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Quaternary Climates and Sea Levels of the U.S. Atlantic Coastal Plain

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Summary. Uranium-series dating of corals from marine deposits of the U.S. Atlantic Coastal Plain coupled with paleoclimatic reconstructions based on ostracode (marine) and pollen (continent) data document at least five relatively warm intervals during the last 500,000 years. On the basis of multiple paleoenvironmental criteria, we determined relative sea level positions during the warm intervals, relative to present mean sea level, were 7 ± 5 meters at 188,000 years ago, 7.5 ± 1.5 meters at 120,000 years ago, 6.5 ± 3.5 meters at 94,000 years ago, and 7 ± 3 meters at 72,000 years ago. The composite sea level chronology for the Atlantic Coastal Plain is inconsistent with independent estimates of eustatic sea level positions during interglacial intervals of the last 200,000 years. Hydroisostatic adjustment from glacial-interglacial sea level fluctuations, lithospheric flexure, and isostatic uplift from sediment unloading due to erosion provide possible mechanisms to account for the discrepancies. Alternatively, current eustatic sea level estimates for the middle and late Quaternary may require revision.

Recent Quaternary paleoclimate studies have focused mainly on isotopic (*1*), paleontologic (*2-4*), and lithologic (*5*) data from deep-sea cores and isotopic studies of speleothems (*6, 7*). These investigations yielded quantitative data for understanding patterns of Quaternary climatic variation culminating in a global climatic reconstruction at glacial maximum 18,000 years ago (*8*) and a demonstrated statistical association linking changes in earth orbital parameters with Quaternary interglacial-glacial transitions (*9*). The magnitude and age of resulting glacio-eustatic sea level fluctuations have been estimated from integration of uranium-disequilibrium-series dating of coral terraces (*10-12*) and fluctuations in oxygen isotope (^{18}O) values in deep-sea sediments. These fluctuations have been attributed to changes in ocean volume (*13, 14*).

Yet until recently (*15, 16*), continental margins have been neglected in combined sea level and paleoclimatic studies. We selected the emerged southern Atlantic Coastal Plain of Virginia and North and South Carolina (Fig. 1) to investigate middle and late Pleistocene (*17*) climates and relative sea levels because: (i) extensive surface and shallow subsurface mapping provides a lithostratigraphic framework (*18*); (ii) relatively accurate sea level indicators are available (*19*); (iii) paleo-oceanography can be reconstructed from ostracode zoogeography; (iv) pollen preserved in marine deposits yields climatic data for the adjacent continent; (v) corals suitable for uranium-series dating are preserved; and (vi) results can be compared with paleoclimatic reconstructions of the adjacent open ocean North Atlantic (*20*) and can be related to continental ice sheet growth and decline in the Northern Hemisphere.

Regional Geology and Coral Ages

Pleistocene Coastal Plain geologic history records marine transgressive-regressive cycles in sediments deposited in brackish water and marine environments (*21, 22*). The landward limit of each sequence is marked by an erosional scarp, brackish water deposits, barrier islands, and beach and other shoreline deposits. Seaward of these paleo shorelines are level to gently inclined (1° to 2°) plains commonly referred to as terraces. Stratigraphic unconformities mark periods of emergence between successive high stands of sea level. Early attempts to correlate transgressions solely by shoreline elevation (*23*) assumed complete tectonic stability and met with criticism because some geomorphic features appear to be tectonically warped (*18, 24*).

Lithologic sections of 12 studied localities are shown in Fig. 2; locality and paleontologic data for each section are given in Table 1. Except for material from locality 6, our data come from areas where lithostratigraphic relationships among transgressive sequences have been studied. However, stratigraphic nomenclature is in a state of confusion in parts of the Atlantic Coastal Plain (*18, 25*) mainly because of a proliferation of local morpho-, litho-, and biostratigraphic terms, many of which have been vaguely or improperly defined and subsequently misused or misinterpreted. This nomenclature problem is especially acute with regard to "terrace formations" (*21, 23*) that were originally named for a geomorphic surface, not a lithologic unit. We prefer not to reconcile stratigraphic problems nor to perpetuate the use of convenient and well-known, but ambiguous or improper, stratigraphic names. In this article, we do not use terrace formation terms, but only clearly delineated lithostratigraphic terms.

With the exception of deposits at locality 8C (Table 1), which are early Pleistocene, all sampled units are middle and late Pleistocene in age (*18, 22*) as judged by field relations, several lines of biostratigraphy (*22, 26*), and preliminary

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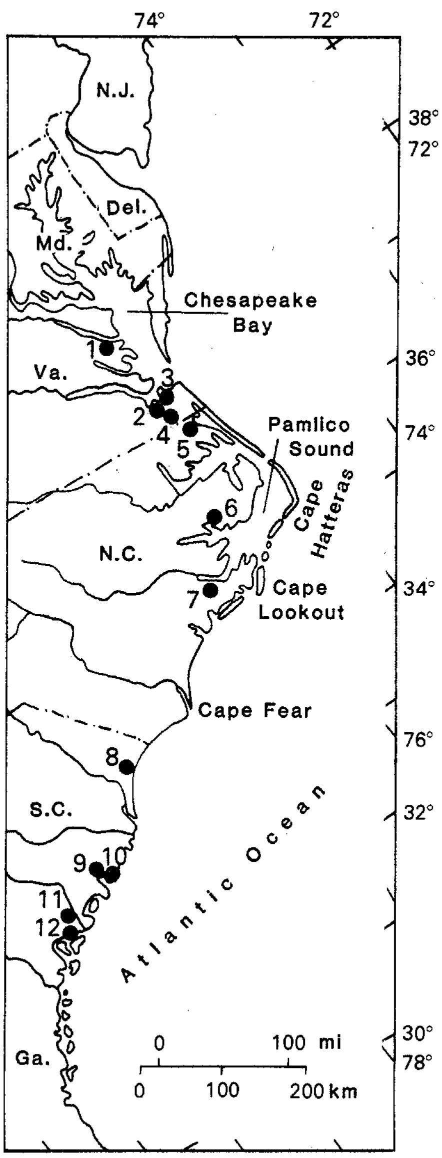
magnetostratigraphy (27). To improve dating of these units, we relied on uranium-disequilibrium-series dating on fossil corals. This technique has been widely used for dating Pacific and Caribbean coral reef terraces (11, 12) and corals and oolites from Florida (28). Our dated corals were preserved in clastic sediments of inner sublittoral depositional environments, not in limestone reefs, and hence we use corals solely to date transgressions, not to estimate the elevations of paleo sea levels.

