DEVELOPMENT AND APPLICATION OF A PLEISTOCENE SEA LEVEL CURVE TO THE COASTAL PLAIN OF SOUTHEASTERN VIRGINIA

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Master of Arts

by
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This thesis is submitted in partial fulfillment of
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Master of Arts

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ABSTRACT

Two interpretations of the Outer Coastal Plain stratigraphy of southeastern Virginia exist. Oaks and Coch (1973) believe that the sediments east of the Suffolk Scarp were deposited during two transgressions and regressions, while Luebke and Johnson state that there was only one.

Vibracores taken off of Dam Neck, Virginia show that the offshore stratigraphy consists of only one Pleistocene transgressive-regressive unit, and the Holocene transgressive sequence. This is also the case to the south off of False Cape, Virginia (Shideler, Swift, Johnson, and Holliday, 1972).

A late Pleistocene sea level curve was developed by Shackleton and Opdyke (1973) from oxygen isotope data. The curve was calibrated by using calculations of the isotopic composition of the Wisconsinan Ice Sheets. This curve is too imprecise for a low-relief area like the Middle Atlantic Coastal Plain, because it does not fit the geomorphology there or on the continental shelf.

The data of Shackleton and Opdyke was recalibrated using the maximum Wisconsinan low-stand value of Dillon and Oldale. The new curve shows that sea level reached a maximum elevation of +16.2 m (+53 ft.) 120,000 years ago, and then retreated to the continental shelf for the remainder of the Pleistocene. The high stand is very close to the maximum elevation of the estuarine and lagoonal facies of the Norfolk Formation (+14.0 m (+46 ft.) and +14.6 m (+48 ft.), respectively), which has been dated to be 120,000 to 130,000 years old. Thus, the sea level curve provides an independent model of the geologic history of the Coastal Plain.

According to the recalibrated curve, sea level did not transgress to its present elevation at any time after the 120,000 year high stand until the Holocene. Therefore, both the offshore stratigaphy and the study of Pleistocene sea level changes supports the interpretation of Luebke and Johnson.

DEVELOPMENT AND APPLICATION OF A PLEISTOCENE SEA LEVEL CURVE TO THE COASTAL PLAIN OF SOUTHEASTERN VIRGINIA

INTRODUCTION

The Coastal Plain of Virginia is the land which lies to the east of the Fall Zone and extends to the edge of the Continental Shelf (Clark and Miller, 1912). The sediments of this region consist of a series of more or less unconsolidated sands, gravels, and marls of Cretaceous to Holocene age (Richards, 1967). The Outer Coastal Plain sediments of southeastern Virginia are composed of a series of marine, marginal marine and fluviatile facies of Pleistocene age (Oaks and Coch, 1973) which were deposited when sea level was higher than present during the interglacial periods.

Geologists have studied the Pleistocene sediments of the Virginia Coastal Plain for over 100 years. When Rogers (1884) first described the area, he recognized two terraces separated by a scarp east of Suffolk. The scarp was identified as a former shoreline, while the terrace formations, according to Rogers, were deposited under marine conditions which existed because the land had subsided relative to the sea. Shaler (1890) also described the same three geomorphic features, but did not hypothesize on the mechanism which caused marine features to be present above sea level. Detailed work in the Coastal Plain began with Shattuck in 1906. He recognized three Pleistocene terraces in Maryland which had been deposited and eroded due to successive periods when the land had been submerged or uplifted. Shattuck's ideas were reiterated by Clark and Miller (1912) in their work on the Virginia Coastal Plain. The volume of the ocean was assumed to have been constant with time, so elevated marine deposits were reasoned to be caused by the submergence and emergence of the land. The mechanism for these apparent vertical movements was unknown, although Shattuck (1906, p. 137) ruled out isostasy because of the anomalous fact that the land had sunk after a period of erosion, and was uplifted after a depositional period.

The first mention of sea level change as a cause of the elevated marine deposits of the Middle Atlantic Coastal Plain occurs in Wentworth (1930). Even at this point, he was reluctant to commit himself, and stated that "the successive emergences and submergences may be regarded as due either to crustal movements or to fluctuations in sea level." He further stated that "So far as the local evidence is concerned, either cause is as valid as the other." (p. 118). Flint (1940) acknowledged the fact that the Pleistocene sea level changes led to the deposition of the Coastal Plain sediments. His ideas were further refined by Oaks and Coch (1973), who did extensive field work in the region during the early 1960's.

The Outer Coastal Plain geomorphology and stratigraphy of southeastern Virginia was mapped and described by Oaks (1965). He found five different Pleistocene sedimentary units (Table I) which are closely associated with geomorphic features in the area (Figure 1). According to Oaks, the Great Bridge, Norfolk

TABLE I

Sedimentary Units-Outer Coastal Plain Southeastern Virginia

Formation	Sediment Description	Sea Level	Environment of Deposition
Sandbridge Formation Upper Member	Clayey-sand Facies-Clayey sand, silt and clay. Silty-sand Facies-Fine to medium silty sand. Silty-clay Facies-Dark to light gray clay and silt with some sand. Sand Ridge and Mud Flat Complex-Ridges of white to light gray, fine to very fine quartz sand with a trace of silt. Mud flats are underlain with a thin layer of silty clay and clayey-silt.	11 to 15 Feet Above MSL.	Barrier-lagoon complex with shoreline at Pungo Ridge.
Sandbridge Formation Lower Member	Well-sorted, angular to subrounded fine to medium quartz sand, locally clayey or silty. Forams and marine fossils present.	12 to 17 Feet Above MSL.	Barrier complex with shoreline at Land of Promise Ridge.
Kempsville Formation	Silty, very fine sand, clay and soft peaty clay grading eastward into fine to coarse angulat to subrounded quartz sand, with rounded and broken shell fragments	18 to 22 Feet Above MSL.	Marsh, dune, beach and nearshore marine sediments with shoreline at Hickory Scarp.

TABLE I (Cont'd)

Formation	Sediment Description	Sea Level	Environment of Deposition
Londonbridge Formation	White to light yellow, angular to rounded fine and coarse sand with fine quartz and quartzite pebble gravel, with beds of soft gray clayey silt and sand grading westward into soft gray to bluish gray very fine sandy and clayey silt.	18 to 22 Feet Above MSL.	Barrier complex with shoreline at Oceana ridge.
Norfolk Formation	*Coarse Sand Facies*-Fine pebble gravel grading upward into medium to coarse sand and very fine pebble gravel.	45 to 50 Feet Above MSL.	Beach and Dune Facies.
	Clayey-sand Facies-Horizontally bedded silt, fine clayey sand and clay with beds of well-sorted fine sand.		Fluvial-estuarine Facies
	Silty-clay Facies-yellow to white, fine sandy clay overlying soft, blue-gray interbedded silty clay, clayey silt, and fine to very fine sand.		Open Bay-Lagoon Facies
	Medium Sand Facies-Blue-green, clayey, fine to coarse, angular to subrounded quartz sand with some clay balls.		Offshore Marine Facies
	Silt Facies-Compact, light gray very fine sandy silt. Scattered fossils include *Elphidium*, *Buccella*, and *Ammonia* species.		Offshore Marine Facies

TABLE I (Cont'd)

Formation	Sediment Description	Sea Level	Environment of Deposition
Norfolk Formation	Fine-sand Facies-light bluish gray, fine sand to silty very fine sand with marine fossils.		Offshore Marine Facies
	Silty-sand Facies-parallel-bedded soft bluish-gray clayey to silty fine to very fine sand and clayey sandy silt.		Reduced salinity, Bay or lagoon facies.
Great Bridge Formation			
Upper Member	Gray to bluish gray, soft, clayey silt and silty clay interlayered with fine silty sand. Grades eastward into white to light gray, fine to coarse, angular to subrounded quartz sand containing shell fragments. To the east, this facies becomes a very fine, micaceous silty quartz sand with some marine fossils.	-4 Ft.	Restricted Bay or Sound.
Lower Member	White to light gray, fine to coarse angular to subrounded quartz sand, with minor amounts of pebble gravel (chiefly quartzite and rock fragments) interfingering with brown peat.	-11 Ft.	Restricted Bay and Marsh.

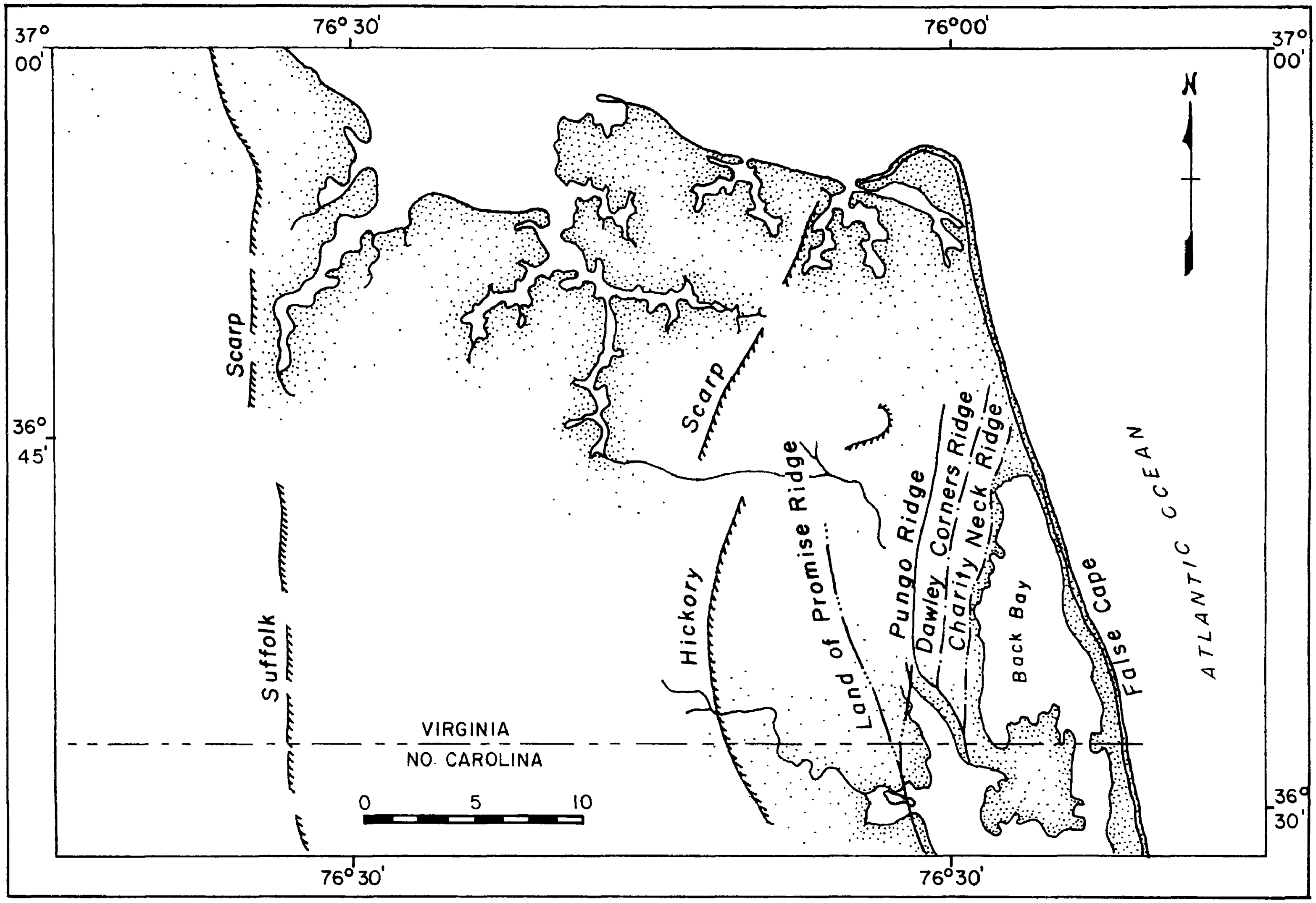


Figure 1-Map showing major ridges and scarps, Outer Coastal plain of southeastern Virginia.

and Kempsville Formations were laid down during one transgression and regression, while the Londonbridge and Sandbridge Formations were deposited during another. Later work by Luebke and Johnson (1967) resulted in a second interpretation. They believe that the five Pleistocene units described by Oaks (1965) were deposited during one transgression and regression rather than two (Figures 2 and 3).

The disparity between the stratigraphic interpretations of Oaks and Coch (1973) and Luebke and Johnson (1967) must be resolved, so the geology of the area can be used to guide studies in other areas. Two methods can be used to determine which interpretation best describes the geologic history of the region. The first method involves the study of the stratigraphy of the Inner Shelf. The stratigraphy offshore of southeastern Virginia will reflect the history on land. If there is evidence of two Pleistocene transgressive-regressive sequences off the area, the interpretation of Oaks is correct. If, however, only one Pleistocene transgressive-regressive sequence is present, the interpretation of Luebke and Johnson should be used as a model for studies elsewhere in the Coastal Plain.

A second method is closely related to the concept of Pleistocene sea level changes. A sea level curve independent of the local evidence can be used to describe the region's geologic history. This model can be compared with the two interpretations of the Coastal Plain geology. The idea which best fits the model developed from a Pleistocene sea level

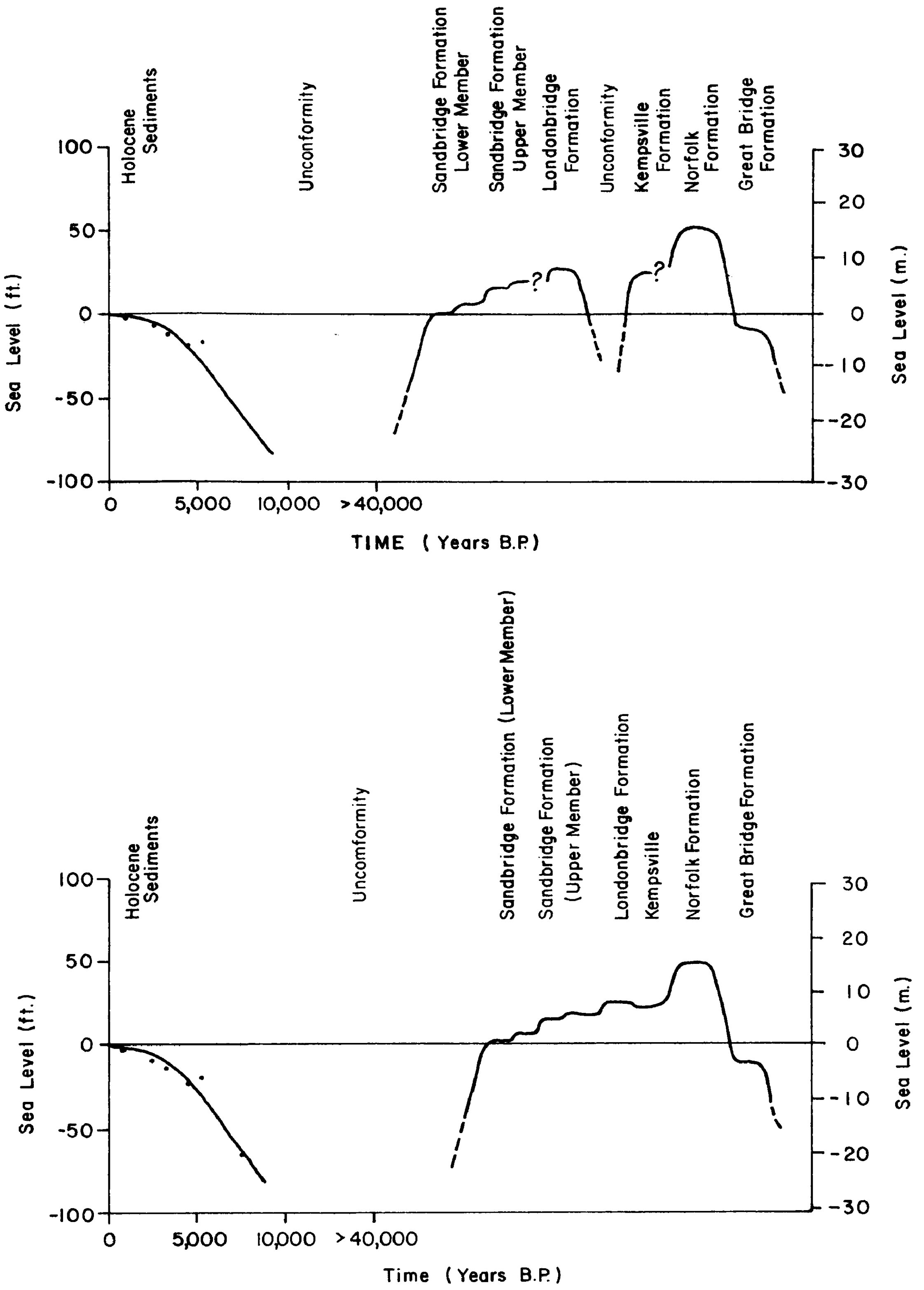
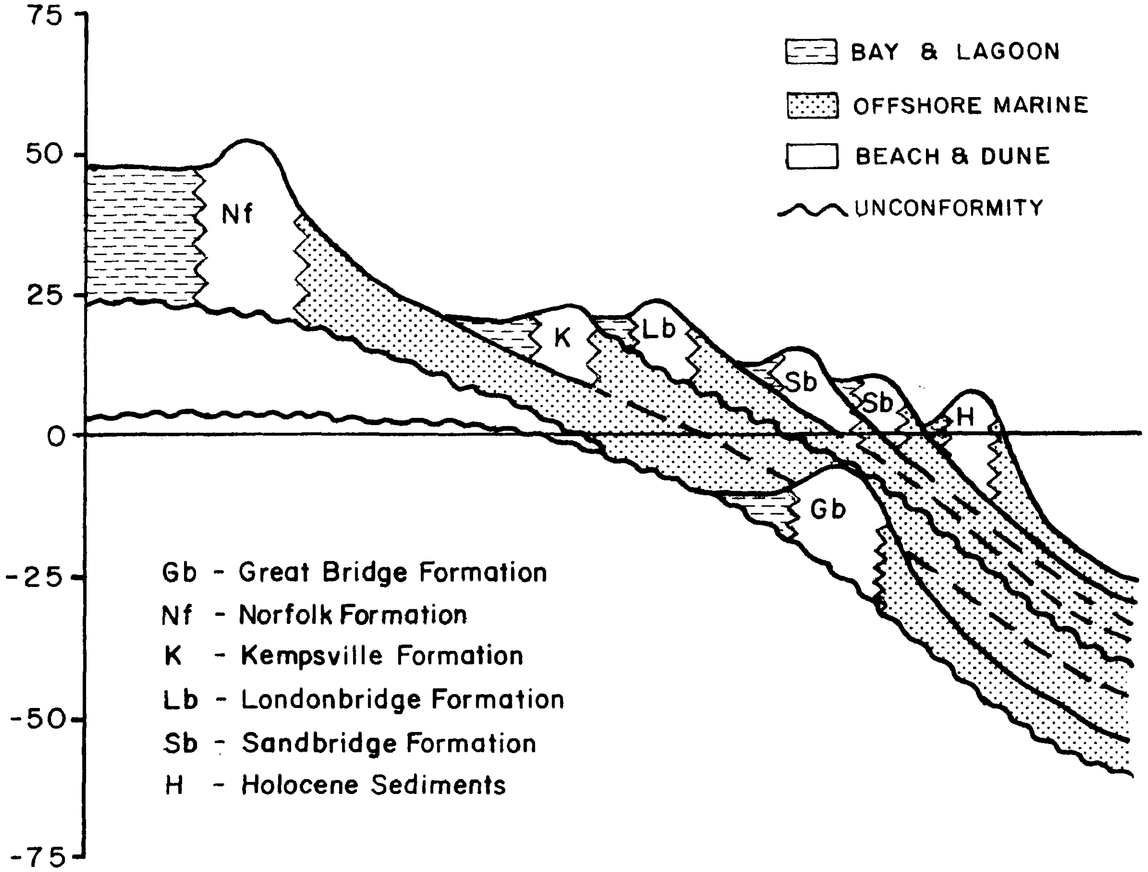
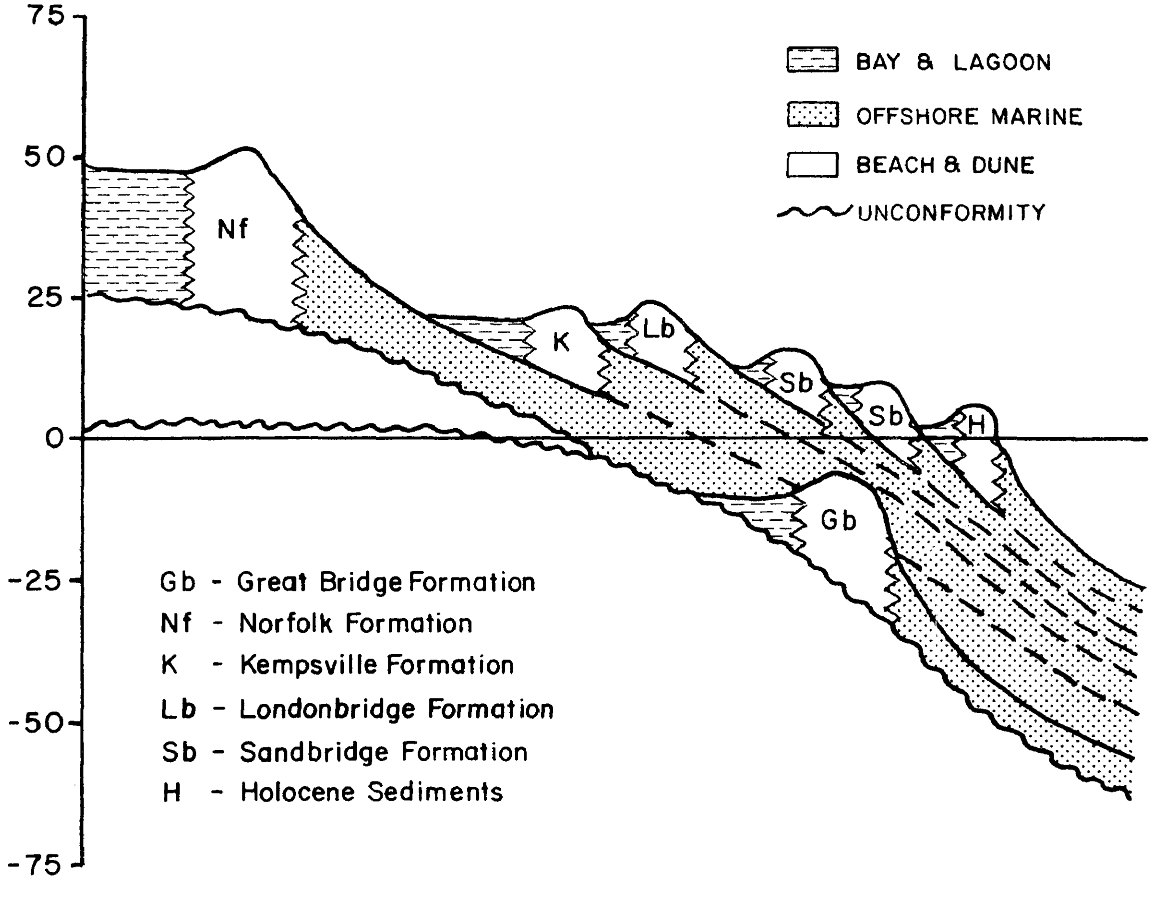


