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Evolution of marine climates of the U.S. Atlantic coast during the past four million years

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Marine climatic and sea-level changes in the eastern United States show two distinct modes: a gradual, directional Pliocene warming that ended with an abrupt regression, and a quasi-cyclic, high-amplitude, high-frequency middle-late Pleistocene pattern of alternating glacials and interglacials. Pliocene marine sediments of the Duplin Formation, deposited during a period of high sea level between 4.0 and 2.8 Ma BP, contain increasing percentages of tropical and subtropical ostracods, signifying a gradual warming. After maximum warm-water temperatures *ca.* 3.2–2.8 Ma BP, sea level dropped; this was followed by extensive subaerial erosion between about 2.8 and 2.0 Ma BP. This series of events reflects the emergence of the Isthmus of Panama between about 3.5 and 3.0 Ma BP, concomitant intensification of warm Gulf Stream flow along the eastern U.S.A., and initial Pliocene glaciation in the Northern Hemisphere.

In the middle-late Pleistocene, glacial-interglacial cycles occurred with a periodicity of *ca.* 100 ka. Four (possibly five) emerged interglacial marine sequences correlate with deep-sea oxygen-isotope stages 13/11, 7, 5, and 1. During some interglacials, however, climatic conditions ranged from full interglacial warmth to cool, nearly interstadial conditions; this observation indicates short-term regional climatic variability.

INTRODUCTION

The Pliocene and Pleistocene marine record of the Atlantic Coast of the United States and the adjacent continental shelf and slope is a sensitive barometer of North Atlantic oceanographic and climatic change. This paper traces the evolution of climatic variability of this region during the past four million years (Ma) and correlates it with climatic events elsewhere. A review of the stratigraphic and climatic literature on the eastern U.S.A. is beyond the scope of this paper. Consequently, with the stratigraphic record as a framework, this paper focuses on the marine palaeontological record, emphasizing temporal changes in the proportions of cryophilic and thermophilic ostracods from key stratigraphic units. Because ostracod faunal provinces on the U.S.A.'s Atlantic continental shelf parallel the distribution of modern marine climatic zones (Hazel 1970), northward and southward range expansion and contraction of temperature-sensitive species reflect oceanographic changes which themselves often signify climatic events. Each formation discussed here exhibits an important climatic and/or sea-level event covering the full range of climatic extremes: glacial, interglacial and transitional. Collectively they form a climatic framework for the past 4 Ma.

REGIONAL STRATIGRAPHY AND MARINE HISTORY

The emerged Coastal Plain of Delaware, Maryland, Virginia, North Carolina and South Carolina is the primary study region (figure 1). In addition, outcrops from Nantucket Island, Massachusetts, and coastal Maine, and two cores from the outer continental shelf and upper

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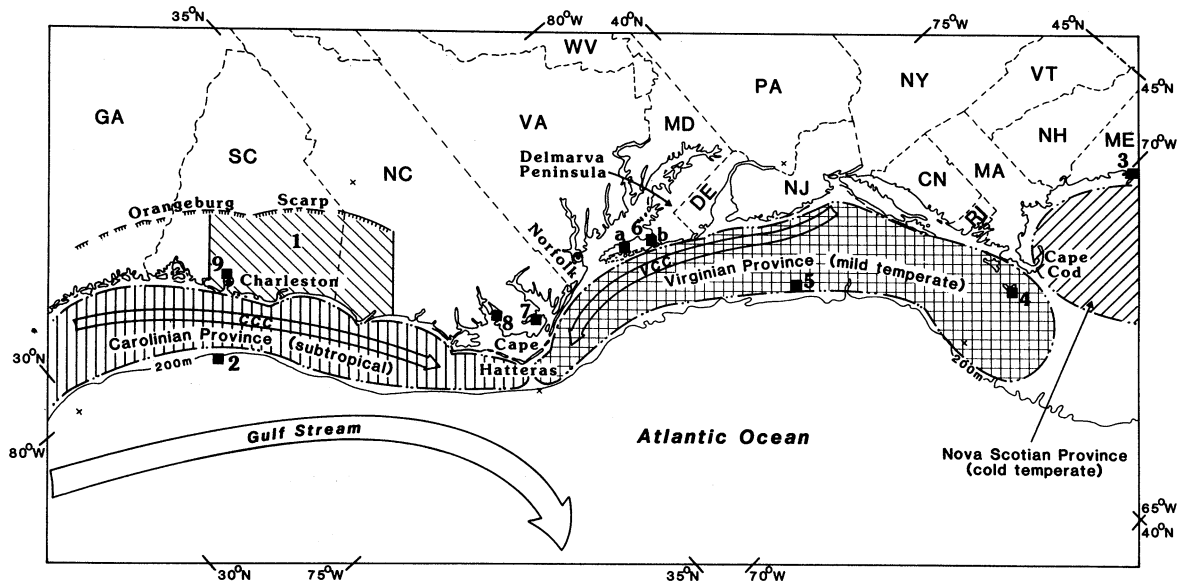


FIGURE 1. Map showing stratigraphic sequences, physiographic features, faunal provinces and associated climatic zones in parentheses. Locality: 1, general location of sections A–L of the Pliocene Duplin Formation (stippled area; discussed in detail by Cronin *et al.* (1984)); 2, AMCOR 6004; 3, Presumpscot Formation; 4, Sankaty Head, Nantucket, Massachusetts; 5, AMCOR 6010; 6, Delmarva Peninsula (a, Wachapreague Formation; b, Omar Formation); 7, Stetson core; 8, Ponzer; 9, Charleston area (a, Wando Formation; b, Ten Mile Hill beds). vcc, Virginia Coastal Current; ccc, Carolina Coastal Current.

slope off New Jersey and South Carolina (AMCOR 6010 and 6004 (Hathaway *et al.* 1979)), are included (figure 1). Table 1 lists the formations and stratigraphic sequences discussed below and gives references describing the stratigraphy and age of each.

Transgressive–regressive marine cycles, mainly reflecting changes in sea level, dominate the Plio-Pleistocene geological history of the Coastal Plain. During periods of high sea level, marine and marginal marine sediments were deposited; the onshore limit of each transgression is marked by an erosional scarp, barrier island and/or lagoonal–tidal marsh sediment (Colquhoun 1974). The local sea-level record is primarily glacio-eustatic (Cronin 1981*a*); with important exceptions (discussed below), marine deposits contain faunas indicating interglacial climates.

Periods of low sea level account for much of the past 4 Ma and can be identified in the Coastal Plain by lithological disconformities, signifying non-deposition and fluvial erosion. This incomplete stratigraphic record poses an obvious limitation to quantifying climatic variability. None the less, many parts of the Coastal Plain have been intensely studied and mapped and provide a climatic record for particular intervals. Further, glacial oceanography can be pieced together by integrating the emerged postglacial record from northeastern North America with the record from cores and dredged samples from the outer continental shelf and upper slope, which represent times of low sea level during glacial periods.

