

Recent Barrier Beach Retreat in Georgia: Dating Exhumed Salt Marshes by Aspartic Acid Racemization and Post-bomb Radiocarbon

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ABSTRACT

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On St. Catherines Island, Georgia, the barrier beach is retreating rapidly landward, burying living salt marsh as it moves and later exhuming it on the ocean side. Two methods were used to reconstruct the history of overwash events, by dating the time of death of salt marsh mussels (*Geukensia demissa*) and grasses (*Spartina alterniflora*) killed by overwash sands (and now exhumed on the ocean side of the barrier beach): aspartic acid (Asp) racemization and post-bomb radiocarbon analysis. The former method involves the conversion of L-Asp to D-Asp in shell proteins and provides good resolution for dating the last few centuries. Radiocarbon analysis offers high-resolution dating subsequent to the thermonuclear bomb tests of the late 1950s. However, for a number of reasons, it is of little use for resolving ages within the preceding three centuries. It is suggested that one problem with radiocarbon dating is that, in intertidal mollusk shells, some atmospheric carbon is incorporated, complicating correction for the marine reservoir age.

Determination of the rate of Asp racemization in *Geukensia* shells on St. Catherines Island was made by comparison of D/L Asp values with the age of one sample determined by post-bomb radiocarbon to be AD 1980 (± 1 yr). This rate was used to determine ages from D/L Asp values at three relict marsh sites on the ocean side of the island. In the southern and middle sites, living marsh was destroyed by overwash around 1980-82, whereas at the northernmost site, the marsh was destroyed in the late 1930s or early 1940s. The rate of retreat on the ocean side of the barrier beach at the northernmost site was determined by study of aerial photos from 1945 and 1990. The retreat rate during this period averaged 3.8 m/yr. The photos also indicate that the landward margin of the overwash fans here have been stationary over this period, so the barrier beach has narrowed considerably at this site. A reduction in the sediment supply to the area combined with the lack of supply of sands from the relict marsh muds eroding along the shoreface probably caused erosion to outpace landward extension of the barrier beach by overwash.

Evidence of the earlier dynamics of the salt marsh is exposed in the relict marshes eroding away on the ocean side of the barrier island. These contain older layers of marsh, buried by muds. At the middle site, accretion of muds buried these portions of the salt marsh ca. 16 and 26 yr before the site was covered by an overwash fan from the barrier island, whereas at the southerly site, the earlier marsh was buried by muds some 160 yr before the overwash event.

Aspartic acid racemization has excellent potential for the analysis of coastal dynamics over the last few centuries. It provides a means of comparing the geological record with historical records and also provides information on coastal behavior before written records.

ADDITIONAL INDEX WORDS: *Amino acid racemization, radiocarbon dating, Spartina, Geukensia.*

INTRODUCTION

In most areas along the East Coast of the United States, relative sea level has been rising and the coast has been retreating during the 20th century. In the Southeast, south of the region affected by isostatic rebound from the ice sheets of the last glaciation and where the coast is considered relatively stable tectonically, relative sea-level rise has averaged ca. 2.5 mm per year during the latter half of this century, based on tidal gauge records (DAVIS, 1987). This rate is similar to rates along tectonically stable coasts in other parts of

the world (EMERY and AUBREY, 1991). Changes in sediment supply to the coast, together with a relative rise in sea level, have resulted in coastal retreat in many areas in recent decades, as documented from surveys, charts, as well as ground-based and aerial photographs. However, reconstruction of coastal retreat rates in the more distant past is problematic. In some cases, historical records stretch back many centuries (e.g., KRAFT, 1971).

Radiocarbon dating of series of cores taken along transects perpendicular to the coast has also been used to reconstruct sedimentary histories (e.g., KRAFT, 1971, 1985). But, of course, erosional or retreat events usually cannot be directly

dated in the sedimentary record. Furthermore, there is a problem with dating the record of the last several centuries because of the poor precision of radiocarbon dates during this interval. There are several sources of error involved:

(1) The analytical precision is usually in the range of *ca.* ± 30 to 60 yr.

(2) The radiocarbon ages need to be corrected for the marine reservoir age, the apparent radiocarbon age of bicarbonate in the sea, which is a function of the turnover rate of the CO_2 -bicarbonate-carbonate pool. These reservoir ages are typically on the order of 400 yr but vary geographically and temporally (STUIVER *et al.*, 1986), so that an additional error term for this correction needs to be added to the uncertainty of the corrected age.

(3) Due to fluctuations in atmospheric ^{14}C levels since *ca.* AD 1650 (STUIVER, 1993), radiocarbon ages in the marine realm have changed slower than calendric ages during this period (STUIVER *et al.*, 1986), so that some temporal resolution is lost when the radiocarbon ages are calibrated (*i.e.*, converted to calendric ages).

Because of these various factors, marine samples usually cannot be dated by radiocarbon with a precision better than *ca.* ± 100 yr for the period from *ca.* AD 1650 up to the late 1950s, when thermonuclear bombs tests dramatically raised radiocarbon levels. The possible age range for any sample falling within this period thus covers most or all of this interval, making precise reconstruction of sedimentary histories from radiocarbon-dated samples impossible.

In the present study, we use aspartic acid (Asp) racemization analysis of salt marsh mussel shells (*Geukensia demissa*) to determine their time of death. The *in situ* mussel shells, now being exhumed on the ocean side of the barrier beach, were killed by retreat of the beach across the marsh. Dating of the time of death of the mussels provides an estimate of coastal retreat rates within this problematic period of the last few centuries, before historical records are available.

