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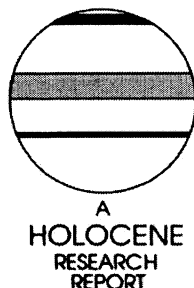
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An association of benthic foraminifera and gypsum in Holocene sediments of estuarine Chesapeake Bay, USA

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Abstract: Two cores of Holocene sediments recovered from the Cape Charles Channel of Chesapeake Bay yielded radiocarbon ages of about 6.8 to 5.8 ka for the lower intervals. Fossil foraminifera preserved in these lower sediments are dominated by species of *Elphidium*, which make up about 90% of the assemblage throughout, and probably signify deposition in hypersaline waters. *Buccella frigida* and *Ammonia beccarii* are the only other species commonly present. Hypersalinity of bottom waters seems to have been maintained by water-density stratification in a basin-like section of the channel. In core PTXT-4-P-1 transition to modern Chesapeake conditions, in which numbers of *Ammonia beccarii* exceed those of *Elphidium*, commenced about 400 years ago. In core PTXT-3-P-2 hypersalinity is further signified by the presence of abundant euhedral crystals of gypsum in association with the fossil *Elphidium*. This occurrence of gypsum is not attributed to palaeoclimatic aridity, but rather to inflow of groundwater from adjacent gypsiferous Miocene strata. The study shows that in palaeoclimatic investigations the significance of the presence of gypsum should be evaluated with caution – it does not necessarily signify an evaporative regime.

Key words: Chesapeake Bay, estuary, foraminifera, gypsum, Holocene, hypersalinity, palaeoclimate.

Introduction

Chesapeake Bay, also referred to as ‘the Chesapeake’, is situated on the eastern coast and is the largest estuary of the United States. From the north, where the Susquehanna River debouches into the estuary, it is more than 300 km to the bay mouth in the south, where the estuary interfaces with the Atlantic Ocean. Average width is about 20 km but the boundaries are irregular, with 19 major estuarine tributaries and several hundred lesser tidal creeks, that together have created more than 7000 km of tidal shoreline. The cores that are the subject of this paper were taken from Holocene sediments adjacent to the mouth of the tributary Patuxent River (Figure 1). The Chesapeake hosts a richly diverse fauna of marine invertebrates, fish and birds (Lippson and Lippson, 1997) and is thus of great economic and recreational significance.

The modern Chesapeake is the expression of the postglacial marine transgression into the coastal tract of the Susquehanna fluvial system. At the height of the last glacial, oxygen isotope stage 2, about 18 ka, when sea level was *c.* 130 m lower than it

is now (e.g., Chappell and Shackleton, 1986; Chappell *et al.*, 1996), the Susquehanna River flowed down its emergent valley and across more than 100 km of the exposed continental shelf before reaching the Atlantic Ocean. Subsequently, as global warming caused extensive melting of the continental ice sheets, sea level rose, submerging the continental shelf to the present coastline and flooding the coastal drainage system of the Susquehanna River. The culmination of this postglacial marine transgression about 7 ka gave rise to the Chesapeake Bay of today (United States Geological Survey, 1998).

A series of seismic investigations within the estuary has revealed much detailed information about the bathymetry and Quaternary sedimentation (Colman and Hobbs, 1987; 1988; Colman and Halka, 1989a; 1989b). An entrenched palaeochannel of the Susquehanna River is thought to have formed during the times of lower sea level that followed the last interglacial, oxygen isotope substage 5e, and particularly during the last (Wisconsinan) glaciation. Known as the Cape Charles Channel, it can be traced for the length of the estuary. Adjacent to the mouth of the Patuxent River, the Cape Charles palaeochannel is expressed as a deep, mid-bay channel which has an irregular profile. In the study area, water depth in the channel varies from 50 to 30 m, generally shallowing