Figure 2-Late Pleistocene sea level curves derived from the interpretations of Oaks and Coch (Upper) and Luebke and Johnson (Lower).

Figure 3-Generalized stratigraphic sequences of southeastern Virginia as interpreted by Oaks and Coch (Upper) and Luebke and Johnson (Lower).


75
50
25
0
-25
-50
-75
BAY & LAGOON
OFFSHORE MARINE
BEACH & DUNE
UNCONFORMITY
Nf
K
Lb
Sb
Sb
H
Gb
Gb - Great Bridge Formation
Nf - Norfolk Formation
K - Kempsville Formation
Lb - Londonbridge Formation
Sb - Sandbridge Formation
H - Holocene Sediments


75
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BAY & LAGOON
OFFSHORE MARINE
BEACH & DUNE
UNCONFORMITY
Nf
K
Lb
Sb
Sb
H
Gb
Gb - Great Bridge Formation
Nf - Norfolk Formation
K - Kempsville Formation
Lb - Londonbridge Formation
Sb - Sandbridge Formation
H - Holocene Sediments

curve can be used as a guide for studies in other areas. Such a curve could be used alone to aid in the interpretation of Pleistocene Coastal Plain sections in other regions. Assuming no tectonism, it could provide a useful tool for the study of the Coastal Plain geology.

STRATIGRAPHIC DESCRIPTION-DAM NECK, VIRGINIA

A series of vibracores were taken off of Dam Neck, Virginia (Figure 4) during September, 1976 for engineering studies associated with the Atlantic Outfall project. One half of each core was given to the Institute by Malcom Pirnie, Inc. for the purpose of geologic studies. The sediments offshore of Dam Neck can be divided into five distinct units on the basis of lithology (Figure 5):

Unit I-Dark to light gray fine silty sand. This layer is made up of the upper two to six inches of each core, and is reworked from the underlying sediment.

Unit II-Peat and tan to light gray, fine to medium sand with some organic clay layers.

Unit III-Interbedded dark gray clay, silt and fine, medium and coarse sand.

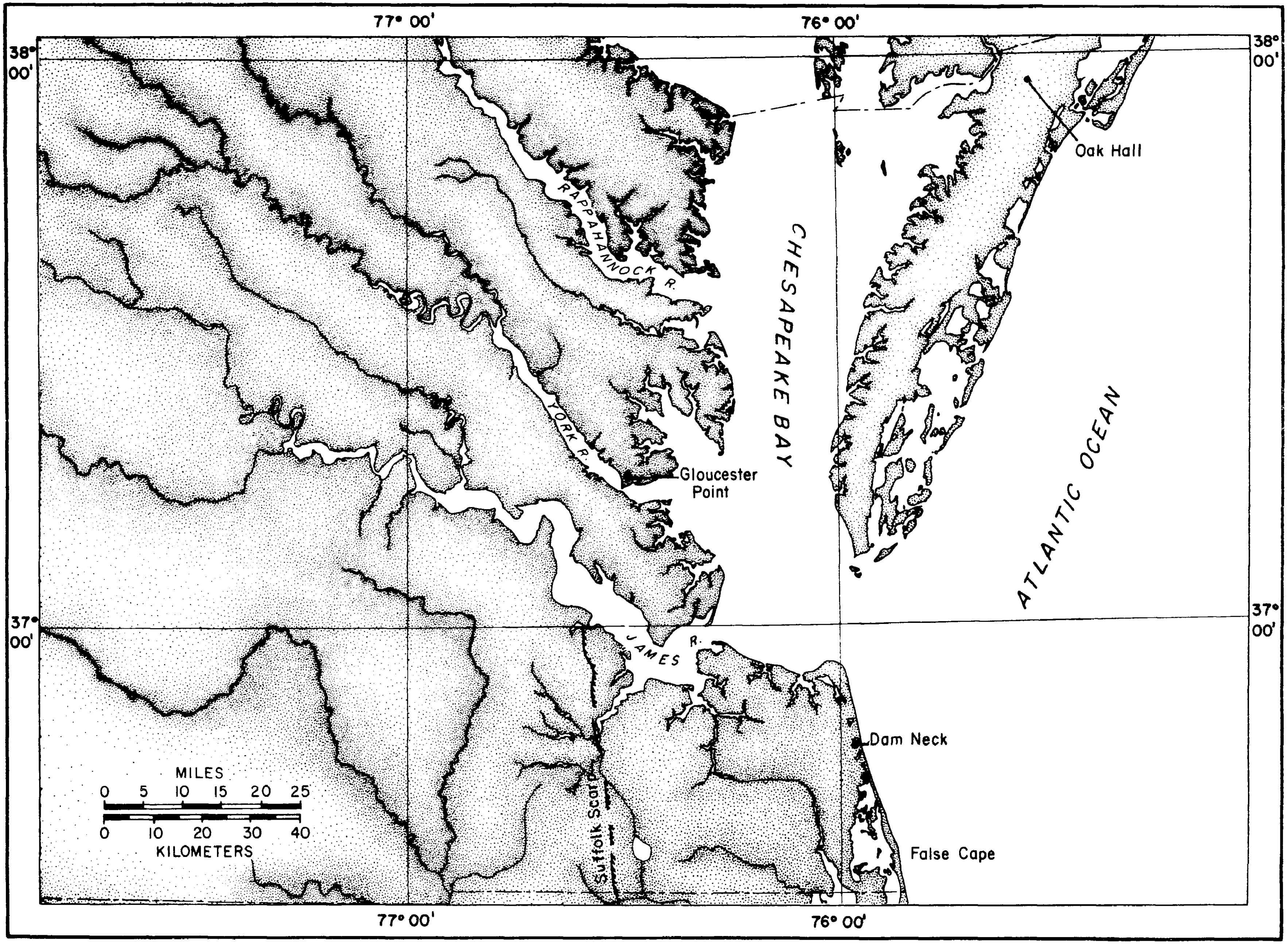
Unit IV-Dark gray silty fine to medium sand with layers of shell hash. Contains Foraminifera. Layer coarsens toward base, where there is a gravel-cobble layer.

Unit V-Dark gray micaceous sandy clayey silt. Upper eight to ten inches is oxidized reddish-brown.

Samples from each unit were examined microscopically, and Foraminifera were collected to aid in determining the environment of deposition of each unit (Figure 6). This information can be used to interpret the the shoreface history at Dam Neck, Virginia.

The Foraminifera in the cores are a nearshore marine assemblage, consisting of members of the genera Elphidium,

Figure 4-Geographic locations mentioned in text.


77° 00'
76° 00'
38° 00'
37° 00'
RAPPAHANNOCK R.
YORK R.
JAMES R.
CHESAPEAKE BAY
ATLANTIC OCEAN
Oak Hall
Gloucester Point
Dam Neck
False Cape
Suffolk Scarp
MILES
0 5 10 15 20 25
0 10 20 30 40
KILOMETERS

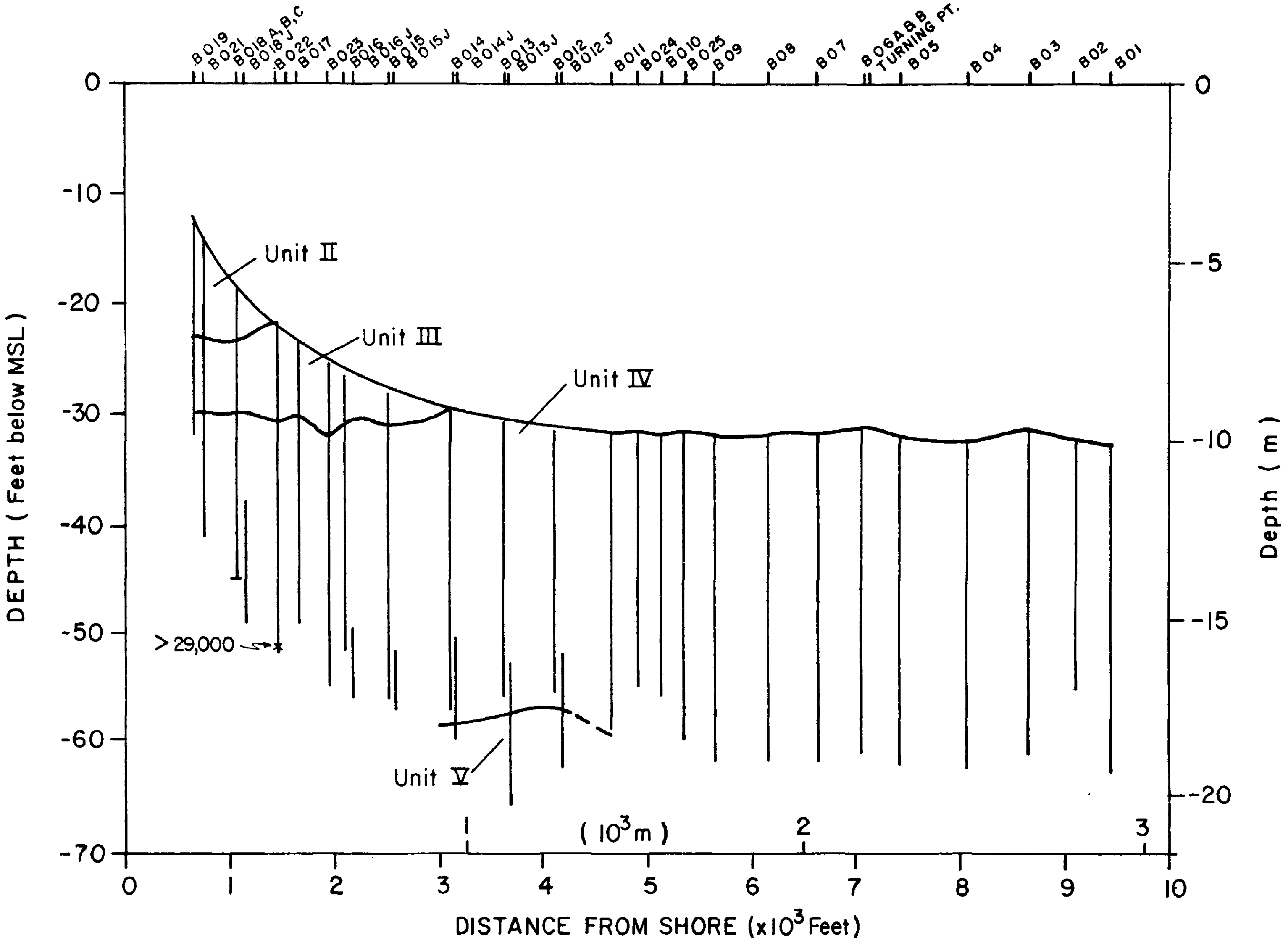


Figure 5-Stratigraphic section showing sedimentary units in the Atlantic Outfall Cores off of Dam Neck, Virginia.

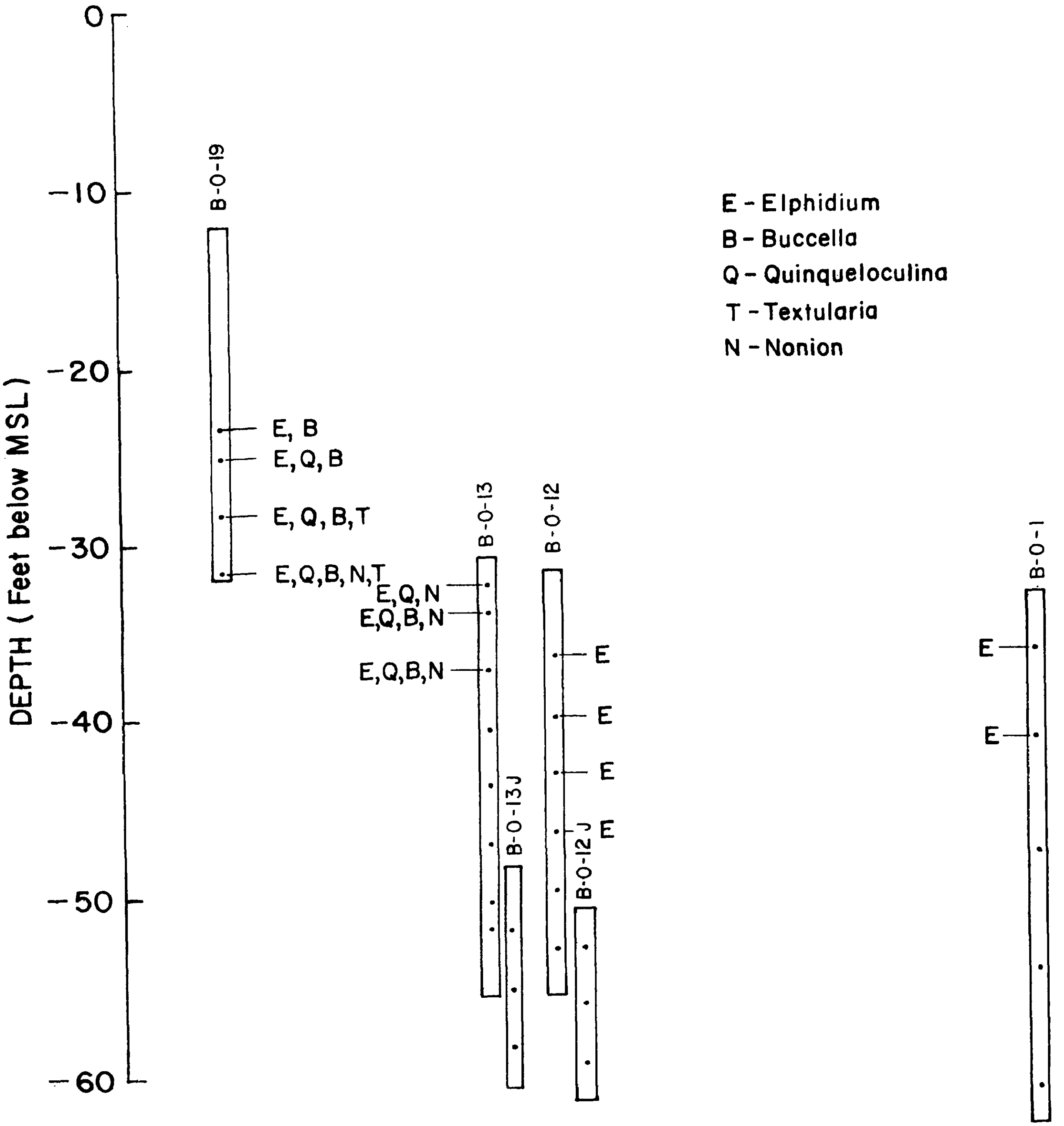


Figure 6-Stratigraphic distribution of Foraminifera from samples in selected cores off of Dam Neck, Virginia.

