

## LATE QUATERNARY PALEOECOLOGY AND HEINRICH EVENTS AT GRAY'S REEF NATIONAL MARINE SANCTUARY, SOUTH ATLANTIC BIGHT, GEORGIA

ERVAN G. GARRISON<sup>1</sup>, WENDY WEAVER<sup>3</sup>, SHERRI L. LITTMAN<sup>2</sup>, JESSICA COOK HALE<sup>1</sup> AND PRADEEP SRIVASTAVA<sup>4</sup>

<sup>1</sup>*Departments of Geology, Anthropology, University of Georgia;* <sup>2</sup>*Science Applications International, Inc.;*  
<sup>3</sup>*U.S. Army Corps of Engineers, Jacksonville District;* <sup>4</sup>*Physical Research Laboratory, Earth Science  
Division, Navrangpura. Ahmedabad, 380 009, India*

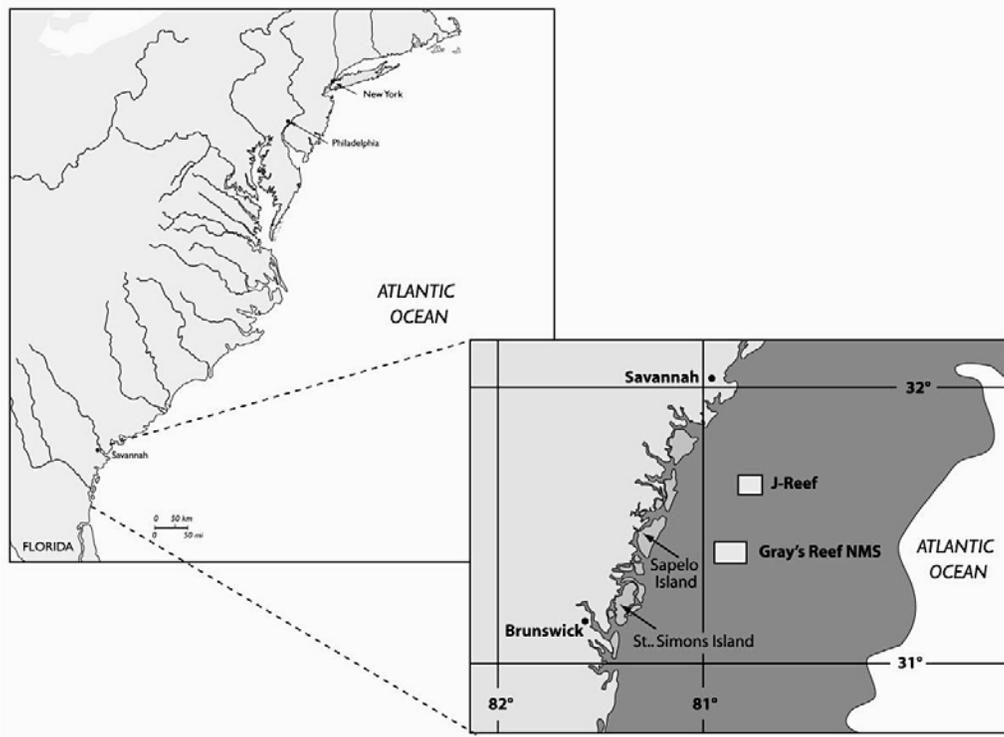
### ABSTRACT

The use of palynofacies as a conceptual tool for the study of depositional environments augments and extends the point-source studies using geophysical, lithological correlation and microfossil analyses of sediment cores in the offshore. We present a synthesis of palynofacies research in the South Atlantic Bight/Georgia Bight, USA. Two research localities - Gray's Reef National Marine Sanctuary (GRNMS) and nearby J-Reef - on the same (-20 m) isobath and only 16 km distant from one another, were characterized in our study. Vibracores to over 4 m below the sea floor were taken at both locations together with hand cores. Outcrops and seafloor exposures were hand sampled. These data are varied and, synthesized elsewhere, yielded insights into the Quaternary paleoenvironments of the coastal plain. Nearshore marine, barrier-back barrier, estuarine-marsh and upland biota provide geologic and ecologic proxies in the form of micro and macrobotanical remains - to include pollen, spores, diatoms, foraminifera and wood. The use of several techniques, notably optical stimulated luminescence (OSL), accelerator mass spectroscopic-radiocarbon (AMS-RC), amino acid racemization (AAR), and uranium series dating methods) has produced a presumptive chronostratigraphy that extends from the Holocene to oxygen isotope stage (M.I.S.) 5. Models based on our pollen results are compared to others proposed for the Mid-Atlantic and Southeast Atlantic regions of the Atlantic coastal plain. Analyses—sedimentological, geophysical, paleoecological and chronological—in the area of Gray's Reef National Marine Sanctuary

(GRNMS), have increased our understanding of the late Pleistocene paleoecology and that of relative sea level (RSL) for the now drowned Atlantic Coastal Plain. Palynological data provide a clearer picture of the ecology of the Atlantic Coastal Plain in the latter Pleistocene Epoch, M.I.S.5 through and post-Last Glacial Maximum (LGM / M.I.S.2/ Holocene). Arboreal species, notably oak and pine, dominate the pollen spectra and show clear climate-related variability most notably with Heinrich Events.

### INTRODUCTION AND RESEARCH OBJECTIVES

Using Gray's Reef (a National Marine Sanctuary since 1968) and nearby J-Reef, as our study sites, we have collected and examined geophysical, sedimentological, palynological and chronological data for the late Cenozoic - Pliocene and Quaternary - geology of the Georgia Bight (Fig. 1). Our research objectives were to relate our findings to other studies of the east coast as well as to larger issues of paleoclimate, paleoecology and relative sea level (RSL) for the late Cenozoic. In this paper we relate the results of a study of pollen, principally from two sediment cores, to late Pleistocene climate and ecology for the North American southeast, specifically what is today, Georgia, South Carolina and north Florida. A chronostratigraphy, developed simultaneously provides a putative temporal context for the observed variability in both terrestrial arboreal and non-arboreal taxa. These are treated as proxies for paleoclimate and plant ecosystems in the American Southeast (Russell, *et al*, 2009). Our research was undertaken to address those areas where knowledge of the Georgia Bight's Quaternary geology and



**Figure 1. Location map. Gray's Reef National Marine Sanctuary.**

paleoecology is not well-developed or is completely unknown. Our results are directly comparative to those of other recent studies for the Middle Atlantic Bight – Virginia and the Chesapeake (Litwin, *et al*, 2010).

Our palynofacies analyses, of sediment facies, at Gray's Reef National Marine Sanctuary (GRNMS), have been carried out on sediment cores - vibracorer and hand - together in tandem with excavated/hand samples from *in situ* outcrops and sea floor exposures. The data for these samples inform us of Pleistocene paleoecology, relative sea level (RSL) and paleoclimate of the now drowned Atlantic Coastal Plain. In particular we present palynological data to provide a clearer picture of the ecology of the Atlantic Coastal Plain in the latter Pleistocene Epoch, M.I.S.5 through and post-Last Glacial Maximum (LGM/M.I.S. 2/Holocene). Using Optical Stimulated Luminescence (OSL), radiocarbon, both conventional and AMS methods, uranium-thorium (U/Th) and Amino Acid Racemization (AAR) dating of sediment cores and shell/wood inclusions, tak-

en in 1996 and 2000, we have produced a presumptive chronostratigraphy that extends from the Holocene to M.I.S. 5.

