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SHALLOW MARINE MARGIN SEDIMENTS, MODERN MARINE EROSION AND THE FATE OF SEQUENCE BOUNDARIES, GEORGIA BIGHT (USA)

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ABSTRACT

Our studies of shallow shelf lithofacies have yielded a clearer understanding of the relationship of lithification, sequence and relative sea level (RSL) just prior - and post - Last Glacial Maximum (LGM) for the Georgia Bight. Data from vibracores and hand samples have been taken from two off-shore sites - Gray's Reef National Marine Sanctuary and J-Reef. Both sites are shallow (-20 mbsl) outcrops of Pliocene – Pleistocene age. Direct age determination using AMS-radiocarbon; Uranium Series and Optical Stimulated Luminescence (OSL) methods confirm this. Using analyses of sediments and inclusions, together with the geological mapping of outcrops/exposures, we have identified at least two new provisional members of the late Pleistocene marine sequence. Our results indicate a subaerial exposure from MIS 3 through late MIS 2 with the subsequent, post–LGM transgression. Our study indicates that survival of sedimentologically observed markers for both relative sea level and at least one sequence boundary. Shell beds, observed at both reefs, are discussed as proxies for sea level and stratigraphy. Modern sediment supply has been reduced by anthropogenic activities and erosion now dominates the shallow, low accommodation space, marine margins of the inner-to-mid shelf of the Georgia Bight.

INTRODUCTION

Ten glacio-eustatic events have been identified (Foyle et al. 2004:73). The record of these 10 events, paleoshorelines, submerged or stranded barriers, is extremely incomplete on the shelf of the Georgia Bight (ibid, 73). These glacio-eustatic events are preserved on the North Carolina shelf in paleochannels (ibid; Duane et al. 1972) as well as further north on the New Jersey shelf as submerged ridges and scour features (Goff et al. 2005). Recent studies (Stubbs et al, 2007) off South Carolina have identified a relic meandering river channel on the inner-mid shelf. Glacio-eustatic events are embedded within stratigraphic sequences of shelf sedimentary lithology that occur on the inner-to-mid shelf. Further, it is observed that these shallow (< 20 m mean sea level or -20 msl) shelf sediments are undergoing modern erosion from both geostrophic and seasonal storm-related bottom currents. Coupled with erosion processes associated with cyclical changes in relative sea level (RSL) in the Pleistocene, the net result of this Quaternary erosion, coupled with lower modern sediment budgets, is the less than 20 m sedimentary section observed in the Georgia Bight. These sediments consist of fine-to-coarse grained sandstones that range from cemented or weakly-cemented rock strata (Gray's Reef and J-Reef) to a non-consolidated sediment prism observed across the inner-to-mid shelf.

In this study we characterize, lithologically and chronologically, as well as map, Quaternary sediments at two locations in the Georgia Bight: Gray's Reef, a National Marine Sanctuary and J-Reef a low exposure of shell beds about 16 km north of the Gray's Reef (fig. 1). By so doing, we develop a geologically-based scenario for RSL and examine its implication for the preservation of sediment sequences on a shallow marine shelf such as the Georgia Bight. Foyle, et al (2004), in noting the incomplete nature of the sequence record, on the Georgia shelf, indirectly allude to a larger issue in the

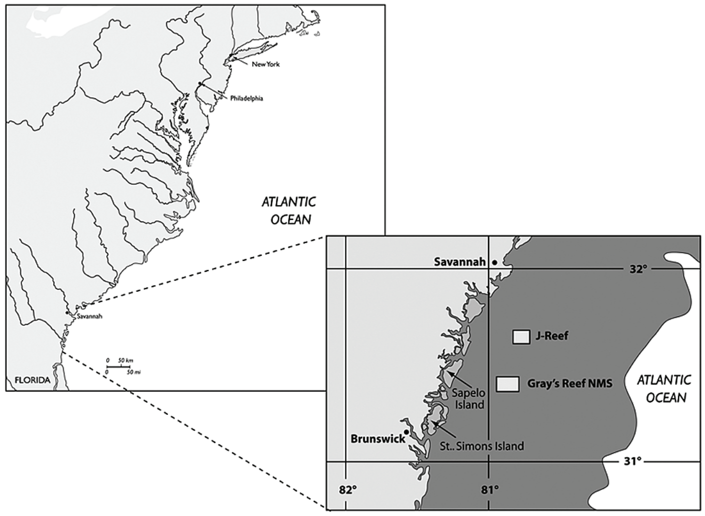

Figure 1. The Georgia Bight highlighting the study area of Gray's Reef National Marine Sanctuary and J-Reef.

nature of sediment sequences along shallow marine margins – how, if at all, may we reconstruct these sequences or, at least, how may we use their fragmentary nature to discuss sea level (and climate) cyclicity?

One helpful aspect of the stratigraphic record discovered at both Gray's and J-Reef, that allows us to speculate on changes in sea level and basin edge environments, is the well-preserved shell beds in both these locations. These unique sediments contain both paleobiological and lithological proxies for sea level and climate in the form of the taphocenose and its burial matrix of coastal sediments. First observed in 2002, the shell beds opened up a productive line of inquiry into both paleobiology and depositional environments - sedimentological and climatological - that constrained that biology. Numerous authors (Kidwell, 1986, 1988; Meldahl and Cutler, 1992; Kidwell, et al, 1993; del Rio, et al, 2001, Brett, 1998; Holland, 1993; 1995), have emphasized the importance as clues to sea level change. In this study we shall use these deposits to discuss sea level change and its preservation - or lack of preservation - in shallow marine sediments of the inner-to-mid shelf of the Georgia Bight.

