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Changed Late Quaternary Marine Environments on Atlantic Continental Shelf and Upper Slope[1]

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About 2000 large sediment samples were collected during the early 1960s throughout the continental shelf off the Atlantic coast of the United States to establish and map sediment types including sediments relict from times of glacially low (and subsequently higher) sea levels. In about 510 of these samples we found fossil shells of mollusks remaining from environmental conditions different from those at present. Publications and collections by others contain about 70 additional samples having relict mollusks. Some of these shells indicate lower sea levels, others colder water, and still others warmer water than is now present. Radiocarbon measurements from earlier studies by us and others established the dates of colder water (late Pleistocene), and we made additional measurements to learn the dates of warmer water (about 1000 to 2000 yr B.P.). The results show reasonably enough that continental shelves are the sites of relict faunas as well as of sediments that indicate changed and complex environmental histories.

INTRODUCTION

Glacial advances during the Pleistocene Epoch were accompanied by widely recognized lowerings of sea level (the latest major one reaching perhaps 130 m below the present level) and by equatorward shifts of climatic belts. Evidence for associated changes in areas of glaciers, areas of ocean, and belts of climate are preserved on land, ocean floor, and the transitional margin between land and ocean. Most evidence is in the form of topography, sediments, and fossils. Least well known is the fossil evidence from the transitional margin, the subject of this study, which is based upon investigations of bottom samples from the Atlantic continental shelf and upper slope off the eastern coast of the United States.

SOURCES OF SAMPLES

Collections of mollusks and other benthic animals from the Atlantic shelf were made during the 19th and early 20th centuries, mostly by government bureaus, and analyzed by Verrill *et al.* (1873), Dall (1889), Smith (1889), Sumner *et al.* (1913), and others. The object then was to identify distribution patterns of marine animals according to water depth and latitude mainly for aiding commercial exploitation of fisheries. Little attempt was made to separate living from fossil Holocene species.

During a single cruise (60-7) in 1960, R/V *Delaware II* (Bureau of Commercial Fisheries) occupied 96 stations in the Middle Atlantic Bight at depths of 26 to 146 m hauling a 75-cm wide Digby dredge 1 to 3 km through the surface sediments (Merrill, 1960; Merrill and Edwards, 1961). A screen liner allowed finer sediments to pass but retained animals and shells larger than 1.2 cm for special studies (Merrill, 1960; Merrill *et al.*, 1965, 1978a, b; Franz and Merrill, 1980a). Many of these shells had neither resilium nor periostracal covering and were dull or chalky in appearance; thus, they were considered fossil forms. About 200 Digby dredgings collected aboard R/V *Delaware II* and R/V *Albatross IV* of the Bureau of Commercial Fisheries (now the Na-

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tional Marine Fisheries Service, National Oceanic and Atmospheric Administration) established distribution patterns for these fossil mollusks, especially for the relatively rare small ones.

Similar fossil shells, especially of the larger and more common species, were found in a subsequent series of sediment samples collected during cruises aboard R/V *Gosnold* (Woods Hole Oceanographic Institution) between 1963 and 1970 (Emery and Schlee, 1963; Hathaway, 1971). These samples (volumes to 0.2 m^3) were obtained with a Campbell clam-shell grab (Emery *et al.*, 1965) in a 10- to 15-min (latitude and longitude) grid across the entire continental shelf and upper slope from eastern Nova Scotia to southern Florida. Animals in the samples were screened and preserved aboard ship; fossil shells were bagged and dried. About 1800 such samples were obtained and studied for their sediments (Emery and Uchupi, 1972) and their animals (Wigley and Theroux, 1981).

HOLOCENE HABITATS IDENTIFIED BY FOSSIL REMAINS

General

Because of their lack of mobility during life and as skeletal debris after death relatively large calcareous sessile or nearly sessile animals are most diagnostic of former environmental habitats on the continental margin. The more than 2000 large bottom samples that have been collected from the shelf and upper slope contain abundant living and fossil remains of mollusk species that have identical habitats (same depth, latitude, and substrate). Distribution patterns permitted identification of regional habitats such as arctic, boreal, temperate, and tropical (Hedgpeth, 1957; Franz and Merrill, 1980b) arranged roughly by latitude, with further subdivisions by other authors (Deevey and Flint, 1957; Edwards and Merrill, 1977), and classification as estuarine, lagoonal, littoral, neretic, and bathyl. Because nearly all fossil remains occur in the same areas as those of their living forms, many ecologists have failed to recognize differences in latitude and depth distributions of fossil and living forms of some species of mollusks.

Distributions of certain Holocene mollusks differ from distributions of living ones of the same species in three main aspects: their greater present water depth, their more northerly distribution, or their more southerly distribution. Care must be taken to ensure that movement of shells by waves and currents did not occur; large size of fossils, attachment to the bottom (as for corals), imbedment in burrows, and association with substrates typical of the different species are useful criteria for lack of displacement. Support is provided by the fact that fossil and subfossil mollusk shells are confined essentially to areas of relict sediments—ones that generally are somewhat coarser grained than modern sediments that are accumulating closer to shore. Relict sediments commonly are stained reddish by iron coatings formed during thousands of years of oxidation by overlying waters (Emery and Uchupi, 1972, Fig. 279).

Former Shallow-Water Environments

Early evidence for former low sea levels was provided by gently sloping shelf topography and by coarse offshore sediments. Later, support came from discovery on the shelf of marine and shore plants and freshwater peat (Emery *et al.*, 1967) and by bones and teeth of mammoth, mastodon, horse, musk ox, tapir, sloth, and giant moose (Whitmore *et al.*, 1967) on the continental shelf. A mammoth tooth from 35-m depth off Boston was ^{14}C dated (by tandem accelerator mass spectrometry) to 10,930 ± 315 yr B.P. and a mastodon tooth from 37 m nearby to 11,070 ± 130 yr B.P. (Oldale *et al.*, 1987). Large mammals, mollusks, and fish were abundant on the former subaerial region during the more than 11,000 yr that humans are known to have inhabited the present coastal region (Haynes *et al.*, 1984). A discrepancy in the depth range of living and fossil mollusks that live intertidally was recognized for some species:

Crassostrea virginica (*Gmelin, 1701*). The eastern oyster is one of the largest and most widespread examples. It lives from the Gulf of St. Lawrence to the Gulf of Mexico and the West Indies. The species inhabits intertidal or shallow waters of estuaries and lagoons and it tolerates considerable changes in temperature and thus occurs in a wide range of latitudes. We have found fossil and subfossil shells and fragments in samples from 458 stations between the Gulf of St. Lawrence and southern Florida as deep as 100 m. Other workers have reported these oyster shells at 56 other stations. Positions of all stations known to contain these fossil shells are indicated on Figure 1, along with information on depths, radiocarbon ages, and sources of samples. Corroboration of original intertidal or shallow-water habitats now in deeper waters is provided by present depths of other fossil mollusks that lived only in estuaries, lagoons, and shallow shelf environments.

Mulinia lateralis (*Say, 1822*). The coot clam ranges from Maine to Texas and is abundant in sand and muddy sand beneath warm estuarine waters to a depth of 13 m. Eroded shells were present in dredge samples at 13 stations—none north of Cape May, NJ. Eleven samples came from depths of 30 to 34 m. The other two samples were from the extreme southern end of the survey near Cape Hatteras, NC, in 74 and 140 m. Bush (1885) also recorded dead shells north of Cape Hatteras, NC, in 26–27 m.