Arboreal taxa, notably oak and pine, dominate the pollen spectra and previous researchers have shown clear climate-related variability using these taxa (Grimm, *et al*, 1993; Groot, *et al*, 1995; and Markewich, *et al*, 2009). Following other workers (Litwin and Andrle, 1992; Grimm, *et al*, 1993; and Markewich, *et al*, 2009), we use oak as a *reference taxa* for determining temperate paleoclimate in the South Atlantic Bight coastal region. This variability is to be expected for M.I.S. 3, (60-25 ka), as M.I.S. 3 was a period considered ~~to have been~~ highly unstable, climatologically, with conditions not existing (non-analog) in present-day environments. There seem to have been repeated decadal - scale warming events of 8° – 15° C (Dansgaard-Oeschger (D-O) Events) during this stage (Stewart, 2005; Siddall, *et al*, 2008) With Gonzalez and Dupont (2009) reporting as many as five high-amplitude vegetation shifts during the stage. The timing of excursions, in

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the pine-oak ratio, likewise, suggest possible correlations with Heinrich events (HE 2-4) date (Hemmings, 2004; Watts et al. 1992; Grimm, et al, 2006). In conclusion, we will represent our findings in modeled biome maps of the Georgia Bight for selected dates in the late Quaternary in order to graphically illustrate the fluctuations we detect in our data sets.

### PHYSIOGRAPHIC AND GEOLOGICAL SETTING

The submerged coastal plain, together with its subaerial component, is covered by Quaternary sediments. Antoine and Henry (1965) described the 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. This is a reasonable characterization of the Outer Shelf. The situation of the Inner Shelf is a bit more complex. Quaternary sediments thicken shoreward to 18 meters or more (Woolsey, and Henry, 1974; Woolsey, 1977; Harding and Henry, 1994). Seaward of the modern shoreline Cretaceous-Cenozoic age rocks underlie the Continental Shelf and Slope (Buffler, *et al*, 1978). Current thinking about Quaternary geology in the Southeastern Georgia Embayment/Georgia Bight is found in the comprehensive synthesis by Foyle, *et al* (2004); Foyle and Henry (2004); Huddleston (1988). Pilkey, *et al* (1981) provide an excellent discussion of the offshore geology that compliments Huddleston. Howard, *et al* (1973) provide a representative example of Georgia coastal geology in the context of Chatham County.

Offshore Quaternary and Pliocene units are unconsolidated clastic shallow-neritic sediments - mainly of suborthoquartzitic fine-to-medium-grained sands - overlying a R2 seismic reflector (Foyle, *et al*, 2001). The late Quaternary - Holocene portion of this sand cover is 10-15 m in thickness and rarely goes beyond 15-20 km offshore, pinching out in water depths of 10-15m, (Pilkey and Frankenberg, 1964; Henry

and Idris, *supra*) and becoming more coarse-grained. Sexton, *et al* (1992) describe this contact between fine-grained sand and coarser-grained offshore sediments as the outer limit of the zone (modern) of active onshore/offshore sediment transport (Milliman, *et al*, *supra*; Howard and Reineck, 1972). Some, small, thin patches of fine grained sediment do occur on the inner shelf but the bulk of these sediments occur in drowned stream valleys such as a paleochannel found at J-Reef (Littman, 2000; Garrison, *et al*, 2008).

These sediments have been well described by many workers (Henry and Hoyt, 1967; Millikan, *et al* 1972; Huddleston, 1988; Swift, *et al* 1972; Swift and Niedorada, 1985). Their nature have been defined on the basis of more than 6000 bottom samples carried out by the Woods Hole Oceanographic Institution (WHOI) and the United States Geological Survey (USGS) prior to 1970 (Milliman, *et al*, *supra*). Continued coring studies by such workers as Coastal Carolina University (Gayes, *et al* 1992) and the University of Georgia (this study) have provided corroboration and detail to the knowledge of shelf sediments. Based on these and other studies (Idris and Henry, 1995; Henry and Idris, 1992), 10 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 (*supra*, 73). These glacio-eustatic events are preserved on the North Carolina shelf in paleochannels (*supra*; Duane, *et al*, 1972).

### METHODS

#### Sediment Coring

A total of 11 vibracores, 7 taken in 1996 and 4 in 2000, (Table 1) were recovered on two cruises on the NOAA Ship *Ferrel*. The data sediment cores were analyzed lithologically and geochemically (Littman, 2000) and then for pollen (Weaver, 2002). The sediment cores, taken in 1996, were retrieved using a 3 inch (7.6 cm) diameter core barrel pneumatic vibracorer provided by Rice University Geosciences De-

**Table 1. 1996 and 2000 Vibracore locations at Gray's Reef and J Reef.**

Site	Year	Latitude	Longitude	Water depth (m)	Core length (m)
J Reef (A)	(1996)	31°E 35.89'	80°E 47.93'	19.2	1.98
J Reef (B)	(1996)	31°E 35.89'	80°E 47.93'	19.2	2.74
Gray's Reef (1)	(1996)	31°E 24.62'	80°E 051.2'	19.5	3.66
J Reef (1996)	(1996)	31°E 35.56'	80°E 47.03'	21.	<2
J Reef (4)	(1996)	31°E 35.9'	80°E 47.75'	20.4	4.57
GR1a site (4)	(1996)	31°E 24.616'	80°E 47.100'	17.6	-2.4
GR - NE (3)	(1996)	31°E 24.7'	80°E 50.8'	19.5	2.15
GR-NW(2)	(2000)	31°E 24.381'	80°E 54.267'	16	<1
GR-SW: (3)	(2000)	31°E 22.30	80°E 55.00'	17.3	1.36
GR-SW:(4)	(2000)	31°E 24.646'	80°E 51.194'	19.4	2.35
GR-SW:(5)	(2000)	31°E 22.646'	80°E 51.194'	19.4	2.04

partment. The 2000 cruise used a 3 (7.6 cm) inch diameter core barrel hydraulic vibracorer built by Coastal Carolina University's Institute of Lowland and Coastal Studies. Both vibracoring systems produced continuous sediment cores of 2 – 3+ m lengths. These cores were taken in two locales along or near the –20 m isobath, Gray's Reef and J-Reef (Table 1). Gray's Reef is a series of natural rock outcrop or hard bottom while J Reef is an artificial reef/fish haven made up of scattered patch reefs. Cores were taken at the latter location because of the presence of a drowned paleochannel and incised valley (Garrison, *et al*, 2008).

In addition to the vibracores, sediments were retrieved by use of diver-deployment hand-and-hydraulic corers with 1 in (2.54 cm) to 2 in (5.08 cm) diameter barrels. These devices, plus simple hand excavation, were utilized in areas too close to the Gray's Reef outcrop for the use of the larger vessel-deployed systems. Two of these cores were analyzed by Rich and reported in Russell, *et al*, 2009; this paper).