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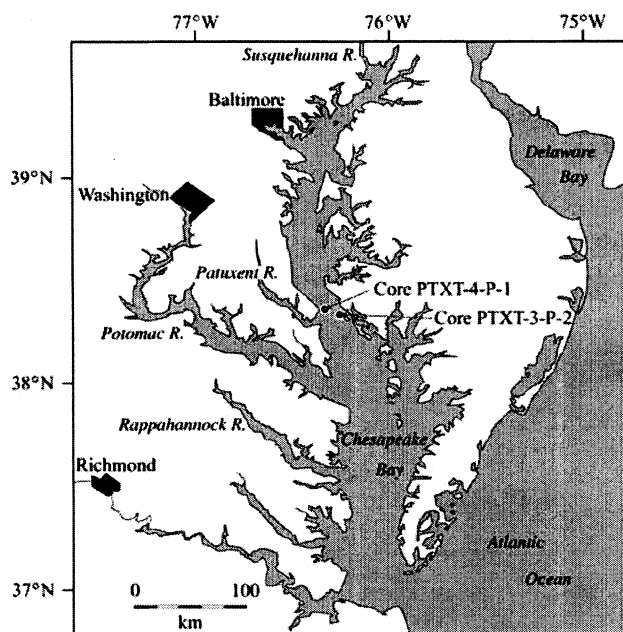


Figure 1 Map showing the outline of Chesapeake Bay and tributaries, and locations of the cores that are the subject of this paper. Core PTXT-4-P-1 (latitude $N38^{\circ}21.48'$, longitude $W76^{\circ}20.25'$) was taken in water 18 m deep. Core PTXT-3-P-2 (latitude $N38^{\circ}20.00'$, longitude $W76^{\circ}18.58'$) was taken in water 22.5 m deep.

southward. Two additional palaeochannels that represent earlier Pleistocene lowstands of sea level, such as oxygen isotope stages 6 and 8, have also been recognized.

Underlying the postglacial (mostly Holocene) and older Pleistocene sediments are Tertiary strata into which irregular Quaternary unconformities have been cut (Figure 2). Land-based geological mapping suggests that these strata are fossiliferous marine sediments of Miocene age. For example, the St Marys Formation of Middle to Late Miocene age crops out above sea level on the western shore of the Chesapeake north

of the Patuxent River, and along the southern bank of the Patuxent River (Shattuck, 1904; 1907). It is likely that in the study area the deep Cape Charles palaeochannel has been cut into the St Marys Formation (Colman and Halka, 1989b).

The seismic studies referred to above suggest that most of the pre-Holocene deposits were eroded during lowstands of sea level and that only remnants of the Pleistocene sediments have been preserved in the deepest parts of the palaeochannels. Postglacial sedimentation has been most pronounced in the palaeochannels. The lowermost sediments are fluvial gravels and coarse sands that were deposited during the erosive episode of the stage 2 sea-level lowstand. As sea level rose following the Wisconsinan glaciation, relatively finer-grained sediments were deposited in the fluvial channels in response to rising base level. Subsequently, marine incursion into the valleys saw a transition to estuarine conditions and deposition of mud, muddy sand and peat. The results of the most recent seismic studies are in accord with this scenario (Vogt *et al.*, 2000a; 2000b; Halka *et al.*, 2000).

At the bay mouth, sand derived from the mid-Atlantic inner continental shelf accumulated in response to the postglacial sea-level rise. Today, sediments are delivered to the bay mouth mostly by southerly longshore drift along the eastern coast, and thence into the bay by bayward net tidal transport. Thus, throughout the Holocene, an extensive prograding sand wedge has developed (Colman and Hobbs, 1987). This depositional feature, which forms a partial barrier at the bay mouth, has the potential to restrict circulation within the Chesapeake and to promote density stratification of waters within the channels. Also, locally thick deposits of sediment in the vicinity of the mouth of the Rappahannock River have completely filled the Cape Charles Channel. Thus there exist channel environments *c.* 40 m deep north of this area which similarly might lead to density stratification. Finally, sedimentation at the mouths of the major tributaries, such as the Patuxent River, has resulted in the formation of sill deposits which partly restrict interchange of waters.

