Atrotorquata lineata as a proxy for *Juncus roemerianus*, Part II: Tracking changes in positions of *Juncus roemerianus* marshes through time by use of the fungal proxy *Atrotorquata lineata*

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ABSTRACT. *Juncus roemerianus* is a species that occurs at the upper reaches of salt water influence in marshes from Delaware to Texas. As such, *J. roemerianus* is a good marker for sea level, defined for this study as mean highest high water; thus, being able to track its positions over time should enable one to track past changes in relative sea level. In 2006, a palynomorphic fingerprint to identify surface sediment from *J. roemerianus* marshes was discovered in a South Carolina study (Marsh 2006, Marsh & Cohen 2008). Further study (Marsh & Cohen 2016) showed that one component of this fingerprint, the spore of the fungus *Atrotorquata lineata*, was so omnipresent in surface sediment from *J. roemerianus* marshes that the fungus, by itself, can be considered a proxy for *J. roemerianus* marshes.

In this study we investigated the potential to use *Atrotorquata lineata* to track past positions of *Juncus roemerianus* marshes. First we investigated whether *A. lineata* is preserved beneath the surface. Cores from South Carolina, North Carolina and Florida were found to contain *A. lineata*, including one from the Harney River area of southwestern Florida in which we had previously found *A. lineata* at ca 250 cm depth at a level that had been radiocarbon-dated to ca 3200 years BP (Cohen 1968, Cohen & Spackman 1972, 1977, Spackman & Cohen 1976, Marsh & Cohen 2016). Building upon that discovery, we then investigated the possibility of tracking changes in the size and position of *J. roemerianus* marshes over time. Additional sets of cores clearly revealed evidence of expansion and contraction of *J. roemerianus* patches over time and further suggested recent past fluctuations in sea level that were both higher and lower than at present but contained within an overall transgressive sequence.

KEYWORDS: *Atrotorquata lineata*, *Juncus roemerianus*, sea level, Southeastern United States, fungal proxy

INTRODUCTION

THE SIGNIFICANCE OF *JUNCUS ROEMERIANUS* STANDS IN COASTAL REGIONS OF THE SOUTHEASTERN UNITED STATES AND THE GULF COASTAL PLAIN

Juncus roemerianus Scheele is a species associated with the upper reaches of salt water influence in salt marshes throughout the southeastern United States and Gulf Coastal Plain (except where replaced by mangroves in certain portions of southern Florida). Since it grows in the transition between fresh and salt water areas, it is an indicator of highest tidal inundation (sea level). Being able to determine former positions of *J. roemerianus* in core samples should therefore provide a good indication of what variations in sea level have occurred in the past.

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The known geographic range of *Juncus roemerianus* today is from Delaware to Texas, with isolated populations found in Connecticut, New York, New Jersey, Mexico and the Caribbean (Eleuterius 1976) (Fig. 1). *Juncus roemerianus* marshes are generally only intermittently tidally flooded. In the upper reaches especially, they may only be inundated during spring tides and storms.

PREVIOUS SALT MARSH ACCRETION AND SEA LEVEL CHANGE IN SALT MARSH STUDIES

It has been suggested by numerous researchers (e.g. Stevenson et al. 1986, Moorhead & Brinson 1995, Donnelly & Bertness 2001, Gardner 2004) that the response of a salt marsh to a rising sea level is for the ecosystem to migrate inland and upslope away from the rising water.

Many previous studies have used a variety of biological and non-biological markers found in sediment cores from salt marshes and nearshore environments in an attempt to track changes in accretion, erosion and sea level (e.g. Redfield & Rubin 1962, Scott & Medioli 1978, 1986, Howard & Frey 1980, DePratter & Howard 1981, Heyworth 1986, Kump & Hire 1986, Laborel 1986, Williams et al. 1999, Gardner & Porter 2001, Törnqvist et al. 2004, Culver & Horton 2005, Horton et al. 2006, Carr et al. 2015). Cahoon (2014) proposed a method for estimating relative sea level change that takes salt marsh accretion and erosion into account.

Salt marshes may erode and accrete. Salt marsh accretion is a topic widely studied. In a study from Florida, Goodbred et al. (1998) reported that the interior of marshes accretes faster than the edges under normal tidal

conditions but that seaward marsh areas and marsh edges accrete more during storm surge events.

In a study of back-barrier areas in Virginia, Finkelstein and Ferland (1987) found that rising sea levels caused landward movement of barrier islands, narrowing of back-barrier lagoons, constriction of inlets, lowering of tidal energy, and creation of salt marshes where there were once lagoons. Continuing marsh growth depends on slower sea level rise and/or high levels of suspended sediments.

It is not only inorganic sediment that causes changes in salt marsh level. The sediment-trapping effects of the vegetation as well as the amount of organic material included in the sediment also play roles. Bricker-Urso et al. (1989) found that inorganic solids make up only 9% of low marsh accretion and 4% of high marsh accretion in a study from Rhode Island. Organic solids made up 9% of the low marsh accretion and 11% of the high marsh accretion. Water and pore space, nearly all of which is actually associated with organic material, made up the rest. They determined, based on Pb^{210} and Cu analysis, that total accretion in their study area (in Rhode Island) is 0.43 ± 0.13 cm/year in the low marsh and 0.24 ± 0.01 cm/year in the high marsh, while sea level rise (based on nearby tidal gauge information for 55 years) is 0.26 ± 0.02 cm/year, suggesting that, for the moment at least, the salt marshes in the study area are stable. They also provided information from their own and other researchers' work on accretion rates and sea level rise for other sites on the eastern U.S. and Gulf coasts. Included in this information is a study from South Carolina, where accretion is 0.13–0.45 cm/year, while sea level rise at the time of the study was 0.34 cm/year. Stevenson et al. (1986) provide an accretion range for North Inlet, South Carolina, of 0.14 (the lowest of any site they studied) to 0.45 cm/year, with a sea level rise of 0.22 cm/year. If these data are correct, parts of the South Carolina coast are losing ground to the sea.

In a multi-year study in South Carolina, Morris et al. (2002) found that by fertilizing marshes to increase plant production the marsh surface elevation of the fertilized patches increased at a rate nearly 40% higher than the untreated control patches. They attributed this to the effect that more standing biomass has on the ability of the marsh to trap sediments.

Fig. 1. Range of *Juncus roemerianus*-dominated high-level salt marshes (outlined in red) and locations of core studies (red stars) (modified from Marsh 2008)

PURPOSE AND SCOPE OF THIS STUDY

Our previous studies provide the foundation for this current work. These studies, described by Marsh (2006) and Marsh and Cohen (2008, 2016), identified the palynomorphic fingerprint of surface sediments taken from *Juncus roemerianus* marshes in South Carolina, and showed that the main component of the fingerprint, ascospores of the fungus *Atrotorquata lineata* Kohlmeyer and Volkmann-Kohlmeyer, are present in the surface sediments of all parts of a stand of *Juncus roemerianus* and, furthermore, are found in surface sediments in all but the northernmost edge of the range of *J. roemerianus*. As a result, *A. lineata* can be considered a proxy for *J. roemerianus* (high level) marshes throughout most of the range of the plant (Marsh & Cohen 2016). Since *J. roemerianus* is a plant associated with the upper reaches of salt water influence in salt marshes throughout the southeastern United States and Gulf Coastal Plain, this study provides the background information necessary to investigate the possibility of using *A. lineata* to trace relative sea level changes.

Atrotorquata lineata was first described by Kohlmeyer and Volkmann-Kohlmeyer (1993). They indicated that *A. lineata* is found in dead standing culms of *Juncus roemerianus*, generally between 11 and 45 cm above the rhizome. The ascospores are 22.8–30.7 μm in length, 7.4–10.5 μm in width, ellipsoidal in shape, and sometimes curved (Fig. 2). They are brown in color and may be constricted at the one septum. They are longitudinally striate and have 5 to 7 germ slits at each apex. Kohlmeyer and Volkmann-Kohlmeyer further suggested that *A. lineata* is probably host-specific to *J. roemerianus*, although there has been one recent report of *A. lineata* being detected in a DNA study of milk from cows grazing in the Italian Alps (Panelli et al. 2013).