Racemization involves the conversion of L- amino acids (only L- forms are present in proteins in newly-formed shell proteins) to their mirror-image D- form. Thus the ratio of D/L amino acids gives an indication of the relative age. Asp is a particularly fast-racemizing amino acid which provides good age resolution for recent decades and centuries (GOODFRIEND, 1992; GOODFRIEND *et al.*, 1992, 1995; GOODFRIEND and STANLEY, 1996). However, since racemization rates are not known *a priori* (they vary among species and depend on temperature), calibration against some other method is required for a selected sample. Once the racemization rate is established, this rate can be used to calculate ages for other samples in the area.

The study sites are located along the seaward (eastern) side of St. Catherines Island, a barrier island on the coast of Georgia *ca.* 30 km south of Savannah (Figure 1A). The Sea Islands of Georgia have a "double" coastline: an inner Pleistocene coastline along the core of the island and an outer Holocene coastline, separated by a lagoon or salt marsh. Some retain both components, *e.g.*, the pair of Sapelo (Pleistocene) and Blackbeard (Holocene) Islands. Other islands, such as St. Catherines, have largely lost the Holocene portion due to ero-

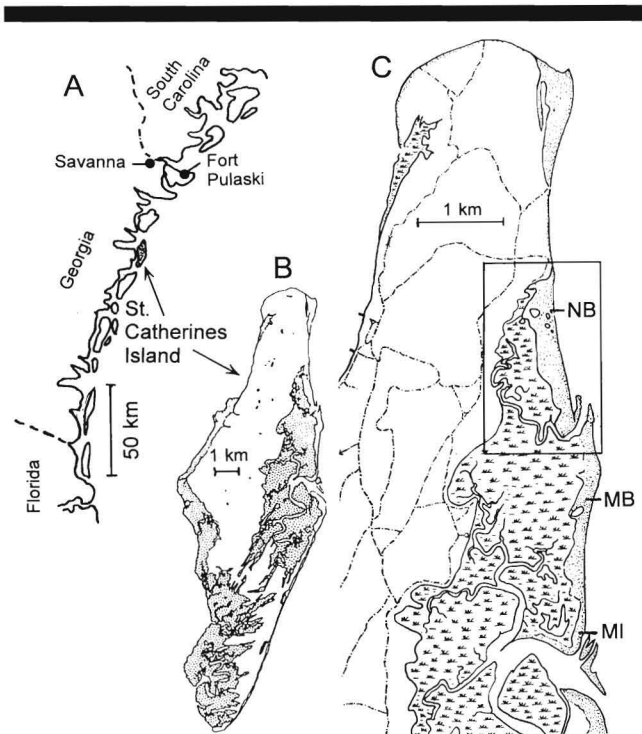


Figure 1. (A) location of St. Catherines Island and vicinity; (B) map of St. Catherines Island showing the distribution of living salt marshes (stippled area) and area shown in greater detail in C (from WEST *et al.*, 1990); (C) northern half of St. Catherines Island showing the location of the study sites and location of map of Figure 2. Areas of living marsh and coastal sands (stippled) are shown (modified from MORRIS and ROLLINS, 1977).

sion and thus retain only a narrow sliver of salt marsh sandwiched between the Pleistocene island core and the barrier beach on the eastern (ocean) side of the island (Figure 1B; MORRIS and ROLLINS, 1977). The salt marsh on St. Catherines Island is dominated by the grass *Spartina alterniflora* and is flooded during the high tides of most tidal cycles. The Atlantic ribbed mussel *Geukensia demissa* is an abundant inhabitant of the marsh and grows in large clumps on the surface of the muds among *Spartina* stems. As the beach retreats landward, overwash fans (Figures 2, 3C, 4) bury the living marsh (Figure 3D), while at the seaward edge, the retreating beach exhumes dead marsh formerly buried under the barrier beach (Figure 2, 3A, B, E). Thus dating of the time of death of mussels exhumed on the seaward side of the beach indicates when the *landward* side of the barrier beach first reached that point.

Beach retreat rates along the east coast of St. Catherines Island, as well as several other islands in the area, were studied by OERTEL and CHAMBERLAIN (1975) using coastal charts for the period 1897 to 1939 and aerial photographs from 1952 to 1975. Because of large error associated with analysis of the charts (errors were estimated at ± 15 m), retreat rate variations within this overall time span are hard to assess. However, it is clear that considerable differences in average retreat rates occurred on St. Catherines over this interval.

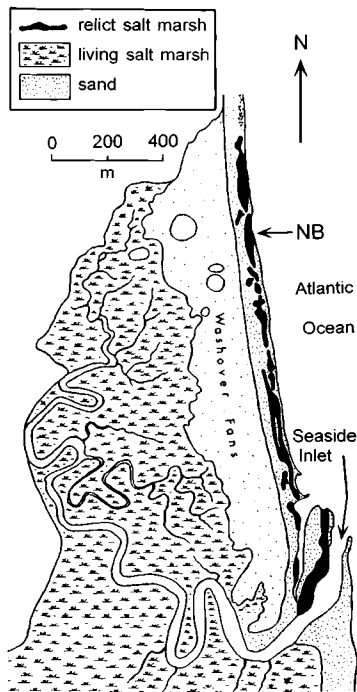


Figure 2. Part of the eastern shore of St. Catherines Island near the northern end (see Figure 1C for location), showing location of site NB, distribution of relict (dead) salt marshes on the ocean side of the barrier beach, overwash fans, and the living salt marsh landward of the overwash fans. (modified from MORRIS and ROLLINS, 1977).

