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The Evolution of the Chesapeake Oyster Reef System During the Holocene Epoch

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Oyster Reef Habitat Restoration: A Synopsis and Synthesis of Approaches

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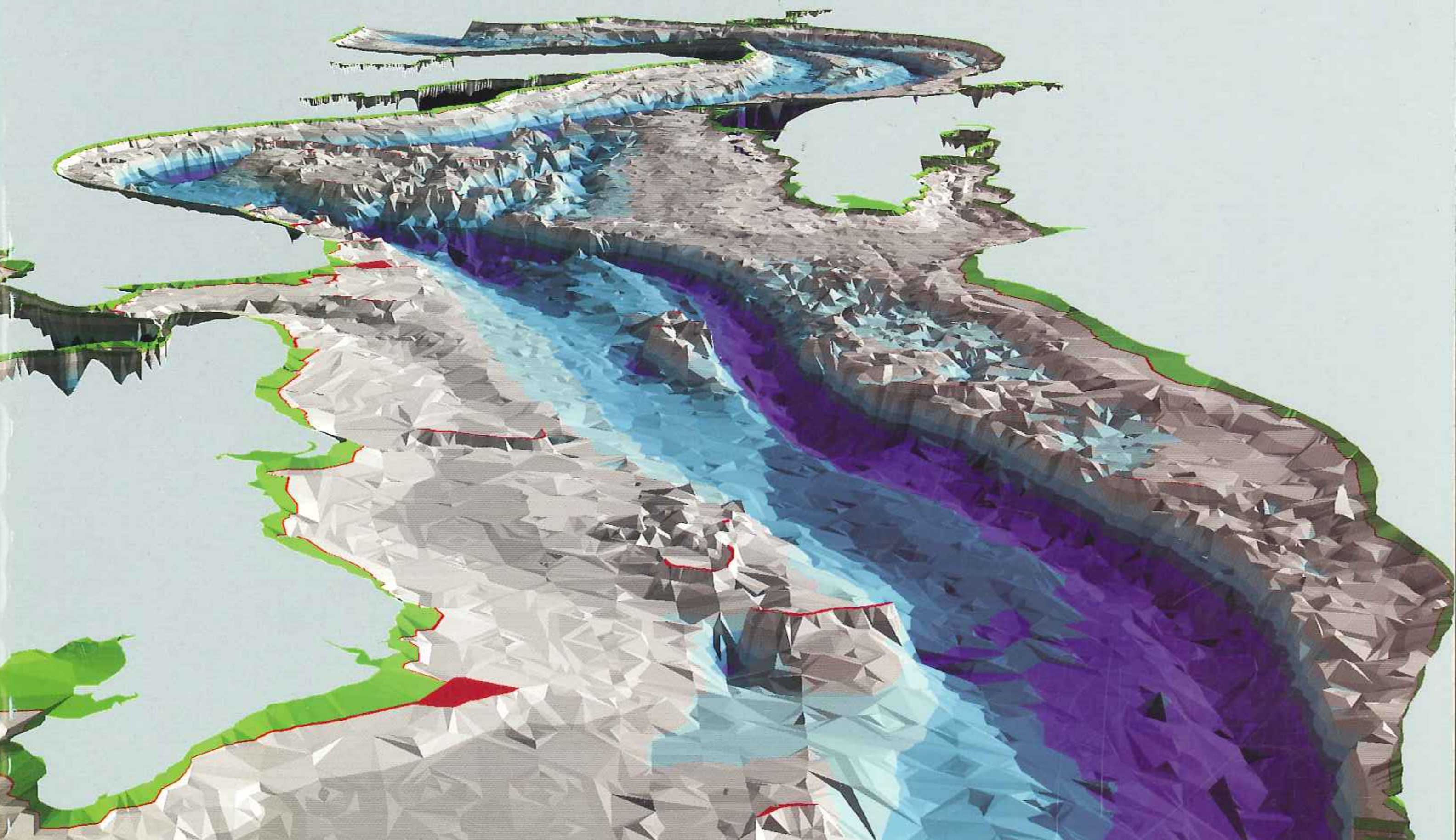

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Chapter 1

The Evolution of the Chesapeake Oyster Reef System During the Holocene Epoch

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Abstract

The oyster industries of Virginia and Maryland were based upon adult and juvenile oysters, and their shells, produced naturally on the reefs of the Chesapeake oyster reef system. Without those reefs the billions of bushels of live oysters and shells taken by humans could neither have been produced naturally nor harvested and the valuable social and economic activities derived therefrom would never have occurred.

The origin and development of the formerly massive, naturally self-renewing Chesapeake reef system were directly associated with the evolution of the Bay. Its destruction can be linked primarily to the increase of humans around the Bay and beyond and their demand for oysters and shells. Both phases, development and destruction, of reef history have occurred during the last three-quarters to two-thirds of the post-glacial Holocene period, around 7,000 years or less.

The current episode of global warming, begun about 18,000 years ago, sent melting ice cap waters seaward. Atlantic waters bearing ocean salts and oyster larvae rose erratically and, after a few significant retreats, advanced between the promontories now called the Virginia Capes into the developing Bay about 7,500 BP. By about 4,500 BP the Bay's head passed the latitude of Annapolis, reaching its present location about 2,500 BP. As larvae-bearing waters reached suitable sites, setting occurred on available cultch and reef formation began. Reef formation moved inland with advancing brackish waters until the reef system extended most of the length of the Chesapeake, about 160 nautical miles (296 km). On its sheltering reefs successive generations of colonial *Crassostrea virginica* struck, grew, reproduced and died leaving their progeny and shells behind and reefs and reef fields increased and expanded as did associated oyster populations.

When English colonists arrived in 1607 AD the reef system extended throughout the Bay and the estuarine portions of its tributaries and was self-maintaining. Nearly 200 years ago the Chesapeake oyster populations and their reef system began to shrink under pressures of increasing harvesting (and other man-affected factors such as increased sedimentation due to extensive deforestation and destructive agricultural practices). Today, destruction of the oyster's prime habitat in the Chesapeake, the natural, self-renewing upthrusting oyster reefs, is nearing completion. When they are gone it will have taken somewhat less than two centuries to destroy some 6,000 to 7,000 years of nature's works.