Using the presence and location of spores of the fungal species *Atrotorquata lineata* in cores as a proxy for *Juncus roemerianus*, as described previously by Marsh (2006) and Marsh and Cohen (2008, 2016), this study identifies sediment from high-level salt marshes and uses that information to track changes in the position of *J. roemerianus* marshes over time.

METHODS

In order to confirm the preservation of *Atrotorquata lineata* beneath the surface and to investigate changes in the size and position of past *Juncus roemerianus* marshes, we collected six short cores (15 cm) from James Island, South Carolina. These cores were taken along a transect through a salt marsh. Cores were taken using a shovel to remove segments of sediments 15 cm deep. The edges of the samples were trimmed to remove contamination. Samples were divided into 5 cm segments and stored in plastic bags until processed. The transect began in a marine influenced area currently covered by *Spartina alterniflora* Loisel. It then passed through the transition between *Spartina* and *Juncus*, crossed into the *Juncus* patch with a core taken on either side, and continued through the *Juncus–Spartina* transition on the other side of the *Juncus* patch, ending at a creek bank covered with *Spartina*. The cores from the James Island study were processed to extract palynomorphs in 5 cm increments. All sediment from the entire 5 cm interval was processed as a unit to extract palynomorphs using standard methods described by Traverse (1988). Samples were then analyzed microscopically for the presence of *A. lineata*.

Benjamin Horton and Andrew Kemp from the University of Pennsylvania provided a core from their
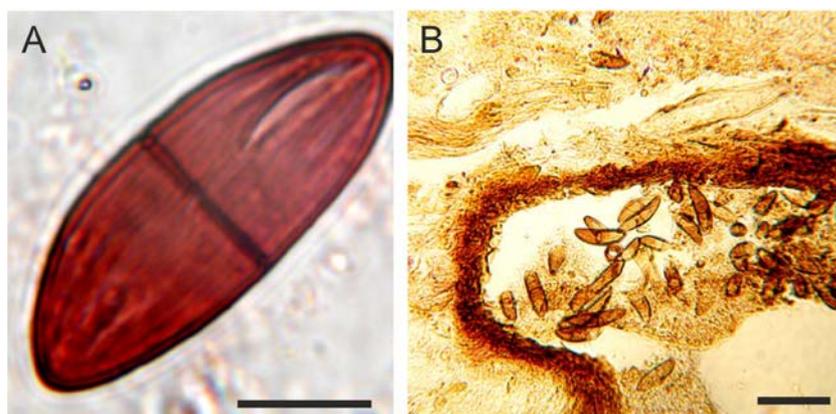
Fig. 2. **A**. Ascospore of *Atrotorquata lineata* (scale bar: 10 μm) **B**. Ascoma of *A. lineata* with ascospores from a microtome section of a peat core from southwest Florida, made using the method of Cohen and Spackman (1972); (scale bar: 25 μm). (Modified from Marsh & Cohen 2008)

study area at Sand Point on Roanoke Island, North Carolina (Kemp et al. 2006). This 90 cm core was sampled at 10 cm intervals and 10 slurry slides were made using the methods of Marsh and Cohen (2016). These slides were examined microscopically for the presence of *Atrotorquata lineata*.

A series of slides from a core taken in the Harney River region of South Florida by Cohen during a previous project were examined for the presence of *Atrotorquata lineata*. These slides were microtome sections of sediment that Cohen had described as "*Juncus* peat" (Cohen 1968) based on analysis of the anatomy of plant tissues using the methods of Cohen and Spackman (1972).

Six longer cores (ranging in length from 32 cm to 200 cm) were collected from the Belle W. Baruch Institute for Coastal and Marine Science in Georgetown, South Carolina. These cores were examined at closely spaced vertical intervals (generally 2 cm) using the slurry slide technique.

RESULTS

James Island, South Carolina Cores
(Figs 3, 4)

An initial small-scale study was undertaken to determine the feasibility of using *Atrotorquata lineata* to detect the past location of *Juncus roemerianus* in cores and also to determine whether the presence and distribution of *A. lineata* would show evidence that the *J. roemerianus* stand had moved over time.

This study was conducted at James Island, South Carolina and reported in a preliminary way in Marsh and Cohen (2007).

The 5 cm processing intervals used in this part of the study, which may represent between 10 and 40 years of accumulation each (based on South Carolina salt marsh accretion data from Bricker-Urso et al. 1989) were too large to determine the exact position of various vegetation layers at a given time and therefore do not represent a snapshot in time, but rather, show all changes that occurred in each 10–40-year span as a single unit. Nevertheless, these cores did show that *Atrotorquata lineata* is preserved beneath the salt marsh surface and that the dimensions of the *Juncus* stand and the positions of relative sea level changed over time.

Harney River, Florida Core
(Fig. 5)

One of the slides examined from this core which had been described by Cohen in 1968 as *Juncus* peat from 251.42 cm depth (99 inches) contained well preserved and readily identifiable *Atrotorquata lineata*. The age at this depth in the core had been estimated at 3190 ± 180 years BP based on the radiocarbon ages of an adjacent core studied by Spackman et al. (1966) and reported in Kuehn (1980) and Spackman and Cohen (1976).

