BIOSTRATIGRAPHY OF THE DELAWARE ESTUARY

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EXECUTIVE SUMMARY

Analyses of sediment cores from 11 locations throughout the Delaware River and Estuary south of Philadelphia show high variability of sediment and nutrient influxes at all locations and pronounced trends at only a few locations. Sources of sediment and nutrients increased over the past 300 years as land was cleared of forests and fertilized for agriculture by European settlers. Sediment and nutrient influxes in sediments deposited in the estuary over the past several centuries show pronounced increases associated with land clearance in areas proximal to the discharge of larger tributaries. However, the ratio of carbon to nitrogen is similar spatially and through time; values range from 10 to 19 and are similar to those measured in the Chesapeake Bay and other coastal regions. Diatom populations increased in those areas where sediment and nutrients increased, but there is no pronounced change in species composition over periods spanning pre- and post-European settlement. There is no history of submerged aquatic vegetation in the sediment cores.

Deposition of up to 20 cm of silt and sand over thick marsh deposits in the lower estuary, particularly on the east side, indicate that the rate of rise of sea level now exceeds the rate of peat formation, and that submergence has increased in recent years.

The results of this study show that the response of the Delaware estuary to a generally similar pattern of land use differs considerably from the Chesapeake estuary, where the effect of agriculture is seen in all cores by a consistent increase in sediment and nutrient influxes and by a consistent change in diatom species. The record of pollen and seeds in the sediments from the Chesapeake also show a long history of submerged aquatic vegetation.

A comparison of both estuaries indicates that tributaries which are the major avenues of transport of materials from the watershed to the estuary are much less extensive in the Delaware than in the Chesapeake. The extensive marshes which surround the Delaware also could act as a buffer in protecting the estuary from anthropogenic activities on land.

The hydrodynamics of the estuary itself is an important factor which was not investigated in this study. The amount of fresh water discharged into the estuary and the circulation patterns which control stratification differ from the Chesapeake, and hence the propensity for anoxia would also be expected to differ.

INTRODUCTION

The Delaware estuary is located in the mid-Atlantic region of the USA between 38° and 39° North latitudes. It is approximately 215 km long with 10 major tributaries that drain 32,060 km² (Fig. 1). The Schuylkill River which drains southeastern Pennsylvania and joins with the Delaware River at Philadelphia is the largest tributary draining into the Delaware. The Delaware estuary consists of three components: a tidal fresh river which extends for about 60 km from the head of tide at Trenton, New Jersey to Wilmington, Delaware; a stretch of about 80 km from Wilmington to the Delaware Bay, characterized by the mixing of fresh and salt water; and Delaware Bay itself which consists of a partially mixed estuary for about 75 km from the lower tidal river and a well mixed estuary which discharges into the Atlantic Ocean.

The estuary drains a variety of geologic substrates. The headwaters of the Delaware River lie in the Appalachian Plateau. From there the river cuts across sandstone with some shale and conglomerate in the Plateau, sandstone shale and limestone in the Ridge and Valley province and igneous, metamorphic and sedimentary rocks in the Piedmont province. The lower part of the estuary, Delaware Bay, is situated in the Coastal Plain province, where the sediments are mostly unconsolidated and semi-consolidated sand, clay and gravel.

Delaware Bay is the drowned river valley of the Delaware River. During late Wisconsin time, the Delaware River consisted of the main river channel and many secondary streams. Fletcher et al. (1990) estimate that about 15,000 years ago, when the southern extent of the glaciers was in the vicinity of the Delaware Water Gap, the head of tide which is now at Trenton was at the present mouth of the Bay. At that time sea level was about 40 m below the present level. About 11,000 to 10,000 years ago, sea level had risen about 10 m, and the valley of the main channel and the tributaries began to be flooded. At that time the mouth of the bay was 5 to 6 km wide. As sea level continued to rise with the retreat of the glaciers, the Delaware River system was gradually flooded and submerged. Between 6000 and 5000 years ago, sea level was 10 m below its present level, and at least 30 m higher than when the glaciers began to retreat. At that time, the estuary included over half of what is the present lower bay. As the estuary continued to enlarge, an area of turbidity maximum developed and migrated upstream with the encroaching sea water. The turbidity maximum serves as an area for the accumulation of fine sediment including clayey silts.

The present Delaware Bay is the latest of several estuaries that formed along the Coastal Plain of eastern USA throughout the Pleistocene. Some of the sediment deposited in older estuaries was eroded during the intervening longer glacial periods, when sea level was much lower. Evidence of two ancestral Delaware estuaries is seen in patchy occurrences of paleochannels filled with estuarine sediments in the Delmarva peninsula (Knebel and Circe 1988). The Delaware paleochannels show a southeast trend similar to those found under the Chesapeake Bay (Colman et al. 1990). Whereas all of the Delaware estuaries appeared, developed and disappeared as climate and sea level changed with the advance and retreat of glaciers throughout the Pleistocene, like the Chesapeake, the rapid expansion of the human population distinguishes today's Delaware from past estuaries.

Except for tidal channels which range in depth from 10 to about 50 m, the average water depth in Delaware Bay is less than 10 m. The areas close to shore are characterized by extensive flats where water depth is less than 4 m.

The average annual air temperature in the area of the Delaware estuary ranges from about 48° F (9°C) in the upper basin to about 54° F (12°C) in the lower basin. Average January temperatures range from 23° F (-5°C) in the upper basin to 35° F (2°C) in the lower basin, and average July temperatures from 65° F (18°C) to 77° F (25°C). The maximum temperature varies from 94° F (35°C) in the north to 105° F (40°C) in the south. The minimum temperature varies from -34° F in the north to -11° F in the south.

Average annual precipitation is about 45" (114 cm) and varies little. February is normally the driest month and July and August the wettest months. Droughts are a major climatic factor, with 3 major droughts having occurred since 1961. Average annual runoff ranges from 18 to 28" (46 to 70 cm). Numerous lakes, ponds and swamps of Pleistocene origin reduce the amount of runoff in the upper Delaware basin. Several reservoirs have been constructed in the central basin which also retard runoff. Stream flow varies greatly in the basin due to seasonal variation, with heavy runoff in late winter and early spring as snow melts and ice thaws. The least runoff occurs in late summer and early fall. There have been a number of major floods in recent years. The largest amount of damage recorded in the Delaware basin occurred as a result of Hurricanes Connie and Dianne in 1955. Hurricane Agnes in 1972 caused flooding throughout the basin. Rapid runoff, particularly from the Schuylkill River, occurred at that time.

HISTORY OF THE DRAINAGE AREA

The history of land use in the drainage area is described by Berger et al (1994). Prior to European settlement in the mid-17th century, most of the watershed was inhabited by small villages of native Indian populations. As in the case of the Chesapeake, the landscape had changed from a boreal type forest about 14,000 years ago when the glaciers were at their maximum extent in the vicinity of the Delaware Water Gap. Atlantic white cedar was more widespread in the earlier stages of estuarine formation, and receded as areas bordering the submerging Delaware became brackish. About 4000 years ago, oak and other hardwoods became an important component of the landscape. This was followed by a cooler drier period 2700 years ago, and by a warmer period about 1000 years ago, which is the approximate time of the Medieval Warm Period. This latter period is well represented by a change to drier species in the Chesapeake marshes.

Prior to European settlement the majority of the landscape consisted of forests and coastal wetlands. The forested areas consisted of a mosaic of wooded and open areas. The open gaps, which resulted from wind damage, fires and Indian clearings, provided a mechanism for forests to regenerate.

The first European settlers in the watershed were Swedes and Finns, who initially occupied Indian clearings where they grew grain and some tobacco. The populations were very small and had little impact on the environment. Dutch, German and English settlers followed quickly. In the early 1600s, the population of the area below Trenton is estimated to have been 2,000. By 1700, it had grown to 20,000 people. The new settlers transformed a landscape of forests and coastal wetlands to arable land by clearing the forest, plowing, ditching and diking. They also dammed many of the streams in order to operate grist mills for processing grain into flour. Hemlock forests were rapidly diminished particularly because hemlock bark was used for tanning leather. In the late 1700s coal was mined, and this also led to further deforestation and deterioration of the landscape draining into the Delaware and tributaries. Quarrying for limestone and iron ore took place. The forests were further diminished because of the need for charcoal which combined with iron ore was used to produce pig iron. Shipbuilding, which also contributed to a reduction in forest cover, became an important industry as water transport was used for shipping grain and other commodities.

During the 18th century, all of the best upland sites along the estuary were being farmed, and large areas of salt marsh had been diked and drained for farming. Areas were farmed as long as the land was productive. Once the soil became nutrient poor, that area was abandoned, and new areas were cleared. This extensive clearance led to considerable soil erosion, evident by the middle 1700s. The clearing of land was the major environmental change during the 18th century.

The 19th century was characterized by increased population growth and industrialization, centered in Philadelphia. But Philadelphia relied for food and other commodities for its growing population on the watershed and the estuary itself. Soil erosion continued; fertilizers were added to the soil after the middle of the century. In addition to the eroded soil and fertilizers that were degrading the estuary, industrial and human waste was also being discharged untreated into the water in fairly large quantities.

During the early 20th century, the watershed of the Delaware estuary changed from predominantly agricultural to a mixture of suburban, agricultural, and urban industrial. In 1890 the watershed was 24% forest, 37% open water, 32% agriculture and 5% industry. By the late 20th century (1984), those numbers had changed to 27% forest, 39% open water, 18% agriculture, and 15% urban and industrial. Pollution, especially from point sources, became a very important problem. The population, 20,000 in 1700, reached 5,000,000 in 1990, with highest densities in the Piedmont and upper Coastal Plain.

BIOSTRATIGRAPHY

Although the kinds and patterns of land use are recorded in historical documents, there are no records of water quality in the estuary, other than anecdotal, prior to most recent time. It is therefore difficult to assess the present condition of the estuary within the context of historical events, and to identify the effect of different land uses and sources of pollution on the condition of the estuary. Environmental history, however, is recorded in sediments deposited in depositional basins including estuaries. Organisms and chemicals preserved in sediments deposited over decades, centuries and millenia provide a record of change from which it is possible to reconstruct environmental conditions for specific time periods. The record contained in the sediments, referred to as stratigraphy, has the added advantage of providing a similar data set of environmental conditions prior to European settlement as well as after settlement. Within the last 1000 years, significant climate changes permit a comparison of the effect of climate change on the estuarine ecosystem with the effects of human activity.

The Medieval Warm Period (MWP) and Little Ice Age (LIA) are recorded in sediments deposited in various parts of the world including North America (e.g., Bryson et al.1970, Nichols 1967, Gajewski 1988, Clark 1988) and in tree ring history (LeMarche 1974, Stahle et al. 1988). The duration of the warm period was approximately 200 years in most places. Effects were different in different parts of the world and were not exactly synchronous. For example, the MWP extended from about 950 to 1200 A.D. in Russia and Greenland, whereas in New Zealand it occurred between 1200 and 1400 A.D.(Lamb 1977). Using pollen data from lake sediment cores, Bernabo (1981) estimated that in Lower Michigan, temperatures during the warm interval of 1000 to 1200 A.D. approximated the mean annual temperatures of 1931 to 1960. The period from 1200 to the 1700s was a period of prolonged cool and or wet conditions, with temperatures averaging 1°C below the 1931 to 1960 mean. Bernabo (1981) estimated that the coldest period in Michigan was between 1650 and 1750, with a 0.5°C warming between 1750 and 1850. Lake level records from Lake Cardiel in Patagonia show a period of low water from 970 to 1160 A.D. indicating arid conditions in South America. This was followed by higher lake levels during the Little Ice Age (Stine and Stine 1990).

The MWP and LIA in the Chesapeake area are recorded in sediments deposited in the Chesapeake Bay and surrounding tributaries and marshes by changes in pollen and seeds of terrestrial and aquatic plants, and changes in influxes of charcoal, sediment, metals and nutrients (Brush 1986; unpublished data; Khan 1993). These climate intervals are also recorded in sediments deposited in the fresh water parts of Duck Creek and St. Jones River, Delaware (Hilgartner and Brush, manuscript in preparation). High sedimentation rates, charcoal and metal influxes in estuarine sediments along with a shift from wet to dry plants indicates that the MWP was characterized by numerous fires. Estuarine sedimentation rates and chemical stratigraphy suggest high river discharge and intensified estuarine stratification (Cooper and Brush 1991). Increased river discharge could result from deforestation caused by burning, or it could also signify high rainfall following fires. In either case, a higher river discharge could be expected to increase runoff of sediment, metals, and nutrients from the burned landscape. Cores from marshes show large amounts of charcoal during the MWP as well as a shift in pollen and seeds from marsh plants to submerged macrophytes, signifying higher water levels at least in parts of the marsh (Thornton 1991). Cores from freshwater tidal marshes in Chesapeake tributaries show increase in pollen of plants that grow in drier habitats including *Ilex, Carya, Pinus* and *Quercus*, and significant decreases in plants that grow in wet habitats such as *Juglans* and *Zizania* (Brush et al. in preparation) during the MWP.

In contrast, the LIA is characterized by lower sedimentation rates and lower charcoal, pollen and metal influxes (Brush 1986; Thornton 1991). Seeds of submerged macrophytes are replaced first by seeds of low marsh plants and later by seeds of high marsh plants. Pollen is dominated by pollen of plants that grow in wet rather than dry habitats. There is no evidence of oxygen depletion in the estuary (Cooper and Brush 1991). The stratigraphic record of the Little Ice Age suggests a wetter climate, where fires were virtually non-existent. Freshwater input decreased because the area was largely forested, thus reducing stratification of the estuary. Wetlands were predominantly low marsh, and submerged macrophyte beds were extensive in shallow estuarine waters.

The stratigraphic record of pollen and charcoal in lake sediments has been used by many investigators to reconstruct climate change (e.g., Davis et al. 1980, Webb et al. 1983, Clark 1988). Diatoms and silica in lake sediments have been used to reconstruct historic changes in the eutrophic condition of lakes (e.g., Schelske and Stoermer 1971, Brugam 1978, Stoermer et al. 1990) and effects of acidification on lakes (e.g., Dixit et al. 1992). Many of the effects observed from stratigraphy of climate variations and sediment and nutrient loading on lacustrine environments are seen also in estuarine stratigraphy (e.g., Brush and Davis 1984, Brush 1986, Cooper and Brush 1991).

Meyerson (1972) showed good pollen preservation including the effect of deforestation on the ratio of herbaceous to tree pollen in the stratigraphy of a tidal marsh in Cape May County, New Jersey. Orson et al. (1990) measured rates of sediment accumulation for a Delaware River tidal fresh water marsh using radiometric and palynological techniques, and showed that the marsh sediments contained both the ragweed horizon dated as 1680 and the chestnut horizon dated as 1940. Orson also showed the effect of diking on sedimentation rates in some fresh tidal marshes of the Delaware.

Stratigraphic studies have been used in the Chesapeake Bay to reconstruct the history of sedimentation, eutrophication, and anoxia using the record of pollen, diatoms, carbon, nitrogen and sulfur preserved in the sediments before and after European settlement (Brush and Davis 1984, Brush 1986, Cooper 1993, Cooper and Brush 199, 1994). These studies have shown that the upper Chesapeake Bay has been transformed from a diverse benthic system to one that is primarily planktonic today, a transformation associated with deforestation, land clearance and fertilization of the land. Stratigraphic records of agriculture and urbanization in other systems throughout the world and at different times show similar patterns. For example, sediment cores from lakes in the central Peten region of northern Guatemala show large increases in phosphorus at the time of extensive forest clearance by the Mayans. Deposition of colluvium in the lakes increased sharply with urban construction (Deevey et al. 1979). Large numbers of people settled in the region of the Great Lakes in central North America during the 19th and 20th centuries. Intensive agriculture was followed by industrialization particularly in the southern region. The shallower Lakes Erie and Ontario became highly eutrophic. The stratigraphic record of diatoms and nutrients including silica in sediments deposited in the lakes was used to analyze the spatial and temporal extent of the eutrophication and to identify the time of deterioration (Schelske 1975, Schelske et al. 1986, Conley et al. 1993).

OBJECTIVES

General Objective

The general objective of this study was to analyze sediment cores from the Delaware Estuary for the purpose of reconstructing water quality and biotic assemblages over time periods that span climatic variability and anthropogenic activity.

Specific Objectives

The specific objectives of the study were to:

(1) estimate the effect of land use on sedimentation rates in the estuary. High sediment loads increase turbidity and decrease light especially in regions of resuspension. These factors in turn affect biotic assemblages and productivity;

(2) measure the effects of different nutrient loadings and nutrient controls on diatom assemblages by analyzing sediments for diatoms and nutrient content. High inputs of phosphorus from agricultural and urban sources and subsequent controls on nutrient loadings especially within the last 25 years, have resulted in shifts in phosphate-nitrogen-silica ratios (Sharp 1989 and personal communication). These changes in nutrient loadings are expected to have profound effects on diatom populations and water quality;

(3) compare the effects of marsh vs urban nutrient loads on the productivity of the Delaware estuary by comparing diatom assemblages and nutrients in cores collected in areas of the estuary most influenced by runoff from marshes and areas influenced by sewage discharge and runoff from a large urban area.

(4) determine whether or not submerged aquatic vegetation (SAV) grew in the Delaware estuary, and if it did to determine the time of disappearance by analyzing sediments for seeds of submerged and emergent plants;

(5) trace the history of the occurrence of *Phragmites* through time in the Delaware estuary;

(6) reconstruct regional climate by analyses of pollen and seeds of terrestrial plants and charcoal in the sediments, and to measure the effect of climate change on biotic (diatom and aquatic macrophyte) populations;

APPROACH

Biostratigraphy requires the use of well preserved organisms and substances extracted from the sediment as indicators of specific conditions. The sediment components that were analyzed for this study are shown in Table 1.

Table 1. Fossil indicators and their use in interpretation of proposed environmental questions.

