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Abstract

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J.R. Butler

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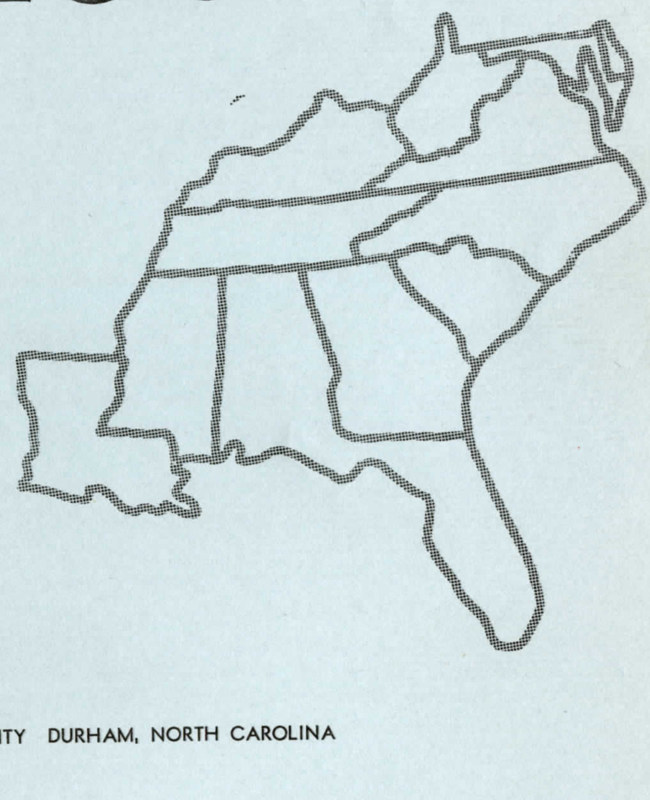

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SOUTHEASTERN GEOLOGY
Vol. 9, No. 4, 1968
Symposium Issue

Marine Geology of the Atlantic Continental Margin of the Southern United States

Organized By
Orrin H. Pilkey

INTRODUCTION

In response to national and regional interests in oceanographic research, recent studies in geological oceanography in the Southeastern United States were summarized and reviewed at a symposium entitled "Marine Geology of the Atlantic Continental Margin of the Southern United States," which was held in Durham on April 4, 1968, as part of the Southeastern Section meeting of the Geological Society of America.

Held in conjunction with the symposium was a field trip to the continental shelf aboard the Duke University Research Vessel EASTWARD, which was attended by forty-five geologists. Copies of the guidebook are available from Southeastern Geology.

Participants in the symposium on marine geology included the following scientists: K. O. Emery, Frank W. Manheim, John D. Milliman and Elazar Uchupi of Woods Hole Oceanographic Institution; Roy L. Ingram of the University of North Carolina; John Hoyt and Vernon J. Henry of the University of Georgia Marine Institute; and Blake W. Blackwelder and Orrin H. Pilkey of Duke University.

The articles in this volume range from expanded abstracts to complete discussions of all the papers presented orally on April 4.

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SHALLOW STRUCTURE OF CONTINENTAL SHELVES AND SLOPES[1/]

By

K. O. Emery

Woods Hole Oceanographic Institution

ABSTRACT

Continuous seismic reflection profiles reveal the internal structure of continental shelves and slopes to a degree that cannot be approached by other geophysical methods or by surface geology. About 100 such profiles have been published for the periphery of the United States, with a smaller number for the rest of the world. Comparison and classification of the profiles show that most portray a basic seaward growth (construction) of the continents followed by faulting or other tectonic alteration (destruction) followed by renewed deposition (construction). Deposition is chiefly in the form of strata that lie at their probable angle of rest, but large sediment traps were formed by fault blocks and smaller ones by organic reefs and diapiric dams. Pleistocene glaciation interrupted deposition and greatly modified the surface of the continental shelf by glacial erosion and deposition at high latitudes and by wave erosion elsewhere at times of glacially lowered sea level. Subsequent deposition has been too slight to return the surface of the shelf to its "normal" marine depositional profile. The complexity of geological history is far greater than has been indicated by those who have described the continental margins on the basis of information that was available prior to about 1957.

INTRODUCTION

For about a century geologists have known of the existence of continental shelves and slopes and have generally considered them to be a submerged extension of the continents. The position of this extension appeared to agree with the previously recognized role of weathering and erosion on the continents, of transportation of the products to the ocean, and of their deposition at and beyond the shore. When episodes of mountain building and igneous intrusion were found to be generally younger nearer the margins than the centers of the continents, the belief in seaward growth of the continents appeared to be substantiated. However, there was little agreement about the internal structure of the shelves and slopes, nor about their stages of development. Disagreement was due to uncertainties in the seaward extrapolation of

1/ Contribution No. 2100 of the Woods Hole Oceanographic Institution.

data from outcrops and drill holes on land and to downward extrapolation of the only available data from the shelves and slopes, namely topography, sediments, and rock outcrops. Summaries of the information that was available before about 1957 are given by Shepard (1948), Stetson (1949), Kuenen (1950), Dietz (1952, 1963), and Heezen, Tharp, and Ewing (1959). Other papers for the period could be cited, but most of them are derivative or incomplete.

About 1935 geophysical methods began to supply much information about the internal structure of the features, mostly at great depth and beginning with the Atlantic continental shelf (Ewing, et al., 1937; Miller, 1937). Most useful were seismic refraction surveys (Drake, et al., 1959), although magnetics and gravity contributed. Information about stratification and structure near the top of the continental slope awaited the development of continuous seismic reflection profiling (Ewing and Tirey, 1961; Hersey, 1963). Using a spark-powered device of moderate size, Uchupi and Emery (1967, 1968) made 59 profiles at more or less regular spacing across the continental shelf and slope of both the Atlantic and the Gulf coasts of the United States as part of a long-term joint investigation of the features by the Woods Hole Oceanographic Institution and the U. S. Geological Survey. Altogether, the total number of published seismic profiles across the continental shelves and slopes of the United States total only about 100; the number for the rest of the world is only slightly more than half that figure.

The intent of this report is to compare the continuous seismic reflection profiles of the Atlantic and Gulf coasts of the United States with those made in many other parts of the world, and to use the results as a general basis for inferring the commonest structures beneath the continental shelves and slopes. An attempt will be made to include reference to most of the published seismic profiles across continental shelves and slopes in view of their importance for understanding the nature, origin and history of these geological features.

TYPES OF SHELVES AND SLOPES

General

The history of most continental shelves and slopes includes one or more episodes of active tectonism, each followed by a period of relative quiet during which deposition and erosion modified the tectonic topography. In southern California tectonism developed a fault-block topography that subsequently was smoothed by deposition and erosion, but the fault blocks themselves consist partly of strata that may once have been part of an earlier continental shelf. Off the Atlantic coast of the United States the shelf and slope has an early history that is obscured by the great thickness of the sedimentary prism that was influenced only by broad warping during its deposition. In general, the continuous seismic reflection profiles adequately show much of the later history, largely after the most recent tectonism, but they cannot serve as the basis for a worldwide comparison of the entire history of continental shelves and slopes. Accordingly, the classification and discussion of the shelves and slopes, as used in this report, will largely be restricted to the later history of the features, as much as can be inferred from the structures exhibited in the top few hundred meters of section. This section commonly reveals something of the tectonism, the subsequent deposition and the modifications produced by glacial and marine erosion during the Pleistocene Epoch.

Fault-Block Dams

Faults and folds in rocks truncated by wave or glacier erosion are common in seismic profiles from the English Channel, the Gulf of Maine, the Gulf of Mexico, southern California, Alaska and elsewhere, but they affect the shelf topography only as minor faultline scarps, if at all. In areas of active tectonism true fault scarps form small to large topographic irregularities at the margin of the continent as well as inland. Many of the fault scarps, perhaps the most important ones, are parallel to the continental slope. In fact, some have been postulated to truncate the seaward edges of strata on the continental shelf to form continental slopes. Most such suggestions are based upon topographic data and have not been investigated by continuous seismic reflection profiling. Other fault scarps serve as dams to trap sediment brought from land. The general tectonic history of the circum-Pacific belt suggests that these fault-scarp dams are common throughout the belt, and that they were formed so recently that post-tectonic sediments are thin enough to permit easy examination of the fault topography by seismic profiling.

The area that is best known for its fault-block dams beneath the continental shelf and slope is California and northwestern Mexico, where the irregular topography has led to the use of a special term, continental borderland, for the sea floor inshore of the continental slope. The many seismic profiles made by Moore (1960, 1966) and Curray (1965) can be sorted into groups that represent progressive stages of filling of fault-block basins and eventual burial of fault-block ridges by sediments mostly from land (Emery, 1961; Moore, 1966). An early stage is represented by a profile off Mexico (Figure 1) that shows post-tectonic sediment of measurable thickness only in the basin nearest shore; each upthrust block remains as a topographic ridge. The next stage is illustrated by a profile off San Francisco in central California (Figure 2) where a typical profile crosses a fault-block ridge that extends for probably more than 1,000 km near the top of the continental slope (Curray, 1965) and consists of Cretaceous quartz diorite and metamorphic rocks overlain by crumpled Miocene shales (Uchupi and Emery, 1963). The dam forms the seaward edge of the continental

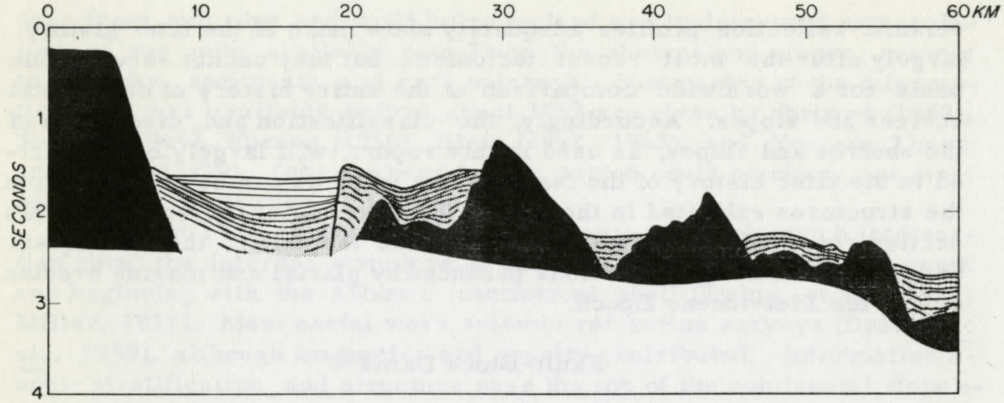


Figure 1. Fault-block topography with little smoothing by post-tectonic (post-Miocene) sediments. The bedrock is volcanic and sedimentary strata of Miocene age off Baja California, Mexico. Redrawn from Moore (1966). For Figures 1 to 11, the vertical exaggeration is 8 at the velocity of sound in water, the solid pattern represents "acoustic basement" rock, the dotted pattern--pre-tectonic sedimentary strata, and the plain pattern--post-tectonic sediments. Two-way travel time.

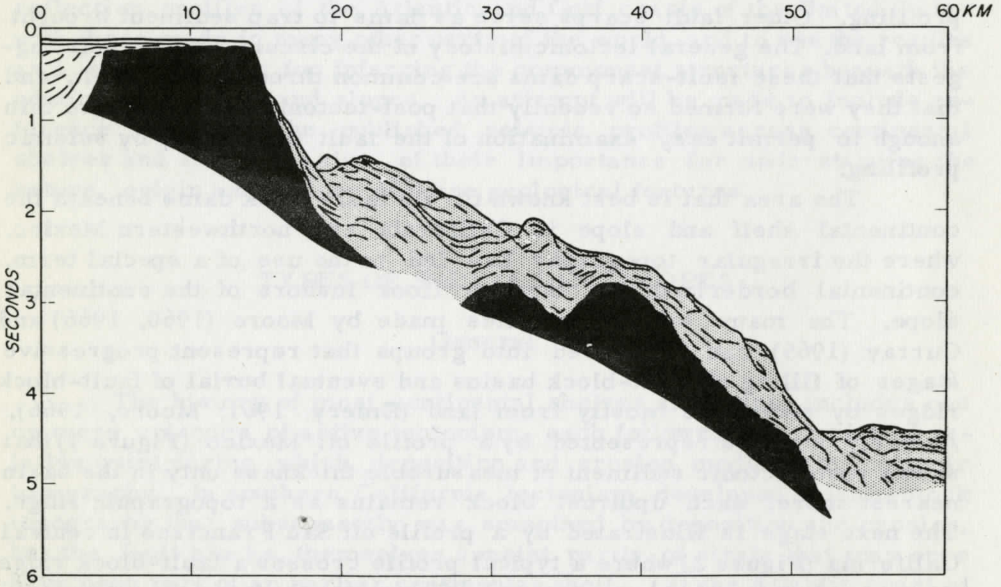


Figure 2. Fault-block dam at the edge of the continental shelf off central California. Cretaceous quartz diorite and metamorphic rocks with folded and crumpled cover of Miocene sedimentary strata have partly been smoothed by post-Miocene sediments. Redrawn from Curray (1965).

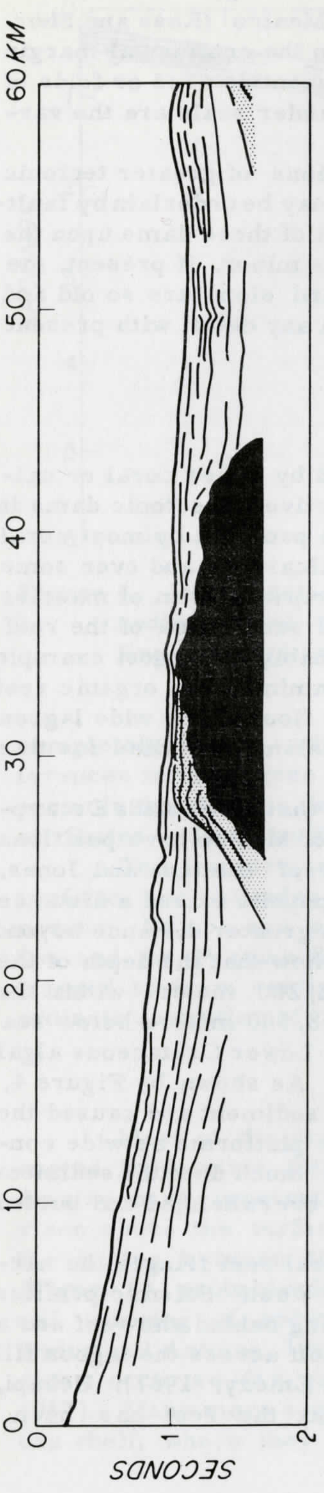


Figure 3. Fault-block barrier in a late stage of smoothing by post-tectonic (post-Miocene) sediments off southern California. Redrawn from Moore (1966).

shelf; wave erosion has bevelled the top of the dam, while post-tectonic sediments have filled the elongate basin between the ridge and the shore. Similar structures occur as far north as Alaska (Scholl, et al., 1966) and as far south as Panama (Ross and Shor, 1965) and perhaps even beyond Peru (Scholl and Von Huene, 1967). The final stage of fault-block damming is represented by Figure 3, which shows the complete burial of a block by sediments whose surface is a smoothly concave depositional profile built from land largely by turbidity currents (Hand and Emery, 1964).

Other examples of fault-block dams have been investigated by seismic profiling off Alaska (Malloy, 1965; Ewing, et al., 1965; Von Huene, et al., 1967). Malloy's study is unique in that it portrays the initial stages, only weeks after the 10-meter uplift of the March 1965 earthquake in Alaska. Representing slightly later stages are studies of the San Andreas Fault along the continental shelf northwest of San Francisco (Curray and Nason, 1967) and of the fault blocks in the Red Sea (Knott, et al., 1966) and in the West Indies (Donnelly, 1965), some of which appear to form the base of coral reefs.

In volcanic areas the volcanoes or faults associated with them can form sediment dams. Examples exist in the West Indies (Hurley, 1966), but sedimentation appears to have been insufficient so far to have developed continental shelves.

Related features that have not been thoroughly investigated by seismic profiling are anticlinal folds that serve as dams for sediment from land. They probably are present in the East China Sea, as indicated by seaward extrapolation of structural trends from land, supported by some rock dredging (Emery and Niino, 1967). Folds rather than fault blocks may also border the shelf off southwestern Mexico (Ross and Shor, 1965). On a much larger scale and unrelated to the continental margin except in the broadest view is the series of concentric arcs or folds of the East Indies (Kuenen, 1950). On an even grander scale are the various island arcs of the western Pacific Ocean.

The continental shelf and slope in regions of greater tectonic stability than the margins of the Pacific Ocean may be underlain by fault-block or anticlinal dams, but the present effect of these dams upon the development of the continental shelf and slope is minor. If present, the dams beneath the Atlantic continental shelf and slope are so old and deeply buried that they cannot be investigated in any detail with present geophysical techniques.

Organic-Reef Dams

The growth of organic reefs (dominated by either coral or calcareous algae) may form dams that are as effective as tectonic dams in trapping sediments. Small-scale examples are provided by most coral reefs, whose lagoons are filled with biogenic calcareous and even some detrital sediments that are retained by a peripheral rim of massive reef which grew upward in response either to subsidence of the reef basement or to eustatic rise of sea level. Probably the largest example of a continental shelf that is due largely to damming by an organic reef is off the northeastern coast of Australia: the floor of the wide lagoon behind the Great Barrier Reef. However, seismic profiles for this area are not available.

Seismic profiles in North America show that the Florida Escarpment and the Campeche Escarpment in the Gulf of Mexico have positions that are controlled by a deeply submerged reef (Antoine and Jones, 1967; Uchupi and Emery, 1968). These escarpments extend a distance of at least 1, 700 km within the Gulf and an even greater distance beyond the Gulf (Ewing, et al., 1966). The profiles show that the depth of the crest of the reef ranges between 1, 900 and 2, 200 meters within the Gulf, and that it continues downward to about 3, 500 meters below sea level. A core sample at 2, 470 meters contains Lower Cretaceous algal limestone (Antoine, Bryant, and Jones, 1967). As shown by Figure 4, the reef has blocked the seaward movement of sediment and caused the building of the Florida and Yucatan carbonate platforms as wide continental shelves. Farther west, off Texas so much detrital sediment was contributed by streams that the reef was overwhelmed and buried by Late Cretaceous sediments.

A shallower and younger (Miocene) coral reef fringes the narrow continental shelf between Miami and Key West. Seismic profiles (Figure 5) across it reveal a lagoon-like filling behind the reef and a subsequent progradation of the continental shelf across the lagoon fill and the reef itself. Other profiles (Uchupi and Emery, 1967); Uchupi, 1966a) show such extensive progradation that the reef has been

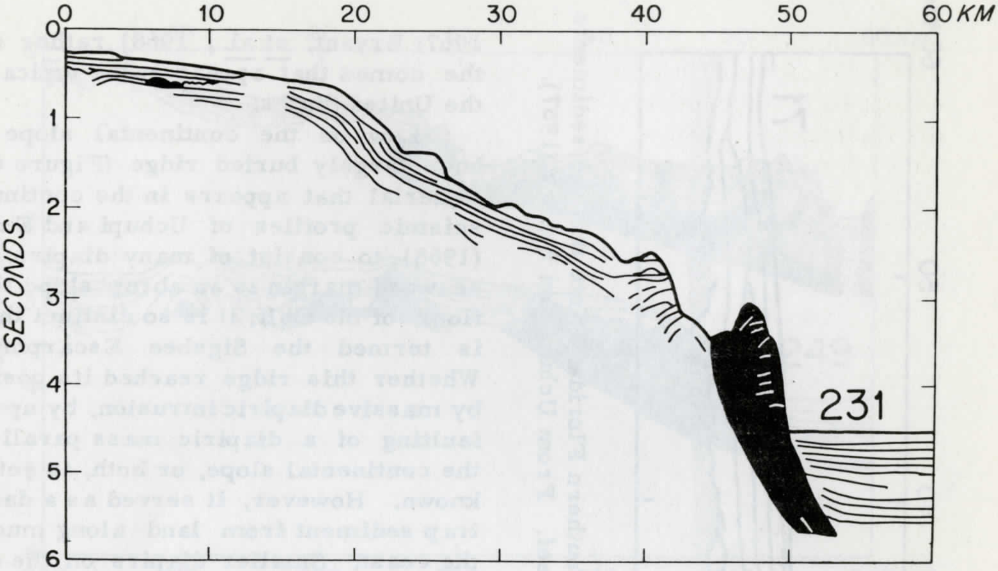


Figure 4. Late Cretaceous algal reef that served as a dam for the sediments of the continental slope off southwestern Florida. From Uchupi and Emery (1968).

completely buried, with no surface indication of its presence. Differences in the degree of progradation appear to account for the differences in topographic level which Jordan, Malloy and Kofoed (1964) had attributed to local faulting.

Temperature controls have limited large Cenozoic calcareous reefs to low latitudes in the western half of the Pacific and Atlantic oceans. Others are present in largely enclosed seas, such as the Red Sea and the Persian Gulf. For the most part, the sediments that are trapped to form continental shelves are biogenic calcareous with subordinate quantities of land-derived detritus.

Diapir Dams

Most of the continental shelf off Louisiana and Texas is interrupted by diapiric intrusions of salt (probably Jurassic in age). The diapirs have penetrated thick Pleistocene and older strata and even risen above the surface of the continental shelf. Detrital sediment in the basins between the diapirs exhibits slumps and unconformities (Figure 6), probably indicating discontinuous movement of the diapirs and trapping of sediment between them (Moore and Curray, 1963a; Ewing and Antoine, 1966; Uchupi and Emery, 1968). Some of the intrusions occur as far eastward as Florida (Antoine, Bryant and Jones, 1967). Many more are present southwestward along much of the Mexican shelf, where they take the form of elongate ridges (Jones, et al.,

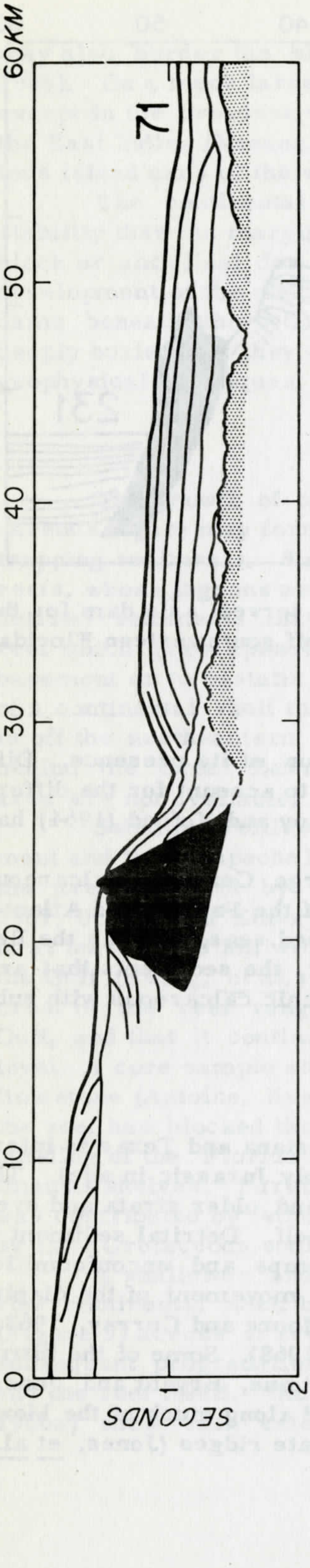


Figure 5. Shelf and slope built across a Miocene coral reef off southern Florida. Note that the sediments have crossed an earlier lagoon filling as well as the reef. From Uchupi and Emery (1967).

1967; Bryant, et al., 1968) rather than the domes that appear to be typical off the United States.

Low on the continental slope is a huge largely buried ridge (Figure 6) of material that appears in the continuous seismic profiles of Uchupi and Emery (1968) to consist of many diapirs. Its seaward margin is an abrupt slope to the floor of the Gulf; it is so distinct that it is termed the Sigsbee Escarpment. Whether this ridge reached its position by massive diapiric intrusion, by upward faulting of a diapiric mass parallel to the continental slope, or both, is yet unknown. However, it served as a dam to trap sediment from land along much of the coast. Smaller diapirs on the deep floor of the Gulf have also been attributed to salt intrusion (Ewing and Antoine, 1966).

A feature similar to the salt domes, but of shallow origin, occurs in the deltas of some large rivers. These are mud lumps or mud diapirs, and they were described for the Mississippi Delta by Morgan (1952, 1961), and have been examined by continuous seismic profiling on the Magdelena Delta by Shepard (1967). As suggested by Matthews (1963), at least one prominence off the Gulf coast of the United States may be a bioherm rather than a salt dome.

Deposition at Grade

In its simplest form the continental shelf and slope that has been deposited in the absence of a barrier or dam illustrates the classical concept of a wave-built terrace. A rare example is given by Figure 7, which portrays continuous beds extending from atop the shelf down the slope and across the adjacent continental rise.

Continuous seismic reflection profiles made with higher power equipment

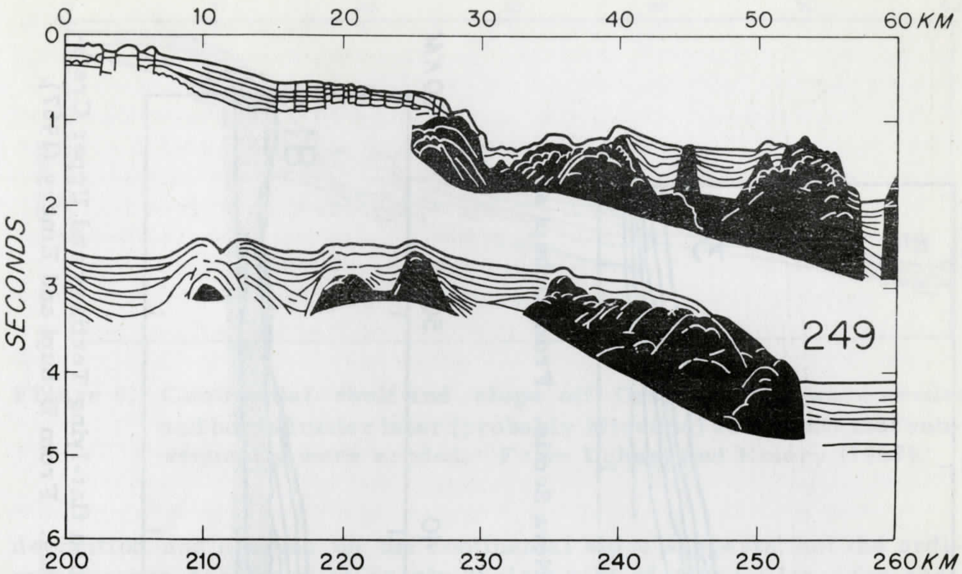


Figure 6. Continental shelf and slope sediments intruded by and deposited between diapiric salt domes off Louisiana. From Uchupi and Emery (1968).

or profiles in different geological environments exhibit many variations in history even in the absence of a well-defined dam. Profiles across the continental shelf off eastern Florida, Georgia and South Carolina are bordered by a slope that extends eastward and downward to the surface of the Blake Plateau. All of them depict a major progradation (Figure 8) atop the Late Cretaceous to Miocene strata of the top of the plateau. The top of the strata is marked by an unconformity believed to have been eroded far below sea level by the Gulf Stream (Pratt, 1966; Uchupi and Emery, 1967). Inferences about the general structure are supported by core data from JOIDES drill holes (Bunce et al., 1965) and by close comparison of a nearby seismic profile with the logs of the holes (Emery and Zarudzki, 1967).