Coral samples were ultrasonically cleaned in water, ground to fine powder, and ashed at 900°C for about 6 hours. Uranium and thorium percentages and the activity ratios of ^{234}U to ^{238}U and ^{230}Th to ^{234}U were determined by alpha-spectrometry measurements from a combined spike solution of ^{236}U, ^{229}Th, and ^{228}Th (29). Analytical results and coral ages are presented in Table 2. Fourteen uranium-series dates yielded the following clusters of coral ages: (i) more than 400,000 years old (localities 7 and 8), (ii) about 188,000 years old (localities 1 and 6); about 120,000 years old (locality 11); about 94,000 years old (localities 9, 10, and 12); and (v) about 72,000 years old (localities 2 to 5).

Ostracodes and Pollen: Paleoclimatic Tools

Oceanic paleoclimate studies rely on planktic floras and faunas to reconstruct sea-surface temperatures (2–4, 30, 31); continental studies emphasize pollen (32). Ostracodes are benthic, shelled Crustacea, which traditionally are used for biostratigraphy but more frequently are being used in freshwater (33) and marine continental shelf (34–36) paleoclimatic reconstructions. Many species have zoogeographic distributions limited by the water temperatures necessary for their reproduction and survival (37, 38). North Atlantic ostracode faunas migrated south several hundred kilometers in response to climatic cooling associated with the Wisconsin glaciation (34, 36). This migration demonstrates the temperature sensitivity of marine ostracodes and underscores their paleoclimatic potential, particularly along continental margins where they are widely preserved as fossils and where planktic groups are rarely preserved. Five faunal provinces have been defined in the western North Atlantic. Four of these provinces correspond to modern frigid, subfrigid, mild temperate, and subtropical marine climatic zones (35, 37, 38). A warm temperate zone, in evidence in Virginia during the late Pleistocene (35) (localities 2, 3, and 5 in our study), is missing today due to strong isothermal convergence at



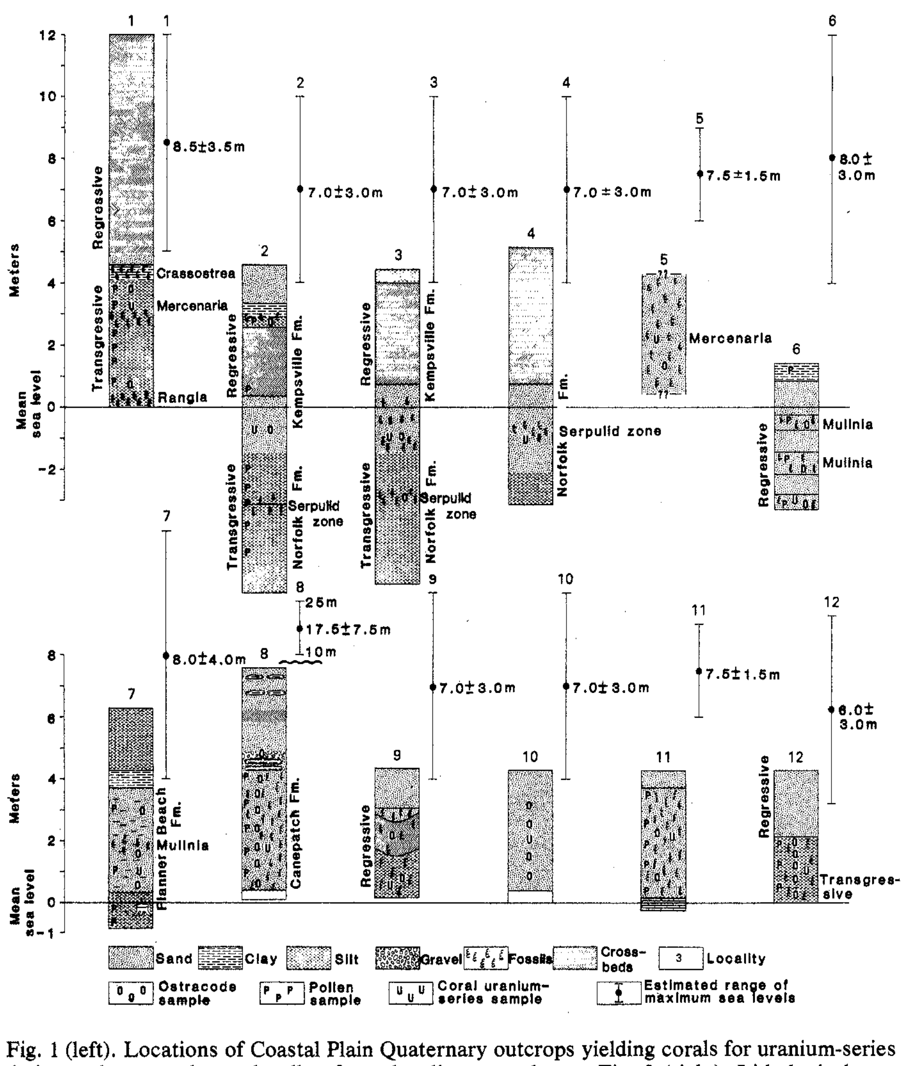


Fig. 1 (left). Locations of Coastal Plain Quaternary outcrops yielding corals for uranium-series dating and ostracodes and pollen for paleoclimate study. Fig. 2 (right). Lithological sections, elevation, estimated range of maximum sea levels, and location of ostracode pollen and coral samples for 12 studied localities. Section for locality 5 had to be inferred from dredged material because the pit was filled with water, and the coral from this locality was not in place. Predominant molluskan genera are given for some beds.