Foraminifera are common throughout the modern sediments of the Chesapeake, its estuarine tributaries and the

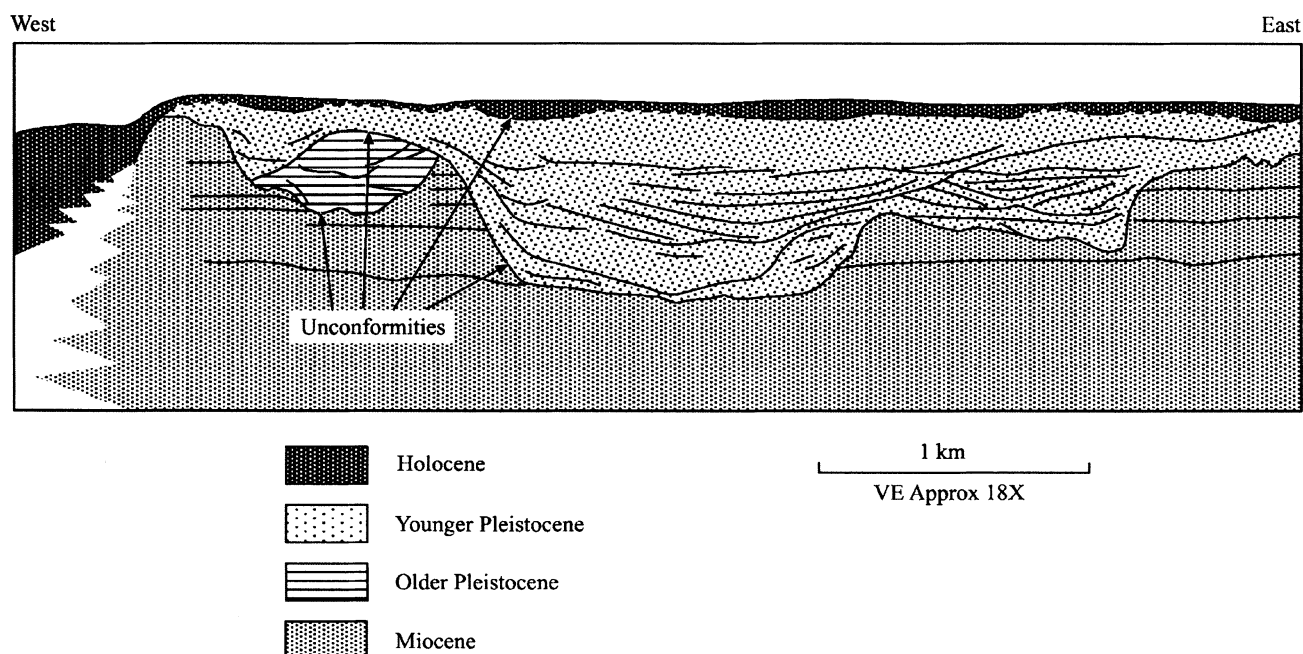


Figure 2 A typical Chesapeake submarine stratigraphic section, inferred from seismic data. The Cape Charles palaeochannel lies to the west. In the study area, the Miocene sediments are thought to include the St Marys Formation. After Colman and Hobbs (1988).

adjacent saline wetland marshes, and the distribution of their species has been the subject of several previous investigations (Buzas, 1974; Ellison *et al.*, 1965; Ellison and Nichols, 1970; 1976; Ellison, 1972; Nichols and Norton, 1969). The findings of these investigations and observations of the present authors lead to some general conclusions concerning the distributions of some selected species.

Buccella frigida is a species which is common in the coastal and shelf waters north of Chesapeake Bay (Culver and Buzas, 1980; 1981). Close to the bay mouth, foraminifera such as *B. frigida* are transported from the inner shelf into the estuary. Thus, the extent to which this species occurs in estuarine deposits is *prima facie* evidence of the marine influence in sedimentation. For most of the Holocene, *B. frigida* was an important component of the Chesapeake Bay foraminifera. From sediments recovered from the deep part of the Chesapeake Bay channel, core MD99-2209 due west of Washington, Cronin and Ishman (2000) found that, for the time interval 7000–2000 yr BP, *B. frigida* comprised up to almost 15% of the foraminiferal assemblage. In overlying younger sediments, numbers declined to 2–3% and the last appearances of the species in that core is dated at about 500 years ago. The consistent recorded occurrence of *B. frigida* during the early to middle Holocene probably signifies more saline and better-oxygenated waters than those of the modern bay.