All vibracores were split into working and archival halves. The hand cores were extruded into core trays or split into halves. The 1996 vibracores were logged and photographed along their length. Sediment samples were taken at natural stratigraphic breaks, 5 cm on either side of an observed contact. The cores were sampled

for shells and macro-micro paleobotanical (wood/pollen) remains. Shell (*Mercenaria*, *Astarte*) taken from these cores was utilized in AAR dating studies (Table 2). The 2000 vibracores were logged and photographed as in 1996. In contrast to 1996, due in part to a focus on palynological study, two 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 (8 from core 3, 9 from core 5). Cores 1 and 2, from 2000, were left unopened. Core 4 was sampled for chronostratigraphy purposes. The working halves of the 1996 cores (GRNMS 1; J Reef 1 & 4) were used for geochemical studies (metal oxides), and organic matter (OM), Loss-on-ignition (LOI). Acid digestion of the carbonate fraction was measured on the Gray's Reef cores. No geochemical studies were made on the 2000 cores. LOI was done and, for the 2000 cores, magnetic susceptibility was measured using a Williams magnetic bridge susceptibility meter. All particle size analyzes were done using the Flealer method (Indurante, *et al.*, 1990). LOI results were used to select cores taken in 2000 that were suitable for pollen studies. Munsell soil color (wet) was recorded for all cores. The geochemical results were reported in Littman's unpublished masters thesis (2000).

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### Geophysical

The 1996 geophysical study used a Datasonics SBP 5000 seismic profiling system and an EG&G Model 260 side scan sonar. While both side scan sonar (100 kHz) and subbottom seismic reflection (3.5 kHz) data were acquired in the 1996 *Ferrel* cruise, only subbottom (3.5 kHz) data were acquired in a second geophysical cruise in 1998. In 2000, the seismic profiler was used again without concurrent side scan sonar mapping. In 2001, a multi-beam sonar mosaic was made of the sanctuary by the NOAA Ship *Whiting*. The reasons for the focus on seismic data were twofold: (1) the shelf, with exception of the Gray's Reef outcrops are more-or-less featureless sand bottom in the study area and (2) a paleochannel discovered in 1996 was more thoroughly mapped and characterized in 1998. The vertical resolution of the 3.5kHz system, a Datasonics SBP5000, is approximately 1m. Results of these surveys were compared to baseline seismic studies such as those by Henry *et al* (1981) and Henry and Idris (1992).

### Palynological and Macrobotanical

Samples for pollen processing were taken from cores 3 and 5 taken in 2000. Since the sediments in both cores contained sand (except for the surface of core 5) and therefore, less organic content, more sediment (10-15 cc) was required to obtain pollen concentrations comparable to the typical 1cc sample of peat or clay. Heusser (1983) and Heusser and Stock (1984) have shown this to be an effective strategy and equivalent to smaller samples collected from peat. The United States Geological Survey (USGS) also recommends the use of larger samples in sandy sediment to obtain a significant number of countable pollen grains (Deb Willard, 2000, personal communication). This technique was confirmed in a previous attempt to extract pollen from a small core taken from Gray's Reef (Littman, 2000; Russell, *et al*, 2009).

The 1996 sediment cores were examined by Rich and Booth and reported in Russell, *et al* (2009). Two of these cores – 1 and 2 (Table 4) - were only sampled in the upper 10-15 cm of the

core so only the upper sections of cores 3 and 5 are comparable. The core referenced in Table 4 as "Gray's Reef clay" was bulk sampled within it less than 0.5 m length.

Core 3 pollen samples were collected within 1 cm intervals and contained 10 cc or about 13-15 grams of sediment. Eight samples were taken. All attempts were made to avoid fragments of shell in the collection process and obtain exactly 10 cc of sediment. Core 5 pollen samples were also collected within 1 cm intervals and contained 15cc or about 16-18 grams of sediment. The amount of sediment sampled was adjusted upwards to obtain greater pollen concentration in case core 3 samples failed to yield substantial amounts of counting. No attempt was made to make the surface clay sample from core 5 equivalent to the sand samples to adjust for pollen density. All attempts were made to avoid fragments of shell in the collection process and obtain exactly 15cc of sediment. Core 5 produced 9 samples that were selected on the basis of higher organic content and relevant spacing in the core.

Pollen processing was conducted according to Shane (1992) and Heusser and Stock (1984). *Eucalyptus* spike was used as exotic marker pollen and standardized according to Shane (*supra*). Both core 3 and core 5 samples received 5 ml of *Eucalyptus* spike. Processing involved the use of hot 10% KOH to remove organic acids. After sieving through 180 micron mesh to remove sand, the samples were treated with hot 10% HCl and concentrated HF to remove inorganics and silicates. Acetolysis removed remaining organics and then stained the pollen grains. Pollen was then mounted in silicone oil for viewing.

Pollen slides were counted along systematic transects at 400x magnification. A minimum of 300 pollen grains per sample interval were counted. Unknown, indeterminate (crumpled and deteriorated), and *Eucalyptus* pollen grains were also counted. Number of slides per sample interval ranged from 1.5 to 7 to achieve a total of 300 grains of pollen per interval. Identification of the pollen taxa to family or genus was based on the reference collection at the University of Georgia Paleoecology Laboratory.

Table 2. Chronology of Sediments at Gray's Reef and J-Reefa

Method	Sediment	Material	Location	Laboratory	Age <sup>14</sup> C Yr BPb	Age cal yr BPc	Age OSL / U/Th Yr BP
AMS	Gray Shelly Sand	Bone	Surface Sediment <sup>d</sup>	Beta-103683	6090+/-60	7160-6790	
AMS	Gray Shelly Sand	Shell	Surface Sediment <sup>d</sup>	UGA-11688	8950+/-70		
AMS	Gray Shelly Sand	Carbonate	Surface, ( <i>Ophimorpha</i> ) <sup>d</sup>	Beta-92356	18970+/-140	22479-20571	
OSL	Gray Shelly Sand	Quartz Sand	Core 4, ~30/cm <sup>d</sup>				24023+/-4954
AMS	Gray Shelly Sand	Shell	Core 4, ~30/cm <sup>d</sup>	Beta-172381	29120+/-690		
AMS	Gray Shelly Sand	Shell	Core 4, ~170/cm <sup>d</sup>	Beta-172380	24640+/-460		
OSL	Gray Shelly Sand	Quartz Sand	Core 4, ~170/cm <sup>d</sup>				23702+/-5411
AMS	Gray Shelly Sand	Shell	Core 1, ~170/cm <sup>d</sup>	UGA-11689	43770+/-470		
OSL	Brown Sand	Quartz Sand	Core 1, ~220/cm <sup>d</sup>				39265+/-5692
U/Th	Brown Sand	Sediment	Core 1, ~220/cm <sup>d</sup>				37481+/-1372
AMS	Gray Shelly Sand	Shell	Reef Front, ~15/cm <sup>d</sup>	UGA-11690	45170+/-1530		
AMS	Gray Mud	Wood ( <i>Taxodium</i> ?)	Core 1, ~220/cm <sup>e</sup>	Beta-103780	>50290		
AMS	Gray Mud	Wood	Core 4, ~220/cm <sup>e</sup>	Beta-105507	>48020		
AMS	Brown Sand	Oyster Shell	Reef Front, ~10 cm <sup>e</sup>	UGA-00887	31082+/-180		
AMS	Brown Sand	Scallop Shell	Reef Front, ~10 cm <sup>e</sup>	UGA-00888	35055+/-248		
AMS	Gray Shelly Sand	Wood	Reef Front, ~10 cm <sup>e</sup>	UGA-01045	35767+/-264		
AMS	Gray Shelly Sand	Wood	Reef Front, ~10 cm <sup>e</sup>	UGA-01046	39316+/-316		
AMS	Concreted Shelly Sand	Scallop Shell	Reef Front, ~10 cm <sup>e</sup>	UGA-00889	421496+/-396		
AMS	Gray Shelly Sand	Wood ( <i>Licaria</i> sp.)	Reef Front, ~10 cm <sup>e</sup>	UGA-00782	41326+/-455		
AMS	Gray Shelly Sand	Wood ( <i>Juniper</i> sp.)	Reef Front, ~10 cm <sup>e</sup>	UGA-00890	40488+/-350		
AAR	Gray Shelly Sand	Mercenaria	Grays Reef	jw2009-018-001		MIS 5	
AAR	Gray Shelly Sand	Mercenaria	Grays Reef	jw2009-018-000	47900+/-560	MIS3	
AAR	Gray Shelly Sand	Mercenaria	Grays Reef	jw2009-018-005	47900+/-610	MIS 3	

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<sup>a</sup>The chronostratigraphic zones correspond to lithostratigraphic levels: 6 000 YBP to 18 000 YBP, surface sediment, Gray Shelly-Sand; 23 000 YBP to 28 000 YBP, Concreted 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 Gray Shelly-Sand are assignable to the Concreted Shelly-Sand which is their place of origin.

