and Rohlf, 1981). F-statistics were generated first on the complete sample sets, and then again only on samples taken directly from the sand ridges/sand bodies, for each of the four sedimentary properties (Appendix B). Based

on the results of the F-test, a student t-test was performed, assuming either equal or unequal variances between data sets (Appendix B).

The MS96M sand body-only samples differed significantly from the MS98JL sand body-only samples with respect to mean grain size (Tables 30 and 31, Appendix B). A 0.25  $\phi$  difference in the average mean  $\phi$  of the two distributions could be hypothesized at a 95% confidence interval. There was a significant difference in the variance of the distribution of the sorting parameter between the data sets (the F-statistic exceeded the critical-F), but not in the mean value of the sorting parameter (the t-statistic did not exceed the critical-t) (Tables 30 and 31, Appendix B). For percent carbonate there was no significant difference in the means or variances between the two sample populations. However, the mean value of the percentage of fine material was significantly different between MS96M and MS98JL (Table 31, Appendix B). Thus based on the differences in mean grain size, sorting, and to a lesser extent, percent fine material, it was concluded that the MS96M and MS98JL data sets were significantly different and could not be considered together for comparison to the IRB samples.

For the IRB samples themselves, no significant difference in mean grain size or sorting existed between ridge-only samples from the IRB97N and IRB98JL samples sets (Tables 32 and 33, Appendix B). However, there was a significant difference of 12.36% in carbonate content that could be hypothesized at 95% confidence between the means of each population. There was also a significant difference of 0.34% in the percent of fine material that could be hypothesized between the mean values, which over the small range of values is substantial, but probably not important overall. Since the only significant difference between the two sample sets was in carbonate content, it was concluded that the IRB97N and IRB98JL sediment samples did not differ significantly overall.

It was possible, then, that the IRB97N and IRB98JL sample sets could be considered together for comparison to any of the MS samples. However, it was decided to

compare only the IRB98JL and MS98JL samples, since they were taken during the same time frame (July 1998), processed in exactly the same manner, and thus were most directly comparable.

First, the average values for mean  $\phi$ , sorting, percent carbonate, and percent fine materials were compared (Table 22). Mean grain size value for the MS98JL distribution is more than 0.5  $\phi$  finer than in IRB98JL. The average sorting value of 0.556 is moderately well sorted for MS and only moderately sorted (0.842) for IRB (Folk, 1980). The IRB98JL samples contained an average of almost 33% carbonate while the MS98JL samples only ~21% carbonate; the amount of carbonate also varied more about the mean (std = 17.67) in the IRB samples than in the MS samples (std = 3.34) (Table 22). Percentage of fine materials, while differing between the two areas, was still very small and may have been an artifact of the sampling methods (diver-collected in IRB vs. ship-deployed grab sampler in MS).

**Table 22. Comparison of the means and standard deviations of the distributions of mean grain size, sorting, percentage of carbonate and percentage of fine material for the MS98JL (Table 12) and IRB98JL (Table 16) sediment sample sets. For IRB98JL properties, the high standard deviations (std) about the means of the different properties compared to the range of the data indicated sediments were less homogeneous in the IRB area than in the MS area.**

<b>MS98JL</b>	<b>mean <math>\phi</math></b>	<b>sorting (<math>\sigma</math>)</b>	<b>% CaCO<sub>3</sub></b>	<b>% fines</b>
mean	2.179	0.556	20.55	5.59
std	0.154	0.057	3.34	1.58
<b>IRB98JL</b>	<b>mean <math>\phi</math></b>	<b>sorting (<math>\sigma</math>)</b>	<b>% CaCO<sub>3</sub></b>	<b>% fines</b>
mean	1.681	0.842	32.70	2.66
std	1.010	0.294	17.67	1.57

