Maps Showing the Stratigraphic Framework of South Carolina's Long Bay from Little River to Winyah Bay

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Introduction

South Carolina's Grand Strand is a heavily populated coastal region that supports a large tourism industry. Like most densely developed coastal communities, the potential for property damage and lost revenues associated with coastal erosion and vulnerability to severe storms is of great concern. In response to these concerns, the U.S. Geological Survey (USGS) and the South Carolina Sea Grant Consortium have chosen to focus upon the Grand Strand (the arcuate strand of beaches between the North Carolina Border and Winyah Bay, SC) and adjacent Long Bay (Figures 1 and 2) as a portion of Phase II of the South Carolina/Georgia Coastal Erosion Study (SC/GCES).

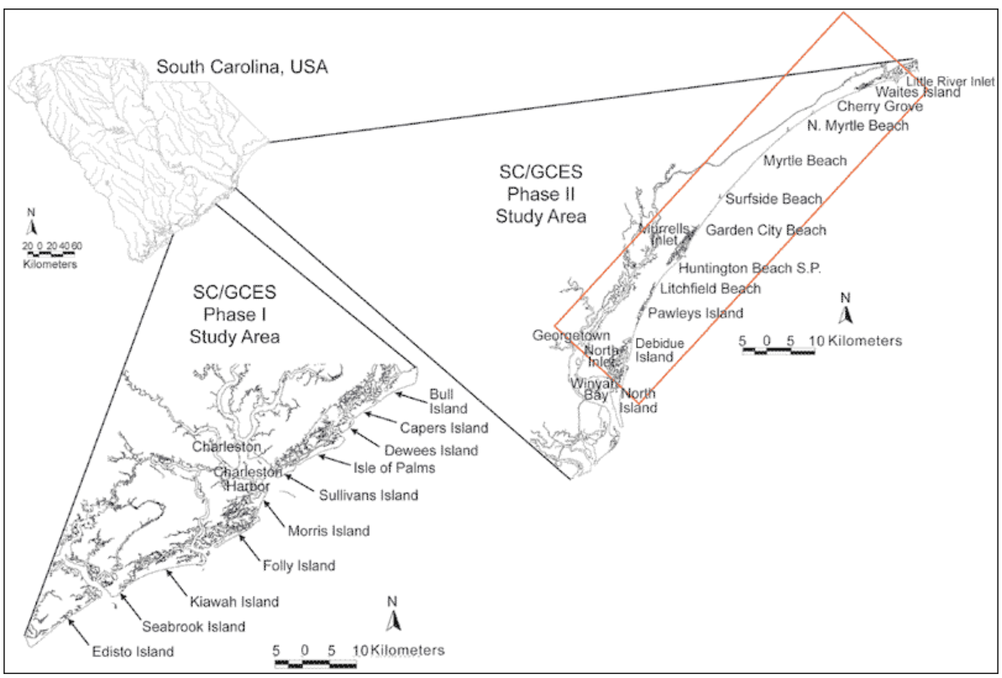

Figure 1. Regional map display. Inset map of South Carolina and blow up images of the South Carolina portions of both Phase I and Phase II study areas for the South Carolina/Georgia Coastal Erosion Study. Islands, beaches and major water bodies are labeled. Detailed location map from Figure 2 is outlined in red within the Phase II study area (modified from Baldwin, 2002).

Phase I of the SC/GCES (1994 - 1999) focused upon critical areas of erosion along the central portion of the South Carolina coastline (Figure 1). Research conducted during Phase I began to identify how physical processes, inlet-beach interaction, framework geology and shoreline geometry combine to control patterns of erosion along the central South Carolina coast. Phase II of SC/GCES (1999 - present) was designed to gain a further understanding of the factors affecting shoreline change within northern South Carolina (Figure 1) and Georgia. Specific goals of the Phase II study include: 1) quantifying historic shoreline change and identifying erosional hotspots; 2) mapping geologic framework and determining its role in the area's coastal evolution; and 3) calculating a sediment budget and identifying transport mechanisms within the study area.

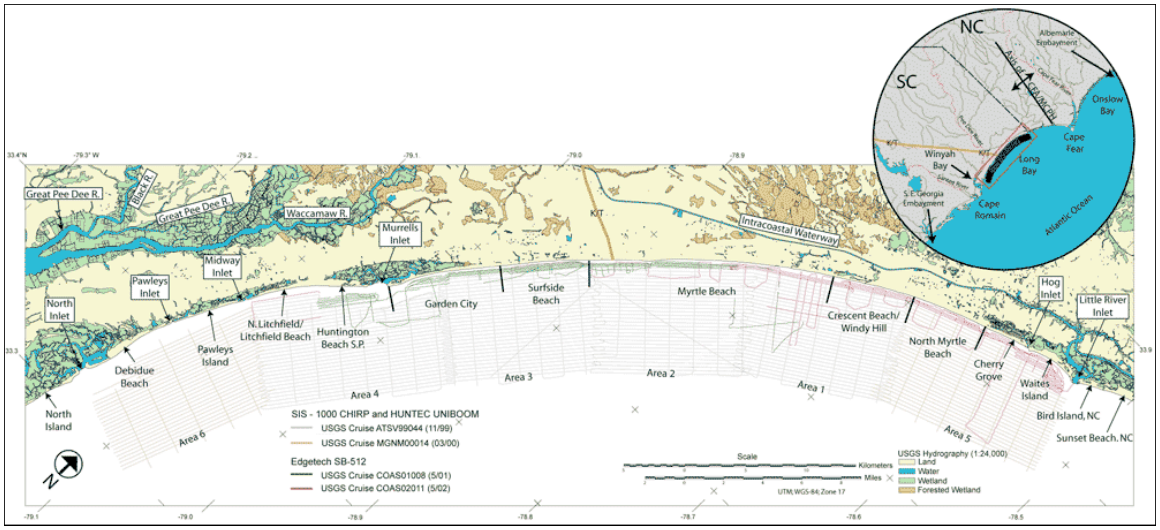

Figure 2. Map showing location of study area. Geophysical tracklines are color coded based on survey year and sub-bottom data type. Also depicted are local municipalities, landmarks, water bodies and rivers. Inset provides regional orientation, including identification of influential structural arches (Cape Fear Arch (CFA), Mid-Carolina Platform High (MCPH)) and embayments, capes and water bodies. Piedmont draining rivers are displayed in red (inset). Inland Cretaceous/Tertiary contact in orange approximated from Owens (1990).

In November 1999, to address the second goal of Phase II of the SC/GCES, the USGS, Coastal Carolina University (CCU) and Scripps Institution of Oceanography (SIO) began a program to systematically map the geologic framework within the South Carolina segment of Long Bay (Figures 1 and 2). Data sources used to produce these maps include high-resolution sidescan-sonar, interferometric sonar swath bathymetry and sub-bottom profiling. Surface sediment samples, vibracores and video data provide groundtruth for the geophysical data. The goals of the program include determining regional-scale sand-resource availability (needed for ongoing beach nourishment projects) and investigating the role that inner-shelf morphology and geologic framework play in the evolution of this portion of coastal South Carolina.

This report presents preliminary maps generated through integrated interpretation of geophysical data, which detail the geometries of Cretaceous and Tertiary continental shelf deposits, show the location and extent of paleochannel incisions, and define a regional transgressive unconformity and overlying bodies of reworked sediment. Defining the shallow sub-surface geologic framework will provide a base for future process-oriented studies and provide insight into coastal evolution.

Setting

South Carolina's Long Bay fronts approximately 100 km of the state's northeastern coast, known as the Grand Strand, located between the North Carolina border and the tidal estuary of Winyah Bay (Figure 2). In general, the vertical stratigraphic sequence landward of the study area consists of indurated to unconsolidated Cretaceous, Tertiary and Quaternary sedimentary units. Table 1 (Colquhoun and Muthig, 1991; Colquhoun and others, 1991) summarizes the names and estimated ages of formations mapped within the Lower Coastal Plain,

	Formation	Estimated Age	Reference
	Waiter Island	Holocene	DuBar and others, 1974
	Ocean Forest Peat	Holocene 6-3 ka	DuBar and others, 1974
	Wando Formation	ca. 120 to 90 ka	Owens, 1990
	Fluvial Terrace I	Late Pleistocene	DuBar and others, 1974; DuBar, 1987
	Fluvial Terrace II	Late Pleistocene	DuBar and others, 1974; DuBar, 1987
	Socastee Formation	Middle? Pleistocene	DuBar, 1971; Blackwelder, 1981a,b; Cronin and others, 1981; Liddicoat and Opdyke, 1981
		ca 200 ka	Wehmiller and Belknap, 1982
		ca 450 to 200 ka	McCarten and others, 1982, 1983
		ca 200 ka	Owens, 1990
	Fluvial Terrace III	Middle to Late Pleistocene	DuBar and others, 1974
	Canepatch Formation	Middle or Late Pleistocene	DuBar and others, 1974; DuBar, 1987; Cronin and others, 1981
		Mollusk Zone M2	Blackwelder, 1981a
		Middle Pleistocene	McCarten and others, 1982
		Middle Pleistocene	Wehmiller and Belknap, 1982
		460 +/- 1 ka	Szabo, 1985
		ca. 450 ka	Owens, 1990
	Penholoway Formation	Early to Middle Pleistocene 1.6 to 0.76 Ma	Owens, 1990
	Waccamaw Formation	Pliocene	Various Authors
		Early Pleistocene	DuBar and others, 1974; DuBar, 1987
		1.6 to 1.25 Ma	Blackwelder, 1981b
		1.8 to 1.6 Ma	Owens, 1990
	Bear Bluff	Late Pliocene to Early Pleistocene?	DuBar, 1971
			DuBar and others, 1974
		Late Pliocene	Owens, 1990; DuBar, 1987
	Duplin	Miocene	Dall, 1898
		Pliocene	Campbell and others, 1975; DuBar and others, 1974; DuBar, 1987
	Santee Limestone	Middle Eocene	↑
Black Mingo Grp.	Unnamed Unit	Lower Eocene	
Black Mingo Grp.	Williamsburg Formation	Paleocene (Thanetian)	Sloan (1908); Van Nieuwenhuise and Colquhoun, 1982a,b; Coulquhoun and others, 1983
Black Mingo Grp.	Rhems Formation	Paleocene (Danian)	
	Pee Dee Formation	Cretaceous (Maastrichtian/Campanian)	↓

Table 1. Table of Cretaceous to Holocene Formations identified within the northeastern South Carolina Coastal Plain. Modified from Colquhoun and others, 1991 (Pliocene and younger units), and Colquhoun and Muthig, 1991 (Eocene and older units).

including Horry and Georgetown Counties. Hayes (1994) describes the coastal compartment from Bogue Inlet, North Carolina (located just south of Cape Fear) to Debidue Island, South Carolina as consisting of predominantly wave-dominated, welded barrier islands and barrier spits, interrupted by segments of Pleistocene mainland beach. Several small tidal inlets and swashes separate these beaches and barriers, providing localized drainage for adjacent upland areas. Seaward, the inner continental shelf is low relief and largely sediment-limited, covered by a patchy and discontinuous sand sheet.