Seismic profiles along most of the Atlantic continental shelf and slope contain many unconformities that slope seaward, as in Figure 9. Ones off Cape Hatteras (Uchupi and Emery, 1967, profile 130; Rona and Clay, 1967) exhibit steeply truncated Tertiary strata, as projected from wells on shore by Heezen, Tharp, and Ewing (1959). In profiles farther north or south this surface of truncation was later mantled by sediments that in turn also have been eroded. The erosional agents probably were chiefly large landslides or slumps (Moore and Curray, 1963b; Andrews, 1967; Uchupi, 1967), but they probably also included turbidity currents and other currents, and even wave erosion prior to downwarping (Krause, et al., 1966). The frequent alternation of

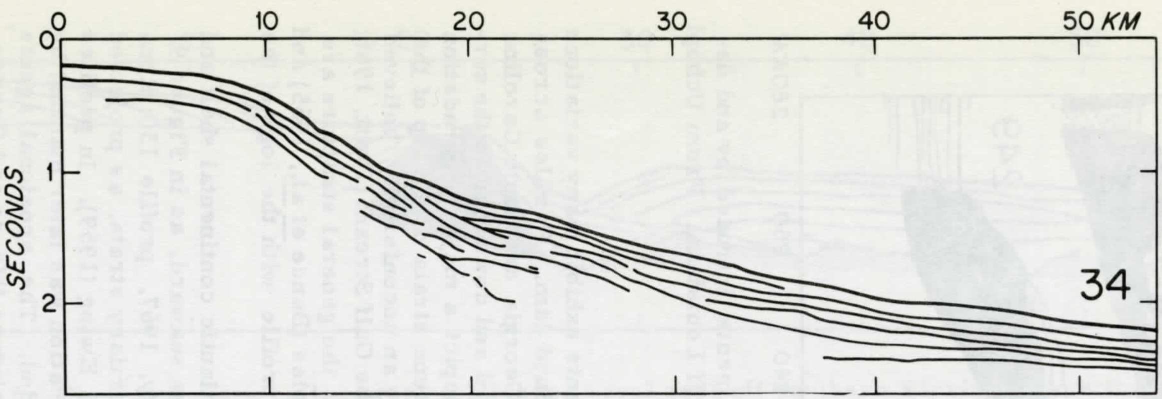


Figure 7. Simple smooth continental shelf and slope off Nova Scotia. From Uchupi and Emery (1967).

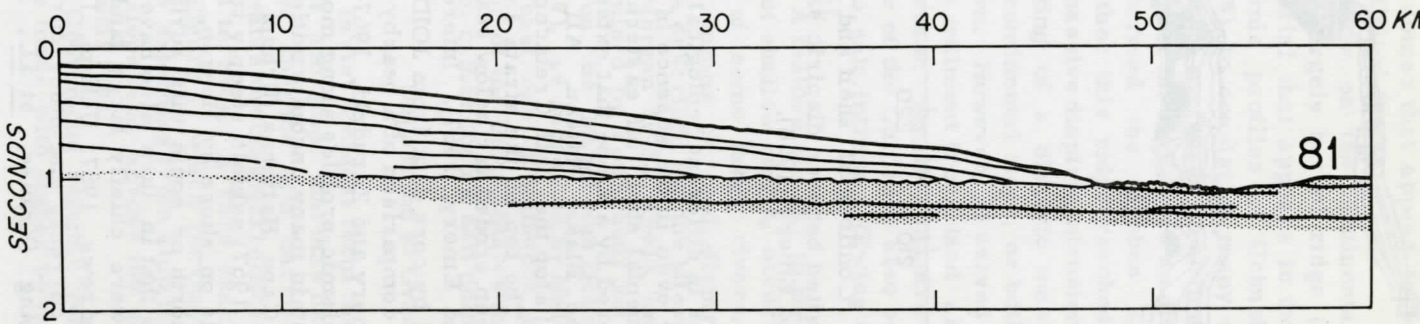


Figure 8. Continental shelf sediments prograded across the eroded flat-lying Tertiary and Upper Cretaceous strata of the Blake Plateau off northeastern Florida. From Uchupi and Emery (1967).

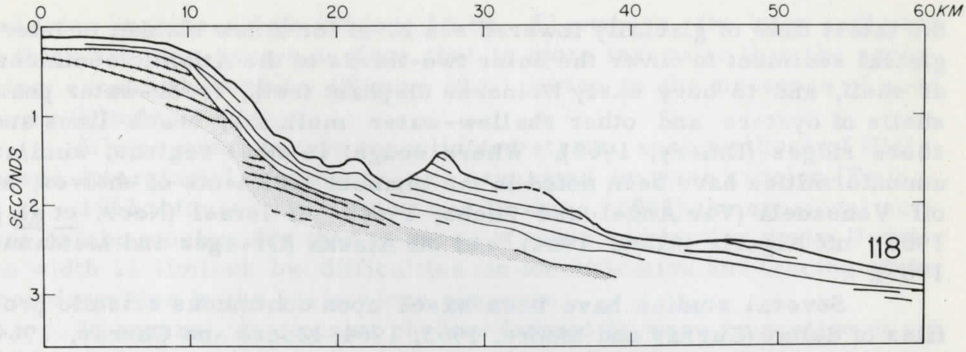


Figure 9. Continental shelf and slope off Delaware that were eroded and buried under later (probably Miocene) sediments that subsequently were eroded. From Uchupi and Emery (1967).

deposition and erosion on the continental slope suggests that the sediments were deposited at nearly their angle of rest (at least for great thicknesses) and that interruptions in the supply of sediments or other relatively minor changes in the environment caused erosion to dominate for a time over deposition. Similar but probably less extensive changes also led to variations in rates of deposition by upbuilding and outbuilding, as described by Moore and Curray (1963a) and Curray (1967).

The continental shelf and slope off Argentina appears to be similar to much of that off eastern United States with its thick accumulations of Tertiary strata (Ewing, et al., 1964; Ewing and Ewing, 1965). A single continuous seismic profile off eastern Africa suggests that the continental shelf and slope there was also probably deposited at grade (Bunce, et al., 1967). The area south and west of Great Britain is similar in that thick Tertiary and Cretaceous strata are generally horizontal on the shelf (but with many small folds and faults) and they steepen at the shelf edge and the top of the slope (Curray, et al., 1966; Hersey and Whittard, 1966). However, this shelf has been extensively eroded by waves and currents so that most or all of the Tertiary section is missing in large areas; thus the shelf has been classified as marine eroded in spite of other characteristics which favor classification as deposition at grade.

Alternation of deposition and erosion atop the shelf off eastern United States is exhibited by detailed profiles of Ewing, Le Pichon and Ewing (1963), of Knott and Hoskins (1968) and of others. The alternation takes the form of nearly horizontal unconformities that separate thin cross-bedded sequences composed of beds that have prograded seaward with an angle of slope that is nearly the same as that near the top of the present continental slope. The average of four or five unconformities in the top 100 meters of shelf strata is just what should be expected of the lowerings of sea level associated with the several glacial stages of the Pleistocene Epoch. Insufficient time has elapsed since the latest time of glacially lowered sea level for a new blanket of interglacial sediment to cover the outer two-thirds of the Atlantic continental shelf, and to bury early Holocene elephant teeth, fresh-water peat, shells of oysters and other shallow-water mollusks, beach lines and shore ridges (Emery, 1968). Where sought in other regions, similar unconformities have been noted in the topmost sediments of shelves, as off Venezuela (Van Andel and Sachs, 1964), off Israel (Neev, et al., 1966), off Nigeria (Allen, 1964), and off Alaska (Creager and McManus, 1965).

Several studies have been based upon continuous seismic profiles of deltas (Curray and Moore, 1963, 1964; Moore and Curray, 1964; Moore, 1964; Shepard, 1967). The deltas have many analogies with depositional shelves and slopes and their sediments are spread far over adjacent shelves and slopes, so for the purpose of this study they are grouped with shelves and slopes that were deposited at grade but are not singled out for detailed discussion.

The evidence provided by continuous seismic reflection profiles shows that the depositional type of continental shelf and slope is far from being a simple seaward progradation from the continents. Instead, there have been many alternating times of deposition and of erosion. Reflection seismic data does not penetrate deeply enough to reveal the initial form of the continental shelf and slope prior to modification by deposition. For example, the initial stage for the continental shelf and slope off eastern United States could have been a fault-block topography as complex as that of Figure 1. After the fault basins had been filled to overflowing (as in Figure 3) the only barrier would have been the limiting angle of deposition, an angle that is gentler than the foreset beds of deltas, but one that has the same function of restricting the seaward distribution of sediments from land.

Wave-Eroded Surface

Some continental shelves appear to have been formed mainly by simple wave erosion of strata that are much older than the date of erosion. The simplest form is one where the shelf truncates intrusive igneous or metamorphic rocks, but these are rare because such rocks are usually so far inland that they are not available for wave erosion. Much more common are shelves that waves and currents have eroded across folded and faulted sedimentary rocks of Early Tertiary, Mesozoic and even Paleozoic age. This type is particularly common off southern California (Moore, 1960), where folded Miocene, Eocene and Cretaceous sedimentary strata have been truncated. It also is typical of northwestern Africa (McMaster and Lachance, 1968) where Tertiary to Paleozoic strata have been eroded. Some seismic profiles reveal the remnants of resistant beds projecting above the general level of the shelf (Figure 10A). Other eroded shelves have been smoothed by thin blankets of Pleistocene and Holocene sediment of both relict nonmarine and later marine origin (Figure 10 B). Elsewhere, the later sediment is thick but may have a surface that is more irregular than the underlying erosional surface (Figure 10 C) owing to the presence of sand waves (Dingle, 1965).

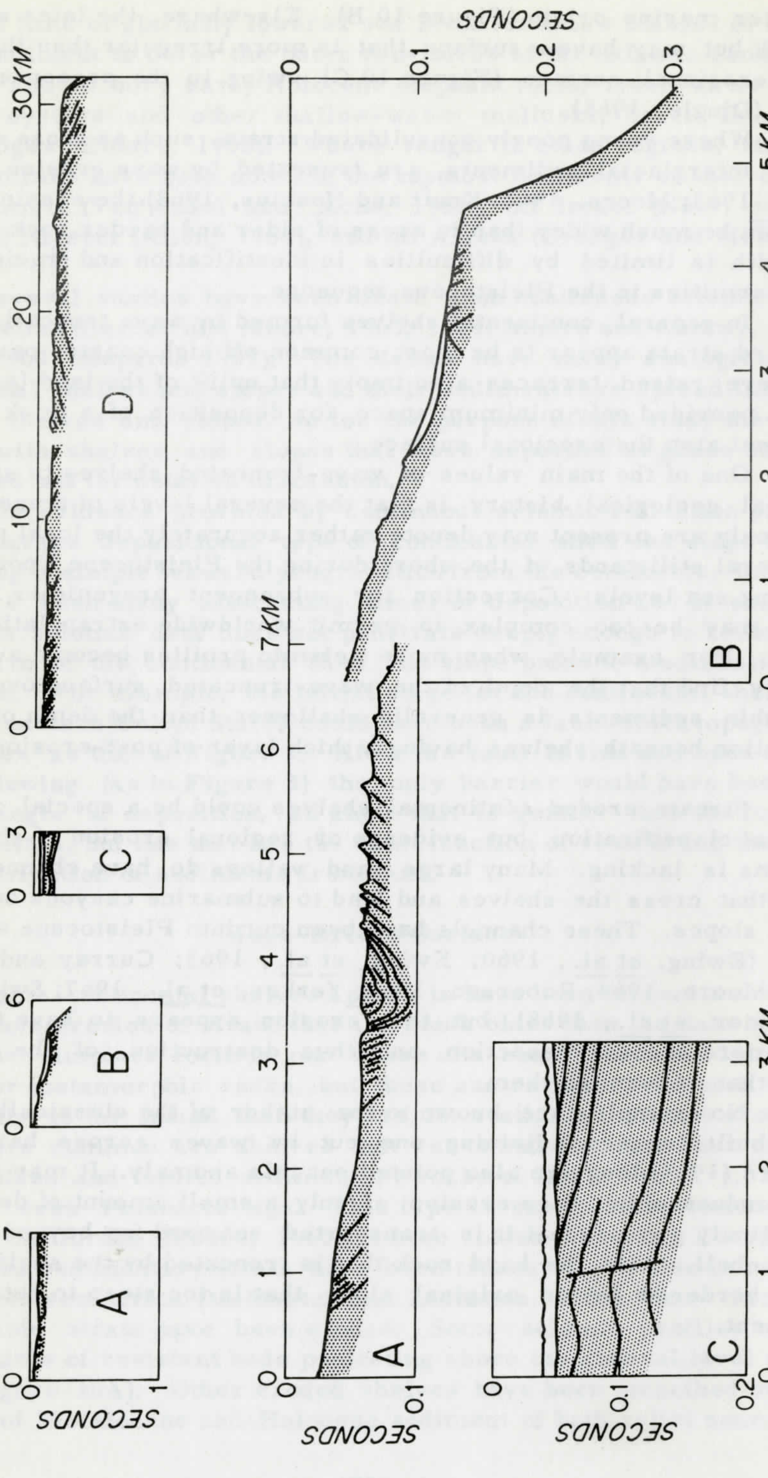
Where young poorly consolidated strata, such as those of Pleistocene interglacial sediments, are truncated by wave erosion (Ewing, et al., 1963; Moore, 1964; Knott and Hoskins, 1968), the erosional surface can be much wider than in areas of older and harder rock. Usually the width is limited by difficulties in identification and tracing of the unconformities in the Pleistocene sequence.

In general, continental shelves formed by wave truncation of old and hard strata appear to be most common off high coasts, particularly where raised terraces also imply that uplift of the land (and of the shelf) provided only minimum space for deposition of a thick layer of sediment atop the erosional surface.

One of the main values of wave-truncated shelves to studies of regional geological history is that the several levels of truncation that commonly are present may denote rather accurately the local positions of several stillstands of the shore during the Pleistocene Epoch of oscillating sea levels. Correction for subsequent orogenic or isostatic uplift may be too complex to permit worldwide extrapolation of the levels. For example, when more seismic profiles become available, we may find that the depth of the wave-truncated surface overlain by only thin sediments is generally shallower than the depth of marine truncation beneath shelves having a thick layer of post-erosional sediments.

Stream-eroded continental shelves could be a special category of this classification, but evidence of regional erosion of shelves by streams is lacking. Many large land valleys do have channel extensions that cross the shelves and lead to submarine canyons on the adjacent slopes. These channels have been cut into Pleistocene and older strata (Ewing, et al., 1960; Ewing, et al., 1963; Curray and Moore, 1963; Moore, 1964; Roberson, 1964; Yerkes, et al., 1967; Swift, 1968; McMaster, et al., 1968), but this erosion appears to have taken the form more of local dissection, and thus destruction, of the shelf and slope than of forming them.

No examples are known to the author of the classically simple wave-built terrace adjoining one cut by waves across hard rock. Shepard (1933) long ago also pointed out this anomaly. It may be due to the production by wave erosion of only a small amount of debris that is so finely ground that it is transported seaward far beyond the edge of the shelf. Also the hard rock that is truncated by the shelf is likely to be bordered by an original slope that is too steep to retain much sediment.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Glacier-Eroded Surface

Rock-floored continental shelves truncated by glacial erosion are common at high latitudes, but few of them have been examined by continuous seismic reflection profiling. Best known is the Gulf of Maine (Uchupi, 1966b), where at least one Pleistocene ice sheet crossed and eroded the Gulf well below the level of a normal continental shelf, of which a remnant is Georges Bank. The glacier eroded granite and probably other intrusive igneous rocks as well as Triassic and Cretaceous shales and sandstones (Figure 11). Bedrock crops out locally as shallow banks and ledges; elsewhere, it is buried beneath glacial till and post-glacial marine sediments mostly thinner than 20 meters.

Another area of glacier-eroded topography off the Atlantic coast occurs between Cape Cod and Long Island. Seismic profiling in Long Island Sound and elsewhere near this coast (Tagg and Uchupi, 1967; McMaster, et al., 1968) shows that the bedrock, largely granites, is irregularly eroded but covered with some post-glacial sediments as in the Gulf of Maine.

Continental shelves similar to the Gulf of Maine also occur off Nova Scotia (King, 1967; Swift, 1968), eastern and northern Canada (Loring and Nota, 1966: Grant, 1966), Greenland, the Baltic Sea (Ulst, et al., 1961), the Irish Sea (Belderson, 1964), northwestern Siberia and southern South America. In each area the shelf is deep, irregular, rocky, and known to have been covered by Pleistocene ice. Some of these shelves also are broad, a reflection of the great erosional power of continental ice sheets. The shelf around much of Antarctica is still beneath the ice sheet and is virtually inaccessible for detailed exploration. In all areas the glacier-eroded shelves contain little post-glacial sediment owing to the short span of post-glacial time and to the probable slow rate of erosion and transportation of sediments from land during this span.

Erosion and deposition by valley glaciers occurred in many of

Figure 10. Bedrock truncated by wave erosion.

A. Miocene strata off southern California with resistant layers projecting above a thin cover of sediment. Redrawn from Moore (1960).

B. Eocene strata off southern California smoothed by cover of sediment. Redrawn from Moore (1960).

C. Probable Cretaceous strata in the English Channel covered with somewhat thicker sediments whose surface is marked with sand waves. Courtesy Edgerton, Germeshausen and Grier, Inc.

D. Tertiary and possibly Mesozoic strata off northwestern Africa with no sediment cover. Redrawn from McMaster and Lachance (1968).

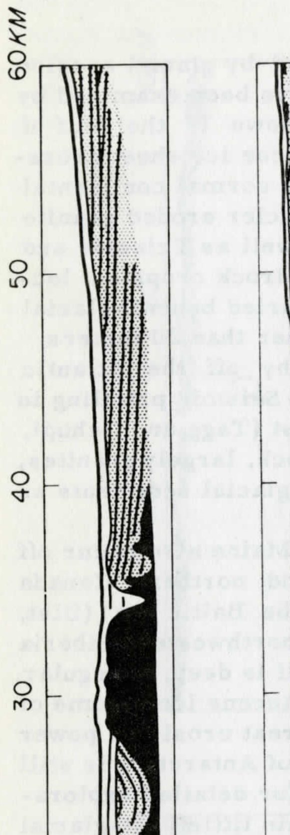


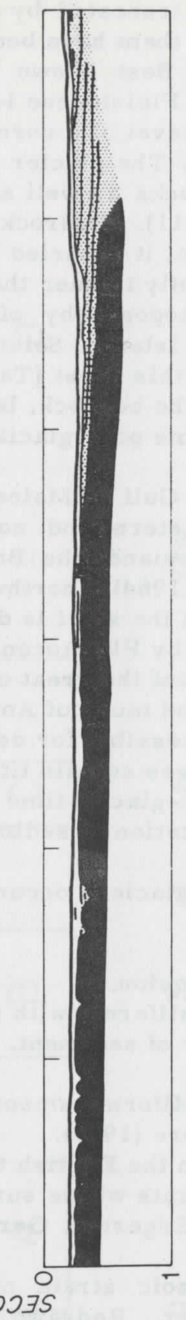
Figure 11. Bedrock truncated by glacial erosion in the Gulf of Maine. Most of the basement rock is probably Paleozoic granite; the sedimentary strata are Upper Cretaceous shales and sandstones that dip beneath Georges Bank to the right. The thin cover is post-glacial sediment. Redrawn from Uchupi (1966b).

the same areas that were crossed by continental glaciers, as well as in areas that were not covered by the larger ice masses. Examples of modification of the continental shelf by valley glaciers are given by continuous seismic profiles off Alaska (Von Huene, 1966; Von Huene, et al., 1967) and Norway (Cone, et al., 1963). As on land, the valley glaciers make the topography more rather than less irregular; thus they, like streams, probably tend more to destroy than to produce continental shelves.

ORIGIN AND DISTRIBUTION

The ultimate origin of the continental slope is the lower density of continental rocks as compared with oceanic rocks that causes the continents to lie several kilometers above the ocean floor. The original slope between continents and ocean basins no longer exists; instead, secondary forms are present, as modified by faulting, folding, warping, deposition of sediments and erosion by landslides, turbidity currents and other currents. These modifying agents are more dependent upon the presence of a steep original slope than upon the flat plane of sea level.

The flatness of continental shelves indicates their control by sea level, through deposition of sediments by currents, glaciers and streams, and through erosion by waves, currents, glaciers and perhaps streams. Many alternations of depositional and erosional agents resulted the same areas that were crossed by continental glaciers, as well as in areas that were not covered by the larger ice masses. Examples of modification of the continental shelf by valley glaciers are given by continuous seismic profiles off Alaska (Von Huene, 1966; Von Huene, et al., 1967) and Norway (Cone, et al., 1963). As on land, the valley glaciers make the topography more rather than less irregular; thus they, like streams, probably tend more to destroy than to produce continental shelves.



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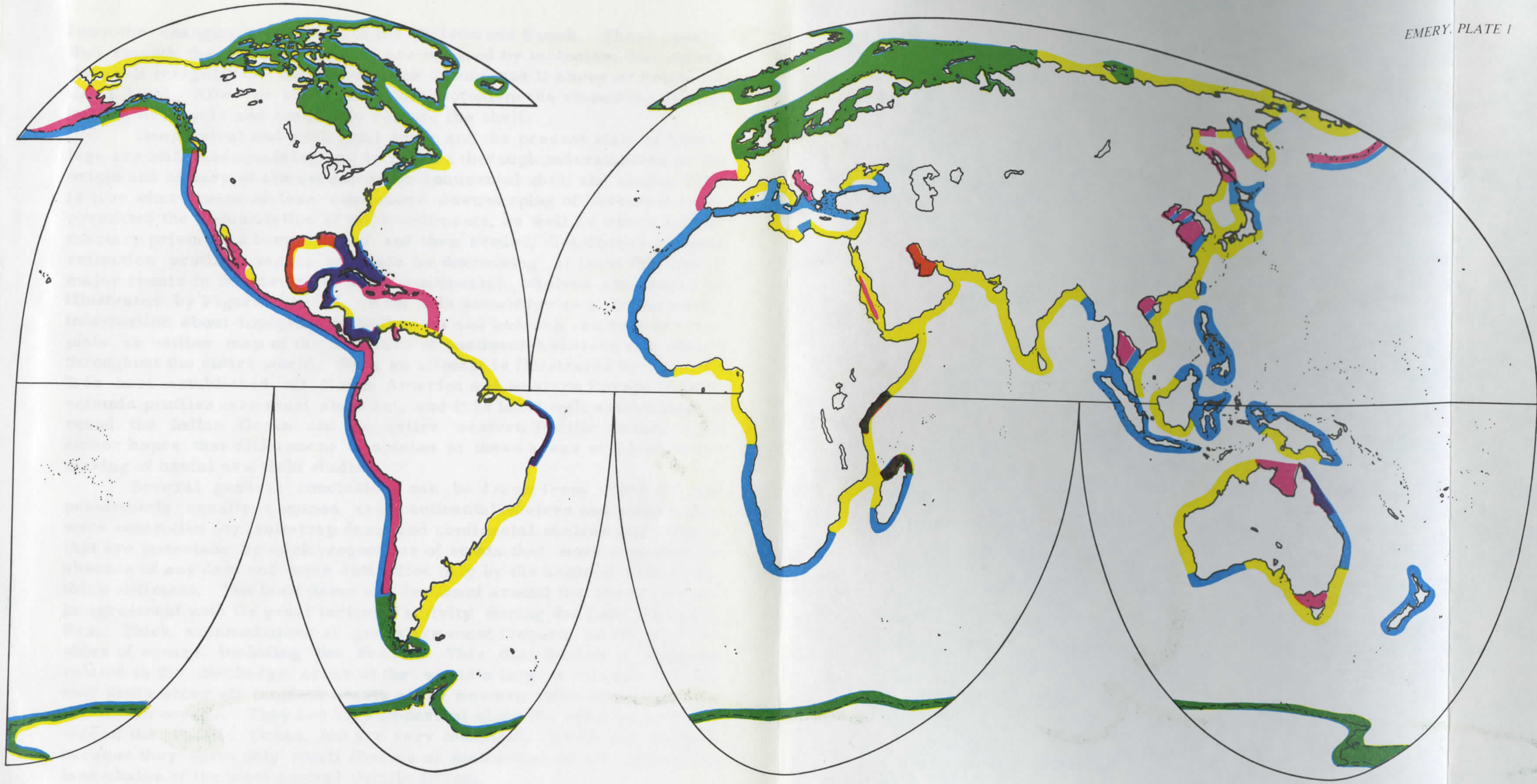
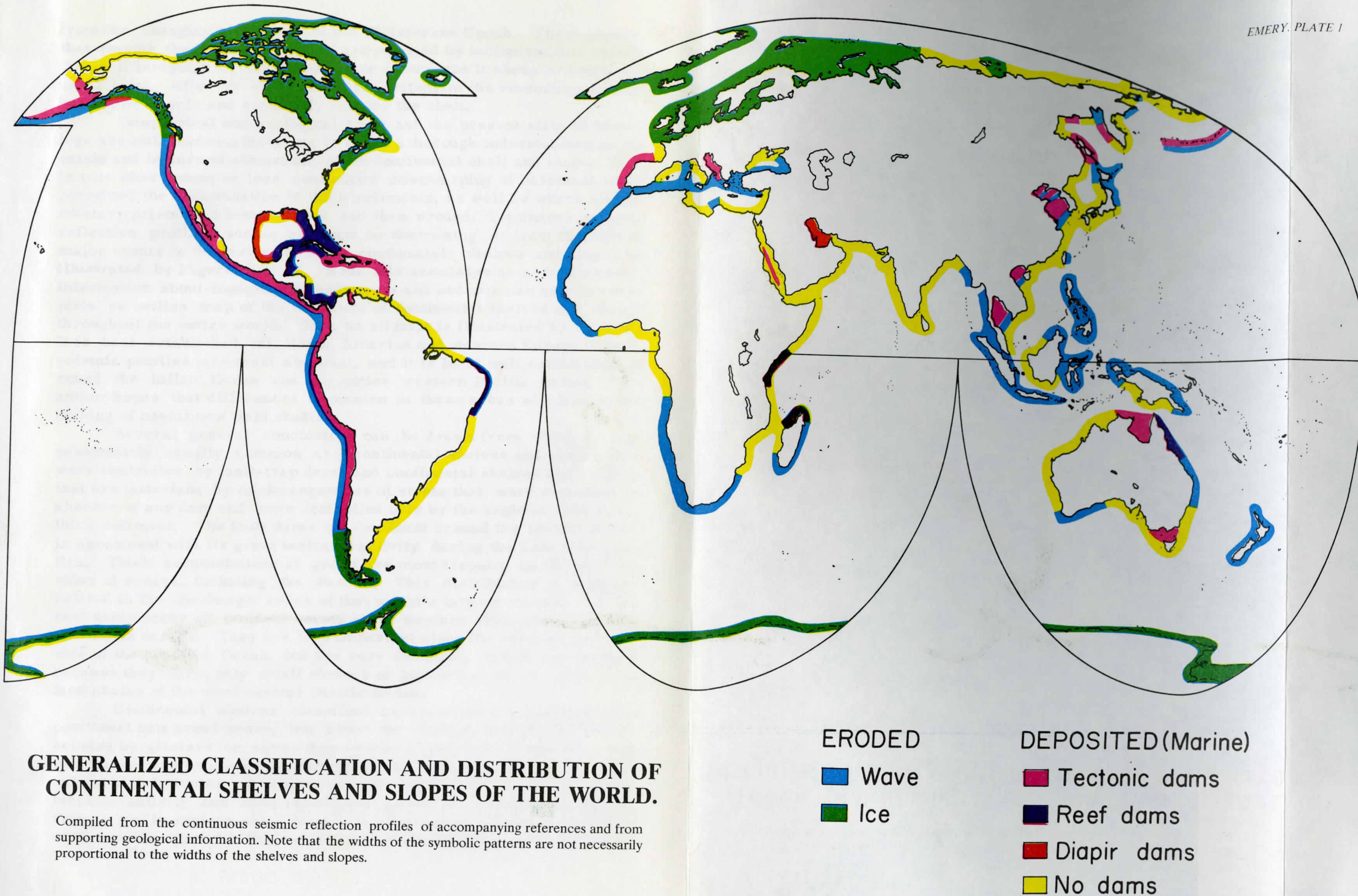


GENERALIZED CLASSIFICATION AND DISTRIBUTION OF CONTINENTAL SHELVES AND SLOPES OF THE WORLD.