Correggiari et al. (1996) investigated a field of asymmetric bedforms (~3 m amplitudes and ~600 m wavelengths) in 20-24 m water depth on a sediment starved shelf in the north Adriatic Sea. In characterizing the sediments, they plotted mean grain size against sorting and found that finer mean grain size and a high degree of sorting correlated with

ridge sediments, while coarse sediments and poorer sorting correlated with trough sediments. This same relationship was investigated for both the MS and IRB sediments. Considering just the MS98JL and IRB98JL sample sets, mean  $\phi$  was plotted against sorting (Figure 61). A clustering of data points about moderately or better sorted medium to fine sands were found to correspond with samples taken from sand ridges in both the MS and IRB areas (Figure 61). In fact, except for two samples taken off-ridge, all MS samples fell within this cluster. However, other IRB samples taken from the sand ridge in the study area did not fall within this cluster. Rather, the IRB sample set exhibited a trend toward poorer sorting with increasing grain size. The IRB data also showed more spatial variation than the MS samples in the relationship between mean grain size and sorting, even when comparing only those samples taken from sand bodies or ridges.

The relationship between mean grain size and sorting in the IRB98JL and MS98JL data sets can be further examined by comparing the correlation coefficient,  $r$ , for each (Tables 13 and 17) (Isaaks and Srivastava, 1989). For the MS98JL samples,  $r = -0.4403$  (Table 13), showing a moderate but not significant negative correlation between the sorting statistic and phi size (a positive correlation between sorting and grain size): the larger the mean grain size, the more poorly sorted the sample. For the IRB98JL samples overall,  $r = -0.7511$  (Table 17), and a stronger and statistically significant correlation between increasing grain size and poorer sorting existed. However, there was variation even within the three IRB transect sub-sets. For samples from IRB98JL-T1,  $r = -0.8241$ ; for T2,  $r = -0.9516$ ; and for T3,  $r = -0.6542$  (all significant). The lower correlation in the T3 samples (from the northern end of the sand ridge in the study area (Figure 26)) weakened the overall IRB relationship. However, in all cases the correlation between mean grain size and sorting was stronger in the IRB area than in the MS area.

The IRB98N1 and IRB98N2 sediment samples, collected 16 days apart in November 1998, differed in their sedimentary properties. For mean grain size, there was a

Figure 61

significant difference in the variance ( $F$  exceeded critical  $F$ ) of their respective distributions, but not between the mean values ( $t$  did not exceed critical  $t$ ) (Tables 34 and 35, Appendix B). The mean values for sorting also differed. The distribution of sorting values for IRB98N1 had a mean of 0.736 while the value for IRB98N2 was 0.917. A difference of 0.0154 between the two means could be hypothesized at 95% confidence (Table 35). However, both mean values fell in the same range of "moderately sorted" as defined by Folk (1980). Carbonate content values for both data sets were comparable. The percentage of fine materials differed significantly, with a hypothesized difference of 0.009% between the means of the two distributions. Once again, the small range of values in this property, and its overall small contribution to overall sedimentary characteristics, made this difference less significant.

#### Analysis of Sedimentary Properties and Backscatter Intensity

Recent work in establishing the relationship between backscatter intensity and sedimentary properties has been published by LeBlanc et al. (1992, 1995), Panda et al. (1994), Muthukrishniah et al. (1995), Davis et al. (1996), Ryan and Flood (1996), Gao et al. (1998), and Goff et al. (2000). Most of these efforts have been to establish empirical models from which sedimentary classification can be extracted from some measure of the sonar signal.

An analysis to quantify the relationships between backscatter intensity and sediment properties for the IRB and MS areas follows, with the purpose of establishing an empirical formula/model from which mean backscatter intensity can be predicted from sedimentary properties. Such a model can be used in establishing a reverse relationship, that is, predicting one or more sedimentary properties when the mean backscatter intensity value is known. Estimates for some sedimentary parameters could be used, for example, to then solve equations simultaneously and calculate values, or a range of values, for unknown

sedimentary properties. This would be, at best, a rough estimation. However, examining the relationships through multiple regression, in the MS and IRB areas, between the observed side-scan signal and the sediment properties that produce the sonar image, is a step toward later creating a more sophisticated model to predict sedimentary properties from remotely sensed data.