Where sediment comprising the sand sheet is relatively thick (2 - 6 m), it has been reworked into bedforms of varying scale. In other locations the sand sheet is absent, exposing underlying Cretaceous/Tertiary strata and paleochannel fill at the seafloor (Wright and others, 1999; Ojeda and others, 2001; Baldwin, 2002). This coastal configuration is largely the result of regional tectonics, eustacy, and modern coastal processes.

Limited sediment supply has played an important role in the evolution of the area since the late-Cretaceous/early-Paleocene, when uplift of the Cape Fear Arch (CFA), or Mid-Carolina Platform High (MCPH, Riggs and others, 1985; Riggs and Belknap, 1988) was initiated (Colquhoun and others, 1983; Sohl and Owens, 1991, Figure 2). Uplift of this post-rift structural feature has effectively diverted large volumes of Cenozoic

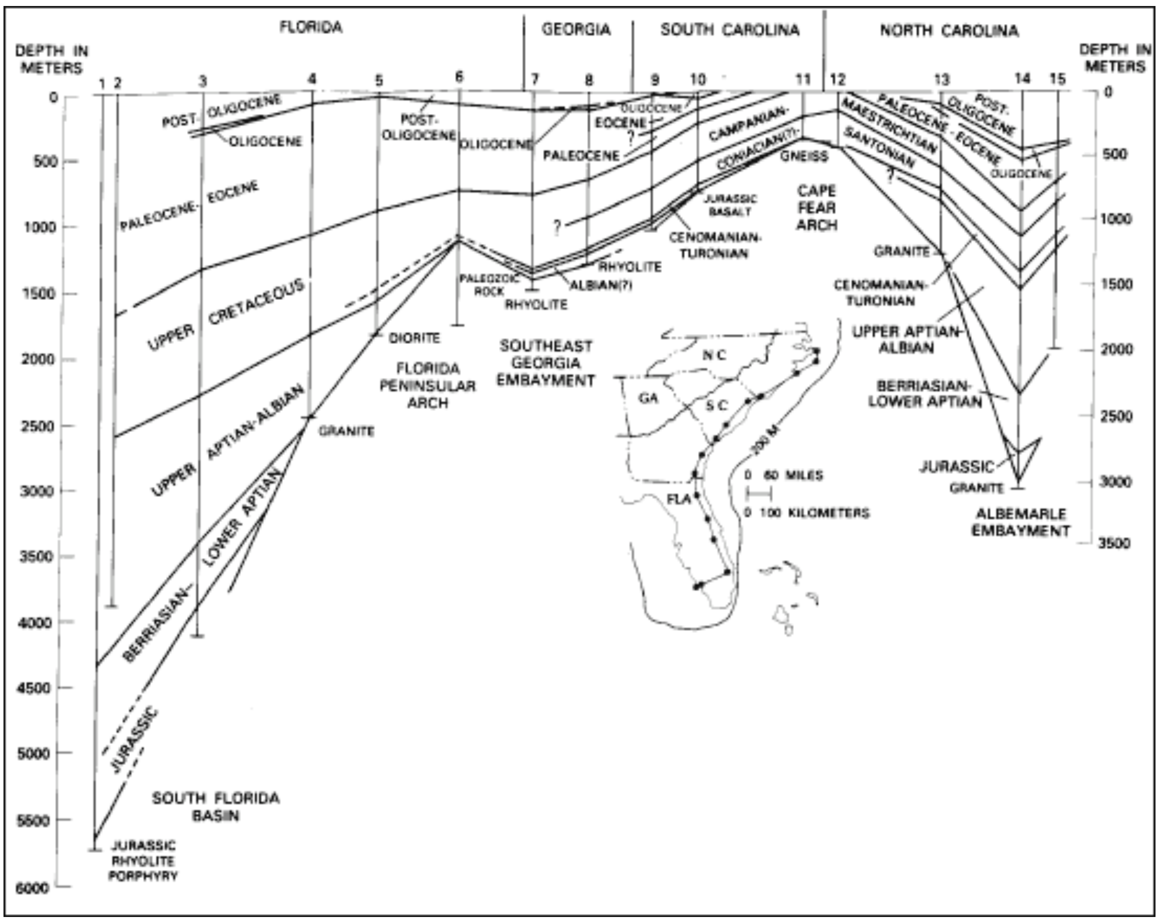

Figure 3. Generalized stratigraphic cross-section along the modern coast line from Florida to North Carolina. Adapted from Plate 9 of Maher and Applin (1971) using data in Applin and Applin (1965), Brown and others (1972), Gohn and Others (1977), Valentine (1979), and Applegate and others (1981). The names of the numbered wells are: 1. Bass Enter-Pumpkin Bay; 2. Humble-Collier #1; 3. Humble-Tucson #1; 4. Humble-Carroll #1; 5. Sun Oil-Powell Land #1; 6. Humble-Foremost #1; 7. California-Buie #1; 8. Larue-Jelks and Rodgers #1; 9. U.S.-Parris Island #2; 10. USGS-Clubhouse Crossroads #1; 11. USGS-Brittons Neck #1; 12. USGS-Calabash #1; 13. Karston-Laughton #1; 14. Standard Oil-Hatteras Light #1; a5. Stanard Oil - Esso #2 (from Gohn, 1988).

sediment into the adjacent Albemarle and Southeast Georgia embayments (Colquhoun and others, 1983, Owens and Gohn, 1985; Gohn, 1988, Figure 2). A stratigraphic cross-section of the Atlantic Southeastern Lower Coastal Plain illustrates the absence of Cenozoic sediment overlying the CFA/MCPH and a gradual thickening of Cenozoic sediment with distance from its axis (Gohn, 1988, Figure 3).

Historically, the major source of sediment to Long Bay has been via Piedmont and coastal plain draining rivers (Figures 2 and 4), which deliver large quantities of sediment, primarily derived from the Appalachian Mountains and the Piedmont (Hayes, 1994). Fluctuation in sea level throughout the Pleistocene caused deposition of beach barrier complexes or "terraces" throughout the lower Coastal Plain (Colquhoun, 1965, 1968 and 1969; Colquhoun and others, 1972; Dubar and others, 1974 and 1980, Figure 4). These barriers diverted the rivers, generally parallel to the coastline. The Myrtle Beach barrier complex (Figure 4) caused significant diversion of the Pee Dee, Waccamaw and Black Rivers to the southernmost extent of Long Bay, where they now share a common confluence at Winyah Bay (Figures 2 and 4). Discharged sediment is now dominantly deposited within the Winyah Bay estuary, which appears to be an efficient sediment sink (Patchineelam and others, 1999).

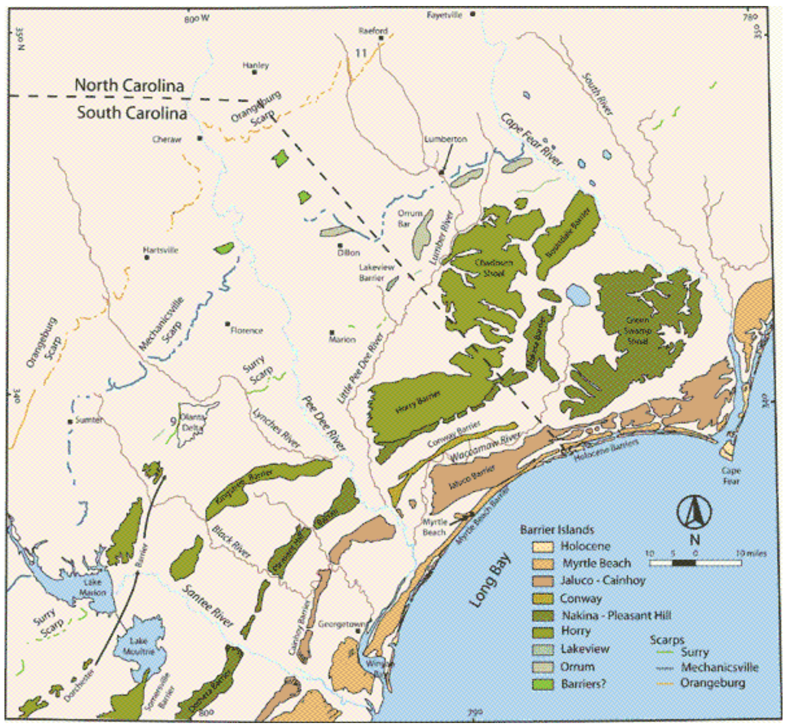

Figure 4. Geomorphological map of southeastern North Carolina and northeastern South Carolina (modified from DuBar and others, 1974). Pleistocene and Holocene barrier systems are shown. The sections of these terraces dissected by Piedmont (blue color) and Coastal Plain (brown color) rivers on their way to the coast are also illustrated.

Multiple phases of subaerial exposure and marine transgression, associated with fluctuations of sea level, have caused erosional truncation of the Cretaceous/Tertiary sedimentary units that underlie the inner continental shelf within Long Bay. These units crop out in areas where surficial sediment is absent. Without contribution from fluvial sediment sources, the Cretaceous and Tertiary continental shelf strata, and the deposits that comprise the mainland beaches and barriers, become the main source of sediment for the Long Bay sediment budget (Gayes, and others, 2003). Pleistocene transgressions and regressions have assisted in liberating sediment from these sources in the past, and storm events and day-to-day hydrodynamic processes continue to rework this material and incorporate it into the deposits and bedforms observed on the inner continental shelf (Pilkey, and others, 1981).