<sup>b</sup>Conventional radiocarbon age,  $\delta^{13}\text{C}$  corrected using the Libby14 (half-life 5568 years). Errors represent 1 standard deviation.

<sup>c</sup>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.

<sup>d</sup>Sample located at Grays Reef

Differences in preservation of pollen can bias interpretation. The substance in the outer covering (exine) of the pollen grain, sporopollenin, is variously resistant to decay, depending on the species. Pine (*Pinus*) pollen is the more resistant, while maple (*Acer*) is very susceptible to decay. Oak is a resistant pollen type. Production of pollen is also variable between species. A single pine tree produces about 10 billion grains per year. *Artemisia* species are, likewise, high pollen producers and represent 40-50% of the pollen spectra in some plant communities (van Geel and Dirkesen, 2006). Hence, species may be either over-represented or under-represented in the pollen record.

Mode of dispersion also determines representation in the pollen record. Pollen transported via wind tends to be over-represented, as grains of pine and *Ephedra* can be found hundreds of kilometers from where they grow. Pine pollen has even been found in the Arctic. Animal transport tends to under-represent pollen with dispersal distance only a few meters. In the marine environment the dispersal of pollen can occur one of two ways or both – aeolian and waterborne. From M.I.S. 5 (ca. 125 ka) to mid-M.I.S. 3 (ca. 45 ka) the latter dispersal mode dominated in the area of Gray's Reef. After that time, until the early-to- mid-Holocene, the aeolian mode dominated over a subaerial coastal plain.

Studies of pollen found in marginal marine and marine epicontinental deposits have examined both modes of dispersal and preservation (Pieńkowski and Wakmundzka, 2009; Williams, et al, 1995). Typically, the transport paths for pollen begin with aeolian dispersal into a marine environment becoming waterborne thereafter. Such dispersal can lead to the extra-local

deposition of “exotic” pollens much like that of the pine example for the Arctic.

Bissacate pollen grains, produced by conifers, as well as some other arboreal species, have air sacs which assure wider dispersal of this grain type as opposed to monosulcate varieties (Pieńkowski and Wakmundzka, 2009). Likewise, sporomorphs tend to be less frequent in marine environments because they are more easily destroyed by waves and currents. Arboreal pollen, notably, the bissacate species, increase in proportion to other taxa, becoming preferentially concentrated in offshore deposits.

Surprisingly enough, our surveys at both Gray's Reef and J-Reef recovered wood on the seafloor and shallowly buried in the sediment outcrops. A relatively intact *Licaria triandra* (Pepperleaf sweetwood) sample was recovered, identified and dated (see Table 2) as was a sample of *Juniperis* (red cedar) also identified and dated. An *Abies* cone was found at J-Reef, which dated to the present day. A fragment of *Fagus* was found in a J-Reef core. The exact genus remains to be determined for this find. While not enough macrobotanical material to allow speculation on the species composition of a M.I.S. 3 forest, none of these genera are out-of-place in Southeastern arboreal communities of that time albeit the modern range, today, for *Licaria* does not extend beyond south Florida (Richter, 1985). Certainly, based upon our findings, the coniferous macrobotanical material is consistent with the palynological data shown in Table 3.

The beech, cedar and bay families, represented in the macrobotanical remains, were all identified on the basis of wood architecture by the U.S. Department of Agriculture Wood Identification Laboratory located at the

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**Table 3a. Pollen species and counts, core 3, Gray's Reef**

Taxa	3 cm	21 cm	41 cm	57 cm	81 cm	99 cm	121 cm	134 cm
Pinus	237(75)	227(76)	238(76)	253(84)	247(82)	225(75)	228(76)	259(86)
Picea	0	0	0	0	0	0	0	0
Taxodium/Juniperus	7	1	0	3	3	0	1	0
Quercus	54(17)	45(15)	32(10)	30(10)	47(16)	48(16)	54(18)	12(4)
Nyssa	3	0	0	0	0	1	0	0
Alnus	0	0	0	1	0	1	0	0
Liquidambar sp.	0	5	7	5	6	6	6	4
Betula	1	1	1	2	6	2	4	0
Carpinus/Ostrya	8	1	2	1	0	2	0	1
Corylus	0	0	0	0	0	0	0	0
Carya	0	0	2	1	0	1	4	1
Ulmus	0	0	2	1	2	0	0	0
Liriodendron tulipifera	0	0	0	1	0	0	0	0
Fagus	0	0	16(5)	6(2)	0	6(2)	2	0
Salix	0	0	0	0	0	1	0	0
Fraxinus	0	0	0	0	0	0	0	0
Castanea	0	0	1	0	0	1	0	0
Myrica	0	0	0	0	0	0	0	0
Ilex	0	0	0	0	0	0	0	0
Smilax	0	0	0	1	0	0	0	0
Graminae	0	0	0	0	0	0	0	0
Ambrosia type	5	1	2	1	5	3	5	1
Artemesia	0	0	0	0	0	1	0	0
Chenopodieae	11	0	4	2	3	1	1	0
Plantago	0	0	0	0	0	0	0	0
Lycopodium	0	0	0	0	0	0	0	0
Osmunda	0	0	0	0	0	0	1	0
Sphagnum	0	0	0	0	0	0	0	0
Sagittaria	0	0	0	0	0	0	0	0
Myriophyllum	0	0	0	0	0	0	0	0
Typha	0	0	0	1	0	0	0	1
Unknown and Indeterminate	9	11	37	32	18	29	10	21

Percentages are shown, in parentheses, for selected taxa for a better comparison with those same taxa shown in Table 4.