STUDY LOCATION AND CENOZOIC GEOLOGIC SETTING

The Coastal Plain province offshore of Georgia, USA (Milliman et al. 1972) (fig. 1) is characterized by a gradual regional dip (0.4 - 1.0 m / km) and is composed of Jurassic, Cretaceous, Tertiary and Quaternary sediments that thicken seaward (ibid). Although relatively uniform in a geomorphic sense, a flattish coastal plain, this continental shelf is marked by various topographic features such as outcrops/live bottoms like Gray's Reef and J-reef, canyons (north of Cape Hatteras), and shoal complexes (Sexton et al. 1992) as well as drowned coastal stream valleys. The former subaerial, or emerged component of this Coastal Plain decreases from 300 km in northern Florida to less than 50 km in northern New Jersey, while in the Quaternary its emergent width increased by 100 km in the south and by over 50 km in the north (cf. Kraft 1977; Miller 1998:43). The inner shelf of the study area can be described as an accommodation dominated shelf with a significant amount of thin, transgressive lag deposits (Johnson and Baldwin 1996:238). The inner shelf can be characterized as a passive continental margin with little or no tectonism or eustasy. The dominant water mass (and current) in the Georgia Bight is the Gulf Stream. The west wall of the Gulf Stream is typically 15-20 or more km seaward of Gray's Reef.

Antoine and Henry (1965) described Quaternary sediments of the Outer Continental Shelf of the Southeastern U.S. as a thin veneer overlying Tertiary bedrock. The Georgia Bight stratigraphic sequence compresses 2 million years of Quaternary basin-margin evolution into deposits no more than 20 m thick across its breadth (Woolsey and Henry 1974; Woolsey 1977; Harding and Henry 1994). This is a reasonable characterization of the Outer Shelf as well. Seaward of the modern shoreline, Cretaceous-Cenozoic age rocks underlie the Continental Shelf and Slope (Buffler et al. 1978). Adesida (2000) reviews this stratigraphic framework for the Eocene through Miocene sequences in her shallow seismic reflection study of Sapelo Island, Georgia.

METHODS

Sediment Coring

A total of nine vibracores, five taken in 1996 and four in 2000, utilizing the NOAA ship *Ferrel* for both collection cruises, these cores were collected in two locales along or near the -20m isobath, Gray's Reef and J-Reef (Table 1). Sediment cores taken in 1996 were retrieved using a 3 inch (7.6 cm) diameter core barrel pneumatic and the 2000 cruise used a 3 inch diameter core barrel hydraulic vibracorer. Data sediment cores were analyzed first lithologically and geochemically (Littman 2000), and then for pollen (Weaver 2002) in their respective theses.

In both 1996 and 2000, all vibracores were split into working and archival halves. Hand cores were extruded into core trays. The 1996 and 2000 sediment cores were logged and photographed along their length. Sediment samples were taken at natural stratigraphic breaks, 5 cm on either side of any obvious contact. Cores were sampled for shells and botanical (wood) remains suitable for radiometric dating. In contrast to 1996, due in part to a focus on her palynological study reported on elsewhere (Weaver 2002), two 2000 cores, #3 and #5, were sampled at 10 cm intervals along their length. In both cores, every other sample from top-to-bottom was eliminated, yielding a total of 17 sediment samples of 15 cc each (eight from core #3, nine from core #5). Cores #1 and #2 from 2000 were left unopened. Core #4 was sampled exclusively for chronostratigraphy purposes.

In addition to the vibracores, sediments were retrieved by use of diver-deployed, hand-and-hydraulic corers with 1 inch (2.54 cm) to 2 inch (5.08 cm) diameter barrels. These devices, plus simple hand excavation, were utilized in areas too close to the outcrops for the use of the larger, vessel deployed coring systems. Along with use of diver-deployed corers, surface surveys and limited excavations examined the sediment near the reef fronts.

Geochronology

Chronology of the cores are based on conventional/accelerator mass spectrometry (AMS) radio-carbon dates (16); optical stimulated luminescence (OSL) dates (3); and one uranium-thorium (U/Th) age. The AMS ages were determined from a variety of material found in the cores or in excavation - bone, shell, carbonate and wood.

The OSL dating was carried out under controlled red-light conditions in the laboratory. Samples were treated with 10% HCl and 30% H_2O_2 to remove carbonates and organic material, and sieved to obtain the 120-150μm size faction which was dated. The SAR protocol (Murray and Wintle 2000) was used to determine the paleodose. Data were analyzed using Duller's (1999) ANALYST program.

The U/Th age was determined by gamma counting the reef sediment with inductively coupled plasma - mass spectrometry (ICP-MS). Uranium activity/amount was determined using the isotope Pa-234m while thorium was estimated using the isotopes Bi-214 and Pb-214.

Paleobiology

Beginning in 2002, our attention turned to the invertebrate paleontology of, first, Gray's

Table 1. 1996 and 2000 vibracore locations at Gray's Reef and J-Reef.

Site Date	Date	Latitude (N)	Longitude (W)	Water Depth (m)	Core length (m)
J-Reef	1966	31° 35.89'	80° 47.93'	19.2	1.98
J-Reef	1966	31° 35.89'	80° 47.93'	19.2	2.74
Gray's Reef	1966	31° 24.62'	80° 051.2'	19.5	3.66
J-Reef	1966	31° 35.56'	80° 47.03'	21.	<2
J-Reef	1966	31° 35.9'	80° 47.75'	20.4	4.57
Gray's Reef Station 16	1966	31° 23.833'	80° 53.473'	18	Rock, no core
GR1a (4)	2000	31° 24.616'	80°.47.100'	17.6	-2.4
GR-NE (3)	2000	31° 24.7'	80° 50.8'	19.5	2.15
GR2a	2000	31° 24.62'	80° 51.2'	19.4	Rock, no core
GR-NW:	2000	31° 24.381'	80° 54.267'	16	<1
GR-SW: (3)	2000	31° 22.30'	80° 55.00'	17.3	1.58

Reef and later in 2005, J-Reef. At Gray's Reef, there are two stations, 16 and 20, which have the focus of our investigations. Station 16 had the largest number of vertebrate fossil finds. Station 20 was first identified for study because of the discovery of a thick (>1 m) sea scallop stratum or shell bed adjacent to the Gray's Reef outcrops. We later identified the shell beds at station 16 and at J-Reef, at a location called Research Ledge, as Pleistocene-aged shell beds.