Quinqueloculina, Nonion, Buccella, and a scattered Textularia. Phleger (1960) includes several species of these genera in his plate of nearshore marine benthonic Foraminifera (p. 154). This information, combined with the geology, aids in the interpretation of the environments of deposition of the Dam Neck sediments (Figure 7).

Unit I, a layer of reworked sediment with variable thickness covering the other units, is of little importance to this study, except for the fact that it indicates that there is very little new sediment presently being deposited on the Inner Shelf. Unit II consists of peat and sand with some organic layers. Identification of the microfauna and microflora proved unsuccessful, so the environment of the peat is unknown. Although no radiocarbon dates have been made, it is believed that the peat is Holocene in age, because it is closely associated with the sediments of the Holocene barrier, which has become welded onto the fastland in this area. Unit III, which is made up of interbedded dark gray clay, sand and silt, contains a nearshore marine foraminiferal assemblage. The bedding and microfauna are indicative of lagoonal sediments. This unit is also believed to be Holocene in age. Unit IV, a dark gray silty fine to medium sand, also contains a nearshore marine assemblage. A radiocarbon date on a shell, Macrocallista nimbosa (Lightfoot) from Core B-0-22 at a depth of -51.5 feet, gave an age of >29,000 years B.P. It is believed that this unit correlates with the Norfolk Formation, because the environment of deposition and lithology in the Dam Neck

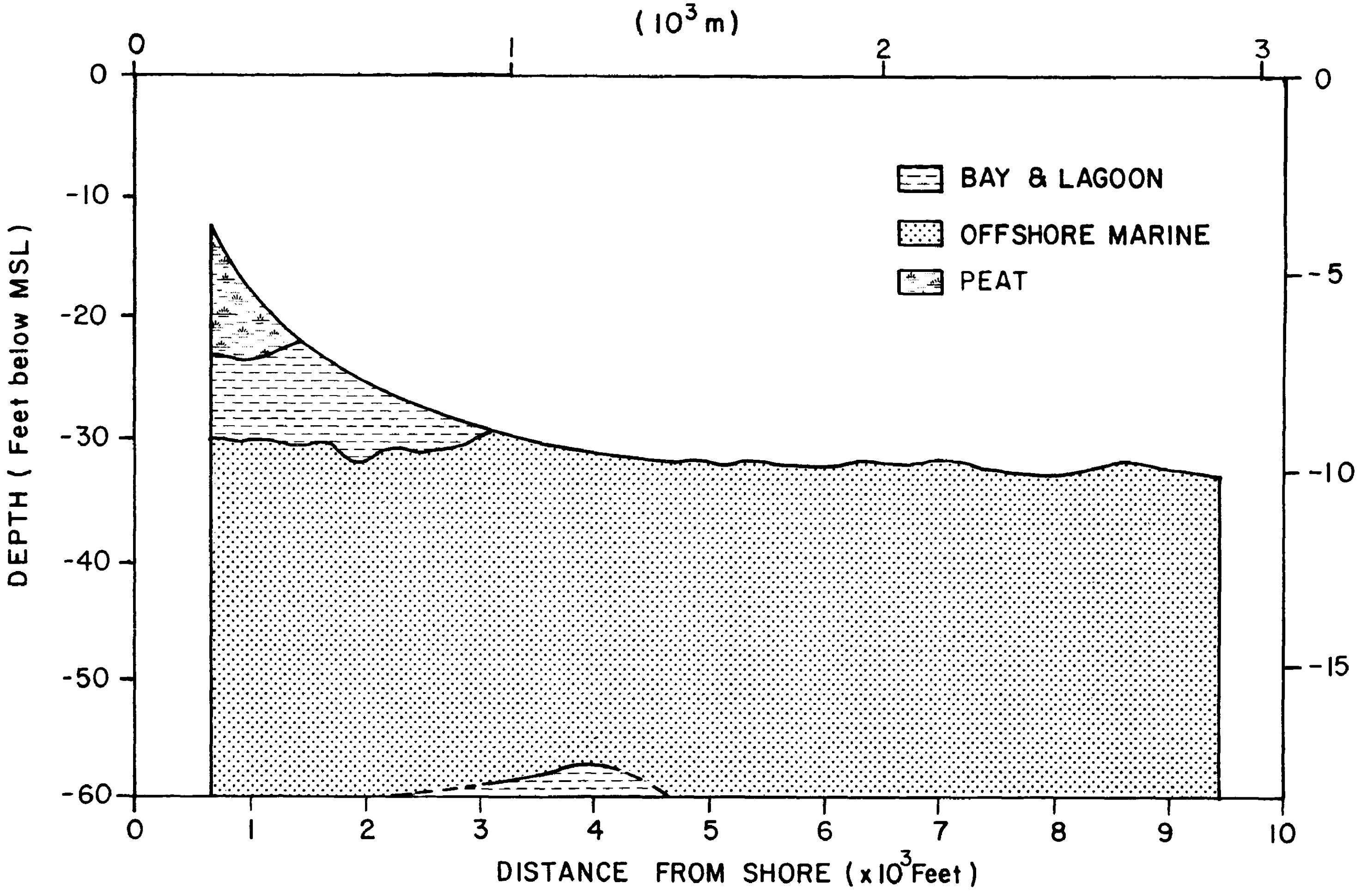


Figure 7-Depositional environments of sediments off of Dam Neck, Virginia.

cores are similar to the sediments of this formation on land in southeastern Virginia. Unit V, a dark gray micaceous sandy clayey silt, underlies the basal gravel-cobble layer of Unit IV. Although this unit does not contain any microfossils, it is believed that it was deposited in a low energy environment, such as a bay or lagoon. The lithology is similar to that of the Great Bridge Formation (Oaks, 1965; p. 107), with which the unit probably correlates.

Based on the description of the sedimentary units at Dam Neck, Virginia and the succession of environments (Figure 7), the shoreface history can be described. The stratigraphic section can be divided into two parts: a Holocene sequence, and a Pleistocene sequence (Figure 8). Based on the succession of environments, it can be concluded that the sediments offshore of Dam Neck are the product of two separate transgressions. The Holocene sediments (Units I-III) are the result of the postglacial rise in sea level, which still continues today. At some time since the Wisconsinan low stand, a barrier has migrated landward, and subsequently become welded onto the fastland.

The underlying Pleistocene sediments were deposited during the transgression and regression of the last high stand, which occurred more than 40,000 years ago. A tentative date on this event is 120,000 to 130,000 years B.P., based on Uranium series dates on Mercenaria from the Norfolk Formation at the A.B. Southall Pit in York County, Virginia. The section offshore of Dam Neck supports the interpretation of Luebke and Johnson

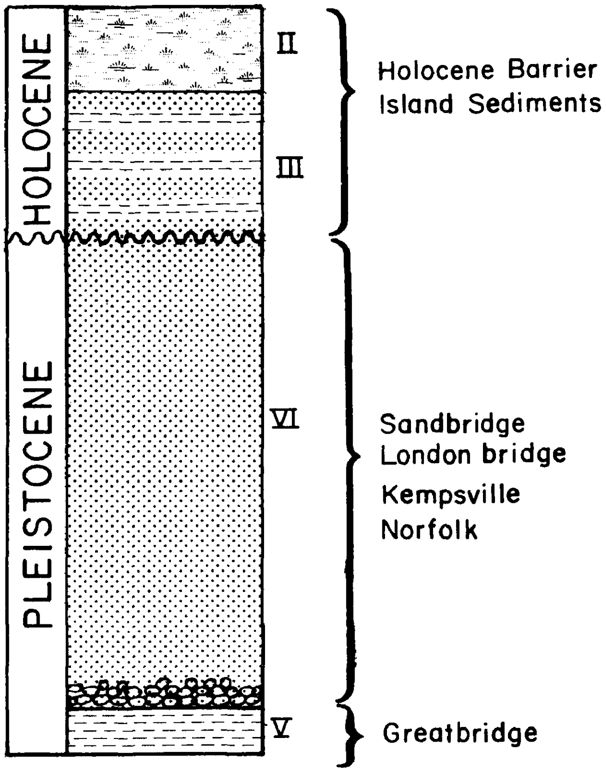


Figure 8-Stratigraphic sequence of sediments at Dam Neck, Va.

(1967), because there is no break in the Pleistocene section. There is little evidence to support the idea of a post-Kempsville regression and transgression, which was hypothesized by Oaks.

This is not the only area of the Virginia Shelf where only one Pleistocene sequence was observed. Shideler, Swift, Johnson and Holliday (1972) also found a single Pleistocene transgressive-regressive sequence. The Pleistocene unit off of False Cape, which is described as a "greenish-gray fine grained, muddy sand" (p. 1794) was also correlated with the Great Bridge through Sandbridge sequence on land. The Holocene unit at False Cape consists of a "discontinuous transgressive sand sheet." Thus, the offshore stratigraphy of two parts of the Virginia Inner Shelf indicates that there is only one Pleistocene transgressive-regressive sequence in the Outer Coastal Plain.

SEA LEVEL CURVES

A sea level curve is a graphical representation of the change in sea level through time. On the abscissa of the graph, time, in thousands of years, is plotted, while the elevation of the sea, with respect to present sea level, is plotted on the ordinate. Information from which sea level curvew are derived comes from dates of sea level indicators which have been collected in the course of geological investigations. Many such curves have been derived on the basis of work in several areas of the world. They can generally be classed into three groups, based on the type of evidence used, and the length of the time scale. The three types of curves are local postglacial, short-term eustatic and long term eustatic sea level curves.

Local Postglacial Curves

Local postglacial sea level curves are the simplest type of curves (Figure 9), being constructed on the basis of geologic investigations in a small area (Belknap and Kraft, 1977; Redfield, 1967; Scholl, Craighead and Stuiver, 1969; Ellison and Nichols, 1976; and many others). These curves usually have maximum time scales of 10,000 to 15,000 years B.P., because they are limited by the return of the sea to the area under consideration. Local postglacial curves are derived from Carbon-14 dates of sea level indicators, such as salt

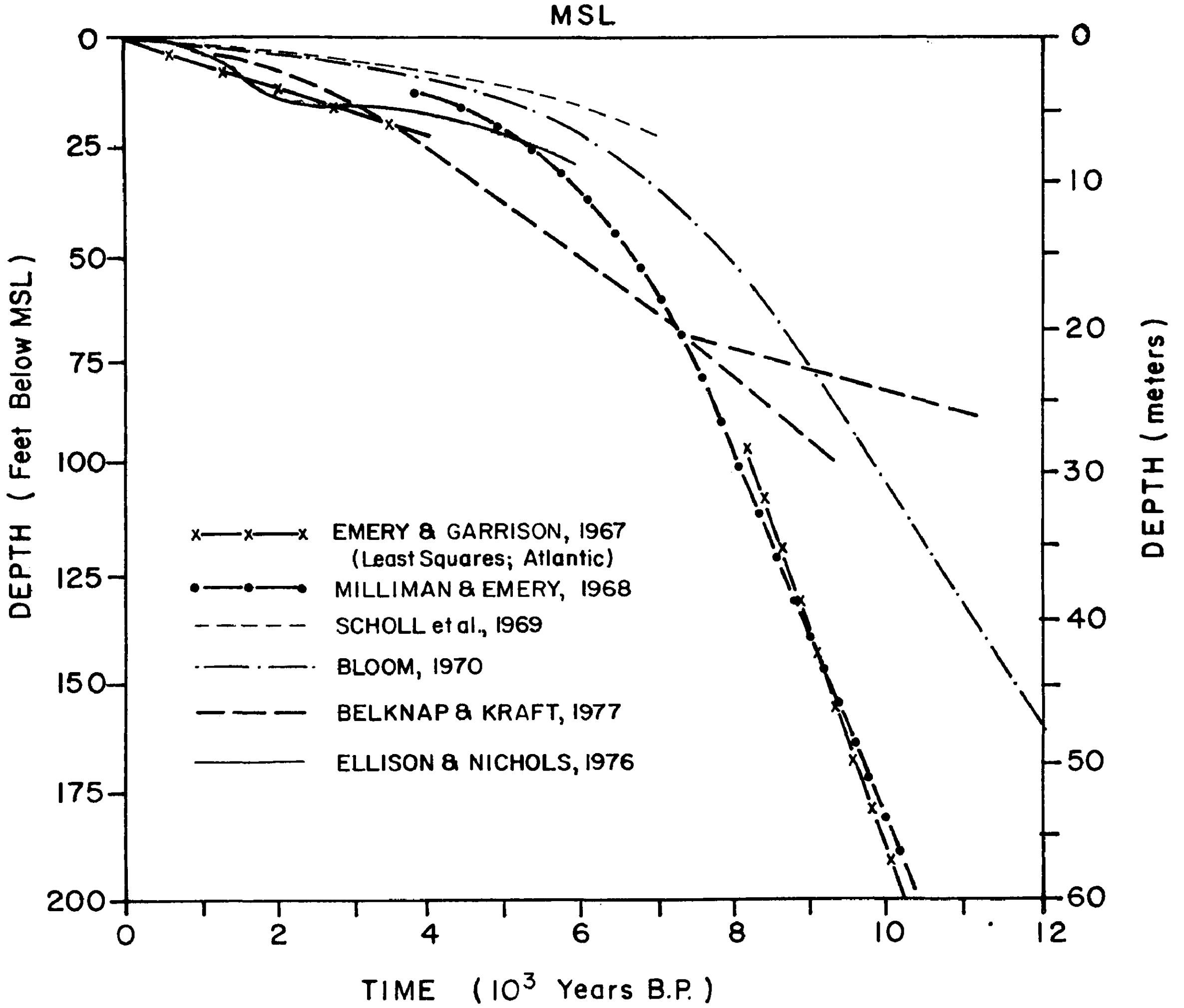


Figure 9-Plot of several local postglacial sea level curves (Belknap and Kraft, Delaware; Emery and Garrison, Milliman and Emery, Northeastern United States; Scholl, et al., Florida; Ellison and Nichols, Virginia Chesapeake Bay; Bloom, Eastern Caroline Islands). After Belknap and Kraft, 1977.

marsh peat (Newman and Rusnak, 1965; Redfield, 1967) and mangrove peat (Bloom, 1970, Scholl, Craighead and Stuiver, 1969). These curves have been used to interpret the Recent history of a small area, such as a marsh (Newman and Rusnak, 1965; Bloom, 1970; Scholl, et al., 1969) and to compare the postglacial transgressive history of two or several areas (Belknap and Kraft, 1977). Because not all areas have been tectonically stable, these curves contain the effects of local diastrophism, which cannot be corrected for unless an independent check can be made to compute the rate and amount of tectonism that has occurred. Because local postglacial sea level curves have relatively short time scales, their applicability to this study is limited, except in the study of the thin veneer of Holocene sediments in the outermost Coastal Plain.

Short-term Eustatic Curves

Eustatic sea level curves give the world-wide change in sea level with time. They are based on Carbon-14 dates of sea level indicators, which were collected over a wide area of the shelf, and sometimes are supported with evidence from other parts of the world. The curves of Milliman and Emery (1968) and Curray (1965) are generally believed to describe world-wide sea level changes from the Pleistocene to the present. The dates used to derive these curves have been reviewed by a number of workers (Poag, 1973; Macintyre, Pilkey and Stuckenrath, 1978). This has prompted Dillon and Oldale (1978) to revise the curve based on data from the East Coast of North America (Figure 10).

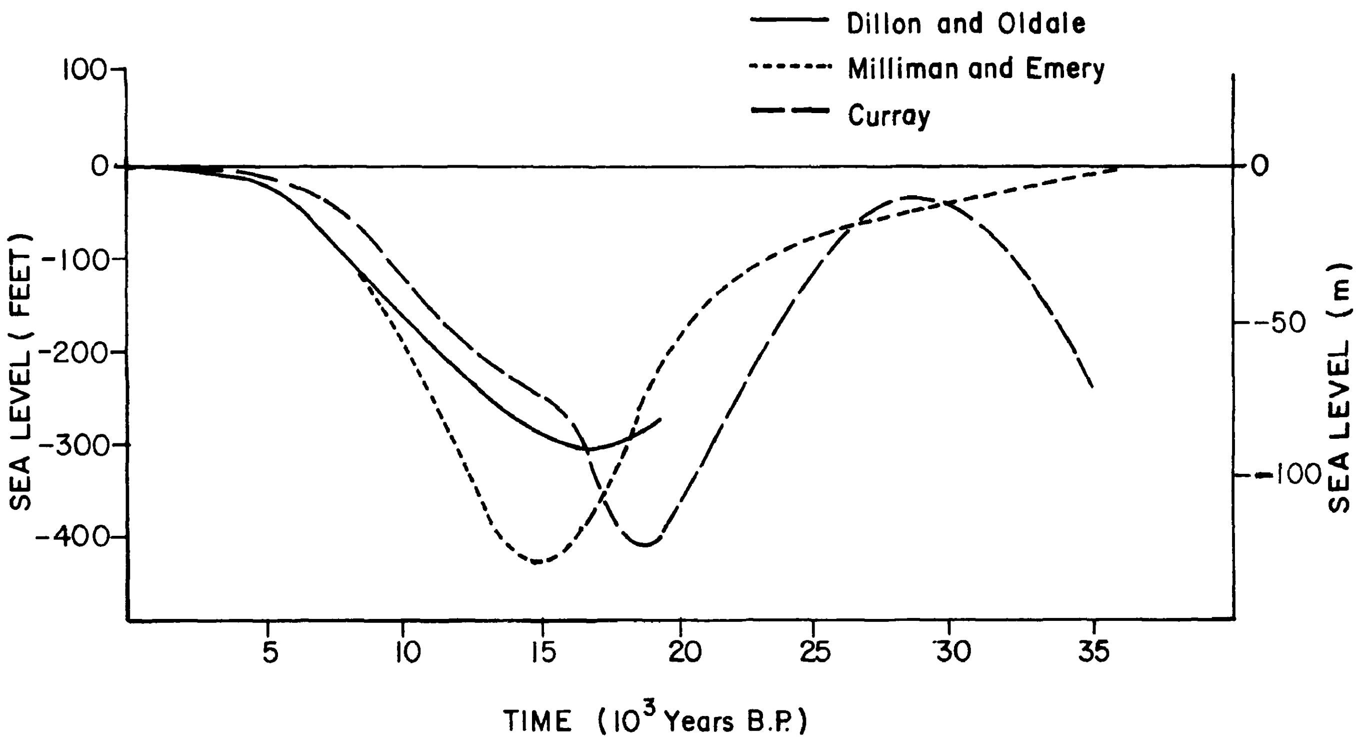


Figure 10-Plot of the three most widely accepted short-term eustatic sea level curves for the East and Gulf Coasts of North America (After Dillon and Oldale, 1978).