Within the main estuary and its tributaries, *Ammonia beccarii* is common. (Other workers, such as Karlsen *et al.*, 2000, have referred the Chesapeake form of *Ammonia* to *A. parkinsoniana*). This species is well known for its tolerance to fluctuating and particularly low salinity, but there are established limits to environments in which it is viable. Growth and reproduction are possible only within a salinity range of 15–40‰ and temperatures of 42–45 °C are lethal (Bradshaw, 1957; 1961).

Species of *Elphidium* that have been identified as *E. clavatum* and *E. incertum* favour the more saline lower reaches of the estuary, but are absent at salinities <10‰ (Ellison and Nichols, 1970; 1976). Low-salinity sediments of tributaries and wetlands are characterized by an assemblage of agglutinated fauna in which species of *Ammobaculites* and related genera are dominant; other species commonly present include *Ammoastuta salsa*, *Miliammina fusca* and *Trochammina inflata*.

Scanning electron photomicrographs illustrating the common Chesapeake foraminifera are available in Ishman *et al.* (1999). Cronin *et al.* (2000) have applied the established environmental associations of these species to interpret distributions of fossil foraminifera (and other biota) within cored sediments of late-Holocene age. Thus they were able to infer a record of palaeosalinity, which in turn was taken as a proxy for rainfall and the extent of surface runoff into Chesapeake Bay.

Chesapeake Bay has long been acknowledged as a valuable natural resource which has been environmentally threatened by the activities of the c. 20 million people who now live within the immediate vicinity of this water body. Furthermore, anticipated changes in climate and sea level are issues which may impact significantly on coastal processes. In order that effective management strategies can be progressively implemented, the United States Geological Survey and other agencies have recognized the need to determine the long-term natural history of the Chesapeake. Thus a programme was established in which cores of postglacial sediment taken from the estuary were examined for the many physical, chemical and biological indicators of the Holocene palaeoenvironments (Cronin *et al.*, 1999).

Materials and methods

The work reported here details the foraminiferal records obtained for two exploratory piston cores taken from the

western side of the modern Chesapeake Bay channel near the mouth of the Patuxent River (Figure 1). Core PTXT-4-P-1 (latitude N38°21.48', longitude W76°20.25') was taken in water 18 m deep. Core PTXT-3-P-2 (latitude N38°20.00', longitude W76°18.58') was taken in water 22.5 m in depth. Both cores recovered >4 m of early- to middle-Holocene estuarine sediments, deposited within the Cape Charles palaeochannel during the final phases of the postglacial marine transgression.

Core PTXT-3-P-2 was taken in 1996 as part of an investigation of anthropogenic and climatic impacts on Chesapeake Bay for the past few centuries (Kerhin *et al.*, 1998; Cronin *et al.*, 1999). Although the younger sediments of this core contributed little within the timeframe of that study, it nevertheless recovered an early-Holocene succession which preserved significant assemblages of benthic foraminifera, and these constitute part of the materials for the present study. At the Maryland Geological Survey, X-radiographs of core PTXT-3-P-2 revealed the presence of molluscan shells and fragments in the interval 290–434 cm. The sediments consisted of 0–25% sand, 50–60% silt and 30–40% clay.

Seismoacoustic profiles at the site of core PTXT-4-P-1 revealed a succession of c. 13 m of Holocene sediments. The core recovered the uppermost 4.4 m of these deposits, in which sediments below 400 cm preserved significant numbers of middle-Holocene benthic foraminifera, complementing the faunal assemblages of the other core. Near the top of PTXT-4-P-1, c. 50 cm, there was a much younger horizon in which there were also significant numbers of foraminifera.