Fossil component	Indicator of	Intepretation
Pollen and seeds of terrestrial habitats	Availability of water in soil	Climate (precipitation)
Pollen and seeds of submerged and emergent vegetation	Occurrence of submerged aquatic vegetation and emergent vegetation	Occurrence of nursery grounds for shellfish and finfish; indicator of water levels; indicators of filling in from sedimentation or also of changes in sea level)
Pollen and seeds of marsh plants	Type of marsh - salt or fresh, high or low	Climate (sea level); precipitation; deforestation (erosion)
Rhizomes	Marsh plants	Occurrence of *Phragmites*
Benthic diatoms	Salinity; light availability; available oxygen	Land clearance (turbidity); eutrophication (fertilizers and sewage); anoxia
Planktonic diatoms	Available light	Turbidity; eutrophication
Total organic carbon, nitrogen, sulfur	Benthic oxygen demand; eutrophication	Anoxia; nutrient loading and reductions
Mass sediment	Sediment accumulation; turbidity	Deforestation from anthropogenic activity

METHODS

Collection and location of cores:

Three expeditions were made to retrieve sediment cores. Facilities of the University of Delaware were used to obtain cores in the fall of 1992 and in the spring and summer of 1993. Cores were collected, using a hand-driven piston corer, at 11 locations (Fig. 1) where the substrate was silt and mud. The cores range in length from 0.5 m to a little over 1 m, and are 5.7 cm in diameter.

All coring locations were open water close to shore. The center of the river and estuary were not sampled because the Delaware has been extensively dredged, and also because one of the objectives of this study was to determine whether or not SAV had ever been an important component of the ecosystem. SAV grows only in shallow water.

Furthermore, areas close to shore should also provide a better pollen record than areas farther from land. Diatom records close to shore should also reflect the impact of human activity. Cores were analyzed from 7 locations of the 11 collected. Cores were collected from additional sites in order to avoid the expense of having to return to the field for additional collections if one or more sites designated for analysis proved unsuccessful.

Cores were extruded from the core tube, split open, and described macroscopically. The longest core showing no evidence of disturbance from each location was selected for analysis, subsampled into 1 cm intervals, placed in plastic ziploc bags, and stored at 4°C. One core from each of 7 locations was dated by ^{14}C and ^{210}Pb, and pollen analysis. ^{14}C analyses were done on bulk sediments by Beta Analytic Corporation, and ^{210}Pb analyses were performed at the University of Maryland Center for Environmental and Estuarine Studies.

The designated core from each of the 11 locations was analyzed for seeds and rhizomes, from 10 locations for mass sediment influx, from 7 locations for diatoms, and from 5 locations for nutrients.

Components analyzed for dated cores are expressed as influxes. Influxes (g cm^{-2} yr^{-1} or # cm^{-2} yr^{-1}) are obtained by multiplying concentrations (g cm^{-3} or # cm^{-3}) by the appropriate sedimentation rate (cm yr^{-1}) for the particular interval of the core being analyzed. In the case of undated cores, components are expressed as concentrations.

***Sediment* (g cm^{-2} yr^{-1})** From each 1 cm interval of core, a measured volume of sediment is weighed wet, dried, and weighed again when dry.

***Pollen (% and#* cm^{-2} yr^{-1}):** A measured volume of sediment is washed in hydrochloric acid, hydrofluoric acid, and acetylzed with a mixture of nitric acid and acetic anhydride to remove carbonates, silicates and organic material. The residue is washed in glacial acetic acid, distilled water and alcohol, then stored in tertiary butyl alcohol. Aliquots of known volume (usually 0.2 ml) are mounted in silicone oil on microscope slides, and all pollen in the aliquot identified and counted. Identifications are made using various pollen identification manuals and also when necessary using the Smithsonian (Washington, DC) pollen reference collections.

***Seeds* (% and # cm^{-2} yr^{-1})**: A measured volume of sediment is submersed in 10% nitric acid and washed through a column of nested 20 mesh (0.8 mm) and 60 mesh (0.25 mm) sieves. Seeds and other remaining material are placed in water in a clear petri dish and examined under 15x to 40x magnification. Seeds are isolated with forceps and stored in vials in water to which a drop of formalin is added as preservative. Seed identifications are made using various seed identification manuals, and the seed reference collections of the Patuxent Migratory Bird Habitat Research Laboratory and the Johns Hopkins University. All seeds in a sample are identified and counted.

***Diatoms (% and #* diatoms cm^{-2} yr^{-1})**: Volumetric samples of sediment weighed before and after drying are washed in hydrogen peroxide, 25% hydrochloric acid and concentrated nitric acid with potassium dichromate, using a modified method of that published by Funkhauser and Evitt (1959). A measured volume of the diatom residue is mounted in Hyrax on a microscope slide. All diatoms are counted on the slide and the two or three dominant forms identified. Identifications are made from diatom identification references and also by comparisons with reference collections at the Philadelphia Academy of Natural Sciences. Because the centric/pennate ratio is an important indicator of eutrophication in Chesapeake Bay and elsewhere, this parameter was investigated in the Delaware as an indicator of trophic level.

***Nutrients* (g cm^{-2} yr^{-1})**: Total carbon, nitrogen and sulfur were measured by analyzing totally combusted sediment with a GC/Conductivity bridge detector for carbon, nitrogen and sulfur.

Rhizomes: Cores were analyzed microscopically for rhizome material, specifically *Phragmites*.

The following table summarizes the analyses done at each location:

Table 2. Summary of analyses (+ indicates that the analysis was performed)

Location	C-14	Pb-210	Pollen	Rhizomes	SAV seeds	Diatoms	Nutrients
7	+	+	+	+	+		+
6			+	+	+	+	
4	+	+	+	+	+	+	+
5	+	+	+	+	+	+	+
2	+		+	+	+	+	+
13			+	+	+	+	
12	+	+	+	+	+		
11			+	+	+		+
10	+	+	+	+	+	+	
8			+	+	+		
9	+	+	+	+	+	+	+

DATING OF CORES AND DEVELOPMENT OF CHRONOLOGIES

The agricultural horizon was looked for first in each core by analyzing the pollen of selected intervals. Oak pollen, ragweed pollen, and total pollen are enumerated for each interval analyzed. The protocol is to first examine 12 samples interspersed evenly throughout the core (samples are routinely analyzed in batches of 12). Then, samples between those with no ragweed and those with a large amount of ragweed are analyzed, until finally the horizon where the change occurs is identified. The ragweed horizon is dated 1680 for the Delaware watershed (Orson et al. 1990), or approximately 300 years ago. If this horizon is about midway in the core, seeds or wood fragments from the bottom sediment are sent to the University of Arizona Accelerator Dating Facility or bulk sediment to Beta Analytic Corporation for ^{14}C dating. The reason for identifying the agricultural horizon first is because if it is close to the bottom of the core, there is no point in having the bottom sediment analyzed for a ^{14}C date, because it will be too young to be so dated. The youngest age that is reliably dated by ^{14}C is 500 years, and the ragweed horizon identified in cores in the Delaware River has been dated as 1680 or 310 years before present (Orson et al. 1990). The top sediments of selected cores are dated using ^{210}Pb to complement the pollen date. ^{210}Pb is capable of dating sediments 100 years in age or less.

RESULTS

Stratigraphy

The stratigraphy of the cores is described below and presented graphically in Figs. 2-4. The Munsell soil color charts were used to describe the color of the sediment in the cores. Cores collected in the lower estuary on both the Delaware and New Jersey sides show extensive peat deposits. In four of the cores, one on the Delaware side and all three collected on the New Jersey side, the peat is overlain by up to 20 cm of silt, silt and clay or sand.

Location Description	Length of core(cm)	Stratigraphy		Soil color
		Depth (cm)	Description of layer	
Location 7: in the river in the area of Tinicum Island	97.0	0-1.5	sand	2.5/2.5Y black
		1.5-20.0	fibrous peat	
		20.0-90.0	silt and clay; no peat	
		90.0-97.0	medium peat	

Location 6: in the vicinity of Delaware City	62.0	0-2.0	sand	3/1 10YR (v. dk. grey)
		2.0-62.0	homogeneous silt and clay	
Location 4: south of the Chesapeake-Delaware Canal	77.0	0-8.0	moist silt; sand on surface	2.5/1 5Y black)
		8.0-19.0	silt and clay with little or no sand and no organic soil	3/1 5Y (v. dk. grey)
		19.0-22.0	very sandy	2.5/1 5Y (black)
		22.0-25.0	fine-grained silt	2.5/1 5Y (black)
		25.0-62.0	fine silt	3/1 5Y (v. dk. grey)
		62.0-69.0	fine silt	2.5 5Y (black)
		69.0-77.0	fine and coarse silt and sand	2.5/1 5Y (black)
Location 5: at Bombay Hook south of the Smyrna River	89.0	0-89.0	fine silt and clay with some peat	
Location 2: in the vicinity of the Mahon River	91.0	0-91.0	fine silt and clay with some peat	
Location 13: at Bowers Beach	85.0	0-65.0	high marsh sediment	2/0 7.5YR (black)
		65.0-75.0	homogeneous silt and clay; no peat	4/0 7.5YR (dk. grey)
		75.0-85.0	sandy with shells	4/0 7.5 YR (dk. grey)
Location 12: in the area of Slaughter Beach	96.0	0-6.5	high marsh peat	
		6.5-60.0	low marsh peat	
		60.0-96.0	homogeneous silt and clay with little or no peat	4/1 5Y (dk. grey)

Location 11: in the vicinity of Broadkill River	93.0	0-15.0	sand	2/0 2.5Y (black)
		15.0-93.0	homogeneous silt with some peat	3/1 5Y (v. dk. grey)
Location 10: off Nantuxent Point, N.J.	116.5	0-8.0	very wet silt and clay with little organics or peat	3/2 5YR (dk. red. brown)
		8.0-14.0	high peat content	2.5/1 5YR (black)
		14.0-116.5	very wet peat with low viscosity	3/1 5YR (v. dk. grey)
Location 8: in Maurice River Cove, adjacent to Egg Island Point, N.J.	82.0	0-20.0	silt and clay with alot of peat and roots	
		20.0-40.0	peat	3/1 5Y (v. dk. grey)
		40.0-82.0	low marsh peat	
Location 9: at the mouth of the Maurice River, N. J.	108.0	0-18.0	silt and clay with some peat	
		18.0-99.0	high concentration of marsh plants in sediment	4/1 5Y (dk. grey)
		99.0-108.0	not much plant material	

Dating of Cores

Bottom sediments of seven cores were ^{14}C dated by Beta Analytic. Pollen preservation was very poor in the cores, and consequently it was difficult to identify precisely the oak-ragweed horizon. For similar reasons, it was not possible to use the pollen stratigraphy to compile detailed chronologies. We do not know why pollen preservation is poor in all of these cores. In this respect, these cores are entirely different from those collected in the Chesapeake or in St. Jones Creek and Duck Pond, Delaware, where pollen preservation is excellent and the pollen occur abundantly. We have encountered some highly organic peat type samples, e.g. in the James River, Virginia where very few pollen grains were recovered, but these are rare occurrences. Pollen will not preserve well if the sediment is oxidized, but this is rarely the case in estuarine or marsh sediments. Samples of top sediments of each of the cores that were ^{14}C dated were analyzed for ^{210}Pb to obtain a sedimentation rate for the top portion of the cores. In each case, the ^{210}Pb analyses indicated considerable mixing at the top, making it possible to obtain only a rough estimate of the sedimentation rate. The results of the dating analyses are summarized in Table 2. These estimates have been used to calculate pre- and post-European influxes of nutrients and diatoms for the dated cores.

Table 2. Dates and average sedimentation rates of sediment cores (ybp = years before present)

Core	Carbon-14		Ragweed		Lead-210		Other		Sed	pre-Eur	post-Eur
	ybp	depth (cm)	ybp	depth (cm)	ybp	depth (cm)	ybp	depth[1] (cm)	rate (cm/yr)	sed rate (cm/yr)	sed rate (cm/yr)
7C	1210±120	95-97		?		?			.08		
4B	2350±180	74-77		?		?	300	40	.03	.02	.13
5B	890±70	86-89	300	5	100	15			.10	.09	.15
2C	1000±70	90-92	300	73					.09	.02	.24
12B	1490±90	94-96	300	23	100	5			.06	.06	.08
10B	590±90	115-116		?					.19		
9A	1540±110	107-109		?	100	20			.07	.06	0.2

[1] The large change in nutrients in this core at 40 cm suggested to us that this might be the agricultural horizon, but this is very tentative.

Pollen:

The pollen content of the cores was extremely sparse. This characteristic of the cores is discussed in the preceding section on dating of cores.

Seeds:

The seed content of the cores was likewise sparse. Seeds were found only in cores from 3 locations:

Location 2: 6-7 cm (~ 1970)- a few seeds of sedge
71 - 72cm (~ 1700) - *Zannichellia palustris* (horned pondweed) and *Ruppia maritima* (widgeon grass)

Location 5: Sedges occur sporadically throughout this core

Location 4: 28-29 cm (~ 1760) - sedge and *Polygonum*
59-60 cm (~ 200) - *Carex sp.*
67-68 cm (~ 300 B.C.) - *Carex sp.*

Rhizomes:

There was no evidence of rhizomes of *Phragmites* in any of the cores.

Sedimentation rates:

Each of the dated cores spanned a period of from 600 to over 2000 years, and thus includes a history of pre- and post-European time. The average sedimentation rate for the entire time period ranges from .03 cm/yr in Core 4B located just south of the Chesapeake and Delaware Canal to the highest sedimentation rate of 0.19 cm/yr in Core 10B collected at the mouth of the Maurice River on the New Jersey side of the Delaware estuary. Post-European rates range from 0.08 cm/yr in core 12 B located in the vicinity of Slaughter

Beach to 0.24 cm/yr in core 2C located close to Mahon River on the Delaware side of the estuary. Sedimentation rates increased from 2 to 10 times during the period of European settlement over pre-European deposition rates. The pattern is highly variable and is similar to that seen in the Chesapeake, where local hydrodynamics plays a large role in patterns of sediment deposition.

The mass sedimentation rates (grams deposited/cm2/yr) or bulk density (grams/cm^3) for undated cores are plotted in Fig. 5. Mass sediment at locations 4, 2 and 9 increased greatly at the time of European settlement and remained high thereafter. At location 5, mass sediment increases slightly at the time of settlement, but it is much less pronounced than at the other locations.

History of eutrophication

Sediments in cores collected at locations 7, 4, 5, 2, 11 and 9 were analyzed for carbon, nitrogen and sulfur (Figs. 6-8). Core 11 is not dated. Nutrients increased dramatically in cores 4 and 9 at the time of European settlement, but the pattern is more complicated in other cores. Since 11 is undated, all that can be said is that the concentrations of nitrogen are smaller in the top sediments than in the bottom sediments. The top 20 cm of sediment, all sand, has scarcely any sulfur. Carbon increases in concentration from the bottom to the top. Other than a decrease in nitrogen and carbon during the 13th century Medieval Warm Period in core 7C, there are no large changes. Sulfur shows an increase during the 12th century. No further changes occur until the late 19th to 20th century, when there is a large increase. Core 2C, which is characterized by very high sediment influxes following European settlement (see above), shows a large decrease in nitrogen and carbon in the 14th century, and not much change following that initial change until the last half of the 20th century when there is a huge increase. Sulfur is highly variable throughout the core, but also shows a significant increase in the top sediments. Core 5B shows very little change throughout the core in nitrogen and carbon, except in the early 19th century when there is a large increase, and a subsequent decrease back to previous levels. Sulfur is variable throughout, but does show large increases also in the 19th and 20th centuries, with a significant decrease in the late 19th century.

Carbon - nitrogen ratios:

Ratios of carbon to nitrogen (Fig. 9) show very little variation within and between cores. There is no pattern related to European settlement and land use. All of the ratios range from 9 to 19, and are similar to C:N ratios ranging from 6.9 to 23.3 measured in bottom sediments of the Delaware Estuary throughout the year (Cifuentes 1991).

History of diatoms:

Increased nutrients and sediment from land clearance and fertilizers as well as from sewage provides food for algal populations. At the same time, the turbidity of the water is increased and light is reduced. Hence there is often a proliferation of planktonic algae which can live in the surface waters where light is not limited by sediment. At the same time, the diversity of the algal populations decreases. Diatoms are well preserved in the stratigraphic record and are a sensitive indicator of what is happening to biological populations. In many areas, pennate diatoms tend to grow in the bottom waters or on the sediment, and centric diatoms in the surface waters. Hence, in addition to total diatoms, the ratio of centric to pennate diatoms is often used to assess the degree to which eutrophication characterizes the system. The use of the centric-pennate ratio to describe changes in benthic and planktonic abundances has been found useful in the Chesapeake, but there is no evidence from living flora to indicate whether the same relationships hold true for the Delaware.

Profiles of total diatom influxes for all cores are shown in Fig. 9 and the ratio of centric to pennate diatoms in Fig. 10. The cores that show a large increase in diatoms at the time of European settlement are from locations 4, 5 and 9. At location 4, the ratio of centric to pennate diatoms increased at the time of settlement, but by the late 1800s the ratio had returned to pre-settlement patterns. The pattern at location 5 is similar to that at 4, but more variable. At 9, the centric-pennate ratio does not change with the increase in total diatoms, except in the late 1900s, when centric diatoms become dominant. The pattern in undated cores does not show a consistent increase or change in ratio in the top parts of the cores.

GEOGRAPHIC ANALYSIS OF ENVIRONMENTAL CONDITIONS

To assess the impact of the site characteristics on the estuary, each location is described with respect to the analyses performed.

Location 7 (Fig. 11)

Location 7 is the northernmost site where cores were collected. It is located in the vicinity of Tinicum Marsh, but where there is no discharge from a tributary. The sediment core analyzed from this location is 97 cm long. It consists of peat at the bottom overlain by a thick deposit of of silt and clay, and a second layer of peat capped with a fine lens of sand at the surface. ^{14}C analysis of the bottom sediments yielded a date of 1210 years ± 120 years. The ragweed horizon could not be identified in the core, nor did ^{210}Pb analysis yield a sedimentation rate. Consequently, only an average sedimentation rate of 0.08 cm/yr could be derived. The mass sediment profile (grams of sediment /cm^2/yr) shows no pattern of increase or decrease, but does show high variability. The profiles of nitrogen and carbon influxes are similar. Both show a significant decrease at about 1200 A.D., the time of the MWP. The largest increase in carbon occurs in the late 1800s. Sulfur increases at the time of the Medieval Warm Period and remains unchanged until the late 1800s, when there is a large increase at the same time that there is an increase in carbon.