The side-scan sonar signal in decibels (dB) could not be extracted directly from the side-scan data using the Elics DelphSonar and DelphMap software, as was done by Goff et al. (2000) in their study of the New Jersey margin. However, signal intensity was manifested in the IRB and MS imagery by the software used here as a range of gray scale values from 0 (lowest backscatter) to 255 (highest backscatter) assigned to each image pixel. Regardless of post-processing enhancements to the image (using time variable gain or other techniques), the gray scale value assigned to each pixel, based on the backscatter intensity measured during acquisition, remained constant, such that it could be used as a proxy for the side-scan signal intensity (Ryan and Flood, 1996). These values could also be compared to the physical sedimentary properties that contributed to the observed side-scan signal.

DGPS locations were recorded during collection of all MS96M and MS98JL sediment samples. Positions were also recorded for transect end member samples in all IRB sampling surveys, yielding a total of 50 sites where the side-scan signal could be examined and directly correlated with sedimentary properties. Using the Elics DelphMap GIS software, samples with DGPS locations were located on their respective side-scan mosaics. A 10 m radius buffer was established about each location on the side-scan mosaics. The Elics DelphMap software then extracted the gray scale values of each pixel within the buffer zone, yielding a distribution of backscatter intensity values, a mean value, and a standard deviation (sorting or scattering parameter) for each location (Table 36,

Appendix C). These values were then compared to the physical sedimentary properties at the respective locations.

The relationship between backscatter intensity and mean grain size has been well-established (Davis et al., 1996; Ramsay et al., 1996; Ryan and Flood, 1996; Blondel and Murton, 1997; Goff et al., 2000). High backscatter generally has been associated with larger grain sizes, although Goff et al. (2000) contended that the grain size frequency distribution as a whole, and not just mean grain size, was the primary determinant of backscatter intensity in the sandy environment of the New Jersey margin. The relationship between mean gray scale value and mean grain size for the MS and IRB study areas (Figure 62) shows a trend toward higher backscatter intensity with increasing grain size. The trend was not linear or consistent in the MS and IRB data. The most consistent relationship appeared in the MS98JL data (Figure 62).

The relationship between backscatter and grain size was not as clear in the MS96M data (Figure 62); however, these data were from 100 kHz side-scan (as opposed to 500 kHz for all other data). In addition a lack of spatial variation in sediment grain size in these samples caused most data points to cluster over a small range of values on both axes. Two outliers, collected from a trough site, showed the only variation and contributed to the high backscatter/coarse grain size relationship (Figure 62).

The grain size-backscatter intensity relationship was even less consistent among the IRB samples, with some points falling along the linear trend with the MS98JL samples and others showing varying degrees of higher backscatter with increasing grain size (Figure 62). For the entire set of samples, grain size was significantly correlated with backscatter ( $r = -0.5357$ , Table 37, Appendix C). The MS sample sets showed stronger significant correlations ( $r = -0.7923$  for MS96M and  $r = -0.8212$  for MS98JL) than the combined IRB data sets ( $r = -0.47570$ , Table 37, Appendix C).

Figure 62

The overall correlation between the backscatter proxy and grain size sorting was significant at  $r = 0.3000$  (Table 37, Appendix C). The weakness of this relationship was reflected in the scatter of data points when the two variables were plotted against one another (Figure 63). Individually, only the MS96M samples showed a stronger significant relationship ( $r = 0.6885$ , Table 37, Appendix C). The combined IRB samples showed a significant correlation of  $r = 0.4335$  (Table 37, Appendix C). The MS98JL samples showed poor and non-significant correlations. Overall a weak trend toward higher mean backscatter values correlated with increasingly poor sorting. This trend was expected since poorer sorting was also correlated with increasing mean grain size for most sample sets (Tables 11, 13, 15, 17, 19, and 21).