RESULTS

Inner-to-Mid Shelf Sediments of the Georgia Bight

Paleobiology

Any paleoenvironmental interpretation of the recovered sediments, would include the lithology and morphology of grains – sands to muds; inclusions such as shell, vertebrate and botanical inclusions, separating them, chronologically, into Pleistocene and Holocence facies. We identify the bulk of sediments observed, in this study, as Pleistocene aged with very little evidence of Holocene aged facies. We have detected fluvial and estuarine facies in paleochannels and, as expected, fewer shell species, with less diversity within the assemblages (Kidwell *et al*, 2005).

The mollusk assemblage, found in the various sediments, is representative of several depositional environments. In the unconsolidated sediments, at both Gray's Reef and J-Reef, together with cores of the more consolidated facies, we have identified the following species: Mellita (Sand Dollar); *Crassostrea virginica* (Eastern Oyster); *Olivella florialia* (Common Rice Olive); *Luncina nassula* (Woven Lucina); *Plicatula gibbosa* (Kitten's Paw); *Linga sombresis* (Sombrero Lucina) and *Macona tenata* a tellina-like species). Also present were *Mercenaria mercenaria* (Surf clam); *Mulina lateralis* (Dwarf surf clam) and *Astarte nana* (Dwarf Astarte). In the shell beds, the dominant species is *Placopecten magellianicus* (Sea Scallop). Within these various species, together with the lithofacies, we can more readily identify a nearshore and open marine depositional environment with some back barrier species. Because the shell assemblage is mixed, both in unconsolidated and consolidated facies, the most ob-

Table 2. Georgia Bight Sediments – Gray's Reef and J-Reef Localities

Facies	Shelly Sand	Brown Sand	Gray Mud	Gray Mud Laminated	Cemented Shelly-Sand	"Reef rock" (Raysor)
Location	Gray's Reef J-Reef	Gray's Reef J-Reef	J-Reef	J-Reef	Gray's Reef J-Reef	Gray's Reef
Lithology	M-C-S_1 Sand Shell Fragments	M-F-S_2 No shells	C-R-S-S_3	S-S_4 M-F-S_2	M-C-S_1 Shell	C-$sandstone_5$ D-$Sandstone_6$ S-$Biomicrite_7$
Structures	None	Blocky peds	None	Laminations	Weakly Cemented	Cemented
Color (Munsell, wet)	2.5Y6/1-2.5Y7/1 10Y5/1-6/1	5Y3/2-2.5Y 5/3 (dry)	5GY5/4-4/1	5GY5/5-41	5Y6/1-2.5Y7/1	5Y6/1
Sand (wt.%)	94-98	90	10-12	10-12	94-98	80-98
Clay (wt.%)	0-2	2-4	10-14	10-14	0	<1
CO_3 (wt.%)	0-11	<1	<1	<1	11-13	<20
Heavy Minerals (%)	11	<1	<1	<1	<1	<1
Magnetic Susceptibility (SI units)	0.73-6.43 x 10^{-5}	--------	--------	--------	0.6-0.7 x 10^{-5}	--------

$_1$Medium-Coarse Sand;$_2$Medium-Fine Sand; $_3$Clay-Rich-Silty Sand; $_4$ Silty-Sand; $_5$Calcareous Sandstone; $_6$Dolomitic Sandstone; $_7$Sandy Biomicrite

vious conclusion is that this is the result of erosional and diagenetic processes. Erosion is indicated by abrasion, fragmentation, color and luster loss, as well as shell edge damage. Diagenesis is inferred from shell thinning (although erosion can produce the same result), color and luster loss. Shell thinning, and concomitant loss of shell architecture, is common where shell dissolution, through chemical diagenesis, is prevalent.

Lithostratigraphy

Sediments recovered from the analyzed sediment cores were divided into two principal sediment facies: those associated with the well-described Pleistocene-aged Satilla Formation, and that of the Raysor (Duplin) Formation dated to the Pliocene (Huddleston 1988; Harding and Henry 1994). The Satilla and Raysor Formations are two members of a suite of nineteen unconformably bound Oligocene and Miocene, three Pliocene, and two Pleistocene stratigraphic units (Weems and Edwards 2001:7-15) (Fig. 2). Of the two formations, we have been able to directly date the Satilla Formation to the late Pleistocene (Table 3). In both locations the upper Satilla Formation sediments are capped by the exposed shell beds of significant thicknesses (> 3 m or more). Based on the results from vibracores; hand cores and samples, we can define, within the Satilla Formation, the following provisional members: (a) a Brown Sand Member, (b) a Cemented Shelly Sand Member and (c) a unconsolidated Shelly Sand. Taking the Raysor and Satilla Formation, together, we describe the following lithostratigraphy for the Gray's Reef area of the Georgia Bight:

1. Unconsolidated shelly sand - Holocene
2. Brown sand – Pleistocene
3. Cemented shelly sand - Pleistocene

Table 3. Chronology of Sediments at Gray's Reef and J-Reef[a]