On the basis of lithology alone, it is often impossible to correlate marine units over broad areas, owing to limited exposures and complex lateral facies changes. Sometimes it also is difficult to determine whether the apparent diachronous relations between the marine deposits of two regions reflects local tectonic subsidence or uplift, erosion and channelling, or errors in

U.S. ATLANTIC COAST MARINE CLIMATES

663

TABLE 1. SUMMARY OF PLIOCENE AND PLEISTOCENE STRATIGRAPHY

(Figure 1 shows location of sequences 2–9; sequence 1 is a composite of 12 sections located in hatched area in figure 1; figure 3 shows climatic data from sequences 3–9.)

no.	stratigraphic sequence	formation	age	reference
1A–L	Pliocene composite	Duplin	early–middle Pliocene	Cronin <i>et al.</i> (1984), Owens (1987)
2	South Carolina continental slope	none	late Pliocene, Pleistocene	Hathaway <i>et al.</i> (1979)
3a–c	coastal Maine	Presumpscot	late Wisconsinan	Stuiver & Borns (1975), Bloom 1960, Cronin (1988)
4	Nantucket Island	Sankaty Sand	late Pleist.	Oldale <i>et al.</i> (1982)
5	New Jersey continental shelf	none	late Pleistocene	Hathaway <i>et al.</i> (1979)
6a, b	Delmarva Peninsula	a. Wachapreague b. Omar	late Pleist. mid. Pleist.	Mixon (1985) Mixon <i>et al.</i> (1982)
7	Stetson core, North Carolina	Core Creek sand	late Pleist.	Mixon & Pilkey (1976), York & Wehmiller (1987)
8	Ponzer, North Carolina	Flanner Beach	mid. Pleist.	Miller (1985)
9	Charleston, South Carolina	Flanner Beach a. Wando b. Ten Mile Hill beds	middle Pleistocene late Pleist. mid. Pleist.	Cronin <i>et al.</i> (1981), Miller (1985) McCartan <i>et al.</i> (1984) Weems & Lemon (1984), Szabo (1985)

dating techniques. Consequently, biostratigraphic, radiometric and palaeomagnetic data have played an important role in regional correlation of the formations discussed here (Hazel 1983; Cronin *et al.* 1984).

OSTRACOD ZOOGEOGRAPHY AND CLIMATIC CHANGE

Marine Ostracoda – small, bivalved Crustacea common in marine and marginal marine sediments – have long been used to reconstruct palaeoceanographic conditions of eastern North America (Brady & Crosskey 1871), although much more so in the past 20 years (Hazel 1968; Cronin 1981*b*, 1988). The modern geographic distributions of ostracod species on the Atlantic continental shelf between Maine and Florida is known from about 700 modern bottom samples (Hazel 1970, 1975; Valentine 1971; Cronin 1983; Lyon 1988). These and several hundred additional Neogene and Quaternary samples described in papers mentioned below constitute the zoogeographic, taxonomic and biostratigraphic *terra firma* for this paper. Six ostracod faunal provinces, delineated qualitatively (Hazel 1970) and quantitatively (Valentine 1971; Hazel 1975), are shown in table 2 with associated climatic zones, geographic limits and bottom-water temperatures.

Boundaries between faunal provinces are regions of strong thermal gradients that limit the poleward or equatorward expansion of species. For example, at Cape Hatteras, North Carolina, the confluence of the warm, northeastward-flowing Carolina Coastal Current (figure 1) and the cool, southward-flowing Virginia Coastal Current causes cryophilic (cold-water) and thermophilic (warm-water) ostracod species to have Cape Hatteras as their southern or northern boundary. One hundred and four species, each of which is restricted to one or several

TABLE 2. OSTRACOD PROVINCES AND ASSOCIATED CLIMATIC ZONES

faunal province ^a	climatic zone	geographic range	temperature ranges (°C)
Arctic	frigid	circumpolar, Greenland	-2-4
Labradorian	subfrigid	S. Greenland-Gulf of St. Lawrence	-2-12
Nova Scotian	cold temperate	Gulf of St. Lawrence-Cape Cod	2-20
Virginian	mild temperate	Cape Cod-Cape Hatteras	3-26
Virginian-Carolinian ²	warm temperate	Cape Cod-Cape Canaveral	12-26
Carolinian	subtropical	Cape Hatteras-Cape Canaveral	15-28
Caribbean	tropical	Caribbean, south Florida, Bahamas	20-30

^aHazel (1970) described ostracod provinces along the eastern United States.

^bThe warm-temperate zone does not exist today, owing to strong isothermal convergence at Cape Hatteras, but is recognized in the late Pleistocene (Valentine 1971; Cronin 1979). Annual temperature ranges are approximate; see text for references.

climatic zones, were divided into six groupings of species with similar temperature tolerances. From coldest to warmest these are: frigid zone only, subfrigid-cold-temperate, cold-temperate-mild-temperate, mild-temperate-subtropical, subtropical only, and tropical (Appendix 1). Changes in the proportions of each species-group in fossil assemblages were used as a measure of change in water temperature and regional climate.

The use of modern zoogeography to estimate species' temperature tolerances and nearshore oceanographic conditions is analogous to the use of planktonic Foraminifera from deep-sea core tops to infer surface-water conditions and climatic patterns from deep-sea sediments (Imbrie & Kipp 1971). In each case it must be assumed that, in lieu of direct experimental evidence, species' ecological limits can be reasonably estimated from their association in Holocene sediments (and plankton tows, for planktonic foraminiferans) with water temperatures and other physical and chemical parameters. Unlike planktonic foraminiferans with global distributions, most ostracods used here (except circumpolar Arctic species) are endemic to the western Atlantic, the Gulf of Mexico and the Caribbean and can only be applied to a regional oceanography.

In addition to latitudinal zonation, ostracods also show a bathymetric gradient from coastal to deep-sea environments (Cronin 1979, 1983); the percentages of species characteristic of inner-shelf, outer-shelf and upper-slope environments in Pleistocene sediments are also used to identify bathymetric changes related to eustatic sea-level fluctuations.

EARLY PLIOCENE CLIMATIC WARMING

During an interval of high sea level in the early and middle Pliocene, the Duplin Formation of South Carolina and southern North Carolina and the Yorktown Formation of Virginia and northern North Carolina were deposited. During this period, the Orangeburg Scarp, the highest, most conspicuous geomorphic shoreline feature in the Coastal Plain (figure 1), was occupied for the final time (Oaks & DuBar 1974; Colquhoun 1986). In some areas this scarp is 80 m above sea level at its crest, but it appears to be tectonically warped (Winker & Howard 1977) so it is not clear to what extent it represents a eustatic sea-level position (Cronin 1981*b*).

Thirty-six samples of the Duplin Formation (from 12 outcrops and cores within the stippled region in figure 1), when placed in the stratigraphic framework of DuBar *et al.* (1974) and Owens (1988), provide a representative Pliocene palaeoclimatic record. The Duplin Formation shows no obvious breaks in deposition and major hiatuses can be excluded.

