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POSSIBLE LATE PLEISTOCENE UPLIFT CHESAPEAKE BAY ENTRANCE¹

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ABSTRACT

Paleontological and lithological studies of engineering borings and boring logs indicate that a buried, subaerial erosion surface of Pliocene (?)–Pleistocene age cuts across clastic sediments of pre-Yorktownian Miocene age in the subsurface and subbottom of the lower Chesapeake Bay area. When the bore-hole data are coupled with the results of subbottom echo profiling and piledriving records, it is possible to construct accurate cross sections of the buried Miocene–Pleistocene contact. The cross sections show “lows” in the erosion surface that may be correlated with the buried channels of the Pleistocene Elizabeth, James, York, and Susquehanna river valleys. Probable channel depths below mean low water at control points are: 100 feet (Elizabeth River, beneath Tunnel no. 1), 155 feet (James River, at Hampton Roads Tunnel), 120 feet (York River, at Yorktown), 158 feet (Susquehanna River, off Cape Charles City), and 160 feet (Susquehanna River, at Fisherman Island, Cape Charles). The channel depths of what is believed to be the buried Susquehanna River valley are less than expected when placed on a curve showing the expectable gradients of that stream during the time of the most-recent, maximum lowering of sea level (*ca.* 18,000 years B.P.). The discrepancy suggests uplift of that channel of approximately 170 feet in about the last 18,000 years.

Pollen analysis and C¹⁴ dating of peats and shells immediately overlying the Miocene–Pleistocene contact indicate that the peats were deposited in brackish-water marshes or on boreal flood plains, probably only slightly above sea level, and that they were subsequently submerged and covered by estuarine sediments. The peats date between 10,340 and 15,280 years B.P., and occur at depths of 82–89 feet below mean low water. Because points for these age-depth values fall well above those used in developing curves of eustatic rise of sea level on relatively stable coasts, it seems possible that the peats may have been uplifted as much as 160 feet in the last 15,000 years.

Additional possible evidence of uplift within the last 1,900 years also is suggested by C¹⁴ dates on a peat and underlying shell bed cropping out on the seaward side of Hog Island on Virginia's eastern shore. The peat bed, assumed to have formed at about high tide, and the shell bed, deposited below low tide, now crop out some 5 feet above mean low water, and date from 1,170 to 1,900 years B.P., respectively.

Rates of uplift suggested by three localities of dated horizons indicate an average value of about 1.05 feet per century for the past 15,000 years, although the rate of uplift varied with time and actually involves a calculation for subsidence between 6,000 and 2,000 B.P. The rate of uplift seems to have approximated the rate of eustatic sea-level rise (about 2.8 feet per century), between 15,000 and about 8,000 B.P. Apparent reversal of crustal uplift between about 6,000 and 2,000 B.P., coupled with continued eustatic rise of sea level, allowed for extensive flooding of the Susquehanna valley lowland and eastern shore of Virginia.

Crustal uplift appears to have resumed between 2,000 B.P. and the present. The crustal-movement curve for the period 14,000–3,000 B.P. is remarkably similar to that found by Kaye and Barghoorn (1964) for the Boston area.

АБСТРАКТ

В науке Палеонтологии и Литологии при изучении данных, полученных при бурении земных скважин и связанных с результатом изучения эха, полученного посредством измерительного инструмента эхолота, а также приняв во внимание при бурении темп скорости парового молота, позволяет сконструировать график поперечного сечения, погребенного Миоцви-Плейстоцена (Miocene–Pleistocene) в поддонном отложении. Плейстоцен физиографии обнаруживает в этом поперечном сечении обратный наклон в погребенной далине реки Сускуиханна (Susquehanna).

Это противоречие в наклоне внушает, что произошло поднятие русла реки почти что на 170 футов от мыса Варлз в Виргинии (Cape Charles, Virginia), приблизительно за последние 18000 лет.

Анализ пылицы и C₁₄ (carbon-14), взятый для анализа из торфа и раковин непосредственно

покрывающих Миоцен-Плейстоцен (в месте соприкосновения бурава), показывает, что отложение торфа произошло в затопленной равнине. Эта равнина по всей вероятности только слегка возвышалась над уровнем моря и что эти отложения торфа затем были затоплены и покрыты устьевым донным осадком.

Давность торфа классифицируется в пределах от 10340 и до 15280 лет и появляется на глубине от 82 до 89 футов ниже среднего низкого уровня воды.

Все выше изложенное показывает, что слой торфа по всей вероятности был поднят на высоту 160 футов за последние 15000 лет. Норма поднятия видимо имеет приблизительно норму эвстатического поднятия уровня моря (2.8 фута в столетие), в период между 15000 и 8000 лет тому назад до нашей эры. Видимое обратное поднятие земной коры приблизительно между 6000 и 2000 лет тому назад до нашей эры, связанное с непрерывным эвстатическим поднятием уровня моря, допустило обширное затопление низменности долины Сускуиханна (Susquehanna Valley) и образовало залив Чесапик (Chesapeake Bay). Земная кора видимо опять возобновила поднятие между 2000 лет тому назад до нашей эры и настоящим временем. Кривая движения земной коры за период времени от 14000 лет и до 3000 лет до нашей эры замечательно похожа на открытие, сделанное учеными Кайе и Баргхурн (Kaye and Barghoorn) в 1964 году в районе Бостона (Boston area).

I. INTRODUCTION

In 1957 J. T. Hack published an interesting study of the "Submerged River System of Chesapeake Bay." He was able to locate the thalweg of the Pleistocene Susquehanna River in upper Chesapeake Bay from an analysis of data and lithological cross sections compiled from numerous engineering borings. Data from several tributaries to the bay were treated in a similar way to establish their thalwegs. On the reasonable assumption that all submerged channels entering Chesapeake Bay form an interconnected system, Hack extended the longitudinal profile of the Susquehanna thalweg for a distance of 150 miles downstream. According to an assumed gradient, this inferred profile was terminated at a depth of about -370 feet off Cape Henry, Virginia. No direct evidence was available to Hack at that time to confirm the inferred channel near Chesapeake Bay entrance, but the speculation seemed acceptable. Beckmann, Drake, and Sutton (1960), however, could not find such a deep channel in their Sub-

bottom Depth Recorder (SDR) "traces" that extended from near Chesapeake Beach to Cape Charles, Virginia (fig. 1).

As new data became available from numerous engineering projects that involved test borings (fig. 1) from the Norfolk and lower Chesapeake Bay area, Harrison (1961, 1962) tentatively interpreted apparent channels of the Pleistocene Susquehanna and James rivers more directly. Additional stratigraphic study and radiocarbon dating (Harrison and Rusnak, 1962) subsequently indicated the possibility of gradual crustal uplift at the Chesapeake Bay entrance since some time around 18,000 years B.P. (before the present). The area clearly required more study, and so the investigation was broadened. Geophysical, paleontological, and palynological techniques were applied to the problem and correlated by additional radiocarbon analyses in a co-operative effort among interested colleagues. The resulting interpretations and the evidence upon which these are founded can now be presented as they developed. Our study begins with a description of the Miocene-Pleistocene contact and proceeds to the conclusion that gentle crustal warping occurs in the area and has in general accompanied glacio-eustatic sea-level rise and the subsequent deposition of marine and estuarine sediments.