The relationship between backscatter intensity value and the carbonate content of the sediment samples was strongest in the MS96M ( $r = 0.8788$ ) and IRB ( $r = 0.6518$ ) sample sets (Table 37, Appendix C), which showed an increase in backscatter intensity with increased carbonate content. This was also expected since increased carbonate content was associated with increased mean grain size in these samples sets. However, the overall trend was obfuscated by the MS98JL samples, which showed almost no relationship between the two variables ( $r = -0.1066$ ). Outlying data points (Figure 64) for this data set, from the two samples taken off the main sand body, were primarily responsible for the weakness in this correlation. However, even without those points, the trend exhibited by the remaining MS98JL data points was not strong (Figure 64).

No discernable relationship was evident between percent fine material and mean backscatter intensity (Figure 65). Correlation coefficients were very low and mostly not significant (Table 37, Appendix C). The small amount of silt and clay material found in all the sample sets had little bearing on the resulting side-scan sonar backscatter at the sample sites. Larger quantities of fine materials, however, normally will attenuate the side-scan signal and provide a low backscatter return (Blondel and Murton, 1997).

Figure 63

Figure 64

Figure 65

Two other relationships among the backscatter and sedimentary characteristics were notable. The standard deviation of the gray scale distribution of each sample location, a measure of signal sorting over the 10 m diameter area around each sample site, was plotted against mean gray scale value (Figure 66) and also against grain size sorting (Figure 67). Correlation coefficients for these two relationships (Table 37, Appendix C) showed a consistently strong and significant correlation between increasing mean backscatter intensity and increasing gray scale sorting ( $r = 0.7886$  for all samples), indicating that with higher backscatter intensity the amount of signal variability also increased (Davis et al., 1996; Blondel and Murton, 1997). This relationship was likely the result of an increase in the number of larger grain size sediment particles and/or increased carbonate content, which have been found to dominate backscatter response in otherwise fine sediments (Goff et al., 2000). There was also a moderate significant correlation between grain size sorting and gray scale sorting, showing a trend toward more variability in backscatter intensity with poorer sorting (Figure 67). This relationship was strongest in the IRB samples ( $r = 0.6913$ , Table 37, Appendix C), where there was more variability among the samples in the degree of grain size sorting and in the backscatter variability. The relationship was not as strong in the MS sample sets ( $r = 0.5315$  for MS96M and  $r = 0.2261$  for MS98JL, Table 37, Appendix C), where spatial variations in grain size sorting were small.

The individual relationships between sedimentary properties and backscatter intensity indicated that no one factor was wholly responsible for the variability observed in the side-scan signal. A combination of factors contributed to produce the signal intensities approximated by the gray scale value distributions. A series of multiple regression analyses were calculated to model the backscatter variability in terms of sedimentary and environmental properties. Multiple regression quantified the contributions of each of five independent variables toward the variability observed in a dependent variable, simultaneously reducing the unexplained portion of the variability observed (Sokal and

Figure 66

Figure 67

Rohlf, 1981). Mean backscatter intensity was used as the dependent variable, and mean grain size, sorting, carbonate content, percent fine materials, and the gray scale sorting parameter were used as independent variables.

In summary outputs of regressions (Figure 78, Appendix C), the key Regression Statistic is "R Square," the coefficient of multiple determination, which quantifies the percentage of variability seen in the dependent variable that was explained by the regression of the independent variables (Sokal and Rohlf, 1981). In the ANOVA (analysis of variance) portion of the output (Figure 78, Appendix C), the variances in the distribution of values calculated for the dependent variable were compared in terms of the regression and residual, i.e., the unexplained error around the regression. The ratio of these two variances determined the F value, which in all cases exceeded the significant F, indicating that the differences between the regression and residual variances were significant at 95% confidence. For each variable, a coefficient was calculated as well as a t-statistic. The coefficients were used to create a regression equation (including a y-intercept value) from which backscatter intensity values could be calculated given values for the independent variables. Where the t-statistic of the variable exceeded the critical-t, the contribution of the variable coefficient towards the calculated values of the dependent variable was significant at 95% confidence.