Ilyanassa obsoleta (*Say, 1822*). The eastern mud snail lives between the Gulf of St. Lawrence and northeastern Florida. It is a very common small gastropod on mudflats or sandflats between low tide and 12 m depth; its upper spiral usually has been eroded. The species is a nonselective deposit feeder, subsisting almost entirely upon organic debris in sand and mud (Brown, 1969). Richards and Werner (1964) found relict specimens 150–165 cm deep within a core from south of Fire Island, NY, at a depth of 22 m. Fossils of eastern mud snail were taken at 15 of our stations (*Delaware* 60-7) between Block Island, RI, and Cape Hatteras, NC. They were at three stations in a narrow belt between eastern Long Island, NY, and Block Island in depths of 36–52 m and at 12 stations between Cape May and Cape Hatteras in depths of 34–82 m.

Mya arenaria (*Linné, 1758*). The soft clam ranges from Labrador to Cape Lookout, NC, burrowing deeply in intertidal mudflats and sandflats. The species has been recorded from interglacial Pleistocene sediments on land from Greenland to New Jersey (Richards, 1940). Fossil shells were taken at three stations off Long Island, NY, to Cape Hatteras, NC, in present water depths of 55 to 84 m.

Mercenaria mercenaria (*Linné*). The hard clam lives between the Gulf of St. Lawrence and Florida and the Gulf of Mexico in sandy and sandy-mud bottom to 6 m water depth. Bush (1885) found dead shells north of Cape Hatteras, NC, in depths of 26–27 m. We collected shells at two stations off Currituck Beach, NC, and off Cape Hatteras, NC, at depths of 35 and 26 m.

Cyrtopleura costata (*Linné, 1758*). The angel wing lives intertidally between southern Massachusetts and Texas and south to Brazil. It is a common estuarine species south of Cape Hatteras, NC, in thick soft mud and sandy mud into which it burrows as deeply as 60 cm. Fossil fragments were taken at two stations off Currituck, NC, at water depths of 33 and 37 m.

Petricola pholadiformis (*Lamarck, 1818*). The false angel wing ranges from the Gulf of St. Lawrence to Texas and south to Uruguay. It is a common clay and peatmoss borer that lives intertidally and to 13 m depth. A fossil specimen was obtained at one station off Currituck Beach, NC, in 35 m.

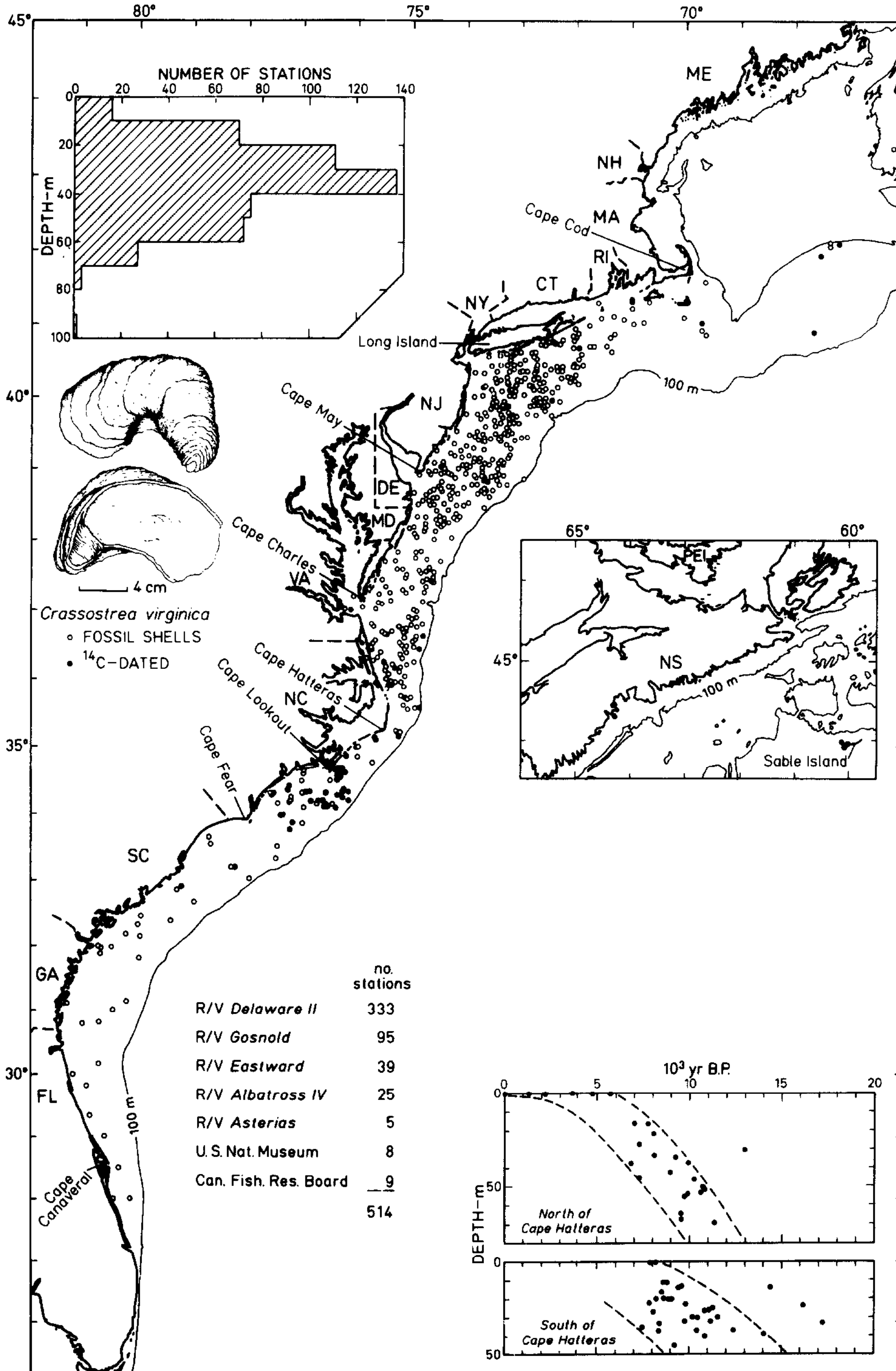

FIG. 1. *Crassostrea virginica*. Areal distribution of fossil shells and radiocarbon-dated shells on Atlantic continental shelf from all known sources. Important capes, islands, and boundaries of states and provinces are indicated. Insert at middle right extends the chart northeastward to include five radiocarbon-dated shells on shores of Sable Island, Nova Scotia, and Prince Edward Island. Insert at upper left shows depth distribution of all stations that contain *C. virginica* shells. Insert at lower right shows depth distribution of ages of shells from regions north and south of Cape Hatteras. A listing at lower left indicates sources of shell samples.