II. RECOGNITION OF BURIED MIOCENE- PLEISTOCENE CONTACT

Evidence of multiple erosional and depositional surfaces are clearly indicated in

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cross sections compiled from engineers' bore-hole data (Harrison, 1962) as well as in SDR traces (Beckmann *et al.*, 1960). Although it is well known that recent and late Pleistocene sediments directly overlie upper Miocene deposits in the area (no Pliocene sediments having been identified), the recognition of the Miocene-Pleistocene contact sur-

A. FAUNAL AND LITHOLOGIC EVIDENCE

Where large numbers of borings are involved, drillers' logs offer the fastest method for identification of the first encounter of the Miocene. In these logs, the Miocene sediment is typically described as "greenish-gray silty clay, some fine sand, trace shells." Rarely, one encounters "trace of gravel"

FIG. 1.—Map of Norfolk area, Virginia, and entrance to Chesapeake Bay. Locations of cross sections 1, 2, and 3, shown with locations of borings referred to in text.

face as a specific stratigraphic horizon is accomplished in the subsurface only with some difficulty. On the basis of lithology alone, it has been possible to assign a tentative distinction between Miocene and Pleistocene sediments, but conclusive evidence has been developed only from paleontology. Recognized paleontologic horizons have been correlated specifically with soil-mechanical, engineering, and geophysical properties of the sediments.

appended to this description, because pebble and granule units are known to occur in the Miocene of this area (Sinnott and Tibbitts, 1957). This description of the Miocene differs from descriptions applied to immediately overlying sediments, which are usually devoid of "shells," are "gray," "brown," or (very rarely) "blue" in color, sometimes exhibit traces of "organic material," and usually are coarser grained than the "silty clay" of the Miocene.

The subaerial erosion surface of Pleistocene (and possibly Pliocene) age that separates these units is cut entirely into clastic sediments of pre-Yorktownian Miocene age. This age assignment of the sediments underlying the erosion surface was made by J. D. McLean, Jr., from paleontologic and lithologic analyses⁶ of samples obtained from borings A1, A2, C1, 5, and 11 (fig. 1). Within these sediments, directly beneath the unconformity, McLean found fossils belonging

pizarrensis (Berry), or *Bulimina gracilis* is found to occur in samples immediately below *Nonion mediocostatus*. This "zone" is further characterized by a marked increase in numbers of specimens of Foraminifera and Ostracoda, although the actual number of species is small per sample. There is, indeed, a wide differentiation of particular species from boring to boring, but the fauna can always be noted by means of one or more of the three species, *N. mediocostatus*, *N. pizarrensis*, and *B. gracilis*. Echinoid spines are also indicative of the Miocene.

TABLE 1
FAUNAL ZONE FOUND AT TOP OF MIOCENE*

Boring Number and Sample Position	Depth (Ft. Below MLW)	Remarks
A1:		
Top of Miocene.....	84	<i>B. gracilis</i> present
Zone base at.....	113	
A2:		
Top of Miocene.....	70	<i>B. gracilis</i> present
Zone base at.....	101	
5:		
Top of Miocene.....	85	<i>B. gracilis</i> absent;
Zone base at.....	110	<i>Nonions</i> present
11:		
Top of Miocene.....	135	<i>B. gracilis</i> present
Zone base at.....	155	

* James D. McLean, Jr., analyst.

to a rather wide spread zone typical of the Miocene. He wrote (in Harrison, 1962):

The Yorktown formation appears to be missing in borings A-1, A-2, 5, and 11. Typical Yorktownian microfossils (McLean, 1956, 1957) are nowhere to be found in the samples. *Nonion mediocostatus* (Cushman) is found in the Miocene portion of the section where the Pleistocene and Miocene are in contact. *Nonion mediocostatus* is absent from the Yorktown formation fauna, but is present in the underlying St. Mary's, Choptank, and Calvert formation of Virginia and Maryland.

With the exception of boring number 5, *Nonion mediocostatus* is either associated with *Bulimina gracilis* Cushman and with *Nonion*

Where lithological criteria are obscure, this "zone" offers the surest and easiest criterion upon which to base the Pleistocene-Miocene contact. The zone is further characterized by the fact that it can be readily traced as a well-defined unit, having decided thickness and boundary characteristics. It should prove of considerable assistance in bringing the lithologic units into alignment in the area under discussion, if used as a "key" or "marker" zone. [Contact zones in the four borings are given in table 1.]

Because the Calvert formation can be easily determined from the pyritized Calvertian faunas, characterized by their larger forms and distinctive species, the only question concerning the *Nonion mediocostatus*-*Bulimina gracilis* zone is that of assigning it to either the St. Mary's or the Choptank formation. As of the present this will be difficult, in that species restricted to either formation have not been recognized. The ranges of the forms in this zone are either

⁶ Lithologic descriptions for these core samples are entered as boring logs elsewhere (Harrison, 1962). These descriptions have provided the control required for interpreting subbottom profiling records as well as for constructing cross sections showing the Miocene-Pleistocene contact.

greater than the two formations, or at least the forms persist throughout both formations. Paleontologically, therefore, one still must determine *what* Miocene formation may be at the Pleistocene-Miocene contact locally, but the fact and position of that contact can be demonstrated easily.

Bulimina gracilis, *Nonion mediocostatus*, and *Nonion pizarrensis* have not been found in the section here called Pleistocene, but one or more of these forms could possibly be found in the seaward extension of the Pleistocene; *Nonion mediocostatus* and *Bulimina gracilis* are thought to have become extinct before the Pleistocene; *Nonion pizarrensis*, however, exists in present oceans.

In boring 5 (see figs. 1 and 5), the break between the Pleistocene and Miocene is best placed at 85 feet below mean low water (MLW). Between -80 feet and -85 feet is a bed of coarse sand and gravel; between -85 feet and -110 feet, in sandy to clayey silt, is a prolific fauna including echinoid spines and dominated by *Nonion pizarrensis*. Between -110 feet and -205 feet is a barren gray clay, while from -205 to -220 feet the *Bulimina gracilis*-*Nonion mediocostatus* zone is again found. With the exception of the barren zone just mentioned, these two faunal zones are found also in the boring for the Coleman Bridge at Yorktown (see fig. 4), where they have been assigned to the Miocene section.

B. EVIDENCE FROM CONSOLIDATION TESTS

A significant difference between the Miocene and post-Miocene sediments is that the Miocene sediments are overconsolidated, while the Pleistocene sediments are normally consolidated. "Overconsolidated" sediments have been stressed to a greater extent than would be expected from the weight of the overlying sediments. The specific consolidation states of these sediments are revealed by results of standard laboratory consolidation tests (cf. Harrison, 1958). Miocene sediments are overconsolidated (fig. 2) to depths of at least 200 feet below MLW in the Norfolk area. Where the post-Miocene sediments are slightly overconsolidated (fig. 2), there is evidence that over-

lying bay-bottom muds have been scoured (Harrison, Lynch, and Altschaeffl, 1964) or dredged because present sediment cover could not have produced the stress indicated by the consolidation tests. That the Miocene sediments above -200 feet are overconsolidated is shown especially well by the con-

FIG. 2.—Degree of overconsolidation of sediments of Miocene and post-Miocene age as a function of depth below MLW. All values from Chesapeake Bay crossing.

solidation data for borings A1 and A2 located in figures 1 and 7.⁷ Thus, where consolidation-test data are available and the top of the Miocene can be determined (as with borings A1 and A2), it is found that the post-Miocene sediments are normally consolidated and the Miocene sediments are

⁷ McLean's lithologic logs for these two borings are given elsewhere (Harrison, 1962).

overconsolidated. This criterion, therefore, may be applied confidently to more extensive regions.