The first regressions were calculated for all MS sediment sample sites (MS96M and MS98JL). This analysis combined 100 kHz and 500 kHz side-scan data. The first regression was between backscatter intensity value and all independent variables. The R Square for this regression was 0.9725 (Figure 78, Appendix C), meaning the multiple regression of the variables explained > 97% of the variability in the distribution of backscatter intensity values. The lone significant regression coefficient was gray scale  $\sigma$  ( $t = 14.23025$ ). Thus, while all variables contributed in the regression, variations in gray scale  $\sigma$  were the most significant factor in determining what backscatter intensity value would

result. A second regression was calculated removing the factor gray scale  $\sigma$ . The result was a lower R Square value (0.6944, Figure 78, Appendix C). In the absence of gray scale  $\sigma$  as a factor, mean grain size (mean  $\phi$ ) and percent fine materials (% fines) emerged as significantly affecting backscatter intensity.

A regression calculated for all factors for the MS96M sample sites only (100 kHz side-scan data) yielded an R Square of 0.9826 and again showed gray scale  $\sigma$  as the only significant independent variable (Figure 78, Appendix C). Removing gray scale  $\sigma$  as a factor reduced the R Square to 0.8005, and none of the other coefficients was individually significant (all values of  $t < \text{critical-}t$ ). A separate regression of all variables for the MS98JL (500 kHz side-scan) data yielded an R Square of 0.8981 (Figure 78, Appendix C), a weaker coefficient than for the MS96M data. Gray scale  $\sigma$  was again the only significant coefficient. Its removal reduced the R Square to 0.7851, and mean  $\phi$  and the y-intercept then became individually significant coefficients.

When all variables were regressed against IRB backscatter intensity values, R Square was 0.6527 (Figure 78, Appendix C), meaning ~35% of the variability observed in the distribution of backscatter intensity could not be explained by the values of mean grain size, sorting, carbonate content, percent fine materials, or the sorting of the gray scale values. Gray scale  $\sigma$  was the only significant coefficient. A regression excluding gray scale  $\sigma$  yielded an R Square of 0.4407 (Figure 78, Appendix C), and % carbonate became the individually significant coefficient. Interestingly, a regression excluding only mean  $\phi$  yielded an R Square of 0.6506 (with gray scale  $\sigma$  as the significant coefficient), meaning that the contribution of mean grain size toward explaining the variability in backscatter intensity was small in comparison to the other factors (Figure 78, Appendix C).

A combined regression of all 500 kHz samples (MS98JL and all IRB data) for all factors yielded an R Square of 0.6161, with gray scale  $\sigma$  and grain size sorting ( $\sigma_{\phi}$ ) as the

significant coefficients. A regression excluding mean  $\phi$  yielded an almost identical R Square (Figure 78, Appendix C). Regressing only mean  $\phi$ , R Square was 0.1583 and was significant, along with the y-intercept value. Regressing only gray scale  $\sigma$ , R Square was 0.4614 and the coefficient was the only significant one (Figure 78, Appendix C).

A comparison of actual backscatter intensity values vs. those predicted by the regression equation for the 500 kHz data set (Figure 79, Appendix C) compared cumulative values for each distribution. The regression equation for all independent variables overpredicted actual mean backscatter intensity values in the lower ranges (under ~85) and then underpredicted actual values in the upper gray scale ranges ( $> \sim 90$ ) (Figure 79, Appendix C).

#### Current Meter Data and Analyses

*MS98S4*. The MS area S4<sup>®</sup> current meter data, in five minute hourly averages, were split into their across-shore ( $u$ ) and along-shore ( $v$ ) components and compared with depth ( $h$ ) (Figure 68). Positive values indicate easterly flow in the across-shore direction and northerly flow in the along-shore direction; negative values indicate westerly flow across-shore and southerly flow along-shore. There may be errors/artifacts in the first two days of data, as the values for  $u$ ,  $v$ , and  $h$  for that period were not consistent with values from the rest of the data set (Figure 68).