Table 1. Climate, environment, age, and locality data for middle and late Quaternary material, U.S. Atlantic Coastal Plain.

Locality					Elevation of fossils (m)	Marine environment*		Continental environment†		Uranium-series age (years)
No.	Name	Formation	Latitude (°N)	Longitude (°W)		Ostracode biofacies	Climatic zone	Major pollen type	Climatic interpretation	
1‡	Norris Bridge, Va.	Unnamed	37°38′00″	76°24′30″	0.3 to 2.4	Inner sublittoral (estuarine)	Subtropical	Oak, pine, hickory	Warm temperate to humid subtropical (interglacial)	187,000 ± 20,000
2‡	New Light, Va.	Norfolk	36°48′00″	76°11′15″	−1.1 to 1.8	Inner sublittoral	Warm temperate, sub-tropical	Oak, pine, hickory	Warm temperate to humid subtropical (interglacial)	74,000 ± 4,000
3‡	Womack, Va.	Norfolk	36°58′30″	76°10′20″	−2.1 to 0.6	Inner sublittoral	Warm temperate	No data		62,000 ± 4,000
4	Mears, Va.	Norfolk	36°47′15″	76°11′45″	0.0	No data	No data	No data		75,000 ± 5,000
5§	Moyock, N.C.	?Norfolk	36°30′30″	76°09′00″	1.5 to 3.0	Lagoon to open sound	Warm temperate	No data		72,000 ± 4,000
6	Ponzer, N.C.	Unnamed	35°33′00″	76°26′30″	3 0 to 0.0	Inner sublittoral to open sound	Warm temperate, sub-tropical	Oak, pine, hickory with spruce, hemlock	Warm temperate with boreal influence (transitional: glacial-interglacial)	189,000 ± 15,000
7	Flanner Beach, N.C.	Flanner Beach	34°58′45″	76°56′45″	0.3 to 2.1	Open sound	Subtropical	Oak, pine, bald cy-press, hickory	Warm temperate to humid subtropical (interglacial)	> 500,000
8A‖	Canepatch, S.C.	Canepatch	33°46′00″	78°49′00″	0.6 to 5.5	Inner sublittoral	Subtropical	Pine, oak, hickory with spruce, hemlock	Warm temperate with boreal influence (transitional: glacial-interglacial)	$^{230}Th = 560{,}000^{+\infty}_{-190{,}000}$; $^{234}U = 440{,}000 \pm 140{,}000$
8B‖	Canepatch, S.C.	Canepatch	33°46′00″	78°49′00″	2.3 to 6.2	Inner sublittoral	Subtropical	Oak, pine, hickory	Warm temperate to subtropical (interglacial)	$^{230}Th = 376{,}000^{+201{,}000}_{-68{,}000}$; $^{234}U = 440{,}000 \pm 140{,}000$
8C‖	Canepatch, S.C.	Waccamaw	33°46′00″	78°49′00″	1.0 to 2.3	Inner sublittoral	Subtropical	Oak, pine, hickory	Warm temperate to subtropical (interglacial)	$^{230}Th > 424{,}000$; $^{234}U = 740{,}000^{+360{,}000}_{-210{,}000}$
9	Venning, S.C.	Unnamed	32°48′45″	79°50′30″	0.0 to 1.5	Inner sublittoral	Subtropical	No data		94,000 ± 6,000
10	Mount Pleasant, S.C.	Unnamed	32°49′30″	79°49′30″	0.0	No data	No data	No data		96,000 ± 6,000
11	Mark Clark, S.C.	Unnamed	32°49′30″	80°01′35″	−1.0 to 0.0	Open sound to inner sub-littoral	Subtropical	Oak, pine, hickory, birch	Warm temperate to humid subtropical (interglacial)	120,000 ± 6,000
12	Scanawah Island, S.C.	Unnamed	32°33′30″	80°21′30″	0.0 to 1.2	Inner sublittoral to oyster bank	Subtropical	Oak, pine, hickory, black gum	Warm temperate to humid subtropical (interglacial)	93,000 ± 6,000

*Inferred from modern ostracode zoogeography. †Inferred from pollen assemblages. ‡In R. Mixon *et al.*, in preparation. §Coral not in place, collected from spoil pile. ‖Sample A from 0.5 km upstream from samples B and C. Sample B from the Canepatch Formation. Sample C from the Waccamaw Formation, unconformably underlying the Canepatch Formation.