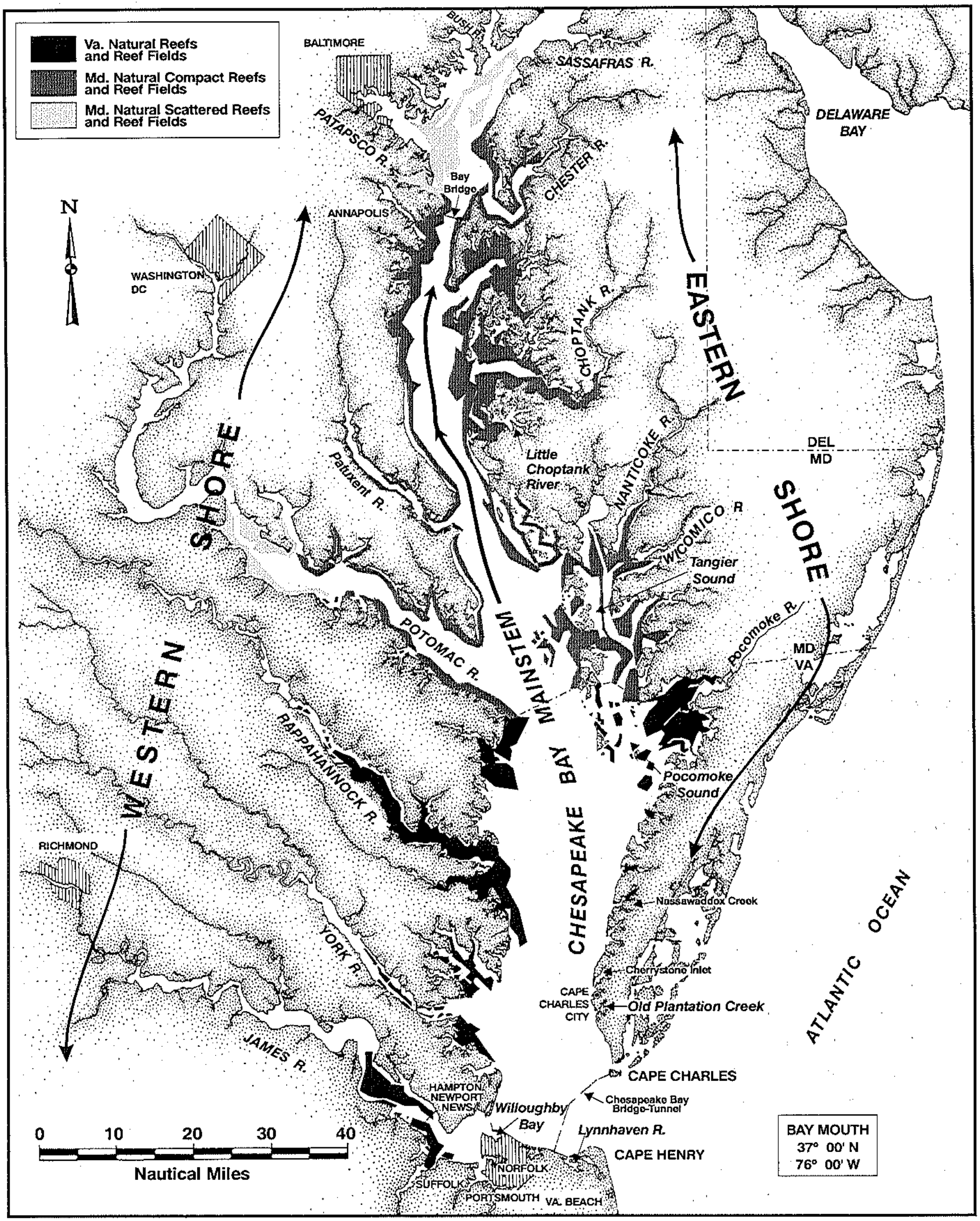


Figure 1. *The Chesapeake Oyster Reef System of the mainstem of the Bay and its tributary estuaries. A composite of the chart of Stevenson (1894), which depicted the reef system of Maryland (including the Potomac River and the mainstem of the upper Bay and its tributaries), and that of Baylor (1894) with later modifications, for Virginia's Chesapeake and tributary waters, this chart also identifies the principal tributaries of the Bay and the places mentioned in the text but not illustrated elsewhere.*

Introduction

Most oysters of the Chesapeake Bay have occurred in large colonial aggregations extending almost the entire lengths of its mainstem and of the estuarine portions of its tributaries (Figure 1). Chesapeake Bay oystermen have called these aggregations oyster beds, bars, banks, bottoms, shoals, and rocks. By these or any other names they are really reefs, as has long been recognized in waters of the South Atlantic states and those along the Gulf of Mexico (Chestnut 1974). Like those made by corals, oyster reefs were and their remnants still are important to the well-being and productivity of the colonial animals which established, formed, and maintained them.

In 1894, Stevenson, reporting on his study of the oyster industry of Maryland and the resources it depended upon, correctly identified the Chesapeake oyster rocks as reefs. He also established their importance to Bay oyster populations and charted their general extent and density in Maryland waters (upper portion of Figure 1). Further, he noted early warning signs of the decline of the reefs and their oysters and its bearing on the increasingly precarious future of the resource. J. W. Bailey, scientist at the Virginia Fisheries Laboratory (VFL), predecessor of the Virginia Institute of Marine Science (VIMS), referred to oyster rocks of the York River as reefs in 1940. Further, he reported a significant decline in the height of one York reef (Page's Rock) during the period between 1858 and the 1930s as indicated by comparisons of soundings reported on relevant charts of the U.S. Coast Survey (USCS) and its successor, U.S. Coast and Geodetic Survey (USCGS). This retrogression he attributed to harvesting (Bailey 1940). About 10 years later Nelson Marshall, second Director of the VFL, determined that the oyster bars of the James River seed area (Figures 1 and 2) had declined in height under pressures of harvesting and natural forces based upon comparison of soundings made in 1854-55 and 1871-73 by the USCS and in 1943-48 by its successor, the USCGS. He called the intertidal portions of these bars—oyster reefs (p 176, Marshall 1954). [Unfortunately, his restriction of the term reef to the intertidal parts of the oyster bars was too narrow. As with coral reefs the entire structure (biocoenose), submerged as well as intertidal, is "the oyster reef".] Recognition of the shrinkage of oyster reefs and their diminishing contribution to the welfare of oyster populations of the Chesapeake (and of the industry dependent thereon) prompted a review of their general histories during geological and recent times. The results of this study are reported herein.

I recognize two *basic* types of natural oyster reefs, *upthrusting reefs* (protruding upward from the bottom and *fringing reefs* extending outward from and usually attached to adjacent exposed coastal formations or shorelines.) The former usually occur in deeper estuarine and enclosed coastal waters such as the Chesapeake and Delaware bays, the mouth of the Hudson River, and Long Island Sound—especially "drowned" river valleys. The latter are usually found in

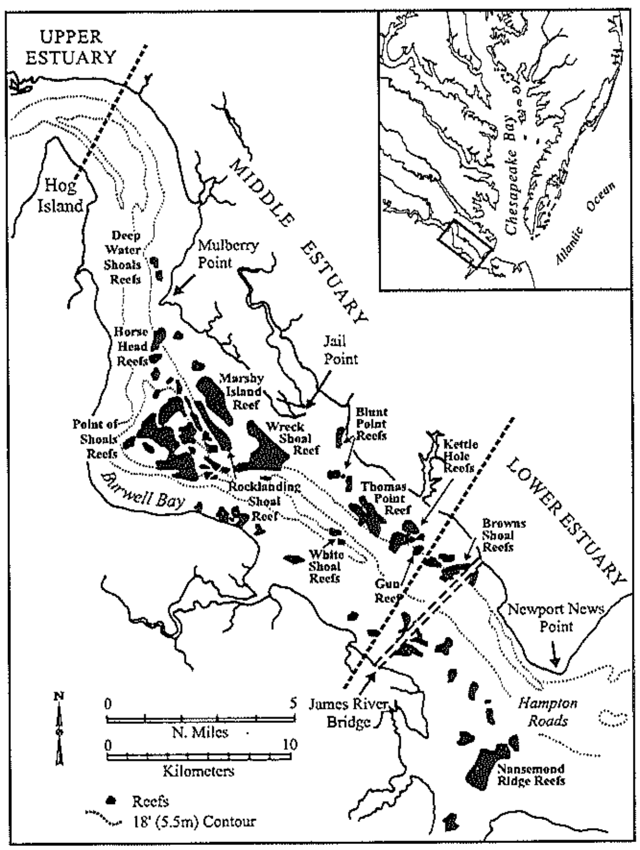


Figure 2. *Reefs and Reef Fields of the James River Estuary exclusive of those in Hampton Roads, as of 1878 and 1879 and later. (Names of of some reefs excluded for simplicity.)*

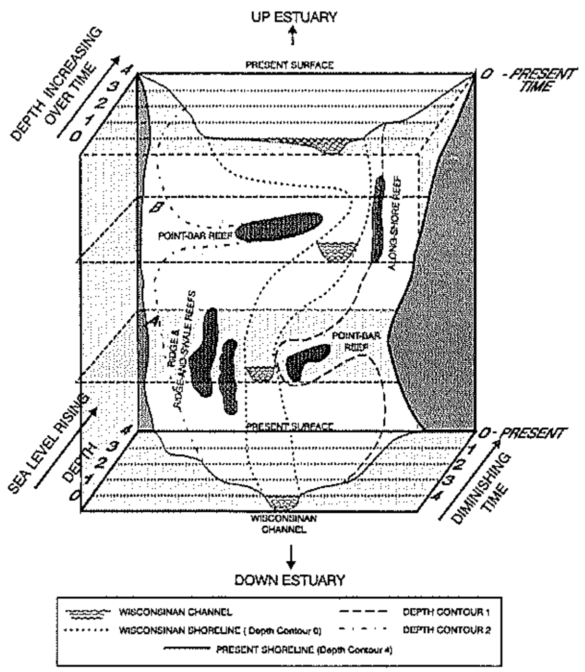
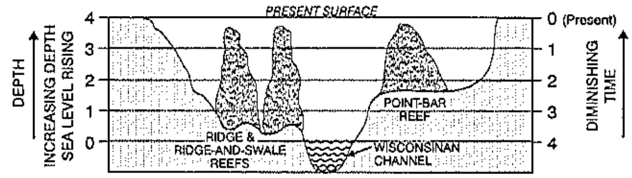
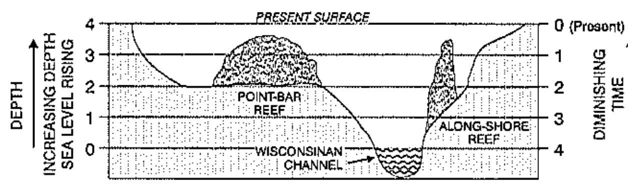


Figure 3a.