Geophysical Data

Acquisition

The study area covers nearly 700 km^2 of the lower shoreface and inner-continental shelf of Long Bay, from just seaward of the breaking waves (> 1 km) to ~ 10 km offshore (Figure 2). High-resolution side-scan sonar, seismic reflection and interferometric sonar bathymetry were acquired during four USGS cruises: October-November 1999 aboard the R/V *Atlantic Surveyor* (USGS cruise ATSV99044, Hill and others, 2000a; Hill and others, 2000b; Roberts and others, 2002), March 2000 aboard the R/V *Megan Miller* (USGS cruise MGNM00014, Dadisman et al, 2001a; Dadisman and others, 2001b; Denny and Schwab, In Prep.), and May 2001 and 2002 aboard the R/V *Coastal II* (USGS cruises COAS01008 and COAS02011). Data from a fifth offshore cruise, conducted in June 2002 aboard the R/V *Atlantic Surveyor* (USGS cruise ATSV02014), extend southward between North Inlet and the mouth of Winyah Bay. Analysis of these data will be incorporated into this mapping in a subsequent report.

Acquisition systems for the 1999 and 2000 offshore cruises (ATSV99044 and MGNM00014) included a Datasonics SIS-1000 side-scan sonar (100-120 kHz swept FM) and CHIRP sub-bottom profiler (2-7 kHz swept FM), a Huntec 300-3000 Hz boomer, and an SEA Ltd. Submetrix 2000 Series interferometric sonar system (234 kHz). Boomer and CHIRP seismic data were acquired digitally during both offshore cruises. During the ATSV99044 cruise, CHIRP data were acquired at a 0.27-s fire interval, a 274-ms sweep length, and a 0.263-ms sampling interval, and boomer data were acquired at a 0.5-s sampling rate, a 180-ms sweep length, and a 0.083-ms sampling interval. During the MGNM00014 cruise, CHIRP data were acquired at a 0.27-s fire interval, a 263-ms sweep length, and a 0.274-ms sampling interval, and boomer data were acquired at a 0.5-s sampling rate, a 250-ms sweep, and a 0.2-ms sampling interval. CHIRP data acquired with the SIS-1000 system were logged in the QMIPS format using Triton Elics International (TEI) ISIS acquisition software. CHIRP data were extracted and converted to single-channel SEG-Y standard format (Barry and others, 1975) using a USGS C program (QMIPSTOSEGY). Boomer data were acquired using TEI Delph Seismic acquisition software and recorded in SEG-Y standard format. Shore parallel lines were spaced at ~ 300 m, and shore perpendicular tie lines were spaced at ~ 2 km to provide adequate cross-shelf control within the seismic reflection data set.

The 2001 and 2002 cruises (COAS01008 and COAS02011) aboard the R/V *Coastal II* focused upon nearshore portions of the study area, from the inshore extent of the 1999 and 2000 surveys to approximately the seaward edge of the nearshore sand bar (typically < 200 m from the coast). Acquisition equipment used during these cruises included an Edgetech DF-1000 side-scan sonar (dual frequency 100/500 kHz), an Edgetech SB-512 CHIRP sub-bottom profiler (500 Hz - 12 kHz swept FM), and an SEA Ltd. Submetrix 2000 Series interferometric sonar system. During both nearshore cruises, Edgetech CHIRP data were acquired digitally at a 0.25-s fire rate, a 10-ms pulse length, and a 1 to 5.5 kHz sweep (swept frequency). CHIRP data acquired with the SB-512 system were logged in the Edgetech raw seismic format using an Edgetech X-star acquisition system. These data were converted to single-channel SEG-Y standard format utilizing the SIOSEIS seismic processing package (copyright University of California, written and maintained by Paul Henkart at Scripps Institute of Oceanography). Variable line spacing was used during nearshore cruises to maximize seafloor coverage while navigating shallow waters.

Side-scan sonar data were acquired digitally at a 0.125 second ping rate, yielding a 400 m swath, during all cruises. Side-scan sonar data from both the SIS-1000 and DF-1000 systems were logged at a 2K sample rate, to QMIPS format, using the TEI ISIS acquisition software.

The SEA Ltd. Submetrix 2000 Series interferometric sonar was deployed on a side-mount and mounted below a Seatronics TSS DMS2-05 motion reference unit (MRU) during all cruises. The MRU calculates heave, pitch, roll and yaw of the survey vessel. Bathymetric data were acquired at a 0.133 second ping rate and logged at a 2K sample rate using the SEA Ltd. RTS2000 acquisition software. Bathymetric swath width varied as a function of depth, but averaged roughly 10 times water depth within the depth range between 6 to 14 meters.

Coastal Oceanographics HYPACK MAX hydrographic surveying software was used to acquire Differential Global Positioning System (DGPS) data and send a navigation string to each acquisition system.

Precise measurements were made prior to survey operations to record the offsets between the navigation antenna and the MRU (the MRU is treated as the reference location for all systems).

During the ATSV99044 and MGNM00014 cruises, slant range distance to the SIS-1000 towfish was recorded using an acoustic ranging system. Using slant range measurements and ship navigation, arcuate towfish positions (± 5 m horizontal) were calculated in real-time within HYPACK and incorporated into the navigation string sent to the ISIS system. This calculation assumes that the towfish follows directly behind the vessel, which is relatively arcuate when running in a straight line with a small amount of tow cable deployed. However, because the towfish position error increases in turns by tens of meters, data collected during turns were discarded.

During the COAS01008 cruise, the position of the SB-512 tow vehicle was adjusted for layback during post-processing. The instrument was towed at the sea surface a constant 60 m behind the ship. Ship navigation recorded to the file headers were corrected for this 60 m layback during post-processing, providing arcuate positioning (± 5 m horizontal) of the tow vehicle. During the COAS02011 cruise, a DGPS antenna and receiver were mounted on the SB-512 tow vehicle. A radio modem system relayed tow vehicle position (± 2 - 3 m horizontal) to the acquisition system aboard the survey vessel and they were recorded to the file headers.

Processing & Interpretation

Bathymetric data were processed utilizing SEA Ltd. RTS2000 and GRID2000 software packages. Processing consisted of filtering the raw data to eliminate, or reduce, noise and outliers, while accounting for sensor position and other real world offsets and adjustments. An average sound velocity of 1490 m/s was used for all data collected during the ATSV99044 and MGNM00014 offshore cruises. During the COAS01008 and COAS02011 nearshore cruises, SVP (sound velocity profile) casts were performed during field operations in order to model the structure of the water column (i.e. variations in speed of sound throughout the water column). Corrections were applied to the bathymetric data to account for refraction of the acoustic wavefront due to speed of sound variations. Refraction artifacts can be introduced if changes in the sound velocity profile are not mapped. Processed data were then gridded at a 10 meter grid cell size using SEA Ltd. GRID2000 program. The data were exported and incorporated into ESRI Geographic Information System (GIS) software. Processing of Bathymetric data from the nearshore cruises is not yet complete, therefore these data are not presented in this report.

Side-scan sonar data were processed using USGS software packages Xsonar and ShowImage, following the methodology of Danforth and others (1991) and Paskevich (1992). Geomatica TM Software Solutions was used to mosaic the processed side-scan sonar data. These data were mapped at a 4 m / pixel resolution, and exported in raw binary format. The data were then imported to Adobe Photoshop and a linear stretch was applied to enhance the contrast between low- and high-backscatter. Data were saved in the geoTIFF image format.

The Boomer and SIS-1000 CHIRP SEG-Y data were processed using the Colorado School of Mines Seismic Unix (SU) processing package (Cohen and Stockwell, 2001). Band pass filter (Boomer only (0-300-2500-3000 Hz)) and automatic gain control (AGC) were applied. SB-512 CHIRP SEG-Y data were processed using SIOSEIS and SU processing packages. Heave correction (compensating for roughness of the sea surface) and AGC were applied. All processed profiles were archived and converted from post-script format to jpeg or gif image formats.

Figure 5 compares the resolution of the three seismic reflection systems utilized within the study. Each system provides sub-surface imagery at a different vertical resolution, and was utilized to meet varied research objectives. The Edgetech SB-512 system (Figure 5a) provides the highest resolution (0.5 - 1 m depending upon substrate) and was used during the nearshore surveys (COAS01008 and COAS02011), providing detailed imagery of the inner continental shelf and shoreface. During the USGS cruises ATSV99044 and MGNM00014, the Datasonics SIS-1000 and Huntec boomer systems (Figures 5b and 5c respectively) were operated concurrently. The SIS-1000 system provided high-resolution imagery (~ 1 m) of the shallow sub-surface. The boomer system provides a lower vertical resolution (> 1 m), but is capable of deeper penetration, yielding information concerning deeper strata.

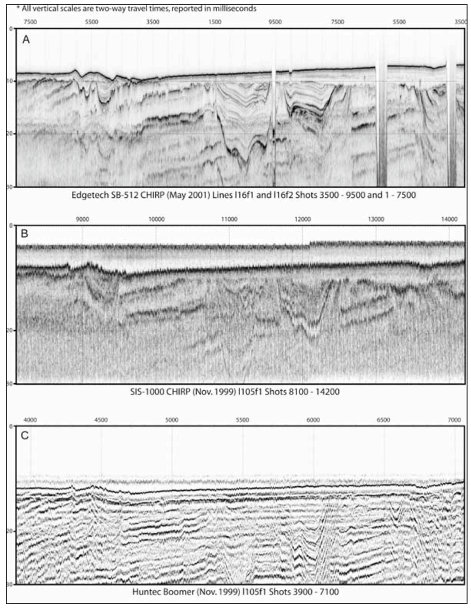

Figure 5. Profiles generated by three seismic reflection systems utilized within this study.

Navigation and SEG-Y traces were imported and interpreted digitally in Landmark Graphics Corporation Inc. Seisworks seismic interpretation software package. Reflections representing the seafloor, marine transgressive surface, and paleochannel incisions were digitized, providing two-way travel time horizons. By subtracting the seafloor from the deeper horizons, isochron surfaces indicating surficial sediment thickness and depth of paleochannel incision were generated. Using a constant seismic velocity of 1500 m/s, Two-way travel time horizons and isochron surfaces were converted to approximate depth horizons and isopach surfaces, and exported from Seisworks as georeferenced point files. ESRI ArcINFO 8.0.2 Geographic Information System (GIS) software was utilized to produce interpolated grid surfaces of horizons and isopachs from the mass point data. All grids were generated with a cell size of 10 m. ESRI ARCVIEW 3.2 and ERDAS IMAGINE 8.5 GIS software were used to generate structure and isopach maps. Products were exported to Adobe Illustrator for figure drafting and editing, and Adobe Acrobat for display.