Compiled from the continuous seismic reflection profiles of accompanying references and from supporting geological information. Note that the widths of the symbolic patterns are not necessarily proportional to the widths of the shelves and slopes.

ERODED
- Wave
- Ice

DEPOSITED (Marine)
- Tectonic dams
- Reef dams
- Diapir dams
- No dams



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Compiled from the continuous seismic reflection profiles of accompanying references and from supporting geological information. Note that the widths of the symbolic patterns are not necessarily proportional to the widths of the shelves and slopes.

from the changing sea levels of the Pleistocene Epoch. These agents that smooth the continental shelf are opposed by tectonism that makes the shelf irregular or that upwarps or downwarps it above or below its usual level. After or even during the tectonism the smoothing agents begin a new cycle and eventually restore the shelf.

Geophysical and geological tools and the present state of knowlege are still inadequate for one to reach a thorough understanding of the origin and history of almost any given continental shelf and slope. This is true where more or less continuous downwarping of basement rock permitted the accumulation of thick sediments, as well as where a sedimentary prism has been uplifted and then eroded. Continuous seismic reflection profiles seems adequate for determining at least the latest major events in the history of some continental shelves and slopes, as illustrated by Figures 1 to 11. With this knowledge as a framework, information about topography, sediments and bedrock can help to complete an outline map of the structure of continental shelves and slopes throughout the entire world. Such an attempt is illustrated by Plate 1. It is best established off North America and western Europe where seismic profiles are most abundant, and it is least well established around the Indian Ocean and the entire western Pacific Ocean. The author hopes that differences of opinion in these areas will lead to the making of useful new field studies.

Several general conclusions can be drawn from Plate 1. Approximately equally common are continental shelves and slopes that were controlled by fault-trap dams and continental shelves and slopes that are underlain by thick sequences of strata that were deposited in absence of any dam and were controlled only by the angle of rest of the thick sediment. The fault dams are dominant around the Pacific Ocean in agreement with its great tectonic activity during the Late Cenozoic Era. Thick accumulations at grade are most frequent on the western sides of oceans, including the Pacific. This distribution is probably related to the discharge areas of the world's largest rivers. Coral-reef dams occur off tropical coasts at the western sides of the Atlantic and Indian oceans. They are less important along the extreme western side of the Pacific Ocean, but are very abundant, though not mapped because they form only small shelves or platforms, in the tropical island chains of the west central Pacific Ocean.

Continental shelves classified as erosional are commonly depositional in a broad sense, but after the shelves underwent severe erosion by glaciers or waves they received little later sediment. The two classes are nearly equally abundant. Glacier-eroded shelves occur only at high latitudes. Wave-eroded ones are present in regions where tectonic activity has been recent and great (as around the Pacific Ocean), and in regions which have been so stable that downwarping failed to provide space for thick sediments on the shelf (as western Africa).

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QUATERNARY PARALIC AND SHELF SEDIMENTS OF GEORGIA

By

Vernon J. Henry, Jr. and John H. Hoyt
Marine Institute and Department of Geology
University of Georgia
Sapelo Island, Georgia

ABSTRACT

The axiom "the present is the key to the past" serves well in studies of Georgia coastal sediments, particularly when supplemented by its corollary "the past is the key to the present". The latter philosophy is important because Pleistocene deposits associated with former high stands of the sea have not been transgressed and therefore retain the characteristic sedimentological and morphological relationships of the modern coast.

Holocene paralic deposits form a lens 20 to 30 miles wide that straddles the shoreline. A maximum sediment thickness of more than 100 feet occurs along the shoreline and is associated with inlet processes. The recent deposits of fine- to very fine-grained sand thin to a featheredge 10 to 15 miles seaward in 40 to 50 feet of water. Farther seaward the shelf is covered by coarse-grained, relict Pleistocene sediments. Landward of the shoreline the sediments are fine-grained barrier sand, and mixed sand, silt and clay of the salt marsh-filled lagoons. Important features of the salt marsh are the meandering tidal channels which rework the sediment. Sand from subjacent barrier and mainland sediments is incorporated into the channel deposits.

Paralic sediments similar to those of the Holocene accumulated during high stands of the Pleistocene sea. The "high and dry" exposure of the Pleistocene sediments facilitates their study in the third dimension.

INTRODUCTION

During the past several years, the coastal and continental shelf sediments of Georgia have been investigated in a variety of ways including grab sampling, coring, underwater television observation, and seismic reflection and refraction on the shelf and shallow coastal water, and by coring with truck- and marsh buggy-mounted equipment along the coast. Natural exposures of Pleistocene deposits have been valuable in interpreting coastal accumulations, not only for the Pleistocene, but also for the Holocene where it is difficult to observe sedimentary relations except for the few feet above low tide level. Acoustical reflection surveys have not been particularly valuable due to lack of velocity differences in the sandy shelf sediments. Refraction surveys lack resolution to define the thin Quaternary sediments.

Recently a number of studies have described aspects of shelf sedimentation off the Georgia coast. Gorsline (1963) discussed sediment size distribution; Pilkey (1963) investigated the heavy minerals and (1964) the carbonate content; and Pevear and Pilkey (1966) analyzed the phosphorite fraction. The stratigraphic and structural framework of the Georgia shelf and adjacent areas has been studied by Antoine and Henry (1965) from seismic refraction profiles, and by Uchupi and Emery (1967) from acoustical reflection surveys. Core drilling by the JOIDES group (Bunce et al., 1965) has provided stratigraphic information on the shelf off northeastern Florida. Television observations of the shelf surface were discussed by Eddy et al., (1967).

Coastal studies have been done by Giles and Pilkey (1965) on the heavy minerals, Hoyt et al.(1964) on Holocene deposits, Hoyt and Henry (1967) on aspects of inlet sedimentation, and Hoyt and Hails (1967), on Pleistocene stratigraphy. Particularly useful aspects of the burrows of Callianassa major, were discussed by Weimer and Hoyt (1964). Land (1964) described eolian deposits.

Investigations now in progress in the Georgia coastal area include the distribution and inflow-outflow budgets of suspended sediments in estuarine waters (Levy and Henry, 1968), development and diagenesis of Quaternary salt marsh deposits and Pleistocene stratigraphy (Logan and Henry, 1968), and the comparison of Quaternary and Cretaceous coastal environments (Howard, 1966; Howard and Henry, 1967).

Acknowledgements

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CONTINENTAL SHELF

Topography

The Georgia continental shelf is 70 to 80 miles wide and occupies the center of a broad reentrant between Cape Hatteras and Cape Kennedy. Water depth at the shelf break averages about 165 feet, giving an overall slope of about 2 feet per mile. Several distinct changes in slope can be recognized on fathometer profiles across the shelf, however, which suggest a possible relationship with stillstands of the sea during the last transgression (Figure 1). Although their location and

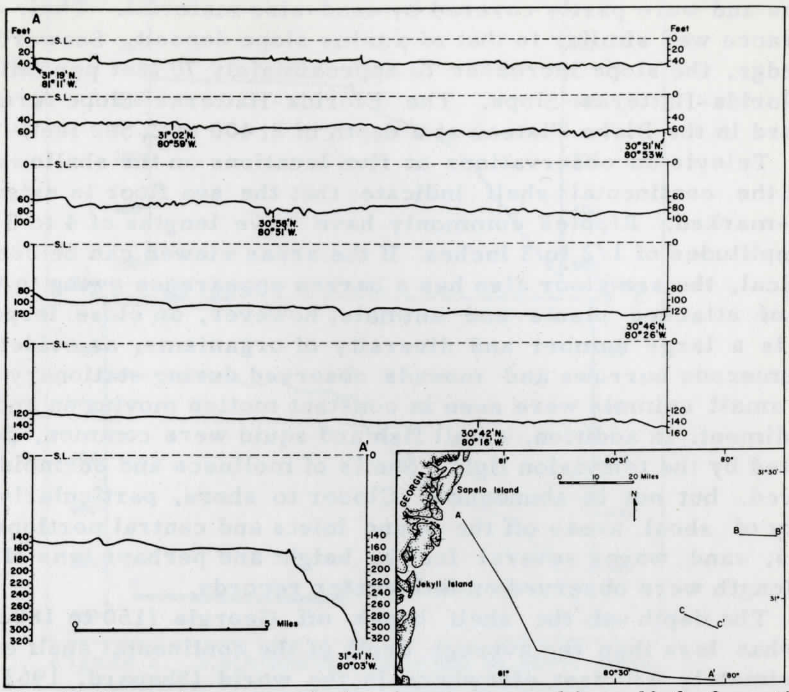

Figure 1. Fathometer record showing topographic relief of continental shelf. Location of traverse shown on map.

depth varies somewhat from profile to profile, as many as five "terraces" can be delineated with associated scarps at depths of approximately 40, 65, 75, 110, and 150 feet. Terrace slopes range from one to four feet per mile and widths from 6 to 25 miles. Relief of the scarp is as much as 24 feet measured from the toe to the terrace surface. The shelf break on most fathometer profiles is characterized by a sharply delineated scarp having approximately 20 feet relief, the crest of which is occupied by a topographic high some 6 to 10 feet above the terrace level (Figures 1 and 2).

Lithified to semi-consolidated rocks are exposed on the sea floor at several locations, but particularly at depths of approximately 60 feet and 150 feet. The rocks in the latter area are believed to represent either a submerged reef-like structure which formed during a low stand of the late Wisconsin sea and, therefore, may be similar to a structure described by Menzies et al. (1966) off the North Carolina coast, or an outcrop of Tertiary (Miocene?) rocks now covered by attached organisms. Brief observations of the shelf edge were made from the R/V Kit Jones during underwater television reconnaissance of the continental shelf. Large blocks of lithified material several feet in diameter were observed as the TV camera was towed up the slope towards the shelf edge scarp. The blocks were encrusted with calcareous growths and were partly covered by sand-size material. Their overall appearance was similar to that of a talus slope deposit. Seaward of the shelf edge, the slope increases to approximately 70 feet per mile along the Florida-Hatteras Slope. The Florida-Hatteras Slope terminates eastward in the Blake Plateau at a depth of 2,400 to 2,500 feet.

Television observations at five locations on the shallower portion of the continental shelf indicate that the sea floor is extensively ripple-marked. Ripples commonly have wave lengths of 4 to 8 inches and amplitudes of 1/2 to 3 inches. If the areas viewed can be considered typical, the sea floor also has a barren appearance owing to the absence of attached plants and animals; however, on close inspection, there is a large number and diversity of organisms, as evidenced by the numerous burrows and mounds observed during stationary views. Many small animals were seen in constant motion moving in and out of the sediment. In addition, small fish and squid were common, perhaps attracted by the television light. Shells of molluscs and echinoids were observed, but not in abundance. Closer to shore, particularly in the vicinity of shoal areas off the sound inlets and central portions of the islands, sand waves several feet in height and perhaps tens of feet in wave length were observed on fathometer records.

The depth of the shelf break off Georgia (150 to 180 feet) is somewhat less than the average depth of the continental shelf edges of approximately 430 feet elsewhere in the world (Shepard, 1963). The shallow depth of the shelf edge is primarily the result of sediment accumulation on the shelf during the Tertiary and Quaternary. The Gulf Stream apparently has effectively reduced sedimentation and in cases has eroded sediments from parts of the slope and Blake Plateau during these periods (Uchupi, 1967).

Structure and Stratigraphy

Seismic profiles across the shelf (Antoine and Henry, 1965; Uchupi, 1967) and core drilling Bunce et al., 1965) indicate that the Cenozoic deposits on the shelf are approximately 2,000 to 2,500 feet thick. These sediments thin to the north and to the east over the Florida-Hatteras Slope and the Blake Plateau and thicken again on the lower continental slope. Cretaceous rocks are about 2,000 feet thick at the shoreline (Maher, 1965). Structure contours on top of the pre-Cretaceous are approximately 4,500 feet below sea level at the edge of the shelf (Antoine and Henry, 1965). Subsurface studies along the coast indicate the pre-Cretaceous basement rises in elevation to the north across South Carolina and is as shallow as 1,400 feet (Maher, 1965) near the crest of the Cape Fear Arch in southern North Carolina. South of Georgia the pre-Cretaceous surface also rises slightly on the flank of the Florida Peninsular Arch and then descends rapidly to over 13,000 feet in southern Florida. The structural low between the Cape Fear Arch on the north and the Peninsular Arch on the south is known as the Southeast Georgia Embayment.

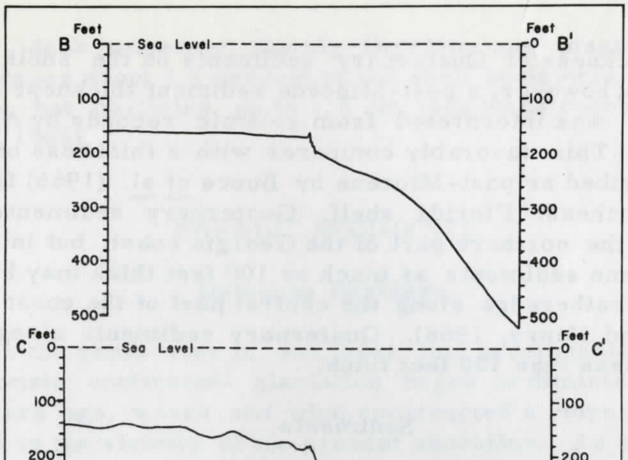

Figure 2. Fathometer records of shelf edge.
Location of traverse shown in Figure 1.

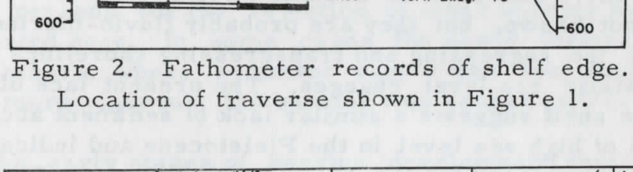

Figure 3. Map showing size distribution of shelf sediments (after Gorsline, 1963; and Pilkey and Terlecky, 1966).

The thickness of Quaternary sediments on the shelf is not accurately known; however, a post-Miocene sediment thickness of approximately 80 feet was interpreted from seismic records by Antoine and Henry (1965). This favorably compares with a thickness of 67 feet of sediment described as post-Miocene by Bunce et al. (1965) from drilling on the Northeast Florida shelf. Quaternary sediments overlie Miocene along the northern part of the Georgia coast, but in the south, possible Pliocene sediments as much as 100 feet thick may be present, thinning to a featheredge along the central part of the coast (Herrick, 1965; Logan and Henry, 1968). Quaternary sediments along the coast are generally less than 100 feet thick.

Sediments

The sediments on the sea floor over most of the shelf are relict Pleistocene deposits. They are primarily medium- to coarse-grained sands and characteristically are iron stained as a result of subaerial exposure during the glacial periods (Figure 3). Subsequent erosion and reworking during transgression apparently has removed the staining in some areas. The time of accumulation of the Pleistocene shelf sediments is not known, but they are probably fluvio-marine deposits associated with the regressing and transgressing shorelines which accompanied eustatic sea level changes. The present lack of Holocene sediment on the shelf suggests a similar lack of sediment accumulation during periods of high sea level in the Pleistocene and indicates a primarily paralic provenance for the Pleistocene deposits. The sediment in less than 40 feet of water is fine- to very fine-grained and is thought to be Holocene in age. It is probable that a part of the nearshore sands were winnowed from the coarser offshore sands during the submergence which accompanied the melting of the Wisconsin glaciers.

The carbonate content of shelf sediment has been studied by Gorsline (1963) and Pilkey (1964). The 50 percent carbonate contour line, the shelf edge and the inner margin of the Gulf Stream approximetely coincide. On the upper slope $CaCO_3$ increases rapidly to nearly 100 percent with foraminifera being the major carbonate component. Over most of the shelf the carbonate content is less than 25 percent and consists mainly of mollusc shells, particularly pelecypods. Echinoid fragments and bryozoans are also common. As pointed out by Pilkey (1964) there are two distinct assemblages of shell material; one shows little fragmentation and wear and may exhibit original color; the other is much bored, fragmented and abraded and has lost all original color. It seems evident that the worn group is older than the other and may date from the Pleistocene; however, this supposition has not been tested by C^{14} dates.

Samples areas of the shelf reported by Gorsline (1963) and Pilkey (1963) contained less than 1 percent heavy minerals and averaged less than 1/2 percent. The dominant constituents of the heavy minerals are opaque, dark minerals, mainly ilmenite and magnetite. Phosphorite averages about 1.1 percent of the shelf sediments and is mostly of sand size, but particles up to 1.5 cm long were recovered (Pevear and Pilkey, 1966).

PARALIC SEDIMENTS

Holocene Barriers

When the rapid rise in sea level that accompanied the melting of the Wisconsin continental glaciation began to diminish some 5 to 6 thousand years ago, waves and wind constructed a ridge just landward of the beach in the vicinity of the present shoreline. As sea level continued to rise slowly the ridge was able to maintain its position and in areas where sediment was abundant successive ridges were constructed thus prograding the shoreline. The area landward of the ridge received very little sediment and was flooded by the rising sea to form a lagoon. Thus, the ridge became a barrier island (Figure 4). This hypothesis of barrier island formation has been outlined in a previous paper (Hoyt, 1967a) and reasons for the rejection of other barrier hypotheses will not be repeated here. In some cases the newly formed barrier prograded, in others, where sediment supply was less abundant or wave attack was more vigorous, the barrier was eroded and/or pushed landward.

In the early stages of barrier development sediment was probably supplied from the sea floor by wave erosion. This was possible because the nearshore profile was not in equilibrium with the wave energy. In addition, river sediment was trapped in the estuaries and not supplied to the shore. Once a profile of equilibrium was established, sediment supply diminished. Further rises in sea level resulted in shore erosion and transgression, as predicted by Bruun (1962) and Schwartz (1967). The filling of the estuaries with sediments will permit the addition of river sediment to the shore and minor quantities now may be entering the marine distributive system (Neiheisel, 1965).

The Georgia coast has the maximum tidal range along the southeastern United States, with spring tides of as much as 10 feet and an average of about 7 feet. The tides are semidiurnal with two nearly equal high and low tides each day. Strong currents are set up in the channels between the islands and in the creeks in the salt marsh. In contrast to the tidal currents, wave energy along the shore is low. Average breaker height at mid-tide along the Sapelo Island beach is about 1 foot and average wave period about 3 seconds (Greaves, 1966).

The Holocene barriers vary considerable in size. Basically, their length is controlled by the location of major inlets inherited from former Pleistocene barriers; however, additional inlets of minor size, subject to sealing, further segment the Holocene barrier chain. Islands

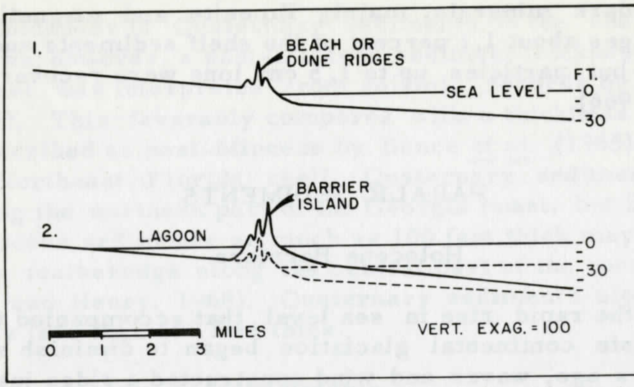

Figure 4. Formation of barrier island by submergence (from Hoyt, 1967a). 1. Beach or dune ridge forms adjacent to shoreline. 2. Submergence floods area landward of ridge to form barrier island and lagoon.

are up to 2 miles wide.

Salt marsh-filled lagoons occupy the area landward of the barrier islands. They also vary considerably in width and in some areas are 5 miles wide. The salt marshes are crossed by a system of tidal channels which are tributary to the inlets. Channels may be as much as 40 or more feet deep, are steep sided and are similar in many respects to fluviatile channels. Point bars develop on the inside of meanders (Land and Hoyt, 1966), and the channels are effectively reworking the marsh sediments. One major difference between the marsh channels and fluviatile channels, of course, is the bi-directional flow in the salt marsh which produces ripple forms which, in some places dip toward the ocean and in others away.

The sediments of the barrier islands are mainly fine, well-sorted, angular sands and the sediments of the beach and dunes are quite similar texturally (Table 1). The low beach sediments are somewhat more poorly sorted as a result of higher percentages of shell fragments. The dune sediments are slightly coarser which is thought to reflect the selective sorting action of the wind; some dune samples contain shell fragments. Furthermore, these are average values and individual samples are sufficiently variable to make the textural differentiation of dune and beach sediment difficult.

Heavy mineral percentage is less than 1 for beach sediments and about 3.5 for dune sediments (Giles and Pilkey, 1965). Heavies characteristically are concentrated on the upper beach and lower dune where values above 5 percent are common. The upper beach and dune have less than 2 percent carbonate based on 22 samples (Giles and Pilkey, 1965); however, shells and shell fragments are abundant in layers 10 to 15 inches thick at about mid-beach.

Table 1. Mean diameter and sorting of beach and dune sediments Sapelo Island, Georgia

	Phi Mean Diameter	Trask Dispersion Coefficient	Number of Samples
Dune	2.50	0.49	14
Mid-Beach	2.55	0.56	14
Low Beach	2.63	0.66	15

The slope of the beach is generally flat with an overall gradient commonly less than 1°, and the seaward dip rarely exceeds 5° (Pilkey and Richter, 1964; Greaves, 1966). A common feature of the beach is a bar and trough (ridge and runnel) which forms on the lower foreshore and migrates up the beach (Hoyt, 1962). The landward face of the bar is much steeper than the seaward face and reaches 30°, the angle of repose for the water-saturated sand. During the period the bar is water-covered, waves wash sand over the top of the bar and deposit it on the steep face of the bar. The bar gradually shifts landward until it approaches the high tide level where it diminishes in height and finally merges with the beach crest. The bar reaches maximum height near mid-beach, where it is as much as three feet high.

For the first mile offshore the sea floor has a slope of 10 to 12 feet per mile, but this rate diminishes rapidly to about 6 feet per mile and 4 feet per mile in the next 2 miles. Farther seaward the slope is characteristic of the continental shelf. Near the major inlets, shallow depths extend farther seaward and bars (subaqueous tidal deltas) may be exposed at low water 3 to 4 miles offshore. Sill depth of the inlet averages only 13 feet below low water at a distance of 5 miles offshore. These features are not found within the estuaries. The major inlets are 50 to 70 feet deep, but holes exceed 100 feet. Maximum depth of the inlets is near the mouth.

A ridge of dunes parallels the shoreline immediately landward of the high spring tide level. Exceptional high water accompanying storms erodes the seaward side of the dunes and removes irregularities; the landward side of the ridge is less regular and shows the effects of the washover at low places between the dunes. Several dune ridges may be developed, each recording the position of the shoreline at the time of formation. Progradation of the shoreline results in the construction of a new ridge. Spacing of the ridges varies from a few yards to several hundred. The seaward ridges commonly truncate older ridges as a result of changes in shoreline position. Dune ridges curve around the south ends of the barrier islands and successive ridges indicate the general southward movement of the islands.

The sediments of the marsh are sand, silt and clay, but the proportions vary from place to place in relation to current energies and source of materials. Coarse sediment is concentrated in the tidal channels, particularly where sand is eroded from an adjacent barrier or from underlying sand deposits of a previous cycle of deposition. Silts and clays settle out in the marsh and along the banks of channels at slack water. The marsh vegetation aids in holding the fine sediment so that it is not removed easily by the flow out of the marsh. The dominant flora of the marsh, the salt grass Spartina alterniflora, grows luxuriantly along the tidal channels where it may be over 8 feet high. Away from the channel banks the marsh grass is commonly 2 to 4 feet in height. The channels are flanked by low natural levees a few inches to a foot in height. Most of the area landward of the barrier is covered by salt marsh and there is little open water except in the major sounds. The vertical range of marsh growth is from mean sea level to spring tide level.

Nearshore Sedimentation

The nearshore sedimentation in the vicinity of Sapelo Island has been studied in detail. More than 600 samples were collected from tidal channel, sound, beach and shallow neritic environments and were analyzed for size, sorting, and coarse fraction composition. Size distribution and sorting are shown in Figures 5 and 6. Mean diameter increases seaward, ranging from fine to coarse sand in size as the boundary between the Holocene and Pleistocene sediment is approached (water depth of approximately 45 feet). Coarse-fraction analyses show terrigenous minerals, mainly quartz, to be the dominant constituents of the sediments, followed by abundant shell material in some areas and low percentages of mica, wood fibre, and foraminifera. Shoals of fine sand develop characteristically off the central sections of the barrier islands, apparently the result of low energy nodes away from the effects of tidal currents sweeping in and out of sound inlets to the north and south. Patches of poorly sorted sediment in the nearshore areas are primarily due to the presence of relatively high percentages of shell fragments, although in the more seaward areas most of the poor sorting is caused by the mixing of modern fine sands with the coarser Pleistocene sands.