Former Cold-Water Environments

The colder climate of glacial times allowed cold-water marine environments to reach much farther south than at present, as indicated also by plant species within pollen profiles of cores from swamps and ponds on land (Deevey, 1948; Davis, 1965) and from former swamps now on the ocean floor (Groot and Groot, 1964; Emery *et al.*, 1967). Former cold water also is identified by the presence of fossil mollusk shells on the continental shelf far south of their present habitat. These mollusks include the following most common ones:

Mesodesma arctatum (Conrad, 1931). The Arctic wedge clam ranges from Greenland to Sandy Hook, NJ, inhabiting both estuarine and ocean waters to depths of 90 m (Edwards and Merrill, 1977). Its southernmost range has been reported at New Jersey (Johnson, 1934), Chesapeake Bay, VA (Abbott, 1954, 1974; Richards and Werner, 1964), and southeast of Beaufort Inlet, NC (Porter, 1974), although Porter questioned the identity of his species. Small live specimens have been obtained from 80 m depth south of Block Island and intertidally at Sandy Hook, NJ (Merrill *et al.*, 1978b). Abbott's, Richards' and Werner's, and Porter's records probably are based upon fossil remains. An extension of the Pleistocene range to South Carolina by Richards (1962) is reasonable, because the annual temperature regime there during the latest glaciation may have been similar to today's temperatures at about the latitude of Sandy Hook, NJ, the southernmost record of living *M. arctatum.*

Fossil specimens of *M. arctatum* were taken offshore at 24 *Delaware* stations between Long Island, NY, and Cape Hatteras, NC, in depths of 30–145 m (Table 1; Fig. 2). The relict shells were found at greater average depths at northern stations; at 14 stations to a distance of about 80 km north of Lat. 38°N the depth averages 80 m, and at 10 stations within about the same distance south of Lat. 38°N the depth averages 47 m. Additional specimens were found by other investigators at other sites in the region. They were abundant in shell layers penetrated by three cores from R/V *Trident* near the shelf break off Rhode Island and Massachusetts (Emery and Garrison, 1967). Two other cores that were obtained by R/V *Atlantis* from beyond the shelf break off New York and New Jersey near Hudson Canyon also contained shell layers with *M. arctatum.* One core was from 156 m on the upper continental slope (Richards and Werner, 1964); the other was from 3470 m on the lower slope, where the shells were presumed to have been carried by turbidity currents from shallower depths (Richards and Ruhle, 1955). Richards (1944) also reported the presence of *M. arctatum* in sediments of spoil heaps left from dredging the Cape May Canal near the southern tip of New Jersey. Farther north, specimens of *M. arctatum* were included among shell beds of the Presumpscot Formation at 27–30 m above sea level (ASL) in southwestern Maine (Bloom, 1963; Merrill *et al.*, 1978b). Still farther north, the fossil shells occur 4 m ASL on the south side of the St. Lawrence Estuary (Dionne, 1977). Their occurrences above sea level probably are due to uplift of the crust after melting of the Pleistocene ice cap that formerly covered the region.

Thracia conradi (Couthouy, 1838). Conrad's thracia occurs northward to Nova Scotia. It has been reported to range southward to Cape Hatteras, NC (Dall, 1903; Johnson, 1934), but Abbott (1954, 1974) limited the southern range to Long Island Sound. It has been taken alive to depths of 275 m and dead to 353 m. It lives buried in the substrate to a depth of about 15 cm on its side with the flattened valve upward (Thomas, 1967). Fossil specimens have been taken in post-Pliocene sediments (the Leda Clay) at Saco, ME (Verrill *et al.*, 1873). Fresh large valves, obviously modern, were obtained at two of our stations off Block Island, RI, at 47 and 82 m, at the extreme end of its reported range. Fossil

TABLE 1. Position and Other Data for Samples Containing Fossil *Mesodesma arctatum*

Ship[a]	Cruise	Station	North Lat.	West Long.	Depth (m)	Age (yr B.P.)
Dionne (1977)			St. Lawrence	Estuary	4 above	2,240 ± 140
Bloom (1963)			43°48′	70°10′	29 above	12,100 ± 300
Merrill *et al.* (1978b)			43°48′	70°10′	29 above	12,210 ± 120
Del.	60-7	2-1	40°32′	72°46′	37	
Del.	60-7	A-44	40°30′	72°17′	59	
Del.	60-7	A-50	40°17′	71°23′	84	
Del.	60-7	1-5	40°10′	71°03′	146	
Tri.		206	40°10′	71°26′	86	10,850 ± 150
Tri.		147	40°09′	70°29′	122	13,420 ± 210
Del.	60-7	A-42	40°08′	72°00′	73	
Tri.		203	40°06′	70°32′	130	14,850 ± 250
Del.	60-7	2-4	39°47′	72°07′	110	
Del.	60-7	A-40	39°45′	72°28′	81	
Richards and Werner (1964)			39°34′	72°09′	156	15,000 ± 150
Del.	60-7	3-2	39°19′	73°18′	55	
Del.	60-7	3-3	39°09′	73°08′	73	
Del.	60-7	3-5	39°01′	72°49′	146	
Richards (1944)			38°58′	74°58′	0	
Del.	60-7	A-27	38°52′	73°23′	66	
Del.	60-7	4-1	38°40′	74°17′	37	
Del.	60-7	A-24	38°32′	73°31′	84	
Richards and Ruhle (1955)			38°23′	70°57′	3470	
Del.	60-7	A-1	38°04′	74°07′	75	
Del.	60-7	5-1	37°51′	74°51′	33	
Del.	60-7	A-20	37°50′	74°24′	64	
Del.	60-7	5-3	37°39′	74°24′	73	
Del.	60-7	A-18	37°34′	74°45′	55	
Del.	60-7	A-3	37°24′	74°39′	64	
Del.	60-7	A-4	37°11′	74°59′	37	
Del.	60-7	A-16	36°59′	74°59′	44	
Del.	60-7	6-2	36°53′	74°59′	37	
Del.	60-7	A-15	36°51′	75°05′	29	
Del.	60-7	A-10	35°33′	74°58′	44	

[a] Del. = R/V *Delaware II* of National Marine Fisheries Service. Tri. = R/V *Trident* of University of Rhode Island.

shells were recovered farther south at 10 stations between Ocean City, MD, and near Cape Hatteras, NC. Distribution is rather uniform, although those taken south of Cape Charles, VA, were in lesser average depths. The range of live and fossil material is discontinuous, as neither live nor fossil *T. conradi* were found between Block Island and Ocean City.

Zirfaea crispata (*Linné, 1758*). The great piddock ranges from Labrador to Delaware between about low tide and 74 m depth. Commonly, it burrows in saltmarch peat to depths of 15 cm. Dall (1889) cautiously suggested that *Z. crispata* ranged to South Carolina; Johnson (1934) restricted its southern range to Anglesia, NJ; recently, Abbott (1974) slightly extended the species' range to Delaware. During the 1960 *Delaware* cruise a live specimen was dredged at a depth of 55 m off Great Egg Inlet, NJ, near the southern end of its range. Fossil shells and fragments were found farther south at three stations from off Ocean City, MD, off Chincoteague Inlet, VA, and off Wachapreague Inlet, VA, at depths of 73, 33, and 55 m, respectively.