Mapping Results

Bathymetry and Side-scan Sonar

Bathymetry (Figure 6) and side-scan sonar imagery (Figure 7) identify a variety of seafloor features and environments within the study area, and provide insight concerning the processes controlling distribution of surficial sediment within Long Bay. A subsequent USGS report will provide detailed interpretation of these data when analyses and descriptions of groundtruth data are finalized. Here, general descriptions of bathymetry and side-scan sonar data are provided, but the data are primarily used to illustrate benthic character associated with sub-surface features identified within the seismic reflection data. Figure locations, tracklines for seismic profiles and locations of groundtruth examples are superimposed upon the regional side-scan sonar mosaic (Figure 7).

Bathymetric data (Figure 6) show the gentle seaward-dipping gradient typical of the inner continental shelf within Long Bay. Water depths range from 5 to 15 m with the deepest areas farthest offshore. Isolated bathymetric highs exist offshore of Waites Island, where a nearshore shoal complex abuts the shoreface, offshore of Myrtle Beach, where a large approximately NE - SW trending lobe extends seaward, offshore of Murrells Inlet, in the form of a large inlet-related shoal complex, and in the southern portion of the survey, where fields of shoreface-attached and shoreface-detached ridges trend offshore to the northeast. The inner continental shelf is generally low relief, but larger gradients do exist within the ridge fields, where crest to trough heights can exceed 5 m.

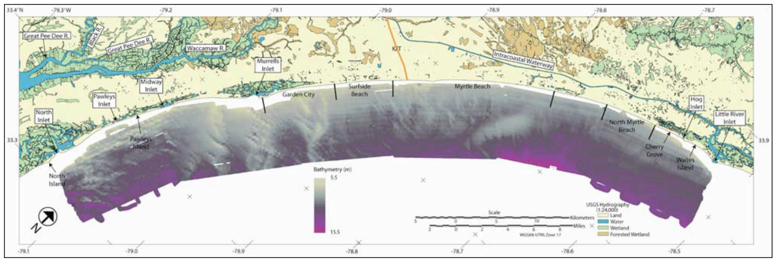

Figure 6. Submetrix Interferometric Sonar Bathymetry (234 kHz) coverage of the study area. Inter-line interpolation was required to generate a continuous bathymetric surface from ~ 70 - 100 m swath widths.

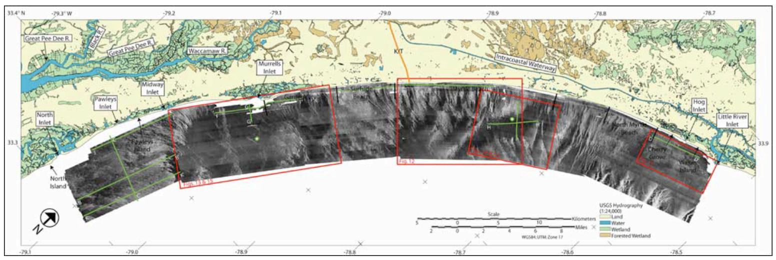

Figure 7. SIS-1000 100 kHz sidescan-sonar image of the study area. Light tones depict areas of high backscatter and dark tones indicate areas of low backscatter. Inset numbered boxes indicate the locations of figures within the text. Green lines indicate trackline coverage of sub-bottom profiles and green circled white crosses indicate groundtruth locations used for illustration.

The regional 100 kHz side-scan sonar mosaic (Figure 7) is an acoustic image of the seafloor in which dark tones indicate areas of low acoustic backscatter and light tones depict areas of high acoustic backscatter. Preliminary analysis of groundtruth data (surficial sediment samples, vibracores and video data) indicate that low-backscatter returns represent less reflective substrates, where the seabed exhibits relatively low roughness (smooth or small rippled bedforms) and is composed of predominantly fine to medium-grained sands and muds. High-backscatter returns represent harder, more highly reflective substrates, where seabed roughness is greater (larger rippled bedforms, rubble surfaces and low relief ledges), and it is composed of coarse-grained sands, shell hash, gravel sized clastics and hardground.

Large, relatively uniform low-backscatter regions (offshore Waites Island, Myrtle Beach and Murrells Inlet) generally coincide with positive bathymetric features, and are likely composed of fine- to medium-grained sand. In contrast, expansive areas of high-backscatter returns are generally found to be coincident with bathymetric lows, or areas of constant bathymetry, where coarse-grained sediment and outcropping hardgrounds are present at the seafloor.

Seismic Stratigraphy

Seismic stratigraphic analysis of the seismic reflection data identified three main units: Cretaceous and Tertiary continental shelf strata, deposits of unknown age that fill an extensive system of ancient paleochannels, and modern (Pleistocene and younger) surficial sediment accumulations. A regionally defined transgressive unconformity separates lithified underlying continental shelf strata and paleochannel fill, from overlying unconsolidated marine sediment. Paleochannels are present both above and below this unconformity, indicating that the ages and origins of the incisions and fill vary significantly.

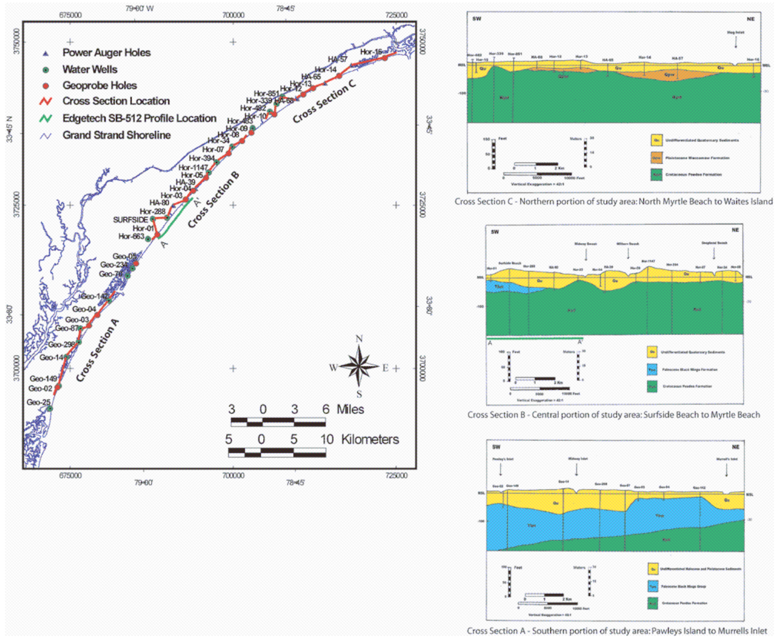

Figure 8. Three shore-parallel cross sections, generated by Putney and others (2002), incorporating drilling data from Geoprobe, water wells and power auger. Location figure (left) shows position for each of the sections. Boring data from the beach transects indicate approximately 10 - 30 m of Quaternary (Holocene and Pleistocene) sediment overlying older Cretaceous and Tertiary continental shelf deposits. The boundary between underlying Cretaceous/Tertiary units is identified within the central and southern cross sections, and is shown to shallow significantly in the Surfside Beach area, between Geoprobe holes Hor-1 and Hor-3. The position of the nearshore Edgetech SB-512 CHIRP sub-bottom profile A - A' (Figure 9) is also indicated on the location figure (left) (modified from Putney and others, 2002).

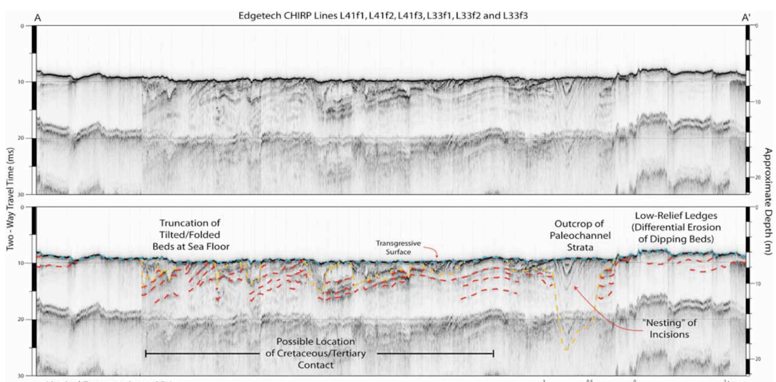

Figure 9. Composite CHIRP sub-bottom profile, with interpretations, from the nearshore area along Surfside Beach where the contact between underlying Cretaceous and Tertiary units has been identified inland. The profile identifies several strong reflections within the underlying continental shelf strata, but does not provide sufficient information for the positive identification of a single reflection representative of the unconformable boundary. Vertical scales for sub-bottom profiles are provided in both milliseconds (Two-Way Travel Time) and approximate depth in meters (assuming a seismic velocity of 1500 m/s). The location for profile A - A' is outlined in Figure 7 and on the inset map in Figure 8.

Cretaceous and Tertiary Shelf Deposits

Boomer and CHIRP sub-bottom profiles contain strong, continuous internal reflections interpreted as bedding planes within underlying continental shelf deposits. Previous studies have established Late Cretaceous (Pee Dee Formation) and Paleocene (Black Mingo Group) ages for these strata (Sloan, 1908; Hathaway et al, 1979; Van Niewenhuise and Colquhoun, 1982a,b; Domeracki, 1982; Colquhoun and others, 1983; Owens and Gohn, 1985; Owens, 1990; Idris and Henry, 1995), and have projected the intersection of the Cretaceous/Tertiary boundary with the coast in the Myrtle Beach/Surfside area (Figure 2) (Colquhoun and others, 1983; Owens, 1990). A series of coastal borings conducted for the onshore component of phase II of the SC/GCES verify the existence of the boundary in this vicinity (Figure 8, Putney and others, 2002). Edgetech SB-512 CHIRP data provide high-resolution profiles of the nearshore (~ 500 m) in this area (Figure 9), showing thin to absent surficial sediment overlying differentially eroded continental shelf strata and paleochannel fill. Several strong reflections represent separate units within the underlying shelf strata. It is possible that one of these near-surface reflections represents the unconformity separating Cretaceous from Tertiary, but at this time there is insufficient evidence to resolve this relation.