C. PROBABLE DESICCATED ZONE

One of several possible explanations for the overconsolidation of the Miocene formations (fig. 2), which stands out above all others, is the probability that the water table beneath the surface of the Miocene sediments fell some distance during lowered Pleistocene sea level and the sediments above the water table then became overconsolidated by drying stresses. Rominger and Rutledge (1952) pointed out that the effect of drying at a land surface is a compaction of surface silts and clays, and that this compaction is reflected in the preconsolidation-stress values. The trend toward greater discrepancies in the preconsolidation-pressure-effective-stress values in the direction of the surface of the Miocene formations (fig. 2) suggests the drying effect. The magnitudes of the discrepancies (up to 7.6 tons/ft²) are similar to those reported from other localities (Tschebotarioff, 1951, p. 103) for clays overconsolidated by drying.

Because some of the consolidation-test values (fig. 2) are for samples taken well below the lowest inferred water-table position, their overconsolidation may be explained in another way. The sediments below the lowered water table very likely became overconsolidated as a result of the increased weight (stress) of the sediments above the water table, when their constituent grains became uncompensated for by buoyancy. A thickness of sediment above the water table exerts a larger effective stress on sediment below the water table than it would if it were submerged. Buoyancy reduces the magnitude of the effective stress, and it is effective stress that causes the volume reduction or consolidation. The two effects of a lowered water table are impossible to separate, however, because reliable data on the amount of lowering of the water table are lacking.

D. POSSIBLE WEATHERING PROFILE

In a very small percentage of the engineers' bore-logs studied, "rotten" or "decomposed" shells are reported at depths that coincide with the uppermost Miocene sediments. Again, some logs mention a color change to "brownish" (oxidized?) sand and silt layers of Miocene age that occur a few feet below the erosion surface. Reports of limy concretions, at depths of about -120 to -160 feet and a few feet below the Pleistocene erosion surface, are similarly not uncommon. Because all these features are common criteria suggesting a weathering profile at the surface of the Miocene formations, the clay mineralogy of the samples of core A1 (fig. 1) was studied to determine if weathering might be reflected in the mineralogy.

Each of twenty samples was run according to the following procedure: A sample was ground, passed through a 140-mesh sieve, suspended in 20 ml. distilled water, and allowed to settle for 1 hour. Two ml. of the remaining suspension were then siphoned off from a depth of 3 cm. The suspension was placed on a glass slide and air-dried; slides were run on the X-ray unit; slides were then placed in a desiccator over a glycol bath for 24 hours; slides were rerun on the X-ray; slides were then heated for 1 hour at 200° C. and rerun on the X-ray. (The analyses were made by J. L. Harrison, clay mineralogist, Indiana Geological Survey.) Results of the analyses are shown graphically in figure 3.

The progressive degradation of chlorite and illite between the sample at the -113-foot altitude and that at the top of the Miocene and the corresponding increase in mixed-layer minerals might suggest a weathering profile. Harrison and Murray (1959, p. 145) examined the clay mineralogy of several weathering profiles and found that significant changes in the clay minerals occur as the degree of weathering increases; chlorite and illite break down, with the corresponding formation of mixed-layer material. The mixed-layer clays thus contain the parent clays plus expandable components, as shown

by the changes taking place during heating and glycolating. But the parent clays in the Miocene sediments are probably composed mainly of detrital clay minerals derived largely from subaerial weathering profiles. The samples analyzed at depths below —113 feet (fig. 3), for example, most certainly indicate the variability of the parent clays. Thus the results are inconclusive because detrital, degraded clay minerals are undoubtedly randomly intermixed with detrital, crystalline clay minerals. An expected weak weathering profile developed upon such parent clays would be difficult to discern, therefore, especially in a series of such widely spaced samples. It is concluded

that clay minerals here are not diagnostic for identifying a weathering profile and therefore are not applicable to distinguishing the erosion surface.

E. GEOPHYSICAL WORK

It appeared promising to utilize the high acoustic-impedance contrast resulting from the overconsolidation of the Miocene sediments (up to 7.6 tons/ft²) to map the Miocene-Pleistocene contact by using a sub-bottom echo profiler to record the subbottom reflections in the area. Beckmann *et al.* (1960) had earlier reported considerable success in mapping the same areas with such a device. A comparison of their records with

FIG. 3.—Clay-mineral composition of boring A1

our stratigraphic analysis (Harrison and Malloy, 1963) indicated that the Miocene-Pleistocene contact provided a good reflector in the vicinity of borings A1 and A2 (see fig. 7), where geological control was unquestioned.

The U.S. Coast and Geodetic Survey's Geological Echo Profiler (GEP), employed in the present study, was used aboard the vessels "R/V Langley" and "R/V Pathfinder" of the Virginia Institute of Marine Science. The GEP is essentially a modification of the "sparker" profiler developed by Knott and Hersey (1956), providing continuous reflection records from subsurface units exhibiting some degree of acoustical impedance. The instruments and techniques employed for the subbottom echo-profiling were similar to those used in routine echosounding except that a more intense, lower-frequency energy burst was used. An electric spark from a 100-J power supply was discharged into the water to produce a high-level, short-duration pulse with maximum energy concentrated between 200 and 600 cps. Repeated outgoing spark-discharge explosions were synchronized with outgoing vertical scans of a variable-density recorder. Echoes returning from the bay floor and from subbottom acoustic interfaces were detected by a hydrophone array and recorded as a vertical cross section (see fig. 10) of the subbottom geologic structure beneath the track of the ship.

The GEP traverses of figure 4 tie in with borehole sections showing the Miocene-Pleistocene contact at the Hampton Roads tunnel (see fig. 6), the Chesapeake Bay crossing (see fig. 7), and the York River Bridge section at Yorktown (see fig. 8). Although most of the actual GEP traces are not reproduced here, the maximum depths to the erosion surface are shown in figure 4, as recorded.

Subbottom echograms from the vicinity of Fisherman Island (the assumed axial position of the ancient valley of the Susquehanna) and the area between about mid-Chesapeake Bay and the York River entrance (fig. 4) were discontinuous, probably

because of patches of gas, sand, and gravel in the shoals. No buried stream channels as deep as -370 feet could be observed in these traces, as had been reported earlier by Beckmann *et al.* (1960).

F. INTERPRETATION OF BURIED STREAM VALLEYS

When the consolidation-test, paleontological, and geophysical data are combined, the information along the three bridge and tunnel projects is sufficiently complete and accurate to permit construction of cross sections that show the general characteristics of the buried Pleistocene erosion surface. These cross sections appear in figures 5-8. Their spatial relationships are shown in figure 1. Each cross section lends support to the interpretations that follow.