Cyrtodaria siliqua (*Spengler, 1793*). The

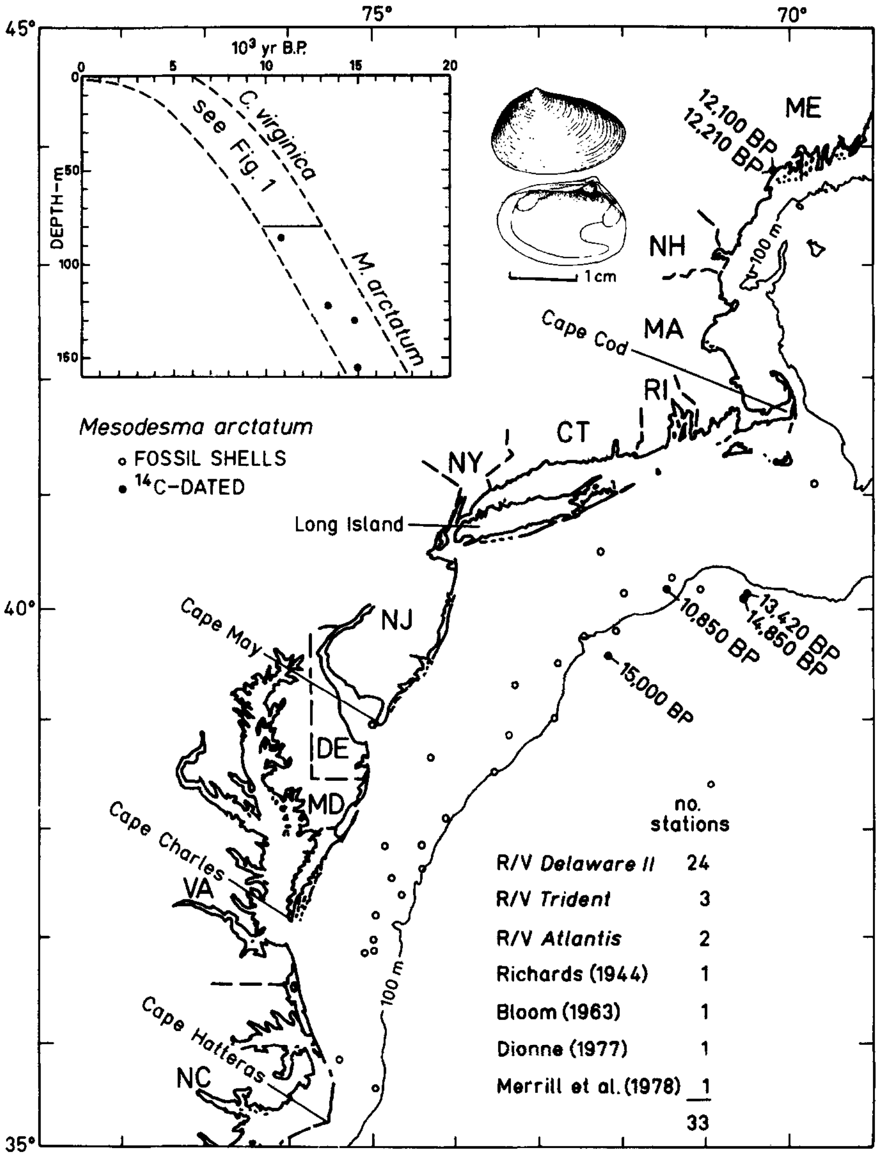

FIG. 2. Areal distribution of fossil shells and radiocarbon-dated shells of *Mesodesma arctatum* on Atlantic continental shelf and slope in a plot similar to that of Figure 1. Insert at top left indicates age–depth distribution of radiocarbon-dated fossils with respect to those for *C. virginica*.

northern propellor clam ranges from Labrador to Rhode Island and is moderately common offshore to 165 m. Occasionally, it is found in fish stomachs. A live specimen was taken off Block Island, RI, at a depth of 48 m at the southern limit of its range. A relict specimen was obtained east of Assateague Island, MD, in 59 m depth.

Thracia septentrionalis (*Jeffreys, 1872*). Jeffreys' thracia lives between Greenland in 110 m and Block Island, RI, in 52 m depth. A live specimen was obtained off Block Island at a depth of 47 m at the extreme southern limit of its reported range. Another fresh shell came from off Long Island, NY, in 52 m depth. Relict specimens were found farther south, off Ocean City, MD, and off Cape Henry, VA, in depths of 37 and 51 m, respectively.

Odostomia smithii (*Verrill, 1880*).

Smith's odostomia is known only from "south of Martha's Vineyard, MA, 85 to 146 fathoms (154 to 266 m)" (Abbott, 1974, p. 299). Fossil forms were collected off Barnegat Inlet, NJ, and Cape Henry, VA, in depths of 75 and 36 m.

Former Warm-Water Environments

Sea levels rose to about 5 m below the present levels about 5000 yr B.P. when most of the Pleistocene glacier ice had returned its meltwater to the ocean (Emery and Uchupi, 1984, Fig. 206). Afterward, sea level underwent variations of only a few meters in response to both widespread episodic warming and cooling of the atmosphere and to relative changes of land level. The higher temperatures marked a long climatic optimum commonly considered to have occurred between about 6000 and 4000 yr B.P. and shorter ones from about 2500 to 1000 yr B.P. and from about 300 yr B.P. to the present. The latter two warm epochs were separated by the Little Ice Age.

Our mollusk collections from the Atlantic shelf and upper slope contain several species whose fossil and subfossil shells are far north of that of their living representatives:

Diplodonta verrilli (*Dall, 1899*). The most abundant of the mollusks that lived north of their present range during at least the Holocene, this is a smooth thin-walled ovate pelecypod rarely larger than 4.0 cm diameter, 2.0 cm width, and less than 0.1 cm wall thickness. Recovery stations of fossil shells range between Long Island, NY, to off South Carolina (Fig 3). Immature live specimens (2 to 9 mm in diameter) were found at seven stations (Table 2), at five of which they were present as single specimens per station; they were considered adventitious and unlikely to reach maturity for reproduction. Probably they were brought by currents from more southerly sources. Positions on outer and inner shelf may be functions of shifting axis of the Gulf Stream. Live specimens or fresh valves have been reported between South Carolina (Merrill and Petit, 1969) and the northwestern Gulf of Mexico (Odé, 1977). Water depth for most (79% to 57 stations) fossil and immature forms is between 40 and 120 m. The four shallowest stations (less than 36 m depth) are south of Cape Hatteras (Fig. 3, Table 2). Only seven stations are deeper than 140 m; five of them are on the outer continental shelf, one at 183 m is on the upper continental slope, and one at 1615 m is on the upper continental rise. This deepest station, with six specimens, may have received them from a turbidity current that carried them down the continental slope far beyond their usual shelf habitat. Most samples contain only a few specimens, six stations having 10 or fewer; these include nine R/V *Gosnold* stations, where only a large clam-shell sampler was used. At each of six stations (*Delaware* 60-7) where the Digby dredge was towed through a kilometer or more of bottom sediments, 30 or more specimens were recovered.

Argopecten gibbus (*Linné, 1758*). The calico scallop's northern range until recently has been reported as off North Carolina. Abbott (1954, 1974) revised the range to "off Maryland to Florida and south Texas to Brazil. . . . Lives in warm, open marine waters from 50 to 200 fathoms [90 to 366 m]." Commercial beds are common along the south Atlantic coast south of Cape Hatteras in depths of 15–35 m. Abbott's (1974) Maryland record probably is adventitious because extensive fishery investigations in the Middle Atlantic Bight have failed to produce live specimens north of North Carolina. Bush (1885) reported live *A. gibbus* north of Cape Hatteras in 88 m. We collected live specimens at three stations farther north to off Albemarle Sound, NC, about 24 km north of Cape Hatteras. Fossil calico scallop shells were taken at 22 stations from Cape Hatteras, NC, to off Rehoboth Bay, DE, in depths of 26–146 m. Shells from only 4 stations were from depths greater than 75 m, whereas shells from 11 stations were from depths less than 37 m.