We studied exhumed, dead salt marsh on the ocean side of the barrier beach at two localities, MB (Middle Beach) and NB (North Beach), on St. Catherines Island (Figure 1C). In addition, samples were analyzed from a third location, MI (McQueen Inlet), sampled in 1988 and 1990 by R. M. Busch and others (ROLLINS *et al.*, 1990). Radiocarbon dating was carried out on samples of *Spartina* and *Geukensia* to provide a calibration for Asp racemization in *Geukensia* for this area. The kinetics of Asp racemization (the form of the trend of D/L Asp with time) was established by laboratory heating experiments which mimic the pattern of racemization at lower, ambient temperatures over longer time periods (GOODFRIEND and MEYER, 1991). This provides a transform function which, when applied to D/L Asp values, linearizes them with respect to time. Additional information on beach retreat in the area was obtained from comparison of aerial photos of the area around NB taken in 1945 and 1990.

MATERIALS AND METHODS

Field work was carried out in August, 1991. Samples of *Geukensia*, *in situ* and in life position, and eroded stumps of *in situ* specimens of *Spartina* were collected from relict salt marshes on the ocean side of the barrier beach at sites MB (Middle Beach) and NB (North Beach) (Figure 1B). Sketches were made of the distribution of relict marsh at these localities and profiles of the ocean-side exposures were construct-

ed. Samples of *Geukensia* were also analyzed from a core taken in 1988 by R. Busch and H. Rollins through the barrier beach at site MI. A lithostratigraphic cross-section of the shore area was constructed, based on four cores and surveying of the profile along a transect at MI.

Radiocarbon analysis was carried out on salt marsh grass (*Spartina*) stumps from locality MB and oyster shells (*Crassostrea virginica*) from NB by liquid scintillation counting of benzene by Beta Analytic (Miami, FL). The *Spartina* sample was washed of sediments and treated with acid and alkali before combustion. Conventional radiocarbon analysis of a sample of *Geukensia* shells from the core was carried out by Geochron Laboratories (Cambridge, MA) after cleaning by ultrasonication and leaching with HCl. AMS radiocarbon analysis of the inner nacreous surface of a *Geukensia* shell (ground off with a Dremel tool after cleaning of the surface with HCl) from MB was performed by the NSF-Arizona AMS facility. All radiocarbon dates were corrected for isotopic fractionation based on measurements of the $^{13}\text{C}/^{12}\text{C}$ ratio. Calibration of the radiocarbon age for the *Geukensia* sample from MI was carried out using the CALIB 3.0 program (STUIVER and REIMER, 1993). Correction for the marine reservoir age was made assuming a ΔR value of 0 (based on data of STUIVER *et al.*, 1986) and error of ΔR of 0.

Samples of *Geukensia* for amino acid racemization analysis were cleaned either by light etching by HCl or mechanical removal of the surface using a motorized, hand-held Dremel tool with a fine, tapered tip. Samples (15–30 mg) were obtained from the middle nacreous layer of the shell* by gently grinding off shell powder from the inner surface of this layer (between the pallial line and the edge of the shell). Preparation procedures follow those of GOODFRIEND (1991). Hydrolysis was carried out in 6N HCl at 100° C for 20 hr. Samples were desalted using HF and derivatized to N-trifluoroacetyl isopropyl esters. Measurements of D/L Asp values were carried out with an HP5890 series II gas chromatograph equipped with a Chirasil-val column. Analysis of samples from live-collected specimens of *Geukensia* from Seaside Inlet on St. Catherines Island gave D/L Asp values of 0.050 (S.E. = 0.0015; n = 3). This represents the racemization induced by the preparation procedures. Analytical error averages 3% of the D/L value.

Heating experiments were carried out on pieces of the nacreous layer of live-collected *Geukensia* from Seaside Inlet (see Figure 2 for location). The outer prismatic layer of the margins of the shells (outside the pallial line) was ground away using a Dremel tool fitted with an abrasive tip. The remaining nacreous layer was cut into small pieces (10–20 mg) and several of these were used for each heating experiment sample. Experimental procedures follow those of GOODFRIEND and MEYER (1991) and involved putting the pieces on top of wet, sterile sand, in glass tubes, sealing them under nitrogen, and heating them at 80° C for varying periods of time (up to 20 d) in the oven of a gas chromatograph. After cracking open the tubes, the pieces were removed, sonicated

*For shell microstructure, see CARTER, 1990. Also cf. *Modiolus modiolus*, Table 6 in TAYLOR *et al.*, 1969.