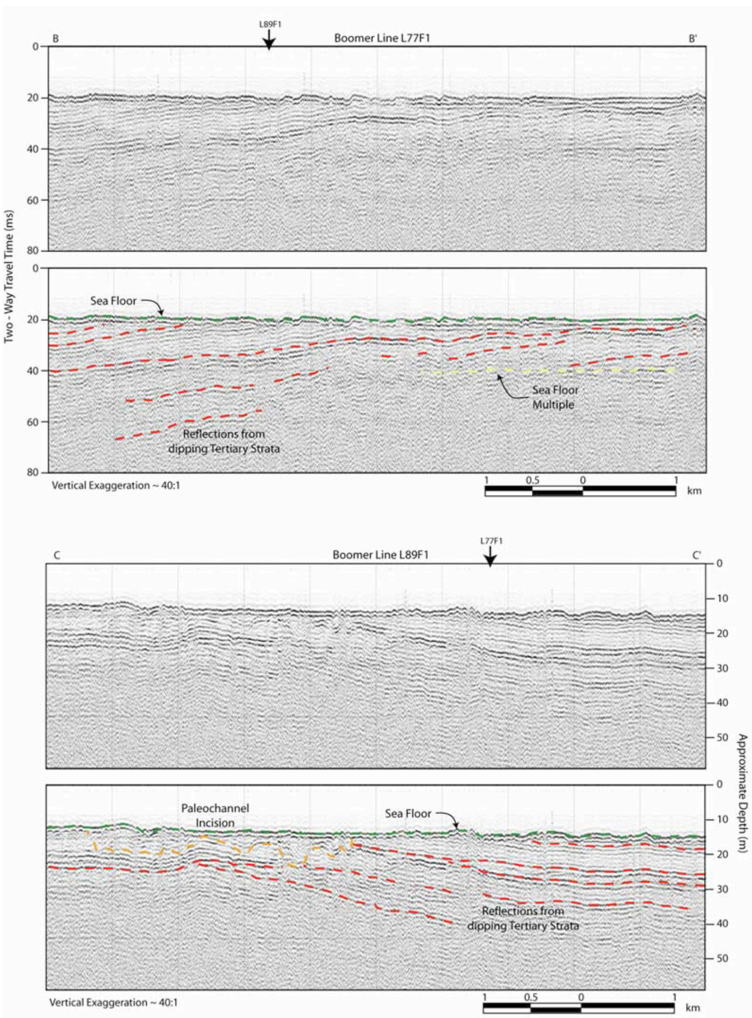

Figure 10. Processed boomer sub-bottom profiles with interpretations. These profiles provide both shore parallel (L77F1) and shore perpendicular (L89F1) images of the subsurface. These images illustrate the slight southerly dip of the Tertiary continental shelf strata underlying the area (Deeper Cretaceous strata are likely not imaged). Vertical scales for sub-bottom profiles are provided in both milliseconds (Two-Way Travel Time) and approximate depth in meters (assuming a seismic velocity of 1500 m/s). Locations for lines L77F1 and L89F1 are outlined in Figure 7.

Two stratigraphic observations illustrate regional tectonic influence upon the area. Generally, the continental shelf strata exhibit a gentle dip (~ 0.19°) to the south-southeast throughout Long Bay (Figure 10). The gentle seaward dip (east component) and upward tilt (south component) of these strata result from their position on the southwest flank of the CFA/MCPH, which apparently plunges seaward. Internal antiform and synform structural features (folding) have also been identified, indicating north - south compression of the strata. Varying degrees of deformation are observed. The most distinct folds exist immediately offshore of Waites Island, between Little River and Hog inlets. Shallow sub-surface folds within this region exhibit a maximum relief of ~ 6 m/km (Figure 11). The crests of several antiforms (Figure 11) are truncated by the

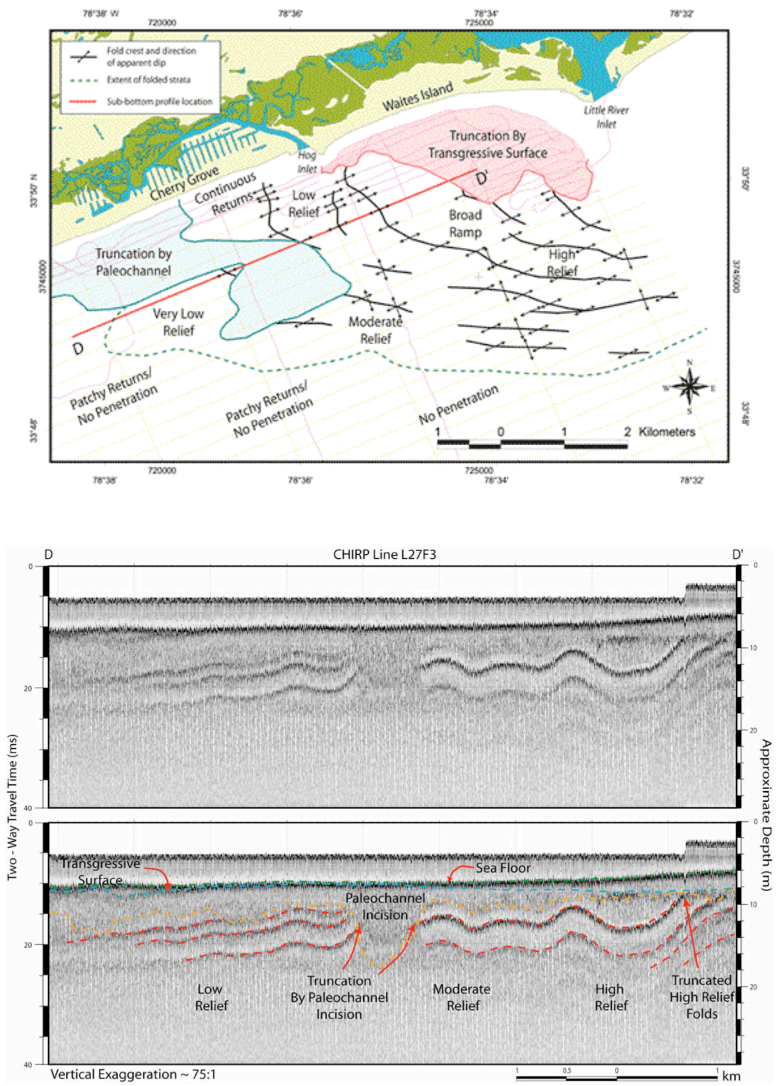

Figure 11. Generalized structure map (top, location outlined in Figure 7) of the nearshore portion of the study area from Cherry Grove to Little River Inlet, which illustrates the folded nature of underlying Cretaceous beds. Folding of this nature is observed throughout the study area, but is particularly prevalent at this location. Below, the CHIRP sub-bottom profile with interpretations (D - D', transect located on inset structure map) shows examples of the varying degrees of relief associated with the folded strata. Also illustrated are examples of folded strata being truncated by the transgressive unconformity, and by paleochannel incision. The high relief antiform structure in the central portion of the profile has been breached at its crest by a paleochannel incision. Thinning and fracturing of the strata at the crest of antiform structures could increase the likelihood of fluvial incision at that location. Vertical scales for sub-bottom profiles are provided in both milliseconds (Two-Way Travel Time) and approximate depth in meters (assuming a seismic velocity of 1500 m/s).

transgressive unconformity or incised by paleochannels. The location of the paleochannels may be due to extension and fracturing of the strata at the crests of the folds, making them more vulnerable to erosion. Although the cause of the compression generating this deformation is not fully understood, it is likely related to the large-scale regional tectonic processes responsible for uplift of the CFA/MCPH.

Sea level fluctuation has resulted in truncation or removal of Cretaceous/Tertiary units by subaerial exposure, paleochannel incision, and wave base erosion. Repeated cycles of transgression and regression have generated several unconformities, which are clearly identified within the sub-bottom data. Variation of the seismic signatures associated with these unconformities suggests that the units have undergone differential erosion. Seismic evidence of differential erosion within the Cretaceous/Tertiary units include low-relief hardground ledges, generated by resistant layers being truncated at the seafloor (Figure 12), and variable erosion patterns at the margins of channels (Figure 13). Unconformities generated by both paleochannel incision and transgression serve to identify the upper boundary of the underlying continental shelf strata (Figures 12 and 13).

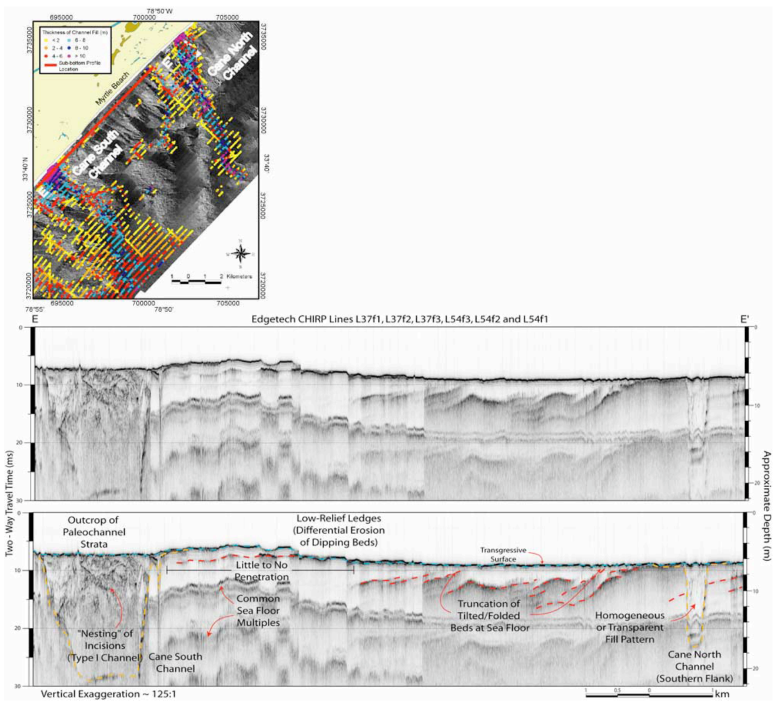

Figure 12. Sidescan-sonar coverage overlain by thickness of channel fill (right, location outlined in Figure 7), showing the location and trends of the Cane North and Cane South channels. The composite CHIRP sub-bottom profile with interpretations (E - E') provides subsurface imagery of the two channel features along a nearshore transect (located at right). The seismic example illustrates how cross-sectional morphology (including width and incision depth) and cross shelf morphologies of paleochannel incisions vary within the study area. Vertical scales for sub-bottom profiles are provided in both milliseconds (Two-Way Travel Time) and approximate depth in meters (assuming a seismic velocity of 1500 m/s).