Several different sea level indicators have been used in the derivation of short-term eustatic curves, including oysters, oolites, Lithothamnion, salt marsh peat, and mangrove peat. Although most of these are generally accepted as sea level indicators, the role of oysters has recently been re-evaluated (Macintyre, Pilkey and Stuckenrath, 1978). Since long-form oysters are widely accepted as intertidal, Macintyre, et al., limited their samples to this form. They concluded that "Relict oysters are . . . unreliable references for reconstructing sea level, due to the fact that there is evidence indicating "significant post-depositional transport of these shells" (p. 277). The results prompt serious reconsideration of several points on the sea level curves of Milliman and Emery (1968) and Curray (1965). Based on this study, it can be concluded that dates on oyster shells should be used only when the sample has been collected in growth position, or when it is sure that the sample has not been transported far from its site of origin.

One other factor which must be considered in the derivation of a short-term eustatic sea level curve is the method of dating used. Carbon-14 dating is the most common technique for peat and carbonate. Carbon-14 is a radioactive isotope which forms in the upper atmosphere when neutrons produced by cosmic rays collide with the nuclei of Nitrogen-14 atoms (Brownlow, 1979):

$$ {}^{14}_{7}\mathrm{N} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{14}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} \qquad (1)$$

The unstable Carbon-14 eventually decays to Nitrogen-14 by the emission of a beta particle. The half life of this process is 5,730 years (Brownlow, 1979).

In the atmosphere, Carbon-14 is continuously produced and readily combines with oxygen to form carbon dioxide. This mixes with the rest of the atmosphere, eventually reaching the earth's surface. During photosynthesis, it is utilized by plants; animals absorb Carbon-14 through the food chain. Aqueous animals and plants also deposit carbon in the form of calcium carbonate. While they are alive, organisms are able to maintain a constant $C^{14}:C^{12}$ ratio, which is in equilibrium with the atmosphere. When the organisms die, carbon is no longer taken up, and the radioactive Carbon-14 begins to decay. By measuring the Carbon-14 content of organic remains, the time of death can be calculated.

Radiocarbon dating is subject to two major problems. First, the $C^{14}:C^{12}$ ratio varies with time (Stuiver, 1971). These variations can be corrected for when Holocene material is being dated, but corrections for the Pleistocene are only approximations (Bowen, 1978). The second problem with radiocarbon dating is that of contamination. If a closed system is not maintained, extraneous carbon can contaminate the sample. This is common with carbonate material, but is not exclusive to carbonates. Such contamination would have a great effect on samples near the maximum range of radiocarbon dating, no matter if the sample is peat or shell (Bowen, 1979). Because of the problems inherent in the Carbon-14 dating method, the maximum age range differs for the type of material being dated: wood, peat, organic mud, and charcoal can be dated to 40,000 years B.P., while organic carbonate has a maximum age range of 20,000 to 25,000 years B.P. (Meyer Rubin, personal communication).

J.R. Curray was one of the first workers to publish a sea level curve based on radiocarbon dates of samples collected in the course of geologic investigations (Table II). This curve (Figure 11) was first published in 1960, and was further developed and refined in later papers. The date which Curray arrived at for the late Wisconsinan low stand is about 18,000 years B.P. Later workers, notably Milliman and Emery, felt that that this date was too old, but recently geologists have returned to a date which more closely approximates Curray's (Dillon and Oldale, 1978; Flint, 1971). Most evidence available, on land and on the continental shelf, supports this date. Curray postulated several minor transgressions and regressions, which have been super-imposed on the gradual rise in sea level since the late Wisconsinan; these were based on the study of the sediments on the Texas shelf, and are similar to those hypothesized by Fairbridge (1961). More study is needed before sea level changes such as these can be precisely defined.

Several recent workers have begun to re-evaluate Curray's data, the first being Curray himself (Curray and Shepard, 1972). Poag (1973) pointed out that several of Curray's dates were on samples collected from banks subject to tectonism due to the presence of salt domes. Dillon and Oldale (1978) state

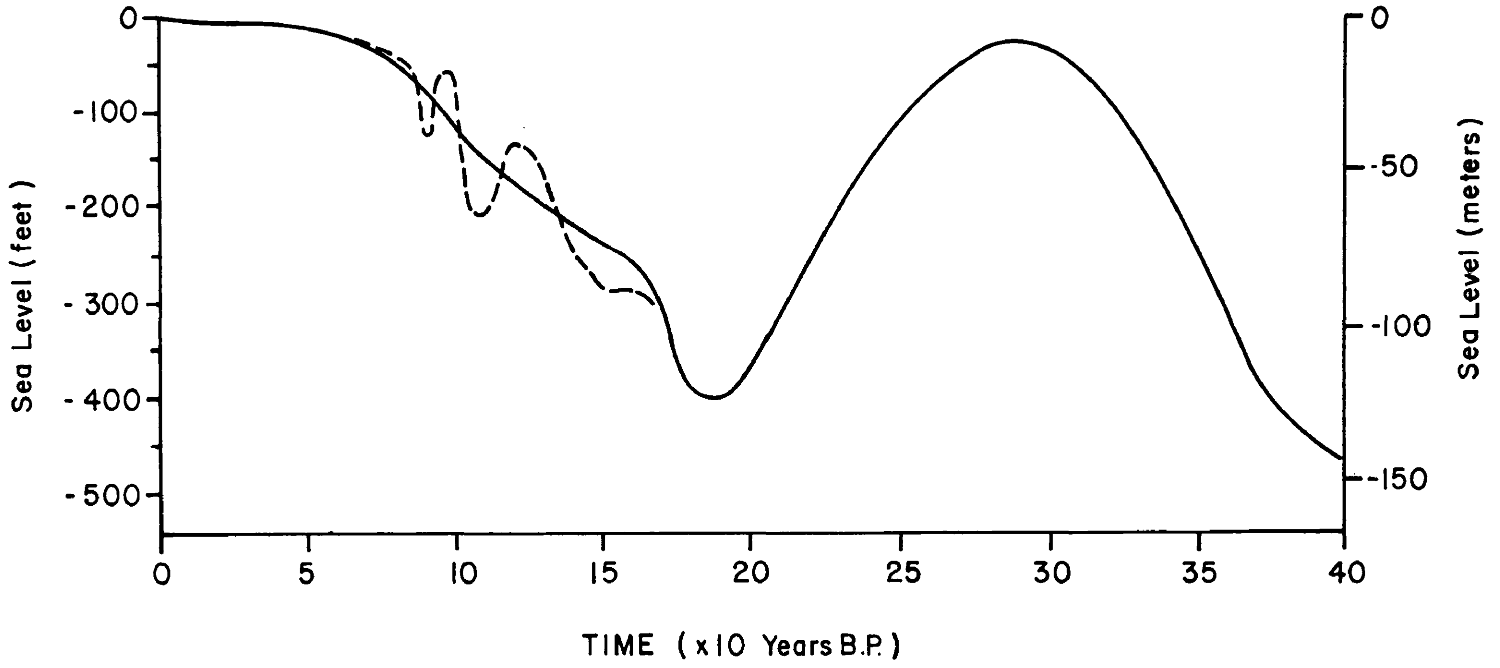


Figure 11-Short term eustatic sea level curves for the Gulf of Mexico (Curray, 1965).

that Curray does not have evidence from the Gulf of Mexico deeper than -88 metres; apparently evidence for his curve deeper than this is based on material from tectonically active California. As is evident from Table II, several of Curray's dates were on Crassostrea virginica (Gmelin) which, in the light of recent investigations (Macintyre, Pilkey and Stuckenrath, 1978) may provide a dubious estimate of former sea levels. Poag (1973) provides an excellent summary on the study of sea levels in the Gulf of Mexico when he says "In order to bring about a new and more thorough understanding of late Quaternary sea levels in the Gulf of Mexico a renewal of intensive investigation is needed . . . Only after the vagaries of local sequences are known can a reliable interpretation of worldwide eustatic changes be accomplished." (p. 399). Curray states the same conclusion, in fewer words, by saying "Let's go back to the field." (Curray and Shepard, 1972; p. 18).

Up to this point, several sea level curves have been discussed in the light of the type of data that constitutes a good sea level indicator. Intertidal organisms provide the best estimate, while those with limited depth ranges, such as Crassostrea virginica (Gmelin) may be used if the study does not require great accuracy. Work in the Gulf of Mexico points out the importance of tectonism in sea level studies. Unless the tectonic history of an area is known, sea level studies should proceed with extreme caution. If, however, tectonism can be corrected for, the revised depth of any sea level indicator can be used to derive a sea level curve.

TABLE II

Data used to derive a Late Pleistocene sea level curve for the Gulf Coast of the United States (From: Curray, 1961; Shepard, 1963).

Sample Number	Material Dated	Latitude	Longitude	Depth (Ft.)	Age (Years B.P.)
J-201	*C. virginica*	28° 11.5' N.	96° 33.8' W.	39	8,030 ± 220
J-207	*C. virginica*	28° 10.0' N.	96° 31.7' W.	54	8,680 ± 270
J-482b	*Rangia cuneata*, *C. virginica*, *Lucina pectinata* *Aequipecten i. concentricus*	26° 34.2' N.	97° 05.3' W.	87	8,740 ± 260
J-715	*C. virginica*	26° 18.9' N.	96° 59.6' W.	100	9,530 ± 270
J-371	*C. virginica*, *Mulinia lateralis*	28° 10.2' N.	95° 43.6' W.	120	10,000 ± 400
J-671	*C. virginica*	28° 19.8' N.	94° 09.0' W.	126-150	12,420 ± 420
J-672	*C. virginica*, *Donax variabilis* *M. lateralis*, *Dosinia discus*, *A. i. amplicostatus*	28° 16.5' N.	94° 14.0' W.	162	9,460 ± 310
J-403	*Rangia cuneata*	28° 09.5' N.	94° 15.8' W.	182	11,900 ± 340
57-9-20	*Rangia cuneata*	28° 09.4' N.	94° 17.6' W.	189	12,960 ± 470 12,820 ± 390
J-660	*M. lateralis* *D. variabilis*	28° 05.9' N.	93° 33.2' W.	228	15,400 ± 510
J-468b	*Turritella sp.* Depth range unknown	26° 46.0' N.	96° 42.0' W.	234	12,900 ± 400

TABLE II (Cont'd)

Sample Number	Material Dated	Latitude	Longitude	Depth (Ft.)	Age (Years B.P.)
J-438	*C. virginica* *Architectonica nobilis*, *Phalium granulatum*, *Strombus alatus* *A. g. gibbus* Mixed fauna-reworked shoreline deposit ?	27° 57.1' N.	95° 10.5' W.	288	16,940 ± 680
J-383	*C. virginica* Beachrock/Coquina-may be older	28° 50.4' N.	95° 08.0' W.	51	26,900 ± 1800
J-526	*Rangia cuneata* Late interglacial	28° 50.4' N.	95° 35.4' W.	48	32,500 ± 3500

Milliman and Emery (1968) published a curve based on information from several areas of the Atlantic Continental Shelf of North America (Table III). Their curve was also supported with dates from other areas of the world (Figure 12). They stated that since their curve fitted the world evidence better than Curray's, their's was a better approximation of a world-wide eustatic curve. They also concluded that there had been uplift on the Texas Coast. However, Milliman and Emery never considered the possibility of tectonism along the East Coast of the United States.

For several years, geologists have recognized the presence of several geomorphic features on the Atlantic Continental Shelf. These features have been identified as the remnants of scarps which formed when sea level was lower during the Wisconsinan Glaciation (Garrison and McMaster, 1966; Emery and Uchupi, 1972). Recent work by Dillon and Oldale has illustrated the value of these features in sea level studies. Several radiocarbon dates have been made on samples collected near these features, giving an estimate of the time since the shoreline was last occupied. When the depth to these relict shorelines was plotted against distance along the shelf, it became apparent that the depth to these scarps increased to the north of Central New Jersey. Since they originally formed at sea level, these shorelines were, at one time, level along their entire length. Therefore, Dillon and Oldale concluded that the continental shelf north of central New Jersey had subsided since the scarps formed. Since

TABLE III

Data used to derive a Late Pleistocene sea level curve for the East Coast of the United States (From: Emery and Garrison, 1967).

Sample Number	Material Dated	Latitude	Longitude	Depth (Ft.)	Age (Years B.P.)
IN 1	*C. virginica*	40° 59' N.	69° 44' W.	148	7,310 ± 300
D 7	*C. virginica*	36° 09' N.	75° 20' W.	108	8,130 ± 400
M 27	*C. virginica*	36° 09' N.	76° 06' W.	69	8,135 ± 160
T 307	*E. directus*	40° 52' N.	70° 52' W.	180	9,150 ± 220
AEV 1	*C. virginica*	41° 18' N.	71° 00' W.	112	9,300 ± 250
D 60	*C. virginica*	37° 24' N.	74° 39' W.	210	9,600 ± 600
D 26	*C. virginica*	38° 49' N.	73° 39' W.	180	9,780 ± 400
D 45	*C. virginica*	40° 43' N.	72° 25' W.	121	9,920 ± 400
S 210	*C. virginica*	41° 55' N.	67° 35' W.	151	10,300 ± 150
S 186	*C. virginica*	42° 05' N.	67° 15' W.	174	10,600 ± 130
D 47	*C. virginica*	40° 40' N.	71° 59' W.	167	10,850 ± 500
T 206	*Astarte* sp. *M. arctatum*	40° 10' N.	71° 26' W.	282	10,850 ± 150
RL 1	Peat (Partly Salt Marsh)	41° 09' N.	68° 43' W.	194	11,000 ± 350
T 228	*P. magellanicus*	39° 37' N.	72° 07' W.	482	13,200 ± 210
T 147	*M. arctatum*	40° 09' N.	70° 29' W.	400	13,420 ± 210
T 203	*M. arctatum*	40° 06' N.	70° 32' W.	426	14,850 ± 250

C=*Crassostrea* E=*Ensis* M=*Mesodesma* P=*Placopecten*

TABLE III

Data used to derive a Late Pleistocene sea level curve for the East Coast of the United States (From: Milliman and Emery, 1968).

Sample Number	Material Dated	Latitude	Longitude	Depth (Ft.)	Age (Years B.P.)
L 1380	Oolite	29° 53' N.	80° 35' W.	115	16,920 ± 200
L 1386	Oolite	29° 53' N.	80° 25' W.	148	20,730 ∓ 2670 - 4030
L 1434	Oolite	28° 54' N.	80° 06' W.	230	13,500 ± 170
L 40	Oolite	34° 12' N.	76° 42' W.	92	29,100 ∓ 1440 - 1750
L 127	Oolite	33° 30' N.	76° 57' W.	213	22,420 + 380 - 400
Gos 1847	Oolite	34° 09' N.	76° 44' W.	108	25,420 ± 850
					27,650 ∓ 1050 - 950
Gos 1806	Oolite	33° 20' N.	77° 30' W.	82	24,200 ± 700
L 1388	Oolitic Rock	29° 53' N.	80° 21' W.	157	12,630 ± 230
E 8851	Oolitic Rock	28° 38' N.	80° 03' W.	243-266	13,730 ± 180
E 8999	Oolitic Rock	29° 14' N.	80° 09' W.	259-282	9,620 ± 180
1087	Algal Rock	33° 43' N.	76° 40' W.	295	19,200 ± 650
E 8200	Algal Rock	33° 58' N.	76° 22' W.	325-354	12,270 ± 190
E 7845	Beachrock	34° 06' N.	76° 15' W.	243	13,500 ± 230
S 185	*C. virginica*	46° 00' N.	62° 37' W.	121	6,850 ± 100
Scarrett	Oyster	46° 49' N.	64° 40' W.	72	7,335 ± 105
Pil 36	Oyster	31° 20' N.	80° 50' W.	62	21,000 ± 800
Gos 1508	*O. equestris*	30° 00' N.	81° 15' W.	62	7,170 ± 300

TABLE III (Cont'd)

Sample Number	Material Dated	Latitude	Longitude	Depth (Ft.)	Age (Years B.P.)
Gos 1790	*C. virginica*	33° 11' N.	78° 15' W.	108	17,290 ± 500
BB 10 a	*Mercenaria campechiensis*	23° 21' N.	80° 13' W.	13	33,750 ± 3200
I 749	*C. virginica*	38° 32' N.	75° 15' W.	33	34,000 ± 2000
I 1745	Salt Marsh Peat	33° 55' N.	78° 09' W.	0	$36,000\,^{+\,3700}_{-\,2600}$