Cross-Section A.
Looking Up-Estuary, Ridge-and-Swale Reefs on Wisconsinan Terrace (between depth contours 0 and 1). Point-Bar Reef on 1st Terrace above Wisconsinan Terrace (between depth contours 1 and 2).



Cross-Section B.
Looking Up-Estuary, Along-Shore Reef on 1st Terrace above Wisconsinan Terrace (depth contour 1). Point-Bar Reef on 2nd Terrace above Wisconsinan Terrace (depth contour 2).

Figure 3b.

Figure 3.
Formation of Point-Bar, Along-Shore and Ridge-and-Swale Reefs Over Time with Rising Sea Level. Figure 3a is a 3-D presentation which is best viewed beginning from bottom of figure and moving eyes upward.

semi-protected shallow embayments, lagoons, creeks and in sheltered, shallow tributaries of larger estuaries. As with most such biological categories there are intergrades and many, probably most, Chesapeake upthrusting reefs began as fringing reefs attached to the shore (i.e. point-bar and along-shore reefs) or to some mid-stream, elongated prominence or "gut" (i.e. ridge or ridge-and-swale reefs, figures 3a and 3b). As sea level rose, the fringing reefs became surrounded and separated from the shore. Afterward, other hydrographically-significant factors, such as erosion of adjacent shores, intervened and isolation increased. Ridge and ridge-and-swale reefs were isolated early-on and their isolation increased further and further as sea level continued to rise. Reefs which were attached to or close to ancient high-energy promonitories, shorelines and spits, could have lost their landward connections because of inshore erosion, heavy sanding and/or siltation, wave and current induced bottom movements, lack of suitable cultch inshore of the developing reefs, and excessive predation by land animals.

As human populations and their use of oysters increased, nearby (handy) inshore oyster populations would have been subjected to increasing harvesting pressure early on. Even sparse aboriginal human populations would have harvested readily accessible shallow water oyster populations first and most heavily. In some places, such as the Burwell Bay-Mulberry Island reach of the middle James estuary, ridge, ridge-and-swale, point-bar and along-shore reefs are close together, often superimposed (Figure2).

De Alteris (1988) described and illustrated the basic process of reef formation in his discussion of the evolution of the Wreck Shoal reef field of the middle James estuary of Virginia. My concept of the development of each type of upthrusting reef (i.e. point-bar and along-shore fringing reefs and ridge and ridge-and-swale reefs) is illustrated by Figures 3a and 3b.

Other papers of this volume will feature the comparatively low-profile shallow water reefs, fringing or isolated, so common in the shallow lagoons and embayments of the Eastern Shore of Virginia, Maryland and lower Delaware and similar waters elsewhere, especially along the South Atlantic and Gulf Coasts. The, generally, higher profile upthrusting reefs (Figure 4) of the deeper and more salinity-variable Chesapeake Bay (and similar estuaries) are the principal subjects of this paper. In all probability the same basic biogeological and hydrographic principles apply to all reef types.

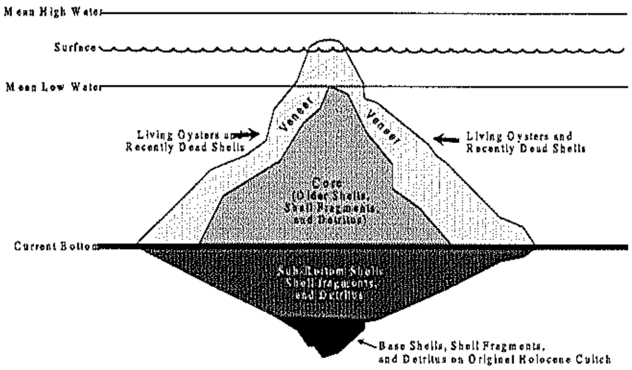


Figure 4. *Diagram of an "Upthrusting" Chesapeake Oyster Reef, the oyster's (a communal animal) "most-hospitable" habitat. (Details of the early post-Wisconsinan, "original Holocene cultch" Base are hypothetical. To my knowledge, no one has actually carefully dissected the sub-bottom portion of an upthrusting reef.)*

The shapes, location, and extent of oyster reefs were determined by the natural geomorphological characteristics of their sites and the hydrographic and biological features pertaining during their establishment and development. In recent times oyster harvesting and shell mining and, to a far lesser extent, the sediment-increasing activities of man have influenced these aspects (Hargis and Haven, Chapter 23, this volume).

In some ecologically favorable areas of the Chesapeake, such as the James estuary of Virginia, or Pocomoke and Tangier Sounds, shared by both states, and the mainstem and north shore of the Potomac River and the upper Bay region of Maryland (i.e., Little Choptank River to Chester River—and elsewhere), numerous upthrusting reefs developed close to each other, even merging in places (Figures 1 and 2). Such aggregations of reefs may be termed reef fields. The extensive natural (self-establishing, self-building, and self-sustaining—formerly) reefs and reef fields of the Bay and its tributary estuaries are here referred to as the Chesapeake Bay's Oyster Reef System (Figure 1).

The utility and economic value of most biological resources whose useful and sought-after individuals (edible and marketable units) are small and of relatively little value by themselves are largely based upon accessible and economically harvestable aggregations of numerous massed individuals. The reefs and reef fields of the Chesapeake reef system provided such aggregations. Without the reefs and reef fields of this great estuarine oyster reef system and their massive accumulations of easily exploited self-renewing populations the once extremely valuable public and private oyster industries of the Chesapeake could not have developed.

Though recognized only recently (unfortunately) the Bay's Oyster Reef System (biocoenose) was its most important, characteristic and productive community before its destruction.

Materials and Methods

Recorded observations (anecdotal, hydrographic or otherwise) of oyster reefs of the Chesapeake can be no older than about 400 years, the time when Europeans began to seriously explore and, later, colonize the area. Information of prior times must be gleaned from writings on historical geology, paleontology, and stratigraphy and written or verbal reports of current researches or reviews involving these and related disciplines.

This study is based partially upon certain historical anecdotal accounts of early explorers, navigators, colonists and later observers. An excellent review of many of them was provided by Wharton (1957) from which I have drawn.

Being primarily concerned with successful voyaging, early marine navigators and pilots recorded very little information pertaining directly to oyster reefs. Such hydrographic information as they left related mostly to location, recognition and avoidance of reefs as perils to navigation. However, in some instances it is possible to work backward from current or recent oyster ground surveys and hydrographic charts to charts or maps of earlier times, such as the 1607 AD chart of Robert Tindall (Figure 5), which illustrated shoals in the Burwell('s) Bay reach of the upper James estuary, calling them Tindall's Shoals (Morrison and Hansen 1990). A Dutch chart of Powhatan's River (another early name for the James River) made around 1638 from earlier ship's soundings, shows similar shoals in the Burwell('s) Bay reach of the estuary and below (Vingboons, ca. 1638). Such a comparison indicates that the shoals, almost certainly the prominent oyster reefs now known to have been present in that area from surviving reefs and reef traces (Haven et al. 1981) and from records and charts of earlier James River surveys (Winslow 1882, Baylor 1894, Moore 1910), were there when Tindall and the other navigators and chartmakers involved made their observations almost 400 years ago. It tells little else. The same is true of a few of the soundings and depictions of other early chart makers.