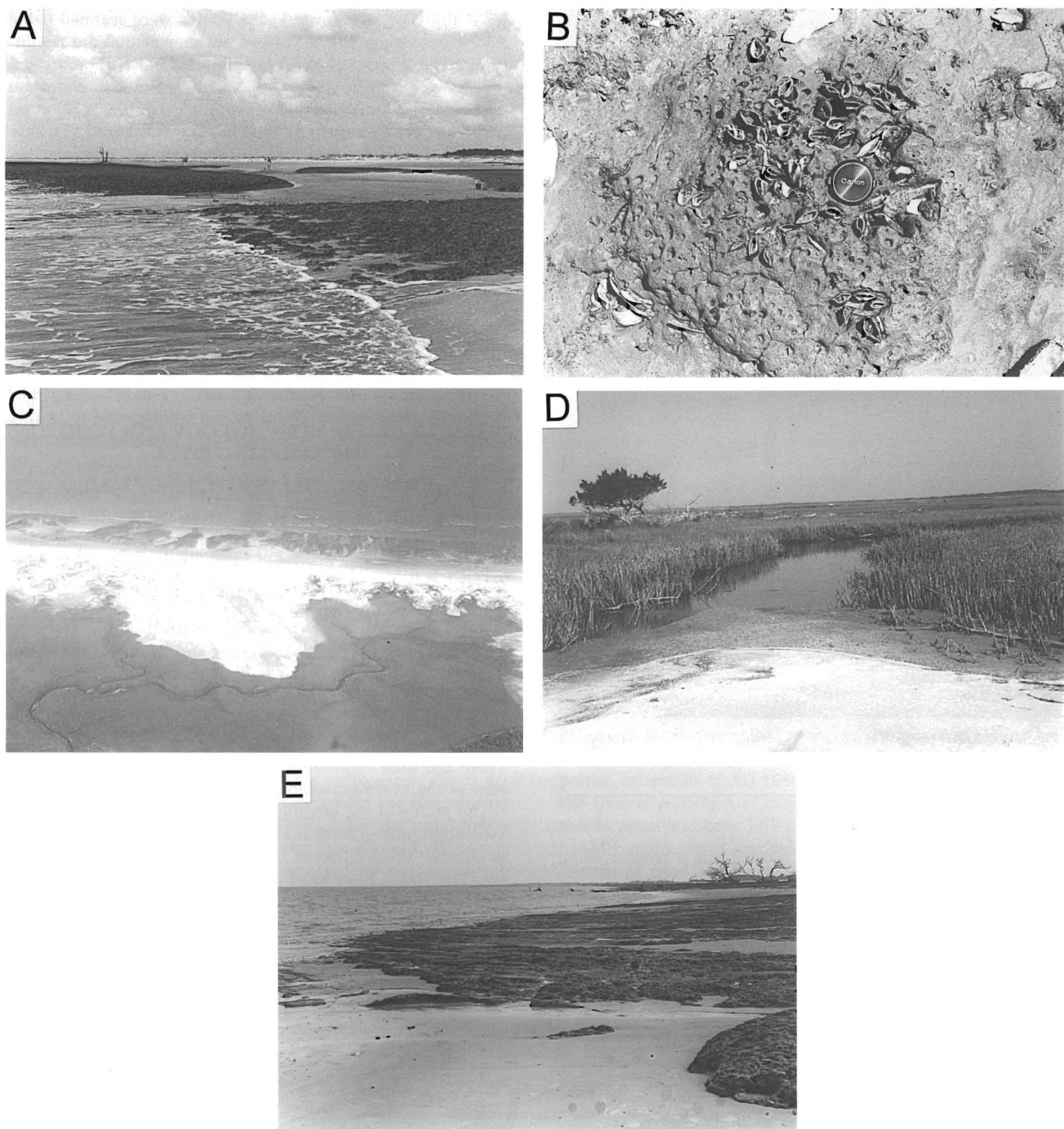


Figure 3. Photographs of St. Catherines Island shorelines. (A) Relict salt marsh muds (dark areas) exhumed on the ocean side of the island (seen in background) at North Beach (1977); a sand-filled relict tidal channel can also be seen between the marsh muds; (B) Dead, *in situ* shells of *Geukensia* in sand-draped marsh muds exhumed on the ocean side of the island at North Beach (1977); (C) Aerial photo, showing living salt marsh (foreground), overwash fans and present beach (light areas), and exhumed relict salt marsh (darker areas beyond beach) at North Beach (1987); (D) Landward edge of overwash fan showing burial of living salt marsh at South Beach (south of McQueen Inlet) (1977); (E) Exhumed relict salt marsh muds on ocean side of barrier beach at Middle Beach; note fallen trees representing the remnant of a hammock present here earlier (1986).



Figure 4. Aerial photo of the North Beach area of St. Catherines Island, taken in 1945. The location of the shoreline (upper edge of beach) as of 1990 is shown by the dark line.

with distilled water, dried, and ground into a powder using a small mortar and pestle.

Aerial photographs of the North Beach area of St. Catherines Island from 1945, 1963, and 1990 were obtained from the National Oceanic and Atmospheric Administration in Silver Spring, MD. In order to assess erosion and overwash de-

velopment at the NB study site, the 1945 and 1990 photos were analyzed as follows: 1) the photos were scanned using Adobe Photoshop and a flat-bed scanner at 300 dpi resolution; 2) the scanned photos were imported to ENVI (an image-processing software program); and 3) geometric distortion was removed by registration (warping), using a 1963 aerial photo as a base image. The 1963 photo was selected as a base image because it represents an approximate midpoint between the 1945 and 1990 photos and had a high resolution and large scale. Warping included identification and matching of common ground control points on the base photo and analyzed photos.

In order to provide a precise scale for the aerial photos, field measurement of the position of the seaward edge of the NB barrier beach was accomplished using a Total Station theodolite to measure a transect between two fixed points (identifiable in the 1990 aerial photo) extending from the center of a marsh hammock to the crest of the barrier beach.