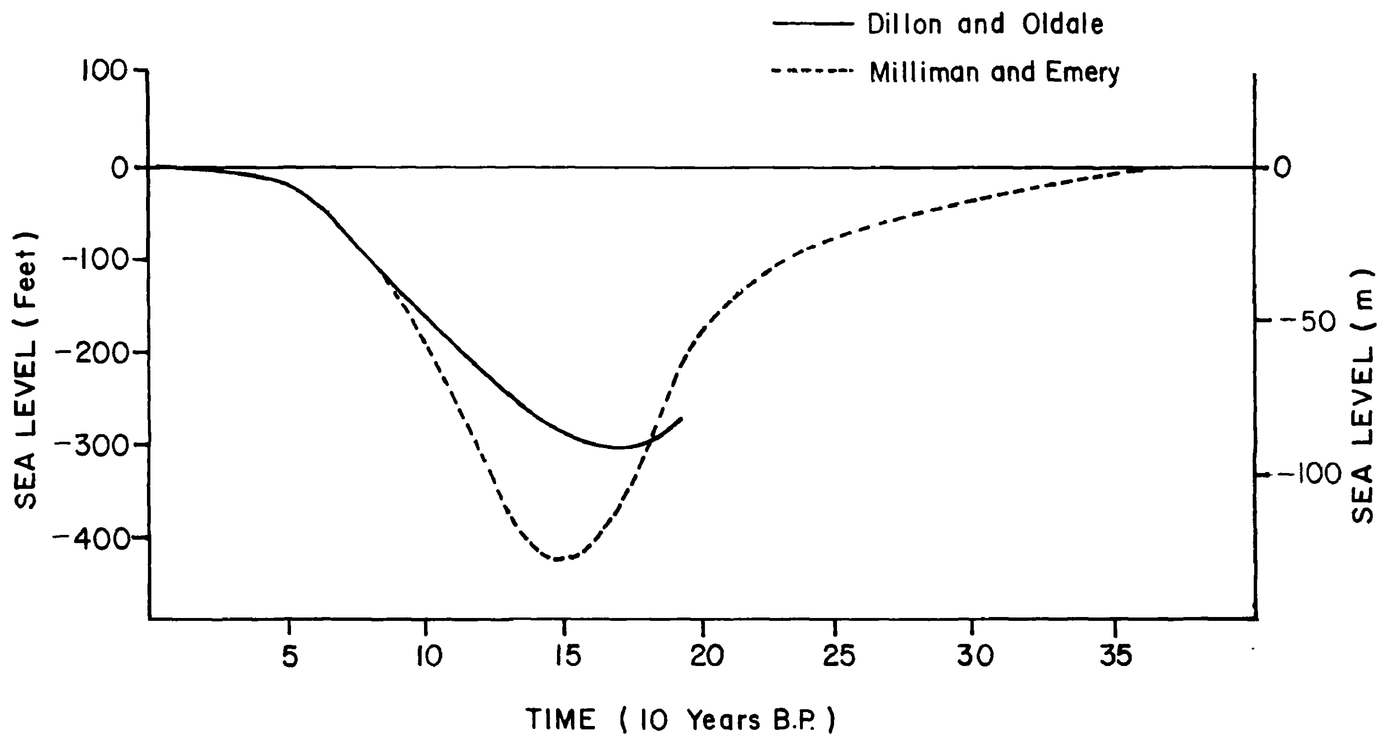


Figure 12-Short-term eustatic sea level curves for the East Coast of the United states (After Dillon and Oldale, 1978).

several of the dates controlling the low point of Milliman and Emery's curve were made on samples from this part of the shelf, Dillon and Oldale corrected the associated depths by the amount of subsidence which had occurred. These corrections, when considered with the other information on samples controlling the low point of the curve (Macintyre, Pilkey and Stuckenrath, 1978; Macintyre, Blackwelder, Land and Stuckenrath, 1975) resulted in a new estimation for the maximum Wisconsinan lowering of sea level. This new value of -93 metres (-305 feet) is very close to the sea level which has long been accepted by other glacial geologists (Flint, 1971; Daly, 1925). The examination and re-evaluation of Milliman and Emery's data by Dillon and Oldale has led to a new eustatic curve. But even this, however, cannot be utilized in the study of the Coastal Plain geomorphology and stratigraphy, because of the limited time scale resulting from the Carbon-14 dating method. This restriction will apply to all sea level curves derived from data collected on the continental shelves of the world.

Long-term Sea Level Curves

Geologists now have a better estimate of the range of sea level changes during the Late Wisconsinan. But all of the curves discussed have time scales limited by the method of dating used. As is evident from the radiometric dates of Oaks and Coch (1973), a sea level curve for the Coastal Plain must have a time scale which covers a time period longer than the limits of the radiocarbon method. The attributes of a sea level curve for use in the Coastal Plain can be compiled based on the curves already studied. First, any sea level curve used must provide information on not only the land area presently below sea level, but also contain information on which to interpret the Pleistocene sediments above sea level. This brings about a second point. Since the sediments under consideration in the Coastal Plain have been dated as being approximately 120,000 to 130,000 years old, the radiocarbon dating method will not work because the maximum limit is much lower than the age of the sediments being studied. A third rule should also be applied to sea level studies: dates on samples should only be used to derive a sea level curve when the tectonic history of the area is known. If the present elevation of a sample cannot be corrected by adding the amount of subsidence, or subtracting the amount of uplift for the area if there has been tectonism, the data is of limited value.

In the study of Pleistocene geomorphology and stratigraphy, three curves have been published, based on widely differing data (Fairbridge, 1961; Chappell, 1974; Shackleton and Opdyke, 1973), which meet the requirement of a time scale greater than 40,000 years B.P. Each of these curves, and the methods used to derive them, will be examined to choose a curve that is best suited for studies in the Coastal Plain.

R.W. Fairbridge (1961) was one of the first geologists to evaluate the literature on the subject of sea level changes, and his summary is still one of the best. From his work, a sea level curve was derived (Figure 13). The altitudes of the high stands were found by studying the elevation of Pleistocene scarps and terraces in the Mediterranean. Scarps and terraces have been widely used by geologists as indicators of high sea levels. To estimate the position of a former high stand, the elevation of the toe and crest of a scarp are used as boundaries. The elevation of sea level must be somewhere between these values. Study of the sediments associated with the scarp aid in determination of the former sea level. In studying the scarps and terraces, Fairbridge noted that "One of the most striking features of these high terraces is the apparent chronologic order of the steps; the older they are, the higher the elevation." (p. 121). The Fairbridge sea level curve shows that sea level was much higher during the Early Pleistocene than it is at present. The decrease is attributed to the fact that the Antarctic Ice Sheet melted back less with each successive interglacial. To calculate the elevation of the Quaternary low stands, Fairbridge assumed that each eustatic change was approximately equal to the fall caused by the Wisconsinan Glaciation. The change during the Wisconsinan (100 m.) was reduced by 5% for each previous glacial period. The change was subtracted from the elevation of each previous high sea level to calculate the low stands associated with each glaciation. Thus, Fairbridge had a record of sea level changes caused by the Pleistocene glaciation and deglaciation. This curve, however, was similar to that of Oaks and Coch (1973), because there was no time

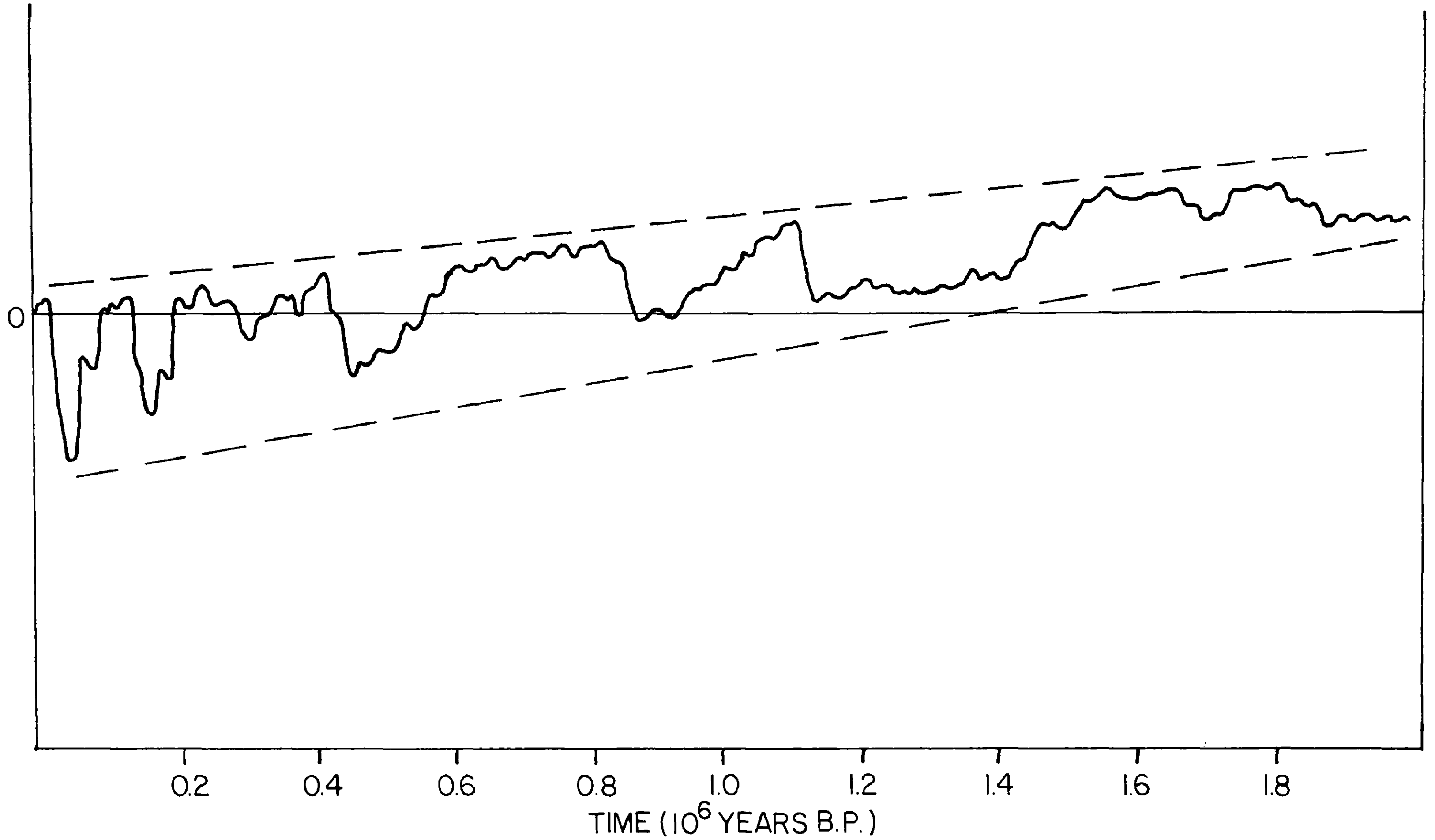


Figure 13-Quaternary sea level curve based on geomorphic interpretation (After Fairbridge, 1971).

scale associated with it. The curve was plotted to fit the time scales of the paleotemperature curves of Emiliani (1955, 1957) and the modified time scale of Broecker, Turekian and Heezen (1958). The curve has since been re-plotted with a longer time scale, making it the first record of sea level changes for the entire Pleistocene (Fairbridge, 1971). There are two problems with the Fairbridge curve. The first was pointed out by Fairbridge himself, when he stated "the precise correlation of Pleistocene high sea levels with definite interglacial phases is not universally agreed upon." The sedimentary units of the Coastal Plain cannot be correlated directly with the unconformity between two till units marking the retreat of a continental ice sheet. There were, and still are, very few exact radiometric dates on the Pleistocene terraces and scarps throughout the world, so correlations between widespread geomorphic features based on altitude alone may not be accurate. Secondly, by basing his curve on geomorphic interpretations, Fairbridge exposes it to errors which arise from differences of opinions in the interpretation of stratigraphic sequences, as exemplified by the disparate interpretations in the Virginia Coastal Plain (Oaks and Coch, 1973; Luebke and Johnson, 1967). Nevertheless, this curve was the first attempt at describing Pleistocene sea level changes, and deserves recognition for inspiring interest in the subject of Quaternary sea level changes.

Uplifted coral reef deposits have been used in sea level studies by several geologists (Broecker, Thurber, Goddard, Ku, Matthews and Mesolella, 1968; Bloom, Broecker, Chappell, Matthews and Mesolella, 1974; Chappell, 1974). These features are particularly useful because if their ages fall outside of the radiocarbon range, uranium series methods can be used (Barnes, Lange and Potratz, 1956). The islands of Barbados and New Guinea have been studied extensively because a number of coral reef terraces have been elevated above sea level by tectonism. Reefs of similar ages have been found on both islands, providing substantiating evidence for each other. The ages of the reefs are approximately 125,000 years B.P. or less, although recent work has established the existance of terraces as old as 640,000 years B.P. (Bender, Fairbanks, Taylor, Matthews, Goddard, and Broecker, 1979).

In order to use uplifted reef deposits in sea level investigations, the present terrace elevation must be corrected by subtracting the amount of uplift which has taken place since deposition. Because neither the rate of uplift, nor the original elevation of the terraces with respect to present sea level was known, a method to solve for one of these variables was needed. Bloom, et al., (1974, p. 199) compared the problem to "that of a man standing on a ladder. We are told the length of time he has been climbing, and his present height above some reference rung." The object of the investigation is to "determine (a) his rate of climb, and (b) the rung on which he began." Since "both unknowns cannot be solved," some simplifying assumptions were made.

A value for the elevation of sea level 125,000 years ago was obtained from work in Florida and the Bahamas (Mesolella, 1968). This assumed value of +6 metres (+20 feet) was accepted as the maximum elevation of sea level at the time Rendevous Hill (Barbados Terrace III) was deposited. From this, Mesolella (1968) and others (Broecker, et al., 1968; Chappell, 1974) calculated the rate of uplift for different parts of the two islands. Given the rate of uplift, the elevation of sea level at the time of terrace deposition was calculated. The resulting sea level curves for Barbados and New Guinea give the high sea level stands for the last 125,000 years (Figure 14). No information on the intervening low stands is available from the study of the uplifted reefs.

Calculations such as these have been the basis for much of the work on Barbados and New Guinea for the last 11 years. Stearns (1976) recently evaluated the work in Barbados. In his summary (p. 448) he states that "the Barbados model is just what it was proposed to be: a fruitful first approximation. It is not sufficiently precise to yield close derivative measurements of 'paleosea levels' or 'control points' to be used as correction factors in other areas." Therefore, the sea level curves derived from work in Barbados and New Guinea can be considered, but should not be used to derive a model for the geologic history of the southeastern Virginia Coastal Plain.

Shackleton and Opdyke (1973) were the first researchers to propose the use of oxygen isotopic deviation, as measured in deep sea cores, to derive a sea level curve. This is

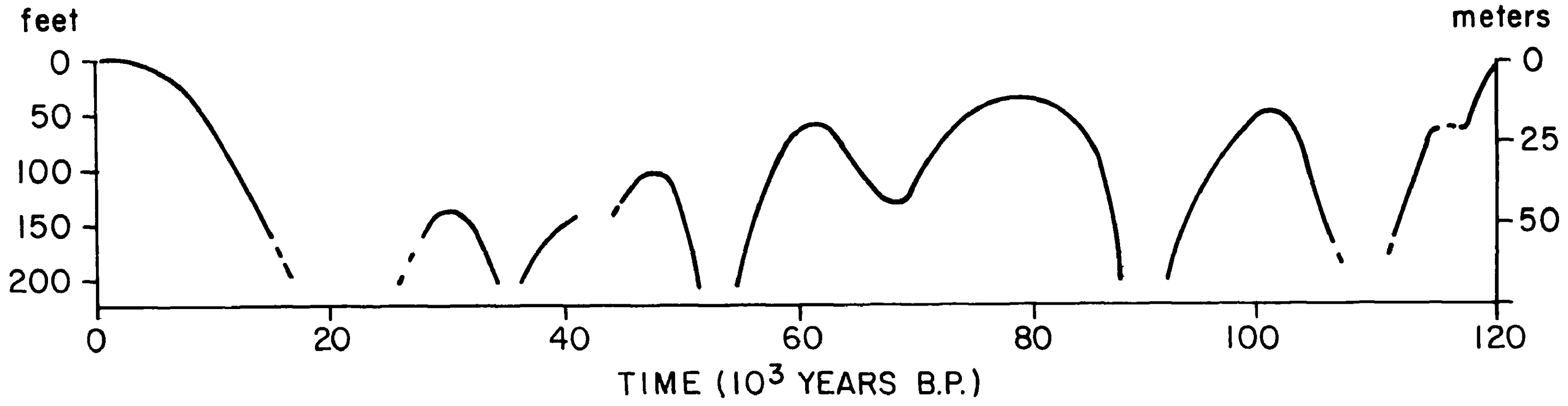


Figure 14-Late Quaternary sea level curve derived from dates on the uplifted New Guinea terraces (Chappell, 1974)

possible because light molecules of water (H_2O^{16}) evaporate more readily than heavy molecules (H_2O^{18}). Thus, during glacial periods, when sea level is lower, the ocean is enriched in H_2O^{18}. H.C. Urey was the first scientist to suggest the use of measurements of oxygen isotope ratios as a geothermometer in 1947 (Hecht, 1976). He and others, notably Epstein, Buchsbaum and Lowenstam (1953), developed the methods for measuring the oxygen isotopic composition which can be applied to almost any marine organism with unrecrystallized shells of calcium carbonate (Hecht, 1976). Emiliani (1955) was the first person to apply oxygen isotope measurements to Foraminifera, and extended his work to the Foraminifera from several Atlantic and Carribean cores. He attributed the variation in oxygen isotopic composition to the temperature changes in the ocean caused by the advance and retreat of the continental ice sheets. Emiliani calculated paleotemperatures according to the equation:

$$T = 16.5 - 4.3(\delta - A) + 0.14(\delta - A)^2 \qquad (2)$$

Where:

$$\delta = 1000 \frac{O^{18}/O^{16}\,\text{sample}}{O^{18}/O^{16}\,\text{standard}} - 1 \qquad (3)$$

and

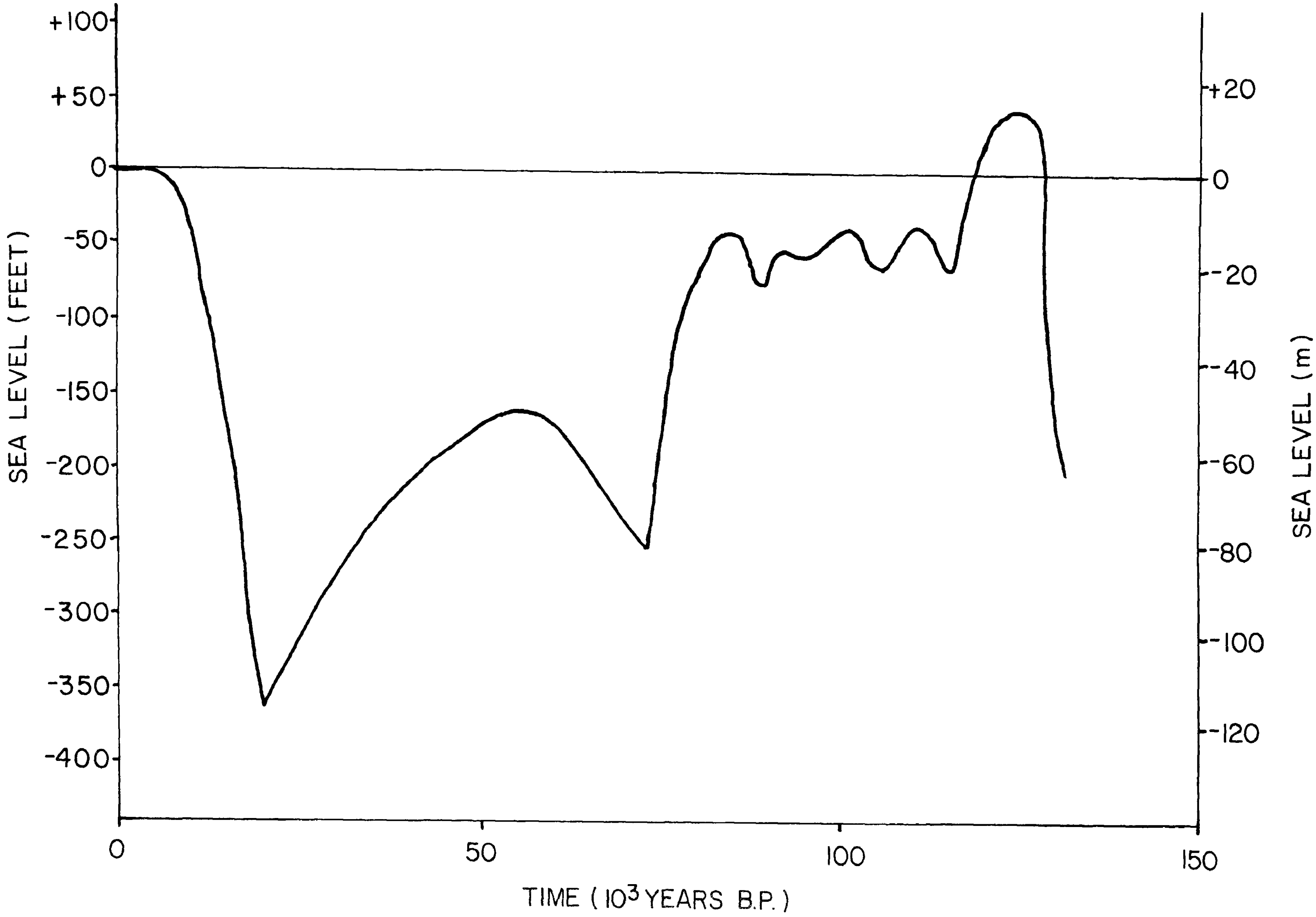
$$A = \frac{O^{18}/O^{16}(W')}{O^{18}/O^{16}(W)} - 1 \qquad (4)$$

The isotopic deviation between the analyzed sample and a standard is δ and "A" is the correction factor applied if the isotopic composition of the water from which the sample was deposited (W') differs from the isotopic composition of average marine water (W). To calculate the paleotemperature, Emiliani used equation (2), substituting the measured value for δ, and using a value for "A" which had been calculated on the basis of measurements of present marine water samples. Emiliani felt that the change in isotopic composition observed in Atlantic and Carribean cores was primarily due to temperature changes, and therefore assumed the deviation caused by the change in volume of the sea to be negligible.