Plotting  $u$  versus  $v$  produced a current ellipse for the MS98S4 data (Figure 69). Though these data represent only a short period of time, and again may contain some errors, a dominant northeast-southwest direction in the tidal forcing, perpendicular to the axial trend of the sand bodies in this area, was evident. The orientation of the ellipse to the axis of the sand body was consistent with the model developed by Huthnance (1982b) and with the results observed by others (Goff et al., 2000).

Figure 68

Figure 69

*IRB98S4A.* These data were collected in the IRB area from 4/27/98 TO 7/30/98 and reflected the mean (tidal) current velocities for this period. Five minute hourly averages of  $u$ ,  $v$ , and  $h$  were compared (Figure 70). Tidal cyclicity was more evident in this longer data set than in the MS98S4 data (Figure 69). Both spring and neap tidal cycles were evident in the data for  $h$ , with greater variations in speed and direction evident in the cross-shore ( $u$ ) data than in the along-shore ( $v$ ) data. The tidal current ellipse that resulted from plotting  $u$  and  $v$  (Figure 71) showed that tidal currents here were also predominantly in a northeast-southwest direction, roughly perpendicular to the sand ridge axes. The shoreline, 8 km to the east, is oriented  $\sim 15^\circ$  east of north (Figure 3), such that the dominant tidal current flows are between oblique and parallel to the shoreline.

*Comparison of MS98S4 and IRB98S4A Data.* The mean velocity distributions of the MS98S4 and IRB98S4A data were compared (Figure 72). Mean current forcing in both areas was predominantly in the range of 0-10 cm/s. Current speeds greater than 10 cm/s occurred less than 25% of the time in the MS area and less than 20% of the time in the IRB area. These hydrologic characteristics are further illustrated by examining the clustering of  $u$  and  $v$  data points close to the origins in the tidal current ellipses for both data sets (Figures 69 and 71).

The maximum, mean, and median values for the cross-shore and along-shore velocity components for the MS98S4 and IRB98S4A data sets were compared (Table 23). Maximum cross-shore ( $u$ ) values for both data sets were similar. However, maximum along-shore ( $v$ ) values were greater in the IRB area. Mean and median values indicated a dominance in the easterly and southerly directions in the MS area, and in the westerly and southerly directions in the IRB area. However, the limited data set from the MS98S4 deployment, which did not encompass even a full lunar tidal cycle, may not have reflected the full range of velocities in that area.

Figure 70

Figure 70

Figure 70

Figure 71

Figure 72

**Table 23. Comparison of maximum, mean, and median values of the cross-shore ( $u$ ) and along-shore ( $v$ ) velocity components of the mean current data from the MS98S4 and IRB98S4A deployments. Positive values indicate eastward ( $u$ ) and northward ( $v$ ) transport; negative values indicate westward and southward transport, respectively.**

<b>MS98S4</b>	<b><math>u</math> (cm/s)</b>	<b><math>v</math> (cm/s)</b>
Maximum positive value (east, north)	15.338	16.790
Maximum negative value (west, south)	-18.102	-17.783
Mean	0.603	-0.762
Median	1.531	-0.290
<b>IRB98S4A</b>	<b><math>u</math> (cm/s)</b>	<b><math>v</math> (cm/s)</b>
Max positive value (east, north)	14.979	21.093
Max negative value (west, south)	-16.120	-22.636
Mean	-0.931	-1.835
Median	-1.057	-1.601