Cross section 1 (fig. 5) shows that the valley of the Pleistocene Elizabeth River bottomed at approximately 100 feet below MLW. Control across this buried channel is adequate, but the steep rise from the lowland to the northeast bank (fig. 5) is difficult to explain, unless it might be related to deformation (cf. later section on possible uplift).

Cross section 2 (fig. 6) indicates that the position of the channel of the Pleistocene James River is just north of Fort Wool Island. Its maximum depth is believed to be close to 155 feet below MLW here, as suggested by the occurrence of coarse valley-floor sediments at the bottom of the borings that did not penetrate Miocene sediments.

Cross section 3 (fig. 7) shows the presence of several buried valleys. The valley that bottoms at -160 feet just off the southwestern shore of Fisherman Island is almost certainly the valley of the Pleistocene Susquehanna. A preliminary conclusion based only on tentative interpretations of engineering boring records suggested that the channel might bottom at about -350 feet. However, information now available from both the GEP and SDR traverses, and from more closely spaced pile-driving records, indicates that cross section 3 accurately represents the buried stream valley. The

FIG. 4.—Chart of area of investigation showing traverses made with GEP and indicating depth to Miocene surface at selected points over water (GEP records) and on land (well logs).

FIG. 5.—Map showing boring locations, Elizabeth River Tunnel no. 2, and cross section 1 showing Pleistocene erosion surface on buried Miocene formations.

FIG. 6.—Map showing boring locations and GEP traverses, Hampton Roads Bridge Tunnel, and cross section 2 showing Pleistocene erosion surface on buried Miocene formations.

Fig. 7.—Map showing boring locations and GEP traverses, Chesapeake Bay Highway crossing, and cross section 3 showing Pleistocene erosion surface on buried Miocene formations (*horizontal ruling*). Stippled zone indicates post-Miocene sediment cover, and heavy dashed line indicates strong-echo, subbottom reflecting horizon in the Miocene.

less deep valley which bottoms at -130 feet near Chesapeake Beach (fig. 7) seems to be an extension of the Pleistocene James.

Another buried valley that occurs on the north side of the divide on the Miocene surface beneath Thimble Shoals channel (fig. 7) appears in plan view in figure 9. Depths to the Miocene surface were here determined by lithological evidence and pile-driving records. This minor valley opens to the NNE, and may make connection with the buried valley of the Pleistocene Susquehanna (fig. 7).

greater significance than the demonstrated high position of the top of the Miocene near the cross sections of figure 10 was the bed of sand and shells (some 35 feet thick), which could be clearly correlated between the two wells mentioned above, that was picked up by GEP as a prominent reflector in the subbottom. The top of this bed occurs at about 185 feet below MLW in well logs and it appears on both subbottom traces (fig. 10) at a depth equivalent to about 0.07 sec. of outgoing and return signal travel time. (This is very nearly the corrected interface

FIG. 8.—Cross section at York River (modified from Hack, 1957) showing erosion surface on buried Miocene formations. See fig. 4 for location of GEP traverses in the York River.

Three echograms off Cape Charles City (see fig. 4) delineate the Miocene-Pleistocene contact in the vicinity of the buried valley of the Pleistocene Susquehanna (fig. 10). Thalweg depth at $A-A'$ is -158 , at $B-B'$ is -158 , and south of $B-B'$ is -168 feet (fig. 4). Reflection profiles were tied to well-log controls at Cape Charles City (see, e.g., Sinnott and Tibbitts, 1955, no. 39, p. 34) whose strata could be correlated with a nearby U.S. Geological Survey test hole (Sinnott and Tibbitts, 1957, p. 9, well 5) where paleontological data were available. The top of the Miocene in the test hole was encountered at 42 feet below MSL. Of even

depth of -185 feet.) We confidently accept this reflector as a continuous reflector in the Miocene sediments; its top coincides with the Pleistocene erosion surface in the vicinity of sections $A-A'$ and $B-B'$ (see fig. 4). The significant fact here is that the reflecting horizon is persistent throughout this northern part of the study area. At no place where sound penetrated to this depth, as in the places between Cape Charles and Yorktown (fig. 4), was the horizon absent. Apparently, then, no Pleistocene river valley was cut into the Miocene surface below -185 feet, from Cape Charles City on the east to the York River on the west.

Assuming the validity of the inference that the valley of the Pleistocene Susquehanna does not occur to the west of its postulated position just off Cape Charles City (see fig. 13 below), it is appropriate to consider now whether the valley could or could not occur to the east of Cape Charles City. Reference to the well logs reported in Sinnott and Tibbitts (1955, p. 21–37, nos. 24, 28, 31, 35, 39, 58, 61, 65, and U.S.G.S. test hole 1) permits a confident interpretation based on reported drilling encounters with marl and shell beds. These well logs all indi-

cate that the top of the Miocene to the east is well above the maximum depth values found in GEP traverse *A–A'* and *B–B'* (see fig. 4), and the logs appear to adequately cover the area of the eastern shore from 5 miles north of Cape Charles City to Cape Charles (fig. 4). It thus appears quite improbable that the Pleistocene Susquehanna could have cut under what is now the eastern shore peninsula of Virginia, to the east of the position postulated here (see fig. 13 below).

It is concluded, therefore, that the valley

FIG. 9.—Contour map of buried subaerial erosion surface on Miocene sediments. Located below North Island, at Thimble Shoals Channel, Chesapeake Bay Highway crossing. Boring locations: X, peat present; ●, peat absent; ■, C^{14} date; 5-foot contour interval (in feet below MLW).

of the ancestral Susquehanna follows the deepest depressions of the Chesapeake Bay bottom, leading continuously from the Bay entrance to Annapolis, where the critical cross section shows that the valley bottoms at 200 feet below MLW (see fig. 13 below). It is difficult to imagine the deepest parts of the present Chesapeake Bay re-

flecting any character other than the ancient Susquehanna Valley, although perhaps other explanations may be possible.

The case against a valley leading eastward under the eastern shore may be fairly good, but the possibility cannot be completely discounted because of possible inadequate controls between Cape Charles and

FIG. 10.—Upper echogram shows buried valley of Pleistocene Susquehanna along traverse A'-A (fig. 4) off Cape Charles City, Virginia. A possible terrace surface is shown as dipping on a 1.5 per cent slope to the southwest and under the channel fill roughly perpendicular to the trend of the channel of the buried Susquehanna. Lower echogram shows buried valley of Pleistocene Susquehanna along traverse B'-B (fig. 4) off Cape Charles City, Virginia. The original echogram from which this figure was made may be obtained from R. J. Malloy.

Annapolis. Other studies have clearly indicated that control wells of as little as 1-mile spacing might have easily missed similarly sized channels (Fisk, 1959; Rusnak, 1960). It is well to note also that several large canyons, such as the Norfolk, Washington, and Baltimore canyons, occur on the outer edges of the continental-shelf areas east of their geographic namesakes. Little is known about the source and age of the possible ancestral tributaries leading to these canyons, if there were such tributaries. Therefore, we can only accept the strongest suggestion (lacking evidence to the contrary) and postulate that the ancient Susquehanna Valley followed the approximate axis of the deepest depressions in the Bay bottom during the last glacio-eustatic low in sea level. Other evidence shows that the previous gradient could have been reversed by uplift at the Chesapeake Bay entrance.