SCUBA and surface diving in the shallow water in the vicinity of Sapelo Island indicate that in many places the sea floor is covered with nearly symmetrical ripple marks 4 to 8 inches in wave length and amplitudes of 1/4 to 5/8 inch. Along the inlet channels on the margins of the island and along the bars that flank the offshore extensions of the inlet channels megaripples are common (Hoyt, 1967b). These are asymmetrical ripple marks with amplitudes of 1 to 3 feet and wave length of 20 to 40 feet. They are orientated perpendicularly to the current, with the steep lee face downcurrent. In general the asymmetry is only

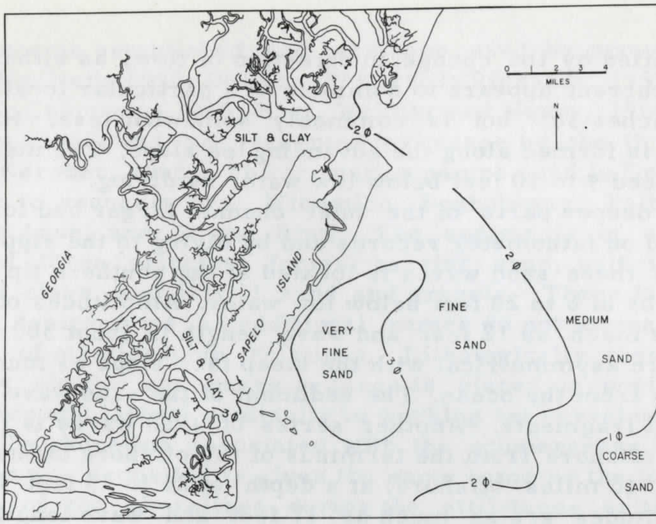

Figure 5. Map showing mean grain size in vicinity of Sapelo Island.

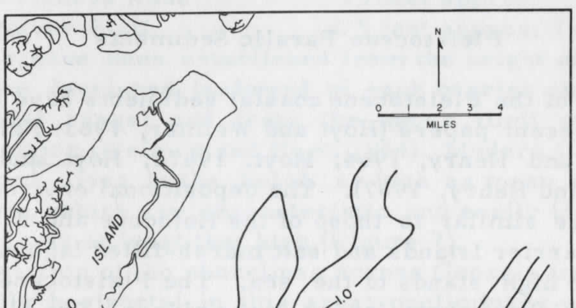

Figure 6. Map showing sorting (Trask dispersion coefficient) in vicinity of Sapelo Island. Low numbers indicate better sorting.

slightly modified by the change in direction of flow, as either the ebb or the flood current appears to dominate at a particular location. The lee slope reaches 30° but is commonly somewhat less. High angle stratification is formed along the advancing lee slope. The megaripples have been traced 9 to 10 feet below low water by diving.

In the deeper parts of the inlet channel larger bed forms have been observed on fathometer records and by diving to the ripple crests. One series of these sand waves is located at the southern tip of Sapelo Island at depths of 6 to 20 feet below low water. Amplitudes of the sand waves are as much as 12 feet and wave length is about 300 feet. The sand waves are asymmetrical with the steep face slope as much as 30°, directed away from the ocean. The sediment of the sand wave is coarse sand and shell fragments. Another series of sand waves is located about a mile offshore from the terminus of the offshore extension of the inlet channel (6 miles offshore) at a depth of 20 to 25 feet below low water. Amplitudes are as much as 17 feet and wave length is about 1,000 feet. Length along the wave crests is over 1/2 mile. These sand waves are also asymmetrical, but the steep slope is directed toward the ocean. The trend of the sand waves is approximately parallel to the coast and they are in line with the extension of the offshore part of the inlet channel.

Pleistocene Paralic Sediments

Aspects of the Pleistocene coastal sediments have been discussed in several recent papers (Hoyt and Weimer, 1963; Neiheisel, 1962; Hoyt, Weimer and Henry, 1964; Hoyt, 1967c; Hoyt and Hails, 1967; Hoyt, Weimer and Henry, 1967). The depositional environments of the Pleistocene were similar to those of the Holocene and it is possible to trace former barrier islands and salt marsh-filled lagoons which were associated with high stands of the sea. The Pleistocene record indicates that the highest shorelines are the oldest. The alternate waxing and waning of continental glaciers during the Pleistocene resulted in fluctuations in sea level. The barrier systems exposed on the surface have not been transgressed by subsequent submergences; however, there may be other barrier systems which were transgressed and are not recognized. The preservation of the Pleistocene sediments permits the identification of barrier islands from geomorphic, stratigraphic, and sedimentologic evidence.

Six systems of former barrier island chains can be identified from the shoreline to an altitude of approximately 100 feet. The barriers and salt marsh-filled lagoons of each system were named and referred to as terraces by early investigators (Veatch and Stevenson, 1911; Cooke, 1943). The sediments of each terrace were given formation names in agreement with the terrace names. The early work showed that the formations could be traced along much of the southeastern United States and widespread correlations were made. The formation names became established and have been used by many later investigators (MacNeil, 1950; DuBar, 1958, 1962; Richards, 1959, 1962; Doering, 1960; Colquhoun, 1965; Hoyt, Weimer and Henry, 1964, 1967; Hoyt and Hails, 1967) and are accepted for usage by the U. S. Geological Survey (Keroher, 1966). The formation names used in Georgia in order of oldest to youngest are: Wicomico, Penholoway, Talbot, Pamlico, Princess Anne, and Silver Bluff. The sediments of each formation consist of three principal facies; barrier sand, salt marsh-lagoon, silts and clays, and fluvial sand and gravels. These facies are given informal designations as additional names do not increase the understanding of stratigraphic relations. Lithologically these formations are very similar and heavy reliance is placed on position within the sesequence and lateral continuity in working out correlations.

The shoreline associated with the submergence during which a formation was deposited is given the same name as the formation. The altitudes of the shorelines during the stillstands or times of major sediment accumulation are as follows:

Wicomico	95-100 feet (oldest)
Penholoway	70-75 feet
Talbot	40-45 feet
Pamlico	24 feet approx.
Princess Anne	13 feet approx.
Silver Bluff	4.5 feet approx. (youngest)

The altitudes have been established from the height of the former salt marsh surface developed landward of each barrier chain (less 1/2 the estimated tidal range) and from the upper limit of the burrows of Callianassa major (Weimer and Hoyt, 1964). Modern C. major, a burrowing decapod, lives in the beach as high as mean sea level and the fossil burrows, which are characteristic and easily identified, indicate that sea level was at least that high (Figure 7).

Correlation of the shorelines across Georgia indicates that they are essentially horizontal in this area; preliminary work to the north and south of Georgia indicates that at least the lower 3 shorelines are horizontal along much of Florida and South Carolina as well. The highest shoreline, the Wicomico, is warped from approximately 100 feet in southern Georgia to as much as 160 feet east of Starke, Florida (Hoyt, 1967c). The Penholoway shoreline, which has an altitude of 70 to 75 feet in Georgia, is also warped in northern Florida and reaches an altitude of 95 to 100 feet east of Starke. The Wicomico and Penholoway shorelines appear to be approximately horizontal in South Carolina (Colquhoun, 1965).

Although the barrier and the salt marsh lagoon facies of the 6 Pleistocene formations can be recognized along much of their respective shorelines, there are areas where erosion has removed segments of the former barriers. Apparently in places where the barriers and sediment supply were small, the barrier sand was thrown back over the salt marsh and/or transported down current so that salt marsh-lagoon

Figure 7. Photo of Callianassa major burrows from barrier island facies of Pamlico formation, Reids Bluff, Florida (south bank of St. Marys River).

sediments were exposed along the shoreline. Remnants of the salt marsh-lagoon are nearly always present, but are less than 1/4 mile wide along a few sections of the former shorelines. Similar erosion of the beach and exposure of salt marsh occurs along the modern coast.

The size and extent of the former barriers vary considerably; the largest and highest barriers make up a topographic feature known as Trail Ridge which extends from the Satilla River in southern Georgia to southeast of Starke, Florida, a distance of over 100 miles. The Trail Ridge barriers marked the Wicomico shoreline and had dunes as high as 70 feet above the Wicomico sea level in southern Georgia. Dunes along other shorelines rarely exceeded 30 feet and are more comparable with the dune development along the modern coast.

The salt marsh lagoons also varied in width. The Wicomico salt marsh landward of Trail Ridge was as much as 14 miles wide in Georgia. The former salt marsh is now occupied by the fresh water Okefenokee Swamp. The Pamlico salt marsh was almost 20 miles wide east of Hinesville, Georgia.

Drilling and natural exposures indicate that the salt marsh lagoons commonly had a thickness of 10 to 15 feet, although in areas reworked by meandering tidal channels they may be as much as 50 feet thick. The sediment, as in the Holocene salt marsh, is sand, silt, clay, and minor amounts of gravel. Gravel is more abundant in the older deposits. Cross bedding related to channeling is common. The marsh sediments weather a reddish to orangish color, and are mottled with gray.

Barrier sediments are commonly 20 to 40 feet in thickness; however, where dunes were well developed they may be thicker. They are also thicker near inlets, where they interfinger with the more variable lithologies of the inlet. In many places the barriers have been driven landward over the adjacent salt marsh and may be only a few feet thick. In these cases the remnants of the barrier may be only a ridge surrounded landward, seaward and beneath by the finer sediment of the salt marsh. In many respects the sand ridge resembles a chenier; however, this terminology is to be avoided when the ridge originally developed as a barrier (Hoyt, 1967d; in press). Cheniers develop in different sedimentological conditions from barriers and have a different sequence of marsh-ridge history.

Inlet and channel sediments range from small gravel to clay in grain size. Gravels and sands are commonly cross-bedded and also interbedded with silts and clays. There is generally enough iron in the deposits to result in red to orange coloration when the deposits are weathered.

Barrier island deposits, including littoral, dune and nearshore neritic, are mainly well-sorted fine-grained sand. Due to weathering of the surficial deposits, dune stratification is rarely observed. Cross-bedding in the littoral and shallow neritic sediments is common, from small scale structures only a few inches along the bedding plane to large scale features several feet in length. The angle of repose for these sands is about 30°, but dips of this magnitude rarely are observed; more commonly dips are less than 20°. The barrier sands characteristically develop an organic-rich, dark brown to black humate layer that cements the sand grains together forming a hard resistant layer that stands in blocks in stream banks or in road cuts. The humate also is relatively impervious so that swamps and ponds are common on top of the barrier sands.

Fossils are rare in surface exposures of Pleistocene sediments because of the leaching and weathering characteristic of this area. In permeable sediments, the calcium carbonate is removed but carbonate fossils may be preserved in silts and clays. Leaching extends to a depth of 15 to 25 feet. An exception to fossil destruction in the surface sediments is the burrow structure of Callianassa major which may be abundant to very abundant in some littoral and shallow neritic sediments (Figure 7). The fossil burrows, Ophiomorpha major, are common in the barrier facies and rare in the lagoon-salt marsh deposits. In some barrier deposits leached outlines of molluscs are abundant and would approach a coquina if the carbonate were preserved.

Correlation of the Pleistocene shoreline sequences with the corresponding interglacial stages is tentative. Uranium-series dating of coral from the Bahamas, Florida Keys and Barbados suggest high stands of the sea at 82,000, 122,000, 190,000 and possibly 103,000 years B. P. (Broecker and Thurber, 1965; Broecker et al., 1968). Dates of approximately 122,000 years B.P. were obtained from the Miami Oolite and Key Largo Limestone. These formations are believed to have been deposited during the Pamlico high stand of the sea. The Princess Anne could date from either about 103,000 or 82,000 years ago, depending on the validity of the 103,000 date and the Silver Bluff high stand of the sea could be 82,000 years B. P. or younger. Five radiocarbon dates from the Silver Bluff Formation in the vicinity of Sapelo Island, Georgia, gave dates ranging from 25,475 to 36,200 years B. P. (Hoyt, Weimer and Henry, 1967; Hoyt and Hails, in press). Three additional samples gave infinite ages. Many dates from other coasts of the world are in the range between 25,000 and 40,000 years ago for wood and shell samples from marine shorelines comparable to the Silver Bluff (Sackett, 1958; Miller and Dabrovolry, 1959; Curray, 1961; Coope, Shotton and Strachan, 1961; Armstrong et al., 1965; Brown, 1965; Hopkins, 1965; Schnable, 1966; Faure and Elouard, 1967). A major retreat of the continental glaciers has been noted at this time and is called the Farmdale-Plum Point-Talbot interstadial in North America (DeVries and Dreimanis, 1960; Frye and William, 1963) and the Paudorf-Gottweig in Europe (Gross, 1958). A retreat of mountain glaciers comparable to present conditions is also noted at this time (Morrison, 1965; Richmond, 1965). The reliability of radiocarbon dates older than 30,000 years is open to question because of problems of contamination and these dates are given to present a complete picture of information available. Additional investigation is needed to determine whether the samples have been contaminated. One anomaly is noted; whereas, some of the Silver Bluff samples give finite dates, samples from Pamlico deposits from similar environments have given infinite dates (DuBar, 1962). If contamination is a problem, then some of the Pamlico dates should be finite also.

CONCLUSIONS

Quaternary paralic sediments of the Georgia coast can be divided into six Pleistocene formations and Holocene sediments. These sediments were deposited in environments associated with barrier islands formed during high stands of the sea which accompanied melting of the continental glaciers. There has been a long-term lowering of sea level throughout the Pleistocene caused by increased storage of water in Antarctica and Greenland, by tectonic depression of a part of the sea floor, or other causes. The fluctuations of Pleistocene sea level are superimposed on this general trend.

There is insufficient information for a subdivision of Pleistocene shelf sediments. It is assumed that these sediments were transported to the shelf by rivers during periods of lower sea level and have been reworked and distributed over the shelf by marine agencies. Some sand grains on the shelf are iron-stained as a result of subaerial exposure; the reworking during the Holocene transgression was insufficient to remove the stain from all grains.

The barriers of the Georgia coast initially formed as a dune ridge immediately landward of the shoreline. Subsequent partial drowning of the ridge resulted in barrier islands and lagoons. The barriers continued to grow upward and seaward with continued submergence and the lagoons have been partially filled to form a salt marsh. The fine-grained sediments of the barriers were derived from the sea floor during the Holocene transgression. These sediments may have a long history of reworking and may have moved tens of miles across the shelf during the submergence. Coarse-grained sediments remained as lag on the shelf. Major rivers are still filling their estuaries and only minor amounts of coarse sediments are added to the barrier systems. The barriers continued to increase in size until a profile of equilibrium was established in the nearshore area and slight additional submergence during modern times has resulted in transgression to maintain the equilibrium profile.

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COMPOSITION OF DEEPER SUBSURFACE WATERS ALONG THE ATLANTIC CONTINENTAL MARGIN[1]

By

F. T. Manheim
U. S. Geological Survey
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

and

M. K. Horn
Cities Service Oil Company
Tulsa, Oklahoma

ABSTRACT

The composition and distribution of deeper subsurface waters beneath the Coastal Plain and continental margin of the eastern United States are poorly known. We have utilized semi-quantitative evaluation of available electrical logs from oil tests, existing water analyses, literature studies from specific areas and analyses of pore fluids from recent drill cores to assemble a rough preliminary sketch of total salt content in deeper sedimentary formations from Long Island to Key West, Florida.

Chief findings include:

1. Sediments in the first 1000 m generally are greatly influenced by meteoric waters. In the Georgia-South Carolina area potable waters may occur beneath saltier layers at depths greater than 1000 m, and also at distances more than 120 km seaward of the coast. Fresh-water flushing and submarine discharge were probably very marked during lowered Pleistocene sea levels along the entire Atlantic coast of the United States, south of Cape Cod.

2. Irregular fluctuations between brackish and saline waters characterize deeper waters, with a pronounced tendency for increase in salinity with depth. Salt concentrations greater than 100, 000 ppm are found in pre-Upper Cretaceous sediments in the Salisbury Embayment (Maryland and Delaware), Hatteras Embayment, southernmost Georgia and beneath all of Florida. Maximum salt concentrations are on the order of 250, 000 ppm total dissolved solids (about 300 g/l at room temperature).

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3. Concentrated brines seem to be associated with redbeds and evaporitic sediments.

4. Salt filtration by clay membranes appears inapplicable to the Coastal Plain strata; rather, clay membranes promote osmotic flushing of salty strata by fresher waters.

INTRODUCTION

The systematic study of deeper subsurface waters on the Atlantic continental margin has been neglected, probably because it falls between two areas of strong interest: hydrologic studies directed toward potable waters, and oil exploration, which has neglected waters outside potential reservoirs of oil and gas.

As a step toward understanding the history and migration of fluids and solutes in sedimentary strata of the eastern margin of the United States, we have prepared a synthesis of the distribution of water composition in deeper strata from Long Island to Key West. Water analyses are available from a number of deep wells in Florida, but there are very few analyses of deep waters from the remainder of the continental margin. Moreover, the available water analyses frequently provide only minimum figures for salt content, unless there is evidence that admixture of fresher drilling fluid was excluded. In addition to water analyses, an essential tool has been electrical logs from deep oil tests, which we used for semi-quantitative estimates of pore-fluid composition in permeable strata. Many gaps in information necessary to apply this technique have been bridged by assumptions and guess-work, which render errors and inaccuracies unavoidable. We emphasize that the salinity patterns shown for deeper strata are strongly generalized in many cases, covering as they do both highly irregular fluctuations in salinity, as well as considerable uncertainty in the estimates of the values. Different interpretations are doubtless possible.

We justify our efforts by our belief that major features do emerge through the background noise, and some significant but unanswered questions are raised by the synthesis.

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METHODS

The chief tool for electrical log analysis has been the SP (spontaneous potential) log. Logs used in this study are listed and identified in Table 1. A major part of the SP variations observed opposite permeable formations is provided by the contrast between the stratal or formation fluids and the borehold fluid (mud filtrate). This relationship can be stated in simplified form by

$$E_c = -K \log R_{mf}/R_w \qquad 1)$$

where E_c is the electrochemical component of the SP, K is a constant dependent on temperature, R_{mf} is the electrical resistivity of the mud filtrate and R_w is the apparent resistivity of the formation fluid.

In principle, the electrical resistivity of fluid permeating the permeable zones can be obtained by substituting the observed SP anomaly with respect to the "shale" baseline, and the temperature-corrected resistivity of the mud filtrate into 1), and solving for R_w. Equivalent salt concentrations for an assumed NaCl solution may then be obtained from R_w by assuming that the formation fluid is a pure NaCl solution. These operations were performed following the scheme and departure curves provided by Schlumberger (1958, 1962), using a computer program developed for the purpose. Temperature-corrected values of mud filtrate resistivity were obtained by linear interpolation between mud resistivity at surface temperatures and bottom-hole temperatures noted on the logs, and from nomograms for the relationship of mud resistivity to mud filtrate resistivity provided in the Schlumberger handbooks.

Many complications and potential sources of error were not taken into account in the computer-derived "salinity" values. These complications include the influence of bed thickness and mud filtrate invasion into the permeable formations; failure to correct for these often leads to low potentials and consequent underestimation of the salt content of the formation fluids. Temperatures in the borehole rarely follow linear patterns. Some logs did not provide bottom-hole temperatures; where these were considered especially important, temperature gradients from other holes in the same general area were sometimes applied to obtain the very important temperature corrections. Standard relationships for mud and mud-filtrate resistivities, and the NaCl dominance assumed for both mud and formation fluid do not necessarily

Table 1. Deep Wells Utilized in Figure 3.
Sources not given in references are listed below. Depths are given in original foot units, usually from drill floor.

FGS	Florida Geological Survey, Tallahassee, Florida
Meyer, 1968	F. W. Meyer, U. S. Geological Survey, Miami, Florida, pers. comm.
Ridgway	L. L. Ridgway Co., Inc., P. O. Box 2277, 103 E. Pearl, Jackson, Miss.
GGS	Georgia Geological Survey, Atlanta, Georgia
Murrah, 1968	W. E. Murrah, Humble Oil Corp., New Orleans, La., pers. comm.
Brown, 1968	P. M. Brown, U. S. Geological Survey, Raleigh, N. C., pers. comm.
Siple, 1968	G. E. Siple, U. S. Geological Survey, Columbia, S. C., pers. comm.
Sampair, 1967	J. L. Sampair, North Carolina Conservation Board, Raleigh, N. C.
Wilder, 1968	H. B. Wilder, U. S. Geological Survey, Raleigh, N. C., pers. comm.
Wait, 1968	R. L. Wait, U. S. Geological Survey, Richmond, Va., pers. comm.

NAME OF WELL	COUNTY	STATE	TOTAL DEPTH (feet)	SOURCE
Gulf Oil Corp. & Calif. Co. Marquesas OCS	Monroe	Fla. (offshore)	15,290	FGS
Fla. East Coast Railway (Key West)	Monroe	Fla.	2,555	FGS
Gulf Oil Corp., FSL 826G (Florida Bay)	Monroe	Fla. (offshore)	12,260	FGS-Hohout, 1967
Peninsular Oil Co., Cory	Monroe	Fla.	10,006	Ridgway-FGS
Sunniland oil field & vicinity	(Collier) (Hendry)	Fla.	12,800	Ridgway-FGS-Meyer, 1968; Babcock, 1962
Gulf Oil Corp., FSL 10004	Hendry	Fla.	12,810	Ridgway-FGS-Meyer, 1968
Serio Oil Co., Barnett (40 Mile Bend)	Dade	Fla.	11,616	Meyer, 1968
La Gorce Golf Course Miami Beach	Dade	Fla.	--	Black and Brown, 1951
Gulf Coast Dr. & Explor. (40 Mile Bend)	Dade	Fla.	--	Meyer, 1968
Humble Oil Corp., Tucson	Palm Beach	Fla.	12,765	Ridgway-FGS
Amerada Petrol. Corp., Cowles Mag. #2	St. Lucie	Fla.	12,736	Ridgway-FGS
Humble Oil Corp., Carroll	Osceola	Fla.	8,049	Ridgway-FGS
Sun Oil Co., Powell	Volusia	Fla.	5,956	Ridgway-FGS
Humble Oil Corp., Foremost Properties #1	Clay	Fla.	5,861	Ridgway-FGS
Humble Oil Corp., Campbell	Flager	Fla.	4,618 (log)	Ridgway-FGS
Jacksonville Test Well (U. S. Geol. Survey)	Nassau	Fla.	2,486	Leve, 1961
Fernandina	Nassau	Fla.	2,130	Leve & Goolsby, 1967
St. Marys River Oil Co. Hilliard Turpentine Co.	Nassau	Fla.	4,817	Black and Brown, 1951; Cole, 1944
South Penn. Oil Co., Mizell #1	Charlton	Georgia	4,577	GGS
Calif. Co., Buie #1	Camden	Georgia	4,947	Ridgway
Humble Oil Corp., McDonald	Glynn	Georgia	4,736	GGS, Murrah, 1968
E. B. LaRue, #1 Jelks-Rogers	Liberty	Georgia	4,264	Ridgway; GGS, 1965
Brunswick Pulp & Paper #10 U. S. Geol. Surv. Test Well #2	Glynn	Georgia	2,000	Wait, 1965
Layne-Atlantic Parris Island	Beaufort	South Carolina	3,450	Ridgway; GGS, Brown 1968
Charleston Muni ipal Wells	Charleston	South Carolina	2,006 (1970)	Lynch et al. (1881) Stephenson (1915)
Lakewood Plantation (Myrtle Beach)	Horry	South Carolina	770	Siple, 1968
Ft. Fisher	New Hanover	North Carolina	1,303 (log) 1,558	Sampair, 1968
Ft. Caswell	Brunswick	North Carolina	1,554	Sanford, 1911; Wilder, 1968
Coastal Plain Oil Co., Bay Land #1	Carteret	North Carolina	5,604	Sampair, 1968
Esso (Standard, N. J.) Hatteras Light #1	Dare	North Carolina	10,044	Ridgeway; Spangler 1950
Blair & Assoc. Marshall Collins #1	Dare	North Carolina	6,296	Sampair, 1968 Ridgway

Table 1. Continued.

NAME OF WELL	COUNTY	STATE	TOTAL DEPTH (feet)	SOURCE
Norfolk City Test Well (U. S. Geol. Survey)	Norfolk	Virginia	2,587	Wait, 1968, Cederstrom, 1945
Janes Island State Park	Somerset	Maryland	1,514	Hansen, 1967
Maryland Esso #1 (Std. Oil, N. J.)	Worcester	Maryland	7,710	Ridgway; Anderson et al., 1948
Sun Oil Co. Apple Orchard D-6	Sussex	Delaware	2,585	Ridgway; Rasmussen et al., 1960
Island Beach State Park	Ocean	New Jersey	3,891	Gill et al., 1963
Atlantic Beach Long Island	Nassau	New York	1,240	Lusczynski and Swarzenski, 1966

hold. Borehole-diameter variations, shaliness of beds and streaming-potential effects due to differences in pressure between the formations and the boreholes also may play important roles. A summary of factors affecting the SP log, as well as other logs, is given by Pirson (1963).

Most of the logs used in this study were taken before introduction of induction electrical surveys, and very few porosity logs (neutron, sonic or "density") are available. No appreciable saturation with hydrocarbons was reported or assumed in the log-evaluated strata.

An example of a log and its interpretation are shown in Figure 1. This well, which is located not far from Coastal Petroleum Company Bay Land #1 (Figure 2), shows a typical development of freshwater beds in the upper 600 feet. The fresh water is reflected by minimal excursions on the SP log and high resistivities on both long normal (dotted line) and short normal (solid line) resistivity curves. The presence of permeable zones is normally indicated on the resistivity logs by higher resistivity on the short normal curve and a separation between the short and long normal curves, in part owing to invasion of fresher borehole fluid into the formation nearest the borehole. An increase in salinity with depth is indicated by increasing SP deflections for the permeable zones. The decrease in resistivity values caused by greater formation salinities and higher temperatures with depth, is counterbalanced, in part, by the tendency for porosities, and hence proportions of conductive pore waters, to decrease with depth. The irregular peak heights shown by thin permeable beds between major SP anomalies may be in a large part attributed to thinness or shaliness of the beds, and these features are usually not considered in the log evaluation procedure.