Method	Sediment	Material	Location	Laboratory	Age ^{14}C Yr BP[b]	Age cal yr BP[c]	Age OSL / U/Th Yr BP
AMS	Reworked Shelly Sand	Bone	Surface [d]	Beta-103683	6090+/-60	7160-6790	
AMS	Reworked Shelly Sand	Shell	Surfacet[d]	UGA-11688	8950+/-70		
AMS	Reworked Shelly Sand	Carbonate	Surface, (*Oph-iomorpha*)[d]	Beta-92356	18970+/-140	22479-20571	
OSL	Shelly Sand	Quartz Sand	Core 4, -30/cm[d]				24023+/-4954
AMS	Shelly Sand	Shell	Core 4, -30/cm[d]	Beta-172381	29120+/-690		
AMS	Shelly Sand	Shell	Core 4, -170/cm[d]	Beta-172380	24640+/-460		
OSL	Shelly Sand	Quartz Sand	Core 4, -170/cm[d]				23702+/-5411
AMS	Shelly Sand	Shell	Core 1, -170/cm[d]	UGA-11689	43770+/-470		
OSL	Brown Sand	Quartz Sand	Core 1, -220/cm[d]				39265+/-5692
U/TH	Brown Sand	Sediment	Core 1, -220/cm[d]				37481+/-1372
AMS	Reworked Shelly Sand	Shell	Ledge, -15/cm[d]	UGA-11690	45170+/-1530		
AMS	Gray Mud	Wood (*Taxo-dium*?)	Core 1, -220/cm [e]	Beta-103780	>50290		
AMS	Gray Mud	Wood	Core 4, -220/cm [e]	Beta-105507	>48020		
AMS	Brown Sand	Oyster Shell	Ledge, ~10 cm [e]	UGA-00887	31082+/-180		
AMS	Brown Sand	Scallop Shell	Ledge, ~10 cm [e]	UGA-00888	35055+/-248		
AMS	Cemented Shelly Sand	Wood	Ledge, ~10 cm [e]	UGA-01045	35767+/-264		
AMS	Cemented Shelly Sand	Wood	Ledge, ~10 cm [e]	UGA-01046	39316+/-316		
AMS	Cemented Shelly Sand	Scallop Shell	Ledge, ~10 cm [e]	UGA-00889	42146+/-396		
AMS	Reworked Shelly Sand	Wood (*Licaria* sp.)	Ledge, ~10 cm [e]	UGA-00782	41326+/-455		
AMS	Reworked Shelly Sand	Wood (*Juni-per* sp.)	Ledge, ~10 cm [e]	UGA-00890	40488+/-350		

4. Dolomitic sandstone - Pliocene

Two facies B a "Brown Sand" (Unit 2) and a "Cemented Shelly Sand" - (unit 3) have been identified by this study as provisional/informal members of the Satilla Formation, while the Gray's Reef outcrops of dolomitic sandstone (unit 4) were identified as Raysor Formation. As one of the two lithified facies, it is the oldest such material in the study area. It is well studied and described by Harding and Henry (1994); Henry and Van Sant (1982); Hunt (1974); and Littman (2000). At Gray's Reef, it forms a northeast - southwest trending (strike) set of low ridges (1-2 m) and overhangs along the - 20 m isobath. The shell beds occur within the cemented sand facies. This sediment was not directly described in Harding and Henry's evaluation of the geology of Gray's Reef (1994). Neither its unique lithology, paleontology nor stratigraphic position was appreciated in this study until 2004. Hand operated coring methods - hand-driven and hydraulic - together with collection of hand samples at outcrops and exposures - were used to examine this facies. Attempts to penetrate these strata were generally unsuccessful using vibracorers in both 1996 and 2000. It is believed, because of its similar lithology to that of the unconsolidated shelf sediments, to be the parent material of the latter (Table 2). At Gray's Reef, the older Pliocene-aged Raysor Formation outcrops were exhumed from these cemented sand and shell beds. At J-Reef, the outcrops are formed entirely from this younger Satilla facies and the older Raysor lithology is not seen. Two-plus meter exposures of the concreted shell beds, at nearby artificial reefs, have been observed to have been created by storm surge and erosion, without exhumation of the Raysor Formation.

The discovery of large numbers (> 100 shells/m^2) of fossil *Placopecten magellanicus* (scallops) in imbricated shell beds at J-Reef and at Gray's Reef led to the direct dating of this sediment using those shell. The scallops, observed as an assemblage in the cemented matrix, are identified at both Gray's Reef and J-Reef in the consolidated beds at the former location and in outcrops at the latter. Mapping of this stratum across Gray's Reef leads to the conclusion that the Pliocene reef facies has been exhumed from the cemented scallop-rich shell beds. Our sediment descriptions are keyed to

Tabel 3. Notes

[a]The chronostratigraphic zones correspond to lithostratigraphic levels: 6 000 YBP to 18 000 YBP, reworked surface sediment, Shelly-Sand; 23 000 YBP to 28 000 YBP, Cemented Shelly-Sand and Gray laminated mud; 39 000 YBP to >50 000 YBP, Brown Sand 31 000 YBP 38 000 YBP. The dates for wood inclusions found in the reworked Shelly-Sand are assignable to the Cemented Shelly-Sand which is their place of origin.

[b]Conventional radiocarbon age, ^{13}C corrected using the Libby14 (half-life 5568 years). Errors represent 1 standard deviation.

[c]Calibrated radiocarbon age in years before A.D. 1950. Based on INTCAL98 calibration data using CALIB 5.01 (Stuiver, et al 1998). Calibration done only for ages <20,26514 C yr. B.P. Range represents 1 standard deviation.

[d]Sample located at Grays Reef , the *Ophiomorpha* is considered a minimum date only and not direct date of the sediment

[e]Sample located at J-Reef, Cores 1 & 4 were taken in a paleochannel, all other dates are from the so-called "Research Ledge" outcrop. The OSL and U/Th ages were derived from sediments taken from cores. Radiocarbon laboratories used in this study were Beta Analytic Incorporated (BETA), Miami, Florida; The University of Georgia Center for Applied Isotope Studies (UGA). All samples were thoroughly pre-treated with standard acid-alkali-acid washes prior to isotopic analysis by accelerator mass spectrometry (AMS). The radiocarbon ages are conventional ages, corrected to the $^{13}C/^{12}C$ ratio, and use the Libby ^{14}C half-life of 5568 years. Calibrated ages are given in years before A.D. 1950 while those of OSL are reported as years before A.D. 2003 when the OSL paleodoses were determined. The U/The age is reported as years before A.D. 1950. Because of large fluctuations in atmospheric ^{14}C content in the >30 ka time range, mainly as a result of variation in the geomagnetic field and the North American thermohaline circulation, AMS age estimates can be as much as 7 ka too young (Beck et al. 2001; Laj et al. 2002). For AMS dates greater than 42 ka the age offset may be somewhat less, possibly in the 3-4 ka range. Reliable calibration curves for this time range remain elusive (O'Connell and Allen 2004).