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Table 3b. Pollen species and counts, core 5, Gray's Reef

Taxa	surface	11 cm	21 cm	31 cm	71 cm	111 cm	151 cm	171 cm	198 cm
Pinus	198(63)	225(73)	233(75)	250(81)	246(79)	240(77)	245(79)	273(88)	267(86)
Picea	0	0	0	0	0	0	1	0	0
Taxodium/Juniperus	4	8	2	0	1	0	0	0	0
Quercus	56(18)	38(12)	46(15)	36(12)	34(11)	32(10)	41(13)	15(5)	50(16)
Nyssa	0	0	0	1	0	0	2	0	1
Alnus	1	0	0	0	0	0	0	0	1
Liquidambar sp.	8(3)	9(3)	2	7(3)	7(3)	7(30)	5	5	5
Betula	5(2)	2	1	1	1	2	1	2	5(2)
Carpinus/Ostrya	1	0	1	2	2	2	3	0	0
Corylus	0	0	0	0	0	0	0	0	0
Carya	1	0	3	0	2	2	4	2	0
Ulmus	2	0	0	1	1	1	0	0	0
Lirodendron tul	2	0	0	0	0	0	0	0	0
Fagus	1	1	0	1	0	0	1	1	3(<1)
Salix	1	0	0	0	0	0	0	0	0
Fraxinus	0	0	0	0	0	0	0	0	0
Acer	2	0	0	0	0	0	0	0	0
Castanea	0	0	0	0	0	0	0	0	0
Myrica	0	0	0	0	0	0	0	0	0
Ilex	1	0	0	0	0	0	0	0	0
Smilax	0	0	0	0	0	0	0	0	0
Graminae	0	0	0	0	0	0	0	0	0
Ambrosia type	5	1	3	3	2	0	2	2	0
Artemesia	0	1	1	0	0	0	0	0	0
Chenopodieae	2	4	2	3	2	0	1	0	0
Plantago	0	0	0	0	0	0	0	0	0
Lycopodium	1	0	0	0	0	0	0	0	0
Osmunda	0	0	0	0	0	0	0	0	0
Sphagnum	0	0	0	0	0	0	0	0	0
Sagittaria	0	0	0	0	0	0	0	0	0
Myriophyllum	0	0	1	1	1	0	0	0	0
Typha	0	0	0	0	1	0	0	0	0
Unknown and Indeterminate	30	22	20	17	13	19	18	9	28

Percentages are shown, in parentheses, for selected taxa for a better comparison with those same taxa shown in Table 4.

University of Wisconsin. The fir was identified by its seed cone. Most of the specimens showed some marine borer damage but were surprisingly intact with some encrusting. The *Licaria* find was freeze-dried when first recovered but simple air drying was sufficient for the remainder of the finds.

### Geochronological

The chronology of the cores are based on conventional/accelerator mass spectrometry (AMS) radio-carbon dates (6); 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 and U/Th ages were derived from sediments taken from cores. The 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).

Optically stimulated luminescence (OSL) dating was carried out under controlled red-light conditions in the laboratory. The samples were treated with 10% HCl and 30% H<sub>2</sub>O<sub>2</sub> to remove carbonates and organic material and sieved to obtain the 120-150µm size fraction. Na-Polytungstate ( $\rho = 2.58 \text{ g/cm}^3$ ) was used to achieve density separation of quartz and feldspar minerals. The quartz fraction was then etched with 40% HF for 80 min followed by 12N HCl for 30 min to remove the alpha skin. Separated quartz grains were mounted on stainless steel discs with help of *Silkospray*<sup>TM</sup>. Light stimulation on quartz mineral extracts was done using a Risr array of combined blue LEDs centered at 470nm. Detection optics comprised Hoya 2xU340 and Schott BG-39 filters coupled to an EMI 9635 QA Photomultiplier tube. Measurements were made using a Risr TL-DA-15 reader. A 25 mCi <sup>90</sup>Sr/<sup>90</sup>Y built-in source was used for  $\beta$ -irradiation. U and Th for dose rate calculation were estimated using a thick source Daybreak alpha counting system. K was esti-

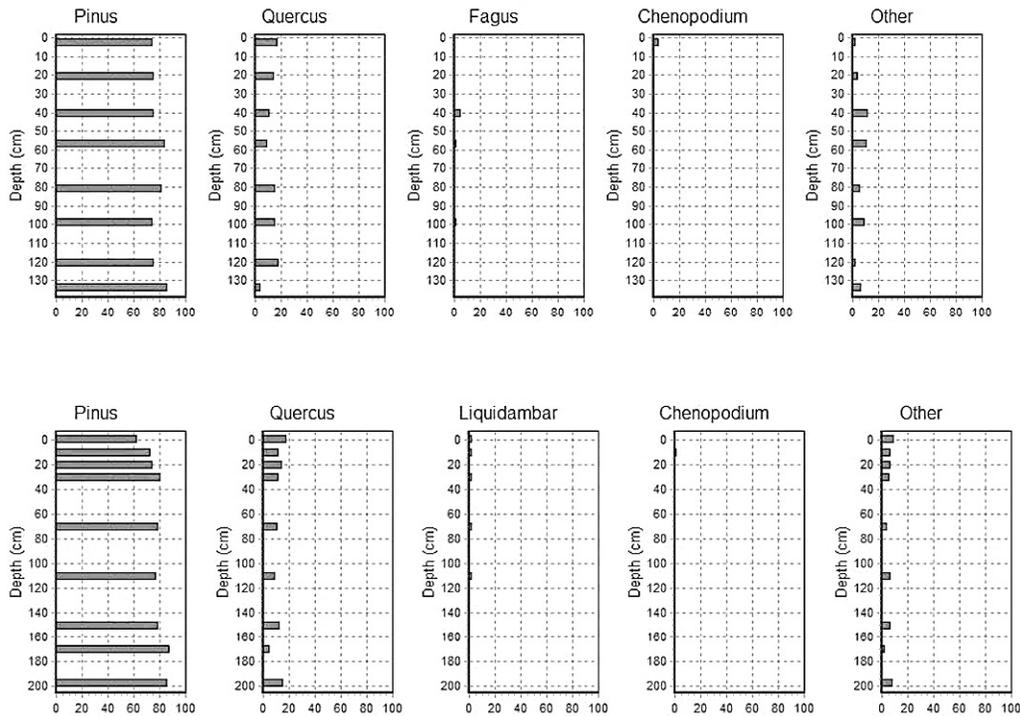
mated through ICP-MS using the fusion technique for total K extraction at the XRAL laboratory in Toronto, Canada.

The SAR protocol (Murray and Wintle, 2000) was used to determine the paleodose. A five-point measurement strategy was adopted with three dose points to bracket the paleodose, fourth zero dose and fifth a repeat-dose point. Repeat dose was measured to correct for sensitivity changes and to ensure that the procedure was working correctly. All measurements were done using a preheat of 220°C for 10s followed by OSL sampling carried out at 125°C for 100s. For all aliquots the recycling ratio between the first and the fifth point was ranged within 0.95-1.05. Data were analyzed using ANALYST software (Duller, *et al*, 1999).

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. The radiocarbon ages are conventional ages, corrected to the <sup>13</sup>C/<sup>12</sup>C ratio, and use the Libby <sup>14</sup>C half-life of 5568years. 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/Th age is reported as years before A.D. 1950.

Groot, *et al* (1995) combined palynological studies of sediment cores from the Atlantic continental shelf with amino acid racemization (AAR) analyses. In our study we have used racemization dating of specimens of *Mercenaria* and *Astarte* from both cores and the sea floor deposits. These results were obtained using gas chromatography to assess the amounts of eight amino acids (Wehmiller, 2010). *Mercenaria* sections, weighing ~ 0.1 to 0.4 g were cut from whole or partial shells. These samples were mechanically cleaned then alternately rinsed with 2N HCL and distilled water for a final hydrolysis satge at 6N HCL at 105° C for 22 hours. Analyses were then done using a 25 m Chirasilval® gas chromatographic Column installed in an Agilent® gas chromatograph equipped with both flame ionization (FID) and nitrogen-phos-

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**Figure 2. Histogram plots of pollen from Gray's Reef (2000) sediment cores 3 (upper) and 5 (lower). *Fagus* was not observed in core 5 whereas *Liquidambar* was observed in 5 but not in core 3 (cf. Table 3).**

phorous (NPD) detectors. Precision of D/L values for multiple derivative samples are better than 2%. Analytical results are managed in a database maintained by the University of Delaware's Department of Geological Sciences.