Both cores were sampled at 2 cm intervals for microfossil analysis. Samples were wet sieved over a 63 µ mesh and the washed and dried residues were set aside for microscopic examination. Each of the washed and dried residual samples was sieved to provide two grain-size fractions for microscopic examination, >250 µ and 125–250 µ. Using conventional micropalaeontological techniques, all observed foraminiferal tests were extracted from the larger size fraction and transferred to a standard microfossil slide. The number of tests in this fraction of a sample provided an indication of the overall abundance of foraminifera in the sample. From the smaller size fraction, small amounts of sediment were randomly taken and sprinkled into a tray, and all observed tests were transferred to the microfossil slide. This procedure was repeated either until >200 tests had been isolated or until all tests had been picked from the subsample. The microscopically extracted tests were identified and counted. Subsequently, the relative abundances of species were determined as percentages of the subsample assemblages and expressed diagrammatically.

Fossil molluscs (*Mulinia lateralis*) and supplementary foraminifera from the cores were subjected to radiocarbon analysis through the US Geological Survey Graphite Laboratory and Lawrence Livermore Accelerator Mass Spectrometer, Livermore, California.

Results

Foraminifera were significantly present for most core samples in the bottom metre of PTXT-3-P-2 (Figure 4). *Elphidium* dominated the assemblages; it was the only genus represented in the >0.250 µ size fraction and on average it constituted c. 90% of the finer fraction. *Buccella frigida* and *Ammonia beccarii* were present in most samples, but rarely did they constitute more than a few percent. The most abundant occurrence of *B. frigida*, a species signifying marine influence, was 12% for the sample at core depth 416–418 cm. Effectively, there were no other species present and significantly there were none of

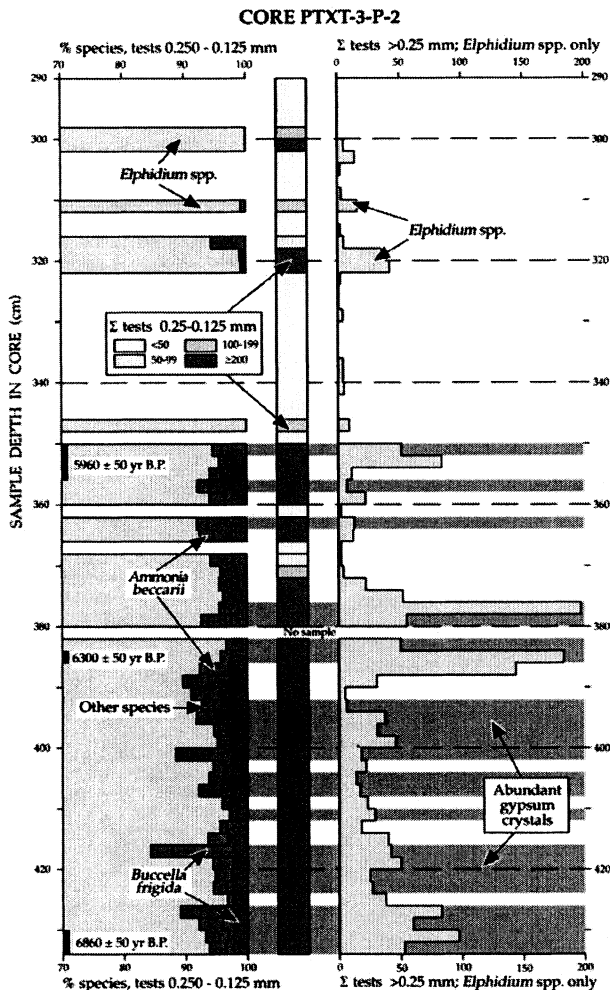


Figure 3 Distribution of foraminifera within the sampled intervals of core PTXT-3-P-2 together with uncorrected radiocarbon ages. The right column shows absolute numbers of tests $>0.250 \mu$ in each sample. These numbers are proportional to the density of tests in the sample and only *Elphidium* spp. was represented. The left column shows the relative abundance of *Elphidium* spp., *Ammonia beccarii* and *Buccella frigida* in the grain-size fraction $250-125 \mu$. Note that the percentage scale commences at 70%. *Elphidium* spp. generally constitutes $\geq 90\%$ of assemblages, signifying ongoing hypersalinity. *B. frigida* originates from the northeastern continental shelf. The low numbers of this species signify little direct inflow of Atlantic water. Low numbers of *A. beccarii* can be attributed to extreme hypersalinity. The middle column indicates the numbers of tests counted for the samples. Percentages are not given where < 50 individuals were present. The grey shading indicates the presence of abundant euhedral crystals of gypsum.

the agglutinated fauna that are associated with waters of low salinity. Between 350 and 300 cm the core samples contained fewer tests, and above 300 cm foraminifera were rare or absent. Paucity of tests can perhaps be attributed to increased rates of sedimentation rather than an absence of foraminifera.