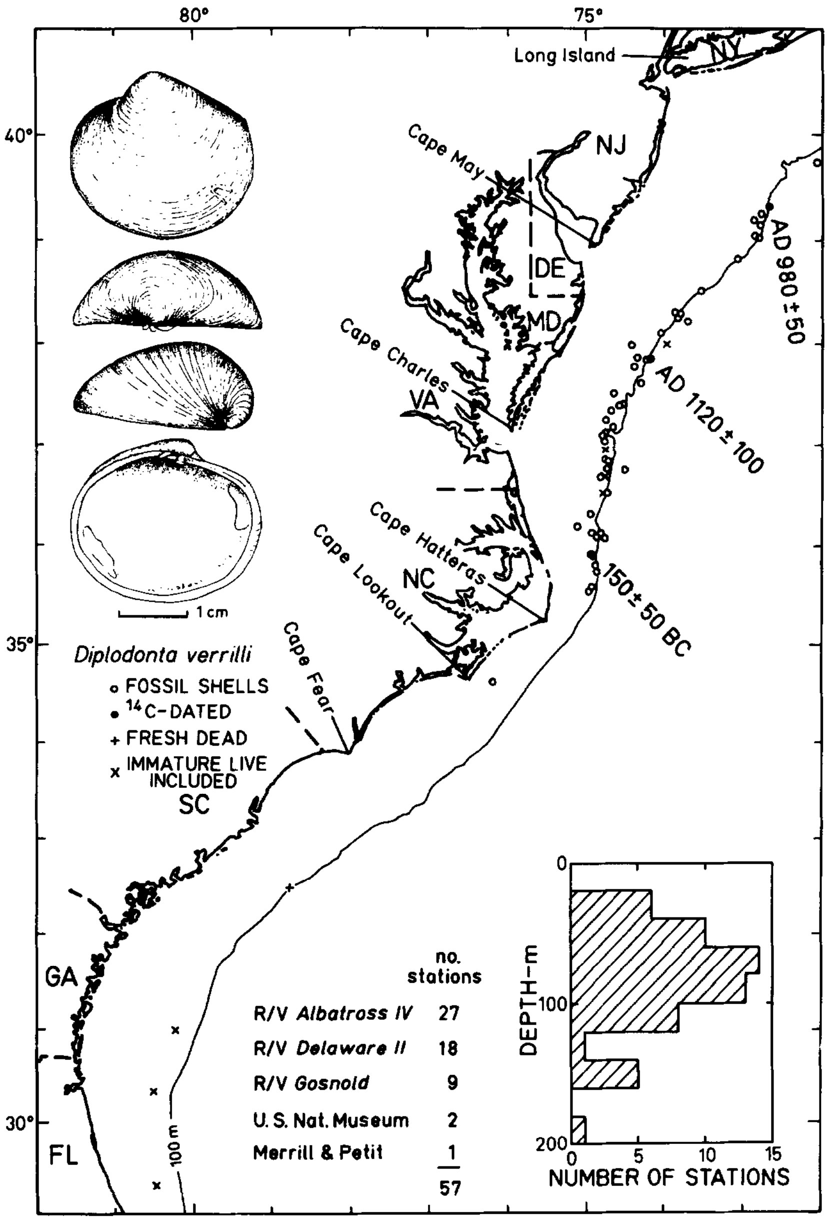

FIG. 3. *Diplodonta verrilli*. Areal distribution of fossil shells, radiocarbon-dated shells, and immature live specimens on Atlantic continental shelf and slope. Insert at lower right corner is histogram of depth frequency.

Cyclopecten nanus (*Verrill and Smith, 1897*). The dwarf round scallop ranges from Virginia to Texas and south to Puerto Rico and Brazil in depths of 40–538 m. It is a common scallop less than 1 cm at adult size. Fossil shells were from seven stations off Indian River Inlet, DE, to southeast of Currituck Beach, NC. Two stations were in depths of 35 and 55 m, the remaining five in 64–113 m.

Noetia ponderosa (*Say, 1822*). The ponderous ark ranges from Virginia to Florida and on to Texas. It is a common shallow-water sand dweller recorded alive to 14 m. South of Cape Hatteras, NC, shells of this nearshore species are common on beaches.

TABLE 2. POSITION AND OTHER DATA FOR SAMPLES CONTAINING FOSSIL *Diplodonta verrilli*

							Libby		
Ship[a]	Cruise	Station	North Lat.	West Long.	Depth (m)	Number shells	WHOI Lab No.	Age (yr B.P.)	Calendar date
Del.	60-7	2-5	39°44′	72°04′	146	A few			
Alb.	79-04	45-28-1	39°20′	72°42′	101	34	676	1650 ± 50	A.D. 980 ± 50
Alb.	79-04	46-28-2	39°14′	72°47′	90	2			
Alb.	79-04	47	39°11′	72°52′	86	6			
Alb.	79-04	48-24-1	39°08′	72°48′	91	9			
Del.	60-7	3-4	39°02′	72°52′	112	A few			
Del.	60-7	3-5	39°01′	72°49′	146	A few			
Alb.	79-04	65-24-3	38°50′	73°04′	91	A few			
Del.	60-7	43-A24	38°32′	73°31′	84	A few			
Del.	60-7	4-3	38°19′	73°51′	73	A few			
Del.	60-7	4-4	38°18′	73°47′	110	A few			
Alb.	79-04	100-1-20	38°15′	73°49′	77	21			
Del.	60-7	4-5	38°13′	73°42′	146	A few			
Alb.	67-20	70-2	38°06′	74°02′	97	3			
Gos.		1891F	38°00′	73°59′	129	2 (live, 3, 4 mm)			
Del.	60-7	4-5,A2	37°59′	74°27′	51	A few			
Alb.	79-04	116-15-8	37°51′	74°21′	57	10			
Alb.	79-04	117	37°51′	74°10′	101	60	629	1470 ± 40	A.D. 1120 ± 100
Alb.	79-04	117-16-1	37°51′	74°10′	101				
Alb.	79-04	118-15-1	37°47′	74°23′	62	1			
Del.	60-7	5-4	37°37′	74°19′	110	A few			
Alb.	79-04	128-10-1	37°30′	74°39′	55	9			
Alb.	67-20	66-2	37°23′	74°34′	95	3			
Alb.	79-04	130-12-2	37°23′	74°32′	97	40			
Alb.	79-04	131-11-4	37°21′	74°41′	57	3			
Alb.	79-04	132-11-5	37°14′	74°45′	57	6			
Alb.	79-04	133-12-1	37°11′	74°39′	85	12			
Alb.	79-04	49	37°07′	72°47′	117	16			
Del.	60-7	6-5,A17	37°06′	74°48′	62	A few			
Alb.	79-04	134-16-6	37°02′	74°47′	64	30			
Gos.		1880	36°57′	74°45′	82	1 (live, 2 mm)			
Del.	60-7	6-3	36°51′	74°45′	73	A few			
Gos.		1879	36°50′	74°44′	77	2			
Alb.	79-04	140-11-7	36°46′	74°44′	66	1			
Gos.		2084	36°45′	74°30′	1615	6			
Gos.		1878	36°40′	74°45′	86	1 (fresh dead, 9 mm)			
Alb.	79-04	141-6-2	36°40′	74°49′	49	3			
Alb.	79-04	143-14-2	36°31′	74°43′	150	3			
Gos.		1877	36°31′	74°46′	96	8 (1 live, 3 mm)			
Del.	60-7	7-6,A12	36°20′	74°56′	53	A few			
Del.	60-7	7-2	36°11′	75°07′	37	A few			
Del.	60-7	7-3	36°09′	74°55′	73	A few			
Del.	60-7	7-4	36°08′	74°49′	113	A few			
Alb.	75-08	7-4	36°08′	74°52′	73	3			
Alb.	75-08	7-6	36°07′	74°46′	146	4			
Del.	60-7	7-8,A8	35°54′	74°55′	66	A few			
Alb.	75-08	7-8,A25	35°53′	74°55′	73	60±			
Del.	79-10	13	35°48′	74°54′	80	21			
Alb.	75-08	7-5	35°45′	74°52′	183	36	678	2620 ± 50	150 ± 50 B.C.