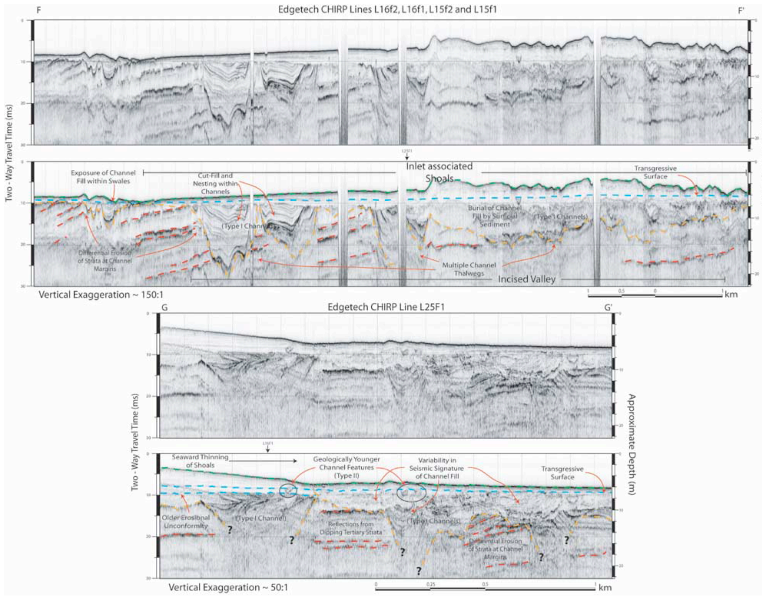

Figure 13. CHIRP sub-bottom profiles with interpretations from offshore Murrells Inlet. The two profiles provide subsurface imagery in shore parallel (Top, F - F') and shore perpendicular (Bottom, G - G') transects (located in figures 7 and 15). Both profiles illustrate the incised valley feature and overlying shoal complex associated with Murrells Inlet. Channels comprising the incised valley demonstrate the variability in cross sectional morphology and complex fill geometries that are observed in type I channel features (F - F' and G - G'). Examples of the geologically younger type II channel features are also illustrated (G - G'). Vertical scales for sub-bottom profiles are provided in both milliseconds (Two-Way Travel Time) and approximate depth in meters (assuming a seismic velocity of 1500 m/s).

Paleochannel Incision Distribution and Fill Thickness

Paleochannels are observed throughout the sub-bottom data, providing information concerning the locations, sizes, geometries and relative ages of fluvial systems that previously occupied the area. Figure 14 illustrates the locations of paleochannels, as well as their orientations and associated fill thickness. It is apparent that the size and number of these features increase significantly toward the southwest.

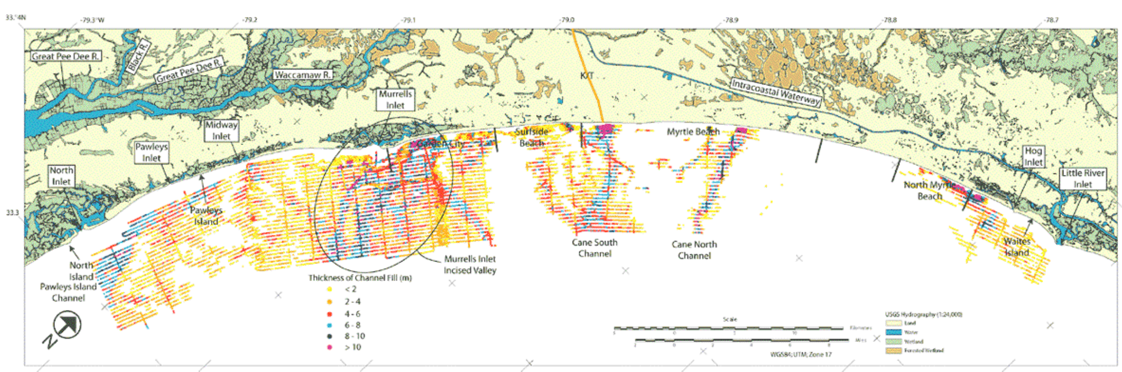

Figure 14. Map showing the locations and thickness of fill associated with paleochannels identified within the seismic reflection data. Indications of paleochannel incision have been interpreted as concave up erosional unconformities that truncate strata of increasing age. Values are presented as approximate depths in meters (assuming a seismic velocity of 1500 m/s). In most cases, these incisions dissect underlying tilted strata of Cretaceous/Tertiary age.

Two main paleochannel types are identified; Type I and Type II. Type I consists of large channels carved into underlying continental shelf deposits, most likely the results of Piedmont and Coastal Plain rivers cutting into subaerially exposed units during sea level low stands. Differential erosion of the underlying strata appears to be an important factor controlling the position of the channels. Many of the incisions occur adjacent to strong impedance reflections that are truncated at the surface, suggesting the presence of more resistant strata (Figure 13). All of these features appear to be truncated by a recent transgressive unconformity. Some portion of every channel's vertical extent has been eroded, making it impossible to assess original depth of incision or relative age according to vertical stratigraphic position. Upper surfaces of these channels are, in places, buried by surficial sediment deposits (Figure 13) and elsewhere exposed at the seafloor, both in broad expanses (Figure 12) and in the swales between sediment ridges (Figure 13). Attempts to penetrate these features with vibracores have been unsuccessful, suggesting that their upper surfaces may be lithified. Ages of the channels remain unknown, but the complex nature of some fill deposits indicate that they likely span a long period of pre-Holocene time.

Type II paleochannels occur above the most recent transgressive unconformity and have been identified offshore of the Murrells Inlet and Waites Island areas. These features are generally much smaller than Type I paleochannels and appear to have less continuity in the cross-shelf direction. Because of this, the features are interpreted as geologically young tidal creeks, ephemeral swashes or small tidal inlets. Figure 13 (G - G') illustrates several of these incisions located immediately offshore of Murrells Inlet. The vertical stratigraphic positions of these features helps to determine their relative ages, but due to their limited extent, they have represented difficult targets for vibracoring operations.

Fill deposits within the paleochannels generate two distinct seismic signatures and geometries. The first is characterized by prominent internal reflections, which identify bedding planes within the fill. Geometries of these reflections are commonly indicative of complex cut-and-fill structures and "nesting" of many incisions within a larger complex (Figures 12 and 13). Also, these geometries indicate the variable age of infill material, possibly due to reoccupation over time or multiple stages of backfill during transgression. The second common seismic signature is characterized by transparent fill, which indicate little or no internal variation in impedance (Figures 12 and 13). Transparent fill may represent rapid aggradation and channel filling with predominantly homogeneous sediment.

Morphologically, paleochannel features prove to be quite variable throughout the study area. Incisions display steep sided, U-shaped and flat-bottomed cross-sectional morphologies (Figures 12 and 13). The features are also observed to be both symmetrical and asymmetrical, and often show evidence of lateral migration. Preserved portions of these channels range from tens of meters to several kilometers in width, and several meters to tens of meters in depth (Figures 12, 13 and 15). Highly variable cross-shelf morphologies are also observed. These include: 1) small localized drainage of the younger channels (Type II) identified offshore of Murrells Inlet (Figure 13) and Waites Island; 2) large straight channels with a single thalweg like the Cane North (Figures 12 and 14) and Pawleys Island channels (Figure 14); 3) large arcuate channels with a single thalweg like the Cane South channel (Figures 12 and 14); and 4) large integrated drainage networks with multiple thalwegs like the Murrells Inlet incised valley (Figures 13, 14 and 15).