Crystals of gypsum were conspicuously present in many of the lower core samples (Figure 3). They were present in both the sediment grain-size subsamples and ranged in size to about 1 mm in length. These crystals were mostly euhedral with sharp edges and terminations, transparent and free of included matter.

In core PTXT-4-P-1, samples below 400 cm were similar to those of PTXT-3-P-2 in that *Elphidium* was dominant, and *A. beccarii* and *B. frigida* were minor components of the fauna (Figure 4). However, there was no evidence of gypsum. The

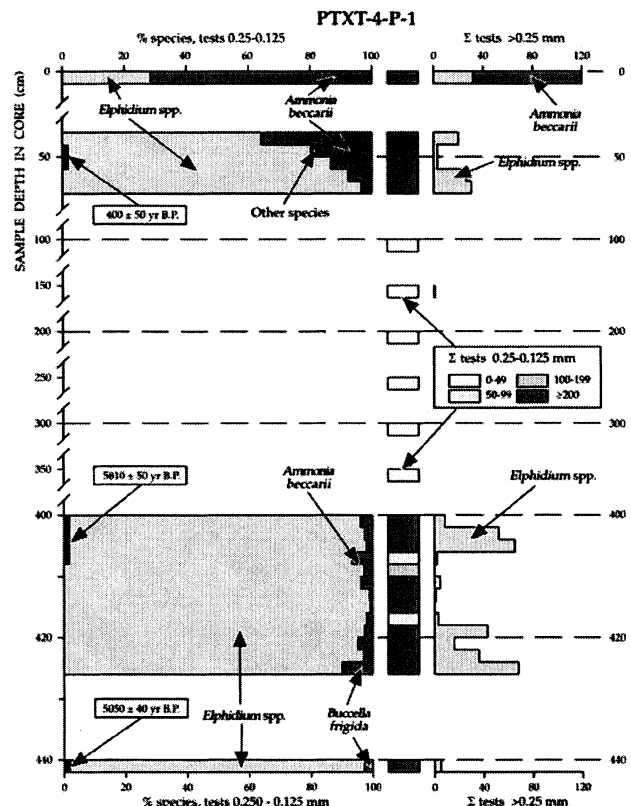


Figure 4 The scheme for this figure is similar to that for Figure 3, except that the full percentage scale is shown for the left column. For the lower core intervals *Elphidium* spp. again constitutes $\geq 90\%$ of assemblages, signifying hypersalinity. In the core interval 46–56 cm, for which there is a radiocarbon age of 400 ± 50 yr BP, the samples record a trend towards dominance of *A. beccarii*, a situation which is clearly apparent in the modern sediment.

surface sample (top of core) revealed that *A. beccarii* is dominant over *Elphidium* in the modern environment and the five samples around 50 cm clearly illustrated part of the transition to the present situation about 400 years ago. The 'other species' refers mostly to a few individuals of *Ammobaculites* sp. Again, samples in which foraminifera were rare or absent may signify increased rates of sedimentation.

Radiocarbon ages derived from analyses of fossil molluscs (*Mulinia lateralis*) and foraminifera (Table 1) indicate that the older sediments recovered by the cores were deposited in the early to middle Holocene. Because of uncertainties surrounding application of the marine reservoir correction factor to ages derived for estuarine shell materials (Alan Hogg, personal communication, in Cann *et al.*, 2000b), ages are expressed as uncalibrated values.