Location 6 (Fig. 12)

This site is located in the vicinity of Delaware City. The core analyzed from this location is 60 cm long and consists entirely of homogeneous silt and clay with a thin layer of sand at the top. The core is not dated. Bulk density of the sediment (grams of dry sediment/cm^3) is the same throughout the core. Diatoms show a sharp decrease in total numbers, with a larger decrease in pennate forms than centric in the lower to middle portion of the core, but this change could be an artifact of variations in sediment accumulation. Pennate diatoms are dominant in the bottom sediment, and though the ratio fluctuates throughout the core, there is no pattern of increase or decrease toward the top.

Location 4 (Figs. 13 and 14)

This site is in the upper Delaware estuary below the Chesapeake and Delaware Canal. The sediment core analyzed is 77 cm long and consists of sand, silt and clay in various proportions. The bottom sediments yielded a ^{14}C date of 2350 years before present ± 180 years. As at location 7, neither pollen analysis nor ^{210}Pb were useful for dating. The agricultural horizon was tentatively set at 40 cm where there is a major change in sediment from predominantly silt to silt and sand. Based on this information, the average sedimentation rate for the entire core is 0.03 cm/yr and ranges from 0.017 in pre-European settlement time to 0.13 cm/yr in post European time. Using these sedimentation rates, mass sediment input increased dramatically with European settlement. Influx profiles for nitrogen, carbon and sulfur are similar and show dramatic increases at the time of settlement. C:N ratios range from 13 to 16, and are not in any particular order. The ratio is 13 for both the bottom and top sediments in the core. The sediment and nutrient input is mirrored by a large increase in diatom populations, but there is no shift in the centric to pennate ratio. Seeds of sedges and *Polygonum* (tearthumb) occur in the bottom silt and sand sediment and also in an upper layer of silt and sand.

Location 5 (Figs. 15 and 16)

Location 5 is south of the Smyrna River. The sediment core selected for study consists of 89 cm of unlayered fine silt and clay with some peat. The bottom sediment yielded a ^{14}C date of 890 years before present ± 70 years, which indicates relatively rapid deposition. The ragweed horizon occurs at 5 cm. Its proximity to the surface suggests that the most recent sediments may have been scoured away. ^{210}Pb sedimentation rates indicate that the 100 year horizon is at 15 cm, and that information was used to calculate sedimentation rates. The average sedimentation rate throughout the core is 0.1 cm/yr. The pre-European sedimentation rate is 0.09 cm/yr and the post settlement rate 0.15 cm/yr. Mass sediment influx increases gradually throughout the core; the profile is highly variable showing some periods of extremely high influx and other intervening years of lower influx. Nitrogen and carbon profiles show a large increase in the early 1800s followed by a sharp decrease and another fairly substantial increase in the late 1900s, but not as large as in the early 1800s. Sulfur is highly variable. The C:N ratio varies between 13 and 19, but with no pattern. Total diatoms show a large increase in the late 1700s followed by a decrease and then another increase in the middle 1800s which follows the increase in carbon and nitrogen, another decrease in the late 1800s and an increase in the late 1900s synchronous with the latest increase in carbon and nitrogen. Centric diatoms are dominant in the late 1700s and mid 1800s, and are much less important in the most recently deposited sediment. Seeds of sedges occur sporadically throughout this core.

Location 2 (Figs. 17 and 18)

This site is located in the upper part of the lower Delaware estuary at Port Mahon. The core analyzed for this site consists of 91 cm of fine silt and clay with some peat. It is very similar to the core analyzed from location 5. The bottom sediments are ^{14}C dated 1000 years before present ± 70 years. The ragweed horizon occurs at 73 cm. There is no ^{210}Pb date. The ^{14}C and pollen dates result in an average sedimentation rate of 0.09 cm/yr for the entire core and 0.025 cm/yr for the period prior to European settlement, with 0.24 cm/yr for post-settlement time. The post-settlement sedimentation rate is 10 times the pre-European rate. Mass sediment influx shows at least a ten-fold increase after European settlement. Nutrient influxes do not reflect this increase in sediment influx. Nitrogen and carbon are relatively low until the mid to late 1900s when influxes of both increase dramatically. Sulfur also increases in the most recently deposited sediments. C:N ratios vary in this core between 10 and 19, with 19 at the bottom of the core and 10 at the top. Total diatoms increase at the time of European settlement, decrease until the beginning of the 20th century, when they increase again, then decrease, and increase in the late 1900s. Pennate diatoms became somewhat more abundant after European settlement, but there is no clear pattern. The only evidence of SAV in any of the cores studied is present in this core. A few seeds of *Zannichellia palustris* (horned pondweed) and *Ruppia maritima* (widgeon grass) are present in the lower sediments in this core.

Location 13 (Figure 19)

This site is located at Bowers Beach south of St. Jones River. The sediment core analyzed at this location is 85 cm long. It consists of a lower zone of sand, on top of which is a layer of silt and clay. On top of these layers are over 60 cm of high marsh peat. The core is not dated. Bulk density of the sediment is lower in the marsh sediment than in the sand and silt. It was not possible to recover diatoms from the bottom portion of the core; the samples dissolved and left no residue. However, in the marsh sediment, diatom concentrations show a steady increase up to the top sediment, where there is a small decrease. The ratio of centric to pennate diatoms is greater in the middle section of the peat deposit.

Location 12

This site is located at Slaughter Beach. The core analyzed is 96 cm long and consists of silt and clay at the bottom of the core, overlain by about 60 cm of low marsh peat which is capped by about 5 cm of high marsh peat. A ^{14}C date of the bottom sediments is 1490 ± 90 years before present. The agricultural horizon, based on ragweed pollen, is located at 23 cm, and the 100 year horizon based on ^{210}Pb analysis at 5 cm. Using this information, the average sedimentation rate at this site over the past 1500 years has been 0.06 cm/yr. The pre-European sedimentation rate is 0.06 cm/yr, and post European is a fairly similar 0.08 cm/yr. The influx of mass sediment increases slightly at the time of European settlement.

Location 11 (Figs. 20 and 21)

This site is the southernmost location and is situated in the vicinity of Broadkill River, Delaware. The core analyzed consists of 93 cm of silt with some peat overlain by about 18 cm of sand. The core is undated. Bulk density of the sediment is higher in the sandier upper layers of the core. Nitrogen decreases toward the top, carbon increases, and there is virtually no sulfur in the upper sandy portion. The C:N ratio varies between 11 and 14. The largest numbers of diatoms are found in the bottom 10 cms of sediment; there are no diatoms in the upper sandy layer. The centric pennate ratio varies considerably.

Location 10 (Fig. 22)

Location 10 is the northernmost site on the New Jersey side of the Delaware estuary. The core consists of 100 cm of very wet peat overlain by a layer of drier peat which is overlain by 8 cm of silt and clay. The sedimentation rate in this core is very high with a ^{14}C date of 590 ± 90 years before present at 115 yo 116 cm depth. A ragweed horizon could not be identified, and ^{210}Pb analysis did not provide an accurate estimate of sedimentation. The average rate of sedimentation for the core is 0.19 cm/yr. Diatom analyses show a decrease for a brief period at the presumed time of settlement, based on the average sedimentation rate for the entire core. Centric diatoms become dominant at the top of the core. The diatom population at this site differs from all other sites studied in that at least 30% of the population is comprised of two species of *Diploneis*. This taxon is particularly important at the time of settlement.

Location 9 (Figs. 23 and 24)

This site is the southernmost location on the New Jersey side of the Delaware estuary and is located at the mouth of the Maurice River. The core analyzed from this location is 108 cm long, and consists of marsh sediment capped by about 20 cm of silt and clay. A ^{14}C date of 1540 ± 110 years was analyzed from the bottom sediments of the core, yielding an average sedimentation rate of 0.07 cm/yr over the past 15 years. The ragweed horizon could not be identified. Based on ^{210}Pb analysis, the 100 year horizon is located at 20 cm. The sedimentation rate for pre-European time is 0.06 cm/yr and 0.2 cm/yr for post-European time, a 3.3 times increase. Mass sediment influx shows a large increase during European settlement. Carbon, nitrogen and sulfur profiles are identical showing a large increase at the time of European settlement, which continued until the mid 1800s and then decreased to the present. C:N ratios vary between 9 and 14. Diatom populations showed an increase from the time of European settlement up to the 20th century.

CONCLUSIONS AND DISCUSSION

The history of land use in the Delaware estuary watershed is similar to the general pattern of deforestation and cultivation throughout eastern North America over the past 300 years. There are some local deviations; for example, wetlands were diked and drained excessively, and more streams were dammed than in some other areas. But the overall picture is one of widespread and rapid land clearance and extensive use of fertilizers once they became available in the late 1800s..

The history of water quality, as reflected in nutrient influxes and diatom populations in sediments deposited in the Delaware tidal river and estuary, shows a highly variable picture. In some areas, there is a clear increase in nutrients and change in diatom populations related to European settlement, but in other areas the changes do not show any clear pattern. However, the carbon nitrogen ratios in the Delaware cores are consistent with values found in the bottom sediment of the Delaware estuary (Cifuentes 1991), Chesapeake estuary and other coastal regions (Jeffrey Cornwell, personal communication and manuscript in press). Overall, the stratigraphic record is much less concise with respect to the demarcation between pre- and post-European settlement in the Delaware sediment cores than in the Chesapeake cores.

A comparison of the land-water interface of the Delaware and Chesapeake estuaries (Fig. 25) shows a pronounced difference between the two bays. The Chesapeake is characterized by numerous large and small tributaries whereas the Delaware has only a few rivers draining into it. Its edge is also bordered more extensively by marshland than is the Chesapeake. Consequently, the avenues for transport of terrestrial materials into the estuary are much fewer than for the Chesapeake. This difference is reflected in the stratigraphic record of water quality and biologic response in that non-point source pollutants appear to impact the Delaware locally, whereas the entire Chesapeake has been affected by non-point source pollution.

The hydrodynamics of the Delaware estuary may also be a factor in the response of the estuary to pollutants, although that factor was not investigated in this study. In dated cores, influxes of diatoms and nutrients both exhibit high variability throughout the cores, even where there is no general trend, reflecting the variability in water movement and sedimentary processes in shallow estuarine waters.

The cores examined show a long history of peat formation, particularly on the eastern side of the Delaware estuary. The peat has been overlain by silt and sand deposits in recent years, which indicate that the rate of rise of sea level has exceeded the growth of peat during recent years, and that land area is being submerged at present.

The sediment cores show that submerged aquatic vegetation was virtually non-existent in the Delaware at least during the last few thousand years. This is not unexpected in that areas of the Chesapeake which have a long history of marsh development are similarly devoid of submerged aquatic vegetation. The reason for this may lie in the fact that the grasses require a silty type of substrate for growth, which does not occur where there are extensive marshes.

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FIGURE LEGENDS

Fig. 1. Map of the Delaware River and Estuary (after Sharp 1989) showing locations of sediment cores.

Fig. 2. Stratigraphy of cores at locations 7, 6, 4 and 5 on the Delaware side of the estuary. N and S refer to North and South.

Fig. 3. Stratigraphy of cores at locations 2, 13, 12 and 11 on the Delaware side of the estuary.

Fig. 4. Stratigraphy of cores at locations 10, 8 and 9 on the New Jersey side of the estuary.

Fig. 5. Mass sedimentation rates (grams dry sediment/cm2/yr) and concentration of sediment (for undated cores) at each of the locations analyzed for sediment.

Fig. 6. Influxes and concentrations of nitrogen at each location analyzed.

Fig. 7. Influxes and concentrations of carbon at each location analyzed.

Fig. 8. Influxes and concentrations of sulfur at each location analyzed.

Fig. 9. Carbon-nitrogen ratios at each location analyzed

Fig. 10. Influxes and concentrations of total diatoms at each location analyzed.

Fig. 11. Centric to pennate ratios of diatoms for each location analyzed.

Fig. 12. Profiles of nitrogen, carbon and sulfur at Location 7

Fig. 13. Profiles of diatoms at Location 6

Fig. 14. Profiles of nitrogen, carbon and sulfur at Location 4.

Fig. 15. Profiles of diatoms at Location 4.

Fig. 16. Profiles of nitrogen, carbon and sulfur at Location 5.

Fig. 17. Profiles of diatoms at Location 5.

Fig. 18. Profiles of nitrogen, carbon and sulfur at Location 2.

Fig. 19. Profiles of diatoms at Location 2

Fig. 20. Profiles of diatoms at Location 13.

Fig. 21. Profiles of nitrogen, carbon and sulfur at Location 11.

Fig. 22. Profiles of diatoms at Location 11.

Fig. 23. Profiles of diatoms at Locatoion 10.

Fig. 24. Profiles of nitrogen, carbon and sulfur at Location 9.

Fig. 25. Profiles of diatoms at Location 9.

Fig. 26. Map showing the geographic boundaries of the Chesapeake and Delaware estuaries.

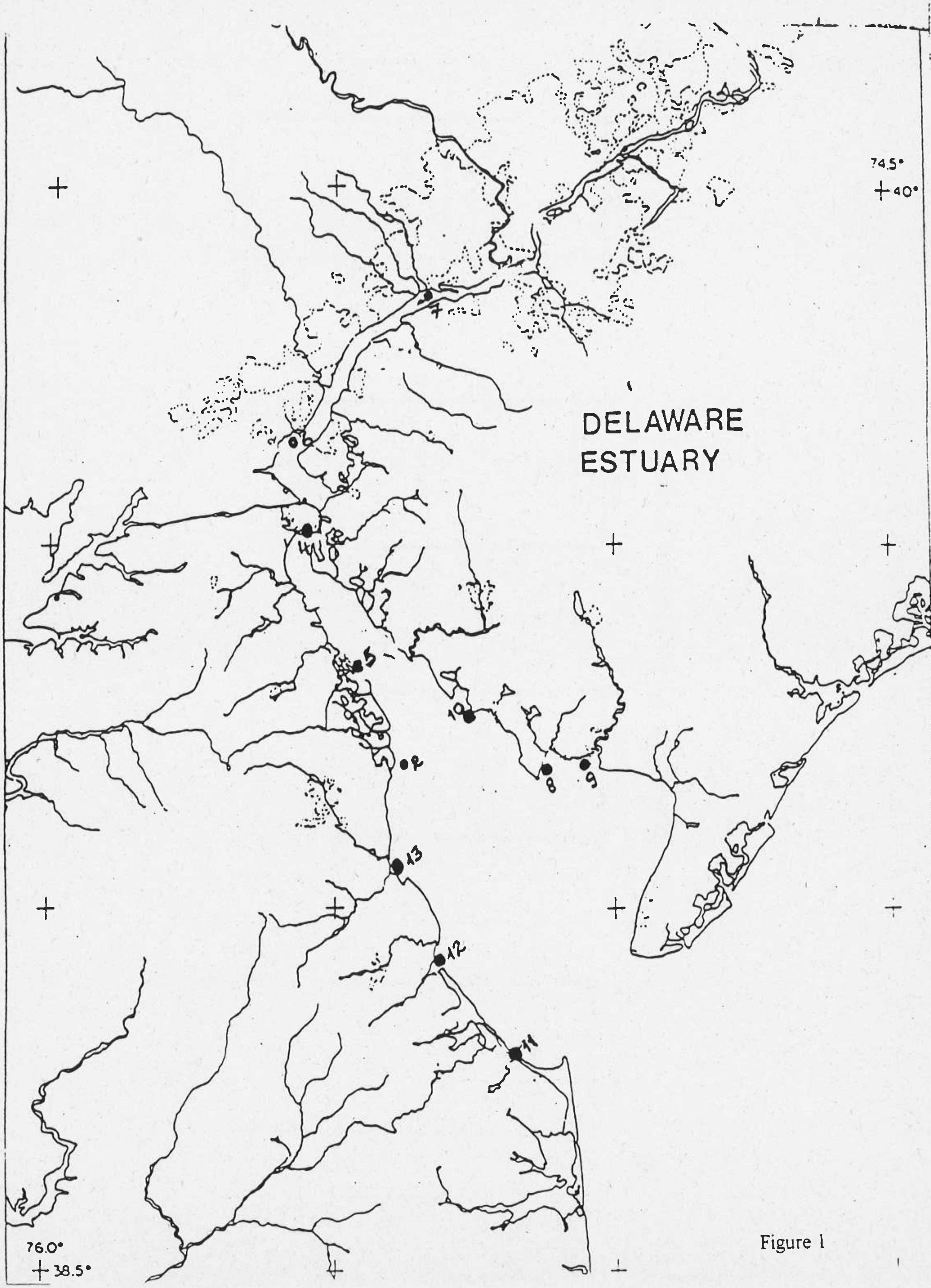
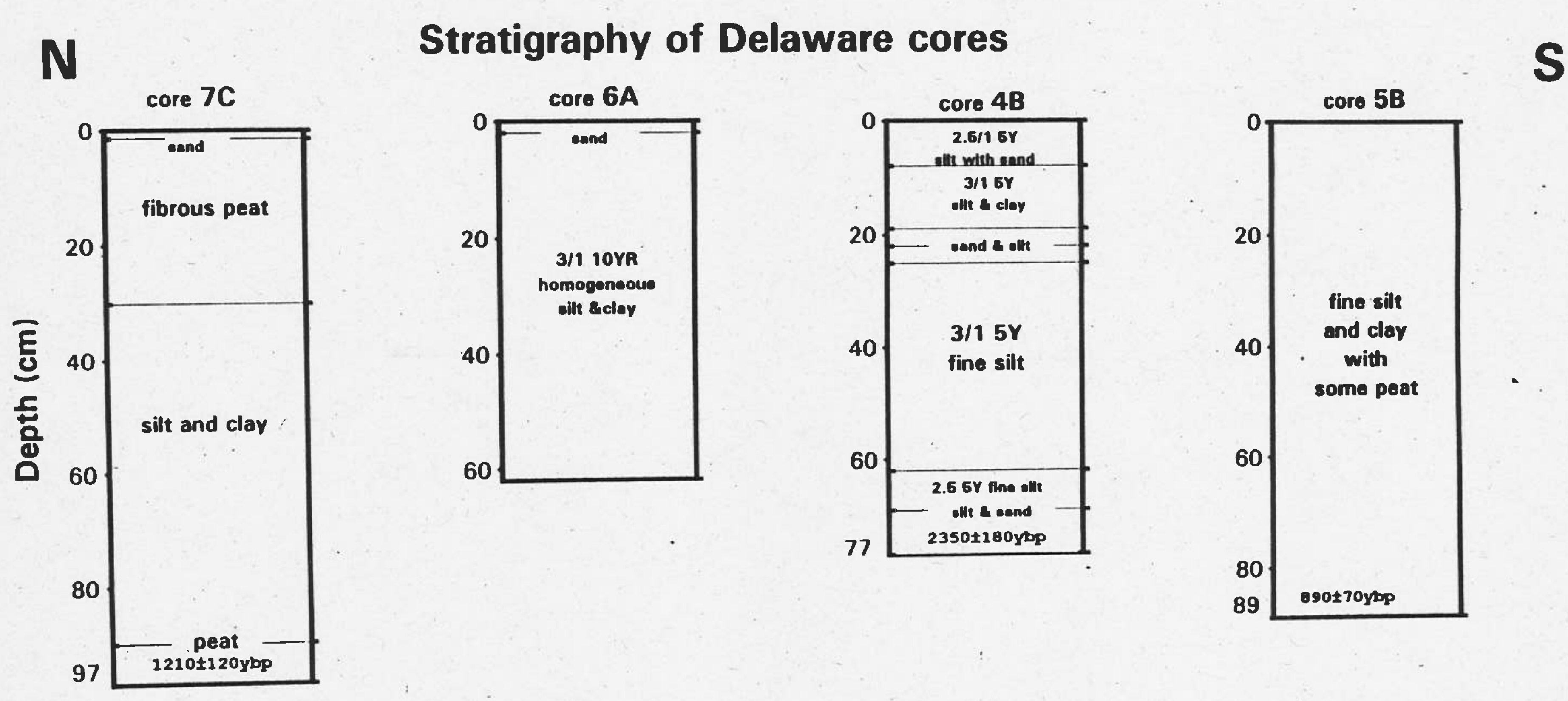