Though governmental entities, such as the British Navy, often surveyed and prepared relatively detailed charts of American coastal areas involved in naval actions or associated military activities, official, organized modern chart-making of North American waters did not begin until the British Admiralty established its hydrographic office in 1795. After that time the accuracy and utility of nautical charts improved. Prior to then most charts were based upon information obtained on an ad hoc basis and many were privately developed and maintained. Hydrographic surveying of those times was unsophisticated and early navigators, or their sponsors, often regarded soundings and sailing

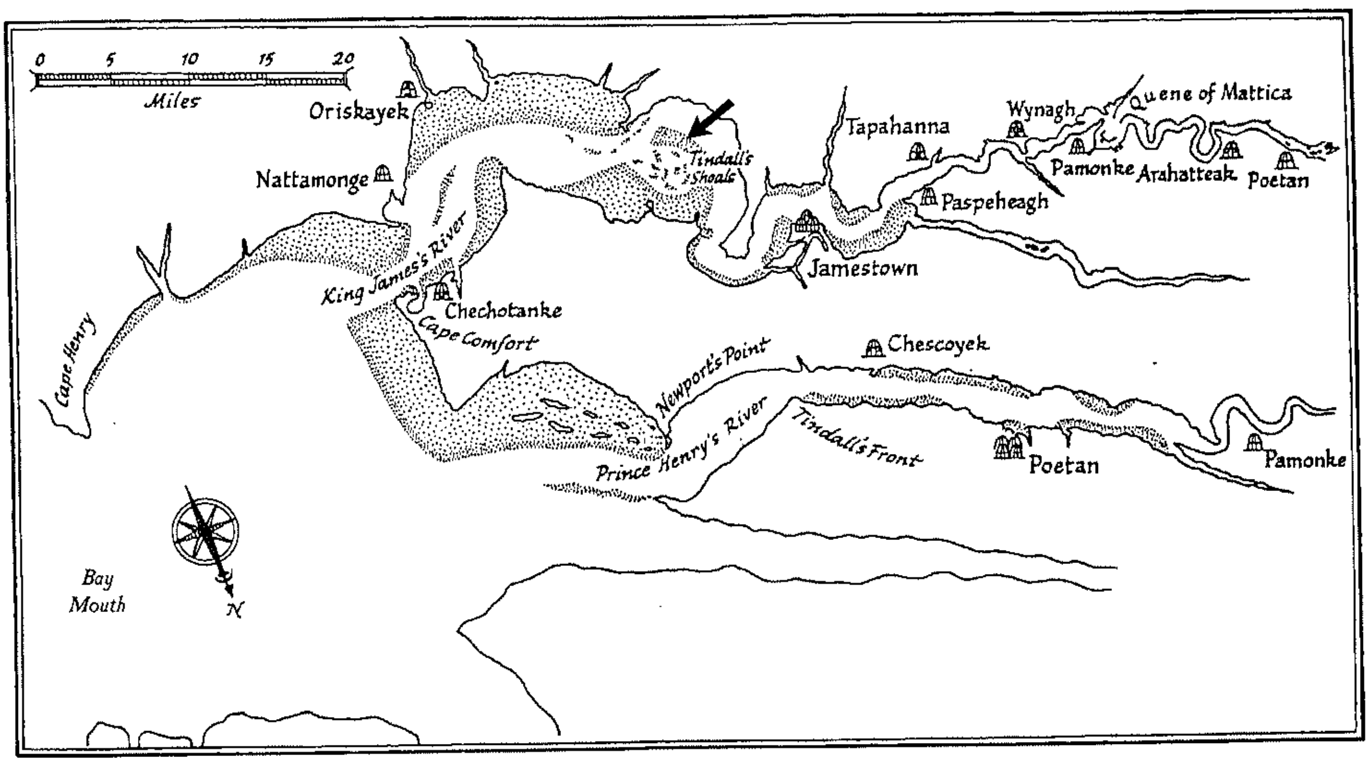


Figure 5. The reconstruction of Robert Tindall's chart (1607) which appeared as Figure 1 in Morrison and Hanson (1990). The James River (King James' River) and York River (Prince Henry's River) are depicted with their northwesterly-directed long axes toward the right (i.e. lying on their "sides"), a common orientation of early American charts and maps. Tindall's Shoals (arrow) are in the area of the James Estuary now known as Burwell('s) Bay (see Figures 2, 6, 7 and 8). (Spellings of Indian town names are Tindall's. Shading, including that alongshore, obviously represents shoals,some of which undoubtedly were oyster reefs and reef fields.)
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instructions as being proprietary and held them closely.

Once the U.S. Coast Survey (USCS), later the U.S. Coast and Geodetic Survey (USCGS) and now the Coast Survey of the National Ocean Service (NOS) of the National Oceanographic and Atmospheric Administration (NOAA), began its hydrographic charting work in 1833, coastal and estuarine soundings of waters around the United States became more accurate and intensive. Certain boat sheets and charts prepared by the Survey have been employed in this study. Of greatest utility thus far have been the two USCS charts with Registry Nos. 1179a and 1179b, approved for registry in 1872 and 1874, respectively. (These registry dates are employed herein as their publication dates, i.e. USCS 1872 and 1874. These two charts, covering most of the estuarine portion of the James, apparently were neither printed nor circulated widely.) Even though these U.S. Coast Survey charts of 1872 and 1874 are not included therein, the extensive review of the history of Chesapeake Bay charts by Morrison and Hansen (1990) provides a particularly valuable and detailed history of surveying and charting of the Chesapeake region and of the resultant charts.

Heavy reliance regarding the late glacial and postglacial history of the Chesapeake region has been given to the writings and/or advice of modern geological scientists specializing in the Chesapeake estuary and/or similar coastal waters. Among them are: R. J. Byrne, C. H. Hobbs, III, J. D. Milliman, M. M. Nichols, and L. D. Wright of the Virginia Institute of Marine Science; G. H. Johnson of the Geology Department of the College of William and Mary; L. W. Ward of the Virginia Museum of Natural History; and J. R. Schubel formerly of Johns Hopkins University and, more recently, of the New England Aquarium, Boston, MA. Information provided by them and/or their relevant publications is included in the text below. Other references from which background material was gleaned are presented in the Literature Cited section.

While a number of geologists and geological references were consulted, establishment of really "tight" estimates of the times at which the events described below proved difficult. Time estimates provided by the various individuals and references differed somewhat. On the one hand, there is genuine disagreement on integration and interpretation of the various types of available data and of their details; on the other, the scarcity of detailed data for certain time periods or geochronically important phenomena prevents precision. Also, the accuracy of some dating techniques allows only approximations of time periods. Nonetheless, available data and consensus permits confidence that the estimated times presented below are reasonably consistent with the evidence and geological opinions at hand.

Results

The earliest available English descriptions of Chesapeake oysters and oyster reefs, called beds, banks, and shoals in at least one Colonial report, were those of certain Jamestown colonists whose writings began shortly following their landing at the place called Cape Henry (Figures 1 and 5) after their ships first entered the Bay (Wharton 1957, Hargis and Haven 1995). Though, with certain exceptions, most notably the 1607 chart of colonist Robert Tindall and the ca. 1638 Dutch chart mentioned above, they did not provide pertinent charts or survey data, colonial observers and later travellers clearly described large shoals of oysters, the crests of which protruded above the water's surface at low tide, and from which live oysters could be harvested directly.

As noted above, log books, boat sheets, and finished charts of the old U.S. Coast Survey and its successors are useful in establishing the geographic locations and rough outlines of some of the Bay's reefs and reef systems. Some were of sufficient detail to allow reconstruction of the elevations and contours of certain oyster reefs in the James River. Figures 6, 7, and 8 were traced directly from charts based upon data acquired during hydrographic surveys made in Virginia's

James estuary by that organization during 1871, 1872 and 1873 (USCS Charts, Registry Nos. 1179 a and b, Registry dates, 1872 and 1874, here cited as USCS 1872 and 1874). These presentations confirm graphically that the intertidal crests of many of the oyster reefs, mentioned in earlier anecdotal accounts, such as those included in Wharton (1957), had persisted for nearly 100 years after the Colonial period ended with the Revolutionary War, or some 264 years after first permanent settlement.

Sustained federal and state interest in the fishery resources and socioeconomic aspects of the fisheries based upon them began soon after the Revolution but did not gain strength until after the massive social, economic, and military disturbances of the Civil War, some 80 years after the Republic was established. The study by Ingersoll (1881), done in conjunction with the 1880 census, incorporated the results of the first extensive examination of the nation's oyster industries . It contains much useful information about the early years of the Chesapeake Bay oyster fishery.