III. NATURE OF OVERLYING PLEISTOCENE SEDIMENTS

A. LITHOLOGICAL AND FAUNAL CHARACTERISTICS

Characteristically, the sediments overlying the erosion surface are unconsolidated sands, silts, and clays of Pleistocene to Recent age. The color of these sediments is "gray," "brown," or (rarely) "blue" in drillers' logs. They are usually coarser than the "clayey silts" or "silty clays" of the Miocene, are more often devoid of shells, but often contain abundant plant debris. Sediments of the Pleistocene section are in general quite similar to the estuarine sediments of Recent age described from lower Chesapeake Bay by Harrison *et al.* (1964). The following notes were supplied by James D. McLean, Jr:

Lithologically, the Pleistocene sections vary considerably, and individual beds undoubtedly pinch out rapidly along any given section. The sparseness of the microfossil records, their rather nondescript faunal characteristics and lack of key species all combine to make paleontological correlation rather dubious at best.

Boring no. 11 [fig. 1] possesses the best faunal sample so far found; certain species are suffi-

ciently well-preserved to offer hope of identification or naming of new species. Paucity of Pleistocene faunas in the Atlantic region, coupled with the fact that the assemblage of boring 11 does not seem to relate to any described assemblage in Atlantic Pleistocene beds (or Pliocene, for that matter), combine to make any definite conclusions difficult at present.

All Pleistocene faunas definitely indicate a shallow water ecology, characterized by the presence of *Elphidium*, *Nonion*, several genera of Ostracoda, a number of species of which, in our collections, are limited to one specimen each. A number of the Ostracods and single-specimen foraminiferal forms appear to be redepositional. Planktonic forms are absent.

The geologic section of boring 11 and the Coleman Bridge sections at Yorktown [figs. 4 and 8] further contain wood or lignite fragments; both wood and microfossils sometimes occupy the same sample, a further indication of brackish, shallow-water environments. This conclusion is further aided by the bad state of preservation of microfossil and macrofossil specimens, as well as by several graviliferous beds. Many Pleistocene intervals are completely devoid of any fossil material; a good many of the fossiliferous beds seem to indicate redepositional rather than *in-situ* occurrences of the fossil fragments and (or) specimens.

Except in the case of the well-preserved fauna in boring 11, there is no evidence that any of the section is oceanic; it appears that a considerable portion of the section is brackish water and a small portion even continental in nature.

In support of the brackish-water or continental interpretation of McLean are the vertebrate remains of land animals that were recovered from the Pleistocene sediments during boring and dredging operations for the Chesapeake Bay crossing. Of interest also were the fragments of turtle bone (identified by J. Ostrom of Yale University, written communication, 1962) and associated charred wood recovered from a bucket dredge at the site of the trench for the highway tunnel beneath the Baltimore channel (see fig. 7).

B. PLANT REMAINS AND C¹⁴ AGES

In the ninety-eight borings for the Chesapeake Bay highway crossing (see fig. 7), two concentrations of "peat" and "plant fibers"

are revealed. One concentration is between 38 and 45 feet below MLW (10 borings) and the other is between 85 and 100 feet below MLW (14 borings); that is, just slightly above the erosion surface. Such deposits occur at various intermediate altitudes in only five of the ninety-eight borings. Peat accumulations at approximately 42 and 93 feet below MLW probably record former swampy conditions in the region of the present entrance to Chesapeake Bay. The accumulations were induced in all probability during ponding by the generally transgressing Pleistocene sea, after about 15,000 years

1962, p. 60) west of Norfolk (fig. 1), for example, penetrated wood at 30 feet below MLW. A sample of the wood was submitted to the Geochronometric Laboratory at Yale University, where it was identified as *Taxodium*, and dated (table 2) at >50,000 years B.P. (Y-1047). The presence of wood at a depth of 30 feet below MLW is not unusual here. Below much of the land portion of the Norfolk area, wood fragments, "peat," "organic silt," or "humus" are sometimes encountered at this approximate depth. For example, in 9 of 105 borings at various places beneath the Little Creek

TABLE 2
RADIOCARBON DATES FROM CHESAPEAKE BAY ENTRANCE

Laboratory No.	Material	Present Altitude (MLW)	Precompaction Altitude (MLW) (estimated)	C ¹⁴ Age* (Years B.P.)
Y-924.....	Stump	0		730 ± 70
Y-1047.....	Wood	-30		>50,000
ML-89.....	Peat	-85	-75	11,590 ± 150
ML-90.....	Peat	-82	-73	10,340 ± 130
ML-91.....	Peat	-89	-80	15,280 ± 200
ML-117.....	Shell	+ 4		1,905 ± 75
ML-121.....	Peat	+ 5	+ 5.5	1,170 ± 80
ML-153.....	Log	-75		10,110 ± 105
ML-195.....	Wood fragments	-72		9,750 ± 140
ML-196.....	Shell	-70		8,135 ± 160

* All ML-dates have been corrected here to account for the age discrepancy noted by Ostlund, Bowman, and Rusnak (1965) in the ML-series reported earlier by them. (See *Radiocarbon*, v. 7, 1965, for correction note.)

B.P. This age interpretation is supported by the palynological investigation and C¹⁴ dates of borings B3 and M28 (figs. 9, 11, and 12) given below, and additionally by a C¹⁴ determination of 10,110 ± 105 years B.P. (ML-153A) made on a log⁸ recovered by bucket dredge from -75 feet in the trench for the Baltimore Channel tunnel (table 2 and fig. 7).

Wood and "humus" occurrences beneath the land portion of the Norfolk area (see fig. 1) at an approximate mean depth of 33 feet below MLW are all believed older than 50,000 years (see, e.g., Oaks and Coch, 1963). An engineering boring C₁ (Harrison,

Naval Amphibious Base, "humus" was encountered at a depth of 22-48 feet below MLW. The mean depth was -32 feet. Oaks and Coch (1963) report that wood in peat, from their Sandbridge formation near the coast and south of Virginia Beach, dates at >40,000 years B.P. The base of this formation in the area is approximately 25 feet below MLW (R. Q. Oaks, Jr., written communication, 1964).

Seven samples from boring B3 (fig. 9) and nine samples from boring M28 were examined for pollen and spores, and results of the investigation have been compiled in two pollen diagrams (figs. 11 and 12).

Hydrofluoric acid and acetolysis (the Erdtman method) were used in chemical

⁸ Log contributed to this study by Dr. Bruce Nelson.

FIG. 11.—Pollen diagram, boring B3 (fig. 9), Chesapeake Bay Highway crossing

preparation of samples. All samples were found to contain inorganic matter, indicating that sedimentation probably occurred in brackish-water or alluvial flood-plain environments. Redeposition of pollen, which might be expected because of the nature of the sediments, appears to be either absent or, at any rate, not present in significant amounts. In general, it was noted that the pollen and spores found were poorly preserved and sometimes contained small, dark particles inside the pollen exines, making examination and identification rather difficult. This condition was particularly noted in samples above the peat layers, and, as these contaminants are often seen in pollen from marine or brackish-water sediments, they lend support to the presumed near sea-level control of peat deposition (D. R. Whitehead, written communication, 1963).