Figure 1



Stratigraphy of Delaware cores
N
S
Depth (cm)
core 7C
sand
fibrous peat
silt and clay
peat
1210±120ybp
0
20
40
60
80
97
core 6A
sand
3/1 10YR
homogeneous
silt &clay
0
20
40
60
core 4B
2.5/1 5Y
silt with sand
3/1 5Y
silt & clay
sand & silt
3/1 5Y
fine silt
2.5 5Y fine silt
silt & sand
2350±180ybp
0
20
40
60
77
core 5B
fine silt
and clay
with
some peat
890±70ybp
0
20
40
60
80
89

Figure 2

Stratigraphy of cores (cont'd)

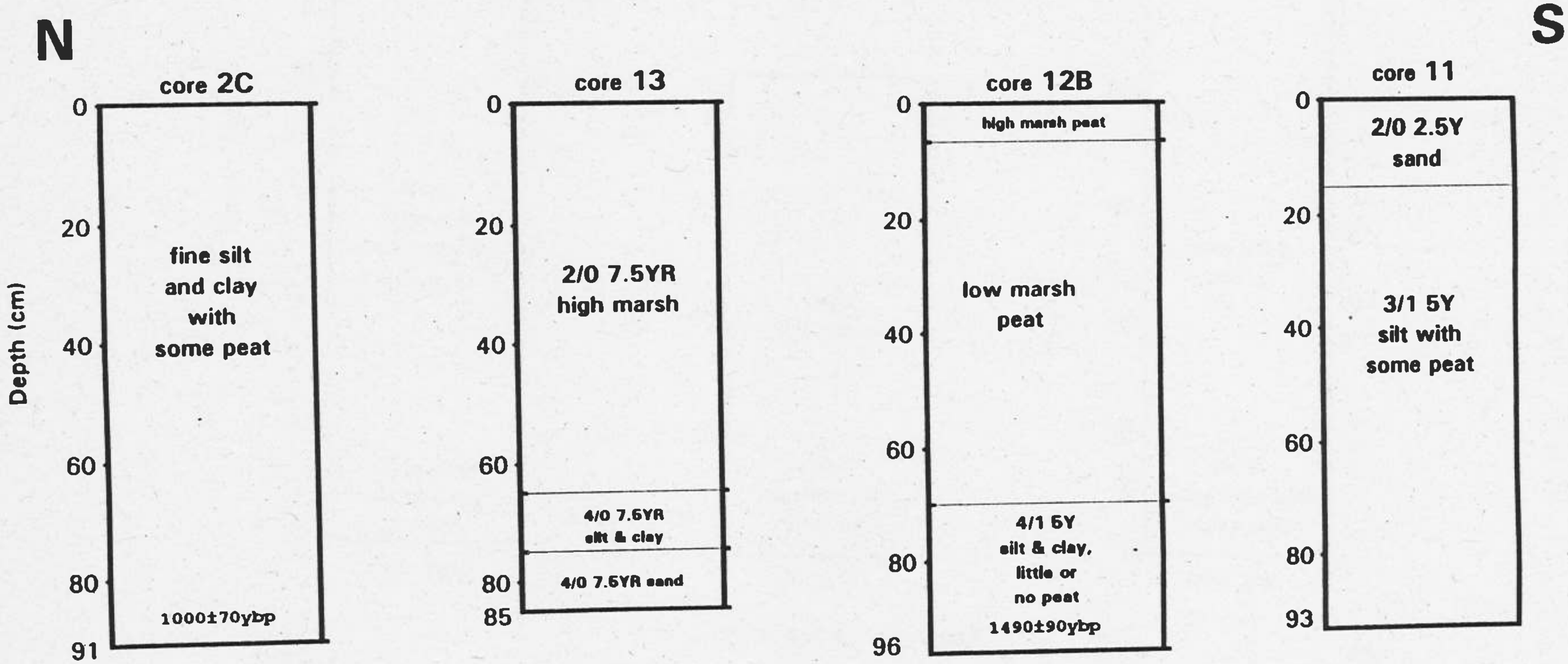


Figure 3

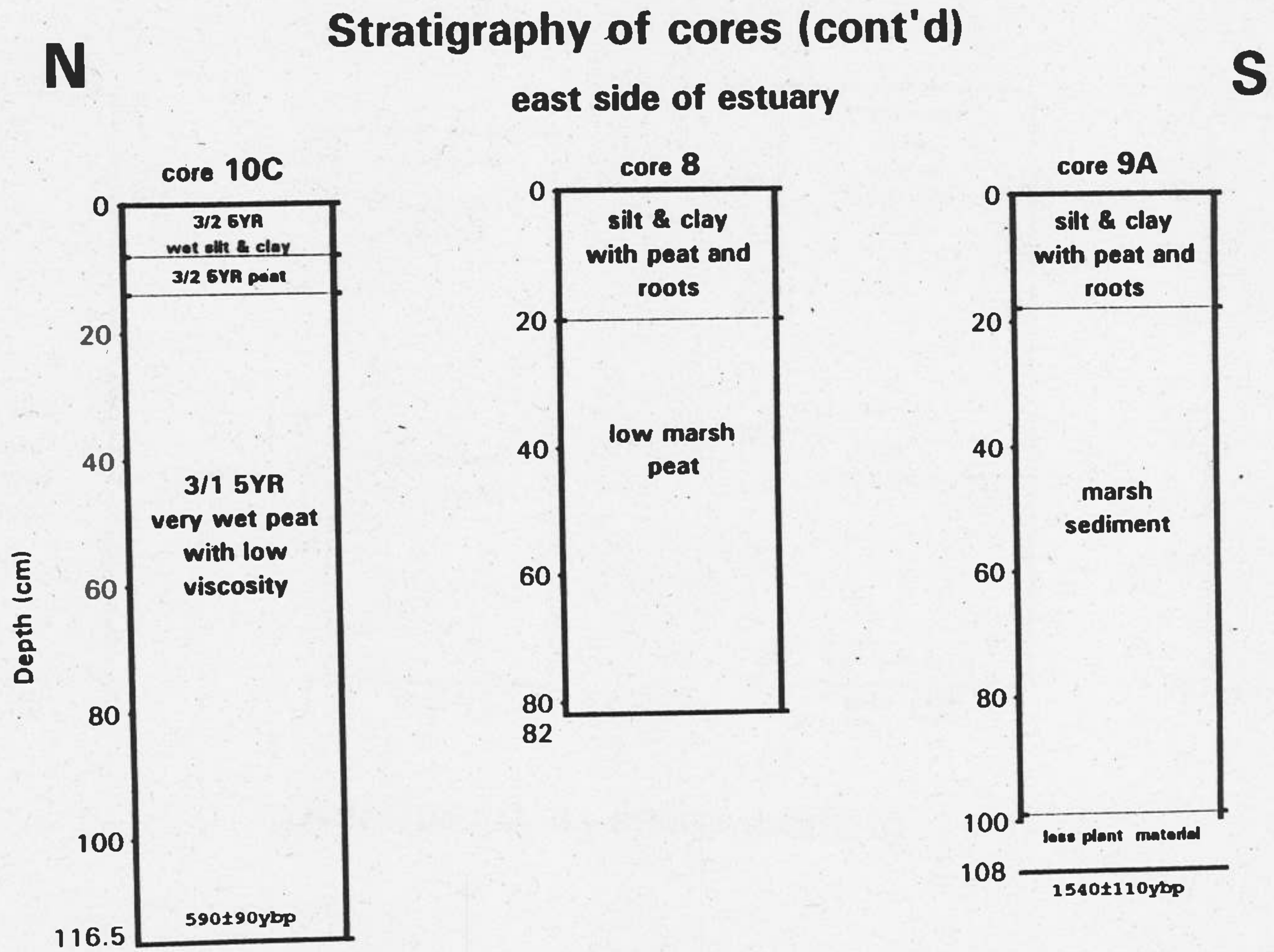

Stratigraphy of cores (cont'd)
east side of estuary
N
S
core 10C
3/2 5YR
wet silt & clay
3/2 5YR peat
3/1 5YR
very wet peat
with low
viscosity
590±90ybp
Depth (cm)
0
20
40
60
80
100
116.5
core 8
silt & clay
with peat and
roots
low marsh
peat
0
20
40
60
80
82
core 9A
silt & clay
with peat and
roots
marsh
sediment
less plant material
1540±110ybp
0
20
40
60
80
100
108

Figure 4

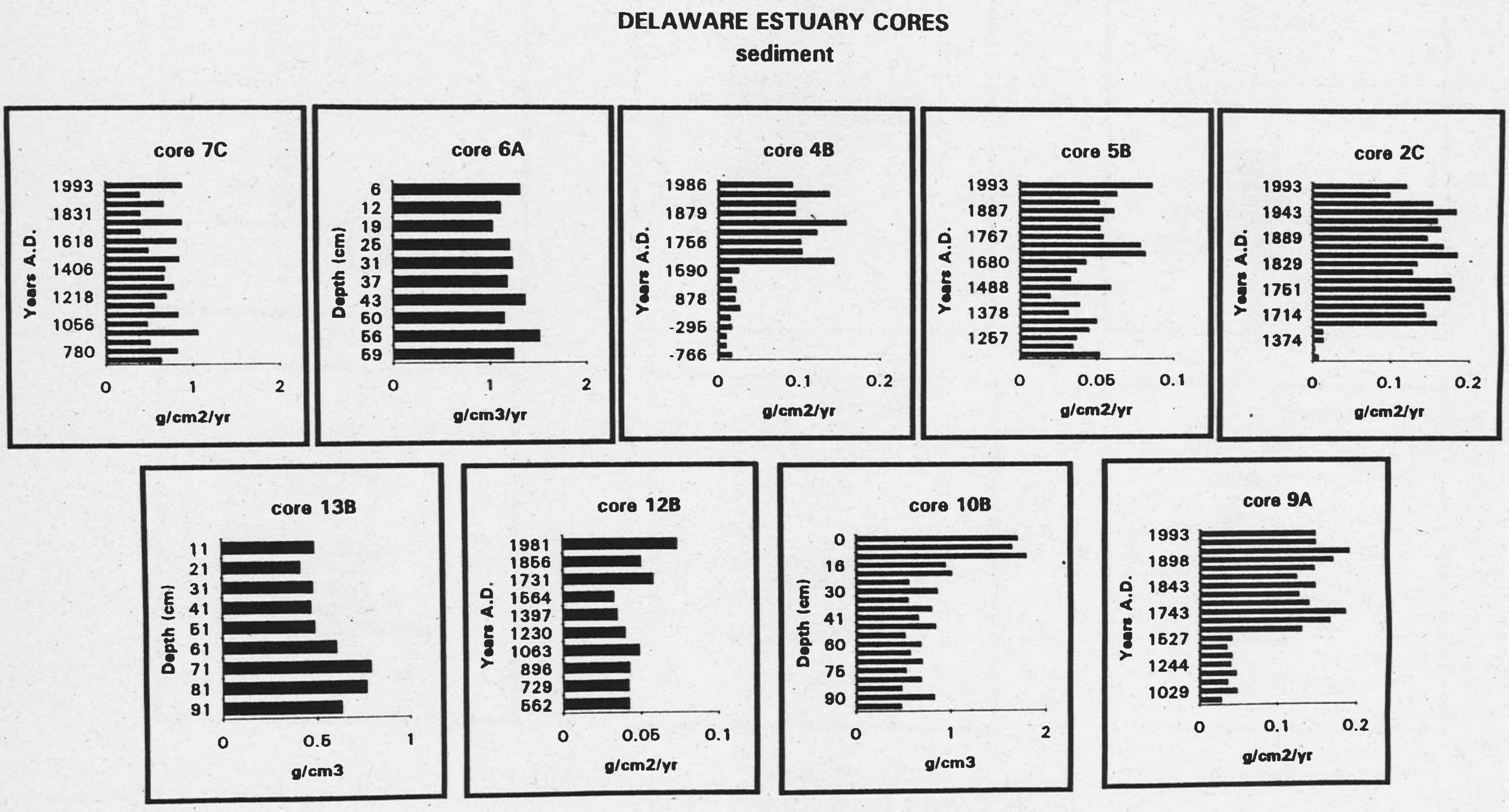

DELAWARE ESTUARY CORES
sediment
core 7C
Years A.D.
1993
1831
1618
1406
1218
1056
780
0
1
2
g/cm2/yr
core 6A
Depth (cm)
6
12
19
26
31
37
43
50
56
59
0
1
2
g/cm3/yr
core 4B
Years A.D.
1986
1879
1756
1690
878
-295
-766
0
0.1
0.2
g/cm2/yr
core 5B
Years A.D.
1993
1887
1767
1680
1488
1378
1267
0
0.05
0.1
g/cm2/yr
core 2C
Years A.D.
1993
1943
1889
1829
1761
1714
1374
0
0.1
0.2
g/cm2/yr
core 13B
Depth (cm)
11
21
31
41
51
61
71
81
91
0
0.5
1
g/cm3
core 12B
Years A.D.
1981
1856
1731
1564
1397
1230
1063
896
729
562
0
0.05
0.1
g/cm2/yr
core 10B
Depth (cm)
0
16
30
41
60
76
90
0
1
2
g/cm3
core 9A
Years A.D.
1993
1898
1843
1743
1527
1244
1029
0
0.1
0.2
g/cm2/yr