TABLE 2—*Continued*

Ship[a]	Cruise	Station	North Lat.	West Long.	Depth (m)	Number shells	Libby WHOI Lab No.	Libby Age (yr B.P.)	Calendar date
Alb.	75-08	7-8,A26	35°37′	74°56′	51	4			
Del.	60-7	8-7,A10	35°33′	74°58′	44	A few			
USNM	41530	2307	Off Cape Hatteras		79	10			
USNM	92611	2607	34°38′	76°12′	33	2			
Merrill and Petit (1969)			32°29′	78°47′	64	1 (fresh dead)			
Gos.		1708D	31°00′	80°15′	36	1 (live, 5 mm)			
Gos.		1697C	30°20′	80°30′	36	1 (live, 7 mm)			
Gos.		1691B	29°20′	80°29′	35	3 (live, 3, 4, 7 mm)			
USNM	193694	7106			23	1			
USNM	271308	2405	28°45′	85°02′	55	1			

[a] Del. = R/V *Delaware II* of National Marine Fisheries Service. Alb. = R/V *Albatross IV* of National Marine Fisheries Service. Gos. = R/V *Gosnold* of Woods Hole Oceanographic Institution. USNM = U.S. National Museum, catalog numbers of samples from early R/V *Albatross* cruises.

Porter and Wolfe (1971) collected dead shells of *N. ponderosa* off Cape Lookout, NC, to a depth of 73 m. Abbott (1974, p. 425) stated that "fossil specimens are rarely found on Nantucket, Massachusetts, beaches." Fossil specimens were dredged at two of our stations off Rehoboth Bay, DE, in 53 m and off False Cape, VA, in 33 m.

Aequipecten irradians sablensis (Clarke). Fossil shells of this bay scallop occur on Sable Island (see insert map at right middle of Fig. 1), but neither at Nova Scotia nor in the Gulf of St. Lawrence, presumably having been blocked by cold water north of Sable Island. It apparently is an extinct Holocene species (Clarke, 1965), but close relatives live along much of the Atlantic coast of Canada and the United States.

RADIOCARBON DATING OF FORMER ENVIRONMENTS

Shallow Water: Crassostrea virginica

Dating of former shallow-water environments that now are submerged is based mostly upon the abundant and large fossil shells of *C. virginica,* supported by the presence of at least six other species. Radiocarbon dates of *C. virginica* and studies of their significance for the Atlantic continental shelf and upper slope were provided by Medcof *et al.* (1965), Merrill *et al.* (1965), Clarke *et al.* (1967), Emery and Garrison (1967), Milliman and Emery (1968), Emery and Milliman (1971), and Macintyre *et al.* (1978). Plots of dates against water depths (Fig. 1) reveal a rather different depth–age relationship for shelf areas north and south of Cape Hatteras, as depicted by the lines that enclose most of the data points for each region. The two regions have rather different hypsometry (Emery, 1979), with a mean shelf depth between Cape Cod and Cape Hatteras of 44 m and between Cape Hatteras and Cape Canaveral of only 28 m.

Macintyre *et al.* (1978) attributed the shallower depth for a given shell age south of Cape Hatteras to movement of the shells by waves and currents. While transportation of loose shells after death of the mollusk undoubtedly can occur, we question whether transport for the necessary tens of kilometers can occur for such large heavy shells as *C. virginica* without seriously abrading the shells. An alternative, of course, is postdepositional deformation of the shelf level caused by glacial unloading, meltwater loading of the shelf, or tectonic deformation caused by plate movements; note that the Cape Hatteras region is a boundary between shelf segments that have different rates and directions of mean annual change of relative sea level or of land level (Aubrey and Emery, 1983).

Radiocarbon dates and present water depths outline the general curve drawn by rising sea level during the past 11,000 yr (Fig. 1, lower right). Supporting dates were provided by saltmarsh and freshwater peats beachrock, oolites, and fossil shells of other mollusks and some corals. The dates and depths provide a rough general guide to late Quaternary changes of sea level.

Cold Water: Mesodesma arctatum

Several studies of ^{14}C-dated cold-water mollusks on the shelf have been conducted. Emery and Garrison (1967) reported the presence of *M. arctatum* 86, 122, and 130 m depths off Massachusetts, where they were imbricated in layers within three cores and thus were judged to have been deposited in former shallow water where waves and currents caused the imbrication (MacIntyre *et al.*, 1978; Merrill *et al.*, 1978b). *M. arctatum* can tolerate colder water than can *C. virginica* and thus can provide older sea-level dates when the water was too cold for *C. virginica*. The ^{14}C ages were found to be 10,850, 13,420, and 14,850 yr B.P. (Table 1).

Richards and Ruhle (1955) described fossil shells in a layer within a core from the upper continental slope near the Hudson Canyon; among the shells were specimens of *M. arctatum*. A ^{14}C age of mixed shells was 15,000 ± 150 yr B.P., presumably the same as would have been obtained for its included *M. arctatum* shells. A shell layer now 27–30 m above sea level in the Presumpscot Formation of southwestern Maine also had shells of *M. arctatum*, and dated to 12,100 ± 100 yr B.P. (Bloom, 1963). Later, Davis (in Merrill *et al.*, 1978b) collected specimens of this species from Bloom's locality and reported an age of 12,210 ± 120 yr B.P. for them, closely confirming the date for the mixed shells. Lastly, Dionne (1977) reported the presence of fossil shells of *M. arctatum* in a gravelly sand 4 m above sea level at the south side of the St. Lawrence Estuary; he reported these shells to have a ^{14}C age of 2240 ± 140 yr B.P.

Except for Dionne's shells, the *M. arctatum* specimens have ^{14}C ages of about 11,000 to 15,000 yr B.P., corresponding to latest glacial times when the climate was cold. Dionne's specimens evidently lived much later than the ones off eastern United States and, in fact, *M. arctatum* still lives in the Gulf of Maine and farther north. The general depth–age relationship of *M. arctatum* off the United States (Fig. 2) forms a good extension of that exhibited by *C. virginica* for north of Cape Hatteras, confirming the belief that the shell beds were deposited in shallow water.

Warm Water: Diplodonta verrilli

Three *Albatross* stations having fossil shells of *D. verrilli* were chosen on the basis of position (Fig. 3), largest number of fossil shells (Table 2), and absence of erosion and calcareous encrustations on the shells. These stations are 45-28-1 at the north, 117 at the middle, and 7-5 at the south. Twenty to 30 shells from each station were selected, any encrustation was chipped away, the outer 30% was removed with 2 *N* HCl, and the cleaned shells were ground; their carbon was converted to CO_2 and then to acetylene and measured in gas proportional beta counters (Griffin and Druffel, 1985). Radiocarbon results are corrected for isotope fractionation to a $\partial^{13}C$ of −25o/oo (Stuiver and Polack 1977). For station 45-28-1, radiocarbon analysis of *D. verrilli* revealed an apparent age of 1650 ± 50 yr B.P. (before 1950). For station 117 the result was 1470 ± 40 yr B.P. and for station 7-5, 2620 ± 50 yr B.P. These apparent ages were converted to calendar dates based upon a calibration scale of marine samples (Stuiver *et al.*, 1986), considering that the fixed reservoir correction (apparent age of the preindustrial surface mixed layer of the ocean with respect to that of atmospheric carbon dioxide) was about 200 yr older for our study area (Druffel and Linick, 1978; N. Tanaka, personal communication, 1986). We obtained a calendar date for the youngest sample of A.D. 1120 ± 100, and calendar dates for the older samples of A.D. 980 ± 50 and about 150 ± 50 B.C.