The apparent salinities obtained from the uncorrected computer evaluations were modified by considering the resistivity logs for their indication of porosity, shaliness, depth of borehole fluid invasion and general water resistivity. Next, water analyses, where available, were considered. Where specific data was lacking, general hydrologic information from the area could often be applied to the upper part of the

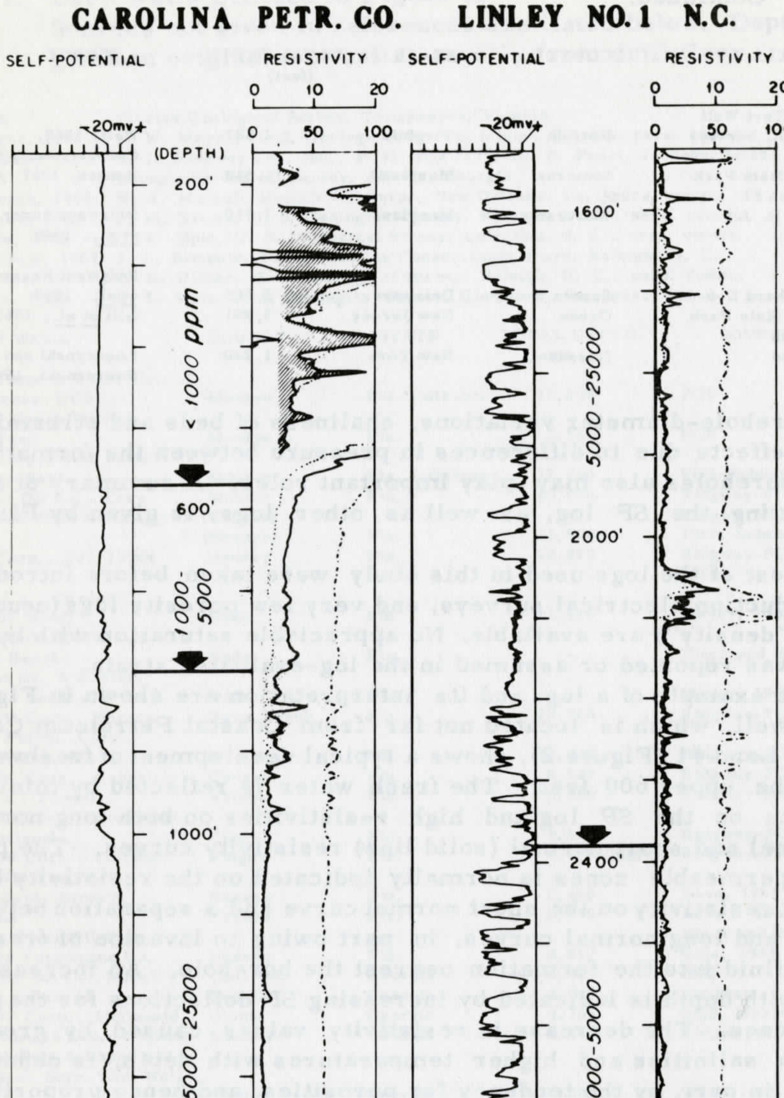

Figure 1. Typical electrical log and evaluation of formation salinity. Salinity is given in parts per million total solids. Resistivity is in ohms. Dotted line is long normal; solid line is short normal. Drilling mud resistivity is 4.2 ohm m^2/m at 21°C, and bottom hole temperature is 41°C.

Table 2. Selected analyses of deeper ground waters along the Atlantic continental margin.

Values given are in parts per million (ppm), although we suspect that some values, especially isolated chlorides, may actually represent mg/liter units. In evaluating the analyses of deeper wells, especially oil tests containing salty water, the possibility that the waters are partly mixed with (usually fresher) drilling fluids should be borne in mind; hence, these values may be minima. Further, the value of pH, Fe, SiO_2, alkalinity and other reactive components may be influenced by chemical reactions during or after water recovery. Detailed data on sampling procedure are unavailable for most wells. However, the interval or approximate depth stated refers to assumed point of origin. Composite flows are excluded except where noted.

Sources

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3. Archives of the Florida Geological Survey, Tallahassee, Fla.
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8. Lichtler, 1960
9. Bermes, 1958
10. Stewart, 1959
11. Stringfield, 1966
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13. Leve and Goolsby, 1967
14. Wait, 1965
15. C. L. Babcock, 1968. Fla. Geol. Survey, Tallahassee, Fla. Oral communication.
16. Counts and Donsky, 1963
17. Lynch et al., 1880
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21. R. L. Wait, 1968. U. S. Geol. Survey, Richmond, Va. Written communication.
22. Hansen, 1967
23. Rasmussen and Slaughter, 1955
24. Gill, et al., 1963
25. Lusczynski and Swarzenski, 1966
26. Cushman, 1964
27. Parker, et al., 1955, Table 113.
28. Babcock, 1962

Notes

a. Analyses may be contaminated by drilling fluid
b. Proportion of suspended solids not known
c. Residue on evaporation at 180°C
d. This analysis showed only 11,300 ppm residue on evaporation, and otherwise displays highly anomalous properties. It contains an appreciable amount of sulfates not balanced by Ca.
e. Another Commonwealth Oil Co. well in this area contained 1,720 ppm Fe and 81,600 ppm total solids at an unspecified depth.
f. Collected in oolitic limestone under anhydrite
g. Alkalinity
h. Minimum value
i. Recalculated HCO_3 refers to total alkalinity
j. Also Mn 0.0, Cu 0.14, Zn 0.54 (sic), Li 2.0, NO_3 0.7 ppm

Name	Depth	Formation	Source	Total Solids	Na	K	Ca	Mg	Fe[b]	Cl	SO_4	HCO_3	Other[b]
FLORIDA - MONROE COUNTY													
Peninsular Oil #1 Cory[a]	3,000	M. Eocene	1	29,460	78	50	1,552	268	---	14,200	1,650	439	
Peninsular Oil #1 Cory[a]	9,500	L. Cret.	2	20,600	5,780	246	1,348	306	42	11,170	1,657	51	Sr 22, SiO_2
Peninsular Oil #1 Cory[a]	9,550	L. Cret.	2	42,100	12,400	541	2,710	410	19	24,620	1,324	82	Sr 60, SiO_2 9
Peninsular Oil #1 Cory[a]	9,772	L. Cret.	2	27,000	8,100	300	853	751	335	15,050	1,840	100	Sr 12, SiO_2 6
Peninsular Oil #1 Cory[a]	9,987	L. Cret.	2	29,900	8,820	350	1,564	328	84	17,080	714	83	Sr 33, SiO_2 11
Gulf Marquesas OCS	12,345	L. Cret.	3	> 100,000									
Gulf Marquesas OCS	14,409	L. Cret.	3	> 200,000									
Pennekamp Park, Key Largo	1,300	M. Eocene	2							(3,000)			
Royal Palm Ranger Sta.	0-1100	Olig.-Pleist.	4	1,000									
Royal Palm Ranger Sta.	1200-1333	M. Eo. (Avon Park)		(Floridan Aquifer)						3,000			"high magnesium"
Key West Waterworks		Miocene		30,450	9,344		507	1,005	20	16,320	2,392	206	SiO_2 36 (sea water)
DADE COUNTY													
Serio Oil Barnett, 40 miles Bend (40 miles West of Miami)	11,383	L. Cret.	2	254,000	56,900	3,950	27,700	4,770	---	152,000	665	32	Sr 1150, Br 6510 SiO_2 .5
Gulf FSL 340 40 Mile Bend	11,500	L. Cret.	2	97,800	25,900	1,230	7,850	1,620	18	59,600	514	47	SiO_2 4.7
La Gorce Golf Course, Miami Beach	1,200	Olig.-U. Eoc.	1	4,820	1,372		162	177		2,475	978	140	SiO_2 14
Gulf Coast Dr. & Expl. 40 Mi. Bend	3,805	Paleocene	2	17,900	5,500	10	357	603	.4	9,660	1,550	176	SiO_2 .2, Br 32, I 2, F 1.5
Commonwealth Oil 40 Mi. Bend[e]	11,675	L. Cret.	2	225,000	50,980	350	27,730	4,080	3.1	140,000	408	150	{ [SiO_2 6.3, Br 14, I 8.3
U. S. Geol. Survey (S. Miami)	5,432		27	3,850	1,190		78	133		2,040	379	65	[F 24, NO_3 1220
COLLIER COUNTY													
Humble #1 Currey	11,670	L. Cret.	2	207,000	48,300	3,150	23,800	3,400	.1	129,000	139	107	SiO_2 21, Br 738, I 19
Humble Gulf Coast Realties #1 Sunniland discovery well, Sunniland	11,626	L. Cret.	28	199,000	50,400	4,050	21,760	2,680	65	123,700	237	126	Br 517, I 0.0, F 0.0, SiO_2 26
Sun Oil C415 (Felda)	752-912	Olig.	2	2,420	580	33	168	83	---	1,080	400	120	SiO_2 14, F .9, pH 7.1
Lee Cypress Co. (Copeland) #1	1,800	M. Eocene	1	4,198	1,050		106	156	1	1,800	504	190	pH 7.8
HENDRY COUNTY													
Riddle-McKay #2 (Clewiston)	1,400	M. U. Eocene	1						1.2	1,426		120	
J. N. Blount (La Belle)	740	U. Eo.	1	2,868	811		64	69	.1	1,021	650	131	
Sun Red Cattle #2 (Felda) HE 341	11,485	L. Cret.	2	209,000	51,500	2,920	21,600	2,970	---	129,000	415	---	Br 978, I 24
Sun Red Cattle #2 (Felda) HE 341	11,485	L. Cret.	2	216,000	53,900	3,100	21,200	3,260	---	133,000	447	---	Br 1110, I 41
Sun Red Cattle #2 (Felda) HE 341	1475-4506	(Boulder Zone)	2	10,100	3,080	124	195	378	1.8	5,270	984	117	SiO_2 1.7
Sun Red Cattle #1 (Felda)	11475-12680	L. Cret.	2	215,000	55,600	2,850	21,100	2,880	1	131,000	1,030	86	F 8.6, NO_3 73
Sun Red Cattle #32-2 (Felda)	2,600	L. Eo.	5	(Boulder Zone)						15,500			
PALM BEACH COUNTY													
SCS Dept. Agric. Hillsboro Canal	97	Plio.-Pleist.	2	7,240	2,290	34	201	166	.7	3,390	730	819	F .4
U. Fla. Belle Glade	1,332	M. Eo.	1	3,470	948		144			1,650	516	151	
Southern Utilities, W. Palm Beach	1,080	M. Eo.	1	4,740	1,343		140	175	.17	2,345	449	187	
Humble FSL 1004	5,295	U. Cret.	6							115,000			
Humble FSL 1004	9,062	L. Cret. (?)	6							113,000			
Humble FSL 1004	10,197	L. Cret.	6							130,000			
CHARLOTTE COUNTY													
Hot Spgs., Inc., Sec. 17, T·425, R·23E	1,600	M. Eo.	2	33,900	10,400	419	627	1,070	---	18,600	2,650	128	SiO_2 6.4, F 1.3
MANATEE COUNTY													
H. C. Ditmas (near Anna Maria)	398	Mio.-Olig.	2	62,000	19,270	---	606	2,466	39	44,000 33,000	6,460	350	Br 20, I 1
V. I. Allen, Bradenton	550	U. Eocene	1	1,273	54		189	75	8	170	644	102	SiO_2 10
MARTIN COUNTY													
Well 150 NE Corner, T·39S, R·41E	1,250	M. Eo. (Avon Park)	8	7,400[c]						4,020			
Well 910 NE of Indiantown	1,096	M. Eocene	8							770			
Adams Ranch N. of Indiantown	1,800	M. Eocene	8	>10,000									
INDIAN RIVER, CY.													
D. Hepner Well 231	1,165	U. Eocene	9							620			

Serio Oil Barnett, 40 miles Bend (40 miles West of Miami)	11,383	L. Cret.	2	254,000	56,900	3,950	27,700	4,770	---	152,000	665	32	Sr 1150, Br 6510
Gulf FSL 340 40 Mile Bend	11,500	L. Cret.	2	97,800	25,900	1,230	7,850	1,620	18	59,600	514	47	SiO_2 .5
La Gorce Golf Course, Miami Beach	1,200	Olig.-U. Eoc.	1	4,820		1,372	162	177		2,475	978	140	SiO_2 4.7
Gulf Coast Dr. & Expl. 40 Mi. Bend	3,805	Paleocene	2	17,900	5,500	10	357	603	.4	9,660	1,550	176	SiO_2 14
Commonwealth Oil 40 Mi. Bend[e]	11,675	L. Cret.	2	225,000	50,980	350	27,730	4,080	3.1	140,000	408	150	SiO_2 .2, Br 32, I 2, F 1.5
U. S. Geol. Survey (S. Miami)	5,432		27	3,850		1,190	78	133		2,040	379	65	{ [SiO_2 6.3, Br 14, I 8.3 [F 24, NO_3 1220
COLLIER COUNTY													
Humble #1 Currey Humble Gulf Coast Realties #1	11,670	L. Cret.	2	207,000	48,300	3,150	23,800	3,400	.1	129,000	139	107	SiO_2 21, Br 738, I 19
Sunniland discovery well, Sunniland	11,626	L. Cret.	28	199,000	50,400	4,050	21,760	2,680	65	123,700	237	126	Br 517, I 0.0, F 0.0, SiO_2 26
Sun Oil C415 (Felda)	752-912	Olig.	2	2,420	580	33	168	83	---	1,080	400	120	SiO_2 14, F .9, pH 7.1
Lee Cypress Co. (Copeland) #1	1,800	M. Eocene	1	4,198		1,050	106	156	1	1,800	504	190	pH 7.8
HENDRY COUNTY													
Riddle-McKay #2 (Clewiston)	1,400	M. U. Eocene	1						1.2	1,426		120	
J. N. Blount (La Belle)	740	U. Eo.	1	2,868	811		64	69	.1	1,021	650	131	
Sun Red Cattle #2 (Felda) HE 341	11,485	L. Cret.	2	209,000	51,500	2,920	21,600	2,970	---	129,000	415	---	Br 978, I 24
Sun Red Cattle #2 (Felda) HE 341	11,485	L. Cret.	2	216,000	53,900	3,100	21,200	3,260	---	133,000	447	---	Br 1110, I 41
Sun Red Cattle #2 (Felda) HE 341	1475-4506	(Boulder Zone)	2	10,100	3,080	124	195	378	1.8	5,270	984	117	SiO_2 1.7
Sun Red Cattle #1 (Felda)	11475-12680	L. Cret.	2	215,000	55,600	2,850	21,100	2,880	1	131,000	1,030	86	F 8.6, NO_3 73
Sun Red Cattle #32-2 (Felda)	2,600	L. Eo.	5	(Boulder Zone)						15,500			
PALM BEACH COUNTY													
SCS Dept. Agric. Hillsboro Canal	97	Plio.-Pleist.	2	7,240	2,290	34	201	166	.7	3,390	730	819	F .4
U. Fla. Belle Glade	1,332	M. Eo.	1	3,470		948	144			1,650	516	151	
Southern Utilities, W. Palm Beach	1,080	M. Eo.	1	4,740		1,343	140	175	.17	2,345	449	187	
Humble FSL 1004	5,295	U. Cret.	6							115,000			
Humble FSL 1004	9,062	L. Cret. (?)	6							113,000			
Humble FSL 1004	10,197	L. Cret.	6							130,000			
CHARLOTTE COUNTY													
Hot Spgs., Inc., Sec. 17, T· 42S, R· 23E	1,600	M. Eo.	2	33,900	10,400	419	627	1,070	---	18,600	2,650	128	SiO_2 6.4, F 1.3
MANATEE COUNTY													
H. C. Ditmas (near Anna Maria)	398	Mio.-Olig.	2							44,000			
				62,000	19,270	---	606	2,466	39	33,000	6,460	350	Br 20, I 1
V. I. Allen, Bradenton	550	U. Eocene	1	1,273		54	189	75	8	170	644	102	SiO_2 10
MARTIN COUNTY													
Well 150 NE Corner, T· 39S, R· 41E	1,250	M. Eo. (Avon Park)	8	7,400[c]						4,020			
Well 910 NE of Indiantown	1,096	M. Eocene	8							770			
Adams Ranch N. of Indiantown	1,800	M. Eocene	8	>10,000									
INDIAN RIVER, CY.													
D. Hepner Well 231	1,165	U. Eocene	9							620			
POLK COUNTY													
Lake Wales Municipal No. 2	1,260	M. Eocene	1	212		4.6	46	12	.16	8.2	14	181	
FLAGLER COUNTY													
Humble #1 Campbell	4,268	L. Cret.	7							151,000			
LAKE COUNTY													
South Lake Well	1,410	M. Eocene	11							20			
South Lake Well	2,258	L. Eocene	11							781			
South Lake Well	2,300	L. Eocene	11							6,020			
South Lake Well	2,352	L. Eocene	11							6,290			
South Lake Well	2,470	L. Eocene	11							23,020			
South Lake Well	2,590	Paleocene (Cedar Keys)	11							(310)?			
South Lake Well	2,593	Paleocene (Cedar Keys)	11							12,000			
South Lake Well	3,410	U. Cret. (Lawson Ls.)	11							58,100			
South Lake Well	3,700	U. Cret. (Lawson Ls.)	11							13,650			
DUVAL COUNTY													
Jacksonville City Test Well	850-922	M. Eo. (Avon Park)	13							16			
Jacksonville City Test Well	1590-3456	M. Eo.-Paleo.	13							14			
Jacksonville City Test Well	2,458	Paleocene	13							7,320			
NASSAU COUNTY													
St. Marys River, Hilliard	2,225	Paleocene	2	64,340	19,242	2,230		995	40	33,600	3,912		SiO_2 56
St. Marys River, Hilliard	4,500	L. Cret.	2	100,890	32,269	4,784		717	70	60,200	218		Br 8, I 25
BREVARD COUNTY													
Titusville	400	M. Eocene	1	26,334		739	688	859	2.0	14,276	2,111	170	
GEORGIA - GLYNN COUNTY													
U. S. G. S. Test Wells, Brunswick	1,000	U. Eo. (Jackson)	12	350	17	1.7	45	24	.05	20	85	146	SiO_2 37
U. S. G. S. Test Wells, Brunswick	1,300	M. Eocene	12	1,450	190	4.8	134	69	.06	320	414	148	SiO_2 35, Br 1.6, I .3, F .7
U. S. G. S. Test Wells, Brunswick	1378-1700	M. Eocene	12	484	34	2.6	55	39	.04	32	195	148	SiO_2 30, pH 7.5
Brunswick Pulp & Paper Well #10	1,800	M. Eocene	12	6,744	1,200	55	448	227		975	3,176	162	F 3.3
Brunswick Pulp & Paper Well #10	1,900	M. Eocene	12	6,010	1,170	58	418	212		900	3,030	158	F 3.2
Brunswick Pulp & Paper Well #10	2,000	M. Eocene	12	3,160	440	21	254	194		500	1,500	156	F 2.6
Unspecified Oil Test	4,150	(Cret.)	14							40,400			
Humble Oil Corp. McDonald #1	4,140	M. Cret. (Tuscaloosa)	7							43,100			
	4,474	L. Cret.	7							23,500			
CHATHAM COUNTY													
U. S. G. S. Test Well #1, Savannah Beach	1,260	M. Eocene	16	21,400	6,920	98	545	376	.06	11,200	2,110	148	F 2.0, SiO_2 39
Cherokee Hill Oil Test (Savannah)	2,000	U. Cret.	16						8	2,600	532		
SOUTH CAROLINA - BEAUFORT COUNTY													
Layne-Atlantic Parris Island	990-1149	M. Eocene	11							8,500			
Layne-Atlantic Parris Island	1850-1900	U. Cret.	11							925			
Layne-Atlantic Parris Island	2600-2811	U. Cret.	11, 3							82		1,389[g]	F 7.0
Layne-Atlantic Parris Island	2,723	U. Cret.	11							1,328			
Layne-Atlantic Parris Island	3,222	U. Cret.	11							1,024			
Layne-Atlantic Parris Island	3,346	U. Cret.	11							722			
CHARLESTON COUNTY													
Wentworth St. Well, Charleston	1,260	U. Cret.	18	2,655	1,014	41	14	8.3	tr.	944	tr.	1,115	SiO_2 36
Charleston Municipal Well (1879)	1900-1970	U. Cret.	17	1,115	426	--	2.2	1.6	2.7	126	8	461	NO_3 6.9
New Artesian Well (1911)	2,007	U. Cret.	18	1,051	421	4.1	3	.4	1.0	92	7.2	872	SiO_2 32
NORTH CAROLINA - BRUNSWICK COUNTY													
Ft. Caswell Baptist Retreat (drilled 1905 and flowed to sampling date in 1958)	221	U. Cret.	19							1,550			T 86°C, I 1.0, Br 6.6, Mn 0.0
	1,444	L. Cret.	19	13,800	4,930	85	165	117	1.4	8,060	113	340	Li 7.3, Sr 12, Br 101
	1,543	L. Cret.	19	13,570	4,760	134	199	107	1.7	8,070	91	299	Li 7.6, Sr 7.2, Br 37, I 0.8, Mn 0.04
DARE COUNTY													
ESSO Hatteras Light #1	6477-6575	L. Cret.	20	116,773	36,097	---	7,180	1,302	---	71,335	840	99	170°C at 10,044' ("Bottom hole temp.")
ESSO Hatteras Light #1	7017-7220	L. Cret.	20	130,310	42,858	---	5,856	1,258	---	70,460	840	47	
VIRGINIA - NORFOLK COUNTY													
Norfolk Test Well #1 (U. S. G. S.)	2391-2412	L. Cret.	21	43,600									
Norfolk Test Well #1 (U. S. G. S.)	2499-2520	L. Cret.	21	44,900									
MARYLAND - SOMERSET COUNTY													
Janes Island Test Wells, Som Ec 33	338-362	Miocene	23	3,440	1,260	45	31	31	.17	1,360	62	1,200	SiO_2 58, F .7, pH 7.6
Janes Island Test Wells, Som Ec 4	726-829	Eocene	22	806	288	4.4	0.4	0.4	.1	59	50	438[g]	SiO_2 12, F 2.3, pH 8.8
Janes Island Test Wells, Som Dc 3	1272-1287	U. Cret. (?)	22	751	240	65	6.9	0.4	.15	110	56	490	SiO_2 14, Mn 0.01, pH 8.9
WORCESTER COUNTY													
Isle of Wight	1,706	U. Eocene	23				100	80		2,550		606	SiO_2 68, pH 7.5
							95	44	17	2,580		138	
NEW JERSEY - OCEAN COUNTY													
Island Beach Test Well	2,756	U. Cret. (Raritan)?	24	1,430	485	8.2	31	6.1	1.8	670	2.5	188	SiO_2 16, F 1.0, T 86°F
NEW YORK - NASSAU COUNTY													
Well N6723, Long Island	52	U. Pleistocene	25	274						48			
Well N6705	135-145	Pleistocene	25	24,100	6,800	181	326	827	97	12,200	1,710	0	SiO_2 19, F 0.0, Mn 1.6, pH 3.4
Well N3862	287-299	U. Cret. (?)	25	3,170	580	15	230	174	146	1,890	139	0	SiO_2 19, F 0.0, Mn 1.8, pH 3.4
Well N3861	515-526	Cret.	25	28,300	8,670	295	365	1,090	78	15,800	2,010	16	SiO_2 10, Mn .3, pH 5.2
Well N129	879-889	Cret.	25	96	25	5.6	0.5	0.2	.24	4.7	29	37	SiO_2 7.6
Well N3687	1190-1240	Cret.	25	51	7.8	1.2	1.6	1.9	.52	4.0	17	7	SiO_2 8.8, Mn 0.06, pH 5.0
CONNECTICUT - HARTFORD COUNTY													
Well H22	502	Triassic	26		129		285	53		28	1,020	121	
Well H11	640	Triassic	26		1,890				.40				

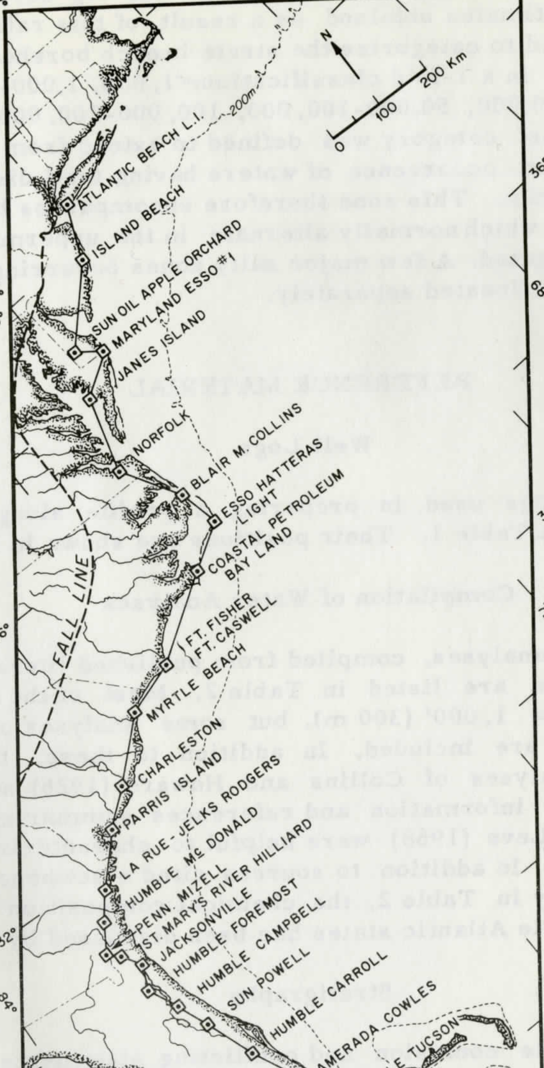


Figure 2. Location map of wells used in constructing Figure 3. See Table 1 for well list.

logged column, and aided in "calibrating" the log-derived "salinity" values. Final estimates obtained as a result of this rather subjective process were used to categorize the strata in each borehole on the basis of total "salinity" in a 7-fold classification: <1,000, 1,000-5,000, 5,000-25,000, 25,000-50,000, 50,000-100,000, 100,000-200,000 and >200,000 ppm. The freshest category was defined to extend from the land surface to the deepest occurrence of waters having total dissolved solids less than 1,000 ppm. This zone therefore encompasses both fresh and brackish waters, which normally alternate in the uppermost levels of the strata investigated. A few major salty zones occurring within fresh sequences were delineated separately.

REFERENCE MATERIAL

Well Logs

The well logs used in preparing a profile along the Atlantic coast are listed in Table 1. Their positions are shown in Figure 2.