Figure 5

DELAWARE ESTUARY CORES
nitrogen

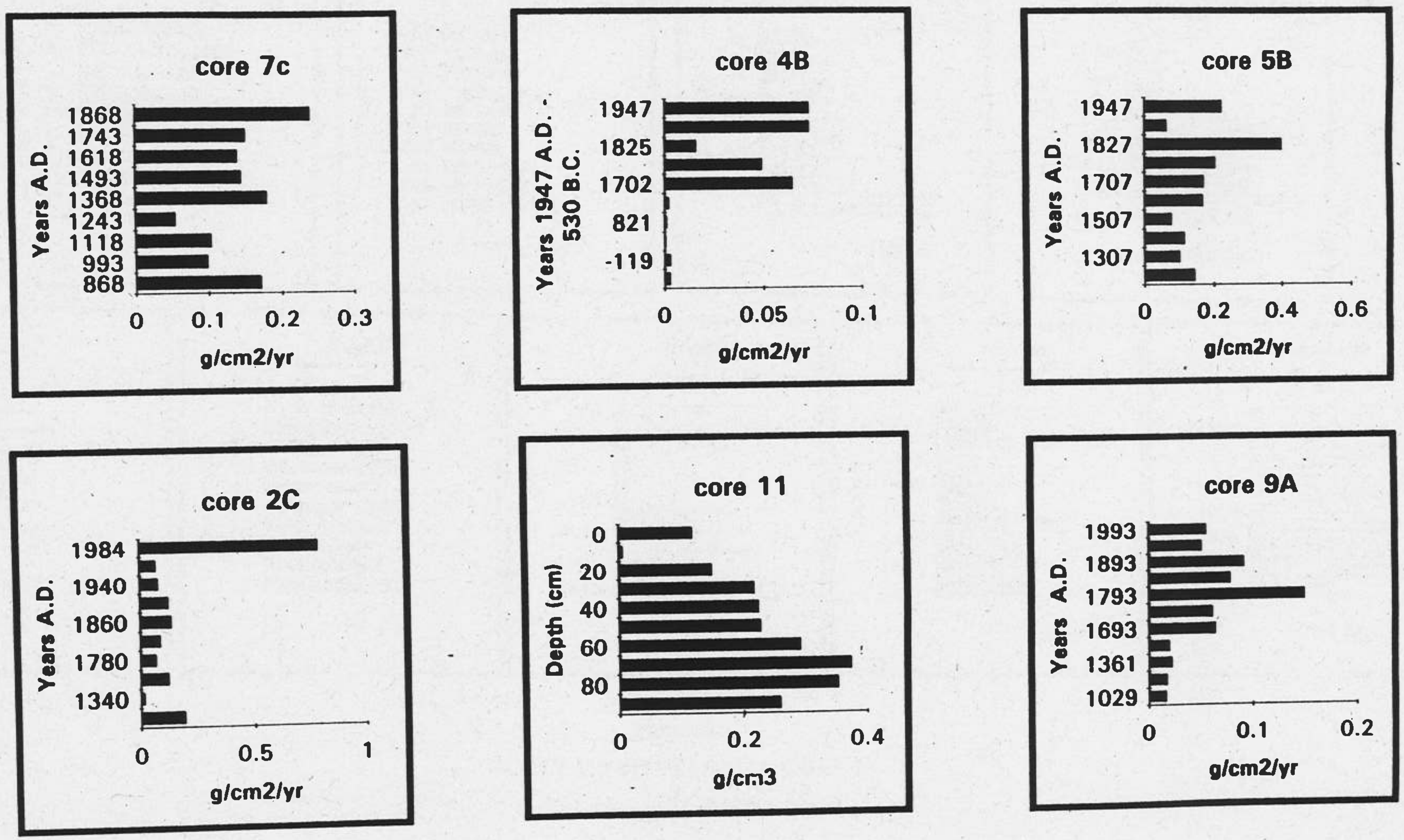


Figure 6

DELAWARE ESTUARY CORES
carbon

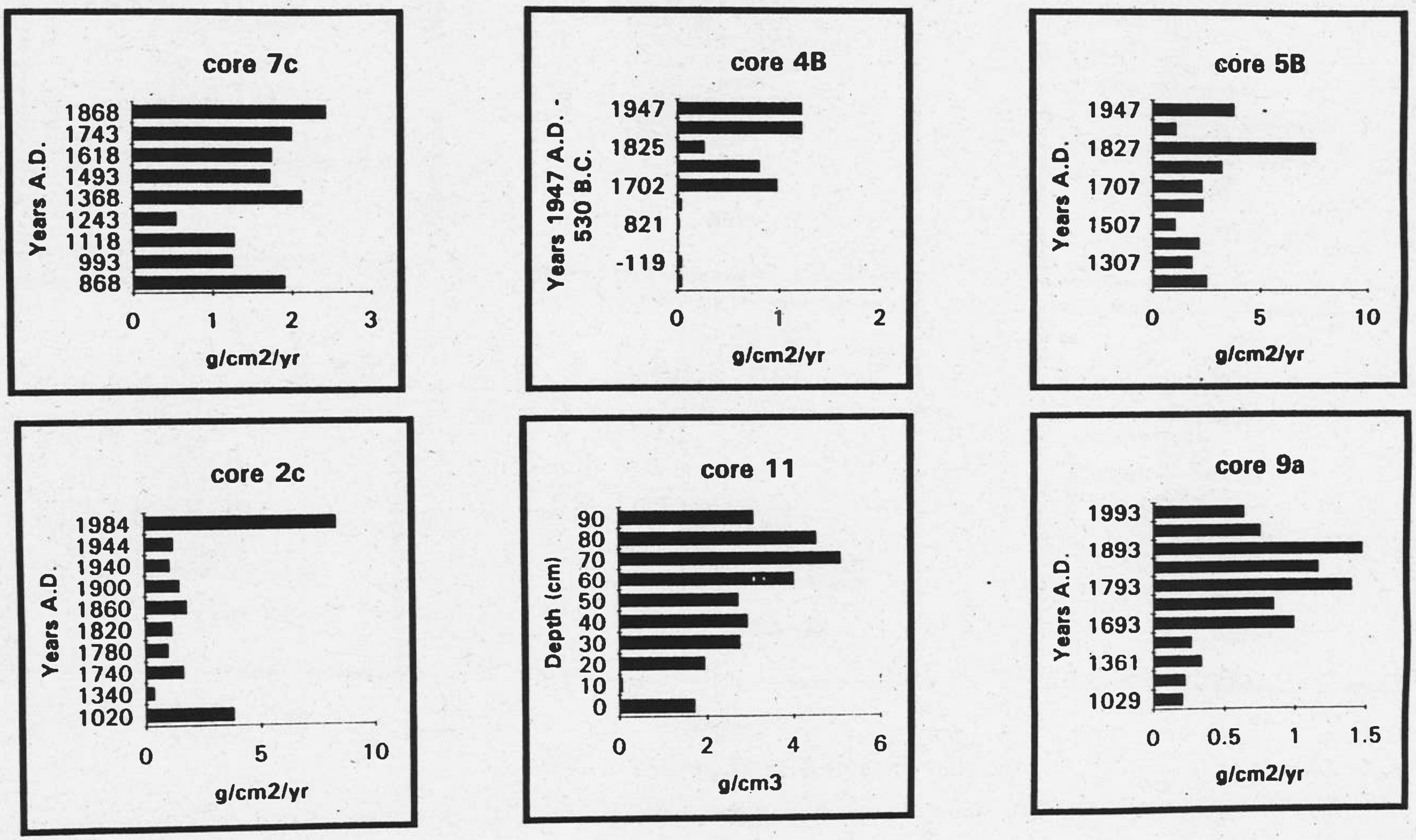


Figure 7

DELAWARE ESTUARY CORES
sulfur

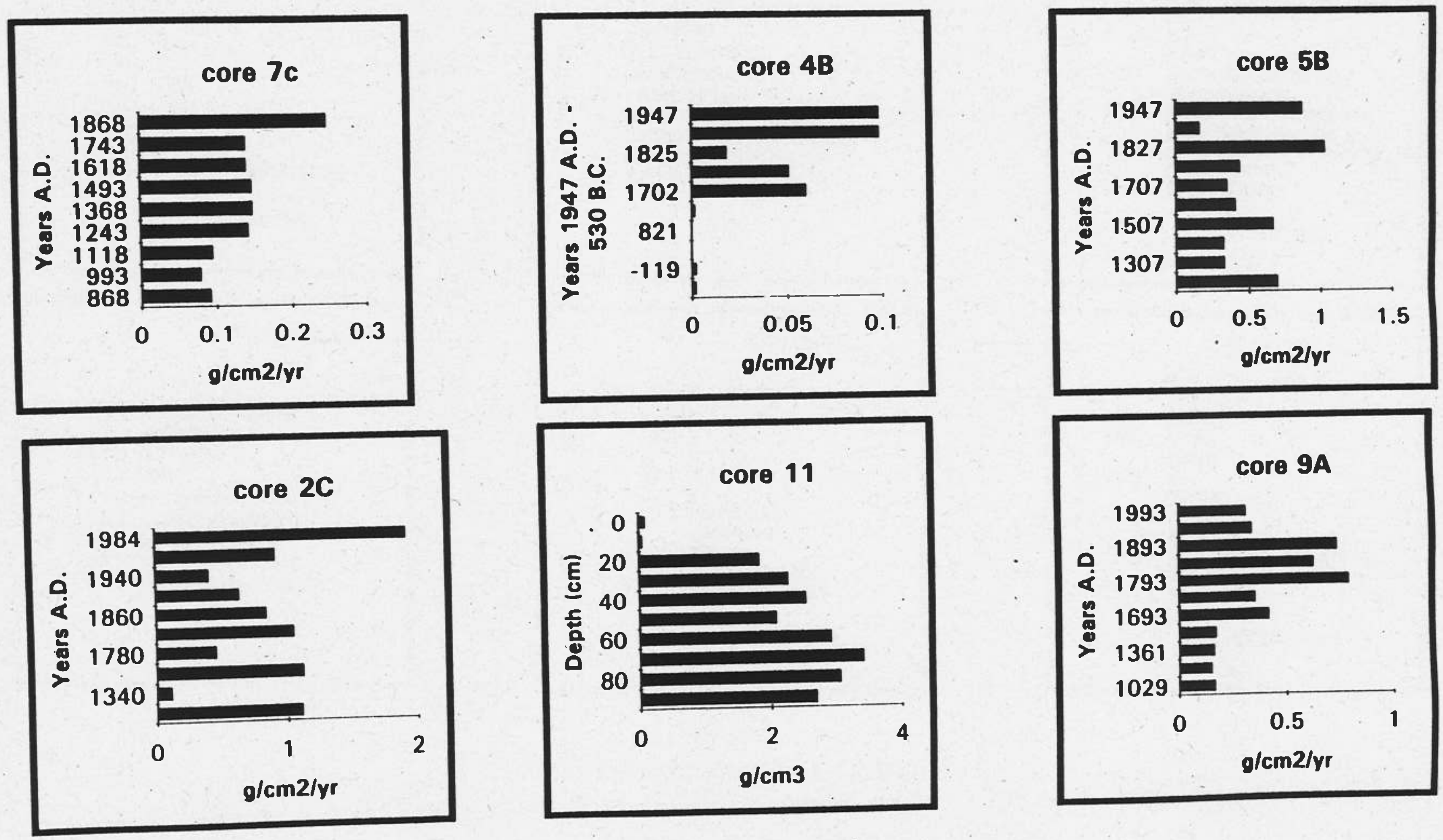


Figure 8

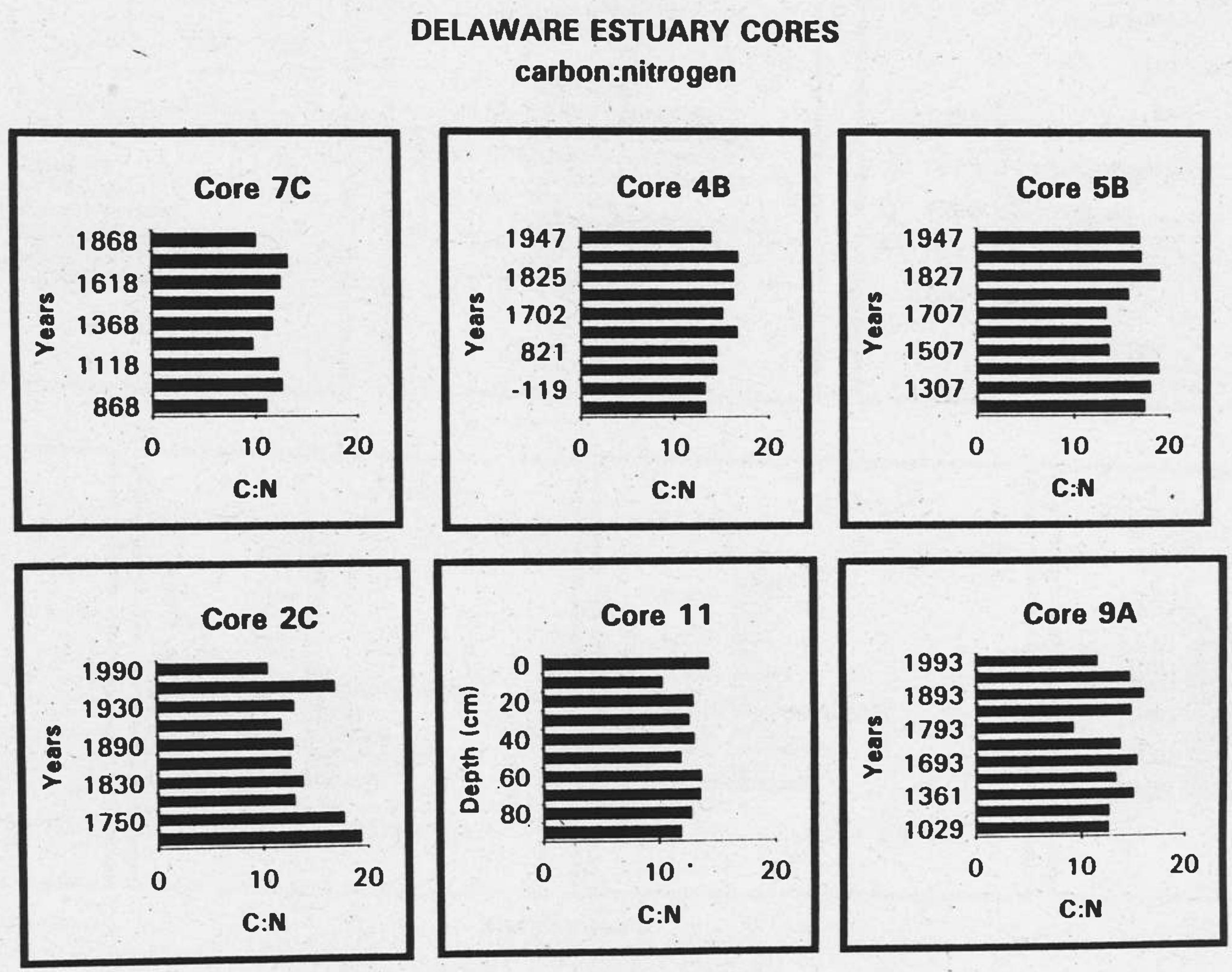

DELAWARE ESTUARY CORES
carbon:nitrogen
Core 7C
Years
1868
1618
1368
1118
868
0
10
20
C:N
Core 4B
Years
1947
1825
1702
821
-119
0
10
20
C:N
Core 5B
Years
1947
1827
1707
1507
1307
0
10
20
C:N
Core 2C
Years
1990
1930
1890
1830
1750
0
10
20
C:N
Core 11
Depth (cm)
0
20
40
60
80
0
10
20
C:N
Core 9A
Years
1993
1893
1793
1693
1361
1029
0
10
20
C:N