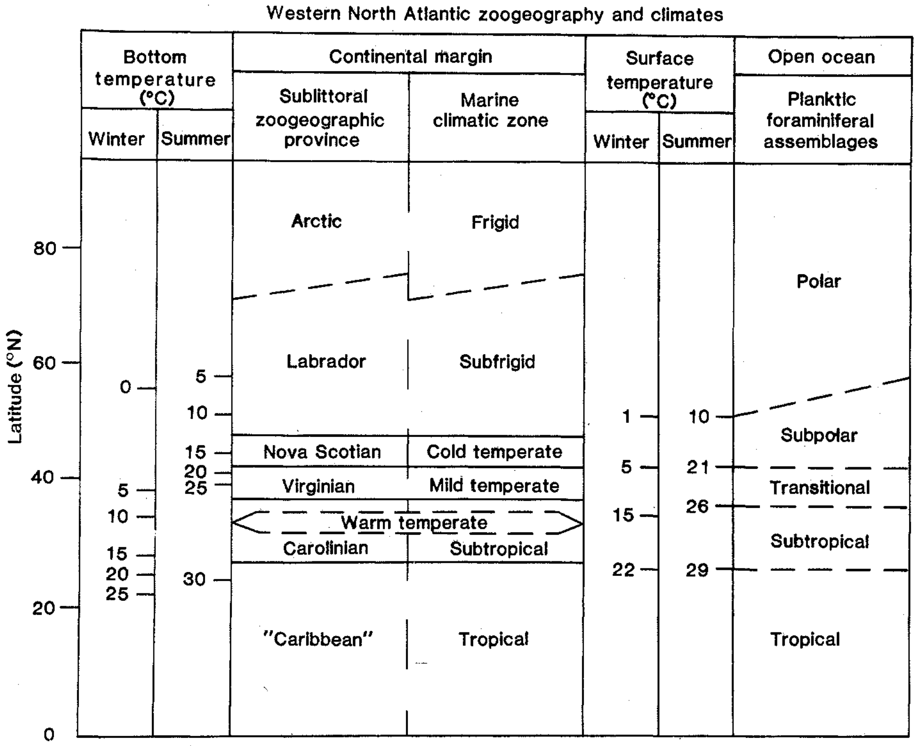


Fig. 3. Modern zoogeographic provinces and marine climate zones of the western North Atlantic. Sublittoral zoogeography and climate zones are adopted from Hazel (*38*). Planktic foraminiferal open-ocean data are summarized from Imbrie and Kipp (*2*) and Kipp (1976) (*31*); boundaries between assemblages are approximate. Winter (February) and summer (August) mean sea-surface temperatures of the open ocean are taken from (*62*). These temperatures were measured in the southwestern North Atlantic at the following latitudes and longitudes: 50°N, 50°W; 42°N, 60°W; 35°N, 70°W; and 26°N, 75°W. This figure shows only a rough correlation between open-ocean and sublittoral climatic zones. Warm temperate zone does not exist today because of strong isothermal convergence on the shelf at Cape Hatteras.

Cape Hatteras. The known modern distribution of ostracodes in these provinces serves as the ecological data base for our study (*35, 37, 38*). In Fig. 3, we relate this sublittoral scheme to the open ocean classification (*2–4, 30, 31*), which is based on modern distributions of North Atlantic planktic foraminifers.

Paleotemperature estimates of all dated ostracode assemblages consistently indicate oceanic bottom-water temperatures as warm or warmer than present interglacial temperatures offshore at the same latitude (Fig. 3) (*35*). The localities yielding coral ages older than 400,000 years (localities 8, A and B), which are south of Cape Hatteras in a modern subtropical climatic zone, also yielded samples with subtropical ostracode assemblages. Our localities dated at 188,000 years (localities 1 and 6) are north of Cape Hatteras in a modern mild temperate zone, and they contain marine subtropical fossil assemblages. We interpret this northward migration of thermophilic ostracode species as a reflection of incursions of warm water, probably from the Gulf Stream, into the present Pamlico Sound and Chesapeake Bay regions during an interglacial interval. Rare temperate species (*39*) at locality 6 may signify a minor cooling in this region, but this interpretation needs further confirmation. In South Carolina, our locality dated at 120,000 years (locality 11) and the three localities with ages clustering at 94,000 years (localities 9, 10, and 12) contain subtropical assemblages signifying warm interglacial climates. Several undated localities near Charleston, which we interpret to be correlative with the transgression at 94,000 years, contain ostracode species known only from the Gulf of Mexico (*35*). Their occurrence in the Atlantic Coastal Plain implies faunal interchange with the Gulf and winter water temperatures slightly higher than those off South Carolina today. In southern Virginia and northern North Carolina, three of the four localities with ages averaging 72,000 years (localities 2, 3, and 5) contain warm temperate ostracode assemblages, indicative of temperatures higher in winter and comparable in summer to present temperatures, which represent mild temperate conditions (Table 1 and Fig. 3).

Fossil pollen and spores from samples of unoxidized clay, clayey sand, and peat collected from the coral- and ostracode-bearing deposits provide insight into contemporaneous onshore vegetation environments and climates. The pollen data provide some of the first documentation for pre-Sangamonian (earlier than isotope stage 5) Pleistocene interglacial vegetation of the southern Atlantic Coastal Plain. Previous investigators of pollen-bearing deposits of the region (*40–42*) presumed these deposits were Sangamonian in age. Two such deposits (the Canepatch and Flanner Beach Formations) now appear to be middle Pleistocene in age.

A variety of environments, including salt marsh, coastal and fluvial swamps, and coastal plain forests, are represented in the pollen assemblages. With two exceptions (localities 6 and 8A), all samples yielded interglacial pollen assemblages similar to late Holocene pollen assemblages from the same region. The interglacial fossil floras include primarily oak (*Quercus*), pine (*Pinus*), and hickory (*Carya*) pollen, and usually smaller percentages of taxa such as sweet gum (*Liquidambar*), black gum (*Nyssa*), birch (*Betula*), and others. This pollen assemblage suggests a warm and humid temperate to subtropical climate similar to that existing today in the Atlantic Coastal Plain of South Carolina, North Carolina, and Virginia (*43*). Further, the pollen data support the interpretation that past high stands of sea level for the southern Atlantic Coastal Plain coincided with warm, interglacial terrestrial climates.