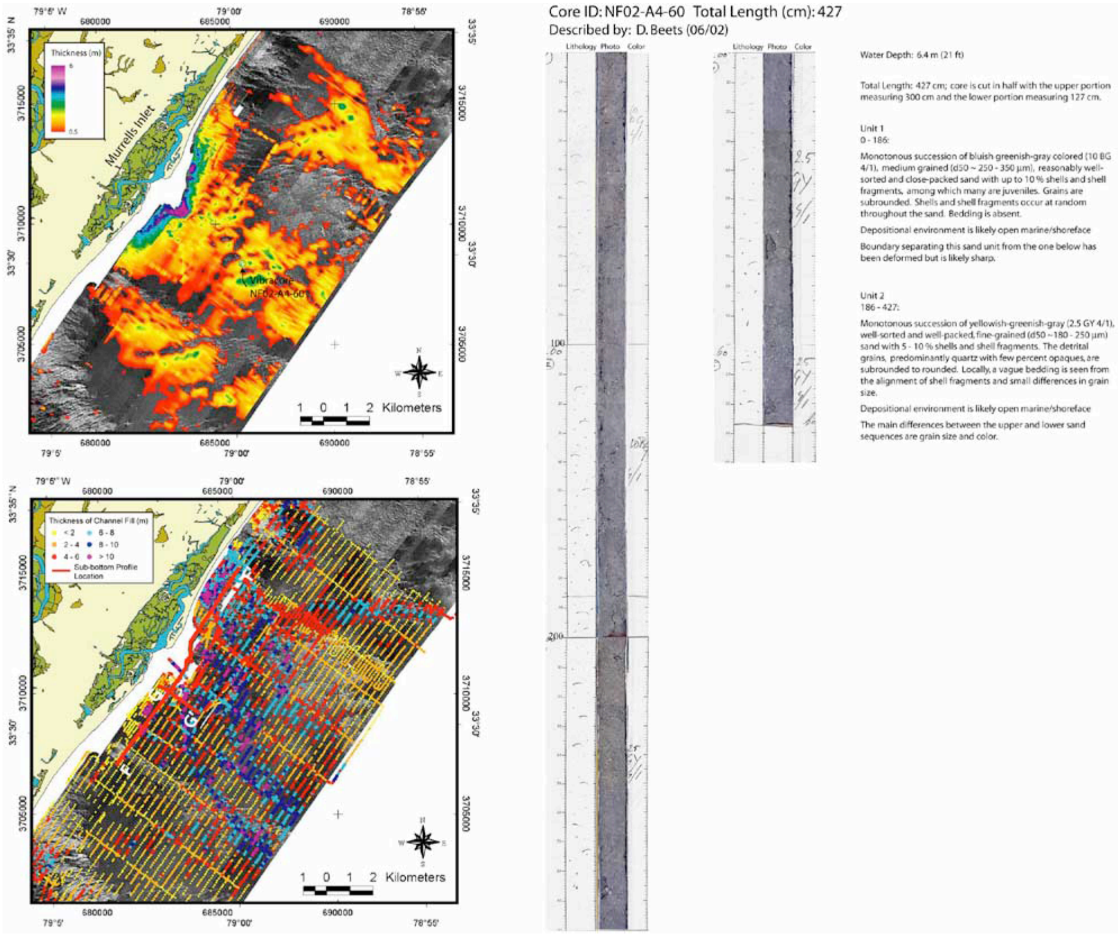

Figure 15. Sidescan-sonar coverage overlain by surficial sediment thickness grid (upper left, location outlined in Figure 7), showing the distribution of surficial sediment within the inner continental shelf offshore of Murrells Inlet. Sediment within the shoals is thickest (4 - 6 m) near the mouth of the inlet, and generally thins seaward. In several offshore locations however, localized accumulations exceed 3 m. Vibracore sample NF02-A4-60 (right, location upper left and in Figure 7) illustrates the type of sediment within the shoals, which is predominantly medium to fine grained sands containing ~ 10 % shell fragments. An ~ 1.5 m discrepancy in sediment thickness is indicated between the core sample and the thickness grid at this location. This may be due to sediment moving into the area between the times of acquisition (from '99 - '00 to '02), or inadequate resolution within the SIS-1000 sub-bottom data. Sidescan-sonar coverage overlain by thickness of channel fill (lower left, location outlined in Figure 7) illustrates the Murrells Inlet incised valley that underlies the inlet associated shoal complex. Channel incisions within this incised valley comprise a complex integrated drainage network with multiple thalweg features. Seismic profiles F - F' and G - G', depicted in Figure 13 (outlined lower left, and in Figure 7), provide vertical cross sections of these sub-surface features. (Vibracore images and descriptions provided by Coastal Carolina University, Gayes 2002, pers. comm.)

Regionally Defined Transgressive Unconformity

Truncation of both underlying continental shelf deposits and incised paleochannels enable mapping of a major erosional unconformity throughout the area. This surface serves as the major bounding unconformity separating underlying geologically older units and overlying younger sedimentary shelf deposits. The unconformity likely represents a recent transgression of the marine environment. However, because it is the only regionally mappable unconformity of this magnitude, the surface may represent erosion caused by multiple periods of transgression, regression and subaerial exposure.

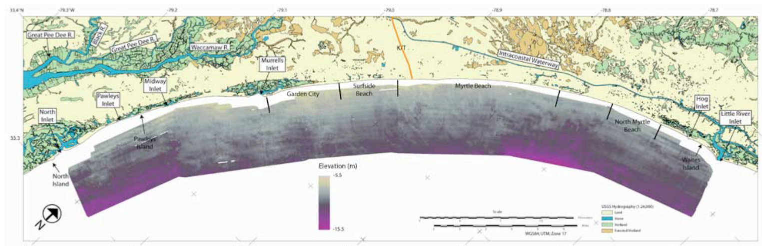

Figure 16 illustrates the elevation of the transgressive surface as mapped from the CHIRP sub-bottom profiles. For much of the study area, this surface coincides with the seafloor, and closely resembles the bathymetric map of the area (Figure 2). This is primarily due to a lack of sediment supply throughout the area, which allows underlying strata (continental shelf and paleochannel fill) to crop out at the seafloor (Figures 12 and 13). In these areas, the surface is considered to be undergoing active modification by day-to-day hydrodynamic processes. Where lenses of surficial sediment are thick, the surface deviates from the regional bathymetry (Figures 2, 16 and 17). No major deviations from the general slope of the coast are recognized on this surface throughout the area.

Thickness and Distribution of Modern Sediment

Sedimentary deposits overlying the regional transgressive unconformity are referred to as modern sediment (Pleistocene and younger). These deposits are acoustically transparent, indicative of homogeneous sediment. Vibracores and bottom grab samples show these deposits to be composed primarily of medium- to fine-grained, well-sorted sand.

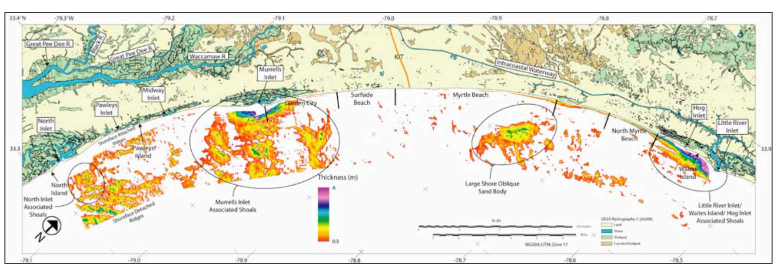

Figure 17. Map showing the thickness of modern surficial sediment accumulation. Measurements of surficial sediment lenses within CHIRP seismic data were used to generate this isopach grid. Thickness values are presented in meters (assuming a seismic velocity of 1500 m/s.) White areas indicate surficial sediment measurements of less than 0.5m.

Figure 17 contains an isopach map of modern sediment accumulation. The thickest deposits occur south of the inferred contact between Cretaceous and Tertiary strata and north of the Myrtle Beach area (Figure 2). Sediment cover is thin to absent in much of the north-central portion of the study area. This region is not completely devoid of sediment, but most of the deposits are too thin to be resolved by the sub-bottom systems utilized here. Side-scan sonar imagery, grab samples and vibracores indicate that surficial sediment deposits less than one meter thick are common throughout the study area. Imagery from offshore of Myrtle Beach illustrates this situation (Figures 7 and 12), where linear low-backscatter areas extending from the shoreface in the sonar image are not resolvable as sediment accumulations within coincident sub-bottom profiles.

Nearly every zone of significant sediment accumulation shown on Figure 17 appears to be related to tidal inlets, welded barrier islands or shoreface-attached and shoreface-detached ridges. One anomaly is a large, shore-oblique, northwest-southeast trending sand body (Figure 18), which shows up as a large low-backscatter area in the side-scan sonar image offshore of Myrtle Beach (Figures 7 and 19). This deposit measures ~ 11 km along its axis and ~ 3 km at it widest point (Figure 19). Sediment comprising the feature is thickest (~ 3 m) near its center. Smaller, ridge-like features, traverse the sand body in an east-west direction. The large sand body and the smaller transverse ridges are composed predominantly of medium-grained quartz sands (Figure 19). At this time the sediment source and generating mechanism for these features are unknown.

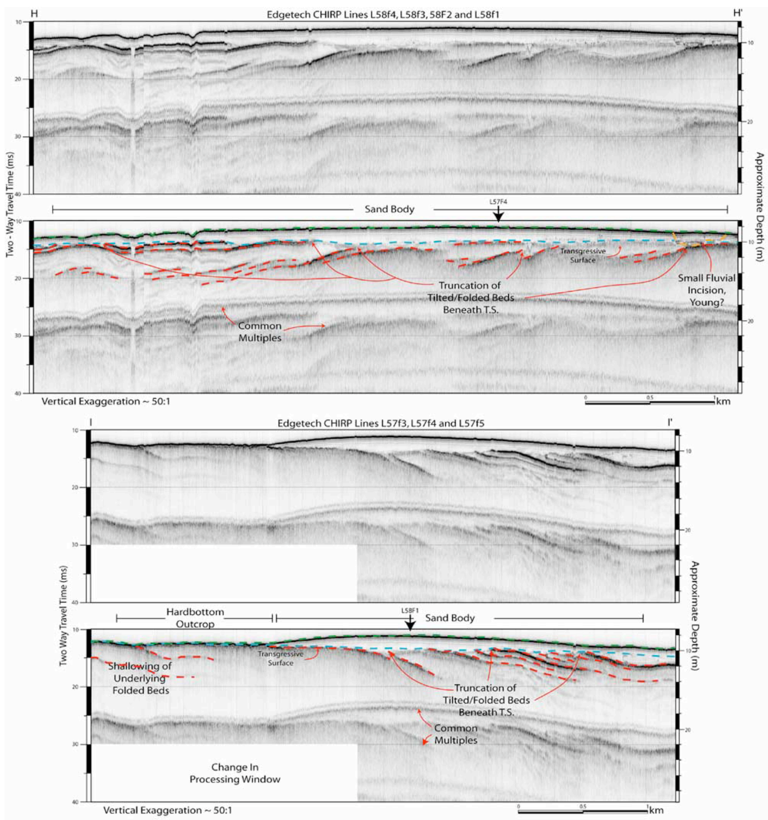

Figure 18. Composite CHIRP sub-bottom profiles with interpretations, from the large shore oblique sand feature offshore of the Myrtle Beach area. These profiles provide sub-bottom images of the feature along its long axis (left) and in a shore perpendicular transect across its thickest short axis (right). They illustrate the transparent nature of the seismic signature generated by surficial sediment lenses, as well as the underlying transgressive surface (T.S.). Vertical scales for sub-bottom profiles are provided in both milliseconds (Two-Way Travel Time) and approximate depth in meters (assuming a seismic velocity of 1500 m/s). Locations for lines H - H' (L58F4, L58F3, L58F2 and L58F1) and I - I' (L57F3, L57F4 and L57F5) are outlined in Figures 7 and 19.