Specific field surveys directed at discovering the location, extent and productivity of oyster reefs of the Chesapeake apparently did not begin until 1878 when Lt. Francis Winslow of the U.S. Navy, then on duty with the U.S. Coast and Geodetic Survey, began his Chesapeake Bay work in the James River estuary of Virginia and then quickly moved his survey team to Pocomoke and Tangier Sounds, shared by Virginia and Maryland (Winslow 1882). These field examinations were followed by the more extensive but less detailed ones of Baylor who surveyed all of the then-recognized public "grounds" of Virginia in 1892 and 1893 and charted them in simple outline form (Baylor 1894). In 1909 H. F. Moore, of the U.S. Bureau of Fisheries, studied the oyster reefs of the James River (VA) in greater detail than either Winslow or Baylor had and provided geographical and density information in the resultant text and charts describing his work (Moore 1910). During the years 1906 to 1912 C. C. Yates, of the U.S. Coast and Geodetic Survey, surveyed

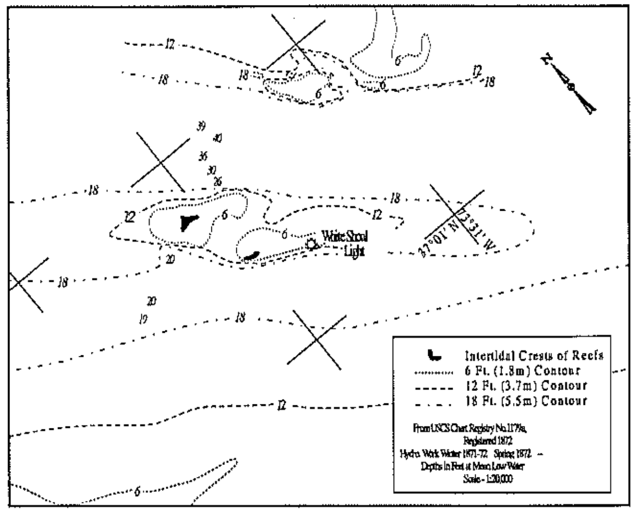

Figure 6. White Shoal Reef Field, Lower Portion of Middle James Estuary

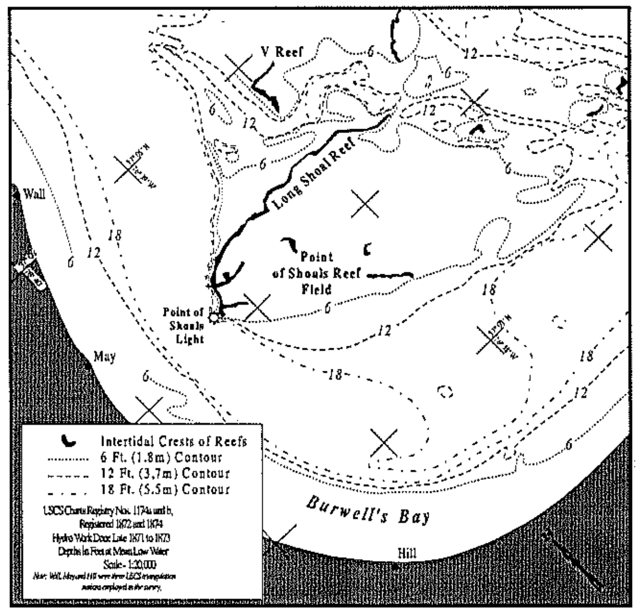

Figure 7. Point of Shoals Reef Field, Middle James Estuary, including dominant Long Shoal Reef and other prominent reefs in the Burwell's Bay complex reef field.

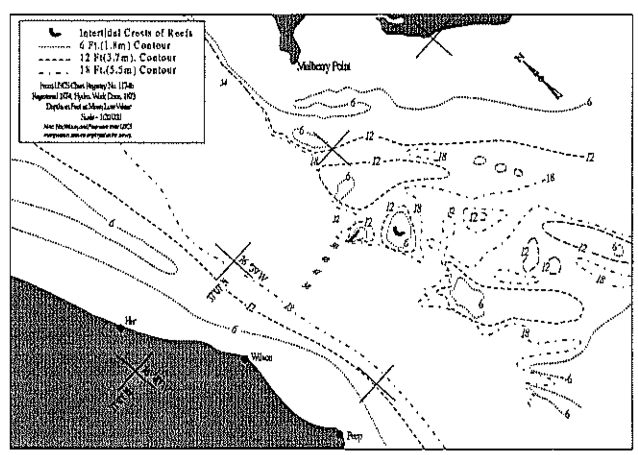

Figure 8. Horse Head Reef Field, Middle James Estuary

the oyster reefs of each Maryland tidewater county bordering waters of appropriate salinity. A series of publications described his results in considerable detail county by county with relevant charts: The entire six-year work is summarized in Yates (1913). Unfortunately, by the time of these efforts, reef destruction had progressed at ever-increasing rates for 100 years or more, resulting in the reduction of most, probably nearly all, of the regularly emergent (intertidal) Chesapeake oyster reefs to the point that their crests no longer surfaced at mean low water (MLW) or any usual stage of the tide. However, the crests of some reefs in the James estuary, and elsewhere, continued to be close to the surface at MLW. When Moore (1910) surveyed these same James estuary reefs in 1909, he reported crest depths as shallow as 2.5 feet (0.76m) and 3.0 feet (0.9m) at MLW, respectively. Assuming reasonable comparability of sounding techniques, sounding stations and of the resulting depth data, it would seem that between 1873 and 1909 the heights or crests of the oyster reefs of the James had declined measurably. Apparently the crest of only one—the upper reef of the White Shoal reef field, still breaks the surface [see National Ocean Service (NOAA) Chart No. 12248] even though it is mostly, or entirely, bereft of living oysters. J. D. Andrews, well-known oyster scientist of VIMS, reports (personal communication) that he was able to stand on and hand-pick numbers of small rounded oysters from the exposed crest of White Shoal Reef as late as 1955. This is possible no more.

As mentioned above, N. Marshall (1954), comparing soundings along selected transects made by the USCS in 1854-55 and 1871-73 with those of the USCGS in 1943, described a loss of 6 inches (15.2 cm) due to harvesting. Though his estimate of crest loss is probably far too small, Marshall's report of a definite reduction in the heights of several James River seed and market area reefs that he had examined was the first quantitative effort published.

By 1981 an extensive survey showed almost no intertidal reefs in Virginia's Chesapeake Bay (Haven et al. 1981) Fathometer traces in typical locations showed tops of hard reef areas in the following depth zones: James River, 5 to 15 ft. (ca 1.5 to 4.6m); Pocomoke Sound, 15 to 20 ft (ca 4.6 to 6.1m); and the Rappahannock River, 10 to 18 ft (ca 3.1 to 5.5m) (Haven and Whitcomb 1983, Whitcomb and Haven 1987, Whitcomb and Haven 1989).

The Chesapeake reef system extended throughout the Bay. Encompassing numerous reefs and reef fields on the Southern Shores of the Bay, it reached from the Lynnhaven River and Willoughby Bay into the James estuary. On the Western Shore, reefs were found in all of the rivers and creeks with appropriate salinities in both Virginia and Maryland, where they extended into waters around and within the mouth of the Patapsco River and northward to slightly above the mouth of the Bush River. On Bayside of the Eastern Shore of Virginia and Maryland they extended up the mainstem of the Chesapeake and were in all of its tributary creeks, rivers and sounds from Nassawadox Creek (or perhaps other creeks below) in Virginia to the mouth of the Sassafras River in Maryland (Figure 1).

Many of these reef fields incorporated more than two reefs. Some individual reefs and reef fields, such as those in the middle estuarine portion of the James River above Blunt Point, known since at least 1909 as the oyster seed area (Moore 1910), were very large (Figure 2). As the oyster industry based upon the Bay's reefs grew and harvesting increased, most reefs or reef fields received individual names. In Virginia there were over 390 individual named reefs at the time of Baylor's survey in 1892 (Baylor 1894). Yates (1913) identified over 700 in Maryland waters. There had been more in each state.

Evolution of the Chesapeake Reef System

Earth's climate has varied considerably through geological time. During the Pleistocene Epoch (from about 2.4 million years BP to about

10,000 BP) wide fluctuations in global atmospheric temperatures resulted in numerous ice ages and warming periods. The paleontological record indicates more than a dozen such periods during the last two million years (Chorlton et al 1983). The cooling phases of the cycle, during which huge glacial ice caps developed around or over Earth's polar regions—extending into lower latitudes in each hemisphere—generally lasted from 100,000 to 125,000 years (Chorlton et al. 1983, Schubel 1981).

During these prolonged periods of intense cold, polar, montane and continental glaciers covered much of the Northern Hemisphere, land and sea, as well (Bailey et al 1982). In the most recent Ice Age, termed the Wisconsinan in North America, the massive Laurentide glacier, covering the northern parts of mid-western and north-eastern North America, extended southwestward from Greenland, Labrador and Hudson Bay reaching as far south as Sunbury in Pennsylvania, which is well below the present city of Wilkes-Barre on the North Branch of the Susquehanna River (Figure 9). Thus, it covered the entire North Branch. It also covered part of the West Branch of the Susquehanna from Sunbury to Williamsport and beyond (Flint 1957, King et al 1974, Mehringer 1988, Redfern 1983). During the depths of the cooling periods great quantities of Earth's freshwater were bound in the snow and ice of glaciers, which averaged a mile or more in thickness, and little reached the oceans. During the Wisconsinan Ice Age the surface of the North Atlantic was as much as 120 m (394 ft) below its current level and the continental shelf of today was mostly above water. At the peak of the Wisconsinan cold period, ice in the ancient "Atlantic" apparently extended as far south as the latitude of current Cape Hatteras with "pack ice" slightly below the latitude of today's Long Island and "drift ice" extending the rest of the way southward.