Correlation between the two borings can be established on the basis of palynological evidence. Owing to the rather wide spacing of available samples, the bar diagram has been used to illustrate frequencies. It is possible that a smaller sampling interval in these cores might have revealed additional changes of significance in the pollen sequence. There are, however, certain major trends present which allow correlation with other pollen diagrams of dated postglacial deposits in New Jersey as well as in the Dismal Swamp.

Because of the high content of oak pollen, the sample level 10 D in borehole M28 (fig. 12) probably corresponds to sample level 5 DA in borehole B3 (fig. 11). Closer sampling would probably provide a more precise correlation, but the approximate one suggested here is supported by the radiocarbon dates obtained. There is some minor variance in sediment types and deposition rates between the cores studied. However, this does not present any serious difficulties for correlation. A comparison of the two pollen diagrams shows that the basal assemblage in B3 is probably older than the radiocarbon-dated level 13 D ($15,280 \pm 200$ years B.P., ML-91) in borehole M28. In an adjacent boring M27 (fig. 10), diatoms and oys-

ter-shell fragments were separated from a sample of olive-gray clayey silt taken 70 feet below MLW. Numerous frustules of pinnate diatom forms were observed (R. A. Mulford, oral communication, 1963), of which the majority have been reported as characterizing brackish waters of less than 20‰ salinity. The diatoms suggest that the materials of the sample were deposited in shallow estuarine waters and this interpretation is strengthened by the presence of the oyster (*Crassostrea*) shell fragments. A C^{14} date on one of these shell fragments (ML-196) from -70 feet yielded the value of $8,135 \pm 160$ years B.P.

An interesting correlation of the upper portions of the sections in figures 11 and 12 is possible with the dated pollen sequence from the Dismal Swamp, reported by Oaks and Coch (1963), and studied by Whitehead. "The *Tsuga* maximum of samples 8U and 9D (M28) and sample 5DA (B3) is, on this basis, certainly older than 7,670 years B.P., and probably on the order of 8,700. Similarly, sample 5D (M28) would probably be on the order of 7,000 years B.P. (possibly a trifle older)" (D. R. Whitehead, written communication, 1963).

The development of vegetation as implied from a study of the pollen diagrams reveals some interesting trends. In late Wisconsin time, some 15,000 years ago, the vegetation in the Chesapeake Bay area was composed of coniferous species (*Picea*, *Pinus*, *Abies*) with birch (*Betula*) and alder (*Alnus*). The few hardwood, deciduous genera were represented by very small amounts of pollen, whereas the non-tree species may have been rather abundant locally. Beginning about 10,000 years ago several species of oak (*Quercus*) quite abruptly gained in abundance. This event was preceded, however, by an episode when spruce (*Picea*) pollen abundance decreased while pine (*Pinus*) pollen reached a maximum.

The initial increase in oak-pollen percentage seems to be followed shortly by a hemlock (*Tsuga*) maximum (or maximums), and later hickory (*Carya*) increased in abundance. It is interesting to note that pollen of

Chenopodiaceae is present only in the upper parts of the diagrams. This occurrence is assumed to indicate the approaching sea shore environment. The presence of Hystriochosperidae at these levels and the generally inorganic sediments overlying peat support this assumption.

A comparison of the two pollen diagrams with those from northern New Jersey (Potzger and Otto, 1943) shows good correlation and indicates that some of Potzger's pollen sequences may extend back in time some 15,000–16,000 years. Potzger's sites were all within the limits of the Wisconsin glaciation. Potzger found that in New Jersey the initial forest (in late Wisconsin time) was a pine-spruce association. Hemlock invaded jointly with broad-leaved genera after the peak control by pine. Potzger interpreted the increase in importance of hemlock as a marker of more abundant available moisture.

In a later study Potzger (1945) found that "all evidence however, very strongly suggests that the Pine Barren '(of New Jersey)' constituted a refugium during Pleistocene times, from which the post-Pleistocene wavelike segregation of associations originated." Potzger concluded that, at the height of the last glaciation, boreal coniferous species were mixed with southern deciduous genera south of the ice margin in New Jersey.

The present study indicates that boreal forest elements existed in some abundance south of the ice sheet at the height of glaciation in eastern North America (cf. Frey, 1951, 1952, 1953, 1955). The study area evidently was too far south of the ice margin to show any evidence of periglacial tundra vegetation.

IV. POSSIBLE UPLIFT AT CHESAPEAKE BAY ENTRANCE

A. EVIDENCE OF THALWEG GRADIENTS

It seems clear from the previous discussion that the well-defined erosion surface, buried beneath Pleistocene and Recent sediments, was formed during the Pleistocene and possibly Pliocene. It is equally clear

that glacially induced sea-level lowering during the Pleistocene caused marked erosion, deep-stream incision, and weathering of underlying late Miocene deposits. Various estimates (see, e.g., Donn, Farrand, and Ewing, 1962) indicate that maximum lowering of Pleistocene sea level approximated —450 feet, rather than the —300 feet often quoted. Given this degree of lowering, it is indeed surprising that the postulated downstream thalweg gradient of the ancestral Susquehanna proposed by Hack (1957) could not be recognized in the lower Chesapeake Bay.

Hack's logical extension of the thalweg gradient for 150 miles downstream indicated that the Susquehanna's channel should have bottomed at about —370 feet (Hack, 1957, fig. 6). Instead, buried channel depths near Chesapeake Bay entrance appear no deeper than —160 feet. A sharp turn to the east of the central (?) depression of Chesapeake Bay could have carried incised tributaries below what is now the eastern shore of Chesapeake Bay and over the continental shelf. This possibility has been rejected here on the basis of lack of evidence, although not without reservation because limited control of subsurface explorations could have precluded the finding of narrow channels. The suggestion is that the lower Chesapeake Bay has undergone upwarping on its coastal side, deforming a previously established gradient that sloped south to one sloping toward the west and north. Several lines of evidence seem to show that this inference is acceptable.

The information most suggestive of uplift in the region of Chesapeake Bay entrance comes from the gradient of the thalweg that coincides with the valley believed here to be that of the Pleistocene Susquehanna River. By definition, the thalweg ("talweg" of Hack, 1957) is the line connecting the lowest points on the bedrock surface (here Miocene sediments) of a stream bed. As shown in figure 13, the observed thalweg of the Susquehanna River is approximately 200 feet below MSL near Annapolis (Ryan, 1953, pl. 2; Hack, 1957, fig.

2). Because our data (see figs. 4, 6–9) indicate a maximum (corrected) depth of the thalweg of approximately –160 feet near Cape Charles (fig. 13), we can reasonably infer at least 40 feet of relative uplift between the two points (i.e., without an assumed gradient) since maximum thalweg development about 18,000 years ago. If we adopt Hack's (1957, fig. 6) inferred gradient for the thalweg of the Pleistocene Susquehanna, the amount of relative uplift would

approximate 170 feet. These relationships are summarized graphically in figure 14.