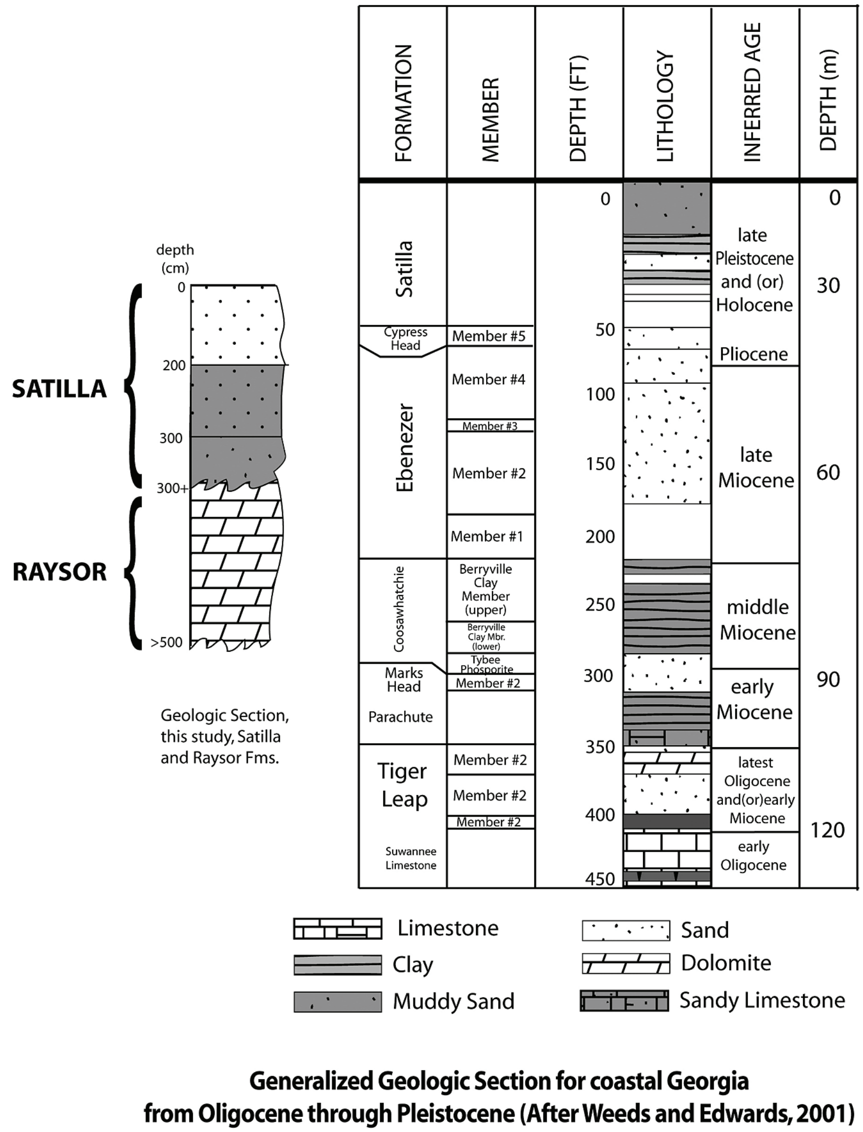

Figure 2. Generalized geologic section for coastal Georgia based on Weems and Edwards (2001). The inset geologic section for this study corresponds to the upper portion of the general geologic section. In the upper portion of the Georgia Bight, the Raysor Formation occurs seaward of the Cypresshead Formation in the Pliocene portion of the geologic section. The muddy sand described in the general geologic section appears in our study's section as Unit 2, the Brown Sand.

the cores taken at Gray's Reef and J-Reef (figs. 3,4). Excavation of the shell beds at the reef outcrops yielded two immediate facts: (1) the density of scallop values per meter is high (over 100 shells per meter), and (2) the scallop stratum is unconformable with the older Gray's Reef rock at that site. That unconformity excludes the bulk of the Pleistocene era or more (>1.6 m.y.). At J-Reef the shell beds are in a conformable relationship with the finer grained sediment, which we informally name the Brown Sand facies. No exposure of earlier than the late Pleistocene was observed at J-Reef.

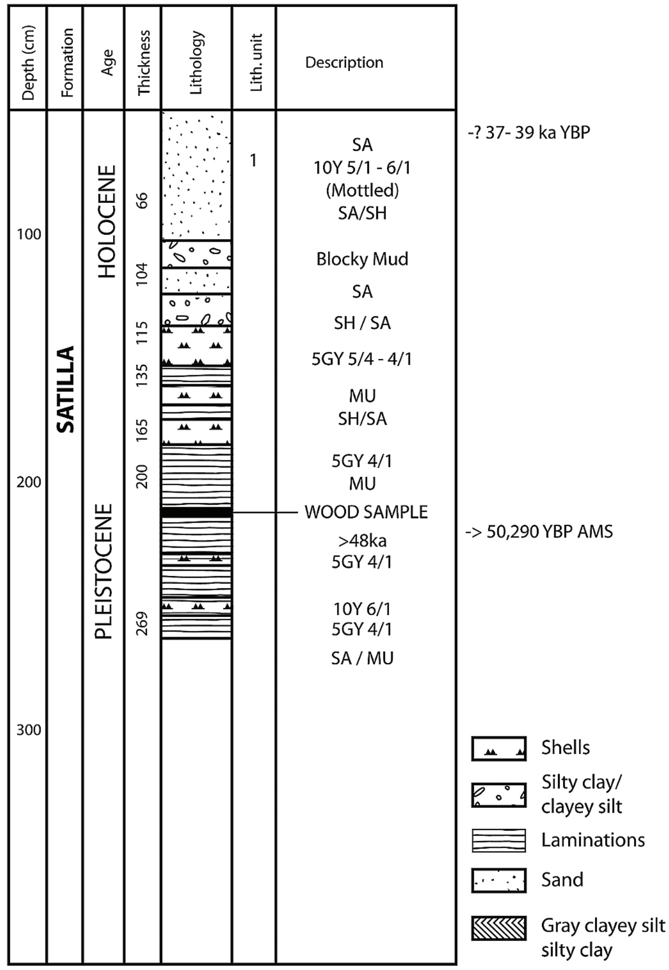

Figure 3. Vibracore from the J-Reef paleochannel's esturarine-fluvial depositional regime of laminated sand-mud and clay Satilla Formation strata with a Unit 1 sand cover. Munsell colors and absolute date ranges are shown.