BARRIER BEACH MORPHOLOGY AND POSITION OF SAMPLING SITES

The lithostratigraphic profile at site MI (as of 1988), from lower intertidal shoreface sands across the barrier beach to the living salt marsh, is shown in Figure 5. This shows the barrier beach sands overlying salt marsh muds, with living marsh occurring landward of the barrier beach. On the seaward side, the eroding salt marsh muds are exposed. Three layers containing dead *Geukensia* in life position are seen along the eroding edge of the muds and were also recovered from the core taken at the base of the beach sands on the seaward side. The surface layer of *Geukensia* represents those individuals killed and buried by the retreating barrier beach sands and now being exhumed on the seaward side. Their age thus represents the time at which the landward edge of the overwash sands transgressed this point.

The profile of the eroding seaward relict marsh muds and associated mussel beds at site MB are shown in Figure 6. As at site MI, three different layers of *in situ* mussels are present. The strata have been progressively peeled back by erosion to expose the subsurface mussel layers as a series of three wide steps, much as seen over a broader lateral extent at site MI. As at site MI, the age of the dead mussels and *Spartina* stumps (eroded remains of sheathing leaf bases) of

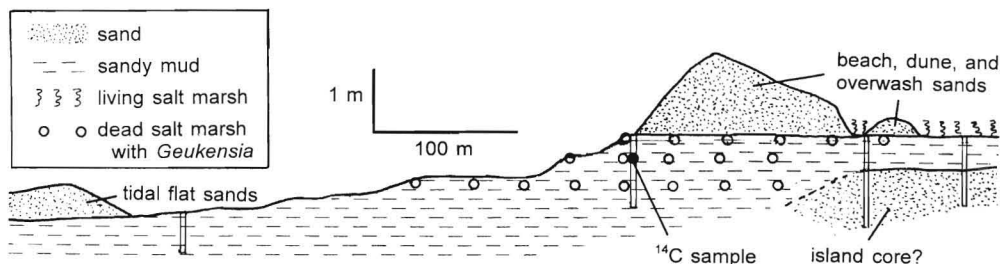


Figure 5. Cross-section through barrier island, east side of St. Catherines Island, and adjacent salt marsh at site MI. Arrows indicate exposed, eroding beds of dead, *in situ* mussels (*Geukensia*). Positions of 4 cores are indicated.

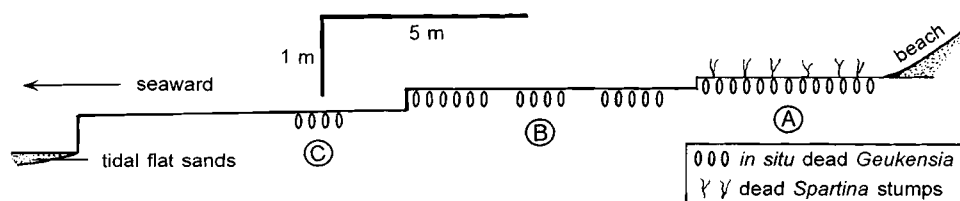


Figure 6. Profile of eroding relict salt marsh muds (with dead, *in situ* *Geukensia* and dead *Spartina* stumps, seaward of the barrier beach) at site MB. Sampling locations are indicated by circled letters. Scale is approximate.

the uppermost bed (A in Figure 6) represents the time that the landward edge of the overwash sands of the retreating barrier beach reached this point.

At site NB, a single layer of dead, *in situ* mussels is exposed, immediately adjacent to the seaward edge of the barrier beach. Patches of dead, *in situ* oysters (*Crassostrea virginica*), representing a former tidal creek channel, occur seaward of the mussels.

DATING OF THE RELICT MARSHES

Radiocarbon Dating

In situ mussel shells from the middle bed (B) at site MI (Figure 5) yielded a radiocarbon age of 545 (± 120) yr BP (Table 1). When this radiocarbon age is calibrated, a possible age range of AD 1660 to 1950 is obtained for the 1σ error and AD 1520 to 1950 for the 2σ error. Thus the shell predates the thermonuclear bomb tests of the late 1950s (it contains no bomb carbon) but could date to any time during the preceding 300 to 400 years. This illustrates the poor age resolution of radiocarbon for this time period, as discussed in the Introduction. Surface samples of *Crassostrea* from site NB give a younger age (370 (± 60) yr BP). This radiocarbon age is actually less (younger) than that expected for any time during the pre-bomb period (up to AD 1958), after the radiocarbon reservoir age of ca. 400 yr is taken into account. However, the age is greater (older) than expected for the post-bomb period. It suggests that the reservoir age may be overestimated for these shells (this point is discussed further below). In any case, radiocarbon analysis does little to resolve the age of these shells, except that they are probably less than 400 years old but pre-date the late 1950s.