B. EVIDENCE FROM RADIOCARBON DATING

In recent years, the study of rate of sea-level rise has received abundant documentation for the period since about 18,000 years B.P. Shepard (1964, fig. 2) has recently summarized the available data to show within the limits of experimental error the former sea-level positions for the last 15,000

FIG. 13.—Thalweg depths of selected buried river valleys in lower Chesapeake Bay, with earthquake epicenters and proposed basement fracture (after Woollard, 1958).

years along the east coast of the United States. We have been able to demonstrate that the peat, wood, and marine shells that we were able to date from the area by radiocarbon most likely were deposited at or very near sea level (see sec. III on pollen and microfossils). However, if one compares these dated and apparent sea-level positions (as indicated by present burial depth of the deposits) with eustatic sea levels, indicated by curves from stable areas resolved with absolute dating techniques (Shepard, 1964), discrepancies exist. The discrepancies can be accounted for by crustal movements. The data are presented in figure 15, where our relative-sea-level curve is compared to Shepard's (1964) curve for eustatic sea level. (The relative-sea-level curve is plotted by using the altitudes of samples relative to present MLW, corrected where indicated for compaction.)

The available evidence suggests that the dated peats (table 2) at Chesapeake Bay entrance were deposited in a flood-plain environment. Assuming, then, that we are dealing with brackish-water peat deposits, and that peat deposition was controlled by a sea-level position only a few feet lower than the base of the peat horizon (Harrison and Rusnak, 1962; see also Stuiver and Dadario, 1963; Kaye and Barghoorn, 1964) and allowing for 9 feet of peat consolidation

after loading by overlying sediments, it would seem that relative sea level stood at about -80 feet some 15,280 years ago. (This compares well with a sea-level position of -100 feet in Maryland some 15,000 years ago [Shepard, 1964, fig. 2].)

Comparing this relative position of sea level with points on the eustatic sea-level curve for 15,280 years B.P. indicates (fig. 15) quite a disparity of sea-level altitudes. The positions on the relative-sea-level curve shown in figure 15 for the Chesapeake Bay peats have been adjusted upward (see table 2) to allow for an estimated 9 feet of post-burial lowering of each peat sample. Kaye and Barghoorn (1964) reviewed the mechanics of consolidation of peat and determined that the Boston Common peat that they investigated had been consolidated beneath

FIG. 14.—Graph showing two interpretations of the probable thalweg gradients of the buried valleys of lower Chesapeake Bay.

FIG. 15.—Sea-level and crustal-movement curves for the area of Chesapeake Bay entrance

the weight of an artificial overburden to one-fourth its original thickness. The percentage of inorganic detritus is larger in the peat samples of this study, while the loading is somewhat greater (but may be comparable) to that for the peats studied by Kaye and Barghoorn (1964, fig. 1). The reconstructed altitudes (table 2) of the peat samples dated in this study were arrived at using expansion ratios slightly less than 4 to 1, based upon consideration of the percentages of inorganic materials admixed with these peats.

The eustatic sea-level curve for supposedly stable areas (Shepard, 1964) falls well below that exhibited (fig. 15) by the Chesapeake Bay peats. Assuming, then, that all the dated peats of figure 10 were deposited only slightly above prevailing sea levels and that Shepard's curve portrays true eustatic sea levels, it would seem that the Chesapeake Bay entrance peats have been uplifted a maximum of some 160 feet since 15,280 years B.P. This is indicated by the crustal-movement curve (fig. 15), constructed after the method of Kaye and Barghoorn (1964), that shows the crust to be 160 feet below present MLW some 15,000 years B.P.

Clearly, assuming that all these peats were deposited only a few feet above sea level in a valley whose drainage was ponded, it can be said that crustal uplift almost kept pace with the rate of eustatic sea-level rise of 2.8 feet/century (Shepard, 1964) for an interval of from at least 15,000 years B.P. to about 8,000 years B.P. (fig. 15). Alternatives that might be considered to the assumption of peat deposition near sea level have been suggested to us by Hack. The peats might have been formed at substantial elevations above the prevailing sea level as a result of deposition in ponds behind beaver dams (Kaye, 1962) or somewhat above sea level by deposition along the lower reaches of streams like the modern Zekiah Swamp Run, in Maryland (Hack, 1957). In the absence of remains of beaver-cut wood or any wood of the type used by beavers and in view of the necessity of a relatively steep gradient of the stream (fig. 10), implied in

the assumption of high-level peat deposition, these alternatives must await further testing.

The crustal-movement curve of figure 15 has been plotted (relative to MLW) by algebraic subtraction of the relative-sea-level curve from the eustatic curve. It indicates that the crust in the area may have stood 20 feet higher than its present position, about 6,000 years B.P. Subsidence apparently then took place until about 2,000 years B.P.

Additional information from the radio-carbon dating of materials of relatively recent age suggests that crustal uplift resumed around 2,000 years B.P. and may have continued to the present. The additional uplift evidence from the area comes from a seaward-facing outcrop of peat and mollusk shells on Hog Island (see fig. 4), one of the barrier islands of Virginia's eastern shore. We believe that this exposure represents crustal uplift since 2,000 years B.P. and not a higher stand of eustatic sea level (Fairbridge, 1961). The top of the peat bed in this exposure is about 5 feet *above* present MLW, or 3 feet above MHW (fig. 16). The peat appears to represent a former marsh environment on the lagoonal side of the barrier island, indicating that the peat was deposited on the shells at about high-tide position. A sample of this peat dated at $1,170 \pm 80$ years B.P. (ML-121). The underlying, laterally extensive shell bed contains an open-bay assemblage (*Mercenaria*, *Crassostrea*) from which a *Mercenaria mercenaria campechiensis* shell was extracted. This shell dated at $1,905 \pm 75$ years B.P. (ML-117; see Rusnak, Bowman, and Östlund, 1963, for further details of these dates).

As the clam- and oyster-shell assemblage is of a type whose depth range does not exceed a maximum depth of 20 feet (J. D. Andrews, oral communication, 1963), and as the peat is a type that grows at or slightly above the high-tide level, there seem to be reasonable indications here of maximum apparent uplift of between 5 feet (in the last 1,170 years) and as much as 25 feet (in the

last 1,900 years). Also indicated is a higher *relative* sea level, of up to 8 feet or so above present MLW (fig. 15), between about 1,500 and 2,000 years B.P.

V. INTERPRETATIONS

A. AREA OF POSSIBLE UPLIFT

Jordan's (1961) study of bottom erosion and deposition in the vicinity of the mouth of the Choptank River, Maryland, involved detailed comparisons of hydrographic surveys made at a 100-year interval. He noted (p. 8) that "the inferred 1-foot rise in sea-level since the original survey is not apparent from the comparison of soundings.

and Lyon, 1963). Death of the pine could have been due to burial by a retreating barrier beach or to rising salt water, but subsequent *preservation* of the stump is here attributed to periodic salt-water immersion by the tide. A C^{14} age determination (Y-924) indicated the stump to be 730 ± 70 years old, which is about 2,500 years younger than the New England stumps exposed at low tide. The stump base is now some 3.5 feet below MHW and the inference is that there has been at least 3.5–4 feet (and in Harrison's opinion no more than 6 feet) of submergence at the site in the last 730 years (see also Oaks and Coch, 1963). This indi-

FIG. 16.—Relationships at the Hog Island, Virginia, exposure

Extensive shallow and deep areas here and elsewhere in Chesapeake Bay appear to have remained essentially at the same depth during the last century." The implication here is that the crust in the area may be rising about as rapidly as sea level is rising (and ignores the alternate suggestions that a deposit of sediment 1 foot thick has accumulated in the last 100 years or that sea level has been essentially stable). The figure we would adopt from available information for the present-day rate of eustatic rise of sea level is 0.5 foot/century (see, e.g., Stuiver and Daddario, 1963).