The only exceptions to the pattern of interglacial pollen assemblages are samples from localities 6 and 8A which, in addition to pollen of oak, pine, hickory, and other common deciduous trees, contain small amounts (generally less than 2 percent each) of spruce (*Picea*) and hemlock (*Tsuga*) pollen. Studies of Wisconsinan age deposits in the study region (*40, 44–46*) indicate that boreal elements such as spruce (probably predominantly white spruce, *Picea glauca*), hemlock, and jack pine (*Pinus banksiana*) migrated far south of their present distributions and became important elements of the regional vegetation of the southern Atlantic Coastal Plain. Red spruce (*Picea rubens*) and hemlock (*Tsuga canadensis* and *T. caroliniana*) now grow in parts of the central and southern Appalachians (*47*). The presence of small amounts of spruce and hemlock pollen with the predominant oak-pine-hickory assemblage from localities 6 and 8A indicates temperate climates, cooler than those of today but warmer than a full glacial climate. These data and the occurrence of temperate ostracode species at locality 6 suggest a transitional climate, intermediate between glacial and interglacial.

Relative Paleo Sea Level

We estimated the ranges of maximum relative paleo sea levels above mean sea level (ASL) for each locality using various shoreline criteria (Fig. 2). Sea level ranges were then determined for each of the coral age clusters at 440,000, 188,000, 120,000, 94,000, and 72,000 years ago from sea level ranges of each locality in each cluster. About 440,000 years ago (localities 8, A and B) in northeastern South Carolina, maximum sea level was between 10 and 25 meters ASL as judged by faunal paleodepth estimates (*19*) and barrier island deposits. Paleontologic evidence, including the presence of *Callianassa* burrows, nearshore faunal assemblages from southeastern Virginia (locality 1), and *Mulinia*-rich deposits in central North Carolina (locality 6), indicate a range of sea levels between 2 and 12 m ASL. Locality 11, dated at 120,000 years ago, contains a fauna in-

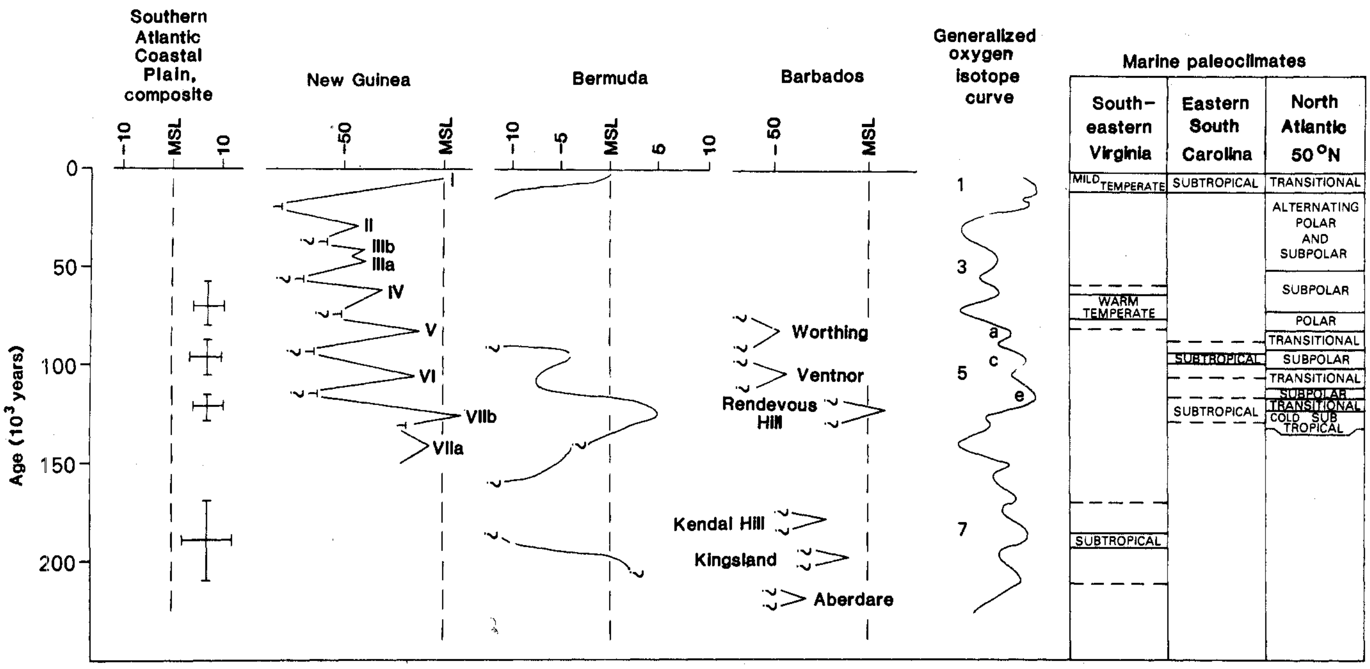


Fig. 4. U.S. Atlantic Coastal Plain sea levels and marine paleoclimates compared with New Guinea (*11*), Bermuda (*7*), and Barbados (*14*) sea level chronologies and North Atlantic (*4*) paleoclimatic history at 50°N. Fairbanks and Matthews (*14*) assigned an arbitrary error value of +20 m on all Barbados sea levels except Rendevous Hill. For Bermuda, not all speleothems of Harmon *et al.* (*7*) are shown. The U.S. Coastal Plain data show the estimated range of maximum sea levels for four uranium-series age clusters and analytical error for dates. This is a composite figure representing several geographic regions that may have different tectonic histories. Under the marine paleoclimates column, the range of uranium-series ages for each cluster is given by solid lines; the analytical errors by dashed lines. Abbreviation: *MSL*, mean sea level.