Ages for Georgia Bight Sediments

Table 3 summarizes our chronometric results. One principal objective of this study was to obtain and analyze Georgia Bight sediments using high resolution radiometric dating methods. Dating of the Raysor Formation is based on lithology and stratigraphy Huddleston (1988). The reef facies, at Gray's Reef, unit 4, is both materially and time-equivalent to the Raysor (also referred to as the Duplin Formation). Woolsey (1977) identified this unit at Sapelo Island, 32 km landward today of Gray's Reef. At Sapelo, it is - 18 m MSL beneath this barrier island. Using a reasonable value for dip, the unit would outcrop at - 22 m MSL or the mean average of the reef substrate. Based on planktonic foraminifera found in the Raysor, (Huddleston 1988) assigns an age of early late Pliocene or 2-3Ma. Dowsett and Cronin (1990) estimate an age of 3.5 – 3.0 Ma for the Duplin and Raysor Formations, again, based on planktonic foraminifera, as well as calcareous nannofossils and marine ostracodes.

Using OSL as a correlative tool, the AMS dates we report are less suspect with regard to well known calibration issues for ages > 30 ka (Van der Plicht 2002). The first of the two consolidated shell beds, the Brown Sand, unit 2,

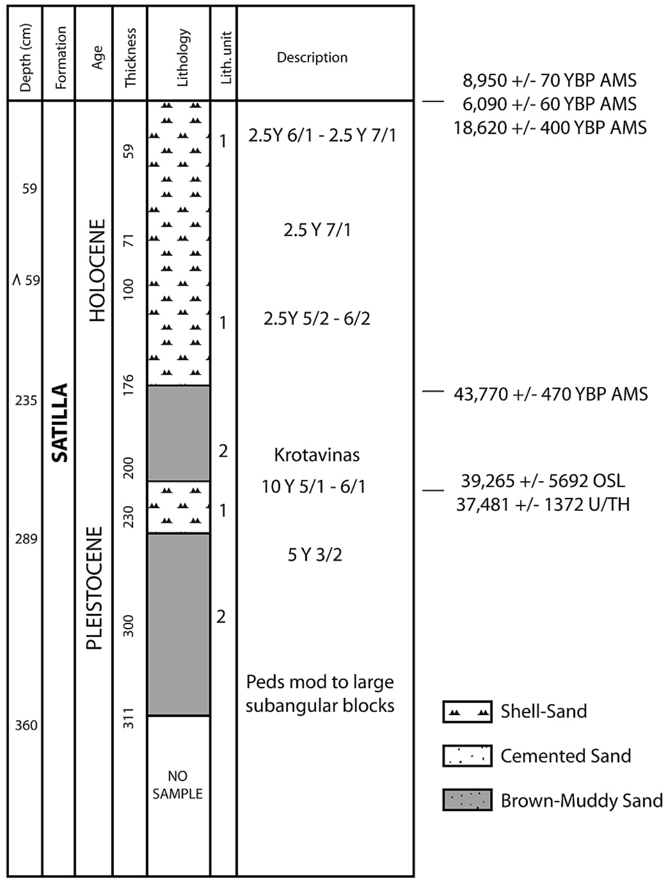

Figure 4. Well dated vibracore from Gray's Reef (GRNMS1). All sedimentological units described in this study are indicated along with Munsell colors. *Krotavinas* indicate burrows that transect Unit 2. Brown Sand pedology is shown suggesting its possible origin as a subaerial, humate rich soil.

sediment dates to at least the early glacial, e.g., late M.I.S. 3/early M.I.S. 2. The lower, conformable cemented shell beds, unit 3, observed below the Brown Sand member at J Reef is the older of these two sediments 31 to 39 ka for the former and 35 to 45 ka for the latter (Table 3).

Littman's studies of a paleochannel at J Reef, found unconsolidated shelf sediments in a unconformable position over a Gray mud (Tables 1, 2), fluvial/estuarine sediment of a ravinement surface. Two AMS dates obtained on wood samples from these sediments were A dead carbon or infinite ages, e.g > 48 ka (Littman, 2000). The age range for the overlying, unconsolidated sediments, unit 1, is 23 - 29 ka, compared to older ages of the paleochannel's muds, leaves a temporal lacuna of unknown magnitude between the two. The chronological picture is much clearer for the shell beds of Gray's and J Reefs with one radiocarbon date for a scallop shell of 45,170 +/- 1530 BP for the former and a range of four radiocarbon dates on wood inclusions of 35 - 41 ka (Table 3) for the latter.

In addition to these dates for J-Reef, a radiocarbon age for a scallop falls within this range as well, at 42,146 +/-396 BP. Based on these ages we conclude the shell beds are correlative at both locations.

DISCUSSION

Depositional Environments

The various sediments observed in the cores and outcrops, while, in many cases, allogenic in nature, can be correlated, with some degree of confidence, to defined depositional environments. The shell beds, principally within unit 3 of the Satilla Formation, are the result of nearshore, shelf depositional environments, probably, best characterized as highly reworked. This reworking, in all probability, took place during transgression when the shelf would be sediment-starved. The overlying, unconsolidated sediments of unit 1 are completely erosional deposits resulting from transgression and ravinement. These course, shelly sands are characteristic of shallow marine shelf environments.