*IRB98S4B.* For these data, depth was compared to overall current speed (Figure 73), as well as to the  $u$  component (Figure 74) and the  $v$  component (Figure 75). Although these data were collected at a higher sampling rate (2 Hz) than the other S4<sup>®</sup> deployments, data were averaged by the current meter software at six second intervals. This averaging masked the part of the effect of high frequency (wave) forcing on bottom current velocities. Tidal forcing dominates the current speeds, with some high frequency forcing evident, superimposed upon the tidal currents (Figures 73, 74, 75). These high frequency forcings were small compared to the tidal forcing component, on the order of a few centimeters per second compared to maximum speeds near 20 cm/s for the  $u$ ,  $v$ , and overall current speeds. The greatest combined current speeds occurred approximately 35-40 hours into the deployment (Figure 73). This period of maximum speeds was dominated by tidal forcing and did not coincide with the period of maximum wind speeds (and, presumably, maximum wave heights) that occurred approximately 72 hours into the deployment (Figure 84, Appendix E). The periods of maximum cross-shore (Figure 74) and maximum along-shore

Figure 73

Figure 74

Figure 75

(Figure 75) velocities also were not correlated to the wind speeds during the deployment period.

*Initiation of Sediment Movement.* Sediment movement consists of both suspended load and bedload transport. Current-induced resuspension is generally minor compared to wave-induced resuspension (Lund-Hansen et al., 1999). However, the relationships between mean flow and bed response, i.e., initiation of sediment movement along the bed, can be established using the grain size and mean current data collected in the MS and IRB areas, providing a benchmark for the prediction of sediment transport from known sedimentary and hydrologic data in the areas.

Mean current data were collected < 1 m above the seabed in both areas (see Chapter 4, Methods); however, it should be noted that it is not clear at which elevation the mean flow must be measured for use in predicting sediment transport (Green et al., 1988). Nevertheless, with the data available, plots of variations in the Shields parameter and boundary Reynolds number can be used to show a range of thresholds where initiation of sediment movement is predicted to occur (Middleton and Southard, 1984; Fredsøe and Deigaard, 1992; Wright, 1995). The Shields parameter represents the ratio of the combined lift and drag forces on sedimentary particles to the gravitational forces holding them in place (Middleton and Southard, 1984). The Reynolds number represents the ratio of shear stresses acting on particle movement to viscous forces which retard movement (Wright, 1995).

The Shields  $\beta$  (Middleton and Southard, 1984) uses the ratio of current shear stress,  $\tau_0$ , to drag forces represented by sediment grain size ( $D_s$ ) and specific gravity ( $\gamma$ ), such that:

$$\beta = \tau_0 / (gD_s(\gamma_s - \gamma)) \quad (1)$$

$$\text{where } \tau_0 = C_d \rho_w U^2$$

In the values calculated here (Figures 80 and 82, Appendix D),  $U^2$  was represented by the range of velocities (in m/s) from the MS98S4 and IRB98S4A current meter deployments. Water density,  $\rho_w$ , had a value of  $1.022 \text{ kg/m}^3$ , utilizing data from Stephens et al. (1997) from the WFS (compared to a mean ocean value of 1.025 (Pinet, 2000)). A range of values from  $10^{-2}$  to  $10^{-3}$  have been proposed for the drag coefficient,  $C_d$  (Whitford, 1988; Wright, 1995), which represents frictional forces and has been known to depend on Reynolds number (Fredsoe and Deigaard, 1992) as well as the distance above the seafloor in which current velocities were collected. A value of  $5 \times 10^{-3}$  was utilized; sensitivity analyses using a range of values from  $3-8 \times 10^{-3}$  revealed little variation in the matrix of values calculated (Figures 80 and 82, Appendix D). Values for  $\gamma_s$  and  $\gamma$  were based on a consistent empirically observed ratio of  $\gamma_s/\gamma \approx 2.65$  (Fredsoe and Diegaard, 1992) and an average value for  $\gamma_s \approx 2.70$  (Tarbuck and Lutgens, 1994). Force of gravity,  $g$ , is  $9.8 \text{ m/s}^2$ . The mean grain sizes from the MS98JL (Table 12) and IRB98JL (Table 16) sediment samples were used to represent the range of grain diameters for  $D_s$ .