Alternating with ice ages were periods of warming in the Northern hemisphere -- probably globally. During prolonged warming periods glaciers melted and meltwaters coursed seaward. In the ocean, floating glaciers calved and melted contributing ice floes and melt water as the sea warmed. Sea and pack ice floes melted farther as warming continued. Meltwaters from all stages of glacier, sea ice, and pack ice disintegration and dissolution contributed to rising sea level and transgression. Fluvial and oceanic water on and from the edge of the melting and retreating land and sea ice cap (glaciers and icebergs, etc.) would have been very cold early on. Oceanic waters in the offing of the current Mid-Atlantic would have been much colder than now due to melting of sea ice and icebergs. The physical and biological impacts of this cold water would have been significant. The "North Atlantic" basin filled and, when rising ocean waters reached the ancient coastal river valleys of the "Susquehanna" and "James," intruded into and "drowned" them and created new

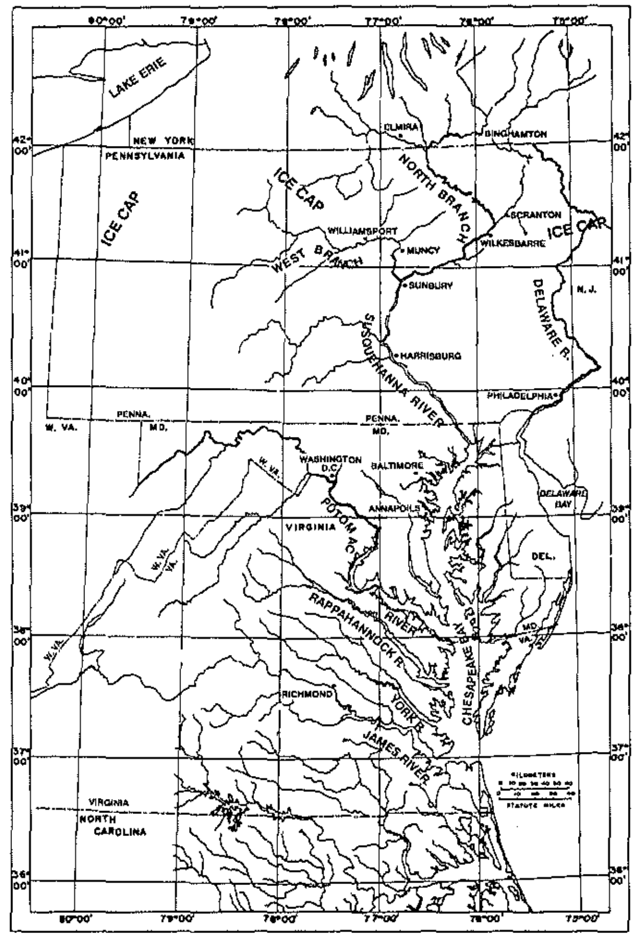

FIGURE 9. Southernmost Extension of Wisconsinan Ice Cap Into Future Chesapeake Bay Drainage Basin.

estuaries. Eventually, "Atlantic" waters reached levels high enough to spill over onto, encroach upon and inundate the previously dry "continental shelves." The warming periods (interglacials) have been much shorter than the cooling ones (glacials), generally lasting about 10,000 years (Chorlton et al. 1983, Schubel 1981). Consequently, the coastal estuaries resulting from associated interglacial oceanic transgressions have been relatively short-lived, persisting around 10,000 years (Schubel 1981).

Estuaries may be defined as more-or-less open (or semi-enclosed) coastal waters where freshwater from the land meets, mixes with and dilutes the higher salinity water from the ocean. Brackish estuarine waters are decreasingly salty in the upstream direction and vice versa. The Chesapeake Bay is both a drowned river valley and an estuary. Actually the Chesapeake estuary consists of the drowned valleys of the lower reaches of the Wisconsinan "Susquehanna" and "James" river systems—at least in its southernmost part. The future Susquehanna (which apparently received all or most of the tributaries north of the James) and James Rivers flowed separately to the sea during Wisconsinan glacial and early post-glacial times (Schubel 1981).

Geologists are in general agreement with the sequence of events described above and below but some disagree over details of timing. Their differences apparently lie in the specifics of the elevation of sea level and associated transgressions through time. Schubel (1981) and others have written that the most recent Ice Age (the Wisconsinan glacial period) ended and the current post-glacial (or the most recent interglacial, should another ice age follow as many believe will occur based upon the sequential occurrence of many glacial-interglacial cycles in the last several million years) began around 20,000 BP to 18,000 BP. Some geologists consider that the Holocene Epoch (see just below) began with this early changeover. Current geological evidence indicates and consensus accepts that, indeed, eustatic (global or general) sea level began to rise because of general climate-warming and resultant glacial melting, in the Northern Hemisphere at least, about 18,000 BP, but that warming halted and eustatic sea-level retreated during at least two periods in which atmospheric temperatures cooled markedly.

The most significant of these pre-Holocene cooling episodes is known as the Younger Dryas event (Fairbanks 1989). The general warming trend resumed at the end of the Younger Dryas cooling event around 11,500-10,000 BP and, with reversals of varying lengths and intensity, has continued since. The current interglacial period, known as the Holocene Epoch, is said by most geologists I have contacted or read for this study, to have begun around 10,000 BP. Some say it began more recently, about 9,000 BP: (Personal Communications; C. H. Hobbs, III, G. H. Johnson, M. N. Nichols, L. W. Ward, J. D. Milliman, L. D. Wright and the books and/or articles by Bailey et al 1982, Chorlton et al. 1983, Colman et al 1990, Colman et al 1992 , Emery and Aubrey 1991, Halka et al 1989, Levin 1983, Fairbanks 1989, Flint 1957, Wright 1995; and, Redfern 1983). For purposes of this paper I have accepted the apparent consensus among these communicants and authors and chosen 10,000 BP as the beginning of the Holocene Epoch.

The timing of the several geological events involved in the development of the Chesapeake Bay, itself, is important to this study which attempts to determine as closely as possible the length of time required for the reefs and reef fields of the Chesapeake oyster reef system to have become established and evolved to their 1600 AD status. *C. virginica* cannot live for long in freshwater. The processes of reproduction, survival and reef formation by this oyster can occur only in waters with appropriate salinity levels. Hence, Chesapeake oyster reefs could not have developed where they have been found in the Bay and its tributary subestuaries until waters of appropriate salinity, bearing setting-stage oyster larvae reached those locations and those larvae settled successfully, survived, matured and reproduced.

Current geological consensus indicates that the Chesapeake we know did not exist 18,000 years ago when the Wisconsinan ice cap began to recede. Instead, the great valleys of the ancient Wisconsinan Susquehanna and James Rivers wound separately (Schubel 1981) seaward through channels which were much deeper than those of today (Halka et al 1989, Colman et al 1990). The two erosive river systems coursed

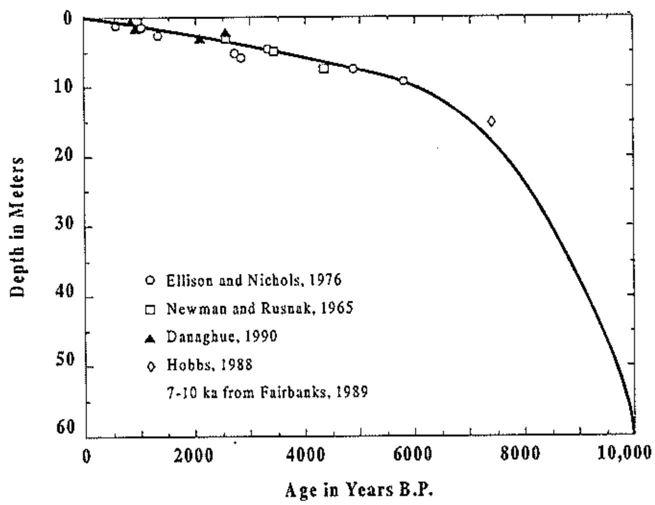

Figure 10. Chesapeake Holocene Sea Level Curve. From Coleman, et.al, 1992. The curve is smoothed and does not reflect the perturbations which actually occurred as atmospheric tempertatues rose and fell (see text below). Reprinted with permission from the Society for Sedimentary Geology.

down their respective valleys across the broad, gently-sloping coastal plain of glacial times, now known as the continental shelf, reaching the ancient Atlantic Ocean via canyons on the edge of that great shallow expanse some 240+ km (150+ statute miles) eastward of the current bay mouth and continental shoreline.