Table 2. Analytical data and uranium-series ages of fossil corals from deposits of the southeastern Atlantic Coastal Plain.

Locality	Coral genus*	Calcite (%)	Uranium (ppm)	Activity ratios $^{234}U/^{238}U$	Activity ratios $^{230}Th/^{232}Th$	Activity ratios $^{230}Th/^{234}U$	Age (10^3 years)
				~ 72,000-year-old deposits			
3	A	< 3	2.53 ± 0.02	1.09 ± 0.02	15.0	0.436 ± 0.017	62 ± 4†‡
2	A	< 3	2.64 ± 0.03	1.10 ± 0.02	25.0	0.500 ± 0.020	74 ± 4†
5	A	< 3	2.98 ± 0.04	1.10 ± 0.02	39.0	0.487 ± 0.019	72 ± 4†
4	A	< 3	2.44 ± 0.05	1.11 ± 0.02	24.0	0.524 ± 0.021	79 ± 5†
				~ 94,000-year-old deposits			
10	A	< 3	3.42 ± 0.07	6.11 ± 0.12	2.0	0.594 ± 0.024	96 ± 6†§
12	A	< 3	2.79 ± 0.04	1.09 ± 0.02	2.0	0.581 ± 0.023	93 ± 6†§
9	A	< 3	2.66 ± 0.04	1.07 ± 0.02	7.1	0.586 ± 0.023	94 ± 6†§
				~ 120,000-year-old deposits			
11	A	< 3	2.86 ± 0.04	1.09 ± 0.02	13.0	0.677 ± 0.020	120 ± 6†
				~ 188,000-year-old deposits			
1	A	< 3	2.27 ± 0.04	1.06 ± 0.02	11.0	0.832 ± 0.033	187 ± 20†
6	A	< 3	2.69 ± 0.04	1.07 ± 0.02	80.0	0.837 ± 0.025	189 ± 15†
				> 400,000-year-old deposits			
8A	S	< 3	2.50 ± 0.02	1.04 ± 0.01	14.0	1.01 ± 0.03	560 + ∞, −190† (440 ± 140)‖
8B	S	< 3	2.99 ± 0.04	1.04 ± 0.01	160.0	0.982 ± 0.029	376 + 201, −68† (440 ± 140)‖
8C	S	< 3	2.62 ± 0.03	1.017 ± 0.010	500.0	1.017 ± 0.030	> 424†; 740 + 360, −210‖
7	S	< 3	2.70 ± 0.04	1.02 ± 0.02	55.0	1.04 ± 0.04	> 500†

*Coral genera: A is *Astrangia* sp. and S is *Septastrea* sp. †The ^{230}Th ages were calculated from half-lives of ^{230}Th and ^{234}U of 75,200 and 244,000 years, respectively. ‡The ^{231}Pa age is 64,000 ± 8,000 years. §The ^{230}Th age, corrected for initial ^{230}Th contamination from the $^{230}Th/^{234}U$ versus $^{232}Th/^{234}U$ isochron plot (*60*), is 94,000 ± 6,000 years. ‖The ^{234}U ages were calculated from the average $^{234}U/^{238}U$ ratio in Atlantic Ocean waters of 1.14 ± 0.02 (*61*) by

$$T = \frac{1}{\lambda_{234}}\left[-\ln\frac{(^{234}U/^{238}U)\ \text{sample} - 1}{1.14 - 1}\right]$$

dicating that paleo sea levels were between 6 and 9 m ASL. At 94,000 years ago, sea levels in South Carolina between 3 and 10 m ASL are in evidence from deposits with high angle cross-bedding interpreted as tidal delta in origin, from beach and dune sands, and from faunal assemblages (localities 9, 10, and 12). In the Virginia-North Carolina border area, at 72,000 years ago, relative sea levels between 4 and 10 m ASL are indicated by in situ oysters (*Crassostrea virginica*), cross-bedding, beach sands, and nearshore faunal assemblages. We emphasize that these paleo sea level positions are estimates; their significance lies in the fact that each is above present sea level.

As the first uranium-series study of this region, our composite chronology must be considered a first approximation. Nevertheless, the uranium-series ages are augmented by detailed paleoclimatic data, biostratigraphy, and lithostratigraphy, and we propose (Fig. 4) some correlations to deep-sea isotope stages and to coral terraces in Barbados, which have been used to date isotope stages (*14*). The 740,000-year age on coral from the Waccamaw Formation (locality 8C) approaches the limit of the dating technique, and we view it with caution. However, it is generally consistent with biostratigraphic and magnetostratigraphic data indicating an early Pleistocene age (*22, 27*). We correlate the transgression of 440,000 years ago in South Carolina (localities 8, A and B), and perhaps the 500,000-year date from North Carolina, with isotope stages 9, 11, or possibly 13. Isotope stage 7, dated at 180,000 to 220,000 years ago, from the Aberdare, Kingsland, and Kendall Hill Barbados terraces, is probably represented by our 188,000-year-old unit. The anticipated predominance of ages near 120,000 years (the peak interglacial stage 5e at 125,000 ± 6,000 years ago, represented by the Rendevous Hill Barbados terrace) is not in evidence—only one 120,000-year age may represent this period. We hesitate to rely heavily on a single date. The Worthing and Ventnor Barbados terraces date late isotope stage 5a at 82,000 ± 5,000 years and stage 5c at 105,000 ± 5,000 years. These two high stands of sea level may be represented by our cluster of four dates averaging 72,000 ± 5,000 years and three dates averaging 94,000 ± 5,000 years, respectively. It is unclear whether or not the discrepancies between the Atlantic Coastal Plain and the Barbados uranium-series dates represent real age differences of several thousand years. If confirmed as real, these differences might signify differential glacio-isostatic effects on observed sea levels in the two regions.