The amino acid racemization (AAR) dates (Table 2) are preliminary, with only three samples dated, all of clam species, *Mercenaria*. The dates for these samples range from M.I.S. 5 (2) to M.I.S. 3(1) (John Wehmiller, Personal Communication, 2009). The latter was confirmed by AMS dating.

### RESULTS AND DISCUSSION

Our paleoecological data provide corroborative support for a lithostratigraphic-chronostratigraphic sequence in the late Pleistocene that more clearly delimits floral communities in M.I.S. 3/2. We have emphasized palynological data in this study.

Grimm, *et al* (1993), in a study of a 18.52 m core from Lake Tulane (Florida) specifically linked pine:oak-*ambrosia* pollen abundance to climatic oscillations. That study linked these oscillations to massive, periodic advances of ice streams from the Laurentide ice sheet (L.I.S.) margin (Heinrich Events (H.E.)(Hemmings, 2004). Their conclusions were that there were frequent, major vegetation shifts from pine forest to open oak-savanna/grassland over the late Quaternary (<50 ka). In the 1993 paper, Grimm *et al*, argued that pine signaled a cooler climate. In 2006, Grimm, *et al*, reinterpret the Lake Tulane data such that peaks in the pine pollen are, indeed, linked to Heinrich events but do not necessarily imply a cooler climate. In this later study, Grimm, *et al*, suggest a wetter, warmer climate associated with peaks in pine. Oak pollen, by contrast, signal a somewhat cooler climate for Florida in the late Quaternary. Watts *et al* (1992) conclude that the late MIS 3 is a peri-

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**Table 4. Palynological composition of samples from Gray's Reef. Values are expressed as percent of total identifiable pollen and spores (minimum number of 300 grains: F. J. Rich, unpublished data (in Russell, 2009; see Table 1 for these core locations))**

Taxon	Gray's Reef clay	Gray's Reef core 1	Gray's Reef core 2
<i>Alnus</i>	2.3	1.3	2.1
<i>Ambrosia</i>	0.89	0.97	0.62
<i>Asteroidae</i>	1.5	–	–
<i>Betula</i>	0.59	0.97	0.98
<i>Carya</i>	3.6	1.9	1.2
<i>Castanea</i>	0.29	1.6	0.62
<i>Chenopodiaceae/Amaranthaceae</i>	15.2	8.1	5.6
<i>Corylus</i>	0.32	0.62	–
<i>Cyperaceae</i>	1.2	0.32	–
<i>Fagus</i>	0.59	0.32	–
<i>Fraxinus</i>	0.29	0.32	0.62
<i>Gramineae</i>	2.7	6.8	0.98
<i>Iva</i>	0.59	0.65	–
<i>Liquidambar</i>	1.8	–	0.30
<i>Myrica</i>	1.2	0.32	0.30
<i>Osmunda</i>	0.59	0.32	–
<i>Ostrya/Carpinus</i>	–	0.32	–
<i>Picea</i>	2.1	–	–
<i>Pinus</i>	41.7	56.5	67.2
<i>Polygonum</i>	0.59	–	–
<i>Polypodium</i>	–	0.65	–
<i>Pteridium</i>	–	0.32	–
<i>Quercus</i>	13.4	12.7	13
<i>Salix</i>	0.59	–	0.62
<i>Sambucus</i>	–	0.32	–
<i>Sphagnum</i>	0.29	0.32	–
<i>Stellaria</i>	0.29	–	–
<i>Taxodium</i>	2.1	–	–
<i>Tsuga</i>	0.59	–	–
<i>Ulmus</i>	0.59	0.97	0.62
<i>Woodwardia</i>	2.1	0.97	–
Indeterminate	2.1	2.6	3.7
Totals	100	100	99.4

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od of unstable climate with little or no homogeneity over many thousands of years. Their conclusions are based on data for northwest Florida (Camel Lake and Sheelar Lake) where a species-poor pine forest, with some oak, existed. A cursory inspection of Table 3/Figure 2 shows the dominance of pine and oak at Gray's Reef during this same interval. Likewise, there are two significant pine:oak ratios shifts in the Gray's Reef pollen (-134 cm, core 3; -171 cm, core 5). In both cases the oak percentage drops to 5% or less. The increase in pine is not as dramatic but significant nonetheless.

Two salient points can be made from these results:

- (1) Palynological studies of pollen from marine sediments have a demonstrated utility in discussions concerning the reconstruction of paleoenvironments, and,
- (2) Oscillations in arboreal pollen spectra, particularly that of pine:oak, can be linked to climatic shifts, at a millennial or higher resolution scales.

Palynological studies of marine sediments, therefore, from both Gray's Reef have allowed us to gain a broad-brush picture of past environments on the Quaternary coastal plain and correlate this to changes in paleoclimate/RSL (Littman 2000; Weaver, 2002; Garrison, *et al*, 2008). Pollen results for cores 3 and 5, have confirmed the utility of marine sediment for pollen studies, as have that of others (Heusser, 1983). Litwin and Andrie (1992:92-263) noted a similar pollen composition and abundance at five sites in central and eastern Florida Bay. Their assemblages were dominated by both pine and oak with pine averaging 70% across their samples (*ibid*). A closer inspection of the core 3 data, in terms of actual grains, shows a significant diminishment of oak pollen at 134 cm to 12 grains/spl. compared to that of 30 - 54 grains/spl. Core 5 shows a similar trend - 15 grains/spl. at 171 cm - but a recovery to the expected range 32-56 grains/spl., e.g. 50 grains/spl at 198 cm (Fig. 2).

Another interesting result is the distribution of a third arboreal species - beech (*Fagus*) - in core 3 (Table 3; Fig. 2). This pollen occurs at a range of 2-16 grains/ spl. in four of the eight

levels. Likewise, in contrast to the uniformity of pine and oak pollen in both cores, Very little beech appears in core 5 - six levels out of nine but with concentrations of only 1 - 3 grains/spl. Birch (*Betula*) is present in small, but consistent, amounts across both cores (Table 3). Russell, *et al* (2009) state that at LGM, south of 34° N latitude, oaks comprised ~20% of forests. The data for the Gray's Reef cores (Tables 3,4) are comparable. *Liquidambar* (sweet gum), a modern (Holocene) southeastern forest species, is present, in low amounts, in Core 5 (Table 3, fig. 2)(Booth, *et al*, 1999).

The presence of birch pollen, while in low proportions, like sweet gum, supports Frey's (1953) and Russell, *et al* (2009) contention, at LGM, that Southeastern forests contained a mixture of boreal and austral arboreal species, in "no-analog" plant communities (Overpeck, *et al*, 1985; Delcourt and Delcourt, 1994; Edwards *et al*, 2005). Because of the qualitative nature of the results, Littman's J-Reef pollen data are not shown (Littman, 2000). In those cores, however, boreal and austral taxa were detected. What cannot be determined, in regard to the presence of birch pollen, in the both the Gray's Reef and J-Reef cores, is whether these are tree or shrub birch species. *Betula populifolia* is representative of the former and *B. nigra* the latter category. Neither does birch signal general climate conditions such as "wetter-cooler" or "more arid". The absence of birch pollen in core 3 at the -134 cm level suggests a climate shift that effectively removed birch from the late Quaternary coastal plain such as during a Heinrich Event (3 or 2) when a colder, drier climate would be expected to prevail. Pine and beech are cool-to-cold tolerant species compared to the oak and birch (Preusser *et al*. 2003:1442). Lachniet *et al*. (2004), in a characterization of the early Holocene cold event (Veski *et al.*, 2004) at 8200 YBP, observed a sharp increase in both the pollen of *picea* and *betula* (*supra*). Tzedakis *et al*. (2004), likewise, report tree population changes in the last glacial, e.g., contraction or of observed of temperate species during Heinrich events (HE) 3/2 (ca. 31/24 ka).