The Brown sand unit (2) is our best evidence for a lowstand exposure. This unit is humate-rich, and represents remnant sediments of a barrier system since such humates are characteristic of spodic soil profiles found on barrier islands (Buol, et al, 1997; Hoyt and Hails, 1974). Pedogenic characteristics are listed in Table 2. The sedimentary character of this silty-sand suggests a fluvial origin for it. Generally speaking, alluvial sediments are poorly-sorted because finer, silt-clay-sized particles, in suspension, are trapped between sand grains or deposited with them when discharge diminishes (Blatt, et al., 1980). The Brown Sand could be back-barrier sediment where finer grained sediments can build up in estuaries (Milliman, et al, 1972). Whichever the case, the Brown Sand unit is most indicative of a barrier-back-barrier depositional environment "stranded" by a falling-to-lowstand systems tract, directly dated to the 39-31 Ka range (Table 3).

Taphonomy of shell beds and implications for RSL and shelf sequences for shallow shelves like the Georgia Bight

Kidwell (1988) in her paper "Taphonomic Comparison of Active and Passive Margins", identifies two types of shell beds and their relevance to sea level fluctuations.

Complex shell beds are thick (1.5 to >10 m) deposits and rest on unconformities. Identified at Gray's Reef, minor or simple shell beds are single event concentrations representing discrete episodes of erosion. Del Rio, et al (2001) in a study of marine Miocene shell beds in Patagonia, recognized Transgressive (TSST), High Stand (HSST), and Regressive (RSST/FSST) phases in these spectacular deposits.

Meldahl and Cutler (1992) examined Pleistocene shell beds in the Northern Gulf of California identifying 3 types of beds that form on Continental margins – beach berm; tidal channel lags and subtidal beds. The latter they identified as unconformity beds. Their study identified unconformity beds as due to neotectonics rather than sea level. Meldahl and Cutler point to these unconformity shell beds as significant stratigraphic markers on active margins. We will argue that the shell beds at both Gray's and J-Reefs are similar but here the isostatic sea level processes are involved in their formation. We argue that these late Quaternary shell deposits denote and calibrate RSL in the shallow Georgia Embayment.

Flessa et al (1993) posit that long-term survival of shells requires frequent, shallow burial which retards bioerosion as well a mechanical erosion. The taphonomy of Georgia shelf shell assemblages, offshore Sapelo Island, was studied by Frey (1973), Frey and Howard (1972, 1986) and Dörjes, et al (1986). The shell assemblages (not shell beds) contained both nearshore and shelf species. In the latter the authors report 44% "relict" shells from 18 genera (*Arcinella, Pectin, Tellina, Argopectin, Chione*, etc.). By their, nature relict and modern, they are time averaged. We expect the same of the shelf shell beds. Valves observed in the beds at Gray's and J-Reef share a common convex-up orientation, which corresponds to a shallow, marine current-dominated environment. Sediments, that form the fine-to-medium sand burial matrix, were provided by coastal streams through M.I.S. 3 into M.I.S. 2.

With the M.I.S. 2 regression, all the shell beds were subaerial until the Holocene transgression, ca. 8,000 BP for the reefs. During this subaerial phase, shell within the Brown Sand underwent diagenesis associated with groundwater, in spodsols, resulting in both shell thinning and complete dissolution of valves. This is observed with almost all shells recovered at Gray's and J-Reef. Transgression removed significant portions of the shell beds at Gray's Reef exposing the unconformity between the Pleistocene and Pliocene deposits. Erosion is ongoing at J-Reef through a process that involves modern bioturbation of the Brown Sand Member. Infauna have extensively burrowed this sediment in its upper portion (~ 30 cm). This disturbance, in turn, facilitates its erosion by bottom currents. The erosion exposes older, conformable facies but no Pliocene exposure was observed at J-Reef, only that of earlier Pleistocene sediments such as the shell beds.

Shell beds as stratigraphic markers

We agree with Kidwell and others in the use of shell beds as stratigraphic markers.

We identify the shell beds at Gray's and J-Reefs as unconformity beds formed during late Pleistocene (M.I.S. 3) highstand(s). The Sea Scallops function as limiting species in that they constrain the depositional environment to the lowest intertidal to shallow subtidal. These shell beds represent condensed sections of depositional sequences (Holland, 1993; 1995). They are predictably "severe" in their concentration and "biasing" of species during highstands and maximum flooding surfaces (ibid). Based on our dating, deposition occurred from 44 to 31 Ka.

A "sequence stratigraphy" for Georgia Bight Pleistocene Sediments

The Quaternary and Pliocene units of the Georgia Bight are both unconsolidated and consolidated clastic shallow-neritic sediments B mainly composed of fine-to-medium-grained quartz arenites overlying a so-called R2 seismic reflector, Miocene aged, described by Foyle, *et al* 2001; Hoyt and Henry 1967; Milliman, *et al*. 1972; Huddleston 1988; Idris and Henry 1995; Henry and Idris 1992; Swift *et al*. 1972; Swift and Niedorada 1985; Gayes et al.1992; Foyle *et al*. 2004. This sand cover is 10-15 m thick and rarely extends beyond 15-20 km offshore, pinching out in water depths of 10-15 m (Pilkey and Frankenberg 1964; Henry and Idris *ibid*) and becoming more coarse-grained. Sexton et al. (1992) and other workers (Milliman *et al. ibid*; Howard and Reineck 1973) describe the observed change in shelf sediments as the seaward extension of the modern marine accommodation space for the Bight. Most fine grained-clay/silt/fine sand - sediment occur in drowned stream valleys, such as seen in the J-Reef paleochannel (Pilkey et al. 1981; Littman 2000; this study). Their preservation is enhanced because ravinement, by the low-energy wave-field, of the Georgia Bight (less than 3 m), is relatively minor (Foyle, *et al*, 2004.).