With global atmospheric warming, North Atlantic waters began to rise as freshwater from the melting North American Wisconsinan Ice Cap flowed into the ocean. (Geologists term the landward movement of rising ocean waters up the ancient river valleys, over the shelves and onto the low-lying portions seaward of today's highlands, transgression). Eustatic (general) sea level rise and the associated transgression was relatively rapid at first with temporary periods of reversal of the warming trend, as described below, and then slowed around 6,000 BP (Emery and Aubrey 1991). (Some place the time of slowing at 5,000 BP.) [Though not critical to this particular discussion of the origin and evolution of the Chesapeake oyster reefs during the Holocene Epoch, it is interesting to note that even after 6,000 BP several cooling periods occurred. Probably those periods, such as the "mini-ice age", which extended some 500 years from about AD 1300 (700 BP) to AD 1800 (200 BP) (Emery and Aubrey 1991), caused minor fluctuations in glaciation and sea-level movements (Chorlton et al. 1983). Such extended temperature fluctuations undoubtedly affected the fortunes of biological populations of the geographical areas involved, including submerged ones such as oysters and their reefs even though water absorbs and releases heat more slowly than air or land. This aspect should be examined.]

Employing the Holocene sea level rise model of Colman et al. (1992) (Figure 10) and considering that the Holocene Epoch began about 10,000 BP, it would appear that rising Atlantic waters flowed up the separate Wisconsinan river valleys of the ancient Susquehanna and James River systems and reached the approximate location of the promontories now called Capes Henry and Charles around 7,500± BP and the formation of today's Bay may be said to have actually begun. Though the curve in the model depicted in Figure 10 is presented as a smooth line, the actual rise of sea level was erratic, slowing as hemispheric or global air temperatures decreased and accelerating as they increased. As Atlantic waters rose, the portions of the Wisconsinan valleys of the two probably separate rivers near the "Capes" were filled and covered; and the waters above them coalesced, forming the lower Bay which today receives water from both the Wisconsinan Susquehanna and James River systems. They also flooded the drowning valleys of the Susquehanna and James rivers (and their tributaries) and moved onto and eventually transgressed and covered the nearby Bay and river shelves and shallows (terraces), as they had the continental shelf earlier.

Rising waters of appropriate salinity brought oyster larvae from "estuarine" and coastal waters of the late Wisconsinan "Atlantic" into the lower Chesapeake and the developing James estuary around 6,000 BP - 4,000 BP. As they did, setting-stage larvae "struck" on such suitable, firm substrates as then existed, clumps and colonies of adult oysters became established and reefs began to form. This process, described in more detail above, continued as estuarine waters of suitable salinity and temperature bearing viable larvae invaded new setting sites. Figures 3a and 3b above, represents an attempt to illustrate the process diagrammatically. New reefs developed upstream and landward on the shoulders and shallows of nearby terraces successively as rising waters of appropriate salinity bearing larvae reached suitable setting sites. Most such larvae-bearing waters by this stage would have come from mature oysters farther, and/or deeper down the developing "Chesapeake" estuary instead of directly from the Atlantic as formerly. Reef initiation and subsequent formation would have occurred in more-or-less continuous fashion as larvae-bearing waters flowed up the Wisconsinan channels of the Susquehanna and James and especially as they rose laterally over adjacent Bay and river shallows and flood plains.

By about 4,000 ± BP saline waters in the mainstem of the Bay reached the latitude of present-day Annapolis. Around 1,500 years later (2,500 ± BP) the Chesapeake reached its approximate present configuration (Figure 1). Its general boundaries and major landmarks would then have been identifiable by today's boatmen, watermen and navigators. (Though its relative rate had slowed and, at times, even reversed, sea level continued its rise as it apparently does today.)

At about the same times the foundations of most Bay oyster reefs and reef fields had been formed around the clumps and colonies of oysters, which had struck on suitable cultch along the old Wisconsinan river bottoms, on the point-bars and along the shorelines and on and in ridges-and-swales of the ancient flood plains (Figures 3a and b). They grew and expanded over time. As eustatic (general) and isostatic (local) sea level rose so did the heights, or crests, of the prospering reefs. Over the next 3 or 4 millennia the self-sustaining oyster reefs expanded basally, vertically and volumetrically, keeping pace with sea level rise, local subsidence and/or emergence (post-glacial rebound, etc.) and sedimentation. Their surface areas increased, as did the numbers of living oysters in the veneer and on its surface and dead shells, shell fragments and detritus (which constitute some of the deeper-lying layers of the veneers and cores of the reefs) (Figure 4). More larvae were produced: More larvae set and survived, and the self-renewing and self-perpetuating reef structures rose. The process was limited only by prevailing general and local geomorphological, hydrographic, and ecological constraints.

As the reefs and reef fields grew and expanded they intruded ever more significantly into the surrounding water column, eventually developing into significant barriers, serving as "dams", wiers and baffles, which interacted with and affected the macro-, meso- and microcurrents and other hydraulic characteristics of their immediate and near-field localities. For example, the USCS Charts (USCS 1872 and 1874) show that, in the Burwell Bay reach of the upper James estuary (the "seed oyster area" of Moore 1910), they extended almost solidly southwesterly to northeasterly from shore to shore about 4.4 miles (7.0 km.) and up and down river for about 9.4 miles (13.5 km), leaving only a few relatively deep but narrow channels open (Figures 2,6,7 and 8), [In the "market oyster area" portion of the James Estuary below Wreck Shoal Reef (Moore 1910), the reefs and reef fields were mostly on the flanks of the natural channel and the shallows (or terraces) alongside, except White Shoal Reefs which were on a ridge or shoal (which, alternatively, might have been a long, centrally-located point-bar) in the middle of the river (Figures 2 and 6).] Erosion and sedimentation patterns in the vicinities of the reefs and reef fields were altered by them as well. Additionally, larval distribution and other biological features were modified, as were setting and survival patterns. Thus, the burgeoning oyster populations established and transformed their own general, meso- and microhabitats throughout the long and close interaction with their immediate environments. The three-dimensional reefs and reef fields served as nature's off-bottom oyster culture structures.

Normal and abnormal seasonal climatic processes and catastrophic natural events involving episodic freshets, severe wind-related water turbulence, icing and heavy sedimentation, as well as diseases, predators and temporary food shortages have undoubtedly always been present in the brackish water areas occupied by coastal oyster populations of the North Atlantic. Before extensive harvesting developed *Crassotrea virginica* continued to increase in numbers and to build and expand its reefs in number and geographical extent, height and volume in the Chesapeake despite these adverse factors. Indeed, the reefs afforded plentiful setting surfaces and kept most of their inhabitants well above the less-hospitable bottom and undoubtedly contributed directly to the survival and success of the Bay's oysters (Hargis and Haven, Chapter 23, this volume). Because of survival advantages offered by the higher portions of the reefs and the suitable setting surfaces of the living and dead shells in and on the veneer, the reef's upward growth towards and even into the "lower" intertidal continued as sea level increased.

And Then Came Humans

Most paleontologists and anthropologists currently agree that the earliest successful human explorers and colonizers (actually hunter/gatherers) reached the North American continent from notheastern Asia by crossing the land-bridge across the Bering Sea (called Beringia by some) resulting from lowered sea level during the last Wisconsinan Ice Age, some 20,000 years ago. Indeed, artifacts such as Clovis spear points found at certain North American sites indicate possible earlier dates for this occurrence, perhaps as early as 30,000 years BP (Garrett 1988, Mehringer 1988).