Confirmation of the dates for the warm-water *D. verrilli* is provided by radiocarbon ages of 1800 ± 125 and 1432 ± 125 yr B.P. for two specimens of *Aequipecten irradians sablensis* Clarke (Clarke *et al.*, 1967). Calibrated dates, using the convention adopted above, are A.D. 850 and A.D. 1190 (Table 3), within the range for our *D. verrilli* results. Note that water temperatures in the Middle Atlantic Bight at these dates probably were higher than those at Sable Island.

The dates of 150 B.C. to A.D. 1120 for *D. verrilli* from depths of 101 to 183 m on the continental shelf between Long Island and Cape Hatteras and of A.D. 850 to A.D. 1190 for *A. irradians sablensis* on Sable Island are much younger than the main climatic optimum, altithermal, or Hypsithermal of 7000 to 4500 yr B.P. advocated by Antevs (1953), 9600 to 2600 yr B.P. by Deevey and Flint (1957) and others, and somewhat older than the Little Ice Age that may have begun about A.D. 1300 (Grove, 1979; Lamb, 1982; Porter, 1986). We suggest that they may denote a period of relatively warm water on the continental shelf that corresponds with warm climate. Obviously, the dating of many additional samples of *D. verrilli* may define possible variations of age with latitude and water depth, and more precisely determine age ranges.

TABLE 3. STABLE ISOTOPE MEASUREMENTS FOR *Diplodonta verrilli* SAMPLES

Ship	Cruise	Station	^{18}O	^{13}C
Alb.	79-04	45-28-1	+1.34	+0.86
			+1.39	+0.67
Alb.	79-04	117	+1.55	+0.90
			+1.39	+0.97
Alb.	75-8	7-5	+1.50	+0.78
			+1.29	+0.82

Evidence from fossil mollusks of the continental shelf that bear upon the main climatic optimum are very scant. To our knowledge it consists only of ^{14}C dates for shells of *C. virginica* collected from beaches of Sable Island off Nova Scotia, where living specimens are unknown (Clark *et al.*, 1967). These authors provided dates for three of their specimens: GSC-635, 5650 ± 140 yr B.P. and 5320 ± 140 yr B.P.; no number, 4710 ± 120 yr B.P.; and GSC-634, 3630 ± 130 yr B.P. and 3540 ± 140 yr B.P. This range, 5650 to 3530 yr B.P., lies within the range for the optimum suggested by Antevs (1953) and Dewey and Flint (1957). Reasonable corrections for the age of water in which the mollusks grew and for variations in ^{14}C activity cannot greatly affect the radiocarbon ages.

Cold Water: Little Ice Age

Cold-water mollusk species that lived later, during the Little Ice Age, were not investigated for the Atlantic Shelf of the United States, but their shells probably are present along the Pacific coast of Mexico. There, Hubbs (1959) and Hubbs *et al.* (1960, 1962) found many fossil shells of *Cryptochiton stelleri* (Middendorf) in Indian kitchen middens having ^{14}C ages ranging between 1600 ± 160 and 110 ± 150 yr B.P. Most were from localities where cold water is upwelled south of projecting coastal points, indicating that a once continuous coastal habitat was preserved temporarily and locally for a species whose distribution remains continuous only much farther north (between Point Conception and Japan). The 1600 yr B.P. oldest age after correction for ^{14}C age of ocean water and for past ^{14}C activity corresponds with a date of about A.D. 1000, and most of the more frequent ages are between 1100 and 600 yr B.P. According to Berger *et al.* (1966), the age of upwelled water off Baja California during the 1950s (prebomb) was 240 ± 80 yr B.P. Thus the range of corrected ages is 860 to 360 yr B.P., or A.D.

1210 to A.D. 1600, (Stuiver, 1982), well within the span of the Little Ice Age.

ESTIMATION OF LATE QUATERNARY WATER TEMPERATURES

Mollusks deposit more of their shell $CaCO_3$ during the relative warm summer months, as shown by thicknesses of seasonal increments and by measurements of the stable isotope ^{18}O (Epstein and Lowenstam, 1953; Jones and Williams, 1984; and others). This means that if we can reliably determine localities for modern growth of *M. arctatum* in high latitudes and of *D. verrilli* in low latitudes, we can use charts of seasonal temperatures of modern bottom waters on the continental shelf and upper slope to learn the reasonable summer temperature for their growth during late Quaternary. Such charts have been compiled for the Atlantic shelf between the tip of Florida and Cape Cod by Walford and Wicklund (1968) and for New York to middle Nova Scotia by Colton and Stoddard (1973). We compiled similar charts for the Gulf of Mexico from temperature–depth contours assembled by Robinson (1973) and for the Gulf of St. Lawrence and the shelves off Newfoundland from temperature–depth averages for 1° squares listed in unpublished files of Woods Hole Oceanographic Institution. Contours for bottom temperatures of all these areas during August of years between about 1940 and 1970 are presented in Figure 4.

Our best information for areas of growth of *M. arctatum* is from Long Island northeastward, and for *D. verrilli,* inshore at Cape Hatteras southwestward to a wider band offshore. The summer average modern bottom water temperatures for these two areas are estimated to be 5° to 10°C and 20° to 25°C, respectively. We can infer that the same temperatures existed at the sites where fossils of these mollusks were recovered at the radiocarbon-dated times of their growth (Tables 1, 2, and 3; Figs. 2 and 3). The isotherms of shelf bottom water are so nearly parallel with the shore of the Middle Atlantic Bight that the best we can do is to infer the paleotemperatures during the past 15,000 yr in the entire area as a single unit between Cape Cod and Cape Hatteras (Fig. 4).

Some confirmation may be provided by results of analyses for ^{18}O (Table 3). Average $\partial^{18}O$ is $+1.41$, with no significant difference between different samples. This is heavier than annually averaged $\partial^{18}O$ in modern *Spisula solidissima* reported by Williams *et al.* (1982) from the Middle Atlantic Bight (average = 0.00 at an average

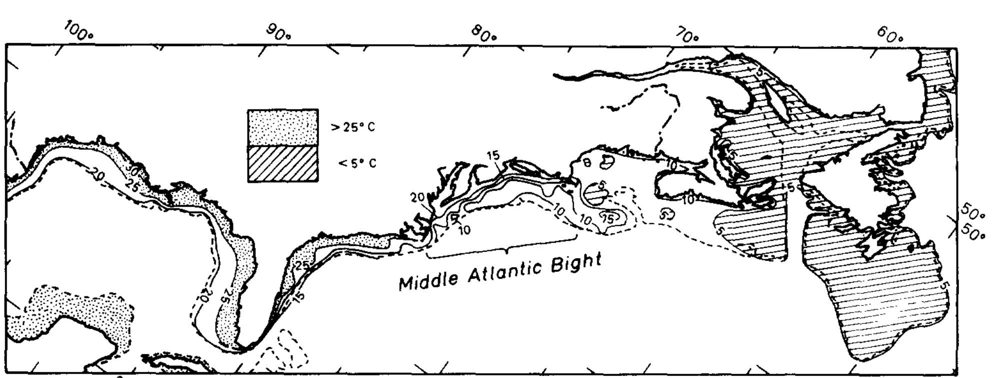

FIG. 4. Bottom water temperatures at 5° intervals compiled for the continental shelf areas of the Gulf of Mexico (Robinson, 1973), Atlantic shelf off United States (Walford and Wicklund, 1968), Atlantic shelf off Nova Scotia (Colton and Stoddard, 1973), and Gulf of St. Lawrence and shelf off Newfoundland (unpublished temperature–depth averages by 1° squares from files of Woods Hole Oceanographic Institution). Most of these temperature data are averages for about 1940 to 1970.