Fig. 3. The James Island transect (image from Google Earth)
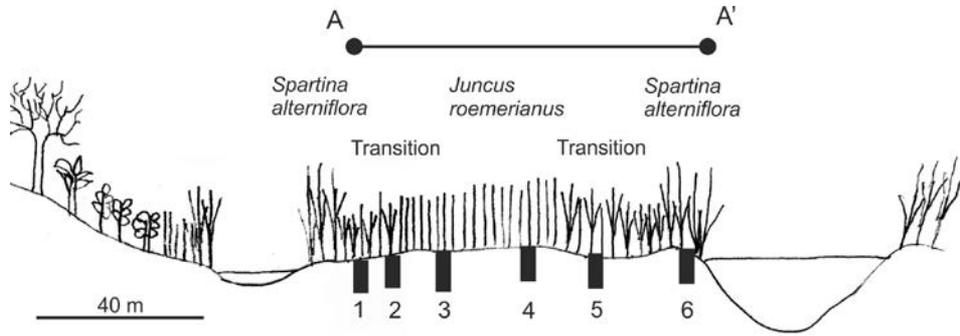
Fig. 4. James Island transect, side view
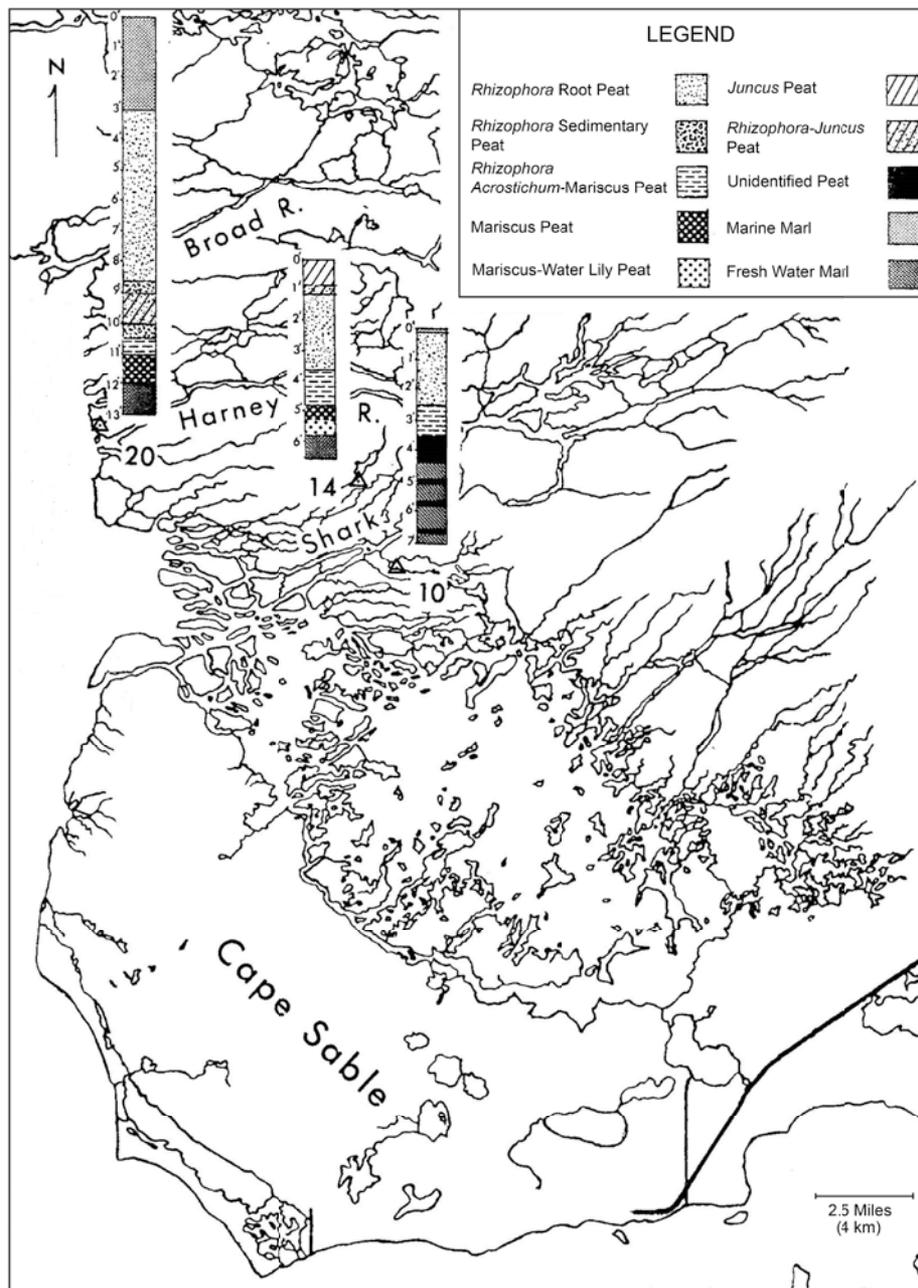
Fig. 5. Geographic location and stratigraphic relationships of *Juncus*-containing peat samples in Core 20 taken at the same site as the Harney River pollen core. Palaeobotanical analyses here were derived from microscopic study of vertically oriented microtome thin sections. Note that the highest sea level occurs near the top of the 9–10 foot zone, as determined from our finding of *A. lineata* fungal spores only in the upper petrographic slide of this zone; (modified from Cohen 1968, and Spackman et al. 1976)

This discovery shows that not only is *Atrotorquata lineata* preserved beneath the surface but that this relationship between *A. lineata* and *Juncus roemerianus* has existed for at least 3000 years BP. Interestingly, slides from the next interval lower in the core, which contained *J. roemerianus* root tissues but no leaves, did not have any *A. lineata*. This confirms that *A. lineata* occurs only in the dead standing culms of the plant, as was described by Kohlmeyer & Volkmann-Kohlmeyer (1993), and not in root tissue. This is important to note because roots of a plant can penetrate deeply enough into the soil that they may be found in sediment deposited years before the plant began to grow. The fact that *A. lineata* is present only in the above-ground portion of the plant means that it can only be deposited on the surface where the plant is growing and not in older sediments. To this point, we have not found evidence of transport through wind or water action, nor does bioturbation appear to have a significant impact on the location of *A. lineata*. This makes *A. lineata* a very accurate proxy for the location of *J. roemerianus* stands within a core sequence, and consequently a very accurate proxy for highest position of relative sea level). Furthermore, this evidence suggests that *Juncus* peat, if defined by the presence of its proxy (*A. lineata*), found in a mangrove sequence, is a more accurate indicator of the highest position of relative sea level than the presence of red mangrove root tissues.

Sand Point, Roanoke Island, North Carolina Core (Fig. 6)

Atrotorquata lineata was found in the surface and at 10 cm depth in this core. While *A. lineata* was not found below 10 cm in this core, the researchers who supplied the core reported that *Juncus roemerianus* fragments are present lower in the core (Kemp, personal communication). If *J. roemerianus* is present lower in the core but *A. lineata* is not, that would lend support to the hypothesis that the range of *A. lineata* is limited on the northern end of the range of *J. roemerianus* by temperature, as proposed by Marsh and Cohen (2016), and, thus the lower portions of this core, containing *J. roemerianus* debris without *A. lineata*, might indicate that the northern limit of the *A. lineata* range may have moved north to this area in recent times (i.e. indicating a relatively recent increase in temperature in this region).
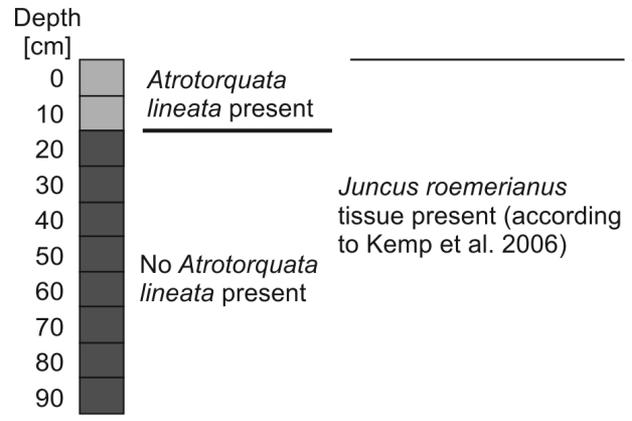
Fig. 6. Description of the North Carolina core. *Atrotorquata lineata* was found in the surface and 10 cm interval but not lower than that in this core. Horton and Kemp, who provided the core, described the entire core as *Juncus roemerianus* based on tissue fragments. This raises the question of whether the tissue fragments are truly *Juncus roemerianus* (or perhaps a different *Juncus* species such as *Juncus gerardii*, which has a range that extends south into this area) or if this absence of *Atrotorquata lineata* is related to the same phenomenon that is the cause of the lack of *Atrotorquata lineata* in samples further north of this point; (after Marsh & Cohen 2016)

Baruch Institute, Georgetown, South Carolina Cores (Fig. 7)

By analyzing these cores at closely spaced intervals (generally 2 cm) we were able to verify not only that *Atrotorquata lineata* is preserved below the surface, but also that its presence or absence can be used to reconstruct changes in the position and size of *Juncus roemerianus* marshes over time. Details of these reconstructions are presented below. Our subsequent analysis provides an interpretation in which the presence of *A. lineata* clearly reveals evidence of expansion and contraction of *J. roemerianus* patches over time and further suggests recent past fluctuations in sea level that were both higher and lower than at present but were contained within an overall transgressive sequence.