Figure 9

DELAWARE ESTUARY CORES
total diatoms

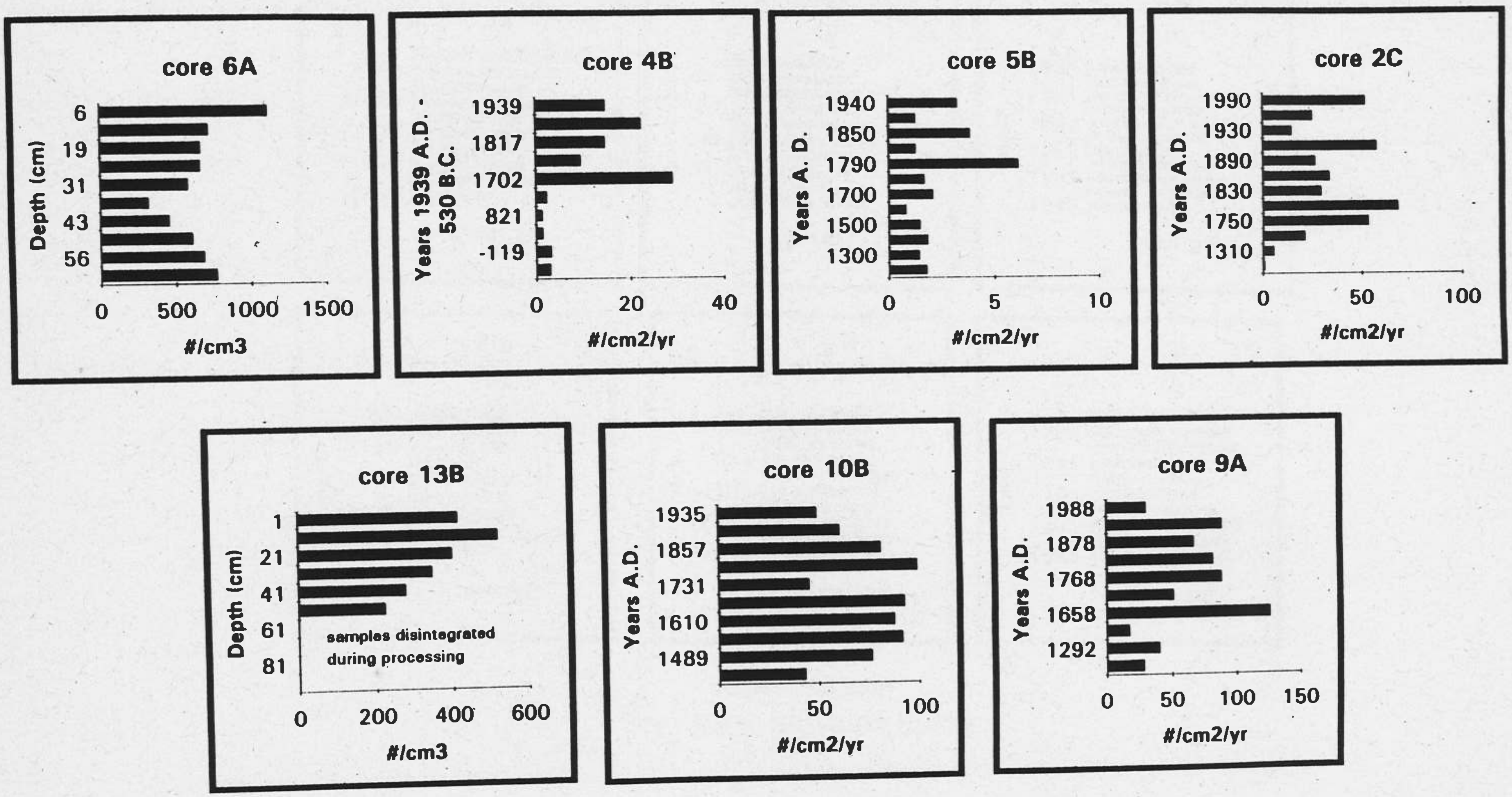


Figure 10

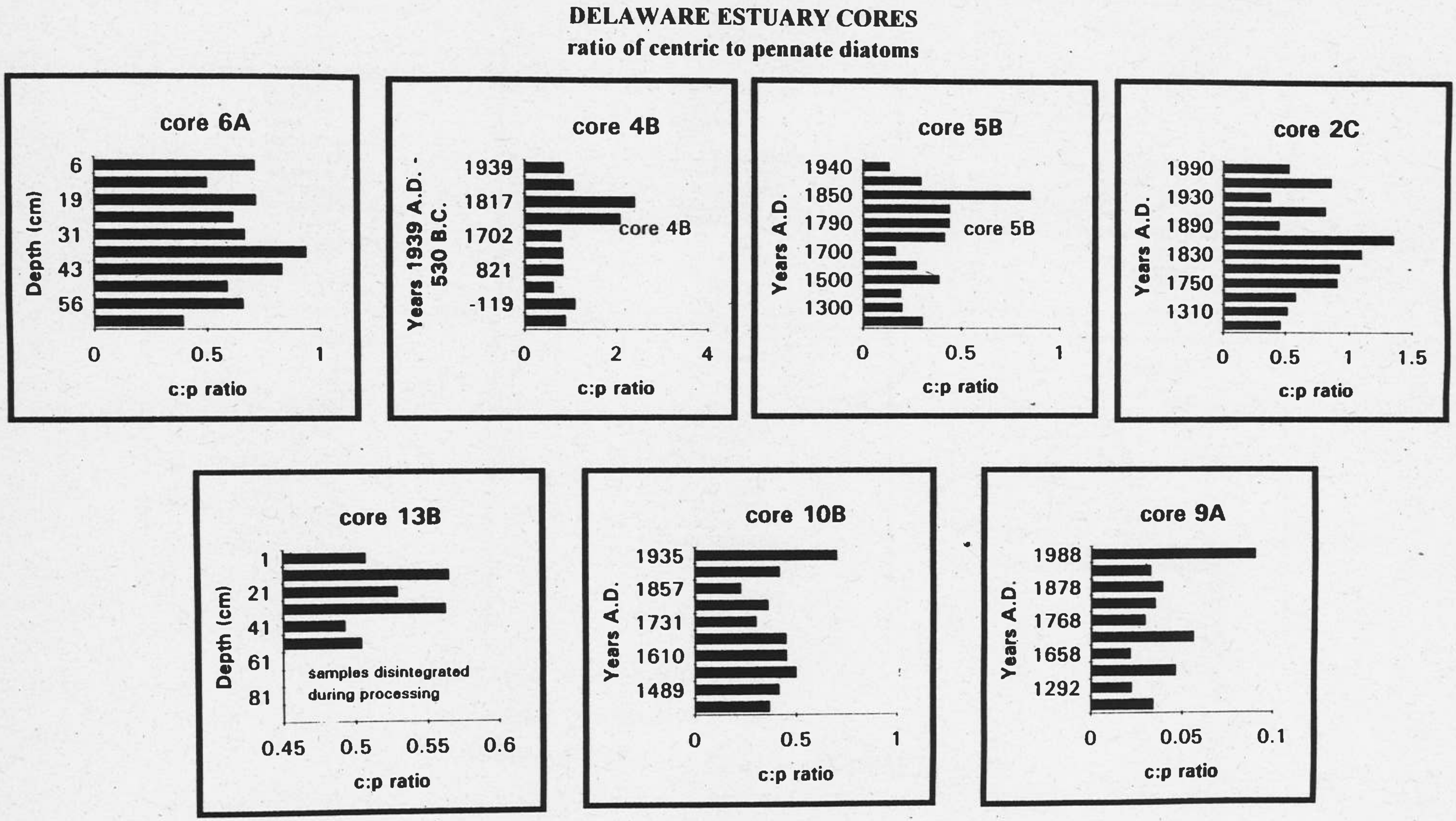

DELAWARE ESTUARY CORES
ratio of centric to pennate diatoms
core 6A
Depth (cm)
6
19
31
43
56
0
0.5
1
c:p ratio
core 4B
Years 1939 A.D. - 530 B.C.
1939
1817
1702
821
-119
core 4B
0
2
4
c:p ratio
core 5B
Years A.D.
1940
1850
1790
1700
1500
1300
core 5B
0
0.5
1
c:p ratio
core 2C
Years A.D.
1990
1930
1890
1830
1750
1310
0
0.5
1
1.5
c:p ratio
core 13B
Depth (cm)
1
21
41
61
81
samples disintegrated during processing
0.45
0.5
0.55
0.6
c:p ratio
core 10B
Years A.D.
1935
1857
1731
1610
1489
0
0.5
1
c:p ratio
core 9A
Years A.D.
1988
1878
1768
1658
1292
0
0.05
0.1
c:p ratio

Figure 11

DELAWARE CORE 7C

Carbon-14 date: 95-97 cm: 1210±120 ybp
No pollen horizon
Pb-210 -- highly variable

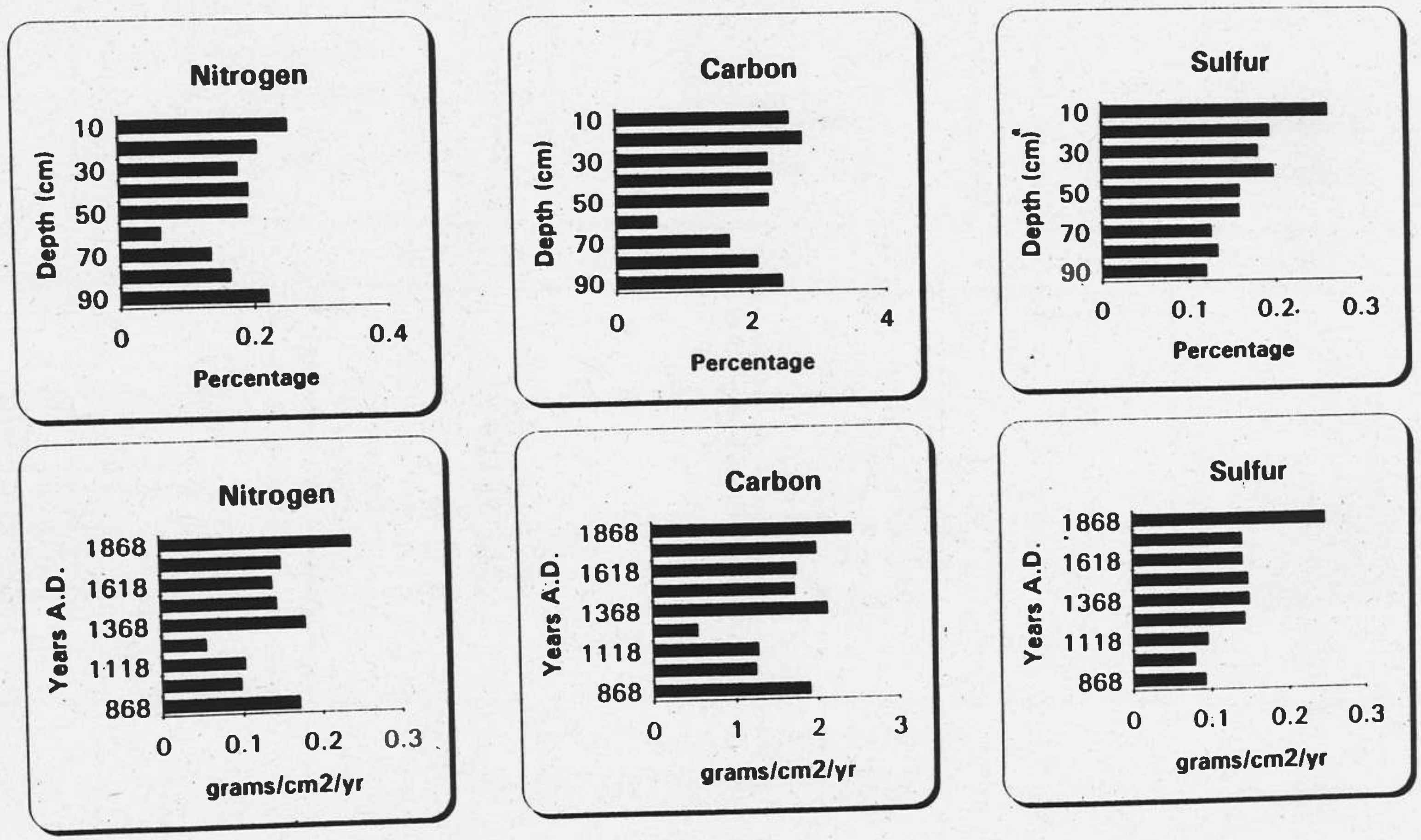


Figure 12

DELAWARE CORE 4B

Carbon-14 date: 74-77 cm: 2350±180 ybp
Agricultural horizon cannot be identified by ragweed
Lead-210 sedimentation rate 0.5 cm/yr

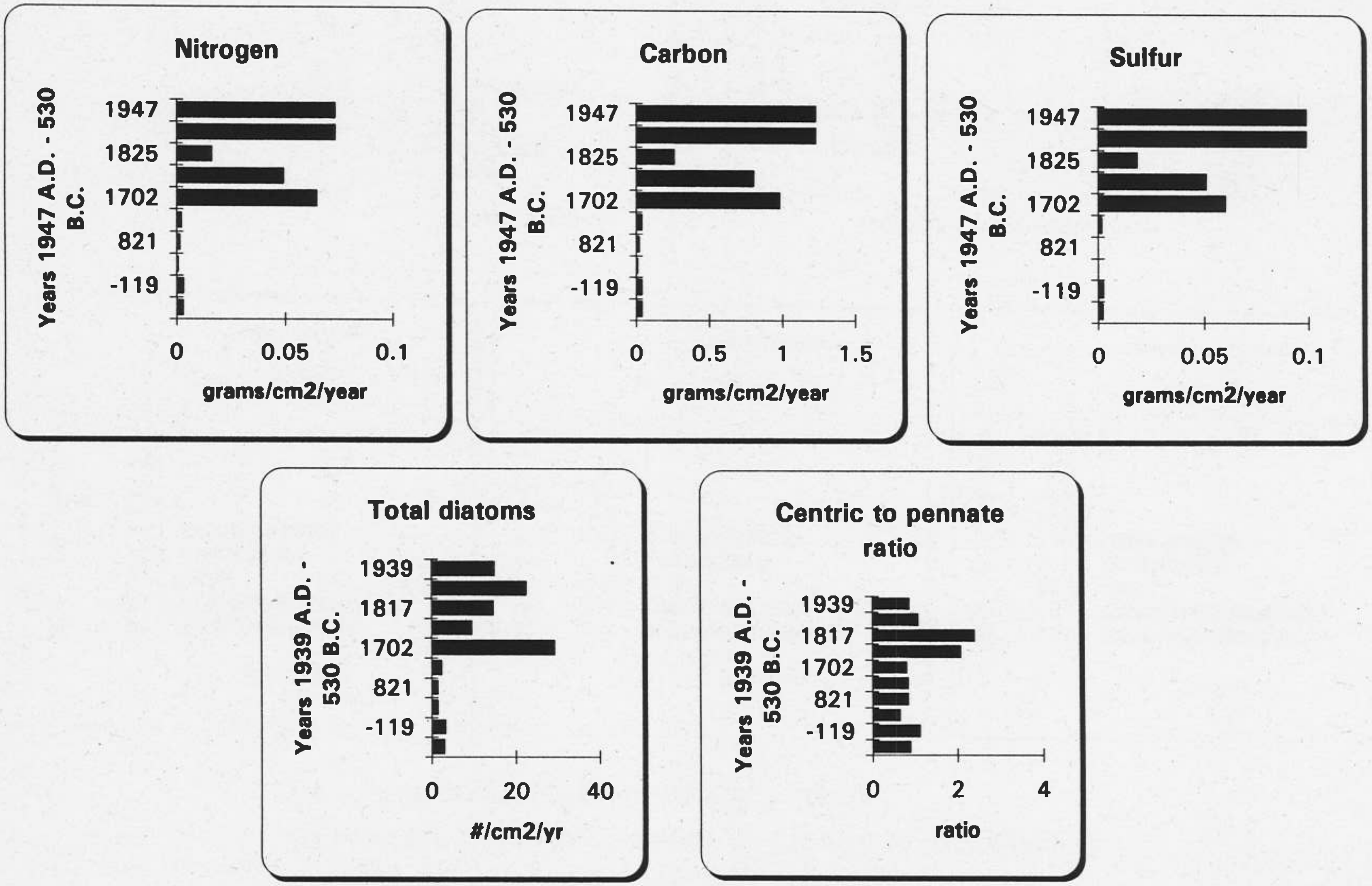


Figure 13

DELAWARE CORE 4B

Carbon-14 date: 74-77 cm: 2350±180 ybp
Agricultural horizon cannot be identified by ragweed
Lead-210 sedimentation rate 0.5 cm/yr

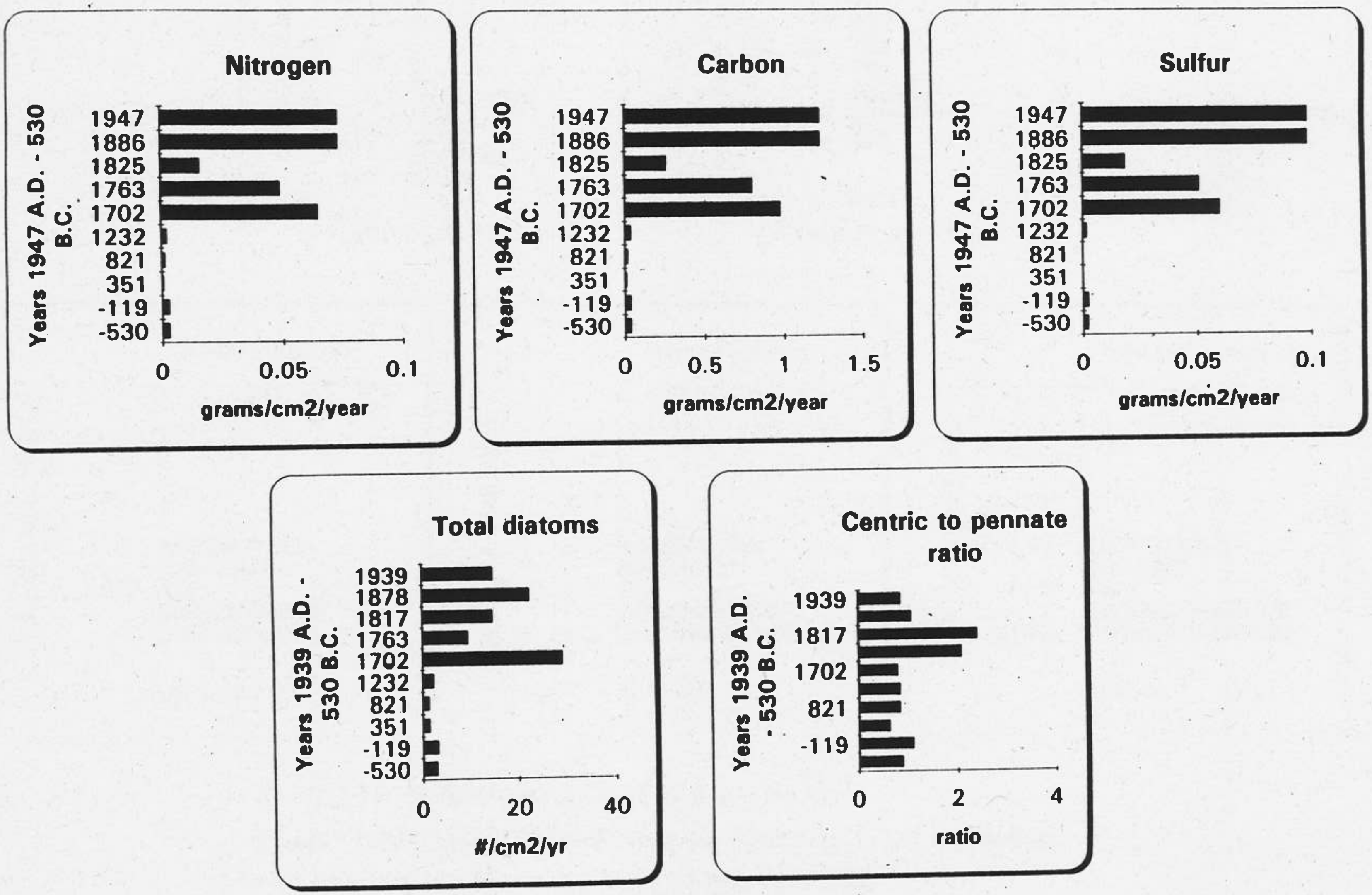
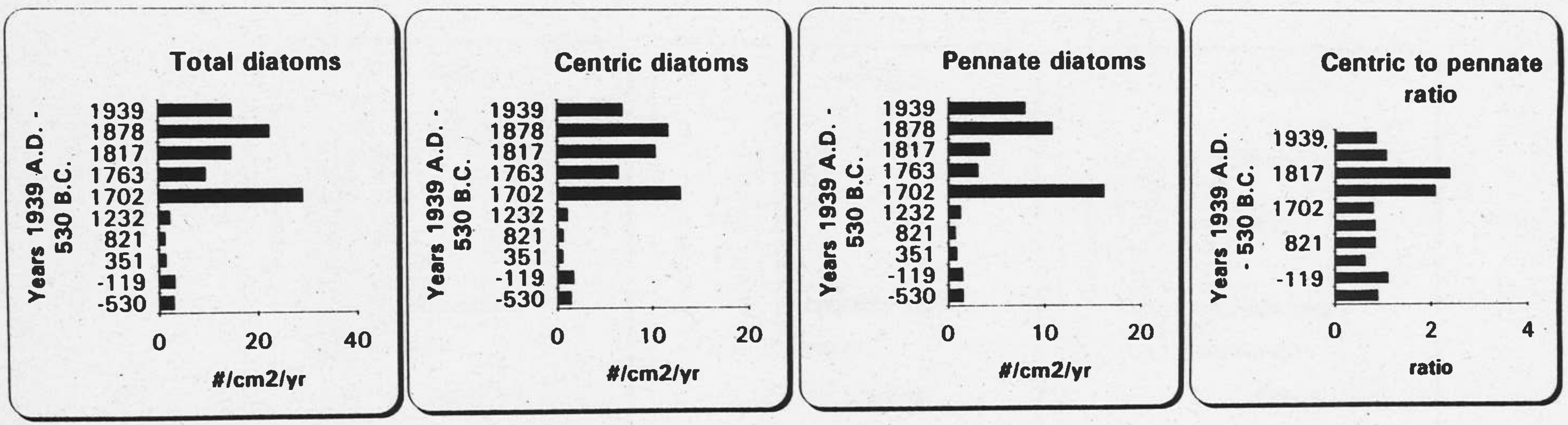