In 1960, Harrison collected a sample of an *in situ* *Pinus* stump exposed along the shore several miles south of Virginia Beach (see fig. 1) at low tide, for a comparison with similar, dated stumps in New Hampshire (Harrison

and Lyon, 1963). Death of the pine could have been due to burial by a retreating barrier beach or to rising salt water, but subsequent *preservation* of the stump is here attributed to periodic salt-water immersion by the tide. A C^{14} age determination (Y-924) indicated the stump to be 730 ± 70 years old, which is about 2,500 years younger than the New England stumps exposed at low tide. The stump base is now some 3.5 feet below MHW and the inference is that there has been at least 3.5–4 feet (and in Harrison's opinion no more than 6 feet) of submergence at the site in the last 730 years (see also Oaks and Coch, 1963). This indi-

the Radiocarbon Dating Laboratory in Miami. Sample WC-1 (ML-191), from 9.2 to 9.5 feet below MHW, provided a date on the humic acid fraction of $2,530 \pm 90$ years. (Sample WC-1 did not have sufficient organic matter as peat for dating, but the humic acid fraction appears reliable when compared with the other samples analyzed.) Sample WC-3 (ML-193), from 15.0 to 15.6 feet below MHW, provided an age of $3,280 \pm 125$ years for the peaty material and an age of $3,460 \pm 120$ years for the humic acid fraction. Sample WC-4 (ML-194), from 23.4 to 23.8 feet below MHW, gave an age of $4,490 \pm 125$ years for the humic-acid fraction; the peaty material was of insufficient size for dating. All of these points fall above the Stuiver-Daddario eustatic curve and indicate that slight overall uplift at Wachapreague, Virginia, since about 2,600 years B.P. is a probability. These dated samples have been plotted on figure 15, relative to mean low water.

It would seem, then, that the crust has been rising as far to the north of the Virginia Capes as Wachapreague (fig. 13), during possibly the last 2,000–2,500 years. It is also possible that to the west, in the vicinity of Hampton Roads (see fig. 1), the amount of relative uplift has been less than that to the east. This difference in relative east-west uplift would be true if it could be shown that the thalweg of the Pleistocene James River at –155 feet at Hampton Roads (see fig. 6) leads into the depression in the Miocene surface at –130 feet off Chesapeake Beach (see fig. 7). Here would be evidence for differential uplift of 25 feet between the two points in the last 18,000 years. More specifically, however, geomorphological analysis of stream directions shows a definite tendency for the lower courses of southern tributaries, such as the James, York, and smaller reaches, to turn north. Similarly sharp changes in stream direction noted in the regions south of Norfolk suggest possible doming or elongated uplift of the crust, a few tens of miles wide, extending from the vicinity of the Virginia–North Carolina state line, subparallel to the

Atlantic coast, to at least Wachapreague, Virginia. The intensive erosion occurring at Cape Henry and along the Atlantic shoreline just mentioned is likewise strongly suggestive of active domal uplift, as along some sections of the Texas coast (especially well exhibited by the High Island dome.)

Finally, McLean (written communication, 1965) has found that the base of the Miocene St. Mary's formation in borings A1 and A2 (see fig. 1) is approximately 50 feet higher than in borings 5 and 11, indicating a *minimum* of 50 feet of differential uplift between Chesapeake Bay entrance and Hampton Roads (fig. 1).

B. MECHANISM OF APPARENT UPLIFT

The postulated uplift in the lower Chesapeake Bay area might correlate with Woollard's (1958, fig. 5) interpretation of differential movements along an arcuate fracture in the underlying basement rocks. The fracture was postulated from earthquake data as running northwesterly through Virginia's eastern shore. The western side of this fracture—including lower Chesapeake Bay and Hog Island—would be the upthrown side of the fracture. Woollard's postulated fracture is based upon his interpretation of the relation of earthquake epicenters (see fig. 13)—including those from the unpublished compilation by Reid based on newspaper reports—and tectonic elements in the United States.

Uplift has been suggested for the Norfolk–Fort Monroe (*Fort Monroe uplift*) area, an area that is considered to mark the southern edge of a structural embayment called the Salisbury embayment (Straley and Richards, 1948). Murray (1961, p. 43) suggests that the Fort Monroe uplift may reflect either faulting rather than simple uplift, or a combination of both.

Whether the uplift, if real, is regional or only local in nature, pulsating or continuous, is presently unclear. Apparently, it is local and has been continuous for the past 15,000 years. A consideration of the contour map of the basement-rock surface in the area, showing a slight nose beneath lower Chesa-

peake Bay (Murray, 1961, fig. 2.14), and of the regional gravity-anomaly map showing a right-angle, negative anomaly departure there from the NE-SW trend of the gravity-anomaly contours (Murray, 1961, fig. 2.15a), provides material in support of regional control but little specific evidence. The combination of observed features does indicate, however, that the structural character of the lower Chesapeake Bay area is sufficiently varied to include basement-controlled uplift as probable.

It is also to be noted here that the crustal-movement curve of figure 15 is remarkably similar to that shown by Kaye and Barghoorn (1964, fig. 5) for the Boston area, in the range 15,000–3,000 years B.P. The implication that there might be some fundamental tectonic control underlying both curves remains for further investigations. Age determinations for samples in the range 5,000–10,000 years B.P. are urgently needed for both areas.

VI. CONCLUSIONS

Geologic studies at three localities in the vicinity of Chesapeake Bay entrance provide evidence suggestive of overall crustal uplift since 15,000 years B.P. Because three independent lines of evidence all permit a similar interpretation, it appears probable that the general picture is a correct one. Details of the movement—such as the relative rates of uplift between localities, and the total extent and possible pulsating nature of the uplift—remain to be elucidated. In spite of these several necessary qualifications, however, it seems possible to make the following statements.

The crust in the immediate vicinity of the Virginia capes, and probably along the entire Atlantic coast of Virginia to somewhat north of Hog Island, has undergone some 160 feet of uplift since at least 15,000 years B.P. Uplift at Chesapeake Bay entrance seems to have been continuous at an average rate of about 2.8 feet/century between 15,000 and 8,000 years B.P. The crust stood possibly some 20 feet above the present MLW datum plane about 6,000 years

B.P. Between 6,000 and 2,000 years B.P. about 30 feet of crustal subsidence took place, allowing for extensive flooding of the Susquehanna lowland (Chesapeake Bay) and the present lagoon and marsh area of the eastern shore of Virginia. Crustal uplift appears to have resumed in the area about 2,000 years B.P. and probably continues at the present.

The crustal-movement curve of figure 15 shows interesting comparisons with similar crustal-movement findings of Kaye and Barghoorn (1964) for the Boston area during the period 15,000–3,000 years B.P. Testing of the curve in coastal areas to the north and south of Chesapeake Bay entrance should be undertaken, and additional work on the curves of figure 15 should be attempted.

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