The Duplin Formation contains the upper part of planktonic foraminiferan zone N19, zone N20, and perhaps the lowermost part of zone N21 (figure 2) (Cronin *et al.* 1984). Its lower part contains *Globorotalia puncticulata*, *Globigerina nepenthes*, *Neogloboquadrina acostaensis*, *Globoquadrina altispira*, and *Sphaeroidinellopsis* spp., an assemblage that restricts the age to between about 4.8 and 3.7 Ma. In South Carolina, the nannofossil *Pseudoemiliana lacunosa* is absent in the lower Duplin but appears in the upper Duplin (figure 2). Based on these data and that available from the correlative Yorktown Formation, the base of the sequence in figure 2 is estimated at approximately 4.0 Ma BP. In the middle part of the Duplin Formation, *Globorotalia puncticulata*, *Globoquadrina altispira*, *N. acostaensis*, *Globigerina apertura*, *Sphaeroidinellopsis* spp. and *Globigerinoides obliquus* occur; *Globigerina nepenthes* is absent. In the upper Duplin, *P. lacunosa* occurs with *Globorotalia inflata* and *Globigerina woodi*; these species indicate a maximum age of *ca.* 3.4 Ma and a minimum of 2.8 Ma, but perhaps as young as 2.5 Ma. The uppermost samples (figure 2, sections A, B, C) contain no diagnostic species and are probably only slightly younger than 2.8 Ma. The Yorktown Formation in Virginia and North Carolina contains a similar climatic

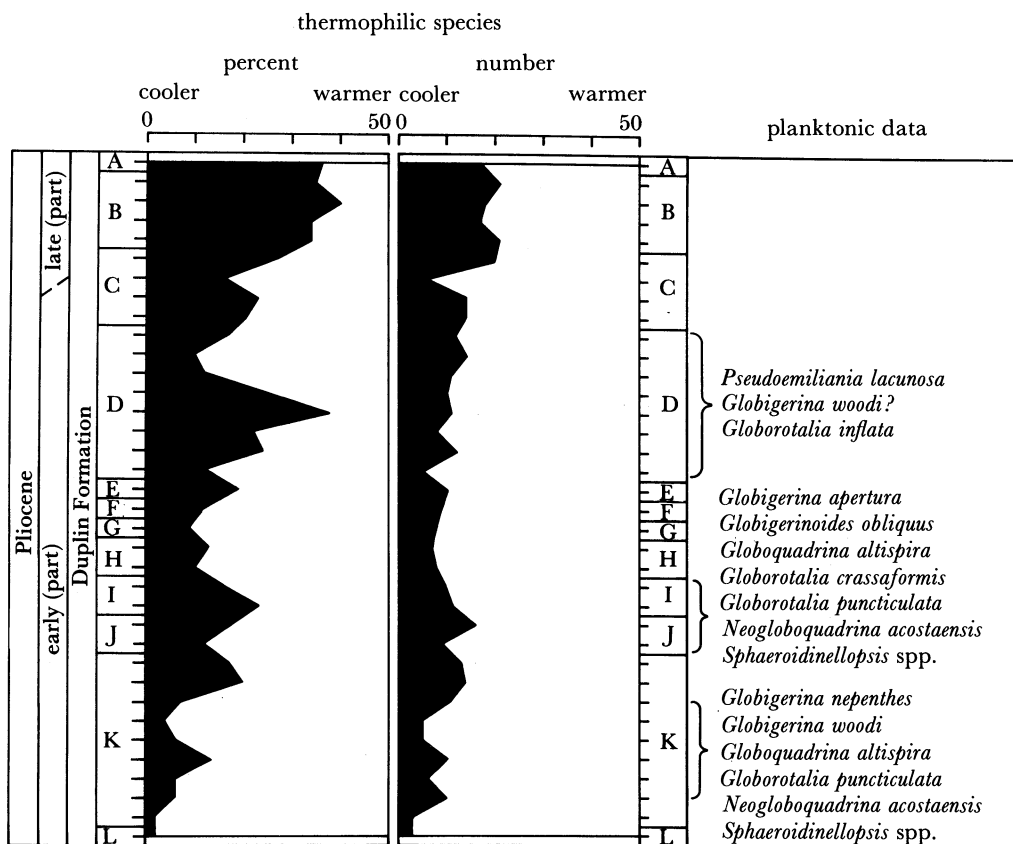


FIGURE 2. Composite sequence of the Pliocene Duplin Formation in North and South Carolina showing percentages and numbers of species of tropical ostracods. Age-diagnostic foraminifers and nannofossils shown on the right; sections A-L shown on the left; tick marks denote samples.

record to that of the Duplin and is about the same age (Akers & Koepfel 1973; Snyder *et al.* 1983; Hazel 1983; Gibson 1983).

The most significant climatic change during the interval 4.0–2.8 Ma BP is a general warming from temperate to near-tropical conditions. Figure 2 shows the numbers of extant subtropical and tropical ostracods in the Duplin sequence and their percentages out of the total assemblage in each sample. From three species in the lower Duplin, where many cryophilic temperate species occur in abundance, the number of thermophilic species increases to between 17 and 21 in the upper Duplin; this figure represents between 35 and 40% of assemblages. Among the abundant thermophilic species are *Radimella confragosa* (Edwards, 1944) and *Orionina vaughani* (Ulrich & Bassler, 1904), two species very common in the Caribbean. Species not accounted for in the 35–40% include subtropical species that live off the southeastern U.S.A. today and extinct species that belong to subtropical–tropical genera. The increase in thermophilic species in the upper Duplin Formation is accompanied by decreasing numbers of cryophilic species. Tropical molluscs also dominate the upper part of the Duplin, and water temperatures were warmer than during any middle or late Pleistocene interglacial. It is noteworthy that a parallel pattern of climatic warming was documented by Hazel (1971) for the correlative Yorktown Formation of Virginia and northern North Carolina.

Some short-term environmental changes are suggested by the staggered pattern in figure 2; however, without a single continuous section and known sedimentation rates, it is difficult to assess them. Nonetheless, with the exception of the spike in section D, the magnitude of these faunal changes is generally small compared with the net Pliocene change. In fact, several lines of evidence argue against high-amplitude, high-frequency climatic oscillations during the Pliocene. First, the cryophilic ostracod species which occur in the lower Duplin Formation and also in the correlative Tamiami Formation in Florida (Hazel 1977) do not occur, even in low numbers, in the upper Duplin Formation. If cool intervals had punctuated the warming trend, one would expect to find evidence for it in the presence of cryophilic species, as in Pleistocene glacial periods (see below). Second, there is no stratigraphic evidence for major unconformities within the Duplin sequence. If sea level dropped 75–100 m, as it did during the late Pleistocene, there would be stratigraphic or geomorphic evidence for it. Third, although each individual exposure and subsurface section of the Duplin Formation represents only a fraction of the early Pliocene record, there is no evidence for cyclic patterns within any single section. This does not mean that fine-scale Pliocene oscillations should be completely dismissed, but if they are to be documented, the documentation is most likely to come from offshore cores containing a more complete stratigraphic record.

A late Pliocene regression after the deposition of the Duplin Formation, considered by many to be at least in part a glacio-eustatic event, began an extended period of emergence and fluvial erosion. In South Carolina, DuBar *et al.* (1974) suggested that sea level might have been lowered in stages reflected in the development of barriers and barrier-flats at lower levels. DuBar *et al.* (1974, p. 156) also stated that ‘the Duplin was subjected to extensive subaerial erosion in pre-Bear Bluff time’ during ‘a considerable period of emergence’ (p. 171). Similarly, Riggs *et al.* (1982) described a significant late Pliocene weathering profile and unconformity between the Yorktown Formation and overlying deposits in North Carolina.