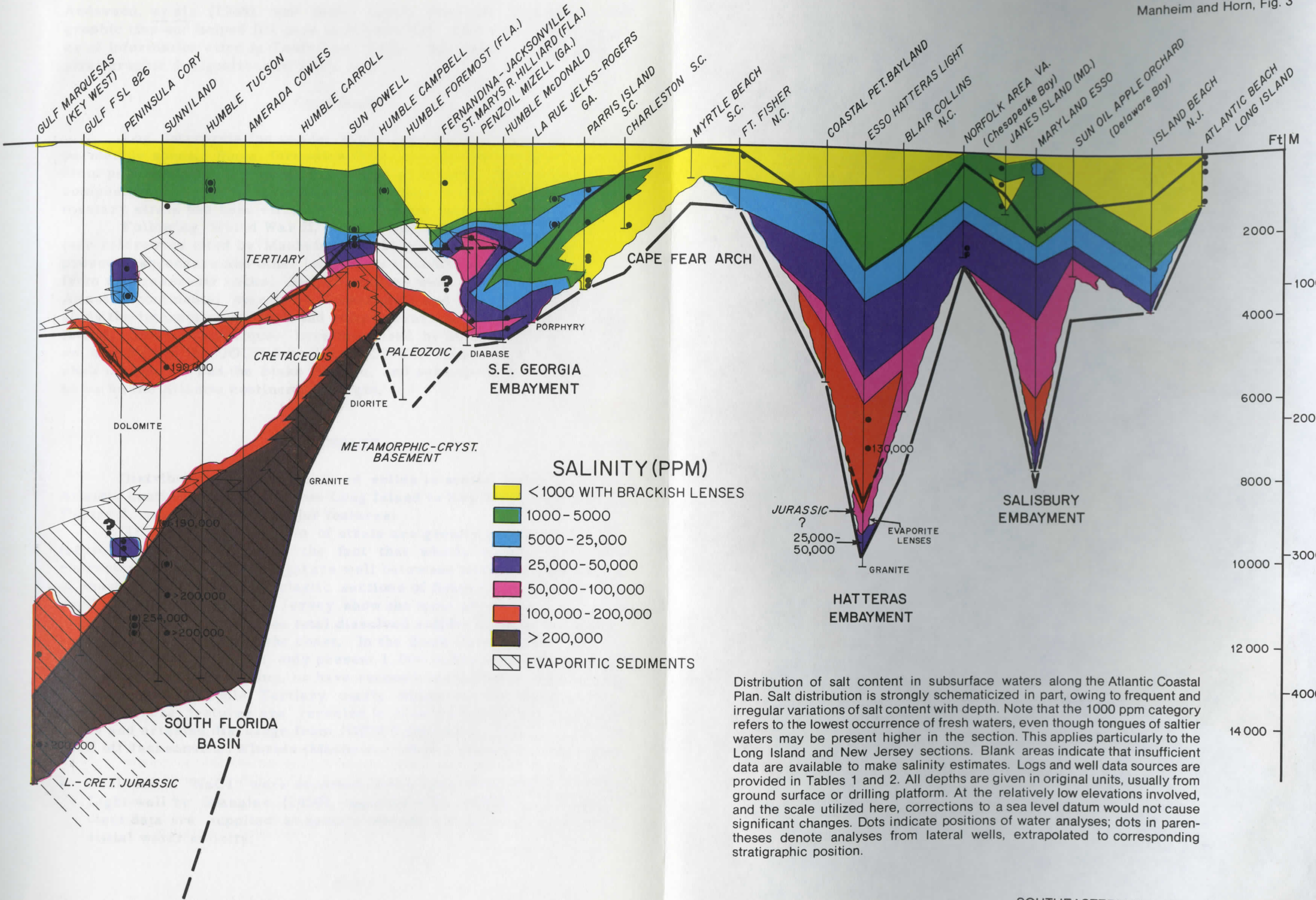
Compilation of Water Analyses

Chemical analyses, compiled from published literature and unpublished sources, are listed in Table 2. Most of the analyses are from strata below 1,000' (300 m), but some analyses of water from shallower strata are included. In addition to these, the collected ground water analyses of Collins and Howard (1928) and Black and Brown (1951), and information and references summarized in Stringfield (1966), and Leve (1968) were helpful to characterize shallower strata in Florida. In addition to sources cited elsewhere in this publication, especially in Table 2, the chemical composition of shallower waters in the middle Atlantic states has been discussed by Back (1966).

Stratigraphy

Considerable confusion and conflicting statements exist on the subsurface stratigraphy of the Atlantic continental margin. Moreover, a detailed analysis of the subsurface based on well samples from Long Island to Cape Hatteras, and currently to be submitted for publication (P. M. Brown, et al.) takes issue with existing delineations, particularly with regard to pre-Tertiary subdivisions and correlations. Since improper correlations may lead to misleading conclusions about potential pathways for fluid movement, we have thought it best to limit our stratigraphic boundaries to the base of the Tertiary and Cretaceous sections (frequently crystalline basement).

Stratigraphic studies and electrical log sections of Maher (1965), Herrick and Vorhis (1963), Applin and Applin (1967), Chen (1965),



Distribution of salt content in subsurface waters along the Atlantic Coastal Plan. Salt distribution is strongly schematicized in part, owing to frequent and irregular variations of salt content with depth. Note that the 1000 ppm category refers to the lowest occurrence of fresh waters, even though tongues of saltier waters may be present higher in the section. This applies particularly to the Long Island and New Jersey sections. Blank areas indicate that insufficient data are available to make salinity estimates. Logs and well data sources are provided in Tables 1 and 2. All depths are given in original units, usually from ground surface or drilling platform. At the relatively low elevations involved, and the scale utilized here, corrections to a sea level datum would not cause significant changes. Dots indicate positions of water analyses; dots in parentheses denote analyses from lateral wells, extrapolated to corresponding stratigraphic position.

Anderson, et al. (1948), and Swain (1952) provided regional stratigraphic ties and helped fill gaps in information. These and other sources of information cited in Table 2 and Table 1 have provided the general stratigraphic designations in Table 2.

Core Studies

Log interpretation can be applied, as previously noted, only to permeable zones. Since formation fluid samples can be obtained only from permeable zones by existing testing equipment, information on the composition of pore fluids in poorly permeable beds from deeper sedimentary strata has been virtually non-existent until recently.

Following World War II, Soviet workers led by P. A. Kriukov (see references cited by Manheim, 1966b) initiated limited use of high-pressure squeezers and other techniques to obtain and study pore fluids from non-reservoir rocks. Such techniques were first employed on the Atlantic continental margin by Lusczynski and Swarzenski (1962)[1] to study the interaction of fresh and salty subsurface waters beneath Long Island. Similar techniques have been used by Manheim (1966a; 1967) on cores from the JOIDES drilling (JOIDES, 1965) on the continental shelf off Florida and the Blake Plateau, and subsequently on other drill holes on the Atlantic continental margin.

RESULTS

Distribution of total dissolved solids in stratal fluids along the Atlantic continental margin from Long Island to Key West, sketched in Figure 3, reveals several major features:

(1) The upper 1,000 m of strata are greatly influenced by meteoric waters, evidenced by the fact that wholly marine strata are characterized by salinities that are well below sea water concentrations of about 35,000 ppm. The clastic sections of South Carolina-Georgia, northern Florida and New Jersey show the most prominent movement of fresh water (<1,000 ppm total dissolved solids) from land recharge areas to deep strata near the coast. In the South Carolina-Georgia region fresh waters are not only present 1,000 m below the coastal land surface, but may be moving, or have recently moved more than 120 km seaward under middle Tertiary marls which act as partial aquicludes. These features are revealed in recent evidence of fresh pore fluids and artesian discharge from JOIDES drill holes on the continental shelf off Jacksonville, Florida (Manheim, 1967). Figure 4, taken from

1. Analyses of "NaCl" were reported from cores of the Esso Hatteras Light well by Spangler (1950), together with porosity, but insufficient data are supplied to permit unequivocal calculation of interstitial water salinity.

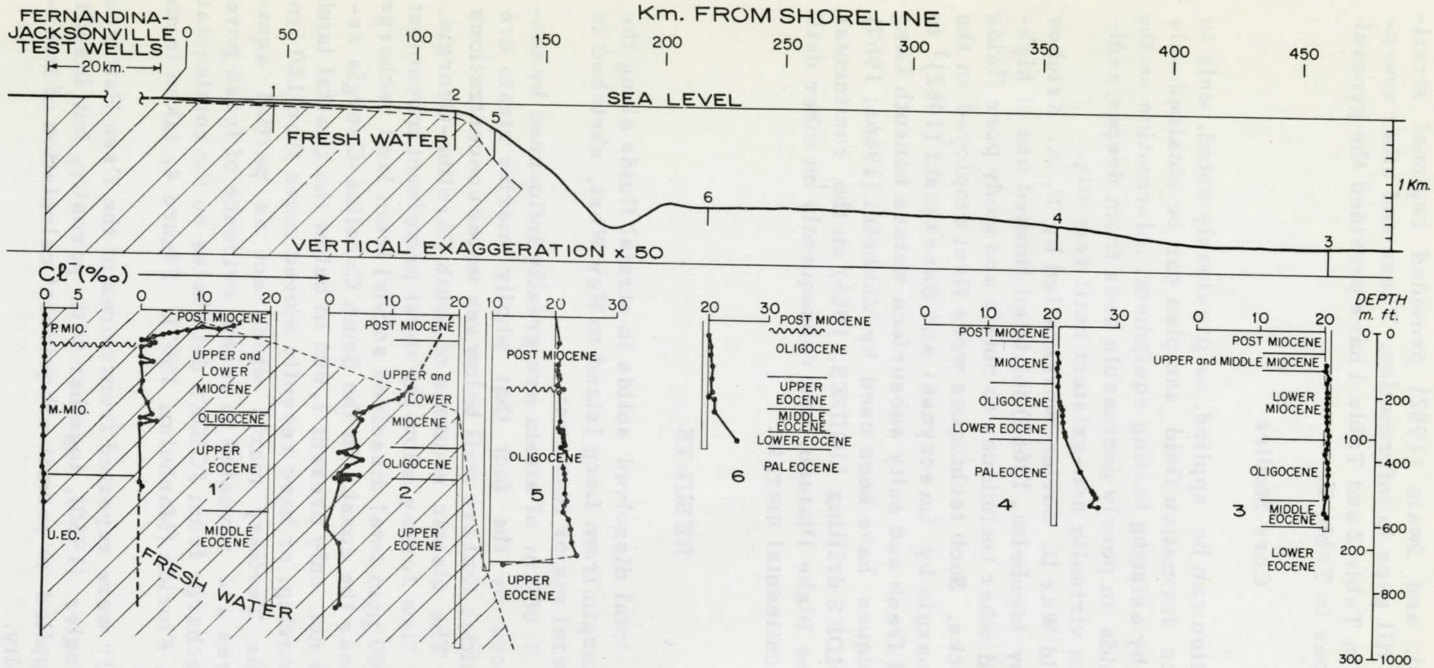


Figure 4. Transect showing chlorinity in JOIDES drill holes seaward of Jacksonville, Florida (Manheim, 1967).

the latter paper, illustrates the distribution of chlorinity in a seaward traverse from the Fernandina-Jacksonville wells (see Figures 2 and 3).

(2) Intermediate sediment layers in southern and central Florida include the cavernous and highly transmissive "Boulder Zone", which occurs at the boundary between dolomitic-evaporitic strata and overlying carbonates at depths on the order of 3,000-4,000' (Kohout, 1967). This zone carries hugh volumes of water of compositions intermediate between fresh and sea water. Below the Boulder Zone, hypersaline brines may be encountered, but only few data are available.

North of Florida, intermediate sediment layers reveal a complex intermixture of brackish and saline waters, with a general downward increase in salinity.

(3) Brines having salt concentrations greater than 100,000 ppm are found in the Salisbury and Hatteras embayments, in southern Georgia and in deeper strata throughout Florida. Brines containing more than 200,000 ppm salt are widespread in the Lower Cretaceous sequences in Florida, and are best documented in the Sunniland-Felda oil fields of south Florida.

Brines are generally observed within, or near sequences of evaporitic sediments and "redbeds" (varicolored shales, sandstones and oolitic limestones). These include Lower Eocene and Paleocene anhydrites in Florida, Lower Cretaceous anhydrite, salt and dolomite in Florida and south Georgia and Lower Cretaceous-Jurassic redbeds with some anhydrite in the deeper sedimentary zones of the Middle Atlantic embayments.

(4) A gap in information remains for much of the Florida subsurface, especially between the top of the Cretaceous, and the onset of evaporitic Lower Cretaceous sediments. The gap is largely due to failure of the log evaluation system in carbonate-evaporite sequences. Further, the thick dolomites and anhydritic sections often have such low interconnected porosity that continuity of water character along stratigraphic boundaries cannot be assured.

(5) In some deeper basins, for example, in the Esso Hatteras #1 well, formation waters become less saline as igneous or metamorphic basement rocks are approached.

(6) The ground waters vary in ionic composition from a very soft bicarbonate type containing less than 1 ppm Ca and Mg (lowest total solids was 51 ppm at 1,194-1,240' in the Cretaceous "Lloyd Sand" member of the "Raritan Formation" on Long Island [Table 2]), to nearly saturated brines containing equal reacting weights of calcium and sodium. For example, the Serio Barnett well in the "40 Mile Bend" region of South Florida yielded a brine that contained 27,700 ppm Ca, 56,900 ppm Na. In addition, it contained 3,950 ppm K, 1,150 ppm Sr, 6,510 ppm Br and 254,000 ppm total solids. The brine came from the evaporitic "Sunniland" oil zone in the Lower Cretaceous, at a depth of 11,303'. The high bromine and potassium suggest association with late stage evaporitic sequences, but the poor communication in the

dolomite-anhydrite strata is strikingly revealed by the fact that a brine from a well only a few km away, containing 225, 000 ppm total solids, had only 350 ppm K and 14 ppm Br (!). Dilution of the Serio waters (254, 000 ppm total solids) with drilling fluid is obviously incapable of producing such phenomena.

Salt water of sea water composition is noted in many shallow zones in Florida, attesting to both subrecent infiltration from the ocean, and remnants of Pleistocene invasions incompletely flushed out by meteoric water. However, in the Ft. Caswell, N. C. well a brackish water from 1, 444' contained too much Li (7. 3 ppm), Br (101 ppm) and too little sulfate and magnesium to be equated with a direct mixture of sea water and meteoric water. Partial leaching of evaporitic strata or mixing with water of such origin is suggested.

DISCUSSION

Connate or Original Pore Fluids

Little of the character of original permeating solutions appears to have been preserved in the pore fluids now filling permeable rocks along the Atlantic continental margin. This is evident in the fresh-water influenced zones discussed later, but is also marked by the manner in which pore water composition cuts across time-stratigraphic and deeper marine-nonmarine facies boundaries. Similar conclusions were already drawn by Sanford (1911).

Studies of O^{18}/O^{16} and D/H ratios in waters from concentrated brines in a number of sedimentary basins (Clayton, et al., 1966; Degens, et al., 1964) have so far failed to provide evidence that the waters in such brines (as distinguished from the salts) were involved in evaporitic processes. No isotopic analyses are known to us from the Atlantic continental margin brines, but if the previously observed (isotopic) relationships hold, the waters themselves may not represent original fluids. Too little is known about pore fluids in shales and non-reservoir rocks to exclude them from containing original interstitial waters.

Mechanisms for Fresh-Water Flushing

Artesian pressure. The effects of present-day artesian aquifers in moving meteoric waters to deep horizons are well-documented in the New Jersey-Long Island area, especially by the studies of Lusczynski and Swarzenski (1966, and references cited therein), and by the many studies summarized by Stringfield (1966) for the southeastern states.

A special case in point involves evidence that lighter-than-normal waters may be discharging at depths below 500 m (1,600') on the Blake Plateau (Atlantic Ocean), more than 200 km from land (Manheim, 1967). Present piezometric heads in the Floridan Aquifer at the adjoining coast do not exceed about 15 m, and even "original" heads of 20 m appear barely adequate to account for massive flow at such depths, assuming a continuing loss of head with distance from shore. However, a remarkable early study of Lynch et al., (1881) directs attention to a much higher head of nearly 40 m observed in Upper Cretaceous strata in the municipal well at Charleston, South Carolina. This well was drilled at a time when no wells of comparable depth existed along the Atlantic seaboard, and G. E. Siple (personal communication) states that unpublished data tend to confirm the order of magnitude of the head. Lynch et al., (1881) further pointed out that the head observed would be consistent with the altitude and distance from Charleston of Cretaceous outcrop belts in the Piedmont—Coastal Plain region, the outcrops serving as recharge zones for the artesian water. The possibility that discharge may be channeled seaward through Upper Cretaceous horizons is strengthened by the fact that Upper Cretaceous outcrops have recently been discovered in the areas of the Blake Plateau in question (Uchupi, 1967; Milliman et al., 1967).

Much greater influence than present-day artesian heads was probably exerted by artesian movements during the Pleistocene, when sea-level was lower than it is at present. With higher piezometric heads up to 100 m available during that time, a column of sea water up to 4,000 m could be balanced, in principle; i.e., fresh water could be caused to discharge at water depths far down on the continental slope. Although the distribution of such discharge is as yet poorly understood, observations on the potential importance of such phenomena by Johnson (1940) have been too long overlooked.

The rise and fall of sea level during the Pleistocene Epoch, with corresponding fluctuations in piezometric head, probably tended to create a complex intermingling of fresh and salt water tongues. It may have also promoted movement of fresh water from outcrop areas along bedrock and weathered bedrock-sediment interfaces, offering one explanation for the freshened waters noted at several such interfaces beneath the continental margin. Of course, if water is to flow basinward, a channel of escape for existing (saltier) waters must be provided to make room for invading fluids. Where the Coastal Plain sediments extend monoclinally toward the continental slope, the truncation of beds there provides an escape for fluids, as pointed out by Lynch et al., (1881) and Johnson (1940). On the other hand, P. M. Brown (personal communication) has emphasized the fact that present basinal position may bear little relationship to original or earlier structural positions in the subsurface. Fault systems or other transverse permeability channels are likewise poorly known. Thus, the pathways for fluid movement are better observed than predicted, in the present state of knowledge.

Diffusion. Two additional mechanisms influence fresh and salt-water mixing: diffusion and osmotic flow. Diffusion moves salts from areas of higher to lower concentration (activity), and may cause salting of fresh-water horizons to the extent of a meter per 10,000 years, or 1 km per 10 million years in relatively unconsolidated sediments. Water molecules also diffuse toward saltier horizons, in response to the lowered activity of water there, but at a much slower rate, corresponding to the lower activity gradient. Diffusion is, of course, much enhanced if combined with some mechanism of bulk fluid mixing.

Studies by Lusczynski and Swarzenski (1966) on poorly consolidated clays on Long Island, and by Manheim (1967) on mid-Tertiary marls penetrated in the JOIDES drillings show that poorly permeable marine clays and marls can be flushed by meteoric waters within a period of a few thousand years; such a rate is incompatible with slow diffusion.

Osmotic mixing. A partial solution to the question of apparently anomalous flushing rates in poorly permeable sediments is provided by experiments on osmotic, or electroviscous flow in sediment systems. For example, Mokady and Low (1968) recently demonstrated that osmotic flow of water in clayey beds, in response to a salinity gradient, may be more than 200 times as rapid as the diffusion rate for ions. As shown in schematic Figure 5, osmotic pressure associated with activity gradients in particle systems containing semi-permeable membranes (clays) tend to pump fresh water toward saltier horizons, at the same time that salt ions are diffusing toward the fresher zones at much lower rates. Fresh water flushing of clays owing to such mechanisms has been documented in field studies by Priklonskii and Oknina (1957), and studies cited by them. The potential force available through such mechanisms may be appreciated by considering that the osmotic pressure across a freshwater-seawater contact is on the order of 30 atmospheres, equivalent to about 900 feet (300 m) of hydraulic head. Moreover, fluids moving in response to osmotic pressure do not necessarily require external escape channels for saltier fluids; equalization of pressures may take the form of convection cells and other local or long-distance circuitous routes along preferred permeability channels. The osmotic mixing potential exists as long as appreciable activity gradients remain in the interstitial water, but actual mixing may be slowed to extremely low levels in well-consolidated, or very poorly permeable sediments. A reverse effect, "membrane filtration", is discussed later.

A special case of osmotic mixing was invoked by McLeod (1958) to account for formation of limestone caprock on salt domes. He suggested that where salt bodies intruded clayey beds, the salinity contrast caused by dissolution of salt caused an osmotic circulation which further promoted leaching of salt and anhydrite. The deep, cavernous "Boulder Zone" (Kohout, 1967), which is present in Florida at the upper transition from evaporitic strata of Paleocene-Eocene age to overlying limestone and dolomite, also shows strong leaching effects. Thermal circulation, as pointed out by Kohout (1967), may well account for a considerable part of present circulation. However, osmotic effects may also be present, and may have had an important role in the earlier

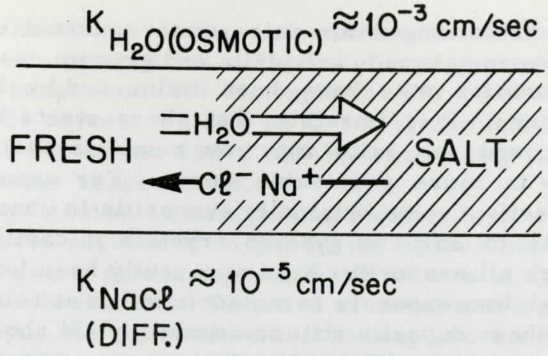


Figure 5. Schematic figure showing relative movement of molecular and ionic species owing to diffusion, and bulk flow owing to osmotic flushing in clayey sediments. K_{NaCl} refers to the approximate diffusion coefficient for ions and molecules and K_{H2O} refers to an apparent diffusion constant for water due to osmotic (bulk) flow.

development of cavernous porosity. Clay minerals and other obvious membrane-forming minerals which might enhance osmotic flow are scarce in the Boulder Zone. On the other hand, ion exchange (membrane) properties have recently been reported for carbonates, as well as clays (Berner, 1966), and their potential for supporting osmotic movements should be investigated.

Brines and Hypersaline Brines

Brines and evaporitic and varicolored shale-oolitic limestone sequences (hereafter referred to as redbeds) are so closely related in the subsurface of the Atlantic continental margin that, wherever the direct influence of meteoric flushing can be excluded or minimized, the presence of these strata at depth can be used to predict the occurrence of pore fluids that are saltier than sea water. This relationship holds in sealed-off strata associated with the Eocene-Paleocene (anhydritic) horizons in Florida, in Lower Cretaceous evaporites and dolomites in Florida-Georgia and in Lower Cretaceous-Jurassic redbeds in the Middle Atlantic states.

The origin of the brines is still uncertain, but two sources appear likely to have contributed to presently observed compositions: leaching of salts, and lateral communication with downdip saline brines. Rock salt deposits are present in the Lower Cretaceous of southern

Florida, but the remaining evaporitic strata reported on the Atlantic continental margin contain only anhydrite and gypsum, as well as dolomite, whose formation may have been influenced by the presence of concentrated brines. It is possible that these strata have lost salts through leaching, and the salts may now compose part of associated interstitial salts in more permeable zones. For example, Triassic redbeds of Connecticut were originally evaporitic in character, as evidenced by molds of salt and gypsum crystals in cavities (Cushman, 1964). Yet, though all evaporites have apparently been leached from the sediments through long exposure to meteoric water at relatively shallow depths, wells in these deposits still occasionally yield abnormal chloride and sulfate concentrations (Table 2). Under more extreme conditions, core samples of Cambrian dolomites, argillites and marls, as well as anhydrites, from the evaporitic Angara-Lena basin (Siberia), have yielded pore water extracts containing 250,000-500,000 ppm total salts (Pinneker, 1966). The leachable salts thus need not form visible segregations, but may be present as occluded salts in anydrites or other sediments. Leaching of evaporitic sediments is particularly likely in Florida, where rock salt is known. Moreover, the presence of localized zones of high potassium and bromine-containing brines suggests possible leaching of later stage evaporites, even though visible accumulation of such salts has never been reported.

Brines may also move updip from better-developed evaporitic facies in a seaward direction, owing to basinal compaction or other forces; basinal here refers to present, rather than original stratigraphic position. Lower Cretaceous and Jurassic(?) anhydrites interfinger increasingly with redbeds in a seaward direction in the Pamlico Sound - Hatteras region (P. M. Brown, personal communication); anhydrite beds are found in the Esso Hatteras #1 well and in the North Carolina Esso #2 well, northwest of the Hatteras well (Swain, 1952).

Brine Formation by Membrane Filtration

Membrane filtration by clayey sediments has been suggested to account for many saline brines in sedimentary strata (see Graf, et al., 1965; White, 1965), and has generated much enthusiasm, especially in the United States. Specific objections to the artesian-powered filtration concept advanced to account for brines in the Eastern Interior Basin (Illinois-Indiana) by Bredehoeft et al., (1963) were listed by Rittenhouse (1964), but no general critique has appeared. Because some workers believe that virtually all brines may have been formed by "membranes", we have added some examples of the practical difficulties in the way of applying salt-filtration concepts to the Atlantic continental margin in particular, and the geological environment in general.

As pointed out by McKelvey et al., (1959), salt rejection by membranes requires application of fluid pressures sufficient to overcome the osmotic pressure differential between salt solutions on the input and output side of membranes, as well as the frictional resistance of the membrane to permeation. Typical osmotic pressures for sea-water solutions range from 7.1 atmospheres for 1 percent salt to 350 atmospheres for 25 percent salt at 25°C (Stoughton and Lietzke, cited by Johnson et al., 1966). At 100°C the corresponding figures are 8.4 and 400 atmospheres, respectively.

Laboratory studies on natural clays and artificial ion-exchange and other media have succeeded in producing appreciable salt separation effects at pressure gradients ranging from tens of atmospheres to thousands of atmospheres/cm. Thinness of membranes, need for good flushing at the input side to remove salt buildup and the reciprocal behavior of permeability and filtration efficiency are the consistent conclusions of the many studies which have been undertaken to test membrane effectiveness for desalination purposes (see review by Johnson et al., 1966).

The pressure requirements for appreciable salt-filtration remain unsatisfied by known geologic environments. Artesian pressures on Coastal Plain strata probably never exceeded 100 m hydrostatic head for any appreciable length of time. For aquiclude thickness of 10 m (33'), which is a minimum figure for any appreciable horizontal extent of a prospective "membrane" stratum, the maximum artesian gradient is about 0.005 atmospheres/cm. Even where compactional pressures approach lithostatic pressure, as in the abnormal pressure zones of the northern Gulf of Mexico, the gradients across the sealing strata do not exceed 0.1 atmosphere/cm (Dickety et al., 1968) and references cited therein). Moreover, abnormally pressured zones of the Gulf of Mexico type appear to be particularly unsuited for effective filtration processes, since such zones permit virtually no fluid passage through them, as evidenced by their isolation, undercompaction, their generally low salinity and ability to maintain abnormal pressures for millions of years.