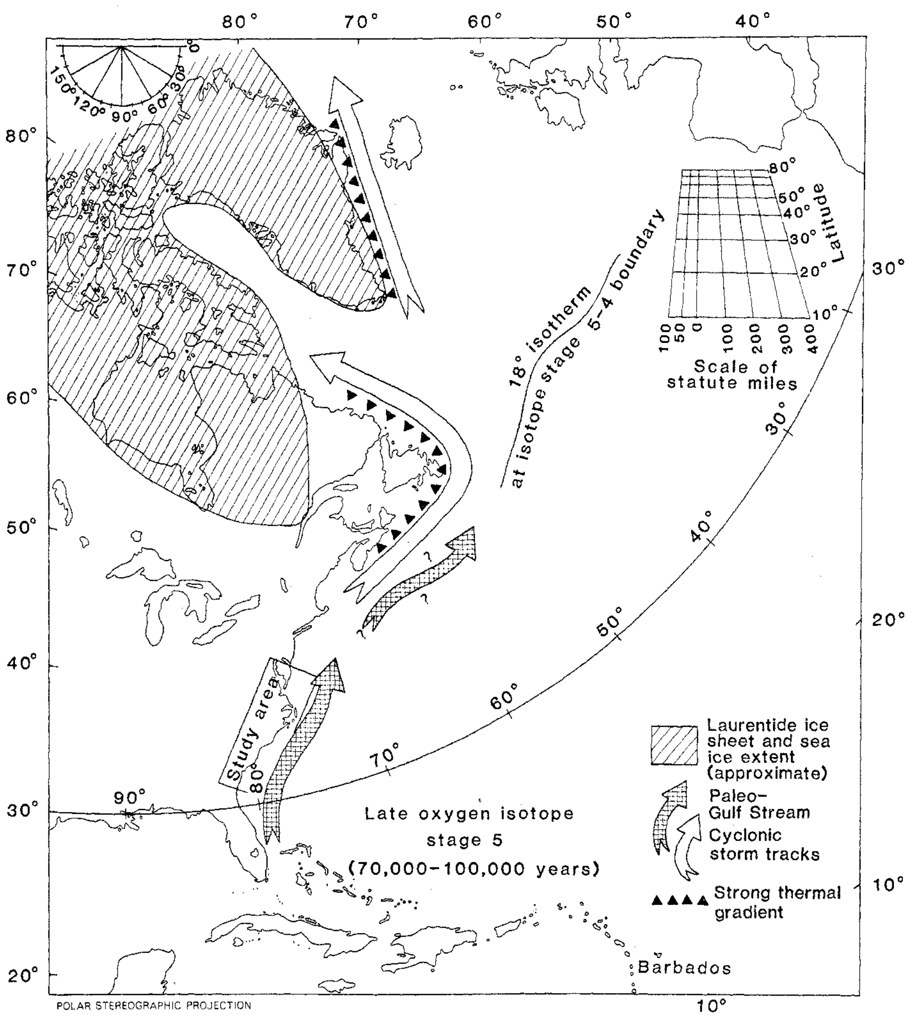


Fig. 5. Western North Atlantic oceanographic reconstruction during late oxygen isotope stage 5, between 70,000 and 100,000 years ago. Position of paleo Gulf Stream and inferred cyclonic storm tracks indicate the existence of a strong thermal gradient between the relatively warm North Atlantic and the North American Laurentide ice sheet and ice shelves [after (*20*)]. Ice margin positions are speculative. The 18°C isotherm for isotope stage 5 to 4 transition after Ruddiman and McIntyre (*20*).

Paleoclimatic Inferences

Our findings have a bearing upon several distinct but interrelated Quaternary problems. Laurentide ice sheet (*48*) and oceanic (*20*) reconstructions portray North Atlantic conditions during ice growth, just before the major Wisconsin glacial interval (isotope stage 5 to 4 transition) (Fig. 5), as having sea-surface temperatures as warm as or slightly cooler than modern temperatures. Rapid growth of the adjacent North American ice sheet was believed to have been caused by a strong thermal gradient between ocean and ice that produced cyclonic storms over the ice sheet. Our climatic data from South Carolina and the Virginia-North Carolina border area for late stage 5 support data (*20, 48, 49*) for such a scenario by providing direct evidence for a relatively warm western North Atlantic Ocean, almost surely reflecting the Gulf Stream passing along the southeastern United States at about 72,000 and 94,000 years ago (Fig. 5). Northeastward deflection of this current, as exists today, would produce the relatively warm subpolar mid-North Atlantic that is in evidence from the deep-sea data (*20, 49*). One of the late stage 5 Coastal Plain intervals probably also correlates with the St. Pierre interstade of the St. Lawrence Valley and the Cape Broughton interstade of eastern Baffin Island (*48*). Further, our sea level high stand of 188,000 years ago appears to correlate with the isotope stage 7 to 6 transition (*49*).