There is a remarkable correspondance between Pliocene Coastal Plain chronology and land and sea events in the Caribbean–Central-American region and the northern North Atlantic. The emergence of the Isthmus of Panama first blocked deep-water circulation *ca.* 3.6 Ma BP

and then shallow-water circulation (Keigwin 1978), eventually isolating the Caribbean and Pacific by about 3.0 Ma BP (Jones & Hasson 1985). Increased erosion and winnowing during the early Pliocene in the Straits of Florida directly reflects enhanced flow of the Florida Current resulting from the Isthmus' closing (Brunner 1979). The age equivalence of these events and the northward migration of tropical species during the deposition of the Duplin suggests a causal relation between Coastal Plain warming and the emergence of the Isthmus. Further, evidence from deep-sea cores in the North Atlantic led Berggren (1972) and Shor & Poore (1979) to suggest a link between the closure of the Isthmus, intensification of the Gulf Stream, and Pliocene Northern Hemisphere glaciation. Shackleton *et al.* (1984) studied DSDP site 552a and determined that a North Atlantic bottom-water mass similar to that of today began by at least 3.5 Ma BP, and that major ice rafting began 2.5 Ma BP, intensifying in scale about 2.4 Ma BP. The early-middle Pliocene Coastal Plain warming and subsequent extended regression correlate well with the deep-sea chronology. Indeed, the concordance of tectonic and oceanographic events in Central America, the Atlantic Coastal Plain and the North Atlantic all seem to reflect a major oceanographic and climatic change signalling the onset of Pleistocene-type climatic cycles.

PLEISTOCENE CLIMATIC OSCILLATIONS

The middle-late Pleistocene record of the Coastal Plain consists of four, possibly five, major interglacial periods during which relatively high sea level deposited marine sediments containing climatically diagnostic species. The Canepatch Formation unconformably overlies the early Pleistocene Waccamaw in South Carolina (DuBar *et al.* 1984) and contains corals that have been dated by the uranium-series method at about 460 ± 100 ka BP (Szabo 1985). A middle-Pleistocene age for this formation is supported by its normal magnetic signal, biostratigraphic data, and its stratigraphic position (Cronin *et al.* 1984). The Canepatch probably corresponds with oxygen-isotope stage 13 or 11. The Bermont Formation of Florida and unnamed deposits in North Carolina are possible correlatives of the Canepatch but these have not been studied in detail.

Overlying the Canepatch in northeastern South Carolina, the Socastee Formation is a candidate as a correlative with isotope stage 9, but its age is unknown and it requires further study (McCartan *et al.* 1982).

A more detailed climatic record is available for the last two interglacial periods, corresponding with isotope stages 7 and 5, and the last glacial period, isotope stage 2. Figure 3 summarizes these results in a composite for the region; age data are used to place each section in the context of the deep-sea oxygen-isotope stratigraphy. Figures 4 (*a-d*), 5 (*a, b*), and 6 plot diagnostic ostracod percentages for six key stratigraphic sequences. Each depicts a particular type of climatic situation: interglacial, glacial and/or transitional periods.

Interglacial climates

The penultimate interglacial is represented by the Omar Formation of the Delmarva Peninsula (Mixon 1985), the Flanner Beach Formation, North Carolina (Cronin *et al.* 1981; Miller 1985) and the Ten Mile Hill beds described by Weems & Lemon (1984) in South Carolina (McCartan *et al.* 1982; Corrado *et al.* 1986). Uranium-series ages on solitary corals (Szabo 1985) and amino-acid epimerization ages on molluscs (Wehmiller & Belknap 1982;

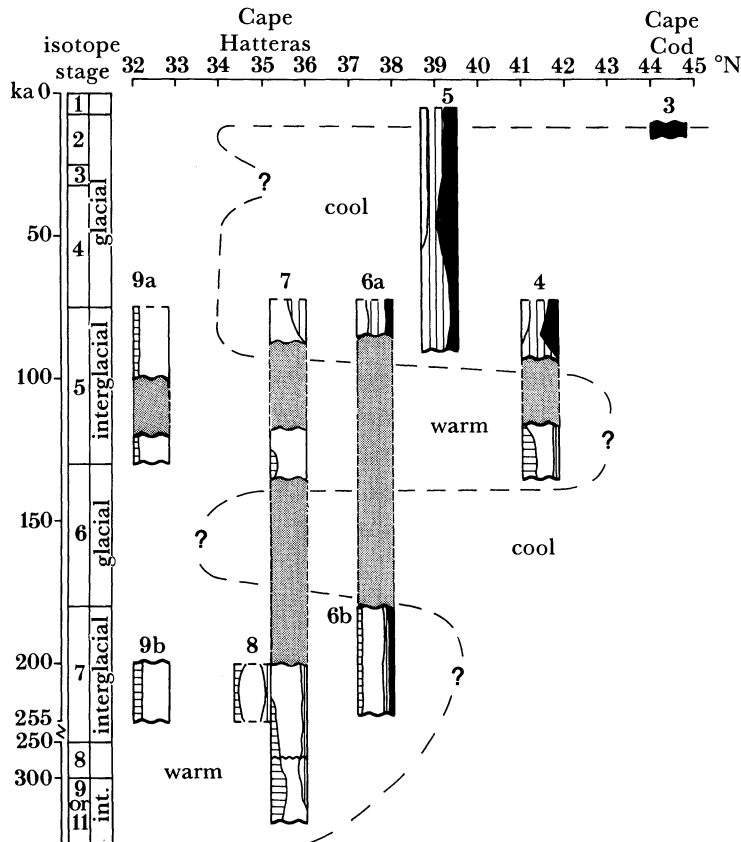


FIGURE 3. Pleistocene composite for eight sequences showing relations between latitude, inferred climate and isotope stages. Stippled portions indicate that no record was available. (Locality numbers as for figure 1; see figure 4 for explanation of temperature patterns.)

Corrado *et al.* 1986) indicate that these deposits are about 220–200 ka old and correlate with oxygen-isotope stage 7 in deep-sea cores (Shackleton & Opdyke 1973).

Figure 4a shows a high percentage of warm-temperate species and lower percentages of mild- and cold-temperate ostracod species in the Accomack Member of the Omar Formation. Cold-temperate species do not occur in corresponding deposits of the Ponzer and Stetson sections (figure 4b, c) and a faunal provincial boundary related to water temperature during isotope stage 7 was probably located near southeastern Virginia. Near Charleston, South Carolina, only subtropical and warm-temperate species occur in the Ten Mile Hill beds (figure 3, section 9b); no species living exclusively north of Cape Hatteras were found. The interglacial period *ca.* 200 ka BP was thus characterized by slightly cooler water than today in the Delmarva region and perhaps a steeper thermal gradient between Virginia and South Carolina.