Thus, the maximum observed pressure gradients in the normal sedimentary environment fall far short of values which theory and experiment indicate must be a minimum to overcome osmotic forces created by the separation of salt and water. Special configurations may be hypothesized to overcome the pressure deficiency, but each seems to create as many problems as it solves. For example, lower pressure gradients would be required by membranes having lower filtration efficiencies, but creation of concentrated brines by low-efficiency filtering beds involves increasingly improbable volumes of forced fluid exchange as efficiency and pressure requirements are reduced. The possibility that gradients may be heightened across narrow intervals in a series of pressure jumps was implied by Hanshaw and Zen (1965). However, if artesian pressures of a few atmospheres or even tens of atmospheres were consumed in overcoming osmotic pressure across discrete millimeter or submillimeter layers, how would the moving fluids summon sufficient energy to permeate the remaining thicknesses of poorly permeable sediment in typical "aquiclude" strata?

A second requirement of a filtration system capable of producing strong brines is that enormous volumes of fluids must be pushed through poorly permeable (membrane-active) strata in preference to permeable channels, under virtually leak-free conditions. Convincing field evidence of such a system has never been offered; such systems would appear to defy standard ground water, petroleum engineering and geological engineering experience and theory.

Other objections could be raised, but the above are basic to the problem. Membrane filtration (reverse osmosis) is well-documented under experimental conditions. This and its esthetic appeal make it an understandably attractive hypothesis for brine formation. However, the burden of proof for its applicability in the geologic environment seems to remain with its proponents.

Lagoonal Formation in Middle Tertiary-Pleistocene Time

Some evidences of brines are available from shallow sediments within the fresh-water zone. A highly localized brine containing 62,000 ppm total solids with 6,000 ppm SO_4 was observed at 398' depth in Manatee County, Florida (Table 3) (Stringfield, 1933, cited in Stringfield, 1966). A brine with 42,000 ppm Cl was noted at only 110 feet depth by Kimrey (1960) beneath the Cape Hatteras barrier bar, and a very thin salt bed was reported at 50' near Titusville, Brevard County, Florida, by Matson and Sanford (1913). All of these occurrences are underlain by fresher waters, and appear to represent the products of evaporation of sea water in saline lagoons.

The above results are complemented and confirmed by reports of Pleistocene oolitic deposits on the continental shelf from Cape Hatteras to Cape Romain (Milliman et al., 1968). $O^{18/16}$ data indicate that the oolites were formed in a high salinity environment such as the present-day Laguna Madre (Texas coast).

CONCLUSIONS

1. Subsurface waters beneath the Atlantic continental margin range in salinity from 51 ppm to at least 254,000 ppm, and display a spectrum of water composition from sodium-bicarbonate (largely fresh) waters in sandstone aquifers to hard (Ca-Mg) waters in limestone and dolomite aquifers, to sodium-chloride and sodium-calcium-chloride brines containing appreciable potassium, magnesium and bromine concentrations.

2. Sediments in the upper 1,000 m (3,300') and some deeper than 2,000 m (6,600') are strongly influenced by meteoric waters. The main mechanisms for fresh water flushing appear to include artesian movements, particularly in Pleistocene time, when sea levels were

lower than at present, and osmotic movement of fresh water into more saline beds.

3. Below the fresh-water horizons, salinity increases irregularly and reaches over 100,000 ppm total salts in association with Eocene-Paleocene evaporites in Florida, Georgia and the middle Atlantic states. The evaporitic strata may be sources of the concentrated brines, owing to leaching. Brines may also move updip from (present) basinal positions seaward of the coast. Osmotic mixing may be an important agent in extending the distribution of saline formation waters beyond their original host strata.

4. Absence of adequate pressure gradients and other factors suggest that membrane-filtration phenomena do not play an important role in the formation of concentrated brines in the Atlantic continental margin.

5. There are still great gaps in information on the composition of intermediate pore waters in Florida, as well as in the rest of the continental margin, and virtually nothing is known of the pore fluids remaining in non-reservoir rocks in deeper horizons. Studies of pore fluids in cores of these materials may be required to decipher the full history of fluid and solute migration in the Atlantic continental margin.

6. Detailed knowledge of the distribution and migration of pore fluids should be not only of academic, but of practical, interest. Such knowledge should benefit the search for petroleum, hydrologic studies, including radioactive waste and other liquid disposal, underground storage and possible recovery of mineral components of deep brines.

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VERTICAL PROFILES OF MODERN SEDIMENTS ALONG THE NORTH CAROLINA COAST

By

Roy L. Ingram
University of North Carolina
Chapel Hill, N. C. 27514

ABSTRACT

The sediments now accumulating landward from the near shore region of the North Carolina coast can be placed in four main depositional environments: barrier island, bar-built estuary, drowned estuary and marsh. As sedimentation processes continue, characteristic vertical profiles will develop.

Four sediment types are present in the barrier bars: laminated, shelly very fine to coarse beach sand; cross-bedded, very fine to medium dune sand; massive, very fine to fine sand leeward of the beach and dunes on beach ridges, aeolian flats and vegetation areas; and massive, highly organic, muddy marsh sands along the sound side of the bar.

Marsh sediments are also found in areas flanking the mainland side of the sounds and bays and on numerous shoal islands.

The bar-built and drowned estuaries have the same basic sediment pattern. Black, highly organic muds accumulate in the deeper holes (usually greater than twelve feet deep) and in the small shallow bays marginal to the larger estuaries. Slightly silty very fine to medium sands floor the shallower portions of the larger estuaries. Narrow beaches of clean sand are usually found along the margins although there may be large shore regions covered by slightly muddy sands as on the western side of Pamlico Sound.

The deeper parts of the inlets through the barrier islands and the tidal channels leading from the inlets into the estuaries contain a shelly coarse sand.

INTRODUCTION

The results of most studies of modern sediments are usually given as maps showing the areal distribution of the different sediment types. The geologist working with ancient sediments sees mainly vertical sections and seldom has enough exposures to deduce these areal relationships. The purpose of this article is to deduce and to present some typical vertical profiles of the sediments that are now accumulating in the shallow waters along the North Carolina Coast.

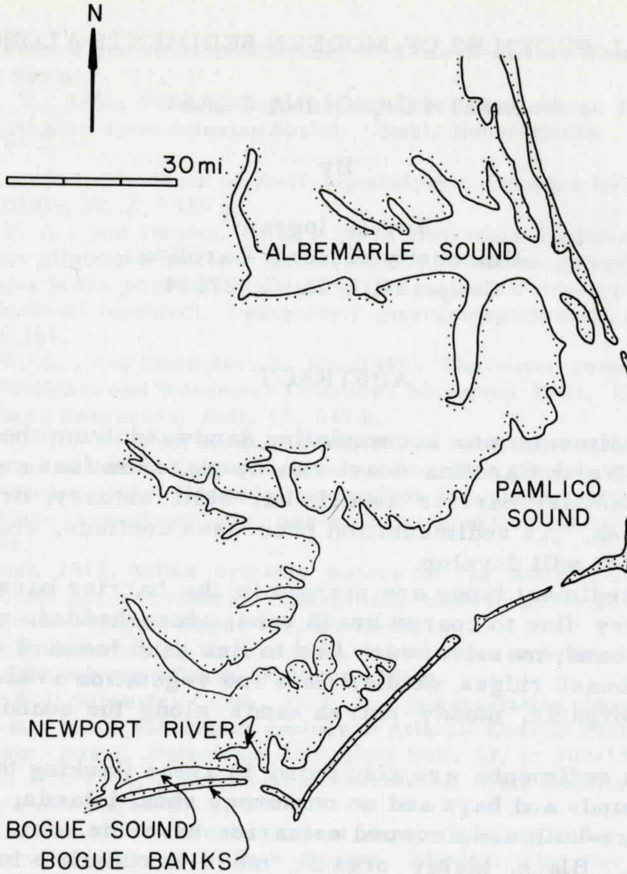

Figure 1. Index map of North Carolina coast.

The broad environments of deposition along the North Carolina coast can be classified in the following way:

- Bay (drowned estuary)
  - Bay away from inlet
  - Bay near inlet
  - Bay near river
- Lagoon (bar-built estuary)
  - Inlet
  - Lagoon away from inlet
  - Lagoon near inlet
- Barrier island
  - Nearshore marine
  - Beach
  - Dunes
  - Aeolian flats
- Marsh

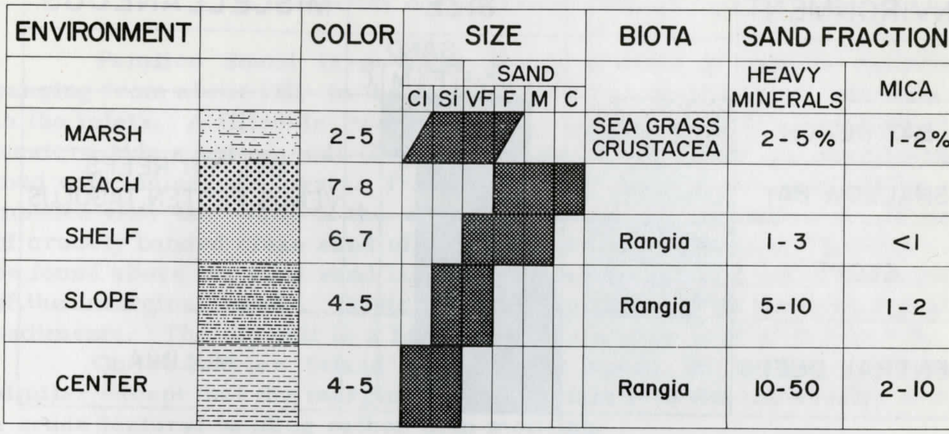

Figure 2. Vertical sequence in Albemarle Sound.

Most of these environments will be illustrated with vertical profiles deduced from facies maps of Albemarle Sound (Pels, 1967), Pamlico Sound (Pickett, 1965), Newport River (Johnson, 1959), Bogue Inlet (Batten, 1962), Bogue Sound and Bogue Banks (Figure 1). All the description of sediments are based on the binocular microscope examination of bottom samples (Ingram, 1965).

BAY AWAY FROM INLET

Albemarle Sound is a low salinity bay away from an inlet. The salinity grades from near zero at the head to about 5‰ near the mouth. If the sedimentation processes now operating continue, the sound will eventually fill up giving a vertical section as shown in Figure 2. The black, highly organic muds of the center deeper parts (12-25 feet) of the sound will be progressively overlain by shallower water sediments. Silty fine sands accumulate on the slopes leading up to the shallow shelf and beach sands. Massive, highly organic muddy marsh sands will cap the sequence as marshes encroach over the filled-in sound. Important in recognizing this type of low salinity bay environment is the extreme paucity of organisms with shells. The only shelled organism is the brackish water pelecypod Rangia, which is present in small numbers throughout the upper and middle portions of Albemarle Sound. Near the mouth some oyster fragments are found.

BAY NEAR INLET

Newport River is a drowned estuary near an inlet. In the upper part of Newport River away from the tidal channels, the vertical

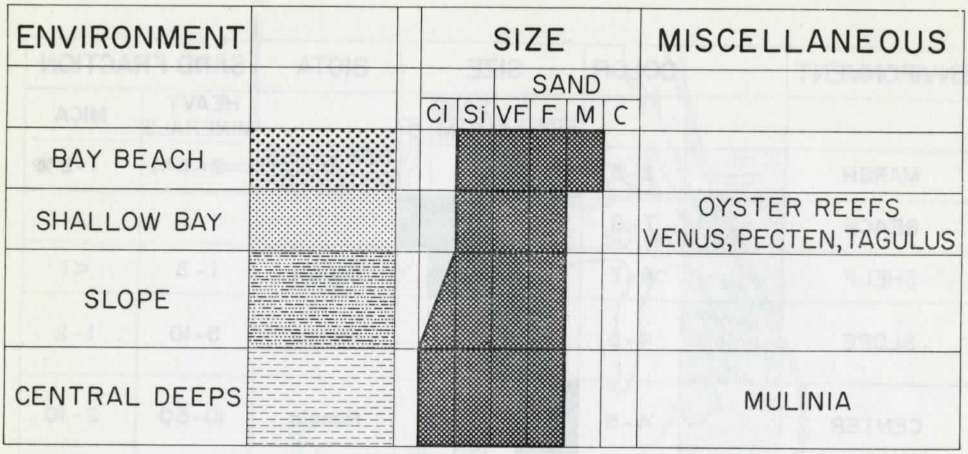

Figure 3. Vertical sequence in upper Newport River.

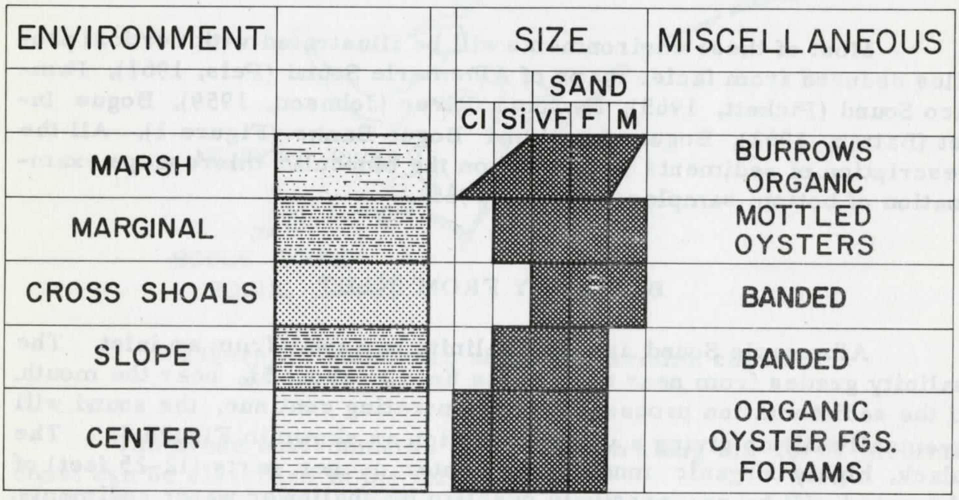

Figure 4. Vertical sequence on mainland side of Pamlico Sound.

sequence of sediments (Figure 3) is very similar to the sequence in Albemarle Sound. Because an inlet is near, however, the salinity is high enough (15-24‰) to allow a different fauna of shelled organisms to be present. The black muds of the central deeps often contain an abundance of the pelecypod _Mulinia._ In the shallower sands shells of _Crassostrea_, _Venus_, _Pecten_, and _Tagulus_ are common.

LAGOON AWAY FROM INLET

Pamlico Sound is a large bar-built estuary with the salinity ranging from about 15‰ in the western part to nearly normal sea water in the inlets. A filled-in Pamlico Sound would show on the mainland or western side a bottom unit (Figure 4) of the central homogeneous black mud with numerous oyster fragments and foraminifera overlain by a mottled silty fine sand of the slopes of the sound. Sometimes a layer of crudely banded clean sand of the shallower water cross shoals will be found above the silty sand layer and under the mottled silty fine sands of the marginal sands. Oyster bands are common in these marginal sediments. The top unit is a highly organic muddy sand of the marsh.

On the barrier island side of the sound the section would be similar except that the marginal sands contain less silt and usually show a crude textural banding rather than mottling.

Bogue Sound is a small bar-built estuary and shows the same general vertical sequence away from the inlets (Figure 5) as Pamlico Sound. The fauna is different, however, as the salinity in Bogue Sound is higher than in Pamlico Sound.

LAGOON NEAR INLET

Near an inlet the basal unit of an estuarine sequence changes drastically (Figure 6). In the eastern part of Bogue Sound near Beaufort Inlet the basal unit is a coarse, often poorly sorted, sand of the tidal channel containing an abundance of highly abraded shells. The fauna is a highly varied one, being a mixture of normal marine forms and brackish water forms. The clean fine sands of the channel sides will accumulate over the channel coarse sands. Between the channel sides and the laminated sound beach sands may be found a fine sand containing 5-30 percent heavy minerals. This zone of heavy minerals occurs in a narrow zone in shallow water on the barrier island side of Bogue Sound.

If an inlet migrates, the inlet sediments will be covered by laminated shelly beach sands and cross-bedded dune sands as shown in Figure 7.

BARRIER ISLAND

On Bogue Banks four main sedimentary facies are found. The beach sediments are laminated shelly sands. Landward from the beach in some areas is a zone of dune sands with large scale cross-bedding. Landward from the dunes is an area of aeolian flats or massive older dunes or beach ridges, with the sedimentary structures having been destroyed by weathering or root wedging. If Bogue Banks were to

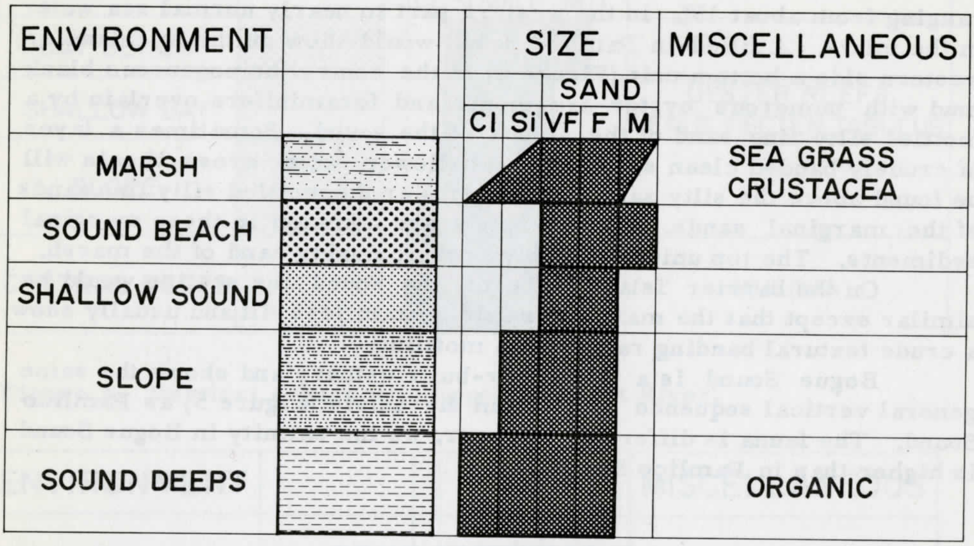

Figure 5. Vertical sequence in Bogue Sound away from inlet.

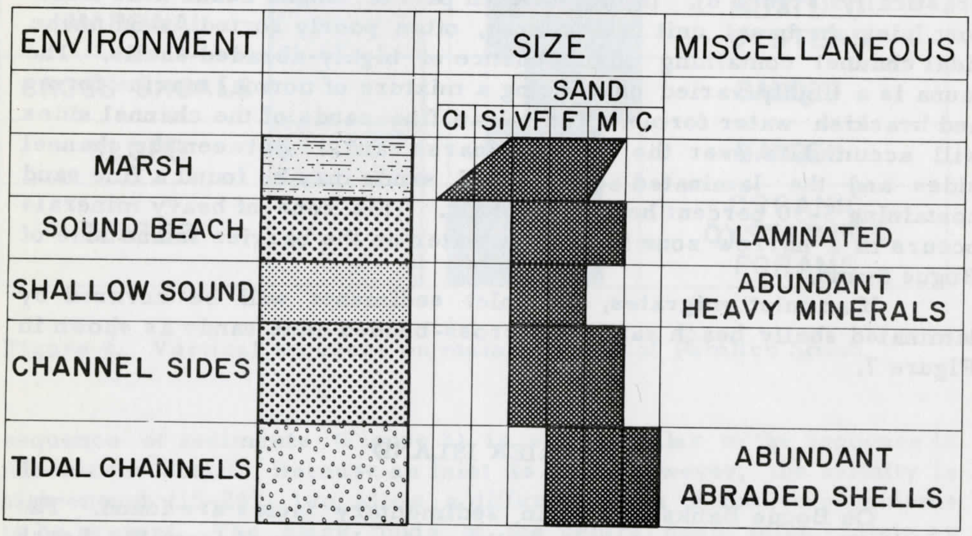

Figure 6. Vertical sequence in Bogue Sound near inlet.

migrate landward over Bogue Sound, a vertical sequence as shown in Figure 8 would be formed.

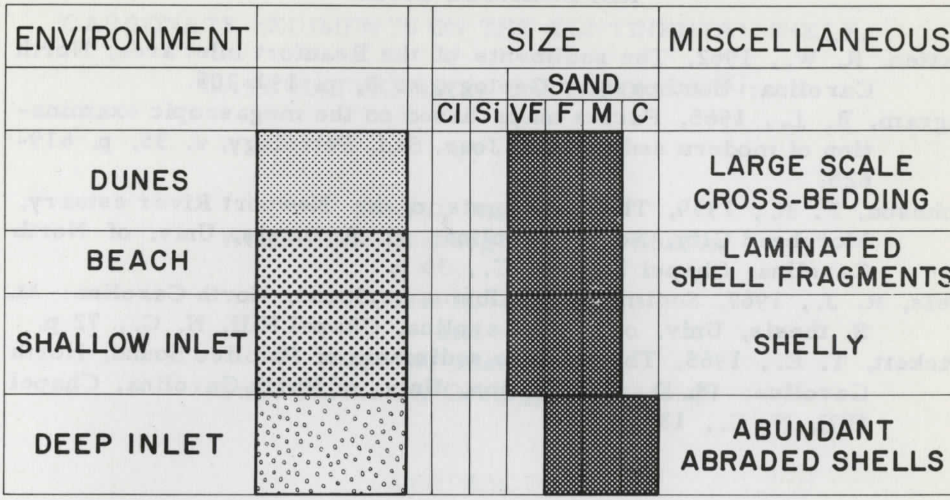

Figure 7. Vertical sequence of barrier island migrating over Beaufort Inlet.

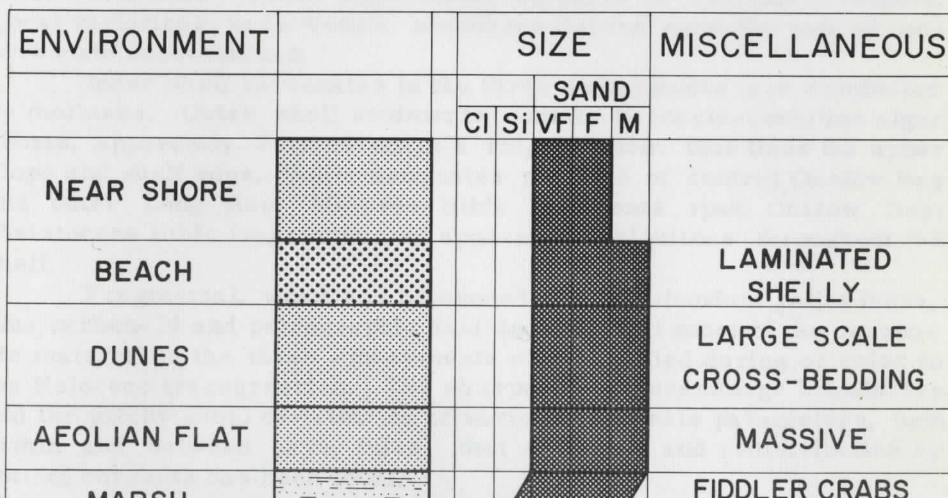

Figure 8. Vertical sequence of Bogue Banks migrating over Bogue Sound.

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CARBONATE SEDIMENTS ON THE CONTINENTAL SHELF, CAPE HATTERAS TO CAPE ROMAIN[1]

By

John D. Milliman
Woods Hole Oceanographic Institution

Orrin H. Pilkey
and
Blake W. Blackwelder
Duke University Geology Department

ABSTRACT

Surficial sediments on the continental shelf between Cape Hatteras and Cape Romain are dominated by terrigenous components. The shelf sediments contain appreciable amounts of calcium carbonate. Local variations in carbonate abundance depend upon the rate of noncarbonate accumulation.

Inner shelf carbonates in the three embayments are dominated by mollusks. Outer shelf sediments contain barnacle-coralline algae debris, apparently derived from a ridge system that lines the upper slope and shelf edge. Oolite dominates portions of central Onslow Bay and outer Long Bay. Miocene lithic fragments span Onslow Bay; Pleistocene lithic fragments are apparently ubiquitous throughout the shelf.

Fragmental, worn and blackened shells, abundant relict fauna, plus carbon-14 and petrographic data indicate that most of the carbonate material in the three embayments was deposited during or prior to the Holocene transgression. The sharpness of assemblage boundaries and the patchy areal distribution of various carbonate parameters, both within and between bays, infer that transport and redistribution by bottom currents has been local.

The composition and distribution of carbonate components on this "terrigenous" shelf are remarkably similar to those found on "carbonate-rich" tropical shelves.

INTRODUCTION

The continental shelf sediments off North and South Carolina are dominantly terrigenous (Gorsline, 1963; Uchupi, 1963; Pilkey and

(1) Contribution No. 2137 of the Woods Hole Oceanographic Institution.

Milliman, in preparation); however a significant calcareous fraction is present. The purpose of this paper is to study calcium carbonate sedimentation in a so-called "non-carbonate" area. Because carbonate components are a product of their environment, they can portray more accurately than clastic particles the ecologic conditions in which they were deposited (Ginsburg, 1956).

In this paper four distinct aspects of the carbonate fraction are discussed. These are: 1) abundance, 2) assemblages, 3) relict fauna and 4) particle characteristics. Together, these aspects contribute to the total carbonate sedimentation picture as well as to the general geologic history of continental shelf sedimentation.

Discussion is based on analyses of the carbonate fractions of over 1,500 samples collected by the Woods Hole Oceanographic Institution - U. S. Geological Survey Program (Emery and Schlee, 1963) and by the Duke University Marine Laboratory. Sample locations are shown in Figure 2.

Acknowledgments

The writers wish to thank the Oceanographic Program of Duke University for the use of the R/V EASTWARD which is part of the biological oceanography program of Duke University supported by the National Science Foundation. The Woods Hole Oceanographic Institution samples were collected in cooperation with the U. S. Geological Survey. Laboratory analyses were supported by the U. S. Geological Survey and the National Science Foundation. V. A. Zullo and R. K. S. Lee presented us with valuable identifications. I. G. Macintyre supplied much useful information as well as stimulating discussions. The paper was critically read by J. S. Schlee.

STUDY AREA

The seaward edge of the continental shelf from Cape Hatteras to Cape Romain is defined approximately by the 60 m isobath (Figure 1). The shelf widens from less than 25 km off Cape Hatteras to about 100 km off Cape Fear. The shelf area emcompasses three cuspate embayments of the Carolina Coastal Plain: Raleigh, Onslow and Long Bays. Well-developed shoals, Diamond Shoals off Cape Hatteras, Lookout Shoals off Cape Lookout and Frying Pan Shoals off Cape Fear, extend across the shelf and essentially separate the three embayments. Previous work has indicated that these embayments tend to act as separate entities in terms of sediment transport, allowing a minimum exchange with neighboring embayments (Luternauer and Pilkey, 1967).

Rivers with headwaters in the Piedmont province empty into both Long and Raleigh Bays. In contrast, Onslow Bay has only a few small coastal plain rivers emptying into it (Figure 1).