O'Kelley's research at Edisto Island, South

Carolina, is similar to that described for Gray's Reef - paleontological and palynological (1976). His work was in the nearshore sediments at Edisto Island where marsh-peat/clay predominate. Radiocarbon ages for the Edisto deposits are within the last 2000 years, as one would expect. In the Edisto data of one core, EB 139A, 55% of the 291 grain-count sample was pine; 12% was oak. This is comparable with our data. Interestingly, while O'Kelley's reports other forest species - sweet gum, maple, hickory and birch he reports no beech (1976:16).

More recently, Groot, *et al* (1995) used palynology, foraminifera analysis and aminos-tratigraphy to examine sediment cores from continental shelf/slope and coastal deposits in the Delmarva. In that study a 305 m marine core (AMCOR 6021C0 together with AMCOR 6007 and 6008 cores from the nearshore/coastal plain were analyzed Groot, *et al* (1995) examined the AMCOR 6008 core sediments, located 15 km offshore, and determined them to be no older than M.I.S. 5. The pollen therein were parsed into the following categories:

- (1) Cold climate taxa: *Picea* and *Abies*.
- (2) Temperate and/or warm taxa: *Quercus*, *Carya*, *Castanea*, *Juglans*, *Liquidambar*, *Nyssa*, and *Taxodium*.
- (3) Herbs and grasses: *Chenopodium*, Gramineae, Compositae, Gramineae, Cyperaceae and Ericaceae.

Groot, *et al* (1995 had the advantage of distinguishing six species of oak thereby allowing resolution of older stages than M.I.S. 5 by their presence or absence (ex. *Q. alba*). High percentages of *Pinus* indicated cool-temperate climate. In the lower portions of AMCOR 6007 and 6008 (Pliocene?), higher percentages of *Quercus* were observed in proportion to lower frequencies for *Pinus* (<50%). In the upper (Pleistocene) sections of these cores, *Quercus* increases in relation to *Pinus* (~34-64% versus 3-15%) over the range of M.I.S. 4 to M.I.S.2. As with Grimm, *et al* (1993), these results signaled climatic oscillations. It should be noted that the Delmarva data is reflective of Quaternary conditions in the northern Mid-Atlantic Bight (MAB) and there are salient differences with those from data of the Southeast such as

the increased presence of boreal taxa as would be expected of communities near the ice margins.

In eastern North America the climax deciduous forest is dominated at present by maples (O'Kelley reports 4.1%), oaks, hickories and other combinations of trees (such as pines in the southern U.S.) (Stern, 1994:412). Watts, and co-workers, reports a similar vegetational and forest history for the Southeast based on pollen records from White Pond (South Carolina) and Camel Lake (N.W. Florida) (Watts, *et al.* 1992; Watts, 1980). In these locations, the middle Wisconsin (40-29 ka, M.I.S. 3) was a time of forest abundant pine, oak and diverse mesic tree species such as chestnut (*Castanea*) together with eastern Hemlock (*Tsuga canadensis*) (Watts *et al.*, 1992: 1056; Ellison *et al.* 2005:479-486). The Camel Lake pollen spectra suggest a species-poor pine forest in the Late Wisconsin (after 29 ka or M.I.S. 2).

The pollen stratigraphy for the Gray's Reef cores suggests a temperate coastal plain, parkland biome dominated by pine (*Pinus*) and oak (*Quercus*) in M.I.S. 3. (Figure 3). The persistence of both *Chenopodium* and, to a lesser degree, Ambrosia, throughout cores 3 and 5, suggest a more open type of biome with grassland present (Table 3). In fact the high percentage for *Chenopodium* in the Gray's Reef clay (Table 4) likely correlates with the sharp increase for this taxa in the upper level of core 3 (Table 3, fig. 2). Reconciliation of pollen stratigraphy with the radiometric ages (Table 2)<sup>1</sup> suggests a mid-to-late last glacial (M.I.S. 3) date for the inversion in the oak-pine pollen spectrum, observed in both spectra (Table 3), suggests an expansion of a colder interval - pine increases - at the lower portions of the cores (-134 cm, core 3; -171 cm, core 5). The timing of this excursion, in the pine-oak ratio, suggests a late M.I.S. 3 (H.E. 3/2) date (Watts *et al.* 1992; Grimm, *et al.* 2006). (Chappell and Shackleton, 1986). Models for northern hemisphere ice volume show a significant reduction (increase in oak?) in the Farmdale interstade (ca. 25 ka) with increased volume peaks (increased pine?) at the Alton and Woodfordian intervals (ca. 37 and 20 ka. - HE 4/2) Resolution in these models

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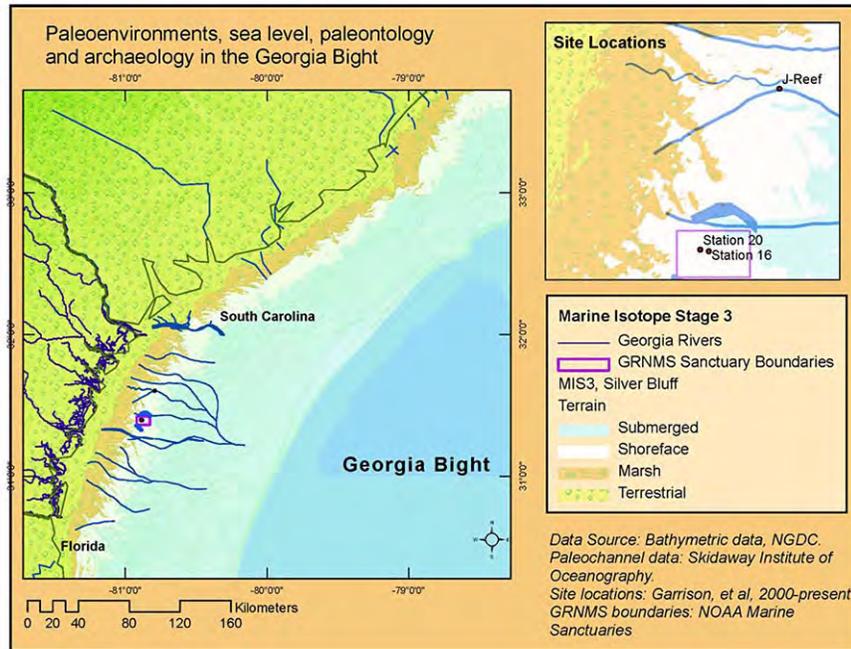


Figure 3a. Sea level and environment reconstruction at 45 ky BP. Biome maps based on this study and others (cf. Russell, et al, 2009;Williams, et al, 2006).