After crossing Beringia and traveling down one or more ice free corridors between the Cordilleran Ice Sheet on the West and the Laurentide Ice Sheet on the East or along the beaches, tundra, and permafrost of the Pacific littoral, the travelers of Asian origin and or their descendants reached the northwestern portion of the area now known as the United States (Mehringer 1988). Descendants of these wandering hunter-gatherers apparently reached the ancient Susquehanna and James basins about 15,000 years ago. Charts in the publication of Barber (1979) show that campsites of ancient Paleo-Indians existed before 10,000 BP along what are now tidal waters but then were unidirectional flowing rivers or creeks of the ancient James and Potomac drainage basins. These peoples undoubtedly ranged widely in the "Chesapeake" region. Recent geological and archeological research at Jamestown Island on the upper James estuary (upper reaches of the normal estuarine zone just above the uppermost oyster reefs around present-day Deep Water Shoals, Figures 1 and 2) unearthed artifacts the dating of which established persistent human occupation at that site beginning about 12,000 BP (Blanton and Kandle 1995, Johnson et al. 1995). It now appears possible that some Paleo-Indians were on the upper Nottoway River nearby as early as 16,000 BP (H. A. McCord, personal communication). Some disagree, placing this occupation at around 14,000 BP. Whichever finally is generally accepted, these early Paleo-Indians and many of their successor generations undoubtedly observed the flooding of the ancient Wisconsinan James river valley nearby as sea level rose. They and their confreres to the north also witnessed the rising of the water into the Susquehanna portion of the developing "Bay" and its tributaries.

Extensive middens from several pre-historic Indian periods reveal widespread use of oysters (*C. virginica*), hard clams (*Mercenaria mercenaria*) and bay scallops (*Argopectan irradians*), among other estuarine and marine molluscs, as food and for other uses, such as tools, jewelry and currency. Because these early people were relatively few in number compared with later Chesapeake region populations and their harvesting technologies limited, oyster populations, except perhaps those closest to shore and most accessible by wading, continued to thrive and the self-renewing reefs continued and probably even expanded throughout most of the Paleo-, Archaic and Woodland Indian periods and early and mid-Colonial times.

European settlers arrived in AD 1607 (ca 391 BP) and spread along the James and nearby rivers and creeks (Figure 5). After a prolonged, faltering beginning, this and other colonization efforts along the Atlantic coast succeeded and numbers of colonists and later immigrants grew and spread throughout the coastal plain and piedmont regions and into the western territories and demands for oysters and shell increased. For almost 200 years after 1607 AD Chesapeake oyster reef populations were able to meet the slowly-growing human demand and yet maintain the reefs upon which they depended and grew well (Hargis and Haven, Chapter 23, this volume).

Around 200 years ago demand for and subsequent harvesting of live oysters (old and young) and of shell increased to proportions which, magnified by improving harvesting technologies, began to outstrip the natural abilities of the oysters to replace themselves and to provide shell for reef maintenance and growth. Oyster populations and oyster reefs began to stop growing, stabilized and then dwindled. A synergistic cycle developed involving ever-smaller self-renewing oyster populations, slower natural reef replenishment and vice-versa. The rate of reef and population decline was not steady, varying with the more-or-less favorable or adverse years of setting, growth and survival and natural replacement and with harvesting pressure, but, over the long term, the trends of natural oyster production, population trends and reef replacement were downward. As noted above, Stevenson (1894) was probably the first to formally and clearly note this cycle of reef destruction and ever-decreasing oyster populations in the Chesapeake and comment on its possible socioeconomic consequences over a century ago. Winslow (1882) had commented obliquely on it as early as 1878 through he apparently did not recognize the oyster "beds" as being true reefs.

Excessive harvesting and associated reef (microhabitat) destruction were the major but not the only human-affected factor that Chesapeake oysters and oyster reefs faced. Land clearing and agricultural practices of colonists and their numerically-increasing successors were extremely destructive of ground-cover and soil. Amounts of sediment reaching oyster reefs grew to damaging proportions. Many were made "poorer." Some were smothered. Additionally, extensive logging over the entire Chesapeake watershed destroyed ground cover and caused further sedimentation. Widespread logging in the northern and western branches of the Susquehanna drainage basin continued into the early 1900s as did contamination of the Susquehanna-influenced waters of the upper Bay by logging-caused sedimentation (Stranahan 1993). Certainly, resultant highland and shoreline erosion and excessive sediment action impacted many susceptible reefs and reef fields, especially those in the shallow waters of the upper estuarine zones of the Bay and of its tributaries. However, had natural oyster reef growth not been impacted by increasingly destructive harvesting and shell-mining, the deleterious effects of increased sedimentation on Chesapeake oyster populations would have been lessened everywhere.

By the time the first formal Chesapeake oyster reef surveys of Winslow in 1878 and later (Winslow 1882), and those of Baylor in 1892 and 1893 (Baylor 1894), Moore in 1909 (Moore 1910), and Yates in 1906 to 1912 (Yates 1913) were undertaken, self-renewing oyster populations, as evidenced by reported public market oyster harvests from the publicly-owned natural reefs of Maryland and Virginia, were in general decline all over the Chesapeake (Hargis and Haven 1995). Though the charts of Moore

(1910) show some water depths of from 0.33 feet (0.10m) to 3.0 feet (0.91m) over some James estuary reefs at MLW, none of the charts and maps prepared from the special oyster surveys examined thus far show prominent broaching or emergent reefs. Modern soundings of Virginia's Baylor grounds made by Haven and his colleagues at VIMS in the 1980s (and by earlier 20th century workers) have clearly shown that most reefs in Virginia's waters had shrunk vertically (and a number in basal extent) by the time their extremely comprehensive and careful survey was conducted. Many are mere flattened "footprints" on the bottom. A significant number are now buried by sedimentary overburden (Hargis and Haven, Chapter 23, this volume). A much smaller number have been destroyed by channel dredging or buried by dredging-associated spoil disposal. A few (probably more than a few) have been "finished off" by directed shell mining (dredging) activities. The general trend of reef shrinkage has continued in Maryland as well. Thus, with (perhaps) a very few local exceptions, reefs and reef fields have diminished Bay-wide and the Chesapeake reef system continues its general, widespread decline.

Summary and Conclusions

The Chesapeake oyster reef system developed as the Bay, itself, evolved during the last 7,000 to 6,000 years of the Holocene Epoch. As sea level rose, colonial *C. virginica* populations developed and thrived, building the oyster reefs (their own special macrohabitats or biocenoses) and reef fields, which came to constitute the reef system encountered by Indians and early colonists. The process continued as the Bay expanded with the rise in eustatic (global or general) sea level and changes in other geological factors affecting the relationship between land and water. The balance between general (eustatic) and local (isostatic) sea level rise, associated hydrography and geomorphology and reef growth apparently continued until about 200 years ago.

Until the growing harvests of Indians and colonists and the eventually overwhelming food- and seed-oyster harvests and shell-mining activities of their successors intervened, the heights of most Chesapeake oyster reefs would have risen along with sea level—and their sides and bases would have expanded except where erosion, deposition and lack of suitable cultch and stable firm bottoms and overwhelming currents prevented expansion. Of course, it was not necessary that the crests of all reefs actually broke the water's surface for Chesapeake oyster populations and their reefs to continue. Indeed, in all probability, a number did not. It was only necessary that the survival advantages afforded by reef-living (nature's off-bottom oyster culture arrangement) be maintained by upward (and outward) growth of the reef keeping pace with rising sea-level and local basin changes due to subsidence, emergence or tectonic forces and increasing sedimentation so common in coastal plain estuaries. But many would have continued to break the surface at mean low water. (Undoubtedly, sedimentation damaged some, even burying a number in the shallow turbid upper reaches of the estuarine zones of the mainstem of the upper Bay and some of its tributary subestuaries or along high energy, eroding shorelines. But, by-and large, the upwardly-growing reefs provided a certain protection from the effects of sedimentation). Instead, the oyster reefs began to dwindle under man's destructive extractive processes. The overall decline of the natural Chesapeake reef system, (erroneously denied by many harvesters and a few state managers), continues, as does that of the naturally self-renewing populations of Chesapeake oysters.

Evolution of the Bay's reef system to pre-Colonial dimensions required about 6,000 to 7,000 years: Its reduction to present low levels has taken only somewhat less than 200 years. In terms of the once extensive and valuable populations of oysters and oyster reefs and the Chesapeake reef system, humans and human socioeconomic and technological advances and the resource management efforts of state (VA and MD) and local (MD) governments have not been favorable but destructive. The need for and possible reversal of this unfortunate situation by bringing about, enabling and/or encouraging recovery of the once naturally self-renewing oyster reefs of the Chesapeake Bay and the public fisheries dependent upon them are discussed by Hargis and Haven, Chapter 23, this volume.

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