The last interglacial period, which corresponds to isotope stage 5, shows a complex oceanography along the eastern U.S.A., including intervals of warm water conditions and cooler climatic intervals (see below). Peak warmth during the last interglacial, corresponding with isotope substage 5e, is illustrated in the Sankaty Head section, Massachusetts (figure 5b), where the ostracod assemblage from the lower Sankaty Sand consists primarily of subtropical

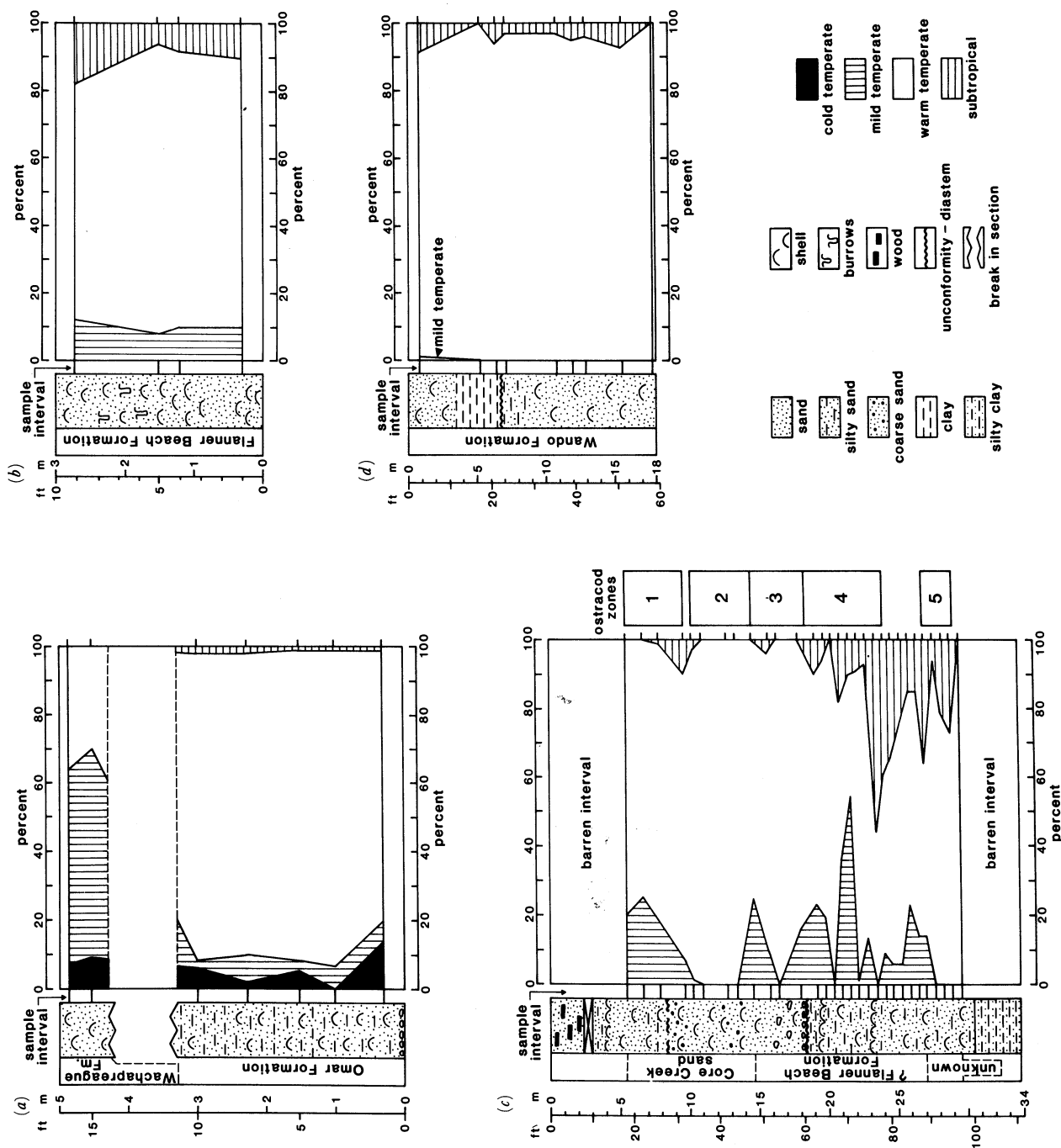


FIGURE 4. Four sequences showing stratigraphy and percentages of temperature-diagnostic ostracod species. (a) Delmarva Peninsula, sequence 6; (b) Ponzer, sequence 8; (c) Stetson core, sequence 7; (d) Charleston area, sequence 9a.

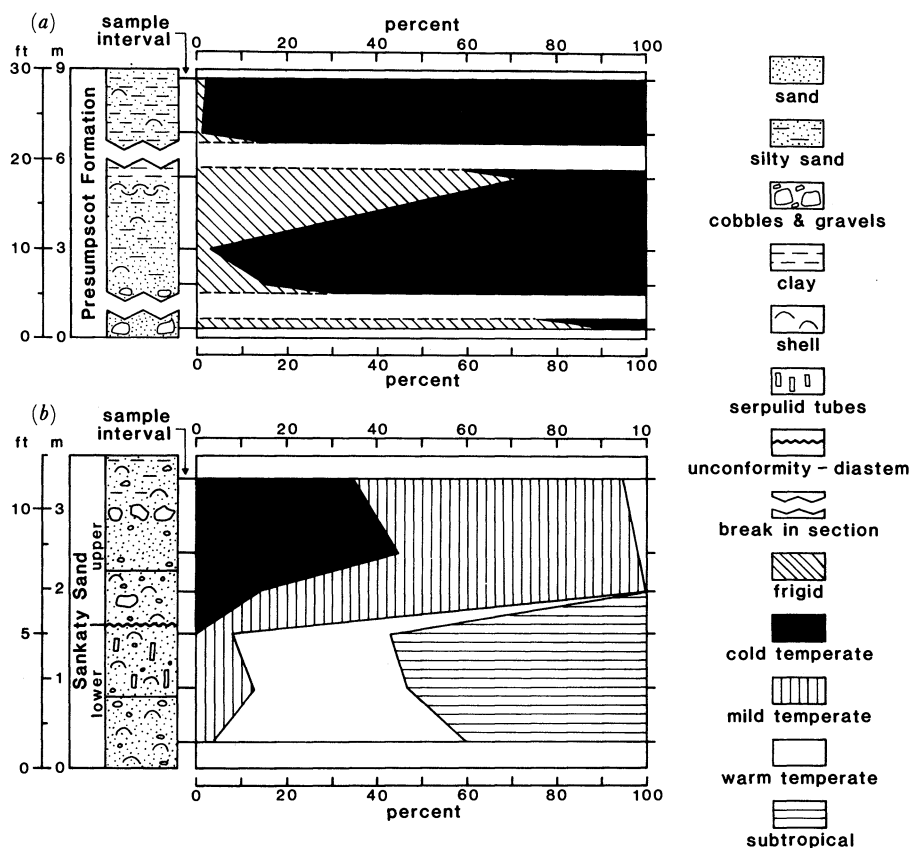


FIGURE 5. Two sequences showing stratigraphy and percentages of temperature-diagnostic ostracod species. (a) Presumpscot Formation, sequence 3; (b) Sankaty Head, sequence 4.

species, from south of Cape Hatteras, and warm-temperate species. Cold-temperate species are absent. Oldale *et al.* (1982) estimate the age at *ca.* 135–120 ka.

In the Stetson core (figure 4c), small percentages of subtropical species at a depth of 9–10 m suggest a relatively warm interval dated about 120 ka BP by amino acid epimerization on *Mercenaria* (Miller 1982). The lower part of the Wando Formation of South Carolina represents the last interglacial interval (McCartan *et al.* 1982; Corrado *et al.* 1986) and contains ostracod faunas almost identical to those living off that region today (figure 4d). Szabo (1985) estimated the age of the lower Wando at *ca.* 125 ka.