DISCUSSION

The small scale study at James Island gave us our first indication that *Atrotorquata lineata* is preserved beneath the surface. This part of the study was not designed to include the fine detail necessary to pinpoint changes in the position or size of *Juncus roemerianus* marshes over time; however, it was possible to see some change in the size of the *J. roemerianus* marsh in these short cores.
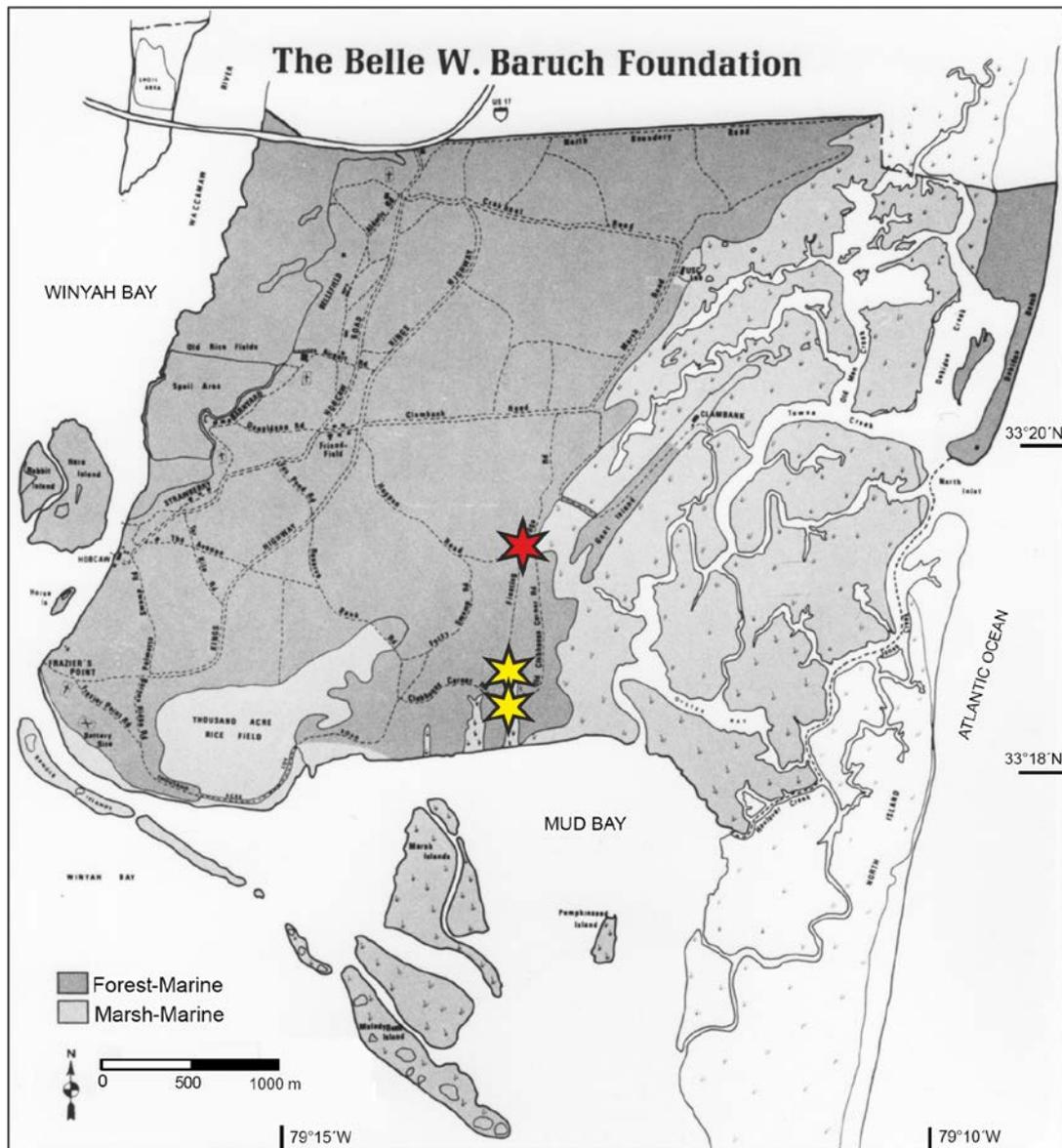
Fig. 7. Location of high resolution coring sites at the Belle W. Baruch Institute for Coastal and Marine Science. Stars mark sample areas. Red star – Floating Bridge Road site; yellow stars – Old Clubhouse Corner Road sites; (from Marsh 2008 and Marsh & Cohen 2016, Map from Belle W. Baruch Foundation)

The series of microtome section slides from the Harney River (Florida) core provided evidence that not only can *Atrotorquata lineata* be preserved beneath the surface but that it can be preserved for a substantial period of time (at least 3000 years BP). These slides also linked *A. lineata* with the above-ground portion of *Juncus roemerianus*, as *A. lineata* was only found in intervals of the core which contained leaf tissue from *J. roemerianus* and not found in intervals of the core which contained root tissues.

The core from North Carolina provided additional evidence that *Atrotorquata lineata* can be preserved beneath the surface. However, since it was found only toward the top of this core while *Juncus roemerianus* tissue was identified deeper in the core, it raises the question of why this is the case. We hypothesize that the range of *A. lineata* is less than the range of its host plant, *J. roemerianus*, at its northern edge. This may be controlled by temperature.

We have shown that *Atrotorquata lineata* is preserved beneath the surface and, in the James Island study, that there are indications that changes in the size and position of *Juncus roemerianus* marshes may be identifiable by the presence or absence of *A. lineata*. In the study of cores from Floating Bridge Road and Old Clubhouse Corner Road (Figs 7, 8, 13) at the Belle W. Baruch Institute for Coastal and Marine Science in Georgetown, South Carolina, we show that such changes are identifiable and able to be interpreted.

THE FLOATING BRIDGE ROAD (FBRD) STUDY
(Figs 7–10)

Four cores were taken with a Macaulay Sampler (in 20 cm increments) to a depth where the denseness of the sediment, generally hard packed sand, precluded deeper sampling. The Floating Bridge Road (FBRD) cores were taken along a transect starting in *Spartina alterniflora* and ending within *Juncus roemerianus* (see Fig. 8, 9). Core FBRD1 (51 cm long) was taken from an area that had *S. alterniflora* growing on the surface. Core FBRD1.5 (54 cm long) was taken at the edge of the *J. roemerianus* area near the transition zone, and FBRD2 (32 cm long) and FBRD3 (69 cm long) were taken from areas of pure *J. roemerianus*. Core FBRD1.5 was 1 m inland from core FBRD1, Core FBRD2 was 1 m inland from core FBRD1.5, and Core FBRD3 was 2 m inland from core FBRD2.

Cores were divided into 2 cm increments and a slurry slide was made for each increment (total 104 slides). These slides were examined microscopically. The primary focus of this examination was to ascertain the presence or absence of *Atrotorquata lineata*. If *A. lineata* (as a proxy for *Juncus roemerianus* stands) was not found, it was assumed that *J. roemerianus* stands were not present, but this alone would not indicate whether the sea level had risen (replacing these *Juncus roemerianus* stands with *Spartina alterniflora*) or the sea level had fallen and the site had become non-marine. To help with this interpretation, slides were examined for the presence of non-marine indicators such as freshwater diatoms or non-arboreal pollen or plant fragments, which would indicate a non-marine upland environment, or marine indicators such as marine forams or diatoms, which would indicate a marine environment. Some samples contained neither marine nor freshwater indicators, and these were labeled according to their juxtaposition to other known increments (e.g. a sample with no indicators located between two non-marine samples was considered non-marine).

Core FBRD1 contained *Atrotorquata lineata* only at the 12–14 cm interval, which suggests a significant though temporary drop in sea level to a point where *Juncus roemerianus* was able to become established briefly. This core was taken from an area currently vegetated with *Spartina alterniflora*, and as a result would not be expected to contain *A. lineata* at or near the surface. The sediments from the surface to 12 cm of this core were determined to be of marine origin by the presence of marine microfossils, as were the sediments from 14 to 30 cm. Below 30 cm there

Fig. 8. Location of the coring site off Floating Bridge Road, Baruch Institute (star). This area is between Pleistocene shorelines, similar to the Sapelo Island sites in Georgia (from Marsh 2008; image from Google Earth)
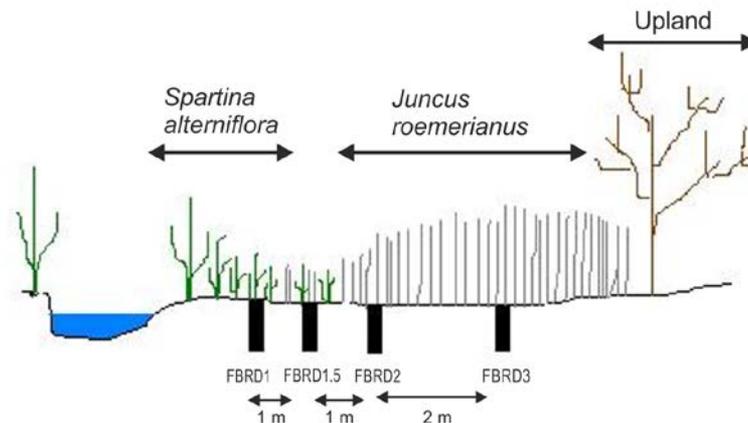
Fig. 9. Diagram of cores along a transect taken near Floating Bridge Road at the Baruch Institute, Georgetown, South Carolina (from Marsh 2008)

was some uncertainty as to whether the samples were non-marine or marine. Again, these were labeled according to their juxtaposition to other known increments.