The sea level curve of Shackleton and Opdyke (1973) is based on the work of Olaussen (1965) and Dansgaard and Tauber (1969), who calculated the effect of the change in volume of the ocean on the oxygen isotopic composition of sea water. They feel that the variation in oxygen isotope ratios in deep sea cores is caused by the removal of water from the ocean, not the change in termperature (as postulated by Emiliani, 1955). By calculating the volume of former glaciers and their mean isotopic composition, Olaussen, and Dansgaard and Tauber, were able to derive the change in isotopic composition of the ocean caused by the removal of that volume of water. These computations are based on the fact that as sea water is removed from the ocean and piled onto the land as a continental ice sheet, the ocean will become enriched in H_2O^{18}. The result is that there will be a higher O^{18}/O^{16} ratio during glacial periods than during interglacials. Shackleton and Opdyke analyzed the tests of Foraminifera from core V28-238, which was taken on the Kapingmarangi Rise in the Pacific Ocean (01° 01' N., 160° 29' E.). In order to apply a time scale to the information, the paleomagnetism of the core was studied. A complete magnetic reversal was found at a depth of 1200 cm. This reversal was interpreted to be the Bruhnes/Matayuma reversal. The date of this event was placed at 700,000 years by Dalrymple (1972). By assuming a constant sedimentation rate, Shackleton and Opdyke were able to apply a time scale to the curve. To convert the changes in oxygen isotopic composition with time to sea level, Shackleton and Opdyke used ice volume calculations. The initial low point on any oxygen isotope curve is accepted as the maximum low stand during the Wisconsinan Glaciation. To this point, Shackleton and Opdyke assigned a value for the volume of glacial ice at the time of the Wisconsinan Glacial Maximum. Since the present value for sea level is known, Shackleton and Opdyke had two known values, which he used to calculate a conversion factor between the difference in oxygen isotopic composition (present value minus some other value in time) and the change in sea level. By computing the conversion factor, Shackleton and Opdyke were able to calculate past sea levels based on the oxygen isotope data.

The sea level curve proposed by Shackleton and Opdyke (Figure 15) is unique, because it meets all four of the prerequisites of a sea level curve which could be used in geologic studies of the Coastal Plain. First, because the data are not based on dated samples from any elevation, the

Figure 15-Late Quaternary sea level curve derived from oxygen isotopic deviation (Shackleton and Opdyke, 1973).


+100
+50
0
-50
-100
-150
-200
-250
-300
-350
-400
SEA LEVEL (FEET)
+20
0
-20
-40
-60
-80
-100
-120
SEA LEVEL (m)
0
50
100
150
TIME (10^3 YEARS B.P.)

concern about the effect and amount of uplift or subsidence is eliminated. Secondly, the data are independent of geomorphic and stratigraphic features, and therefore not subject to the possibility of disparate interpretations of field data. Third, if the assumption of uniform deposition is accepted, the time scale can be extended as far back in time as the data permits, limited only by the length of the core. In this case, the core covers approximately 900,000 years. Fourth, and most importantly, because the oxygen isotopic deviation is a world-wide phenomenon, any sea level curve derived from the change in oxygen isotope ratio would apply to the whole world, and not just a localized area. Thus, the curve would show world-wide changes for an unlimited amount of time, being a truly eustatic curve. More importanly, the derivation of a curve independent of features and dates in the Coastal Plain could prove to be the best tool in the interpretation of the geomorphology and stratigraphy of the region.

Three methods can be used to calibrate a sea level curve based on oxygen isotopic deviation. First, since the change in sea level can be attributed to the removal of a volume of water from the ocean, and the growth of a continental ice sheet, the curve can be calibrated by calculating the effect of the change in volume of the ocean on the oxygen isotopic composition; this computation was done by Olaussen (1965) and Dansgaard and Tauber (1969). Their work was the basis for the calibration of the curve by Shackleton and Opdyke. Fairbanks and Matthews (1978) have proposed a second method of calibrating the change in elevation of the sea with oxygen isotope changes. By measuring the O^{18}/O^{16} ratio of fossil corals of known ages and elevation from the uplifted reefs of Barbados, the δ value for the corals can be calculated. By plotting the oxygen isotopic deviation of each terrace verses the present elevation with respect to sea level, they have been able to calculate a conversion factor between oxygen isotopic composition and the change of sea level. I feel that a third method exists, which up to this point, has not been used. By applying the known elevation of sea level at a given time to the corresponding point on the oxygen isotope curve, a conversion factor between sea level and the oxygen isotopic composition of the ocean can be approximated. Each of these methods of calibration will be evaluated to determine which, if any, will result in a sea level curve which can be applied to the study of the stratigraphy and geomorphology of the Coastal Plain.

Shackleton and Opdyke (1973) used ice volumes to calibrate a sea level curve based on oxygen isotope ratios. The resulting curve (Figure 15) shows a +18 metre (+60 feet) high stand 125,000 years ago. The Wisconsinan low stand of sea level, which occurred 17,500 years ago, was at -120 metres (-394 feet) (Shackleton and Opdyke, 1973; p. 27). Neither of these values are reflected in the stratigraphy and geomorphology of the Coastal Plain and Continental Shelf. There are no submerged or subaerial scarps at either of these two elevations. The problem with such a calibration lies in the conjectural nature of ice volume calculations. In order to calculate an ice volume, two values are needed: the thickness of the ice sheet, and the area which it once covered. The area can be computed through planimeter measurements. This method assumes that the continental ice sheets reached a maximum at all places at the same time. The thickness must be assumed by drawing an analogy between present and past ice sheets. As an example of the accuracy of this method, an error of 5 % was calculated for three estimates on the volume of water in the last ice sheet. The figures for this arbitrarily chosen error are shown in Table IV. The volume of water obtained by figuring this error can be translated into the elevation of the sea by dividing by the present area of the ocean. This error, in terms of sea level, although not corrected for the increase in area of the ocean and isostasy, is substantial and means that even a slight error in ice volume calculations translates into a large area of land which would or would not be inundated, especially in a low relief area such as the Coaltal Plain. Thus it is evident that calibration of a sea level curve by use of ice volume calculations is too inexact a method when the geology of the Coastal Plain is being considered.

Fairbanks and Matthews (1978) published the first paper on the direct calibration of isotopic deviation to a change in sea level. Their work is based on oxygen isotope measurements on the uplifted reefs of Barbados, features which have been the subject of continuing investigation for over ten

TABLE IV

Calculation of a sea level height from a 5% error on Ice Volume Estimates

Source of Data	Volume of Water	5% Error	Sea Level Height	
			metres	feet
Dansgaard and Tauber, 1969	47×10^6 Km^3	2.35×10^6 Km^3	6.5	21.2
Olaussen, 1965	40×10^6 Km^3	2.0×10^6 Km^3	5.5	18.1
Flint, 1971	42×10^6 Km^3	2.1×10^6 Km^3	5.8	19.0

years (Broecker, Thurber, Goddard, Ku, Matthews and Mesolella, 1968; Bender, Taylor and Matthews, 1973; Bender, Fairbanks, Taylor, Matthews, Goddard and Broecker, 1979). In order to calculate a conversion factor between isotopic deviation and sea level, Fairbanks and Matthews measured the oxygen isotopic composition of the coral Acropora palmata, a reef builder with a range of 0 to 5 metres. The resulting oxygen isotope values and their respective elevations relative to present sea level were plotted, and a straight line drawn between points. Since the samples were deposited at different eustatic sea levels, the slope of the lines also represents the change in isotopic composition for a given change in sea level. Fairbanks and Matthews believe that this technique "permits unquestionable direct comparison between the marine oxygen isotope record and known relative elevations of Pleistocene eustatic sea level" (p. 182). In their calculations, Fairbanks and Matthews assumed the "rate of tectonic uplift to be small compared to rates of eustatic fluctuation, and . . . temperature effects to be minimal for each pair of data points" (p. 191). The resulting conversion factor is 1.1 $^{0}/oo$ for a change in sea level of 100 ± 10 metres.

In order to evaluate this calibration, the validity of the assumptions should be examined. The assumption of a more or less constant temperature is probably valid. Sverdrup, Johnson and Fleming (1942) show a temperature variation of 2^{0} from August to February in that portion of the Carribean. This is based on short-term data. Whether this holds true for longer periods of time (glacial to non-glacial) is difficult to determine. The assumption that the rate of uplift is small compared to the rate of change of eustatic sea level cannot be adequately evaluated. In the light of Stearns' evaluation, it is clear that the Barbados data should be considered only with caution. It would be much better if this calibration could be carried out using the sea level at the time each terrace formed, rather than the elevation with respect to present sea level, because the assumption concerning tectonism could be eliminated. Since the data is "not sufficiently precise to yield close derivative measurements of 'paleosea levels' " it should not be used to calibrate a sea level curve for the Coastal Plain of Virginia.

Two methods of calibrating the change in sea level with the change in oxygen isotopic deviation have been discussed. Each of these methods may be adequate for the studies concerned, but neither of them are precise enough to be used in calibrating a sea level curve for a low relief area such as the Coastal Plain of Virginia. In calibrating their curve, Shackleton and Opdyke (1973) assigned a value for sea level from ice volume measurements to the point on their oxygen isotope curve which corresponds to the Wisconsinan Glacial Maximum. I feel that another method, similar to that of Shackleton and Opdyke, exists to calibrate a sea level curve based on oxygen isotope measurements. The change in oxygen isotopic deviation can be calculated by subtracting the oxygen isotope ratio at some depth in the core (δO^{18}_d) from the present value (δO^{18}_o):

$$\Delta\delta O^{18} = \delta O^{18}_o - \delta O^{18}_d \qquad (5)$$

Following the assumption of Shackleton and Opdyke that the sample with the highest O^{18}/O^{16} ratio represents the peak of the Wisconsinan Glaciation, a value for the low stand of sea level can be assigned to this difference, and a conversion factor calculated. The most widely accepted value for the elevation of sea level at the time of the Wisconsinan Maximum is -93 metres (Dillon and Oldale, 1978). This value should provide a much better estimate of ocean volume than an ice volume calculation. A conversion factor between sea level and oxygen isotopic composition was calculated by assigning the value of sea level for the Wisconsinan low stand to the corresponding difference in oxygen isotopic composition. The resulting conversion factor (0.12 ‰ per 10 m.) has been used to convert the oxygen isotopic composition of core V28-238 into a record of sea level changes.
The age of each sample was calculated in a manner similar to that of Shackleton and Opdyke. The first complete geomagnetic reversal in core V28-238 was found at a depth of 1200 cm. (Shackleton and Opdyke, 1973). This was assumed to be the Bruhnes/Matayuma reversal, which has been dated at 690,000 years B.P. (Opdyke, 1972; Cox, 1969). This age, rather than the 700,000 year B.P. value of Shackleton and Opdyke, was assigned to the depth of 1200 cm., and the sedimentation rate computed. The ages of samples at other depths in the

core were calculated from the sedimentation rate. This method of dating carries with it the assumption of a constant sedimentation rate. The resulting data was used to plot a sea level curve for the Coastal Plain (Figures 16 and 17).

Figure 16-Late Quaternary sea level curve derived from oxygen isotopic deviation calibrated with the Wisconsinan low-stand value of Dillon and Oldale (1978).

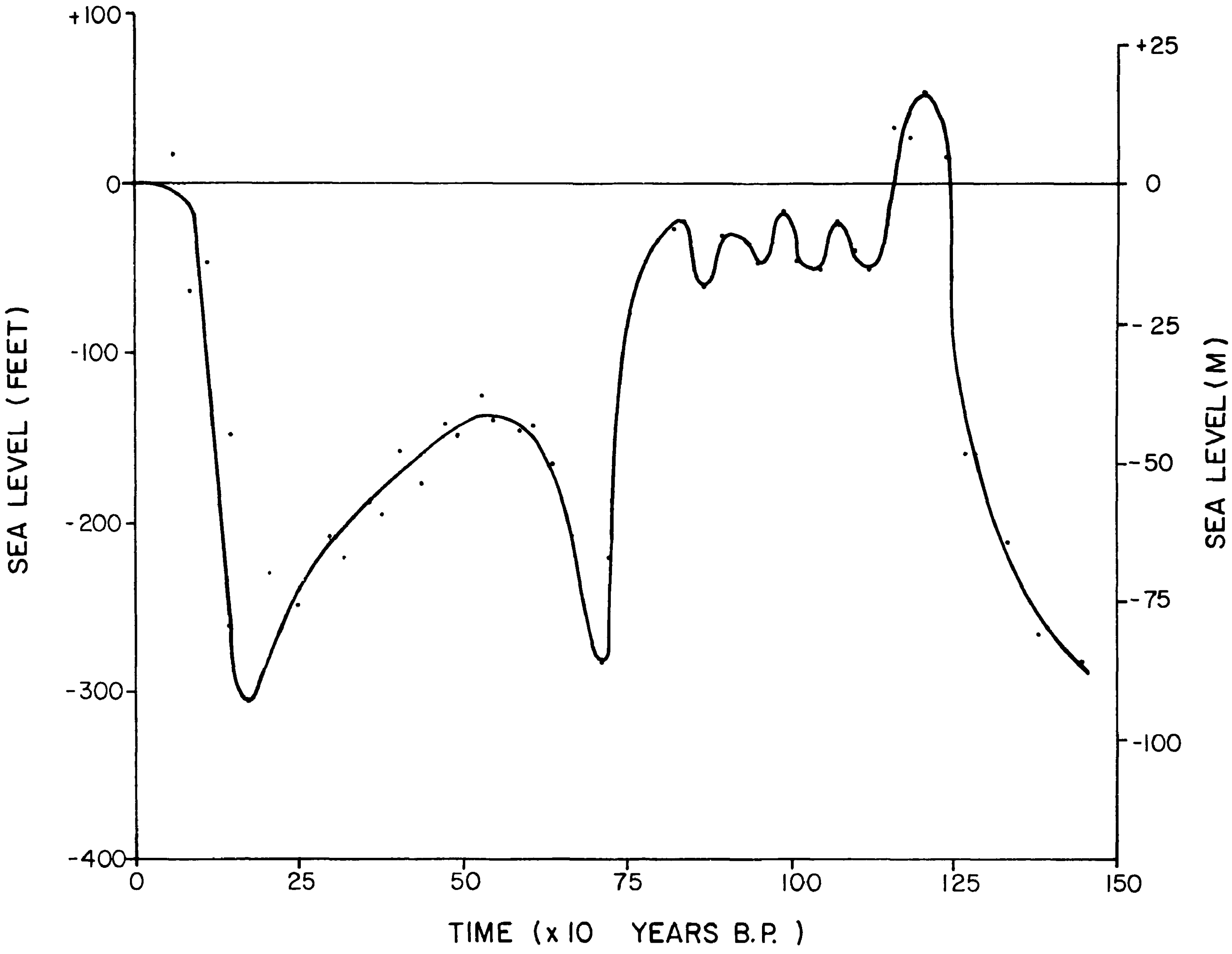
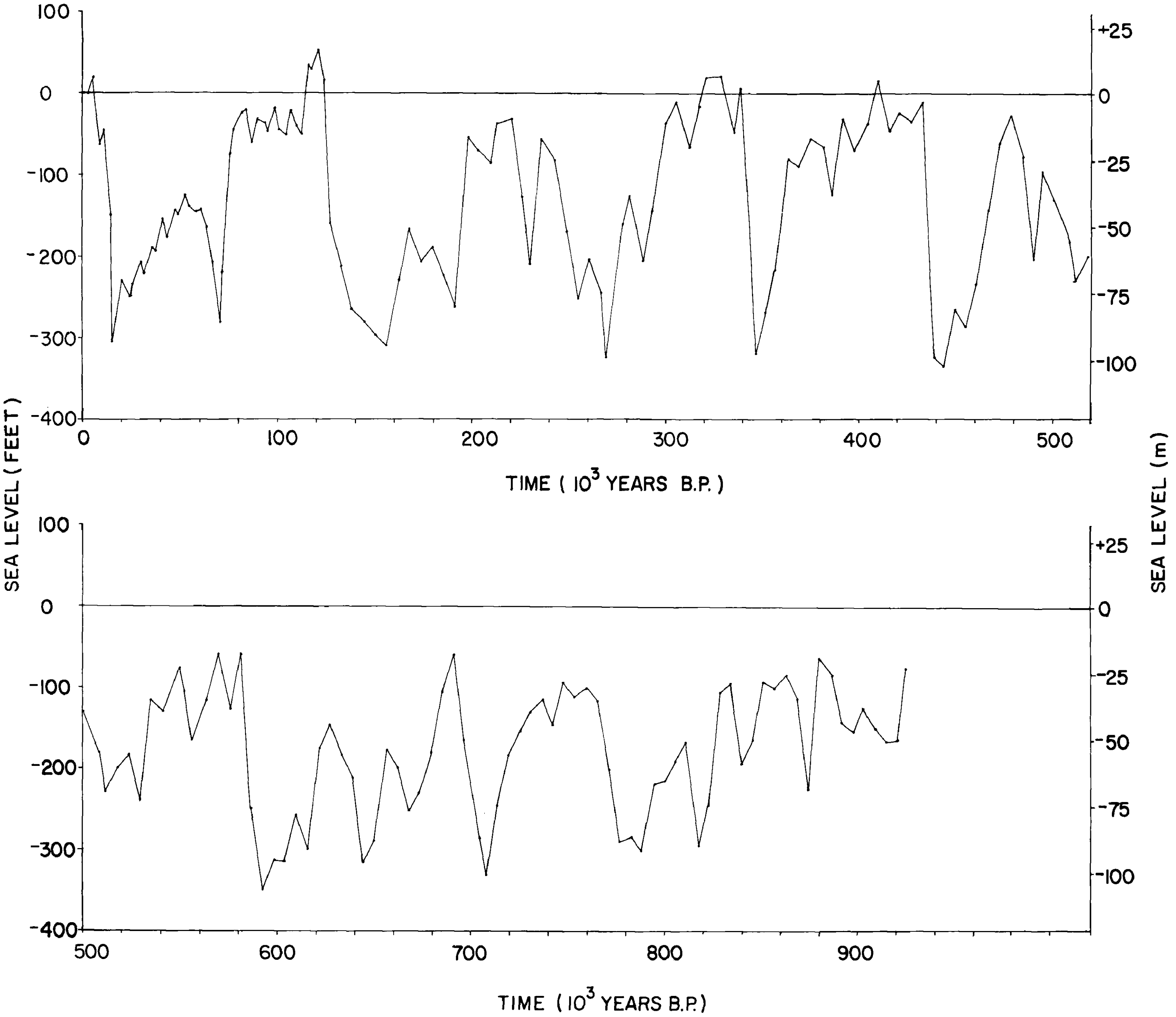