surface sea temperature of 11°C). Our average of +1.41 also is heavier than that expected from equilibrium precipitation of aragonite in this area at 20° to 25°C, or −0.3 to +0.6o/oo (Druffel and Benavides, 1986). *D. verrilli* contains more than 99% aragonite, according to X-ray diffraction analysis of sample 117 by L. J. Poppe of the U.S. Geological Survey in Woods Hole, MA. The $\partial^{13}C$ (Table 3) values average +0.83o/oo, significantly lighter than values expected for equilibrium precipitation (about +4.3o/oo). Perhaps this is a vital effect that includes incorporation of metabolic CO_2 that influences only the carbon isotopes. Our range of ^{18}O and ^{13}C values lies somewhat outside the area reported for mollusks by Swart (1983).

The paleotemperature curve for bottom water of the continental shelf resembles those for surface waters over the continental slope and of the open ocean about 3500 km farther east (Fig. 5). Temperature increase of shelf water after glacial times appears to be larger and later than for waters farther offshore, perhaps because of continued flow of the cold Labrador Current along the shelf after the time of atmospheric warming of surface waters beyond the shelf. In support are the results of studies mainly of planktonic foraminiferans by McIntyre *et al.* (1976), which show that sea surface temperatures at the glacial maximum possibly 18,000 years ago were 18°C lower than now on the open ocean off Nova Scotia, 6° to 16°C lower off the Middle Atlantic Bight, and 2°C lower off eastern Florida.

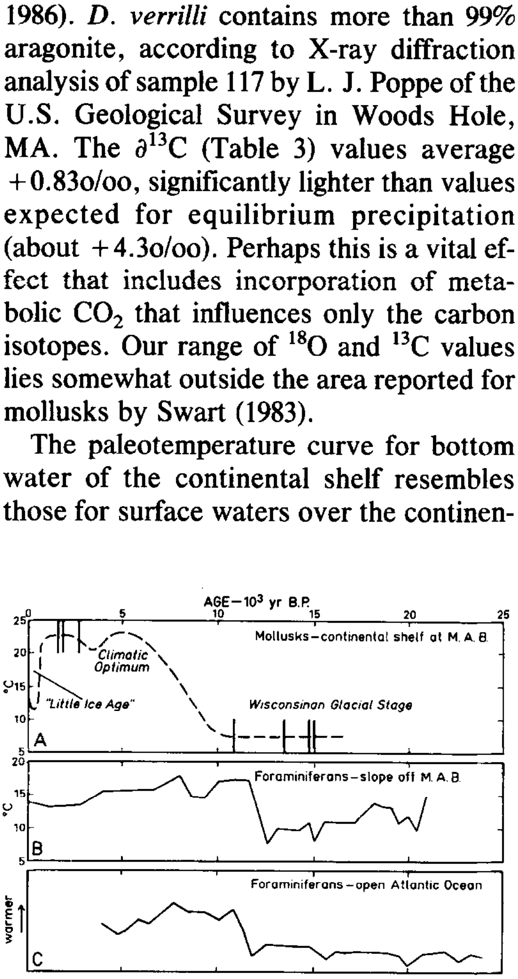

FIG. 5. Estimated paleowater temperatures. (A) Temperatures of bottom waters of the outer continental shelf in the Middle Atlantic Bight (between Cape Hatteras and Cape Cod) during Augusts of the past 15,000 yr inferred from present August temperatures in areas of present growth of *Mesodesma arctica* and *Diplodonta verrilli* transferred to sites of fossil shells (Figs. 2 and 3) at radiocarbon dates of their growth (Tables 1 and 2). Uncertainty is indicated by error bars on temperatures and dashing of temperature–time curve. (B) Winter temperatures of surface waters above the continental slope based upon planktonic foraminiferans (Balsam and Heusser, 1976). (C) Relative annual temperatures in surface waters of open Atlantic Ocean (Lat. 41°24′N, Long. 40°06′W) based upon ratios of warm-water and cold-water foraminiferans (Ericson and Wollin, 1956).

CORRELATIVE EVIDENCE OF HOLOCENE CLIMATE CHANGES

Two main kinds of information are available for testing the degree of correlation of climate with water temperature and ^{14}C age of mollusks on the Atlantic continental shelf. One of them is estimation of former temperatures inferred from organic remains and from changes in glacier areas and compositions. Limitations are set by slow rates of deposition that increase the time span of individual samples, by regional distributions of deposits such as long-lived trees, bogs, and glaciers, and by destruction of the record by erosion, decomposition, or melting of ice. The other kind of information comes from human activities. Best are long records of past temperatures, snowfalls, sea ice, and storms, but reliable observations rarely extend beyond a few hundred years, and they are nearly restricted to the European coast of the North Atlantic Ocean. Both kinds of information come from different geographic regions, mainly continental; thus no one site or kind of information can be expected to directly represent the climate over the Atlantic continental shelf. Moreover, there are only a few worldwide comparisons of climatic datings based upon different kinds of evidence [for example, glaciers (Porter, 1986)], and historical records (Lamb, 1977, 1982). Detailed compilation and comparison of data on late Quaternary climates is beyond the scope of our studies of mollusk distributions and optimum growth temperatures.

CONCLUSIONS

Shipboard and laboratory studies show that relict sediments of the continental shelf of the Middle Atlantic Bight contain many relict mollusk shells that denote changes in the environment during the past 15,000 yr. These are intermixed with far more numerous mollusks that live in harmony with present water depths, temperatures, and other environmental parameters. Special sampling and careful sorting and identification show the presence of three groups of relict species. Most abundant are shells of species that lived intertidally but remain near their growth sites where they were left by rising postglacial sea level. Largest and most common of these is the eastern oyster, *C. virginica*, whose ^{14}C ages, present water depths, and associated remains of flora and fauna trace this rise of sea level. The second group is composed of shells of species that now live only farther north, most numerous of which is the Arctic wedge clam, *M. arctatum*. Their radiocarbon ages are about 11,000 to 15,000 yr B.P., indicating habitation here during late Quaternary when sea level and water temperature began to rise. Lastly are shells of species that now live only farther south, most numerous of which is *D. verrilli*. Their ^{14}C ages are about 1500 to 2600 yr B.P., indicating habitation here during a climatic optimum that occurred when postglacial sea level had reached about its present level. Confirmation of dates for warm water and near-present sea level is provided by fossil shells of *A. irradians sablensis* on Sable Island off Nova Scotia.

Comparison of present water temperatures in the Middle Atlantic Bight with those in areas inhabited by living *M. arctatum* and *D. verrilli* yields some information about paleotemperatures of waters on this shelf. It also indicates that care must be used to assess water-depth ranges of habitation by molluscan species on the basis of only living specimens. Similar relict mollusks must occur on other continental shelves of temperate regions. Their study by biologists, geologists, and radiochemists may provide considerable information about natural changes in the environment that must be considered when attempts are made to assess degrees of alteration of natural habitats by humans.

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