Two of the intervals, 32 to 34 cm and 50 to 51 cm, were processed by both pollen extraction and slurry slides to help establish the palaeoecological setting. The presence of Chenopodiaceae pollen in the 32–34 cm slide suggests that it may have been a salt panne area containing *Salicornia virginica* Linnaeus, and thus of marine origin. However, *S. virginica* is not the only member of Chenopodiaceae. There are many species in this family that can live in freshwater environments as well, although freshwater Chenopodiaceae are typically found associated with a significant number of other freshwater herbaceous species. The lack of any of these types strongly argues for the marine interpretation. The 50–51 cm interval had nothing but tree pollen. As tree pollen is often transported significant distances by the wind, this is not specifically indicative of marine or upland areas, although the presence of upland trees and the lack of marine diatoms or forams would suggest a non-marine environment for this interval.

Core FBRD1.5 had *Atrotorquata lineata* present from the surface to 6 cm, in the 14–16 cm interval, from 18 to 30 cm, and in the 38–40 cm interval. Interspersed among the *A. lineata* intervals in the upper part of the core are layers interpreted as marine sediment, based on the presence of marine forams. Lower in the core, there are some non-marine layers (determination based on non-marine diatoms and non-arboreal pollen) present as well. Three intervals from this core were processed to extract pollen to help confirm the palaeoecological setting:

36–38 cm, 40–42 cm and 50–52 cm. Again, there were few palynomorphs low in the core. The 36–38 cm interval contained some Chenopodiaceae pollen and other indicators of marine origin. The 40–42 cm and 50–52 cm intervals had almost no palynomorphs, but the presence of an occasional *Osmunda* spore and a few tree and other non-arboreal pollen suggested that these levels are non-marine.

Core FBRD2 is the most clear-cut of the FBRD cores. *Atrotorquata lineata* is present in all samples except 8–10 cm and 22–24 cm. Those two intervals were clearly of marine origin based on the microfossils found.

Core FBRD3, the most landward and longest of the FBRD cores, had *Atrotorquata lineata* from the surface to 12 cm, from 14 to 18 cm, from 20 to 30 cm, from 36 to 50 cm, and in the 52 to 54 cm interval. These *A. lineata* zones are interspersed with marine layers in the upper part of the core. The lower part of the core had some layers of marine origin and some that were interpreted to be of non-marine origin. To aid this interpretation one sample from this core, at 66–68 cm, was processed to extract palynomorphs. Although containing few palynomorphs, this sample did contain some tissue fragments that suggested it was non-marine.

Our interpretation of the stratigraphic relationships among the FBRD cores is shown in Figure 10, which illustrates our best attempt at correlating zones among cores.

Starting at the base and proceeding toward the top, the following interpretations are proposed. (1) A non-marine layer occurs at the base of the three longest cores. (2) Just above this non-marine layer, these three cores have a marine layer, which would suggest a rising
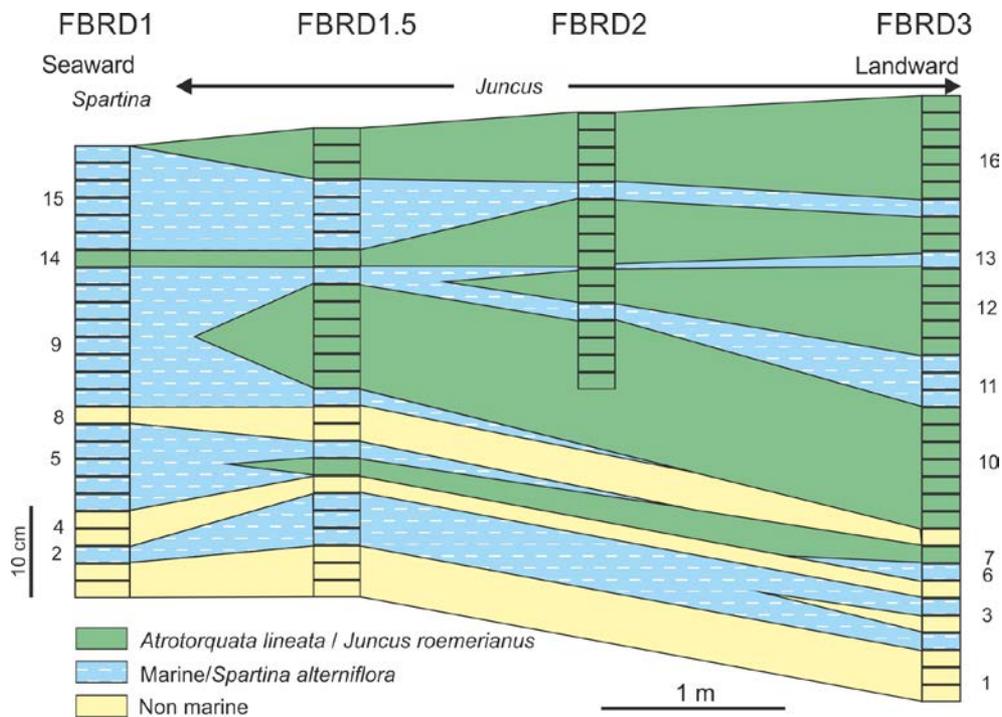
Fig. 10. Correlation and interpretation of the four FBRD cores. Small numbers at the edge of the diagram refer to discussion in the text. FBRD1 is the most seaward. FBRD3 is the most landward. *Atrotorquata lineata* is seen on the surface of cores taken in all *Juncus roemerianus* zones. Marine (but not *Atrotorquata lineata*) sediment is seen on the surface of core FBRD1 from a *Spartina alterniflora* zone. Marine and non-marine layers are interspersed beneath. In this interpretation, the lower parts of the cores show apparent cycles of rising and falling water level, while the upper parts of the cores seem to show sea level rise of varying speeds

sea level. (3) There is a small area of non-marine sediment in core FBRD3 in the midst of this marine layer. As core FBRD3 is the most landward, a non-marine zone in this position may indicate a small drop in sea level. (4) Just above this marine layer is another non-marine layer that also spans the three longest cores. This could indicate a larger fall in sea level. Above this non-marine layer is a somewhat more complicated situation. (5) Core FBRD1 has a marine layer. (6) Core FBRD3 has a small marine layer overlain by a *Juncus roemerianus* layer (7) which continues across to core FBRD1.5, which has a *J. roemerianus (Atrotorquata lineata)* layer overlain by a marine layer. As core FBRD1 is closest to a tidal creek, it seems likely that a sea level rise could take this area directly from upland influence to marine influence with little or no time as a transition area. Core FBRD1.5 was perhaps slightly higher in elevation and a somewhat slow sea level rise would have allowed *J. roemerianus* to become established before an increasing rate of sea level rise caused the area to become too much under marine influence for *J. roemerianus* to survive.

The small marine layer under the *Juncus roemerianus* layer in core FBRD3 (6) may be the result of sediment carried high into the marsh by a storm, a hurricane storm surge, for example. Since *Atrotorquata lineata* occurs only in the above-ground parts of *J. roemerianus*, there would have been a period of time when the marine sediment would not have contained *A. lineata*. However, once the plant was established, *A. lineata* would have been deposited, forming the *J. roemerianus* layer above. Apparently this particular round of sea level rise was not high enough or long enough to wipe out the *Juncus roemerianus* at core FBRD3 before the subsequent sea level drop returned the entire area to a non-marine environment.