The emerged Coastal Plain is the landward part of the subsiding wedge of Mesozoic and Cenozoic sediments that constitute the Atlantic's passive continental margin. Although postrifting subsidence rates from 2 to 4 centimeters per 10^3 years characterize the geosynclinal depocenters of the adjacent continental slope (*50*), net uplift is suspected for parts of the emerged Coastal Plain for the last several hundred thousand years. We compiled a composite sea level diagram from our data for comparison with other sea level chronologies (Fig. 4) to show the combined effects of glacio-eustasy and regional crustal movements on our relative sea level record. Clearly, our paleoclimatic data support the hypothesis that there is a major glacio-eustatic component to the Coastal Plain record because high stands occurred during intervals of demonstrably warm climates both onshore and offshore. How much uplift occurred depends on how close estimates of eustatic sea levels during these interglacial intervals are compared to evidence from observed sea levels. Independent estimates for middle and late Pleistocene interglacial sea levels, based on uranium-series dating of coral terraces and oxygen isotopic studies, call for a eustatic sea level of +6 ± 2 m ASL during isotope stage 5e (about 125,000 years ago) (*11, 14, 51*). Sea level during other middle and late Pleistocene warm intervals supposedly remained below present sea level. Recent isotope stage 7 estimates are −32 m (220,000 years ago), −12 m (200,000 years ago), and −22 m (180,000 years ago) (*14*). However, Shackleton (*52*) predicted stage 7 sea level at 5 ± 5 m, which is remarkably close to our relative sea level. Estimates for late isotope stage 5 are −15 m (*11*), −16 m (*53*), and −43 m (*14*) for stage 5c (105,000 years ago) and −13 m (*11*), −15 m (*53*), and −45 m (*14*) for stage 5a (82,000 years ago).

If, for a moment, we accept the range of eustatic sea level estimates of −13 to −45 m for late isotope stage 5, and −12 to −32 m for stage 7, and also our correlations of Atlantic Coastal Plain transgressions with the isotope stages and dated coral terraces of Barbados, then an explanation must be found for the discrepancies in contemporaneous sea level positions. One possible explanation would be to invoke local crustal uplift of the Atlantic coast, which would require uplift rates of roughly 0.20 to 0.45 millimeter per year for the Charleston and southeastern Virginia regions since late isotope stage 5, and rates of about 0.10 to 0.20 mm per year since stage 7 for the region from southeastern Virginia to northeastern North Carolina. These rates of uplift appear anomalously high for a relatively stable intraplate coast, especially when compared with rates of 0.20 mm per year (*54*) which characterize Barbados, a tectonically active (uplifted) island. Sediment unloading due to erosion may have caused some isostatic uplift but probably not as much as that observed.

Another possible mechanism that would account for the emerged marine deposits on the Coastal Plain is hydroisostasy—crustal isostatic adjustment to the redistribution of mass from continental ice to ocean water during glacial-interglacial transitions. Bloom (*55*) hypothesized that this redistribution might produce an amount of coastal submergence on nonglaciated, nonorogenic continental coasts (such as the Coastal Plain) proportional to the proximity of the coast to deep water. Walcott (*56*) proposed that, rather than coastal submergence, coastal uplift occurred as an increase in water volume depressed ocean basins and adjacent continents rose from redistribution of mantle mass. Clark *et al.* (*57*) expanded this idea and suggested that all coastal regions would undergo this hydroisostatic uplift and tilt. The earth's rheological response to the last deglaciation has, however, only recently been discussed in detail (*58*), and the net effect of multiple hydroisostatic deglacial events such as those recorded in the Coastal Plain would be difficult to predict. This mechanism may have contributed to the relatively high sea levels during the middle and late Pleistocene on the Coastal Plain, roughly 20 to 40 m above some estimates for late isotope stage 5 and stage 7 eustatic sea levels (*11, 53*), and perhaps also for the relative sea levels as high as 30 m on the Coastal Plain during the early Pleistocene (*22*).

The distinct possibility that current models of Quaternary, eustatic sea level fluctuations might need revision must be entertained in light of our insufficient understanding of Atlantic continental margin tectonics and accumulating evidence on sea levels that seems to be inconsistent with these models (*59*). Specifically, estimates of glacio-eustatic ice volume fluctuations and sea level high stands inferred from stable isotope records in deep-sea cores may be no more accurate than those estimates of high stands that are based on observed paleo sea levels on continental and island margins and that have been corrected for neotectonic vertical movements caused by geologic factors such as proximity to ice sheets, location on a passive plate margin, and proximity to the subsiding depocenter of a geosynclinal trough. This latter factor is pertinent to the Atlantic margin because a region like Albemarle Sound, near our locality 5, is within the southern part of the subsiding Baltimore Canyon trough, while eastern South Carolina (localities 8 to 12) is several hundred kilometers from the Carolina trough. Distinct trends in neotectonic vertical crustal movements could be expected in these two regions because of their positions with respect to offshore troughs—specifically subsidence in Albemarle Sound and perhaps lithospheric flexural uplift in eastern South Carolina. But our knowledge of the Quaternary history of these regions is still insufficient to confirm this.

Conclusion

Our study of pre-Holocene sea levels and climates on a nonglaciated, nonorogenic continental coast allows us to propose a correlation between deep-sea isotope stages and coral terrace chronologies that has some discrepancies and some consistencies with current eustatic models. We believe eustatic sea levels for stage 7 were probably near present-day sea level and that −13 and −15 m are more realistic estimates for eustatic sea level during stages 5a and 5c than −45 and −43 m. In general, our climatic inferences match North Atlantic deep-sea data on the timing of warm climatic intervals at 188,000, 120,000, 94,000, and 72,000 years ago. We also conclude that there is a primary glacio-eustatic component and probably a secondary neotectonic vertical component to the local Coastal Plain sea level record which must be considered. The mechanisms for Quaternary verticle crustal movements probably include hydroisostasy and crustal subsidence and uplift caused by long-term sediment accumulation in depositional troughs; the magnitude of crustal movement probably varies along the entire segment of the coast that was studied.

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