Figure 14

DELAWARE CORE 4B

Carbon-14 date: 74-77 cm: 2350±180 ybp
Agricultural horizon cannot be identified by ragweed
Lead-210 sedimentation rate 0.5 cm/yr



Dominant diatom taxa:
Centric: *Coscinodiscussp., Actinocyclus sp., Cyclotella sp., Thalassiosira sp.*
Pennate: *Diploneis smithii, Navicula sp., Diploneis sp., Rhaphoneis sp.*

Figure 15

DELAWARE CORE 5B

Carbon 14 date: 86-89 cm: 890±70 ybp
Agricultural horizon (ragweed): 5 cm
Lead-210 sedimentation rate: 0.15 cm/yr

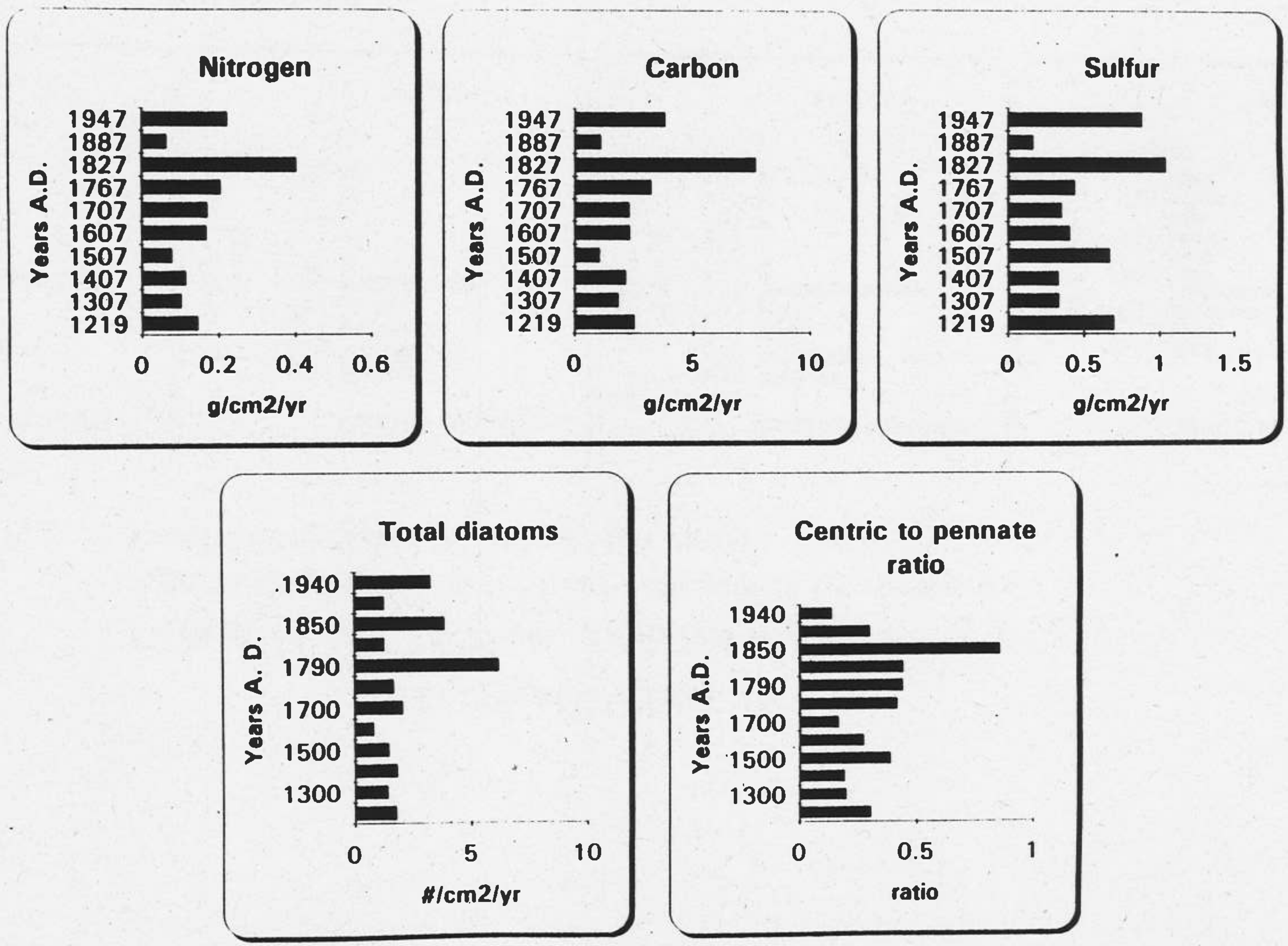
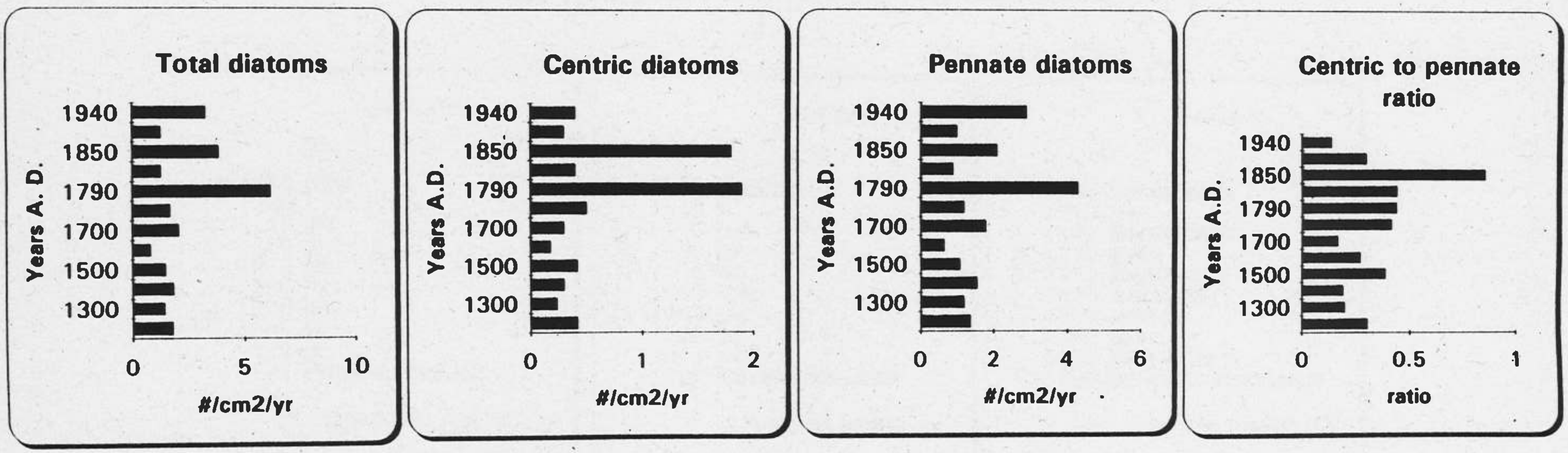


Figure 16

DELAWARE CORE 5B

Carbon 14 date: 86-89 cm: 890±70 ybp
Agricultural horizon (ragweed): 5 cm
Lead-210 sedimentation rate: 0.15 cm/yr



Dominant diatom taxa:
Centric: *Coscinodiscussp., Actinocyclus sp., Cyclotella sp., Thalassiosira sp.*
Pennate: *Diploneis smithii, Navicula sp., Diploneis sp., Rhaphoneis sp.*

Figure 17

DELAWARE CORE 2C

Carbon-14 date: 90-92 cm: 1000±70 ybp
Agricultural horizon (ragweed): 73 cm
Lead-210: not dated

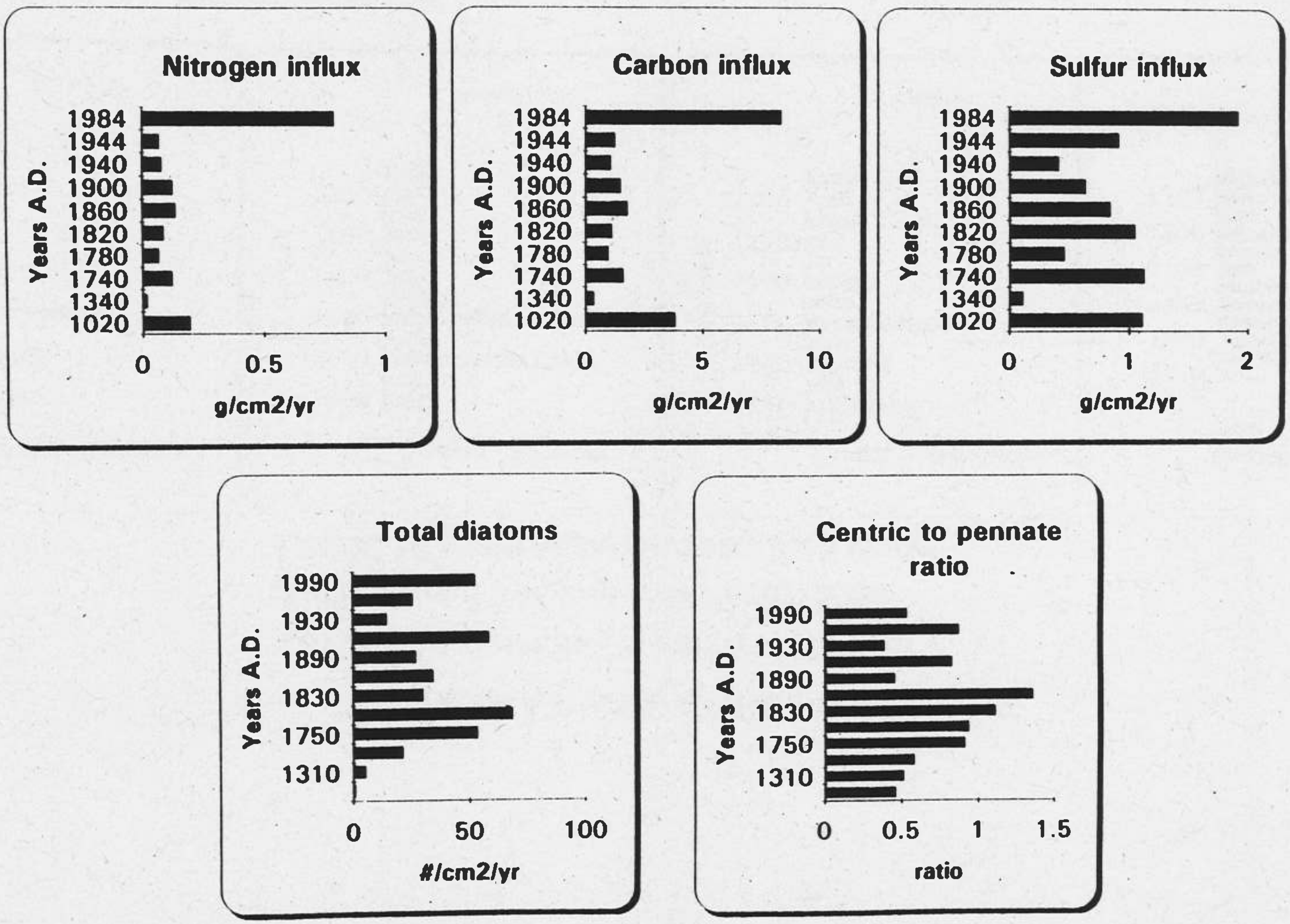
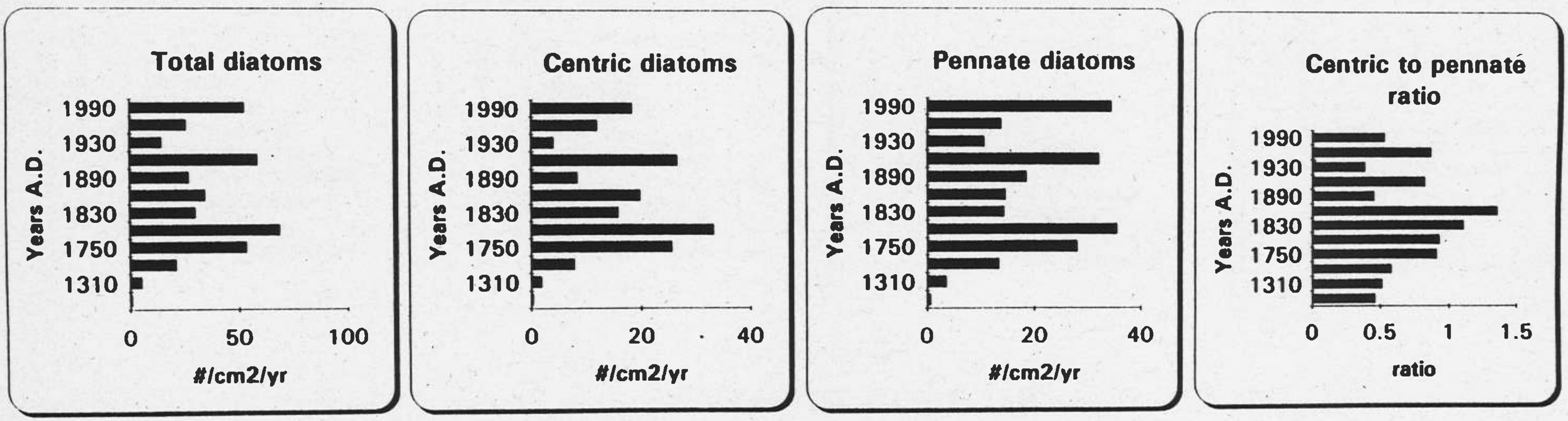


Figure 18

DELAWARE CORE 2C

Carbon-14 date: 90-92 cm: 1000±70 ybp
Agricultural horizon (ragweed): 73 cm
Lead-210: not dated



Dominant diatom taxa:
Centric: *Coscinodiscus sp., Actinocyclus sp., Cyclotella sp., Thalassiosira sp.*
Pennate: *Diploneis smithii, Navicula sp., Diploneis sp., Rhaphoneis sp.*