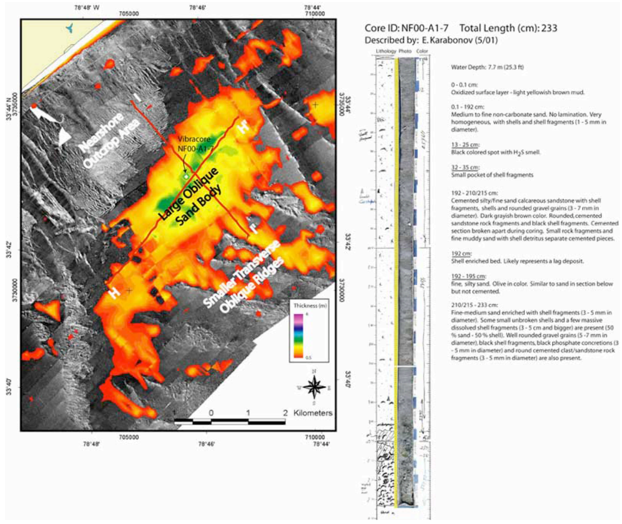

Figure 19. Side-Scan Sonar coverage (left, location outlined in Figure 7) overlain by surficial sediment accumulation grid, showing the orientation and sediment thickness associated with the large shore oblique sand body that trends in a NE - SW direction across the inner continental shelf offshore of Myrtle Beach. The feature is ~ 11 km long along its axis, and ~ 3 km at its widest point. In some areas, sediment accumulation within the feature is in excess of 3 m. Vibracore sample NF00-A1-7 (right, location above and in Figure 7) illustrates the sediment type within the feature, as well as the transgressive surface beneath. The feature is considered anomalous, because it is one of the only significant accumulations of surficial sediment that is non-inlet related, and lies north of the inferred Cretaceous/Tertiary boundary. Seismic profiles H - H' and I - I', depicted in Figure 18 (outlined at left, and in Figure 7), provide vertical cross sections of the sub-surface in this area.

A narrow shoal complex abutting the shoreface between Cherry Grove and Little River Inlet comprises a second significant sediment accumulation north of the inferred contact between Cretaceous and Tertiary strata (Figure 17). The shoals appear as a nearshore low-backscatter area in side-scan imagery (Figure 7), and contain sediment ranging 1 - 6 m in thickness (Figure 17). Sediment within these shoals overly the regional transgressive unconformity (Figure 11) and appear to be associated with the Waites Island transgressive barrier, and the Little River and Hog inlet systems that bound it to the north and south, respectively.

The largest accumulations of sediment are offshore Murrells Inlet, where three nearly shore-perpendicular shoals extend from the coast to the seawardmost reaches of the study area (Figures 13 and 15). The shoals show up as three distinct low-backscatter areas in the side-scan sonar imagery (Figures 7 and 15), and likely represent the landward retreat pathway of the Murrels Inlet system over time. Sediment within each shoal is typically 1 - 3 m thick, locally exceeding 4 m (Figure 15). Superimposed on these shoals are bedforms of varying magnitude, including a series of well-defined, shore-oblique ridges oriented ~ 50° to the shoreline (Figures 2 and 15). In the swales between ridges, and to the north and south of the shoal complexes, sediment thins, exposing the underlying continental shelf and paleochannel deposits on the sea floor (Figure 13). Side-scan sonar data illustrate this situation, as large low-backscatter regions, representing the shoals, are separated by thin high-backscatter lineations, which represent exposure of the underlying strata (Figures 7 and 15). The paleochannel deposits exposed in the swales between these ridges are part of the underlying Murrells Inlet valley fill (Figures 13 and 14).

South of the Murrells Inlet area, offshore of Pawleys Island, significant sediment accumulations are contained within fields of shoreface-attached and shoreface-detached ridges (Figure 20). The shoreface-attached ridges are oriented ~ 35° oblique to the shoreline and exhibit sediment thickness generally less than ~ 3 m (Figures 17 and 20). Shoreface-detached ridges are oriented ~ 45° to 50° to the coast (Figure 17), with sediment thickness ranging from < ~ 2 m to 4 - 6 m (Figures 17 and 20). Strata underlying the shoreface attached and detached ridges are exposed within swales where surfical sediment is thin (Figure 20).

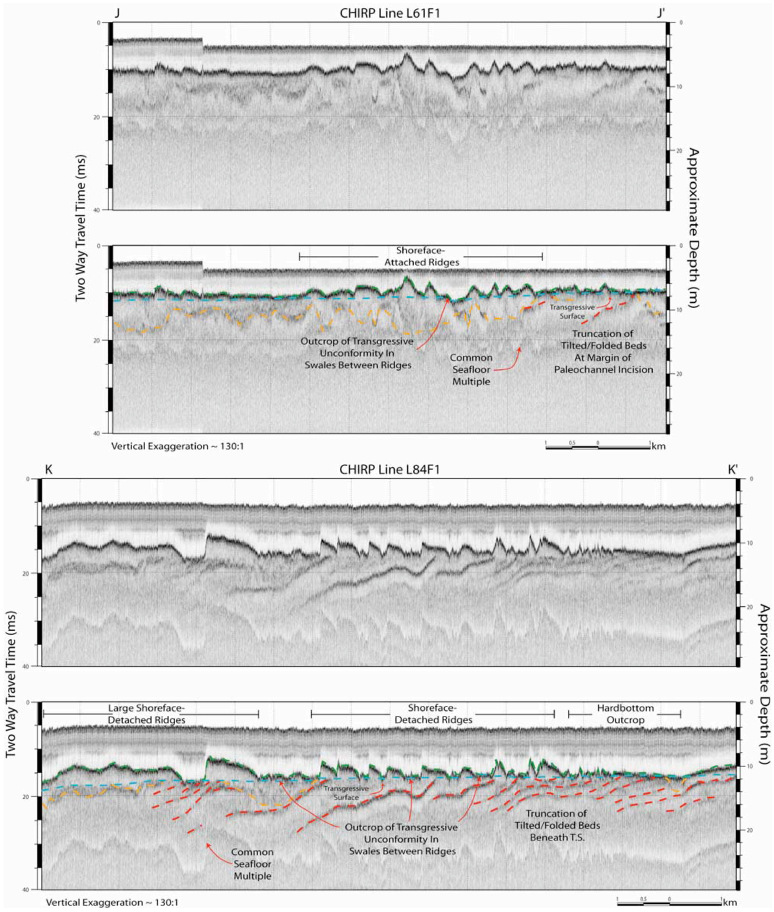

Figure 20. CHIRP sub-bottom profiles with interpretations from the shoreface-attached and shoreface-detached ridges offshore Pawleys Island. These profiles provide sub-bottom images of the features, illustrating their cross sectional profiles. The images also illustrate how the strata underlying the features crop out in the swales between them. Vertical scales for sub-bottom profiles are provided in both milliseconds (Two-Way Travel Time) and approximate depth in meters (assuming a seismic velocity of 1500 m/s). Locations for profiles J - J' and K - K' are outlined in Figure 7.

A third inlet-associated shoal complex is evident on the southern edge of the survey offshore of North Inlet (Figure 17). Though much smaller than the shoals associated with Murrels Inlet, sediment thickness values associated with this feature are between 1 and 3 m. The proximity of the previously mentioned large shoreface-detached ridges suggests that they may be a seaward extension of this inlet-associated shoal complex.

Summary

High-resolution seismic stratigraphy interpreted from CHIRP and boomer seismic reflection profiles provide a detailed description of the shallow geologic framework within South Carolina's Long Bay. This framework includes: Cretaceous/Tertiary continental shelf strata; a regionally defined marine transgressive unconformity that serves as the upper boundary to underlying Cretaceous/Tertiary strata; widespread paleochannel incision and channel fill of varying age; and a patchy and discontinuous lens of modern sediment (Pleistocene and younger) blanketing the shoreface and inner continental shelf.

Lithified late Cretaceous and Paleocene sedimentary strata provide the substrate for mobile sediment on the inner continental shelf. Monoclinal dip and folding of these strata indicate uplift to the north, and regional north – south compression. Layers within these strata exhibit considerable variation in erosional resistance. Fluctuating sea level and modern hydrodynamics have caused the strata to differentially erode, yielding an identifiable upper boundary. The elevation of the unconformity has been mapped across the area and is interpreted to represent an erosional surface formed during the last marine transgression. Variations in the seismic signatures generated by truncation of these strata, both at the seafloor and on the margins of channel incisions, indicate that individual horizons within these strata have undergone differential erosion.

Paleochannel incisions are common features within this framework, and two general types have been identified. Type I paleochannels are large channels incised into underlying Cretaceous/Tertiary strata. These incisions have been truncated by a recent transgression, and are likely the result of large fluvial systems cutting down into subaerially exposed continental shelf strata during prior low stands in sea level. Differential erosion exerts a primary control over the positioning and long-term reoccupation of these features. Channel fill appears to be largely lithified and generates a variety of seismic signatures indicating infill patterns and relative age. Type I incisions increase in size and number towards the southern portion of the study area, south of the inferred onshore Cretaceous/Tertiary contact. Type II paleochannels are observed within sediment accumulations above the regional transgressive unconformity. These incisions are much smaller and have little cross shelf continuity. Type II paleochannels are interpreted to represent previous locations of local drainage systems, such as tidal creeks, swashes or small inlets. Where multiple channels exist in an area, relative ages can be assigned through vertical stratigraphic position.

Modern surficial sediment exists primarily as a patchy and discontinuous sand sheet overlying the transgressive unconformity. Surficial sediment cover increases towards the southern portion of the study area, south of the inferred Cretaceous/Tertiary contact. Throughout much of the northern portion of the area sediment accumulation is below the resolution of seismic reflection systems utilized here. In general, significant accumulations of surficial sediment occur in proximity to tidal inlet systems. The large shore oblique sand body offshore North Myrtle Beach is the exception to this trend. Sediment comprising the shoals associated with tidal inlet systems has been reworked by modern hydrodynamic processes into shoreface attached and detached ridges. Where sediment cover thins, both in broad expanses throughout the northern portion of the study area and in the swales between sand ridges, underlying Cretaceous/Tertiary strata and paleochannel fill are exposed, at the seafloor. Seismic interpretations are supported by backscatter patterns in side-scan sonar imagery, swath bathymetry, and groundtruth data.

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Figure 8. Three shore-parallel cross sections, generated by Putney and others (2002), incorporating drilling data from Geoprobe, water wells and power auger. Location figure (left) shows position for each of the sections. Boring data from the beach transects indicate approximately 10 - 30 m of Quaternary (Holocene and Pleistocene) sediment overlying older Cretaceous and Tertiary continental shelf deposits. The boundary between underlying Cretaceous/Tertiary units is identified within the central and southern cross sections, and is shown to shallow significantly in the Surfside Beach area, between Geoprobe holes Hor-1 and Hor-3. The position of the nearshore Edgetech SB-512 CHIRP sub-bottom profile A - A' (Figure 9) is also indicated on the location figure (left) (modified from Putney and others, 2002).

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