Discussion

Significance of *Elphidium*

The taxonomy of the morphologically variable *Elphidium* species that inhabit the modern Chesapeake, and which are preserved as fossils in Holocene sediments of the bay, remains a matter for debate. *E. excavatum* in the sense of Miller *et al.* (1982) has several formae (=ecophenotypes) which could accommodate the observations of Ellison and Nichols (1970; 1976). More recently, Hayward *et al.* (1997) have also recognized a range of subspecies for *E. excavatum*, in particular *E. excavatum clavatum* and *E. excavatum*

Table 1 Radiocarbon analyses of samples of mollusc shells and foraminifera from cores PTXT-3-P-2 and PTXT-4-P-1. Because of uncertainties surrounding the magnitude of the value that might be applied to estuarine materials, radiocarbon ages are given without correction for the marine reservoir factor

Laboratory code	Core	Sample depth (cm)	Material analysed	¹⁴ C age (yr BP)
WW1295	PTXT-3-P-2	350–356	mollusc shell <i>Mulinia lateralis</i>	5960 ± 50
WW1296	PTXT-3-P-2	384–386	mollusc shell <i>Mulinia lateralis</i>	6300 ± 50
WW1297	PTXT-3-P-2	430–434	mollusc shell <i>Mulinia lateralis</i>	6860 ± 50
WW2304	PTXT-4-P-1	48–52	mollusc shell fragments	400 ± 50
WW2305	PTXT-4-P-1	400–408	mollusc shell fragments	5810 ± 50
WW2306	PTXT-4-P-1	440–442	mollusc shell fragments and foraminifera	5050 ± 40

excavatum. For these subspecies they have listed comprehensive synonymies which include references to *E. clavatum*, *E. incertum* and *E. articulatum*. In detailing the geographic distribution of their subspecies, Hayward *et al.* (1997) have included *Elphidium* species described by Cann and De Deckker (1981) from saline lakes in South Australia. Cann and De Deckker (1981) documented the ongoing survival of monospecific populations of *Elphidium* through the seasonal evaporative phases of ephemeral saline lakes. Cann *et al.* (2000a; 2000b) have subsequently referred these forms of *Elphidium* to *E. articulatum* in the sense of Murray (1971). Thus, from Chesapeake Bay itself and from other localities, the evidence of dominant *Elphidium* sp. in fossil foraminiferal assemblages of extremely low diversity, that are preserved in the two Holocene cores, signifies that sedimentation probably occurred in hypersaline waters.

Significance of gypsum

The euhedral nature of the gypsum crystals in the lower part of PTXT-3-P-2, together with their clarity, signifies crystallization from above the sediment-water interface. The classic model for such chemical precipitation from marine waters in an estuarine or coastal lagoon setting requires evaporative concentration of salinity to about three times that of sea water. The ideal climate is one of high daily temperatures and little or no rainfall, with strong prevailing winds to promote evaporation. When the evaporative brine has reached the concentration at which gypsum begins to crystallize, maintenance of that concentration ensures that crystallization is continuous. The model therefore requires outflow of dense brine that would otherwise precipitate halite, together with inflow of replacement sea water. In the ideal physical setting, there is a sill at the mouth of the lagoon or estuary that restricts access to the ocean and provides potential for density stratification. Thus, a bottom layer of dense brine from which gypsum crystallizes is overlain by a upper layer of evaporating but less dense sea water.

The core site for PTXT-3-P-2 is in the main channel of Chesapeake Bay. Irregular sedimentary infilling of the Cape Charles Channel has ensured that the longitudinal profile of the channel has a number of elongate basins that have the potential for density stratification of saline waters. At the bay mouth there is a restricting sill in the form of a sand wedge. Also, further up the estuary, opposite the mouth of the Rappahannock River, the main channel is blocked by sediment, with deeper water to the north.

In the central part of the modern Chesapeake, salinity is generally about half that of normal sea water (Lippson and Lippson, 1997), waters becoming less saline upstream in bodies such as the Potomac and Patuxent Rivers. Nevertheless, within the Patuxent River, and extending into the main channels of Chesapeake Bay, there is a pronounced salinity stratification which appears to be largely determined by the bathymetry

(Figure 5). This stratification pattern is maintained throughout the year, but is most pronounced in autumn when bottom-water salinity values are higher (Kincaid *et al.*, 1988). Thus the physical setting of the Chesapeake has environments where water-density stratification could have been established in the early Holocene.