Above the highest non-marine layer (8) are an alternating series of marine and *Juncus roemerianus* layers. In general, this most likely indicates an overall transgressive sequence, though the speed of sea level rise probably varies (and may even occasionally pause or reverse) over the time period represented by these cores. Above the highest non-marine layer, a marine layer (9), probably indicating a moderately slow sea level rise, occurs. This is soon covered with *J. roemerianus* (10) (except in the near-creek core, FBRD1, where little *J. roemerianus* would be expected).

Subsequent to the establishment of *J. roemerianus*, an acceleration of sea level rise turned the environment more marine (11) and unsuitable for *J. roemerianus*.

A sea level stand-still or slight drop allowed *Juncus roemerianus* (12) to become established once again. Above this *J. roemerianus* layer is a layer of marine sediment (13). Though it does not show up in core FBRD2, there is probably a connection between the cores nearer the creek and the most upland core. This may indicate a brief period of rising sea level or, perhaps more likely, a storm event that laid down a layer of marine sediment on which *J. roemerianus* (14) was able to reestablish, this time even briefly in the near creek core, FBRD1, probably indicating a more dramatic sea level fall.

A more rapidly rising sea level again produced a marine layer (15) which was again taken over by *Juncus roemerianus* (16) as the rate of rise of sea level slowed. While it is difficult to know the age of any point in these cores with precision, it seems possible that this apparent sea level rise may be the same regional (South Carolina, Georgia, and Florida and possibly Louisiana and Texas) spike in sea level rise rate observed in 1948 in various tidal gauge records presented on Figure 11 (Hicks & Crosby 1974, Donn & Shaw 1963, NOAA). If the South Carolina salt marsh accretion rates (0.13 to 0.45 cm/year) given by Bricker-Urso et al. (1989) are accurate, 1948 sediment would occur somewhere between 8 and 27 cm beneath the surface. The base of this marine layer occurs between 10 and 14 cm beneath the surface in all cores, which is within the expected range. Over time, as sea level rise slowed and/or marsh accretion accelerated, this area was again taken over by *J. roemerianus* as it remains today.

Another feature of note is that the wedge of *Juncus roemerianus* sediment in the layer nearest the surface is thickest farthest from the ocean and thinnest closest to the ocean. This would be expected if the rate of accretion had exceeded the rate of sea level rise (such as when sea level rise is slowing or reversing). This interpretation might be reinforced by tidal records from Charleston, South Carolina (to the south of the study site) and Myrtle Beach, South Carolina (to the north of the study site) as illustrated on Fig. 12, which show an actual downward trend of the water level from about

1990 to 2010, though there has been an apparent resumption in relative sea level rise since about 2010.

THE OLD CLUBHOUSE CORNER STUDY
(Figs 7, 13, 14)

The two Old Clubhouse Corner (OCC) cores were collected at the Baruch Institute for Marine and Coastal Science in an area off of Old Clubhouse Corner Road (see again Figs 7, 13). Note that the cores are located within a trough between two shorelines (probably Pleistocene, as beach ridges in this area are of Pleistocene age (Gardner & Porter 2001)).

Core OCC1 was taken in a *Juncus roemerianus* marsh ca 460 meters north of Mud Bay. Core OCC2 was taken within the *J. roemerianus* in the same *J. roemerianus* marsh near the transition to upland vegetation, ca 460 meters north of OCC1. Cores were taken with a mini Macaulay sampler in 20 cm segments. OCC1 was 200 cm deep. OCC2 was 100 cm deep.

Each core was separated into 2 cm increments. Slurry slides were made for each increment to 34 cm depth for each core. Below 38 cm, the core samples were analyzed at 6 cm increments (total of 74 slides). As with the FBRD cores, these slides were then examined microscopically for the presence or absence of *Atrotorquata lineata*. Marine forams and freshwater diatoms were again used to help establish the palaeoecological environment of samples not containing *A. lineata*.

Core OCC1 had *Atrotorquata lineata* present from the surface to 16 cm and again from 20 to 22 cm. Marine influence was present from 16 to 20 cm, from 24 to 28 cm and from 30 to 32 cm. Non-marine influence is seen between 28 and 30 cm and from 32 cm to the base of the core at 200 cm.

Core OCC2 had *Atrotorquata lineata* from the surface to 16 cm and again from 20 to 26 cm. Marine influence was present from 16 to 20 cm and from 26 to 32 cm. From 32 cm to the base of the core at 100 cm, non-marine sediments were present.

Given the spatial separation of these two cores (460 m), they are remarkably similar. Beneath 34 cm the samples either contained non-marine microfossils or had insufficient microfossils to make a definitive interpretation (but none contained any marine indicators). In all cases, *Atrotorquata lineata* was not present
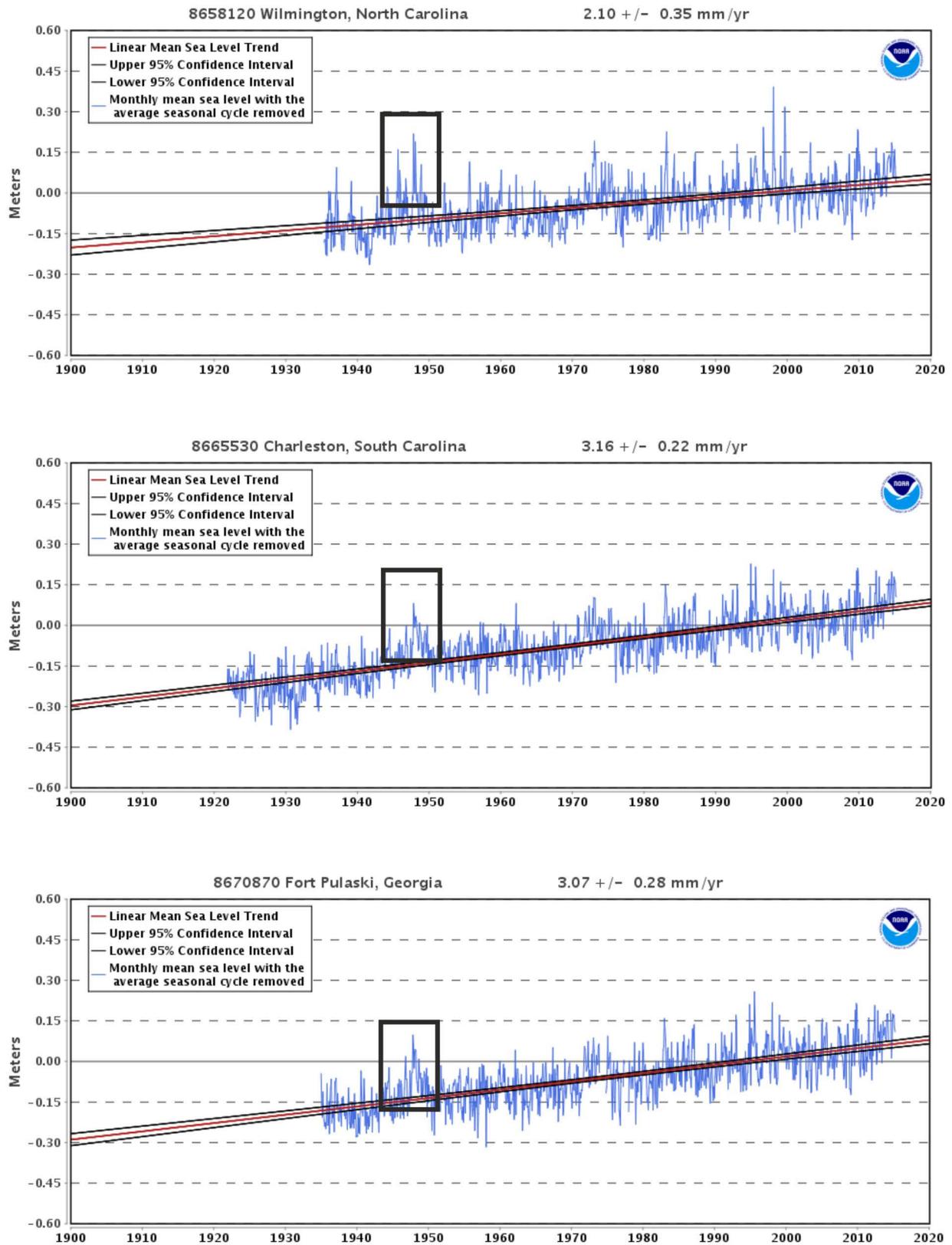
Fig. 11. Tidal records from Wilmington, NC, Charleston, SC, and Fort Pulaski (near Savannah), GA. Note the sea level spike around 1948 at all three sites. (Modified from NOAA Tides and Currents website)

below that level, so only the top 34 cm of each core will be considered here.