More definitive age information is obtained from radiocarbon analysis of the dead stumps of *Spartina* grass in the sur-

face sample (A in Figure 6) of exhumed, dead salt marsh at site MB. These give a clear post-bomb radiocarbon activity of 127.3 (± 1.2) PMC (percent modern carbon). Because emergent aquatic plants derive their carbon from atmospheric rather than aquatic sources (DEEVEY *et al.*, 1954), they do not reflect the marine reservoir age and can be calibrated directly against the curve for atmospheric radiocarbon activity. Relatively detailed curves of post-bomb ^{14}C levels have been produced for Central Europe (away from major industrial inputs) from analysis of time series of atmospheric CO_2 samples (SEGL *et al.*, 1983) and of wine ethanol (MARTIN and THIBAUT, 1995) and for Asian Georgia by analysis of wine ethanol (BURCHULADZE *et al.*, 1989). From the initial thermonuclear bomb tests in the 1950s, atmospheric radiocarbon levels increased, reached a maximum in 1963, and have been decreasing since that time. Thus the observed level of 127.3 PMC for the *Spartina* sample could represent either of two periods: an earlier one when radiocarbon levels were increasing or a later one when they were decreasing. Curves for different locations differ slightly in details but give similar age estimates for the sample. For the earlier possible age, an estimate of AD 1960 (± 1) is obtained. For the later possible period, estimates of AD 1980 (± 1) is obtained. Therefore, at the time of collection of these samples (1991), the marsh at this location had been killed either 11 or 31 years before.

AMS radiocarbon analysis of the last (*i.e.*, most recent) growth of dead *Geukensia* shells associated with the dead *Spartina* stumps (at MB) shows that the younger age estimate for the death of the marsh (11 yr) must be the correct one. Because atmospheric bomb carbon mixed into the ocean relatively slowly, the first bomb carbon is detected in the oceans later. As of 1960, radiocarbon levels in the temperate northwestern Atlantic (as determined by analysis of annual growth bands of Florida corals) were ca. 97.5 PMC (DRUFFEL,

Table 1. Radiocarbon ages of samples from St. Catherines Island relict salt marshes.

Site	Depth (m)	Material	Radiocarbon Lab No.	^{14}C Age ^a	Calibrated Age (AD) ^b	
					1σ	2σ
MI	0.36	<i>Geukensia</i> (shell)	GX-16708	545 (± 120) yr B.P.	1660-1950	1520-1950
NB	surface	<i>Crassostrea</i> (shell)	Beta-72023	370 (± 60) yr B.P.	—	—
MB	surface	<i>Spartina</i> (grass)	Beta-93155	127.3 (± 1.2) PMC ^c	—	—
MB	surface	<i>Geukensia</i> (shell)	AA-22430	120.8 (± 0.6) PMC ^c	—	—

^aCorrected for isotopic fractionation

^bCorrected for marine reservoir age and calibrated (converted into calendric years)

^cPercent modern carbon

1996), indicating that the bomb carbon had by then only partially compensated for the marine reservoir age (prebomb levels were *ca.* 95 PMC). In 1980, Florida corals has radiocarbon levels of 113 PMC. Radiocarbon results for *Geukensia* from MB indicate a clear post-bomb signal (121 PMC; Table 1) and thus rule out the 1960 age. The age must therefore be 1980.

It should be noted that this radiocarbon level measured for *Geukensia* in Georgia is some 8 PMC higher than contemporary corals in Florida. In fact, the maximum post-bomb radiocarbon activity measured for Florida corals was 115 PMC, during the period 1969–1975 (DRUFFEL, 1996), still significantly lower than the value measured in Georgia *Geukensia*. This suggests that the shell carbonate carbon in *Geukensia* may not be entirely of marine bicarbonate origin but that some input of atmospherically-derived carbon also occurred. A partial atmospheric input is also the case for the conventional radiocarbon date of the *Crassostrea* sample, discussed above. Both of these bivalves live intertidally. Radiocarbon reservoir ages that are smaller than expected have also been observed for *Patella* gastropods (limpets) derived from the intertidal zone in Madeira (GOODFRIEND, CAMERON *et al.*, 1996) and in intertidal mussels (*Mytilus edulis*) from Calif I., Gulf of Maine (LITTLE, 1993). Results published for *Geukensia demissa* (misprinted as "*Geukensia elemissa*"; TANAKA *et al.*, 1990) from Branford, CT are ambiguous; the reservoir age is *ca.* 50 yr less than expected, but the analytical error is ± 150 yr.

There are several possible explanations for the presence of atmospherically-derived carbon in the shell carbonate of these taxa:

- (1) Some exchange of atmospheric CO₂ with the body fluid bicarbonate may occur during times of exposure.
- (2) The radiocarbon activity of ocean waters themselves may reflect enhanced mixing with the atmosphere within the intertidal zone.
- (3) Some CO₂ derived from metabolism of terrestrially-derived organic material (which has an atmospheric ¹⁴C signature) may be released into the bicarbonate pool.

This last explanation was suggested by TANAKA *et al.* (1990) for deviation of ¹⁴C reservoir ages of bivalve shells from water bicarbonate values. MCCONNAUGHEY *et al.* (1997) recently estimated from ¹³C measurements that aquatic mollusks derived *ca.* 10% of their shell carbonate carbon from metabolic sources. A simple mass-balance calculation for *Geukensia* (with a radiocarbon level of 121 PMC) deriving its carbon in 1980 from two sources, marine bicarbonate (at 113 PMC; DRUFFEL, 1996) and atmospheric CO₂ (at 129 PMC; BURCHULADZE *et al.*, 1989) indicates that, under this scenario, 50% of the mussel shell bicarbonate would be of atmospheric origin. It seems unlikely that such a large proportion of the shell carbonate carbon could be derived from metabolism of terrestrially-derived material. This points to exchange during exposure or enhanced mixing of atmospheric CO₂ into intertidal waters as the most likely explanations for the observed radiocarbon results.