The Reynolds number,  $Re$ , was calculated from:

$$Re = u_* D_s / \nu \quad (2)$$

$$\text{where } u_* = (\tau_0 / \rho_w)^{1/2}$$

(Middleton and Southard, 1984). A range of values (Figures 81 and 83, Appendix D) for the skin friction velocity,  $u_*$ , were determined from those calculated for  $\tau_0$  in (1), above, and the same values for  $D_s$  were utilized as were used in calculating  $\beta$ . The value of  $\nu$  is on the order of  $10^{-6}$ , with a range of  $0.8$  to  $1.8 \times 10^{-6}$  (Pond and Pickard, 1993).

Values for  $\beta$  were plotted against values for  $Re$  for the MS98 and IRB98 data (Figures 76 and 77, respectively). Separate series of points were calculated for values of  $U$  ranging from  $0.05 \text{ m/s}$  to  $0.391 \text{ m/s}$  (the maximum recorded velocity) in the MS98S4

current meter deployment (Figure 76), and from 0.05 m/s to 0.30 m/s (with 0.264 m/s the maximum recorded velocity) in the IRB98S4 data (Figure 77). Values of  $U = 0.072$  and  $U = 0.084$  represented the median and mean velocities, respectively, of the MS98S4 data;  $U = 0.062$  and  $U = 0.068$  represented the median and mean velocities, respectively, from the IRB98S4A data.

A value of  $\beta = 0.05$  is considered a threshold value for initiation of sediment movement in sandy environments (Middleton and Southard, 1984). Points which represent larger values of  $Re$  and values of  $\beta$  above the threshold value (Figures 76 and 77) indicated conditions of current velocity and grain size in which sediment movement was predicted to occur. However, in both the MS98 and IRB98 area data sets, the current velocities which could initiate movement over the respective ranges of grain sizes occurred only a small portion of the time (Figure 72). Thus, the conditions necessary to initiate sediment movement were not often present during the times current meter data were collected.

It should be noted that the boundary Reynolds numbers and the Shields  $\beta$  values computed for these data may be somewhat underestimated due to the five minute averaging used in collecting and processing data. The inherent unsteadiness of tidal flows requires that averaging intervals be short relative to the rate of acceleration or deceleration (Wright, 1995). If the averaging period is too short, the range of values for current velocities (and thus the Reynolds stresses and Shields  $\beta$ ) will be underestimated because of bursting and intermittency; if the averaging period is too long, the additional variance of the tidal spectrum is added to produce an overestimate of turbulent kinetic energy. Wright (1995) recommends an averaging period of 10-15 minutes; however in these data collections

Figure 76

Figure 77

(MS98S4 and IRB98S4A), 5 minute averaging per hour was utilized, which may have underestimated the boundary Reynolds numbers and Shields  $\beta$  (Figures 76 and 77). If these values are actually larger, then initiation of sediment movement may be occurring more often than indicated by the results of these analyses.

### Summary

Four fundamental data sets -- time series of side-scan images, sediment samples, box core peels, and current meter data -- have been presented in this chapter. Side-scan imagery in the MS area revealed sharp contrasts in backscatter at sand body-trough boundaries and homogeneous backscatter across the sand bodies themselves. This homogeneity was supported by a lack of spatial variation in MS sedimentary properties and by downcore homogeneity in box core peels. IRB side-scan imagery revealed heterogeneous backscatter across sedimentary features. Heterogeneous IRB sedimentary properties correlated well with the backscatter signal, and both were supported by the variations seen downcore in IRB box core peels.

Temporal comparisons of side-scan imagery showed changes in the sedimentary features of both areas that can be interpreted as significant sediment movement. However, the magnitude and direction of these movements was not consistent. Additional evidence that sediment transport events have taken place were seen in the presence of bedding structures in the IRB box core peels, but these structures were absent in the MS peels. Current meter data indicated that mean current velocities were sufficient to initiate sediment movement in both area, but only a small percentage of the time, such that mean currents were unlikely to be the process driving the changes seen in the time series of side-scan images.