Correlation of the two cores is illustrated in Figure 14, which shows alternation between *Juncus roemerianus* and marine sediments, with only non-marine sediments occurring at lower levels. This would suggest an overall rise in relative sea level. The presence of a small
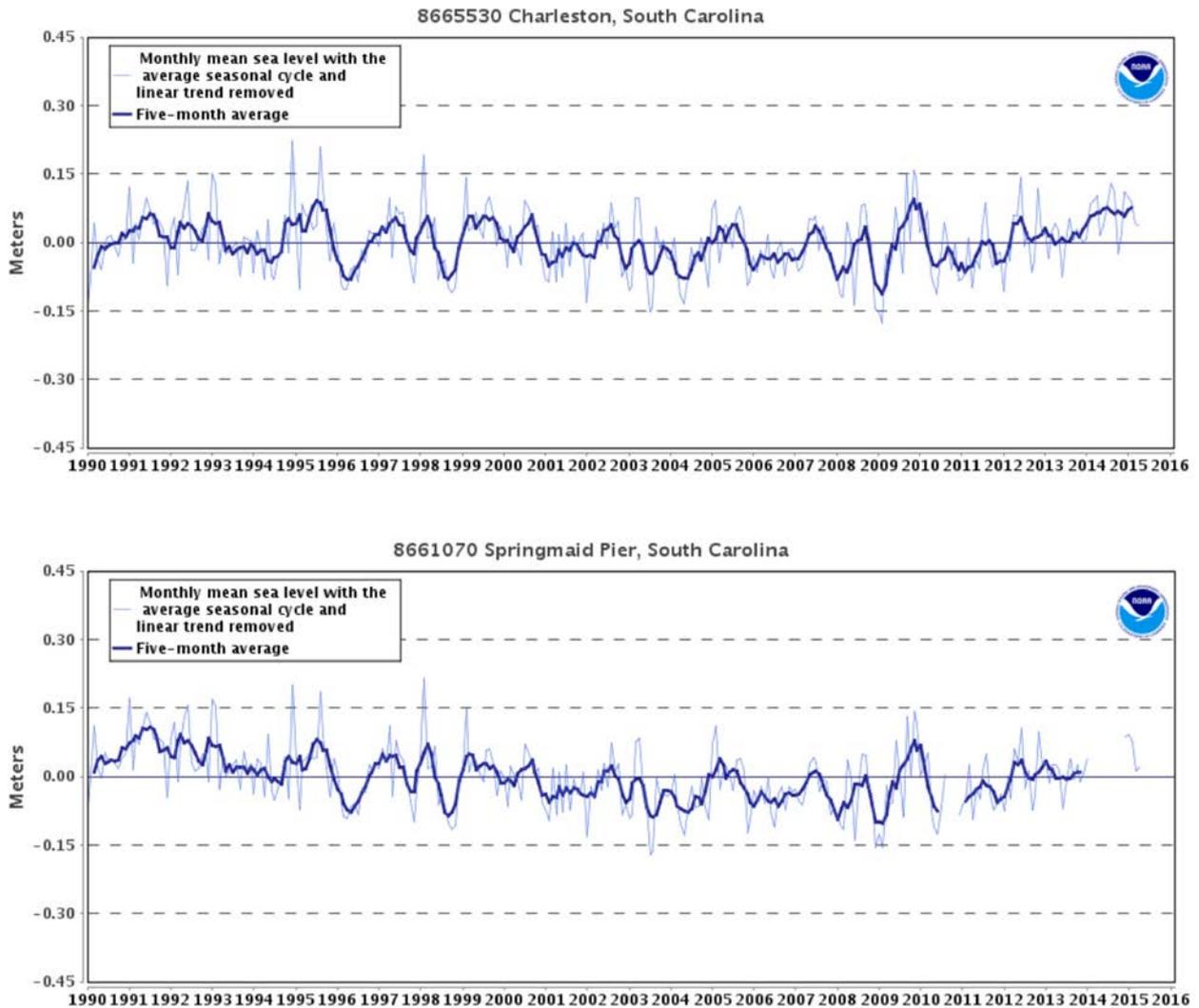
Fig. 12. 25-year tidal record, Charleston, SC (to the south of the study site), and Myrtle Beach (Springmaid Pier), SC (to the north of the study site); (from NOAA Tides and Currents website)

non-marine layer in OCC1 (2), which was closer to the bay, is a little unusual, as is the fact that, while there is a relatively large distance between the cores, the basal non-marine layers (1) begin at the same depths, when they might ordinarily be expected to begin higher in the core closest to the upland environment. The 32–34 cm interval in core OCC2 contains many freshwater diatoms. These are not found in OCC1; nor are they found in adjoining levels of OCC2. There are, however, fragments of what appears to be charcoal at this and other lower levels of OCC2. A possible explanation, therefore, of the unexpected evenness of the non-marine layer is that there was a fire in the marsh that burned an undetermined amount of organic material in the area of core OCC2, possibly lowering the marsh surface to the point that it reached the water table and provided a favorable environment for freshwater diatoms. Additionally,

fires tend to release nutrients from peaty soils, resulting in increased diatom blooms (Cohen et al. 2008). The presence of charcoal and the inability to determine how much material was lost to fire suggest that, while these cores are remarkably similar, there may actually have been differences that are now lost.

Above the marine layer (3) is a layer of *Juncus roemerianus* sediment (4). This layer is thicker in the core farther from the ocean, as would be expected. This suggests a slowing of sea level rise that would allow *J. roemerianus* to become established. A new marine layer (5) was deposited above the *J. roemerianus* layer. This would indicate an acceleration of sea level rise, perhaps again related to the spike in the rate of sea level rise shown in tidal gauge records mentioned in the interpretation of the FBRD cores (Hicks & Crosby 1974, Donn & Shaw 1963, NOAA; see again Fig. 11),
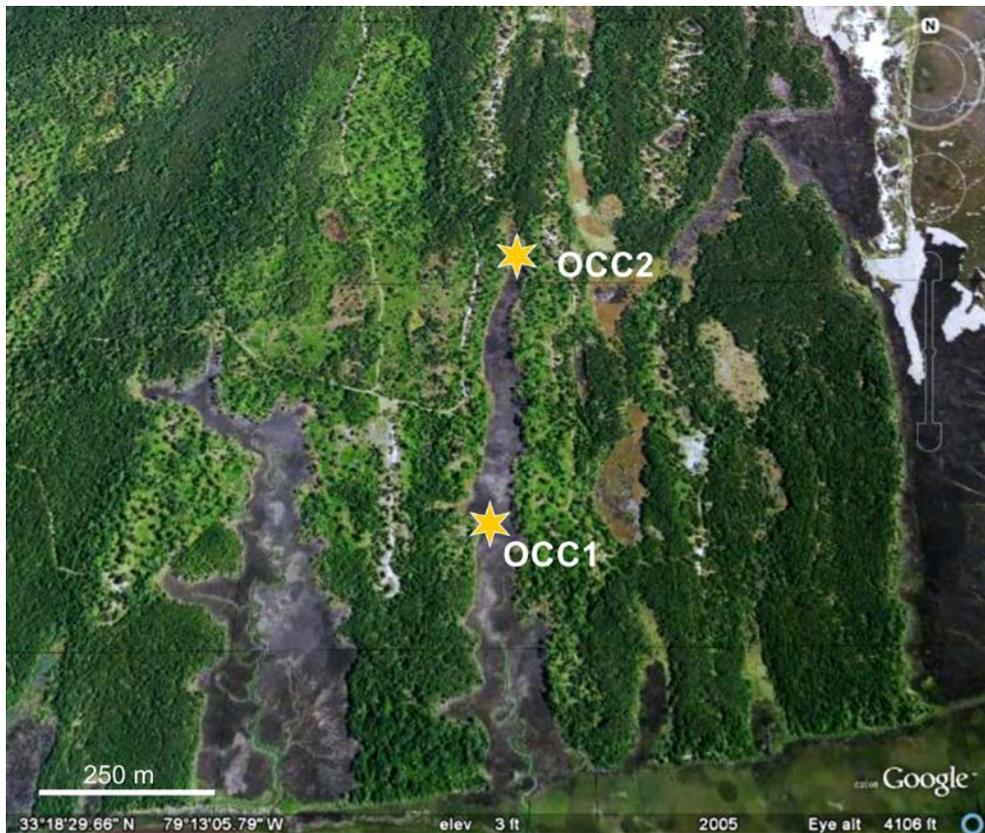
Fig. 13. Locations of the cores taken of Old Clubhouse Corner Road, Baruch Institute. Stars indicate the positions of the two cores. OCC1 is closer to the bay. OCC2 is closer to the upland. These sites are between Pleistocene shorelines (from Marsh 2008; Image from Google Earth)