Figure 19

DELAWARE CORE 13B

Core undated

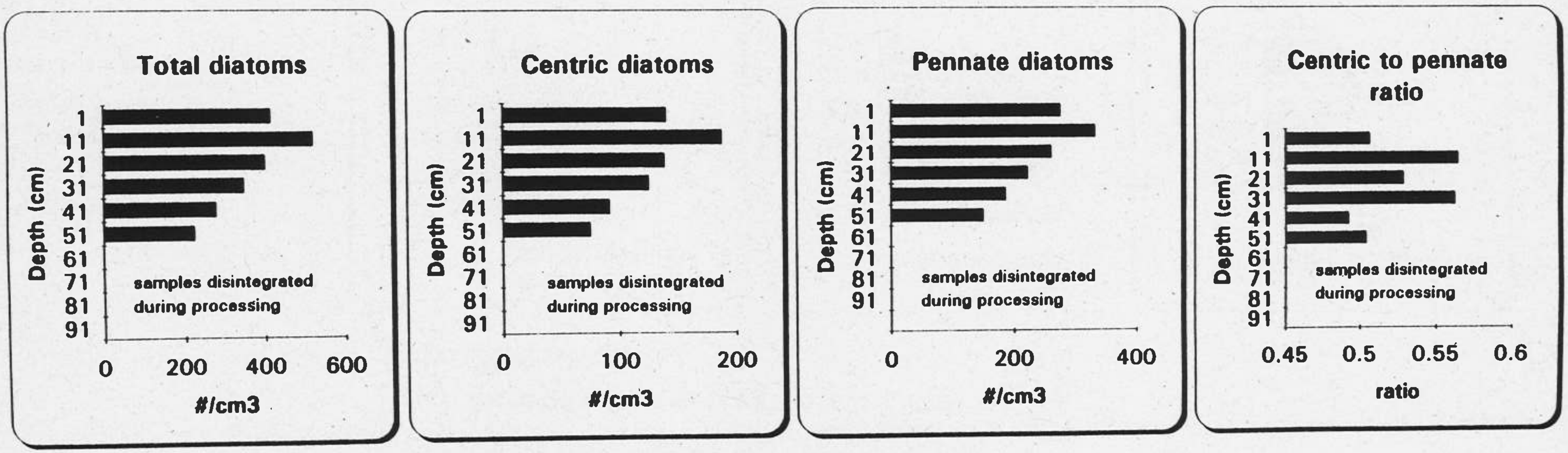


Figure 20

DELAWARE CORE 11
Core undated

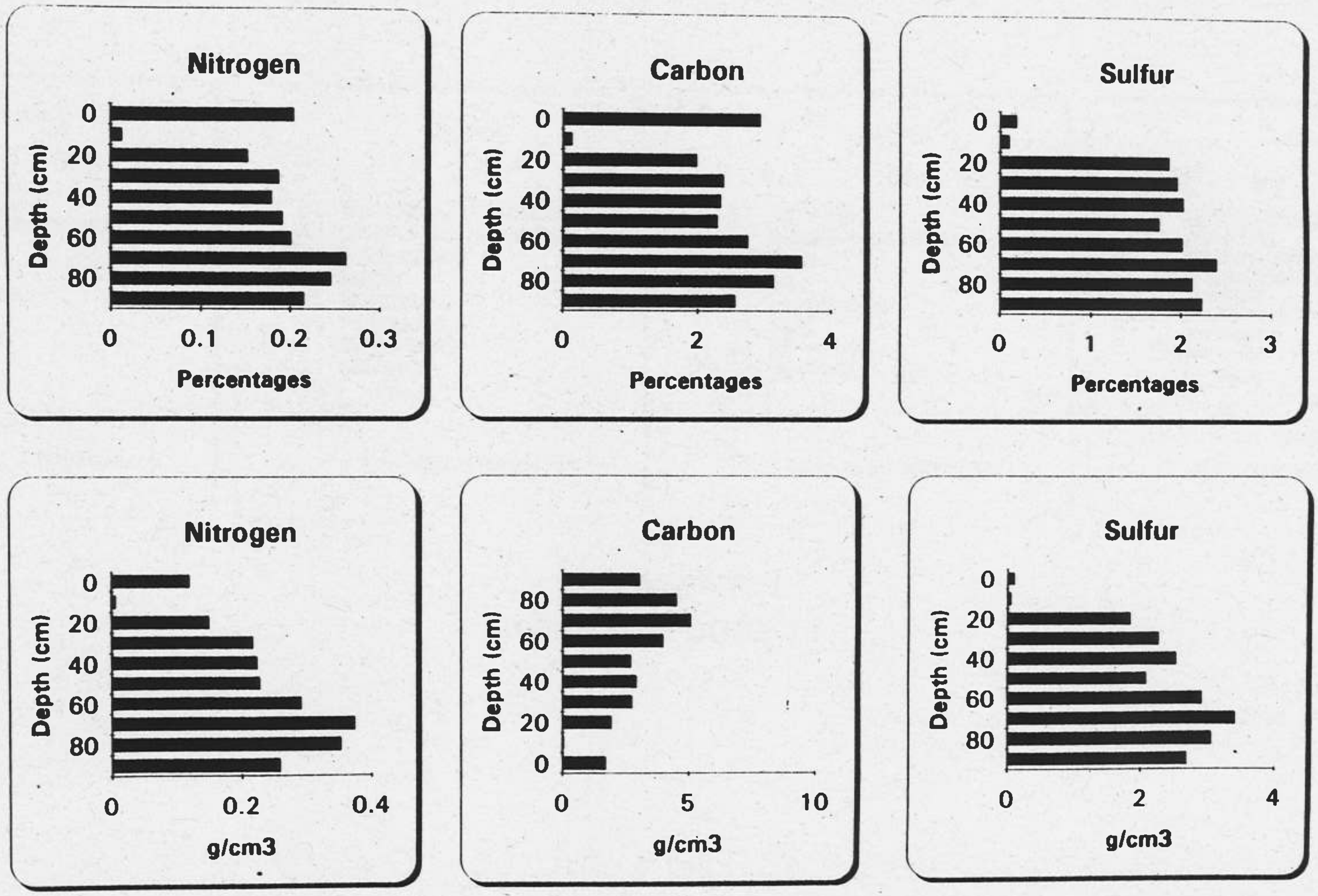


Figure 21

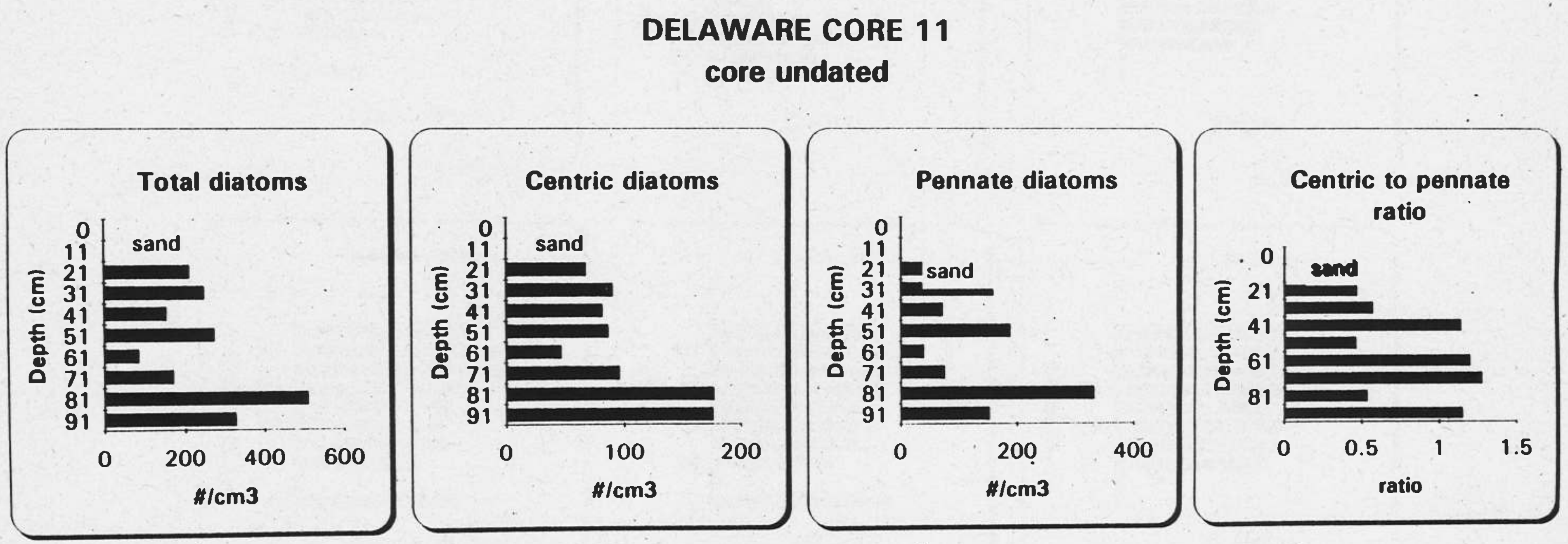
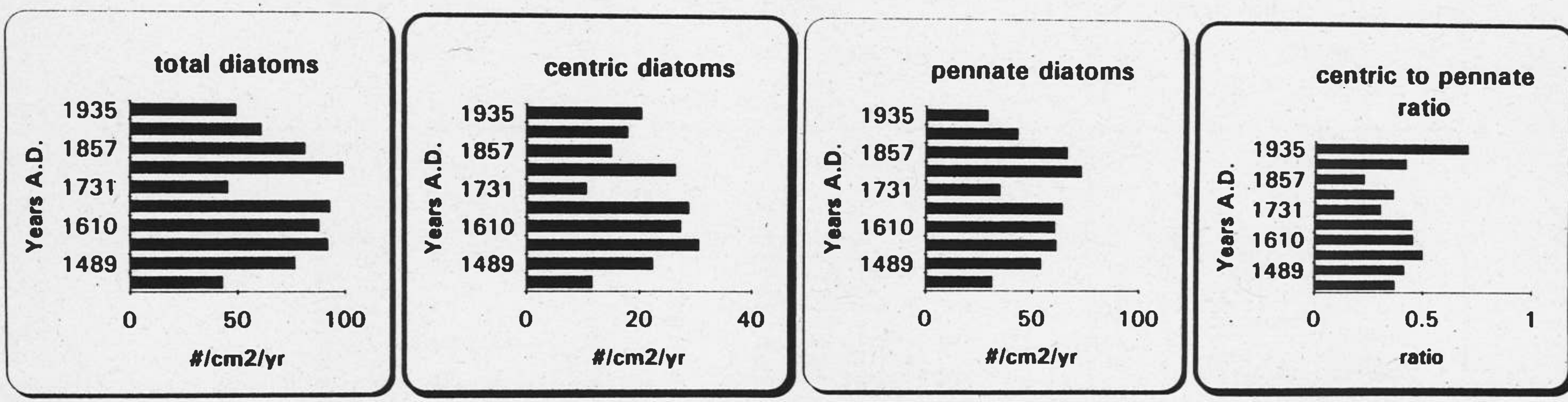

DELAWARE CORE 11
core undated
Total diatoms
Depth (cm)
0
11
21
31
41
51
61
71
81
91
sand
0
200
400
600
#/cm3
Centric diatoms
Depth (cm)
0
11
21
31
41
51
61
71
81
91
sand
0
100
200
#/cm3
Pennate diatoms
Depth (cm)
0
11
21
31
41
51
61
71
81
91
sand
0
200
400
#/cm3
Centric to pennate ratio
Depth (cm)
0
21
41
61
81
sand
0
0.5
1
1.5
ratio

Figure 22

DELAWARE CORE 10B

Carbon-14 date: 107-109 cm: 590 ± 90 ybp



More than 30% of the diatom population consists of 2 species of *Diploneis*

Figure 23

DELAWARE CORE 9A
Carbon-14 date: 107-109 cm: 1540±110 ybp
Agricultural horizon (ragweed): 60 cm
Lead-210 sedimentation rate: 0.2 cm/yr

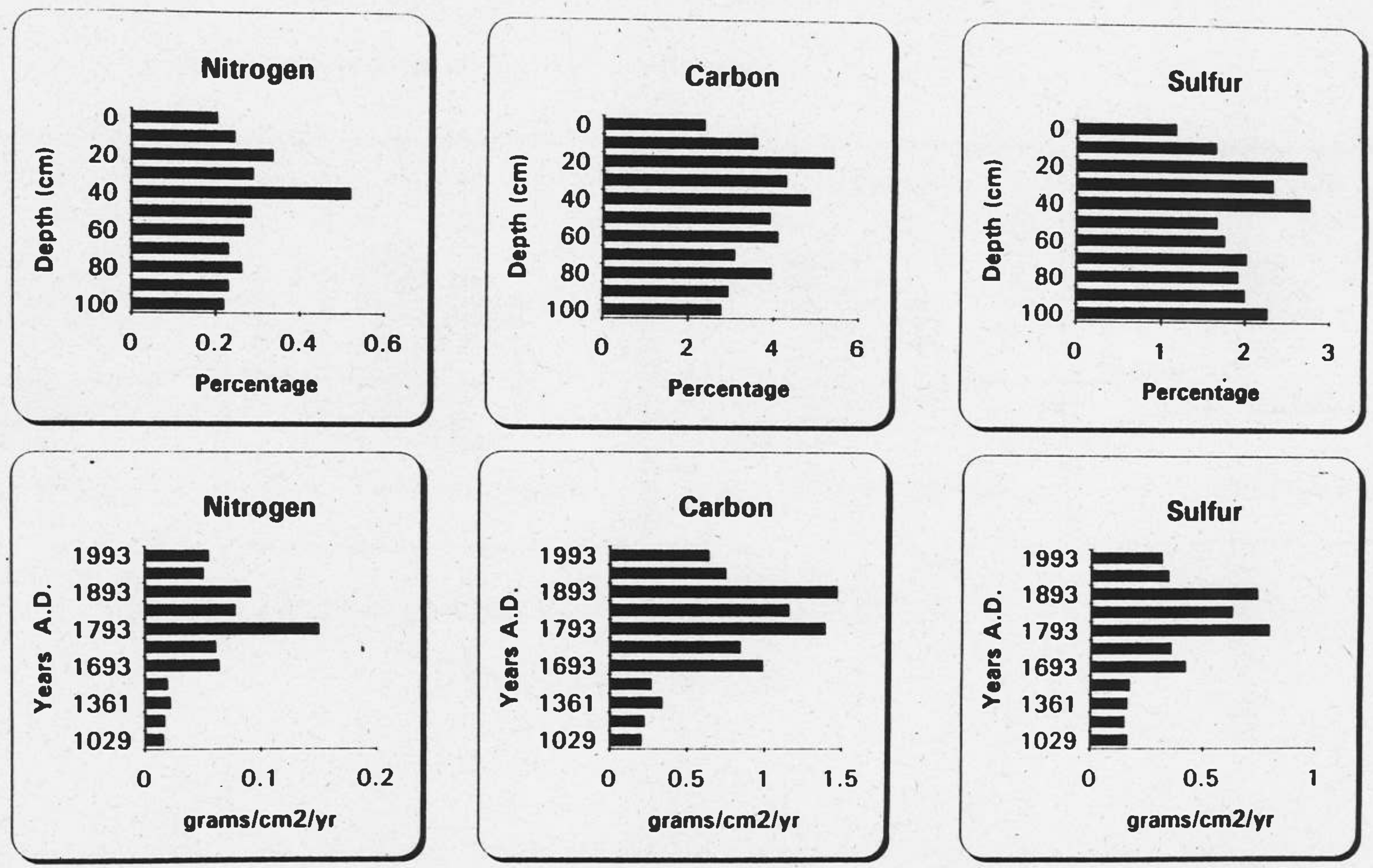


Figure 24

DELAWARE CORE 9A

Carbon-14 date: 107-109 cm: 1540±110 ybp
Agricultural horizon (ragweed): 60 cm
Lead-210 sedimentation rate: 0.2 cm/yr

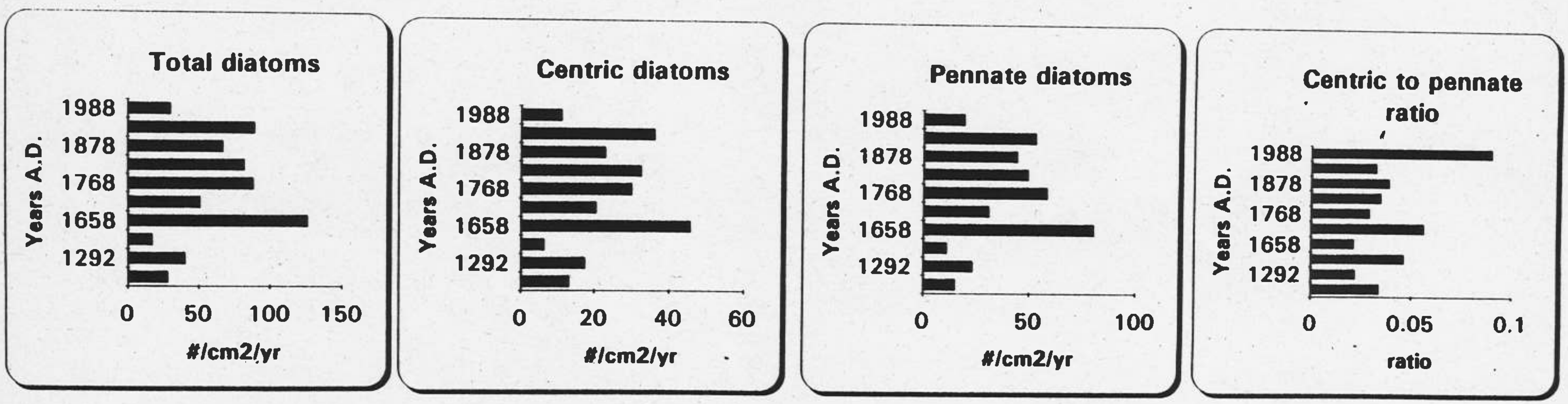


Figure 25

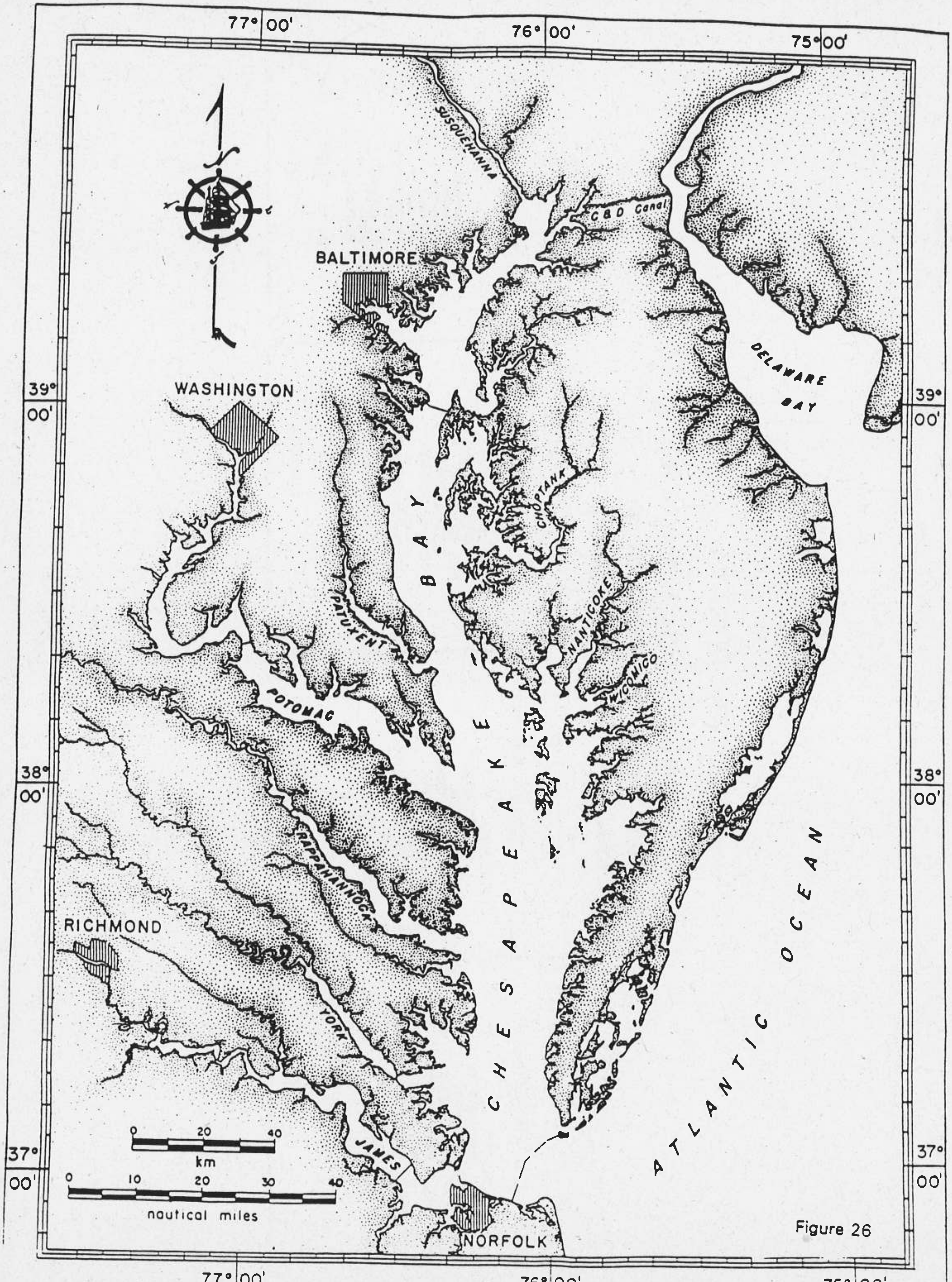

77° 00'
76° 00'
75° 00'
39° 00'
38° 00'
37° 00'
SUSQUEHANNA
C&D Canal
BALTIMORE
WASHINGTON
DELAWARE BAY
CHOPTANK
PATUXENT
NANTICOKE
WICOMICO
POTOMAC
RAPPAHANNOCK
YORK
JAMES
RICHMOND
NORFOLK
CHESAPEAKE BAY
ATLANTIC OCEAN
0 20 40
km
0 10 20 30 40
nautical miles

Figure 26