Direct dating the younger Pleistocene sediments made it possible to address issues of RSL and sequence architecture. At Gray's Reef and nearby J-Reef (16 km north) represent Pliocene-Pleistocene lithologies, the latter being exhumed by sea level rise (transgression) post-Last Glacial Maximum (LGM) ca. 21 KYBP. Gray's Reef and J-Reef were overstepped by the modern transgression ca. 8 KYBP. At Gray's Reef the transgression exhumed a Pliocene exposure; at J-Reef it exhumed the Pleistocene. At both sites Pleistocene age shell beds are present. In addition, at both sites we map, and date, a slightly younger sand facies (Brown Sand, Unit 2) 39 KYBP vs. 43-44 KYBP for the shell beds. This is interpreted as a shoreward subaerial component of a lowstand. Chronology has these two Satilla fm elements in a conformable sequence.

According to Mitchum, et al (1977) the general sequence model of a depositional sequence with a lowstand systems tract (LSST); a transgressive systems tract (TSST) and a highstand systems tract (HSST). The sequence picture painted by our observations is "simple" in that it fits the classic S-sequence model: HSST – SB – LSST – TSST – HSST. The sequence boundary (SB) is the HSST exposure surface through the falling systems tract (FSST). IF the Brown Sand, that overlies the lower shell beds, is truly a shell depauperate subaerial surface then it would have been exposed from after 32

KYBP until ca. 8 KYP. Foyle, *et al* (2001) observes that the Quaternary, Pliocene, Miocene and Upper Floridian Aquifer (UFA) units are separated from each other by subaerial erosional surfaces – sequence boundaries. This being the case, then the Brown Sand, as the best candidate for a subaerial, erosional surface, is, also, the best candidate for a Quaternary-aged sequence boundary, dated to late MIS 3, 39 – 31 Ka.

One other candidate for an earlier sequence boundary is that of the unconformity between units 3 and 4. There is some justification for this as a recent revision of Plio-Pleistocene eustatic cycles by Wornardt and Vail (1991) indicates that cycle 3.6, for the Florida Neogene, contains one major transgressive-regressive cycle dated to 3.0 to 3.8 Ma. Seen in the fossiliferous shell beds of the Pinecrest Formation, in Florida, a large unconformity, separates strata dated to cycle 3.7 dated to 3.0 - 1.9 Ma. This unconformity may be correlative to the unconformity observed between the Raysor Formation unit and the overlying Pleistocene units seen in this study.

CONCLUSIONS

Our studies of the shallow inner-to-mid shelf Quaternary and Pliocene sediments at both Gray's Reef and J-Reef have provided a clearer understanding of these deposits as proxies for relative sea level (RSL). The uppermost Satilla Formation is interpreted as reworked clastic deposits originating from Pleistocene sources located in the Piedmont and Blue Ridge Provinces. Based on the sediment coring, survey of exposed outcrops, and absolute dating of sediments and inclusions, a clearer understanding of late Pleistocene-to-Holocene depositional and erosional processes in the Georgia Bight is now possible.

The lithostratigraphic nomenclature for this Quaternary section is the Satilla Formation. It is composed of at least two provisional members, and in paleovalleys, such as that of Medway drainage, perhaps more. The consolidated facies observed below the palimpset sand sheet are: (1) a weakly cemented Brown Sand and (2) weak-to-moderately Cemented Shelly-Sand. These facies are observed in both cores and at outcrops at or near the -20 m isobath. A facies equivalent to the Brown Sand has been reported off South Carolina's Santee River (Sexton, et al. 1992:169). The Cemented Shelly-Sand is observed at Gray's Reef and J-Reef in bedded form (Gray's Reef) and outcrops (J-Reef). Within this member are assemblages of marine shell species, most notably *Placopecten magellianicus*. Direct dating of both inclusions (AMS) and sediment grains (OSL) has constrained the ages of these two facies to 31-43 KYBP (Brown Sand) and >42-44 KYBP, or M.I.S. 3 for the Cemented Shelly-Sand. The Cemented Shelly-Sand is unconformable, at Gray's Reef, with the arenite of the Raysor Formation (Pliocene). At J-Reef a similar situation is suggested, but not directly observed. What is certain, is this weakly cemented facies is undergoing erosion at the present time and the exhumation of the Raysor Formation, at Gray's Reef, is the result of both transgression and ravinement, after LGM.

The invertebrate (and vertebrate assemblages) observed at Gray's Reef and J-Reef represent both marine (*Placopecten*) and brackish-to-freshwater (*Crassotrea*; clam species - various). The Satilla aged shell beds date to M.I.S. 4 - M.I.S. 3 with subaerial exposure beginning in the late phases of the latter marine isotope stage (< 40 KYBP). From that time on, through M.I.S. 2, until the Holocene transgression, both Gray's Reef and J-Reef were alternately fluvial-estuarine systems. Both locations were, at some time, in both regression and transgression, progradational barrier-island complexes backed by estuaries similar to those seen on the modern coast.

Overstep of the -20 m isobath was post - 10 KYBP. This is attested to by vertebrate fossils of bison, mammoth, and horse, all late Pleistocene in age, and in the case of bison, Holocene in age (Table 3). Because of the observed, ongoing erosion of the Satilla Formation and its members, preservation of the LGM low-stand on the inner-to-mid shelf is difficult to observe. It may be better preserved on the outer shelf. The Cemented Shelly-Sand facies/member is of high stand - falling systems tract origin. Its cementation occurred in the subaerial period, from late M.I.S. 3 through M.I.S. 2. Since transgression, its erosion has continued through the present. Better evidence of a lowstand in the Quaternary may be found in the paleovalleys such as at the Medway paleochannel just north of J reef and others recently observed near Gray's Reef as well as on the South Carolina shelf (Paul Gayes, personal communication, 2007; Stubbs, *et al*., 2007). Our radiocarbon ages for wood samples, taken from the J-Reef paleochannel sediments, indicate "dead carbon" or "infinite" ages for the mud-sand facies found there in sediment cores (Littman, 2001). Overall, this study, provides a better understanding of the late Quaternary stratigraphy, its sedimentology, absolute ages and processes involved in preservation (or loss) of these facies on shallow, marine margins like the Georgia Bight.

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