as this marine layer is found at a depth similar to the marine layer in the FBRD cores. The top of both cores is *J. roemerianus* sediment, from the surface to 16 cm (6). Another significant difference between this set of cores and

the FBRD cores is the presence herein of much more organic-rich sediment than at FBRD. This suggests that the OCC depositional environment was one with much longer hydroperiods (probably due to groundwater seepage
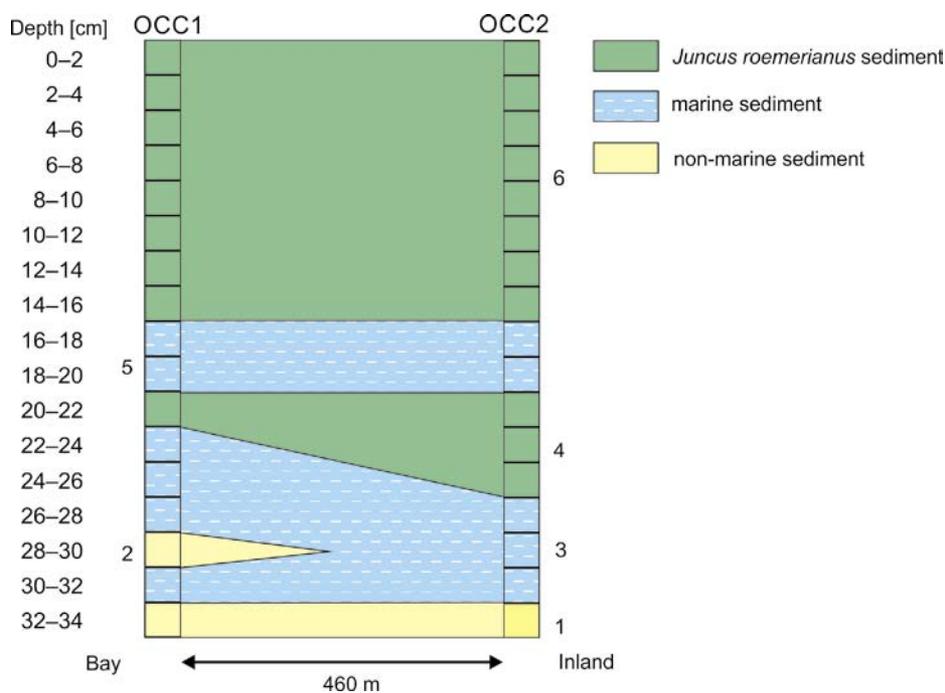
Fig. 14. Correlation of OCC cores

from the surrounding Pleistocene beach ridges that bordered this environment on either side and also protected it from salt water intrusion even during storm events.

COMPARISON OF EVENTS INTERPRETED FROM FBRD AND OCC CORES

With the exception of the near creek core at the FBRD site (FBRD1), all FBRD and all OCC cores have sediments interpreted from the *Atrotorquata lineata* analysis as *Juncus roemerianus* sediments at the surface. Inasmuch as these core sites have *J. roemerianus* growing on the surface, this is to be expected. However, the thickness of the *J. roemerianus* sediment is somewhat more in the OCC cores than in the FBRD cores. This could be caused by differences in sediment deposition at the sites, the FBRD site getting most of its marine influence (water and sediment) from the open ocean to the east along Towne Creek, and the OCC site getting most of its marine influence from Mud Bay to the south (Fig. 7). All five cores have marine sediment beneath the *J. roemerianus* sediments, possibly related to a regional spike in the rate of sea level rise in 1948. Beneath that, all cores have another *J. roemerianus* layer with another marine layer beneath that. Below that, the FBRD cores have another *J. roemerianus* layer, another marine layer, and then various marine and non-marine layers, while the OCC cores become non-marine. The OCC cores do show evidence of fire, however, which may have removed some of the layers that are present in the FBRD cores. Overall, the pattern is similar between the FBRD cores and the OCC cores, with variations in the depth and thickness of layers possibly due to different accretion rates based on location and distance from the ocean, different amounts of storm deposited sediment, and possible organic matter loss due to fire. These cores show an overall transgressive movement of the sea, but it does not appear to be a straight line transgression: rather, a series of transgressions and regressions, which tends to support the sea level interpretations of others who have suggested oscillating sea level (e.g. Fairbridge 1961, 1976, Urien 1970, Ters 1973, Einsele et al. 1974, Gaunt & Tooley 1974, Pirazzoli 1976, Colquhoun & Brooks 1986, Gayes et al. 1992).

While no radiocarbon dates were obtained during this study, Colquhoun & Brooks (1986) date material from salt marsh cores in South Carolina at 0.5 m beneath the high marsh (approximately the depth to which *Atrotorquata lineata* was found in this study) between 250 and almost 2000 years BP. In a study from Murrells Inlet, South Carolina, Gayes et al. (1992) date material from a similar depth at about 600 years BP. The variety of dates for essentially the same depth would suggest that, in addition to errors inherent in radiocarbon dating, there may be other factors, such as different amounts of sediment compaction, changes in tidal creek position or morphology, removal of material due to erosion and fires, or sudden deposition of more than the normal amount of sediment due to storm surges, that may cause difficulty determining an absolute time frame.

SUMMARY AND CONCLUSIONS

As a result of this study, the following conclusions can be drawn.

• *Atrotorquata lineata* is definitely preserved beneath the surface. In this study we discovered well-preserved *A. lineata* spores in core samples dating at least 3000 years BP and they likely will be found in much older sediment.

• The types of sediment in which *Juncus roemerianus* stands grow has no bearing on the presence of *Atrotorquata lineata*. We found them in core samples with substrates of peats, sands, muds, and silts.

• Changes in the size and position of former *Juncus roemerianus* stands over time were observed by using the presence of *Atrotorquata lineata* as a *J. roemerianus* proxy in cores.

• Deeper core results indicate an overall transgressive sequence at all sites studied. However, minor fluctuations in sea level or storm events may be reflected in expansion and contraction of *Juncus* marshes at certain sites, possibly with sufficient sensitivity to show correlations with tidal gauges.

As a result of the multiple parts of this study, it is possible to say with reasonable certainty that the presence of *Atrotorquata lineata* is a valid proxy for the presence of *Juncus roemerianus,* and thus the position of sea level throughout nearly all of the geographic range of *J. roemerianus* except for the

most northern edge of its range, where temperature may be an important (perhaps "the" important) variable.

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