Other deposits which stratigraphically and climatically represent the peak warmth of the last interglacial are the Norfolk Formation described by Oaks & Coch (1963) (Virginia) (Valentine 1971; Spencer & Campbell 1987), the Cape May Formation (New Jersey) (Richards 1962), and the Gardiners Clay (New York) (Gustavson 1976).

GLACIAL CLIMATES

Oceanography along the eastern United States during the last glacial period was pieced together from several sources of information (figure 7). Ostracods from radiocarbon-dated postglacial deposits of the northeast document frigid–subfrigid marine conditions as far south as coastal Massachusetts and Maine between about 14.5 and 12.5 ka BP (Cronin 1981b,

1988). The subfrigid–cold temperature climatic boundary, now at about 48° N, near Nova Scotia, was therefore at least 5–6° farther south during the late Wisconsinan age. As the Laurentide ice sheet retreated from coastal Maine, frigid ostracod faunas of the Presumpscot Formation described by Bloom (1960) were replaced *ca.* 12.0–11.6 ka BP with the cold-temperate species that characterize the region today (figure 5*a*). A similar transition at 11–10 ka BP occurs in Champlain Sea deposits as the ice sheet retreated from New York, Vermont and southern Quebec (Cronin 1981*b*).

Evidence for Wisconsinan palaeoclimates also comes from sediments deposited on the outer shelf and upper slope during low stands of sea level, which along the eastern U.S. were about –100 m (Cronin 1987). In AMCOR 6010 (figure 6), the first appearance of *Emiliana huxleyi*

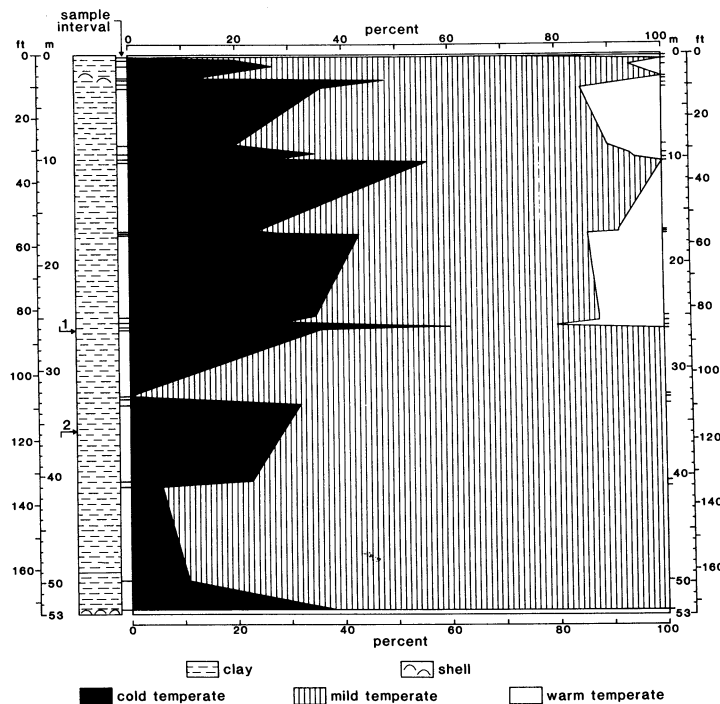


FIGURE 6. Stratigraphic section of AMCOR 6010 (sequence 5) illustrating percentages of temperature-diagnostic ostracod species. Data points on the left of the stratigraphic column are: 1, FAD of *Emiliana huxleyi*; 2, LAD of *Pseudoemiliana lacunosa*.

occurs at a core depth of *ca.* 86 m. If this is its acme zone, 75–85 ka BP (Berggren *et al.* 1980), it suggests a Wisconsinan age for the upper part of the core, where cold-temperate species account for as much as 40–60% of some assemblages.

Hazel (1968) described glacial ostracods in rock samples dredged from ten submarine canyons between Maine and Virginia and provides convincing evidence that during glacial periods, cold temperate ostracods migrated far south of their present range. Hazel estimated the boundary between the cold-temperate and mild-temperate provinces, which now stands at about 42° N, to be about 37.5° N during the late Pleistocene. Ostracods characteristic of modern cold- and mild-temperate zones have yet to be found in Pleistocene deposits south of Cape Hatteras; there is no direct evidence off the southeastern U.S.A. for late Pleistocene

marine climates that were significantly colder than today (although Wisconsinan continental climates in the southeast were colder (Watts & Stuiver 1980).

In summary, glacial climates were characterized by a southward shift of frigid, subfrigid and cold-temperate climatic zones of about 5–6° latitude, presumably owing to the proximity of the Laurentide Ice Sheet and cold-water currents off the northeastern U.S.A. Subtropical zones apparently remained warm, under continued influence of the Gulf Stream, and were not shifted southward as were temperate zones.

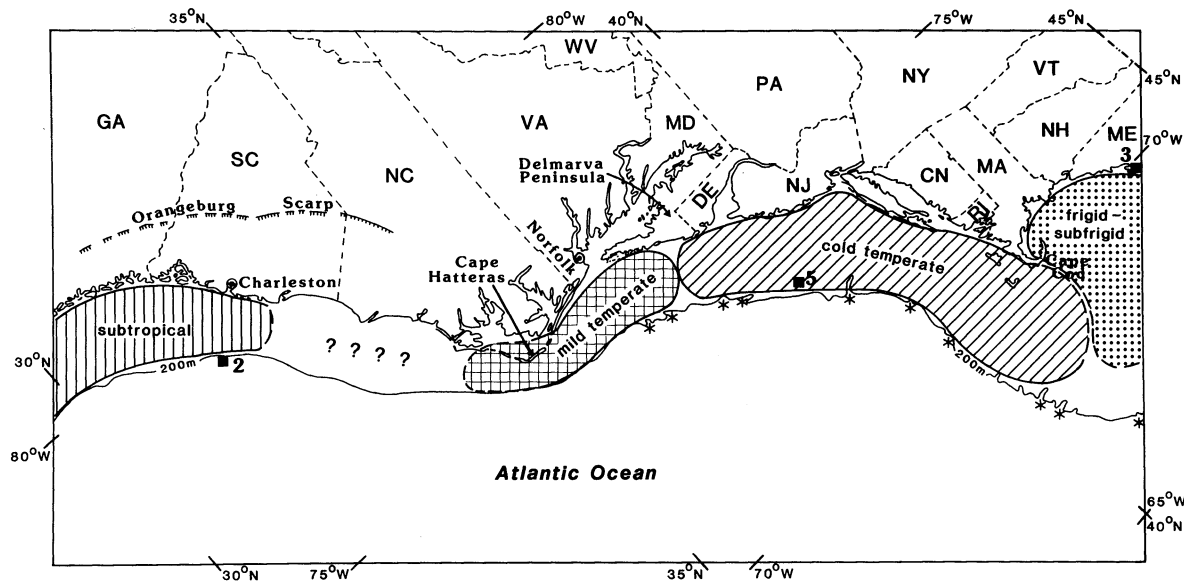


FIGURE 7. Oceanographic reconstruction during the last glacial period based on ostracod data from postglacial deposits in New England (locality 3), AMCOR 6004 off South Carolina (locality 2) and AMCOR 6010, New Jersey (locality 6), and dredged samples (asterisks) from submarine canyons discussed by Hazel (1968). Boundaries between frigid-subfrigid and cold-temperate, and cold-temperate and mild-temperate, climatic zones were about 5–6° south of their present positions. Compare with figure 1 (interglacial oceanography).