Taken together, these observations indicate that the marine radiocarbon calibration may not be valid for organisms living in the intertidal zone—radiocarbon levels in this context are intermediate between marine and atmospheric val-

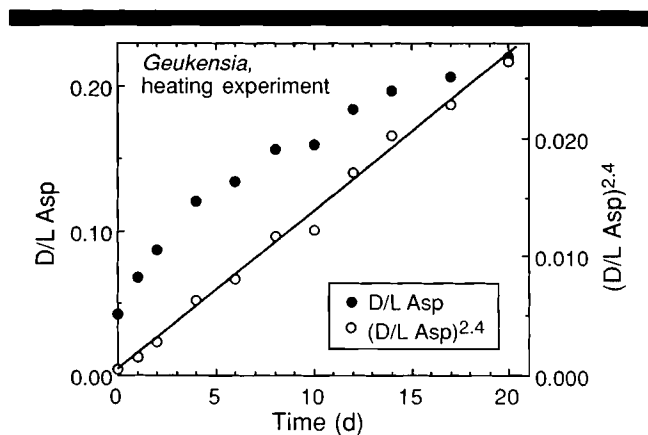


Figure 7. Aspartic acid racemization in the nacreous layer of *Geukensia* shells in heating experiments at 80° C. Raw data (solid symbols) were transformed to the 2.4 power to linearize them with respect to time (open symbols). Simple linear regression (line) gives an R² value of 0.99.

ues. Since marine radiocarbon reservoir age estimates are based primarily on analysis of mollusk shells (STUIVER *et al.*, 1986), this data base itself needs to be reexamined to evaluate to what extent the record may be biased by results for intertidal taxa.

Aspartic Acid Racemization Dating

Form of the Racemization Curve

The racemization of aspartic acid is not linear with respect to time in mollusk shells (as well as other materials) and the form of the curve differs for different taxa (GOODFRIEND, 1992; GOODFRIEND and HARE, 1995; GOODFRIEND *et al.*, 1995; GOODFRIEND, BRIGHAM-GRETTE, *et al.*, 1996). It is therefore necessary to establish the form of the racemization curve for *Geukensia* shells in order to use D/L values for estimation of ages. A series of nacreous layer samples were heated at 80° C for up to 20 days, up to a net D/L value** of 0.17 (measured value of 0.21). As is usual for racemization of aspartic acid, the curve shows a convex upward form (*i.e.*, the rate decreases with increasing D/L) (Figure 7, solid symbols). In order to linearize the D/L values with respect to time, the values were transformed by a power function. A best fit was obtained for the D/L value to the 2.4 power (R² = 0.993) (Figure 7, open symbols). Therefore, for purposes of age calculations, D/L aspartic acid values measured in subfossil samples were converted to (D/L)^{2.4}.

Racemization Rate and Equation for Calculation of Ages

If we accept the MB surface *Geukensia* samples (A) as being 11 yr old, as discussed above, then we can use the D/L Asp values measured for these samples to calculate the rate of

**The net D/L value is the difference between the measured value of a sample and the racemization induced by the preparation procedure, as measured in live-collected, unheated shell samples.

Table 2. *D/L aspartic acid values for the nacreous layer of mussel shells (Geukensia) from St. Catherines Island. Ages are estimated from equation 2.*

Site	Sample	No. of Individuals (no. of analyses)	\bar{X} of D/L	C.V. ^a of D/L (%)	Estimated Age	
					(yr B.P.)	(AD)
MI	A	3 (3)	0.084	6.8	9	1982
	B	3 (3)	0.253	7.3	170	1821
MB	A	5 (8)	0.090	6.6	11 ^b	1980 ^b
	B	3 (3)	0.122	12.2	27	1964
	C	5 (5)	0.138	4.5	37	1954
NB		6 (15)	0.159	11.4	53	1938
SSD	live	3 (3)	0.050	3.0	0	1991 ^c

^aCoefficient of variation (=S.D./ \bar{X} × 100%); where more than one measurement was made on an individual, the mean value for that individual was used in calculating the S.D.

^bAge assumed from radiocarbon analyses

^cDate of collection of live samples

Asp racemization. Eight analyses of five samples of *Geukensia* from MB (A) give a measured D/L value of 0.090 (Table 2). Conversion to the 2.4 power and subtraction of the induced racemization ($0.050^{2.4} = 7.543 \times 10^{-4}$) gives a transformed net value of 2.338×10^{-3} . Dividing by 11 yr gives a rate of 2.125×10^{-4} /yr. So

$$(D/L^{2.4} - 7.543 \times 10^{-4}) = 2.125 \times 10^{-4} t, \quad (1)$$

where t is the age in years before present. Rearranging this to solve for t, we obtain the following equation which can be used for calculation of ages from measured D/L values of *Geukensia*:

$$t = 4706 (D/L^{2.4} - 7.543 \times 10^{-4}). \quad (2)$$

D/L Asp Values and Age Estimates for *Geukensia* Samples

Table 2 gives the D/L Asp values for *Geukensia* samples analyzed from the three study sites, plus the values measured in live-collected specimens. At MB, racemization shows a progressive increase from 0.09 to 0.14 with increasing depth in the 3 exposed *Geukensia* beds. Based on an AD 1980 age for the uppermost bed, the middle and lower beds are dated at 27 and 37 yr, respectively, or AD 1964 and 1954. Thus, bed B persisted for only ca. 10 yr before it was buried by salt marsh muds and bed A persisted for ca. 16 yr before being buried by overwash fan sands from the barrier beach. At site NB, the dead *Geukensia* bed exposed by the retreating barrier beach shows a higher racemization (0.16) than any of the beds at MB; the time of death of the NB bed from burial by overwash fan sands is estimated at 53 yr ago, or ca. AD 1938. At site MI, the surface layer (sample A) of *Geukensia* (i.e., those killed by the retreating beach) have D/L Asp values similar to or slightly lower than the surface samples at MB. Calibration of the mean D/L value gives an estimated date of 1982 for these shells but D/L values of individual shells overlap between sites (compare the coefficients of variation, Table 2). Thus the apparent slight age difference may be insignificant—the mussels may have been killed by the same over-

wash event at these two sites. A significantly older age is seen in the second layer at MI (sample B). Here the *Geukensia* shells, dated by radiocarbon to AD 1520-1950, have average D/L Asp values of 0.25, which yields an estimated age of 170 yr (ca. AD 1821).

ANALYSIS OF AERIAL PHOTOS AT NB

Analysis of 1945 and 1990 aerial photos of the NB area (Figure 4) shows that during this interval, the seaward edge of the barrier beach has retreated some 173 m, or an average of 3.8 m/yr. In contrast, the landward edge of the overwash fan maintains nearly the same position, indicating that overwash fans have not penetrated past this point since 1945, despite the extensive erosion on the seaward side of the barrier island.

DISCUSSION OF BEACH RETREAT HISTORY

Based on the data presented above, we can summarize the pattern of barrier beach retreat on St. Catherines Island as follows. At North Beach, an overwash event in the late 1930s or early 1940s killed off salt marsh which, as of 1991, was being exhumed on the ocean side of the barrier island. Records of coastal storm tracks indicate that several major storms achieved landfall near St. Catherines Island in the period 1935-1944 (Purdue Weather Internet Site, 1996). Overwash sands from one of these events likely killed and buried the marsh and *Geukensia* beds at NB. Before the late 1930s, the barrier beach at NB was heavily vegetated; remnants of this vegetation are visible in the 1945 aerial photo (Figure 8). No overwash events more extensive than this event in the late 1930s or early 1940s have occurred in this area since that time. In the meantime, the seaward edge of the barrier beach has been retreating at an average rate of nearly 4 m/yr. Thus the barrier beach has become considerably narrower in this area over this time period. At Middle Beach and McQueen Inlet, overwash events occurred as recently as ca. 1980. Overall beach retreat rates for the period 1897-1975 are ca. 3 m/yr at Middle Beach, according to the data of OERTEL and CHAMBERLAIN (1975) for their nearby site Sc5. For the McQueen Inlet site, OERTEL and CHAMBERLAIN (1975) record an overall retreat rate of ca. 8 m/yr for the same period but with the great majority of the observed retreat occurring prior to 1952.

Thus, considerable differences are seen among sites with respect to the timing of the landward advance of the barrier beach. Whereas the MI and MB sites show landward incursion of overwash fans across the salt marsh around 1980, no evidence of landward advance is seen at NB since the last event in the 1930s or early 1940s. This spatial heterogeneity has several explanations. First, the presence of wooded hammocks tends to temporarily retard erosion on the ocean side and thus reduce the probability of overwash events. At MB, a hammock present along the shoreline in the early 1970s had been eroded away by the early 1980s, with only partially-rooted trees remaining behind in the surf zone (Figure 8E). Thus, until that time, this area was partially protected from storm events producing overwash. It was only after the loss of this hammock that overwash events are recorded here, in

ca. 1980. The presence of sand bars or shoals offshore may also affect barrier beach dynamics (OERTEL, 1977). In the case of site MI, some protection from overwash events may be afforded by the large ebb tidal delta located to the south.

CONCLUSIONS

This study introduces the methods of aspartic acid racemization analysis and post-bomb radiocarbon analysis to the study of recent coastal dynamics. We show that these methods can be used to obtain ages of overwash events and salt marsh accretion occurring within the past two centuries. The geological record can thus be used to reconstruct barrier beach behavior prior to historical records but more recently than can be analyzed by conventional radiocarbon methods (*i.e.*, prior to ca. AD 1650). Development of a racemization rate calibration for a given area and species of mollusk shell involves a considerable amount of work. However, once this rate is established, large numbers of dates can be readily obtained from racemization analysis, thus allowing detailed spatial and temporal analysis.

Results obtained from the recent geological record of relict salt marsh, exhumed on the ocean side of the retreating barrier beach, agree well with evidence obtained from aerial photos of the area dating back to 1945. They show significant spatial differences in the timing of overwash events on the island, which may relate to heterogeneity of the coast (presence of wooded hammocks and a delta). Retreat of the oceanic side of the barrier beach has outpaced landward extension of the barrier beach by overwash fans, thus leading to a considerable narrowing of the barrier beach since the late 1930s. The coast in this area is unmodified by jetties or other man-made structures, so the sedimentary dynamics along the coast are unaffected (unlike, for example, the situation in the Sea Islands in southern Georgia and northern Florida; BYRNES and HILAND, 1995). However, retreat of the coast may relate to a reduction in the sediment supply to the area. Further contributing to sediment starvation is the fact that shoreface erosion is primarily acting upon relict marsh muds, which supply no new sands to the coastal sediment budget as erosion progresses.

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