SEA LEVEL (FEET)
+100
0
-100
-200
-300
-400
SEA LEVEL (M)
+25
0
-25
-50
-75
-100
0
25
50
75
100
125
150
TIME (x10 YEARS B.P.)

Figure 17-Pleistocene sea level curve derived by calibration of oxygen isotopic deviation with a value for the Wisconsinan low stand.


100
0
-100
-200
-300
-400
+25
0
-25
-50
-75
-100
0
100
200
300
400
500
TIME (10^3 YEARS B.P.)
SEA LEVEL (FEET)
SEA LEVEL (m)
100
0
-100
-200
-300
-400
+25
0
-25
-50
-75
-100
500
600
700
800
900
TIME (10^3 YEARS B.P.)

DISCUSSION

The change in oxygen isotopic composition observed in monospecific samples of the foram Globigerinoides sacculifera from deep sea cores are believed to be caused primarily by sea level changes (van Donk, 1976). The changes in oxygen isotopic deviation observed in Pacific Core V28-238 were used to calculate a sea level curve. This curve is essentially a model of the geologic history of the Coastal Plain. The history derived from the curve can now be compared with the two stratigraphic interpretations of the Virginia Coastal Plain (Luebke and Johnson, 1967; Oaks and Coch, 1973). The interpretation which best fits the model derived from the curve gives the better description of the area's geologic history.

According to Oaks (1965) there are two Pleistocene transgressive sequences represented in the Outer Coastal Plain. The first transgression attained an elevation of approximately 45 to 50 feet, while the second only reached an elevation of +26 feet. Luebke and Johnson (1967) believe that only one transgressive-regressive sequence exists in the Outer Coastal Plain. This transgression attained a maximum elevation of 45 to 50 feet, depositing the various facies of the Norfolk Formation at its highest point. Recent Uranium series dates on material from this unit give an age of 120,000 to 130,000 years B.P. The sea level curve derived from oxygen isotope measurements shows a high stand of + 53 feet during this time period. After this high stand, sea level fell below its present elevation. From this time, it remained below present sea level, until the Holocene rise in sea level, caused by the melting of the continental ice sheets. The geologic history derived from the durve best fits the interpretation of Luebke and Johnson. Thus, their interpretation can be accepted as the best description of the geologic history of the Coastal Plain. This conclusion is based on two studies: the stratigraphy of the Inner Shelf, and the sea level changes of the Pleistocene.

Because the late Pleistocene curve closely approximates the value of the last high stand, both in age and elevation, it can be used as a model of the geologic history of the Coastal Plain. The curve derived for the total length of the core indicates that there were two previous high stands. Neither of them, however, attained the elevation of the last. The maximum Wisconsinan low stand, which was used as a point to calibrate the change in oxygen isotopic composition to sea level, occurred 17,250 years ago, according to the amended time scale. The difference between this value and that of Dillon and Oldale is negligible, lending support to the assumption of a uniform sedimentation rate. A rough estimate of the accuracy of the sea level curve can be made from the precision of the oxygen isotope measurements (± 0.07 $^{\circ}/_{oo}$). When this is converted into a value for sea level, the accuracy of the curve is obtained (± 18.5 feet). This value has been calculated on the basis of the chemical measurements, and should be used with that in mind. A better test would be to compare the curve with Pleistocene features of similar age in other areas of the world.

One topic needs to be discussed before a sea level curve based on oxygen isotope measurements is accepted for use in the Coastal Plain. At present, two schools of thought exist on the subject of the mid-Wisconsinan transgression. One group believes that there is evidence for a high stand of sea level near its present elevation approxiamtely 30,000 to 40,000 years B.P. (Milliman and Emery, 1968; Hoyt and Hails, 1973; Owens and Denny, 1978; 1979), while the other group believes that sea level never transgressed to its present elevation during the mid-Wisconsinan (Bloom, Broecker, Chappell, Matthews and Mesolella, 1974; Chappell, 1974). The evidence for the high stand at present sea level consists of dates on sea level indicators throughout the Coastal Plain. These dates need to be closely evaluated to judge their value in the study of sea level changes.

The mid-Wisconsinan age dates in the Coastal Plain have been widely used in the interpretation of the stratigraphy of the region (Table V). The Silver Bluff Formation in Georgia and the Carolinas (Hoyt and Hails, 1973) and the Sinepuxent and Kent Island Formations in Maryland (Owens and Denny, 1978; 1979) have been identified as mid-Wisconsinan transgressive units. In addition, Milliman and Emery used a date from the

TABLE V

Radiocarbon dates-Outer Coastal Plain and Continental Shelf East Coast of North America

Sample Number	Radiocarbon Age (Years B.P.)	Location	Elevation (Ft. from MSL)	Sample Description	Reference
R-4104	28,400 ± 1800	Whiskey Beach, Del. 38° 45.35' N. 75° 04.82' W.	-48.5	Macerated plant debris in lagoonal-estuarine silt.	Kraft, 1976
I-5207	>39,900	Salt Pond, Del. 38° 33.6' N. 75° 03.6' W.	-25.0	Wood in possible marsh fringe under a barrier	Kraft, 1976
I-7035	31,850 ± 1300	Holly Oak, Del. 39° 47.0' N. 75° 28.3' W.	-4.0	Total organic "rotten" wood fragments in a tan mud of a possible alluvial silt.	Kraft, 1976
I-7799	>40,000	Holly Oak, Del. 39° 46.9' N. 75° 28.5' W.	-1.5	Organic twigs and leaves in a possible alluvial silt.	Kraft, 1976
I-7801 I-7802 I-7800	>40,000	Holly Oak, Del. 39° 47.0' N. 75° 28.3' W.	-4.0	Same as above.	Kraft, 1976
I-6948	>40,000	Big Stone Beach, Del. 39° 01.7' N. 75° 15.4' W.	-32.0	*Crassostrea virginica*	Kraft, 1976
Jordan INQUA VII	34,000 ± 2000	Pepper Creek Ditch, Del.	+18.0	*C. virginica*, *Elphidium clavatum*, *Ammonia beccarii* in lagoon	Kraft, 1976

TABLE V (Cont'd)

Sample Number	Radiocarbon Age (Years B.P.)	Location	Elevation (Ft. from MSL)	Sample Description	Reference
W-2845	37,000 ± 1000	Qu3 Exact Location not given.	Top of hole	Wood-Sinepuxent Formation, Maryland	Owens and Denny, 1978
Wor-BH83	31,0000	Ocean City, Md. 38° 22.2' N. 75° 04.3' W.	-26.9	Non-marine peat	Field, Meisburger, Stanley & Williams 1979
Wor-Dg13	33,000 ± 1000	Assateague Isl., Maryland 38° 14.2' N. 75° 08.2' N.	-31.8	Non-marine peat	Field, et al., 1979
I-4738	32,730 ± 1650	Ocean City, Md. 38° 18.5' N. 75° 05.2' W.	-31.8	Non-marine peat	Field, et al., 1979
I-6885	28,700 ± 580	Chincoteague Is., Virginia 37° 57.0' N. 75° 21.0' W.	-36 to -37	Cedar branch and Stump.	Kraft, 1976
Y-1271	>40,000	Muddy Cross Ck. Benns Church, Va. 36° 55.0' N. 76° 35.0' W.	-2.0	Peat	Oaks, 1965
Y-1194	>40,000	Mears Corners Borrow Pit, Va. Beach, Va. 36° 47.5' N. 76° 10' 19" W.	+5.0	Wood in sand overlying shell-rich sand.	Oaks, 1965

TABLE V (Cont'd)

Sample Number	Radiocarbon Age (Years B.P.)	Location	Elevation (Ft. from MSL)	Sample Description	Reference
Jordan INQUA VII	>37,000	Pepper Creek Ditch, Del. 38° 31.58' N. 75° 14.67' W.	+18.0	*C. virginica*, *A. beccarii*, *E. clavatum* in estuarine-lagoonal sediments	Kraft, 1976
I-7524	31,900 ± 1400	Pepper Creek Ditch, Del. 38° 31.6' N. 75° 14.72' W.		*C. virginica* in oyster reef outcrop	Kraft, 1976
I-747	32,000 approx.	Omar Well, Del. 38° 32.1' N. 75° 11.2' W.	-2.0	Wood in shallow marine-estuarine blue-gray silt.	Kraft, 1976
I-748	20,000 approx.	Omar Well, Del. 38° 32.1' N. 75° 11.2' W.	+14.0	Same as above	Kraft, 1976
I-854	23,300 ± 850	Indian River Inlet, Del. 38° 36.4' N. 75° 03.0' W.	-120.0	Wood in a shallow marine-estuarine organic clay.	Kraft, 1976
I-4155	>39,900	Bethel, Del. 38° 32.4' N. 75° 37.4' W.	-13.2 to -14.2	Same as above	Kraft, 1976
I-4156	>39,900	Woodland, Del. 38° 36.4' N. 75° 39.8' W.	-7.4 to -12.4	Same as above	Kraft, 1976
I-4157	>39,900	Seaford, Del. 38° 36.4' N. 75° 35.8' W.	16.4 to 17.9	Shell in a shallow estuarine-lagoonal sandy silt matrix.	Kraft, 1976

TABLE V (Cont'd)

Sample Number	Radiocarbon Age (Years B.P.)	Location	Elevation (Ft. from MSL)	Sample Description	Reference
I-7526	>40,000	Assawoman Canal, Del. 38° 32.63' N. 75° 05.60' W.	-25 to -27	Grass peat and twigs of a tidal marsh fringe.	Kraft, 1976
W-2603	31,400 ± 750	B17 38° 20.0' N. 75° 09.25' W.	-1.1 to -1.3 approx.	Wood-Sinepuxent Formation, Maryland	Owens and Denny, 1978
QL-142	36,700 ± 450	B17 38° 20.0' N. 75° 09.25' W.	-1.1 to -1.3 approx.	Same as above	Owens and Denny, 1978
W-2605	33,100 ± 950	38° 19.0' N. 75° 11.25' W.	-2.2 approx.	Wood-Sinepuxent Formation, Maryland	Owens and Denny, 1978
QL-143	24,500 ± 150	B18 38° 19.0' N. 75° 11.25' W.	-2.2	Same as above	Owens and Denny, 1978
W-2846	34,000	TI1 Exact location not given.	10.7 from top of hole	Wood-Sinepuxent Formation, Maryland	Owens and Denny, 1978
W-2731	28,750 ± 1000	TI1 Exact location not given.	15.2-16.8 from top of hole	Same as above.	Owens and Denny, 1978
W-2730	34,000	TI2 Exact location not given.	10.7 from top of hole.	Wood-Sinepuxent Formation-Maryland	Owens and Denny, 1978
W-2610	31,100 ± 1000	TI70-13	11.6 to 12.0	Wood-Sinepuxent Formation, Maryland	Owens and Denny, 1978

TABLE V (Cont'd)

Sample Number	Radiocarbon Age (Years B.P.)	Location	Elevation (Ft. from MSL)	Sample Description	Reference
Y-1272	>40,000	36° 20.0' N. 75° 54.0' W.	+2.0	Wood from peat in cliff face. Sandbridge Fm.	Oaks, 1965
Y-1047	>40,000	Churchland, Va. 36° 51' 10" N. 76° 22' 54" W.	-26 to -29	Taxodium Wood	Oaks, 1965
I-1746	$36,000^{+3700}_{-2600}$	W. of Long Beach N.C. 33° 55' N. 78° 09' W.	+9.2	Peat (Salt marsh peat of Milliman and Emery, 1968) Fresh Water	Whitehead and Doyle, 1969
GX-2964	>37,000	Kitty Hawk, N.C. 36° 10.5' N. 75° 45.0' W.	-90	Undetermined Peat	Field, et al. 1979
G-2961	>28,000	Kitty Hawk, N.C. 36° 10.5' N. 75° 45.1' W.	-84	Undetermined Peat	Field, et al. 1979
GX-2962	>32,000	Kitty Hawk, N.C. 36° 10.5' N. 75° 45.1' W.	-70.8	Undetermined Peat	Field, et al. 1979
I-1898	$36,200^{+3600}_{-2500}$	Bull Creek, S.C. 33° 39.0' N. 79° 07' 25" W.	+3.0	Fresh water peat	Whitehead and Campbell, 1976
ML-158	42,670 ± 3720	Wilmington Isl., Georgia	-2.0	Shell	Hoyt, Henry & Weimer, 1965
FSU-9	>42,800	Cabretta Island, Georgia	-20.7	Shell	Hoyt, et al., 1965

TABLE V (Cont'd)

Sample Number	Radiocarbon Age (Years B.P.)	Location	Elevation (Ft. from MSL)	Sample Description	Reference
ML-157	41,400 ± 3200	Cabretta Island, Georgia.	-20.0	Shell	Hoyt, et al., 1965
O-1940	>37,000	Cabretta Island, Georgia	-9.8	Shell	Hoyt, et al., 1965
OR-25	>40,000	Sapelo Isl., Ga.	-20.0	Shell	Hoyt, et al., 1965
O-1875	25,475 ± 1150	Sapelo Isl., Ga.	-20.0	Shell	Hoyt, et al., 1965
O-1869	29,925 ± 2000	Sapelo Isl., Ga.	-37.0	Shell	Hoyt, et al., 1965
FSU-8	27,720 ± 760	Sapelo Isl., Ga.	-37.0	Shell	Hoyt, et al., 1965
GX0490	>38,500	Pumpkin Hammock, Georgia	-3.3	Shell	Hoyt, et al., 1965
FSU-11	>34,000	Meridian, Ga.	-2.0	Shell	Hoyt, et al., 1965
GX2152	23,550 ± 850	Cape Canaveral, Florida 28° 38.2' N. 80° 22.1' W.	-82.0	<u>Donax variabilis</u>	Field, 1974
GX2573	25,200 $^{+3000}_{-2000}$	Cape Canaveral, Florida 28° 37.05' N. 80° 34.9 ' W.	-27.2	<u>Donax variabilis</u>	Field, 1974

Outer Coastal Plain of North Carolina in their sea level curve. The existing dates on samples in the Coastal Plain fall into three categories, based on the type of material dated, and the age of the sample. In several areas, radiocarbon dates on peats have yielded infinite ages (Oaks and Coch, 1973; Kraft, 1976; Meyer Rubin, Bob Mixon, personal communication). The other two categories have finite ages (<40,000 years B.P.), but some have been made on shell (Hoyt and Hails, 1973), while others were on peat (Thom, 1967; Milliman and Emery, 1968; Owens and Denny, 1978; 1979). Both groups of finite dates will be evaluated in the light of recent work to determine their value as indicators of a mid-Wisconsinan transgression.

The Silver Bluff Formation was originally dated as a mid-Wisconsinan transgressive unit on the basis of shell dates in the vicinity of Sapelo Island, Georgia (Hoyt and Hails, 1973). All of these dates would presently be considered with caution. Thurber (1972, p. 9) states "Contamination of carbonates by exchange can be nearly eliminated and should a selection of materials clearly unaffected by recrystallization be possible, reliable estimates of ages at least 35,000 or 40,000 years should be possible. Without suitable treatment, all ages over about 25,000 years must be regarded as minimum ages." Colquhoun (1973, p. 189) stated that he "believes a late Sangamon age to be more likely" for the Silver Bluff Formation. He further states that "The major emergence that followed Silver Bluff time proceeded below -25 meters (-80 feet), and probably represents the entire

Wisconsin." He does not, however, give any reasons to support this statement.

Several dates on peats in North and South Carolina have been used to support a mid-Wisconsinan transgression (Thom, 1967; Milliman and Emery, 1968). One of these peats (I-1745) was identified by Milliman and Emery as a "salt marsh peat." Pollen analyses by Whitehead and Doyle (1969), however, identified the peat as fresh water, thus eliminating it as a conclusive sea level indicator. Both of the peats from the Carolinas (Bull Creek, S.C. and Long Beach, N.C.) are probably contaminated by modern root material (Whitehead and Doyle; Whitehead and Campbell, 1976), which makes the dates even more unreliable. If it were assumed that only 1 % contamination existed, its removal would place the age of that peat beyond the maximum age range of the radiocarbon method (40,000 to 50,000 years B.P.) (Table VI). Thus, the evidence south of Virginia does not warrant support for the mid-Wisconsinan high stand.