Interglacial-glacial transition

Abundant lithological, radiometric and palaeontological evidence indicates that relatively cool marine and continental climates existed at different latitudes along the eastern U.S.A. during one or two periods of high sea level corresponding to oxygen-isotope substages 5a and 5c. This cool interval is recognized across at least 7° of latitude in the youngest marine Pleistocene deposits in many areas (figure 3, sections 4, 6a, 7 and 9a). Lithological and paleontological evidence for a diastem between these sediments and underlying substage 5e sediments, containing warm-climate faunas, indicates breaks in deposition within the last interglacial. Uranium-series ages on corals from the upper sediments, bearing cool-climate faunas, suggest a correlation with oxygen-isotope substages 5c and 5a.

At Sankaty Head, the ostracode fauna in the upper sand is completely distinct from that in the lower sand. It contains as much as 30–40% cold-temperate species and high percentages of mild-temperate species (figure 5a); water temperatures were much cooler than those in the region today. The contact with the underlying lower Sankaty Sand, containing warm-temperate faunas, consists of a ventifacted pebble horizon, signifying subaerial exposure (Oldale *et al.* 1982).

Cool marine climates also characterize the upper part of the Wachapreague Formation on the Delmarva Peninsula, which contains 8–10% cold-temperate and 50% mild-temperate species (figure 4a). According to Mixon (1985) the stratigraphic relation of the Wachapreague to the underlying Joynes Neck Sand (not represented in figure 4a) is unclear but some evidence suggests that the Wachapreague truncates the Joynes Neck; this evidence suggests a brief depositional hiatus. The ostracod and pollen evidence shows a distinct cooling trend for the Wachapreague, approaching interstadial conditions.

In the Stetson core, North Carolina (figure 4c), the percentage of mild-temperate species in the Core Creek sand described by Mixon & Pilkey (1976) increases in the uppermost samples to about 20%; no cold-temperate species occur in the Stetson section. Ager & Shaw (1987) found cool-temperate pollen assemblages in the uppermost sediments at the Stetson section. In North Carolina and southeastern Virginia, Cronin *et al.* (1981) and Szabo (1985) reported several uranium-series ages on corals from several late Pleistocene marine units dated at *ca.* 70–75 ka BP. One coral is from an outcrop at the Stetson section, dating the uppermost marine deposits there at 72 ± 4 ka BP (zone 1 of figure 4c). Lithological and faunal changes at 8 m in the Stetson section suggest a brief depositional break between sediments yielding the 120 ka BP amino acid epimerization date on *Mercenaria* and the overlying sediments yielding the 72 ka BP coral data (York & Wehmiller 1987; T. M. Cronin, unpublished observations).

Finally, near Charleston, the upper part of the Wando Formation shows a slight trace of mild-temperate species at the end of the last interglacial (figure 4d). Strong evidence for a break between the lower and upper Wando (figure 3, section 9) was provided by Lyon (1987) who found low-diversity, brackish-water ostracods near the contact. Szabo (1985) suggested that the upper and lower Wando Formation correlated with the isotope substages 5e and 5c, respectively, on the basis of uncorrected ^{230}Th dates on corals.

The ages of Upper Pleistocene Coastal Plain marine units have been the source of controversy (Mixon *et al.* 1982; Stearns 1984; Cronin 1983, 1987; Corrado *et al.* 1986) because most models of eustatic sea level (Bloom *et al.* 1974; Harmon *et al.* 1983; Cronin 1983; Chappell & Shackleton 1986) call for a single high stand above present sea level during the isotope substage 5e. The 70–75 ka BP Coastal Plain ages indicating correlation with substage 5a are anomalous because most estimates of eustatic sea level for this time are about 9–20 m below present sea level (see Aharon & Chappell 1986; Chappell & Shackleton 1986). This discrepancy led Mixon *et al.* (1982) to suggest the Coastal Plain units in the Chesapeake Bay area dated at 75 ka BP, and those near Charleston, dated about 100 ka BP, were actually 125 ka BP (isotope substage 5e) but that extratropical corals yielded anomalously younger ages the farther north they occurred.

The interpretation adopted here, discussed in more detail in Cronin (1987), is that the ages accurately date at least one and possibly two marine units deposited during substages 5a and 5c. Three lines of evidence support this. First, the concordance of faunal events from Massachusetts to North Carolina indicate that cool oceanic conditions were not localized, but rather a regional phenomenon, signifying a change in nearshore oceanography from those indicated from underlying deposits. Second, while this cool interval could represent the end of isotope substage 5e, this alternative seems unlikely given stratigraphic, lithic and palaeontological evidence for hiatuses between underlying deposits containing warm-water faunas, believed to represent isotope substage 5e, and overlying deposits containing cool-water faunas. Third, uranium-series ages are consistent with the stratigraphy and any post-depositional alteration of corals would have had to alter specimens equally from a broad area.

The concordance between ^{230}Th and ^{231}Pa and uranium trend age estimates on surrounding sediment also support the ages (Szabo 1985).

This hypothesis implies that cool conditions existed immediately before Wisconsinan glaciation but before a major sea-level drop occurred at the isotope stage 5–4 transition, dated by Kukla & Briskin (1982) at 75 ka BP. If we assume tectonic stability (i.e. 15–20 m of uplift has not occurred), it still remains to reconcile these data with eustatic models. The existence of cool marine climates with a high sea level might involve the presence of marine-based ice shelves, which would affect the oxygen-isotope signal in deep sea foraminiferans but would not lower sea level (Williams *et al.* 1981) but Chappell & Shackleton (1986) dismiss this, at least for the early part of the last interglacial. The issue remains unresolved; however, our poor knowledge of mechanisms and rates of vertical tectonic and isostatic movements, not only in the Coastal Plain but in all coastal regions, is such that we should reassess assumptions about 'stable' areas and estimates of uplift rates that form the foundation of eustatic models.

CONCLUSIONS

The Pliocene record of the Atlantic Coastal Plain shows a period of increasing oceanic warmth that was abruptly halted by a major regression and extended period of erosion. Since this event, the frequency and amplitude of climatic oscillations increased significantly such that in the middle and late Pleistocene an approximate cycle of 100 ka is recognized for major glacial–interglacial cycles. Although the east coast stratigraphic record is too discontinuous and dating techniques too coarse to discern a higher frequency signal, there is some indication that short-term climatic changes occurred during the last two interglacial periods.

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APPENDIX 1. LIST OF 90 TEMPERATURE-SENSITIVE OSTRACOD SPECIES USED IN
COASTAL PLAIN CLIMATOLOGY

Group 1: frigid

- Cytheromorpha macchesneyi* (Brady & Crosskey, 1871) *Finmarchinella logani* (Brady & Crosskey, 1871)
Normanicocythere leioderma (Norman, 1869)

These three species are the only frigid ostracods in the Presumpscot formation. Other frigid species occur in other postglacial deposits of North America (see Cronin 1988).