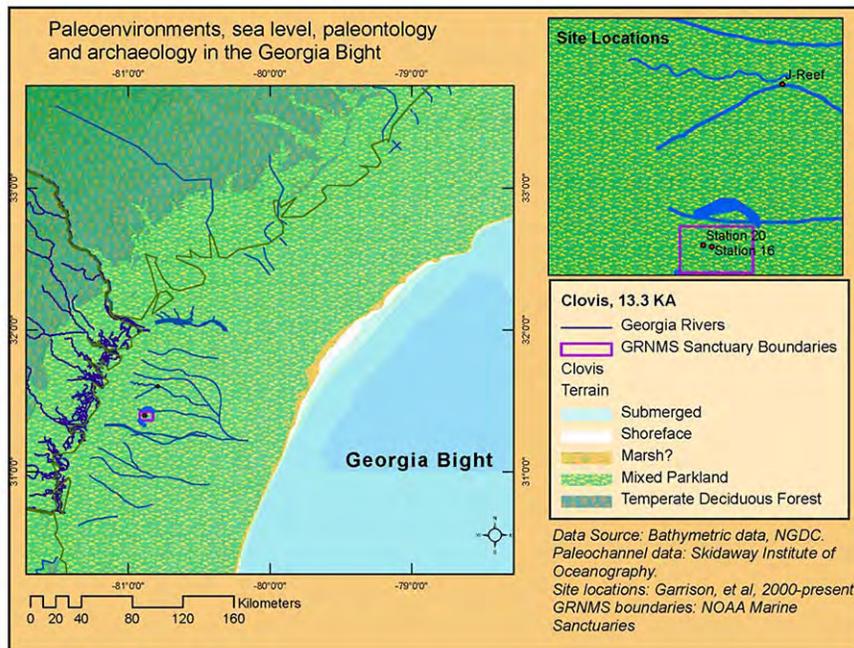
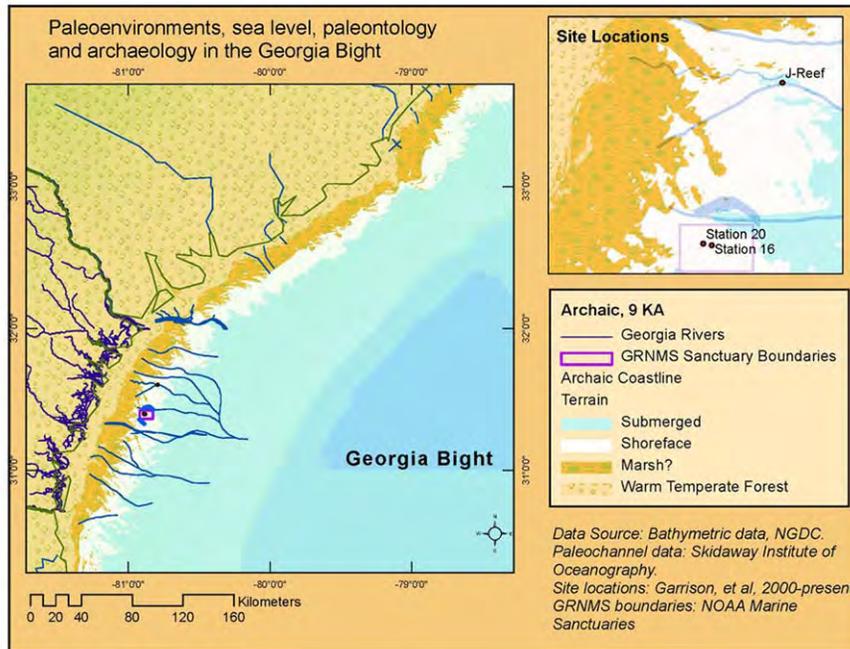


Figure 3b. Sea level and environment reconstruction at 13.3 ky BP. Biome maps based on this study and others (cf. Russell, et al, 2009;Williams, et al, 2006).



**Figure 3c. Sea level and environment reconstruction at 9 ky BP. Biome maps based on this study and others (cf. Russell, et al, 2009; Williams, et al, 2006).**

is generally too coarse to detect millennia - length excursions, in regional climate.

Russell, et al (2009:84) conclude the Gray's

1. By 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 (Richards and Beck, 2001; Van der Plicht, 2002). Because of large fluctuations in atmospheric  $^{14}\text{C}$  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). Both AMS and OSL dates from Gray's Reef sediments, above 170cm b.s. of 27 kaYBP, suggest this near-shore part of the Satilla Fm is at or near late glacial maximum (LGM- M.I.S. 2) in age (Table 2). Conversely the deeper, ~ 2m b.s., Brown Sand member is at least early glacial, e.g. M.I.S. 3 (Plum Point Inter-Stade?).

Reef pollen assemblage documents the presence of "mixed" late Pleistocene-early Holocene floras in Florida and the southern Atlantic seaboard. Around 13,000 k YP, the Warm Mixed Forest Biome (also called the broad-leaved evergreen forest by Williams, et al (2000)) expanded out of the Florida Peninsula into the southeastern lowlands to replace a Mixed Parkland biome while a Temperate Deciduous Forest Biome expanded in the Southern Appalachians and adjacent Piedmont, being well established by the mid-Archaic/mid-Holocene Periods, ca. 9000 y BP (Jardine, et al 2012:31). We illustrate these putative biomes, with attendant sea levels/coastlines in figure 3.

## CONCLUSIONS

Extreme climate events can manifest themselves in proxies such as pollen. Between MIS 3 and LGM, perhaps contemporaneous with the HE 4 to HE 2 events, a contraction of temperate arboreal taxa, such as oak, imply a direct climate-ecology coupling. The chronological and

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sea level data for the Gray's Reef sediment cores indicate a shallow coastal ocean prior to a late MIS 3 coastline. Pine expands, at the expense of oak, in the colder interval detected in the cores 3 and 5. Certainly, HE 3/2, and LGM, can be manifest in the paleoecology. Given the potential for reworking and mixture of the shelf sediments, dating the exact period of the observed shift in arboreal taxa requires more chronological study. We cannot completely rule out LGM as this cold Pleistocene interval within which temperate arboreal species waned and cold tolerant ones waxed. That said, it is important to note that pollen from marine sediments can be used to map these late Pleistocene climate oscillations in the Southeast. The continental shelf sediments of the Georgia Bight show very little to no lithologic variability (Garrison, *et al*, 2008)). There is, however, significant variability in paleoclimate/paleoecological proxies within these sediments. When coupled with direct dating of these marine sediments, mesoscale – millennial or finer - variation of climate and ecology can be reliably inferred.

MIS 3, which the bulk of the Gray's Reef pollen spectra represents, has been called a non-analog climatic period by paleoclimatologists. Likewise, palynologists and paleoecologists have termed many of the biomes of this period non-analog as well. As pointed out by Russell, *et al* (2009) in their proposal for the Quaternary Southeast as a “thermal enclave”, part of the reasons for non-analog communities – plant or animal – are the organisms themselves as well as climate.

The Mixed Parkland biome, no longer present in North America (Williams, *et al*, 2001) was associated with a Rancholabrean fauna of late Quaternary coastal plain, as different from modern communities as is the composition of plant communities within which they lived (Frey, 1973; Webb, 1977; Webb, *et al*, 2004; Russell, *et al*, 2009). These Quaternary ecosystems were non-analog to those of today (Overpeck *et al* (1985); Graham, *et al*, (1996); Edwards, *et al*, (2005); Williams, *et al*, (2004); and Russell, *et al*, (2009)). As we suggest, part of this difference is at the ecosystem level

where Quaternary fauna grazed and browsed a coastal plain biome that was more parkland than forest due to climate, but, also, in large part, to the fauna themselves. As Williams, *et al* (2001) opin, plant associations with no modern analog, such as the Mixed Parkland, grew in environments outside the range of modern climate space. The Quaternary coastal plain that included Gray's Reef, particularly in MIS 3, was just such a climate space.

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interpretations are entirely those of the authors.

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