In Virginia, no material of mid-Wisconsinan age has been found (Oaks and Coch, 1973), so there is little evidence to support the high stand in the area. In Maryland and Delaware, however, several dates of mid-Wisconsinan age have been found (Kraft, 1976; Owens and Denny, 1978; 1979). These dates, none of which is on a salt marsh peat, have been cited as proof of a mid-Wisconsinan age for the Sinepuxent and Kent Island Formations in Maryland. Mixon (personal communication) has dates on a peat from the Southern Delmarva Peninsula west of Oak

TABLE VI

Effects of Modern Contamination on Radiocarbon Dates (Bowen, 1979)

	Approximate Apparent Age with % Contamination					
True Age	0.1	0.2	1.0	2.0	5.0	10.0
10,000	10,000	9,960	9,980	9,630	9,100	8,000
20,000	19,900	19,800	19,000	18,300	16,400	13,000
30,000	29,700	29,300	28,000	25,300	21,270	16,000
40,000	39,000	38,110	32,000	29,900	23,800	18,000
50,000	47,000	45,000	34,000	31,650	24,300	18,000
60,000	52,000	49,000	34,000	32,100	24,650	18,000
Infinite	57,000	51,000	38,000	32,500	24,800	

Hall, Virginia which are "probably from the Lower Kent Island Formation." The date on this peat is >40,000 years B.P. Owens and Denny (1979, p. 26) state that "Spatially, the Kent Island seems to be correlated with the Sinepuxent." Since this unit is considered to be a mid-Wisconsinan transgressive unit, there appears to be some disparity in the radiocarbon ages of the peats of the region. This could be caused by contamination of the peats by younger carbon. The same situation probably exists in Delaware, where several infinite dates and a few finite dates exist on sediments which appear to be closely related.

Several dates of a mid-Wisconsinan age have been made on peat and shell along the East Coast of North America. Because of the possibility of contamination, the dates on carbonate should be regarded as "minimum ages" only. Of the mid-Wisconsinan age peats, several have been reported as possibly contaminated (Whitehead and Doyle, 1969; Whitehead and Campbell, 1976). It is clear that all of these radiocarbon dates fall into a rather nebulous age range when the radiocarbon method is being considered. Any modern contamination of older material would result in a mid-Wisconsinan age. Therefore, the mid-Wisconsinan high stand appears to be an artifact of the radiocarbon method resulting from the contamination of older material by younger carbon.

CONCLUSIONS

The stratigraphy of southeastern Virginia and the geologic history interpreted from it have been studied using two different methods. From both of these studies, it can be concluded that the Outer Coastal Plain sediments are the result of one transgression and regression, during which all of the five sedimentary units of Oaks (1965) were deposited. This study has not been limited solely to the Coastal Plain and Inner Shelf sediments. In conjunction with work on the Inner Shelf stratigraphy, a sea level curve which is independent of local evidence has been developed. This curve is based on the oxygen isotopic deviation observed in the tests of Foraminifera from deep-sea cores. The sea level curve derived from the deep-sea evidence is the first curve independent of the local evidence that can be used to interpret the geomorphology and stratigraphy of the Coastal Plain. As such, it provides an excellent model for the interpretation of the local sequences.

In order to evaluate the curve, the late Pleistocene stratigraphic sequences in other areas of the Coastal Plain have been examined. Several workers (Hoyt and Hails, 1973; Owens and Denny, 1978; 1979) have used radiocarbon dates to identify a mid-Wisconsinan transgressive unit in the Outer Coastal Plain of Georgia and Maryland, respectively. The idea of a mid-Wisconsinan high stand near the present elevation of sea level was first proposed on the basis of dates on samples collected from the Continental Shelf and Outer Coastal Plain of the East Coast of North America. All but one of the mid-Wisconsinan dates used by Milliman and Emery in their curve were on carbonate. Recent work by Thurber (1972) and Bowen (1978) has pointed out the fact that radiocarbon dates on carbonate should be applied with caution, because of the likelyhood of contamination. The non-carbonate date of Milliman and Emery was on a peat deposit from near Long Beach, N.C. This peat was erroneously cited as a salt marsh peat. Whitehead and Doyle (1969) published pollen analyses which indicate that this peat was deposited under fresh water conditions. They also report that there is a possibility of contamination by modern root material and humates, which would cause the peat to give an anomalously young age. This is probably also the case in Maryland and Delaware, where several finite dates have been made on samples from units which contain material yeilding infinite ages. On the basis of the information available, there appears to be little evidence for a mid-Wisconsinan high stand near present sea level. Therefore, the curve derived from the changes in oxygen isotopic deviation observed in deep-sea cores can be freely applied to the geology of the Coastal Plain.

The change in oxygen isotopic deviation in deep-sea cores at first appears to have little relationship to the geology of the Coastal Plain. However, since it is, for the most part, the effect of sea level changes during the Pleistocene, the change in oxygen isotopic deviation of the ocean can be used to interpret the geology of the Coastal Plain. With the calibration proposed herein, a sea level curve is derived that can be used to interpret the stratigraphy and geomorphology of the Coastal Plain, assuming that there has been no tectonism. The curve derived from the oxygen isotope changes observed in deep-sea cores is the first instance where the deep-ocean record has been applied to the geology of the continents. The fact that the curve does aid in the interpretation of the geology of the region means that the key to the Pleistocene may be found in the sedimentary record of the deep-ocean floors.

REFERENCES CITED

Belknap, D.F., and Kraft, J.C., 1977. Holocene relative sea level changes and coastal stratigraphic units on the northwest flank of the Baltimore Canyon Trough geosyncline. Journal of Sedimentary Petrology 47:610-629.

Bender, M.L., Fairbanks, R.G., Taylor, F.W., Matthews, R.K., Goddard, J.G., and Broecker, W.S., 1979. Uranium-series dating of the Pleistocene reef tracts of Barbados, West Indies. Geological Society of America Bulletin 90:577-594.

Bender, M.L., Taylor, F.W., and Matthews, R.K., 1973. Helium-Uranium dating of corals from Middle Pleistocene Barbados reef tracts. Quaternary Research 3:142-146.

Bloom, A.L., 1970. Paludal stratigraphy of Truk,Ponape, and Kusaie, Eastern Caroline Islands. Geological Society of America Bulletin 81:1895-1904.

Bloom, A.L., Broecker, W.S., Chappell, J.M.A., Matthews, R.K., and Mesolella, K.J., 1974. Quaternary sea level fluctuations on a tectonic coast: New Th^{230}/U^{234} dates from the Huon Peninsula, New Guinea. Quaternary Research 4:185-205.

Bowen, D.Q., 1978. Quaternary geology: a stratigraphic framework for multidisciplinary work. Pergamon Press, New York. 221 p.

Broecker, W.S., Thurber, D.L., Goddard, J., Ku, T-L, Matthews, R.K., and Mesolella, K.J., 1968. Milankovitch hypothesis supported by precise dating of coral reefs and deep sea sediments. Science 159:297-300.

Broecker, W.S., Turekian, K.K., and Heezen, B.C., 1958. The relation of deep sea sedimentation rates to variations in climate. American Journal of Science 268:503-517.

Brownlow, A.H., 1979. Geochemistry. Prentice-Hall, Inc., Englewood Cliffs, New Jersey. 498 p.

Chappell, J.M.A., 1974. Geology of coral terraces, Huon Peninsula, New Guinea: a study of Quaternary tectonic movements and sea level changes. Geological Society of America Bulliten 85:553-570.

Clark, W.B., and Miller, B.L., 1912. The physiography and geology of the Coastal Plain province of Virginia. Virginia Geological Survey Bulliten 4. 274 p.

Colquhoun,D.J., 1974. Cyclic surficial stratigraphic units of the Middle and Lower Coastal Plains, Central South Carolina. In: Oaks, R.Q., Jr., and DuBar, J.R. Post-Miocene stratigraphy, central and southern Atlantic Coastal Plain. Utah State University Press, Logan, Utah. P. 179-190.

Cox, A., 1969. Geomagnetic reversals. Science 163:237-245.

Curray, J.R., 1960. Sediments and history of Holocene transgression, continental shelf, northwest Gulf of Mexico. In: Shepard, F.P., Phleger, F.B., and van Andel, T.H. (Eds.). Recent sediments, northwest Gulf of Mexico. American Association of Petroleum Geologists. P. 221-266.

Curray, J.R., 1964. Transgressions and regressions. In: Miller, R.L. (Ed.), Papers in Marine Geology. (Shepard Commemorative Volume). Macmillan Co., New York. P. 175-203.

Curray, J.R., 1965. Late Quaternary history, continental shelves of the United States. In: Wright, H.E., Jr., and Frey, D.G. (Eds.). The Quaternary of the United States. Princeton University Press, Princeton, N.J. P. 723-736.

Curray, J.R., and Shepard, F.P., 1972. Some major problems of Holocene sea levels. Abstracts Second National Conference, AMQUA. P. 16-18.

Dalrymple, G.B., 1972. Potassium-argon dating of geomagnetic reversals and North American glaciations. In: Bishop, W.W. and Miller, J.A., Calibration of Hominoid Evolution, Scottish Academic Press, Ltd., Edinburgh. P. 107-134.

Daly, R.A., 1925. Pleistocene changes of level. American Journal of Science, Fifth Series. 10:281-313.

Dansgaard, W.S., and Tauber, H., 1969. Glacial oxygen-18 content and Pleistocene ocean temperatures. Science 166:499-502.

Dillon, W.P., and Oldale, R.N., 1978. Late Quaternary sea level curve: Reinterpretation based on glaciotectonic influence. Geology 6:56-60.

Ellison, R.L., and Nichols, M.M., 1976. Modern and Holocene Foraminifera in the Chesapeake Bay region. Maritime Sediments Special Publication No. 1., Part A., p. 131-152.

Emery, K.O., and Garrison, L.E., 1967. Sea levels 7,000 to 20,000 years ago. Science 157:684-687.

Emery, K.O., and Uchupi, E., 1972. Western North Atlantic Ocean: Topography, rocks, structure, life, sediments. American Association of Petroleum Geologists, Memoir 17. 532 p.

Emiliani, C., 1955. Pleistocene temperatures. Journal of Geology 63:538-578.

Emiliani, C., 1957. Temperature and age analysis of deep-sea cores. Science 125:383-387.

Epstein, S., Buchsbaum, R., Lowenstam, H.A., and Urey, H.C., 1953. Revised carbonate-water isotopic temperature scale. Geological Society of America Bulletin 64:1315-1326.

Fairbanks, R.G., and Matthews, R.K., 1978. The marine oxygen isotope record in Pleistocene coral, Barbodos, West Indies. Quaternary Research 10:181-196.

Fairbridge, R.W., 1961. Eustatic changes in sea level. Physics and Chemistry of the Earth. 4:99-185.

Fairbridge, R.W., 1971. Quaternary shoreline problems at INQUA. Quaternaria 15:1-17.

Field, M.E., 1974. Buried strandline deposits on the central Florida Inner continental shelf. Geological Society of America Bulletin 85:57-60.

Field, M.E., Meisburger, E.P., Stanley, E.A., and Williams, S.J., 1979. Upper Quaternary peat deposits on the Atlantic inner shelf of the United States. Geological Society of America Bulletin 90:618-628.

Flint, R.F., 1940. Pleistocene features of the Atlantic Coastal Plain. American Journal of Science 238:757-787.

Flint, R.F., 1971. Glacial and Quaternary Geology. John Wiley and Sons, New York. 892 p.

Garrison, L.E., and McMaster, R.L., 1966. Sediments and geomorphology of the continental shelf off of Southern New England. Marine Geology 4:273-289.

Hecht, A.D., 1976. The oxygen isotope record of Foraminifera in deep sea sediment. In: Hedley, R.H., and Adams, C.G., Foraminifera, Academic Press, Inc., London. 2:1-43.

Hoyt, J.H., and Hails, J.R., 1974. Pleistocene stratigraphy of southeastern Georgia. In: Oaks, R.Q., Jr., and DuBar, J.R., Eds. Post-Miocene stratigraphy-central and southern Atlantic Coastal Plain. Utah State University Press, Logan, Utah. p. 191-205.

Hoyt, J.H., Henry, V.J., and Howard, J.D., 1966. Pleistocene and Holocene sediments, Sapelo Island, Georgia and vicinity. Geological Society of America, Southeastern Section, 15th Annual Meeting, Guidebook for Field Trip 1.

Hoyt, J.H., Henry, V.J., and Weimer, R.J., 1965. Age of Late-Pleistocene Shoreline deposits, Coastal Georgia. In: Morrison, R.B., and Wright, H.E., Jr., Eds. Means of correlation of Quaternary Successions. INQUA Proceedings. 8:381-394.

Kraft, J.C., 1976. Radiocarbon dates in the Delaware Coastal Zone (Eastern Atlantic Coast of North America): a Delaware Sea Grant Technical Report (DEL-SG-19-76), publ. by Coll of Marine Studies, Univ. of Delaware, Newark, 12 p.

Luebke, W.C., and Johnson, G.H., 1967. The geology of the Mears Corner Pit, Virginia Beach, Va. Virginia Journal of Science 19:3:194.

Macintyre, I.G., Blackwelder, B.W., Land, L.S., and Stuckenrath, R., 1975. North Carolina shelf-edge sandstone: Age, environment of origin, and relationship to preexisting sea levels. Geological Society of America Bulletin 86:1073-1078.

Macintyre, I.G., Pilkey, O.H., and Stuckenrath, R., 1978. Relict oysters on the United States Atlantic continental shelf: a reconsideration of their usefulness in understanding late Quaternary sea-level history. Geological Society of America Bulletin 89:277-282.

Mesolella, K.J., 1968. The uplifted reefs of Barbados: Physical stratigraphy, facies relationships, and absolute chronology. Ph. D. Thesis, Brown University.

Milliman, J.D., and Emery, K.O., 1968. Sea levels during the past 35,000 years. Science 162:1121-1123.

Newman, W.S., and Rusnak, G.A., 1965. Holocene submergence curve of the Eastern Shore of Virginia. Science 148: 1464-1466.

Oaks, R.Q., 1965. Post-Miocene stratigraphy and morphology, Southeastern Virginia. Ph. D. Dissertation, Yale University. 240 p.

Oaks, R.Q., and Coch, N.K., 1973. Post-Miocene stratigraphy and morphology, southeastern Virginia. Virginia Division of Mineral Resources, Bulletin 82. 135 p.

Olaussen, E., 1965. Evidence of climatic changes in North Atlantic deep-sea cores, with remarks on isotopic paleotemperature analysis. Progress in Oceanography 3:221-252.

Opdyke, N.D., 1972. Paleomagnetism of deep-sea cores. Reviews of Geophysics and Space Physics 10:213-249.

Owens, J.P., and Denny, C.S., 1978. Geologic Map of Worcester County, Maryland. Maryland Geological Survey.

Owens, J.P., and Denny, C.S., 1979. Upper Cenozoic Deposits of the Central Delmarva Peninsula, Maryland and Delaware. U.S. Geological Survey Professional Paper 1067-A. 28 p.

Phleger, F.B., 1960. Ecology and distribution of Recent Foraminifera. The Johns Hopkins Press, Baltimore, Md. 297 p.

Poag, C.W., 1973. Late Quaternary sea levels in the Gulf of Mexico. Gulf Coast Association Geological Society Transactions 23:394-400.

Redfield, A.C., 1967. Post-glacial change in sea level in the Western North Atlantic Ocean. Science 157:687-691.

Richards, H.G., 1967. Stratigraphy of the Atlantica Coastal Plain between Long Island and Georgia-Review. American Association of Petroleum Geologists Bulletin 51:2400-2429.

Rogers, W.B., 1884. A Reprint of annual reports and other papers on the geology of the Virginias. D. Appleton and Company, New York. 832 p.

Scholl, D.W., Craighead, F.C., Sr., and Stuiver, M., 1969. Florida Submergence curve revisited: its relation to coastal sedimentation rates. Science 163:562-564.

Shackleton, N.J., and Opdyke, N.D., 1973. Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238: Oxygen isotope temperatures and ice volumes on a 10^5 and 10^6 year scale. Quaternary Research 3:39-55.

Shaler, N.S., 1890. General account of the fresh-water morasses of the United States, with a description of the Dismal Swamp district of Virginia and North Carolina. U.S. Geological Survey, Tenth Annual Report, p. 255-339.

Shattuck, G.B., 1906. The Pliocene and Pleistocene deposits of Maryland. Maryland Geological Survey, Pliocene and Pleistocene, p. 21-137.

Shideler, G.L., Swift, D.J.P., Johnson, G.H., and Holliday, B.W., 1972. Late Quaternary Stratigraphy of the Inner Virginia Continental Shelf: A proposed standard section. Geological Society of America Bulletin 83:1787-1804.

Stearns, C.E., 1976. Estimates of the position of sea level between 140,000 and 75,000 years ago. Quaternary Research 6:445-449.

Stuiver, M., 1971. Evidence for the variation of atmospheric Carbon-14 content in the late Quaternary. In: Turekian, K.K., The Late Cenozoic Glacial Ages, Yale University Press, New Haven. p. 57-70.

Sverdrup, H.U., Johnson, M.W., and Fleming, R.H., 1942. The Oceans: their physics, chemistry, and general biology. Prentice-Hall, Inc. Englewood Cliffs, N.J. 1087 p.

Thom, B.G., 1967. Coastal and Fluvial landforms-Horry and Marion Counties, South Carolina. Louisiana State University Coastal Studies Institute. Coastal Studies Series 19. Technical Report 44. 75 p.

Thurber, D.L., 1972. Problems of dating non-woody material from continental environments. In: Bishop, W.W., and Miller, J.A., Eds. Calibration of Hominoid Evolution p. 1-18. Edinburgh.

van Donk, J., 1976. Oxygen-18 record of the Atlantic Ocean for the entire Pleistocene Epoch. In: Cline, R.M., and Hayes, J.D., Eds. Investigation of Late Quaternary paleoceanography and paleoclimatology. Geological Society of America Memoir 145, p. 147-163.

Wentworth, C.K., 1930. Sand and Gravel resources of the Coastal Plain of Virginia. Virginia Geological Survey, Bulletin 32. 146 p.

Whitehead, D.R., and Campbell, S.K., 1976. Palynological Studies of the Bull Creek Peat, Horry County, South Carolina: Geomorphological Implications. Southeastern Geology 17:161-174.

Whitehead, D.R., and Doyle, M.V., 1969. Late Pleistocene peats from Long Beach, North Carolina. Southeastern Geology 10:1-16.

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