Group 2: subfrigid–cold-temperate

- | | |
|--|--|
| <i>Acanthocythereis dunelmensis</i> (Norman, 1865) | <i>Hemicythere villosa</i> (Sars, 1865) |
| <i>Baffinicythere emarginata</i> (Sars, 1865) | <i>Hemicytherura clathrata</i> (Sars, 1866) |
| <i>Cythere lutea</i> (O. F. Müller, 1785) | <i>Heterocyprideis fascis</i> (Brady & Norman, 1889) |
| <i>Cytheropteron angulatum</i> Brady & Robertson, 1872 | <i>Munseyella mananensis</i> Hazel & Valentine, 1969 |
| <i>C. inflatum</i> Brady, Crosskey & Robertson, 1874 | <i>Palmenella limicola</i> (Norman, 1865) |
| <i>C. nodosum</i> Brady, 1868 | <i>Patagonocythere dubia</i> (Brady, 1868) |
| <i>C. nodosoalatum</i> Neale & Howe, 1973 | <i>Sarsicytheridea bradii</i> (Norman, 1865) |
| <i>Elofsonella concinna</i> (Jones, 1857) | <i>S. punctillata</i> (Brady, 1865) |
| | <i>Semicytherura undata</i> (Sars, 1865). |

Group 3: cold-temperate–mild-temperate

- | | |
|--|--|
| <i>Actinocythereis dawsoni</i> (Brady, 1870) | <i>Leptocythere angusta</i> Blake, 1935 |
| <i>Bensonocythere americana</i> Hazel, 1967 | <i>Loxococoncha</i> cf. <i>L. impressa</i> (Baird, 1850) |
| <i>B. arenicola</i> (Cushman, 1906) | <i>L. sperata</i> Williams, 1966 |
| <i>B. sp. B</i> of Valentine (1971) | <i>L. aff. L. granulata</i> Sars, 1865 |
| <i>Cytheridea</i> sp. A | <i>Muellerina canadensis</i> (Brady, 1870) |
| <i>Cytheromorpha fuscata</i> (Brady, 1868) | <i>Muellerina ohmerti</i> Hazel, 1983 |
| <i>Cytherura wardensis</i> Howe & Brown, 1935 | <i>Neolophocythere subquadrata</i> Grossman, 1967 |
| <i>Eucythere declivis</i> (Norman, 1865) | <i>Perissocytheridea</i> sp. A |
| <i>Finmarchinella finmarchica</i> (Sars, 1865) | <i>Pseudocytheretta edwardsi</i> Cushman, 1906 |
| <i>Hulingsina</i> sp. A | <i>Puriana rugipunctata</i> (Ulrich & Bassler, 1904) |

Group 4: mild-temperate to subtropical (warm-temperate)

- | | |
|---|--|
| <i>Actinocythereis captionis</i> Hazel, 1983 | <i>Cyprideis mexicana</i> Sandberg, 1964 |
| <i>Bensonocythere hazeli</i> Cronin, 1988, in the press | <i>C. salebrosa</i> Bold, 1963 |
| <i>B. valentinei</i> Cronin, 1988, in the press | <i>Cytheromorpha curta</i> Edwards, 1944 |
| <i>B. whitei</i> (Swain, 1951) | <i>C. newportensis</i> Williams, 1966 |
| <i>Campyloocythere laeva</i> (Edwards, 1944) | <i>Cytherura forulata</i> Edwards, 1944 |

Group 4 (cont.)

- | | |
|--|--|
| <i>C. neusensis</i> Cronin, 1988, in the press | <i>P. setipunctata</i> (Brady, 1869) |
| <i>Cushmanidea seminuda</i> (Cushman, 1906) | <i>Proteoconcha gigantea</i> (Edwards, 1944) |
| <i>Hulingsina americana</i> (Cushman, 1906) | <i>P. nelsonensis</i> (Grossman, 1967) |
| <i>H. rugipustulosa</i> (Edwards, 1944) | <i>Protocytheretta</i> cf. <i>P. sahnia</i> (Puri, 1952) |
| <i>H. sp. B</i> of Valentine (1971) | <i>Puriana mesacostalis</i> (Edwards, 1944) |
| <i>H. sp. C</i> of Valentine (1971) | <i>Tetracytherura choctawhatcheensis</i> (Puri, 1954) |
| <i>Leptocythere nikraveshae</i> Morales, 1966 | <i>T. norfolkensis</i> (Cronin, 1979) |
| <i>Malzella floridana</i> (Benson & Coleman, 1963) | <i>T. sp. A</i> |
| <i>Peratocytheridea bradyi</i> (Stephenson, 1938) | |

Group 5: subtropical

- | | |
|--|---|
| * <i>Cytherura reticulata</i> Edwards, 1944 | * <i>Paracytheroma stephensoni</i> Puri, 1954 |
| <i>C. sandbergi</i> Garbett & Maddocks, 1979 | * <i>Pellucistoma magniventra</i> Edwards, 1944 |
| * <i>Hulingsina glabra</i> (Hall, 1965) | <i>Perissocytheridea brachyforma</i> Swain, 1955 |
| <i>Loxoconcha matagordensis</i> Swain, 1955 | * <i>Proteoconcha multipunctata</i> Edwards, 1944 |
| <i>Neocaudites atlantica</i> Cronin, 1979 | * <i>P. tuberculata</i> Puri, 1960 |
| * <i>Paracytheridea altila</i> Edwards, 1944 | * <i>Puriana carolinensis</i> Hazel, 1983 |
| <i>P. hazeli</i> Cronin, 1988, in the press | * <i>P. convoluta</i> Teeter, 1975 |

* These species also inhabit tropical environments and are included in the totals for thermophilic species in the Duplin Formation (figure 2).

Group 6: tropical

- | | |
|--|---|
| <i>Acuticythereis laevisissima</i> (Edwards, 1944) | <i>Neocaudites angulatus</i> Hazel, 1983 |
| <i>Bairdia laevicula</i> Edwards, 1944 | <i>N. triplistriatus</i> (Edwards, 1944) |
| <i>Bairdoppilata triangulata</i> Edwards, 1944 | <i>N. variabilis</i> Hazel, 1983 |
| <i>Cytherelloidea umbonata</i> Edwards, 1944 | <i>Orionina vughani</i> (Ulrich & Bassler, 1904) |
| <i>C. sp.</i> | <i>Paracytheridea rugosa</i> Edwards, 1944 |
| <i>Cytherura nucis</i> Garbett & Maddocks, 1979 | <i>Paradoxostoma delicata</i> Puri, 1954 |
| <i>Eucythere gibba</i> Edwards, 1944 | <i>Paranesidea sp.</i> |
| <i>Hemicytherura sp.</i> | <i>Perissocytheridea subpyriforma</i> Edwards, 1944 |
| <i>Hermanites ascitus</i> Hazel, 1983 | <i>Protocytheretta reticulata</i> Edwards, 1944 |
| <i>Kangarina sp.</i> | <i>Radimella confragosa</i> (Edwards, 1944) |
| <i>Loxoconcha purisubrhomboidea</i> Edwards, 1953 | <i>Xestoleberis sp.</i> |
| <i>L. reticularis</i> Edwards, 1944 | |