In the lowermost sediments of core PTXT-3-P-2, the occurrence of gypsum crystals, together with an almost monospecific assemblage of *Elphidium*, signify that the water mass of the sedimentary environment was hypersaline. On the basis of this evidence, it would be reasonable to propose that *c.* 6800 years ago the Chesapeake had experienced an arid climate which persisted for about a thousand years. Webb *et al.* (1993) have reviewed lacustrine palaeo-water-levels and fossil pollen data, including those from several sites around Chesapeake Bay, as evidence of late-Pleistocene and Holocene palaeoclimates in eastern North America. They found that for the Chesapeake area the time of maximum warmth was about 6 ka when mean July (summer) temperatures were only 1–2 °C higher than those of today. Over the period 9 to 6 ka, annual precipitation apparently increased from about 1000 to 1200 mm; today the mean annual precipitation for the Chesapeake area is about 1200 mm. In the light of these findings of Webb *et al.* (1993) it is unlikely that any hypothesis of aridity for the Chesapeake at 6 to 5 ka could be sustained.

What then is the source of the gypsum that has been such a powerful distracter in this palaeoenvironmental investigation? Locally, groundwater within the Miocene St Marys Formation is known to be a potential source of saltwater intrusion, contaminating overlying aquifers by upward leakage (Phelan, 1987). The St Marys Formation crops out above sea level on the western shore of Chesapeake Bay north of the Patuxent

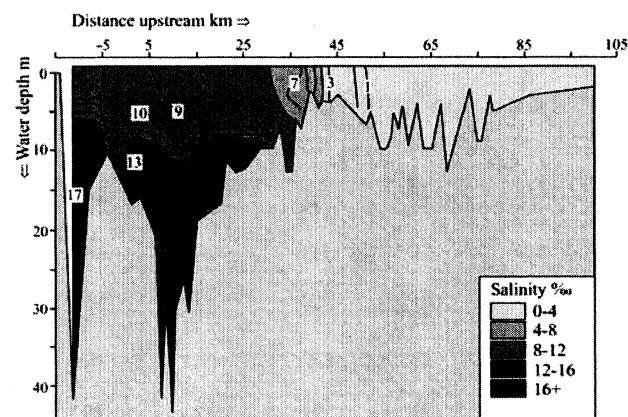


Figure 5 Longitudinal profile of the Patuxent River showing water salinity (‰) determined at a single slack-water event, summer 1984. Note the degree of stratification, especially within the channels of Chesapeake Bay on the left. This pattern is maintained throughout the year, but is most pronounced in autumn. After Kincaid *et al.* (1988).

River, and along the southern bank of the Patuxent River where the beds contain large clusters of radiating gypsum crystals (Shattuck, 1904; 1907). It is likely that at the site of core PTXT-3-P-2 the deep Cape Charles palaeochannel has been cut into the St Marys Formation (Colman and Halka, 1989b). Seepage of saline groundwater from these Miocene strata appears to have been the most likely source. A rising water table, concomitant with the postglacial transgression and increased precipitation, may have been a significant factor. Density stratification of waters within the channel was essential for concentration of the contaminant brine to proceed to the point of crystallization.

Conclusions

Sediments deposited about 6.8 to 5.8 ka, adjacent to the Patuxent River in the Cape Charles Channel of Chesapeake Bay, preserve assemblages of fossil foraminifera that are dominated by *Elphidium* spp. The species signify a palaeoenvironment of hypersaline waters that was at variance with those of the modern Chesapeake, and which did not undergo transition towards present conditions until about 400 years ago. Hypersalinity of bottom waters seems to have been maintained by water-density stratification in a basin-like section of the channel. Hypersalinity is also signified by abundant euhedral crystals of gypsum that occur throughout some of the lower sediments. This occurrence of gypsum is attributed to inflow of groundwater from adjacent gypsiferous Miocene strata. Gypsum commonly originates in coastal marine settings of arid climates and its occurrence therefore has potential in palaeoclimatic investigations. However, the study reported here shows that the significance of the presence of gypsum should be evaluated with caution – it does not necessarily signify an evaporative regime.

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