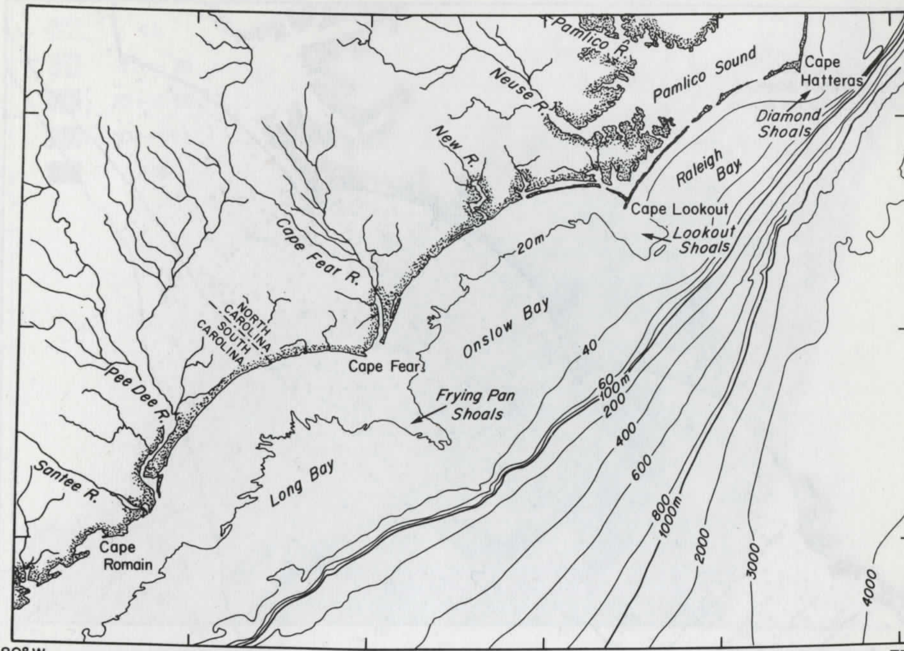

Figure 1. Index chart of study area (after Uchupi, 1965).

CARBONATE ABUNDANCE IN SHELF SEDIMENTS

Cape Hatteras separates temperate northern waters from semi-tropical and tropical southern waters. Winter bottom-water temperatures on the mid and outer shelf south of Cape Hatteras seldom fall below 14°C; summer temperatures exceed 26° (Stefansson and Atkinson, 1967). Under certain winter conditions, the colder Virginia Coastal Current will penetrate into the inner portions of Raleigh Bay (Cerame-Vivas and Gray, 1966). Floral and faunal studies have shown that most species found south of Cape Hatteras have either semi-tropical (Carolinian) or tropical affinities rather than the temperate (Virginian) affinities found north of Cape Hatteras (Taylor, 1960; Cerame-Vivas and Gray, 1966). Judging from relict shelf biota, a similar demarcation was present during the Pleistocene.

Partially as a result of high temperatures and a more tropical marine life, the calcium carbonate content (as determined by acid digestion) increases markedly in continental shelf sediments south of Cape Hatteras. North of the Cape carbonate rarely exceeds 5 percent of the total sediment; south of the Cape, the content is seldom less than 5 percent, and often exceeds 25 percent (Figure 3).

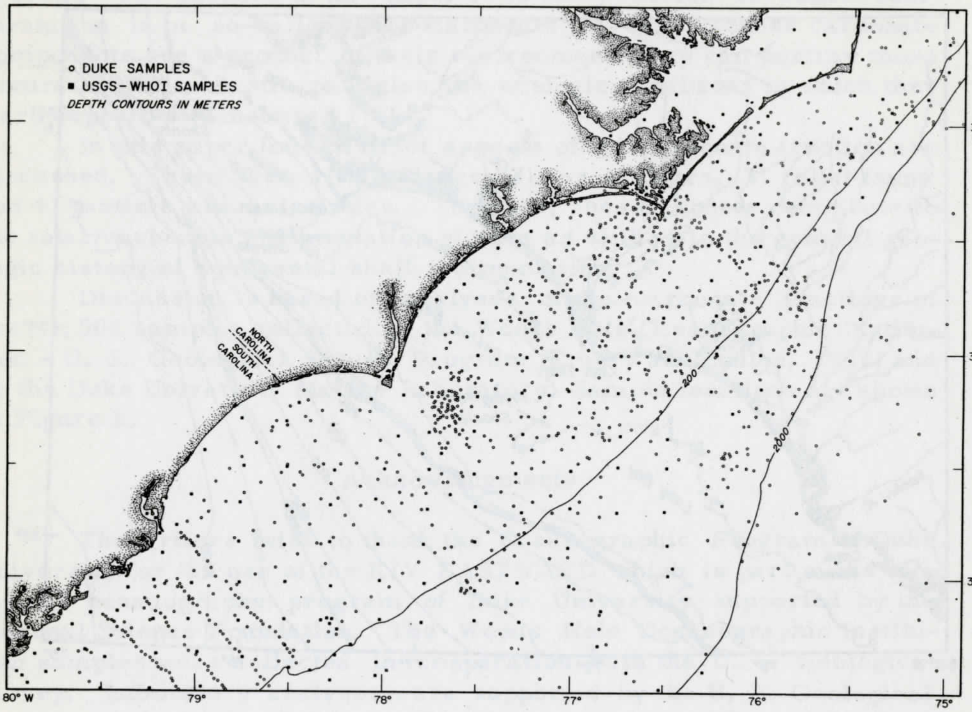

Figure 2. Locations of sediment samples collected on the Carolina continental margin by Duke University and the Woods Hole Oceanographic Institution.

The contribution of detrital sediments, however, locally affects carbonate content. Terrigenous sediments may be considered a dilutant in a potential carbonate environment (Chave, 1962). As a result of low river runoff, calcium carbonate content in sediments in Onslow Bay is relatively high, averaging about 35 percent. In contrast, major rivers flow into both Raleigh Bay (Neuse and Pamlico Rivers) and Long Bay (Cape Fear, Peedee and Santee Rivers). The calcareous material in these bays has been effectively diluted by the detrital sands brought in by the rivers. The carbonate content in each bay averages about 20 percent.

Carbonate material tends to be concentrated in coarse size fractions nearshore and more equally distributed through the sediment offshore. The ratio of carbonate in medium-fine sand (500-125 microns) to carbonate in coarse sand (2000-500 microns) increases offshore (Figure 4). Moreover, the ratio is significantly higher in Onslow Bay as compared to the other two bays. This ratio may indicate that detrital dilution has been largely by medium-fine sands.

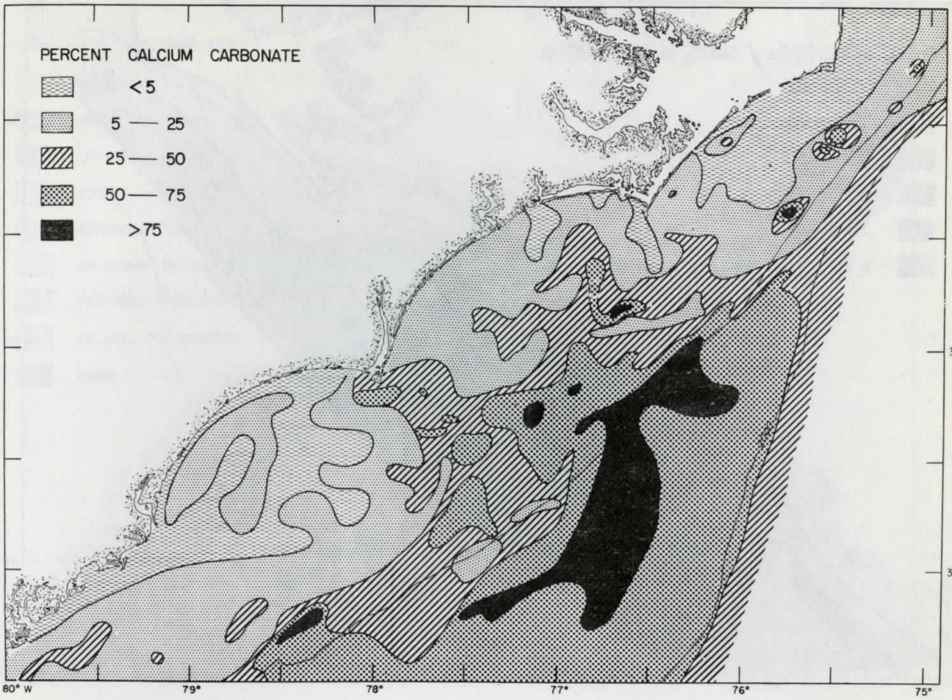

Figure 3. Percentage of calcium carbonate in the continental margin sediments.

CARBONATE ASSEMBLAGES

Carbonate components coarser than 62 microns were identified using various methods. About 60 of the sediment samples were impregnated with a polyester resin and studied in thin section. Another 800 samples were investigated quantitatively with a binocular microscope. The remaining samples were given a cursory examination.

Continental shelf sediments from Cape Hatteras to Cape Romain contain three types of carbonate components: 1) lithic fragments, 2) oolites and 3) skeletally-derived debris (mollusks, foraminifera, echinoids, barnacles, bryzoans, coralline algae and serpulids). Components contributing significant portions (usually more than 20 percent) of the carbonate fraction, constitute a carbonate assemblage. Three major and three minor shelf carbonate assemblages have been recognized and are discussed below. Although this classification is arbitrary, we have found that the boundaries between assemblages are generally distinct; major components within one assemblage usually decrease rapidly within the areal limits of adjacent assemblages.

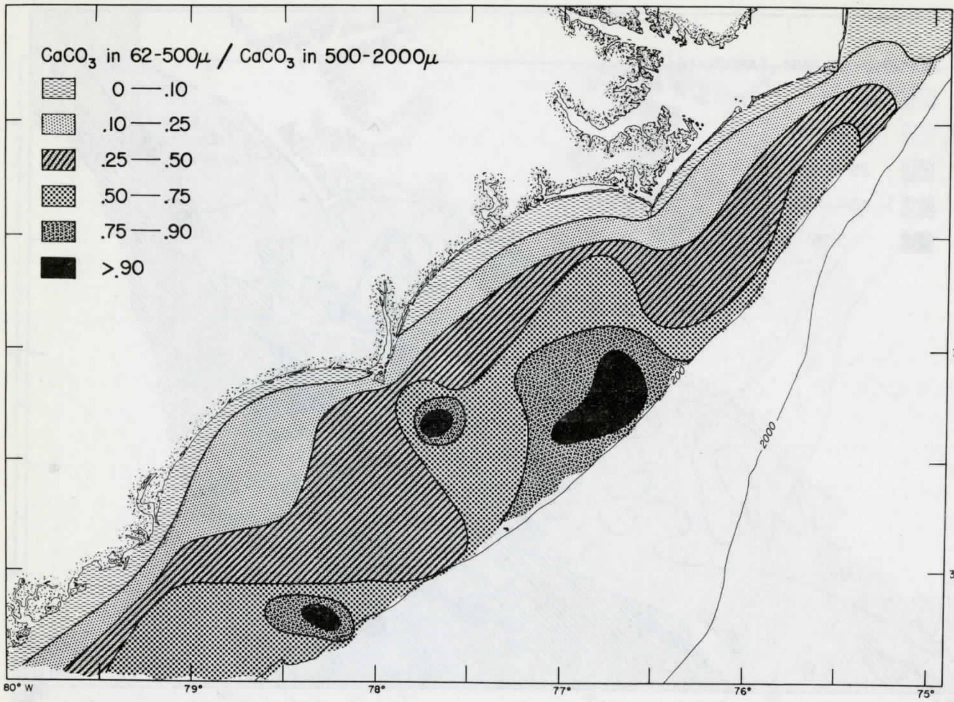

Figure 4. Areal distribution of the ratio of calcium carbonate content in fine sediments (finer than 500 microns) to carbonate content in coarse sediments (coarser than 500 microns).

Lithic Fragments

Several types of detrital limestone fragments, termed lithoclasts by Folk (1962), are present in the shelf sediments. Phosphatic limestone (phosphatic pellets cemented by a calcitic matrix), quartzose limestone, oolitic limestone and coquina limestone are considered to have been derived from shelf outcrops. The matrix for these limestones is usually micritic low-Mg calcite.

Most shelf sediments contain small amounts of lithic fragments. In these sediments the fragments are generally smooth and well worn, suggesting that they have been transported some distance from their original outcrops. Those samples considered as being on or near outcrops usually contain more than 30 percent limestone fragments, usually angular and irregular in shape, (Figure 5). Most rock outcrops are found in Onslow Bay; Cleary and Pilkey (1968) show a partial compilation of rock outcrops in the bay. Fishermen call the larger outcrops (or "reefs"), "Black Rocks", "because they furnish fine fishing grounds for the blackfish, Centropristia striatus (L)" (Pearse and Williams, 1951).

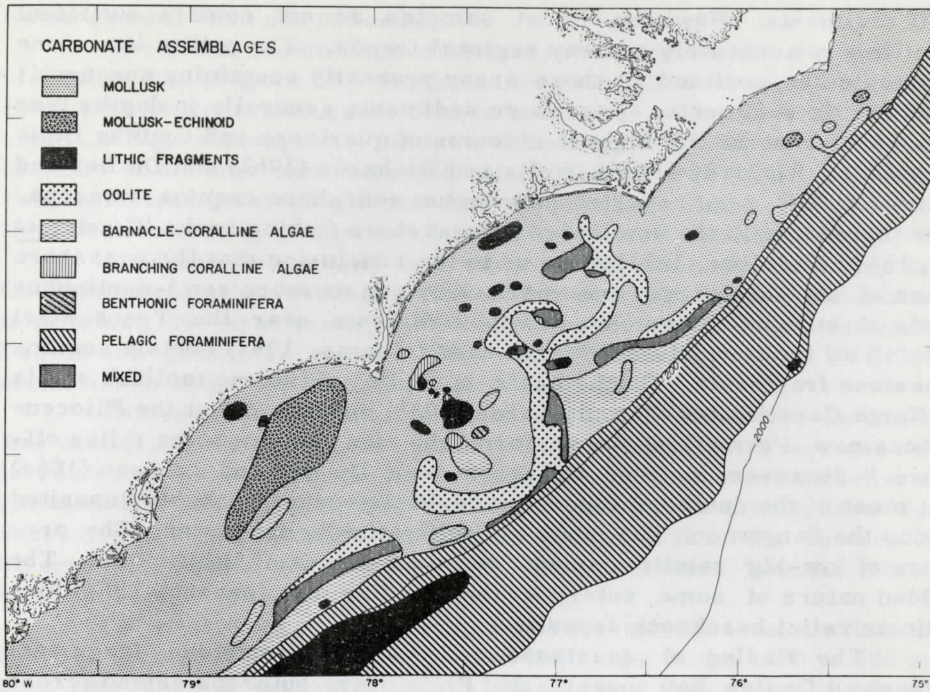

Figure 5. Distribution of carbonate assemblages on the Carolina Shelf and upper slope.

The major outcrop area is adjacent to and northeast of Frying Pan Shoals. Phosphatic limestone is the dominant rock type. Associated sediments include worn and encrusted mollusks, barnacles and coralline algae (especially branching forms), as well as abundant phosphate pellets. As the limestone is abraded and dissolved, the phosphate pellets are freed and tend to accumulate as phosphatic sands (Pilkey and Luternauer, 1967). Some of the associated carbonates are probably also residual, but other components, such as coralline algae, probably represent more recent accumulation (see below). The presence of shark teeth in many samples, plus micropaleontological data (T. G. Gibson, 1968, personal communication) suggests that this is a Miocene outcrop (Luternauer and Pilkey, 1967). Apparently this outcrop extends across the entire central part of Onslow Bay to Lookout Shoals. We find traces of phosphatic lithic fragments, plus associated carbonate assemblages (see below) throughout this entire band. Radcliffe (1914) showed the trend of this outcrop in a chart depicting fishing grounds off North Carolina. Pearse and Williams (1951) identified "reefs" off New River as the Trent Marl. Roberts and Pierce (1967) assigned middle shelf outcrops to the Miocene Yorktown Formation.

Other lithic fragments, non-phosphatic, occur throughout the shelf sediments. However, most samples do not contain sufficient quantities to accurately portray regional trends. The oolitic limestone fragments are confined to those areas presently containing unconsolidated oolitic sediments. Nearshore sediments generally in depths less than 15 m contain the highest amounts of quartzose and coquina lithic fragments. Richards (1936), Wells and Richards (1962) and Du Bar and Johnson (1964) have reported numerous nearshore coquina outcrops. This together with the dominance of nearshore fishing banks (Goode, et al., 1887; Radcliffe, 1914) leads us to the conclusion that the nearshore areas of all three bays are marked by one or more semi-continuous bands of coquina limestone. Even sediments near the Trent Marl "reefs" off the New River (Pearse and Williams, 1951) contain coquina limestone fragments. On the basis of finding Pliocene mollusk shells on North Carolina beaches, Richards (1936) suggested that the Pliocene (Waccamaw Formation) "may form the sea bottom some miles offshore." However, we tend to agree with Du Bar and Johnson (1964) that most of the outcrops appear to be Pleistocene, probably deposited during the Sangamon. The mode of lithification is not known. The presence of low-Mg calcite cement suggests subaerial lithification. The bedded nature of some outcrops (see Du Bar and Johnson, 1964) may indicate relict beachrock deposits.

The finding of quartzose and coquina limestone fragments throughout Onslow Bay suggests that Pleistocene outcrops extend across the entire shelf. I. G. Macintyre, of the Duke Marine Laboratory, has found extensive amounts of coquina limestone on the outer shelf. It is assumed that this limestone is also late Pleistocene or Holocene in age, although further analyses are needed.

Oolite Assemblages

Oolite-rich sediments on the North Carolina shelf have been described by Stetson (1939) and Terlecky (1967). Gorsline (1963) apparently mistook blackened ooids for phosphate pellets. The ooids tend to be superficial to mature. Quartz particles, which comprise about 60 percent of the nuclear grains, average about 8 percent (by weight) of the ooids (as determined by acid leaching). Other nucleii include fecal pellets, mollusk shells and foraminifera. The average nucleus therefore represents 13 percent by weight, or the inner 44 percent (by diameter) of the ooids. The ooids generally are finer than 1000 microns and coarser than 200 microns; Terlecky (1967) calculated a mean size of about 500 microns. The surfaces can be shiney or pitted; surficial colors range from tan to black, but most are dark brown or black.

The ooids are chiefly aragonitic (averaging about 90 percent of the carbonate) with a subordinate amount of high-Mg calcite (9 percent). Little or no low-Mg calcite is present. Data from Terlecky (1967) show that the elemental composition is similar to present-day Bahamian oolite, with the exception of exceedingly high concentrations of iron (often greater than one percent).

The oolite assemblage dominates the middle and outer portions of Onslow Bay (Figure 5). Depths range from 25 to 40 m. The Onslow Bay oolite is generally restricted to sediments with more than 25 percent $CaCO_3$, although no obvious direct relationship seems to exist between oolite and carbonate content (Terlecky, 1967). Highest oolite concentrations (averaging more than 40 percent of the carbonate fraction) are found in a band parallel and southwest of Cape Lookout Shoals.

A narrow oolite band is present on the outer shelf of Long Bay. Oolite concentration averages about 35 percent of the carbonate fraction, which in turn averages about 15 percent of the total sediment. Depths are generally greater than for Onslow Bay, about 38 m. No oolite assemblage has been found in Raleigh Bay.

Terlecky (1967) obtained two carbon-14 dates for the Onslow Bay oolite; 22,000 and 29,000 years. These dates, however, are subject to some error. First, for old ages (low C-14 concentrations) any contamination by young carbon can drastically lower the apparent age. Second, the nature of oolite precipitation is such that the nucleus can be several thousand years older than the outer-most laminae (Martin and Ginsburg, 1966).

To resolve these problems, an oolite sample from Onslow Bay (WHO1 sample 1847) was sieved, and the ooids in the 1000 to 500 micron size fraction separated. The sample was then split and one-half leached with dilute HCL until 60 percent (the outer 39 percent of the radius) was removed. The sample was aggitated during this process so that the leaching was nearly uniform. The total oolite sample and inner nucleus sample were each dated by the carbon-14 method. The total sample had an age of 25,450 $\pm$ 850 years, the inner portion an age of 27,650 $\pm$ 1,050-950 years. By interpolation, the outer leached portion had an age of 24,600 years. Therefore, the age of dominant precipitation must have been between 24,600 and 27,650 years B.P. Another sample (WHO1 sample 1806) has been dated as 24,200 $\pm$ 700 years agreeing closely with the age of the total unleached sample 1847. Pilkey et al., (1966) found a similar age for oolite on the Georgia shelf.

Lowenstam and Epstein (1957) showed that present-day Bahamian ooids are in isotopic equilibrium with their environment. Thus, by assuming that 1) when deposited the North Carolina shelf ooids were in isotopic equilibrium with the ambient waters and 2) the North Carolina shelf ooids are unaltered (a reasonable assumption considering their petrography, chemistry, and mineralogy), we can speculate on the environmental conditions during precipitation.

Several Onslow Bay oolite samples were analyzed for stable oxygen and carbon isotopes by E. T. Degens, of Woods Hole. Values for δO^{18} from WHO1 samples 1806 and 1847 are +1.84 and +2.01, respectively. The δO^{18} values for the total and inner portions of WHO1 sample 1847 were essentially the same.

Decreasing temperature and increasing salinity increase

δ O^{18} values. If the salinity had been the same as at present, the temperature during the precipitation of these ooids must have been about 8 or 9°C. At present temperatures (about 22°, annual average), salinities over 40 o/oo would have been required for such high δ O^{18} values. Since ooids precipitate in shallow warm waters (Newell, et al., 1960), the high salinity environment would seem to have been a more likely condition for precipitation. An environment such as Laguna Madre (Rusnak, 1960) might be envisioned, although this would require a climate more arid than present-day conditions. There is no faunal evidence for such a high salinity environment, but, as discussed below, most of the non-oolitic carbonates are not contemporaneous with the oolite.

Mollusk Assemblage

Dominated by shells of infaunal filter-feeding pelecypods, molluscan components within the mollusk assemblage average 66 percent of the carbonate fraction. This is the most common assemblage on the shelf (Figure 5). Foraminifera, echinoids, barnacles and lithic fragments seldom individually contribute more than 10 percent. This assemblage tends to characterize low-carbonate sediments and dominates most of Raleigh and Long Bays; the average carbonate content of sediments within this assemblage is 13 percent. In the inner portion of Onslow Bay the mollusk assemblage sediments have much higher carbonate content (34 percent average) and locally contain significant amounts of oolite, barnacles, coralline algae, foraminifera and lithic fragments.

Figure 6 shows a plot of the areal distribution of two shallow water assemblages of mollusk species. The assemblages are based on a number of key species listed in Table 1. In order for an assemblage to be identified, several key species had to be present in the sample. Wherever the "0-20 meter" assemblage is present, so is the "inlet and intertidal" assemblage, but the reverse is not necessarily the case.

In some of the nearshore portions of the continental shelf the shallow water faunas may be indigenous. However, over most of the shelf these faunas are relict, and as such are indications of pre-existing shallow water conditions. Raleigh Bay is characterized by widespread distribution of shallow water fauna except in the vicinity of the Diamond Shoals off Cape Hatteras. In both Onslow and Long Bays the middle and outer shelf sediments are rich in algae and oolite, thus reducing the size and importance of the molluscan fraction. As a result, the shallow water fauna is largely absent in these areas.

In some areas echinoids comprise a major second component, averaging 32 percent of the carbonate fraction. This assemblage, termed the mollusk-echinoid assemblage, usually is found on the inner shelf, and is associated with sediments containing very low carbonate values (about 4 percent) (Figure 5). This assemblage resembles shelf

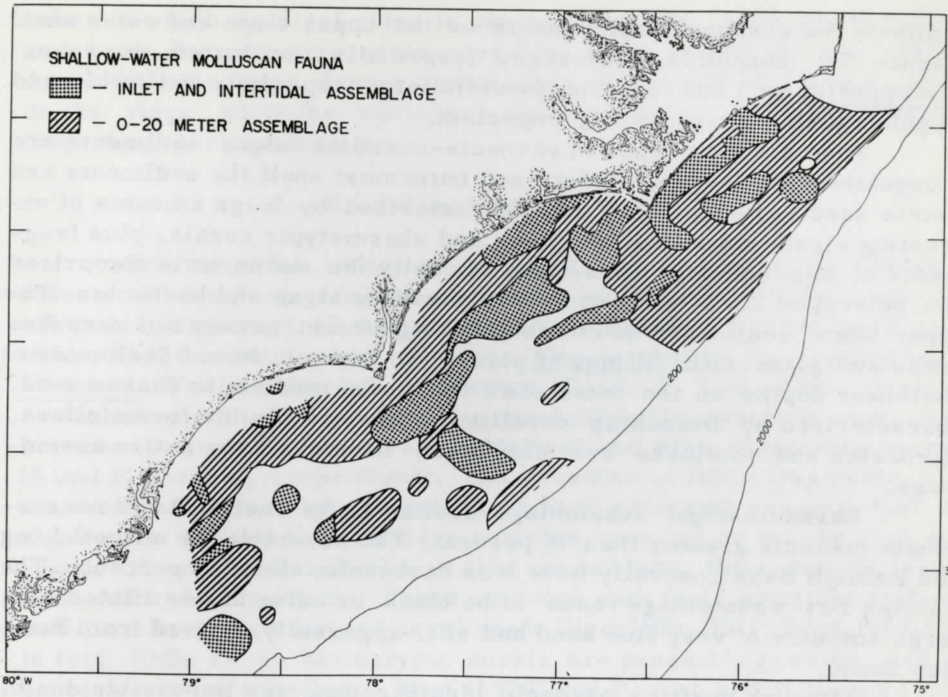

Figure 6. Areal distribution of shallow-water molluscan assemblages. These assemblages are defined by species listed in Table 1. Blank areas shown on the chart indicate the absence of shallow-water assemblages.

Table 1. Molluscan Assemblages Utilized in Determination of Shallow Water Elements on the Continental Shelf.

Inlet and Intertidal Assemblage	0-20 Meter Assemblage
Crassostrea virginica (Gmelin)	*Donax variabilis* Say
Gemma gemma Totten	*Mercenaria campechiensis* (Gmelin)
Littorina irrorata Say	*Mulinia lateralis* (Say)
Nassarius obsoletus Say	*Spisula solidissima* Dillwyn
Tagelus plebeius Solander	*Terebra dislocata* Say

sediments north of Cape Hatteras in which the echinoid *Echinarchinus parma* is prominent (Emery, *et al.*, 1965).

Barnacle-Coralline Algae

Barnacles (27 percent, average), encrusting and branching coralline algae (21 percent, average) and mollusks (21 percent, average) dominate the carbonate components on the upper slope and outer shelf (Figure 5). Serpulids, bryozoans (especially the button bryzoan, Discoporella sp.) and benthic foraminifera (especially miliolids and amphistogerinids) are locally important.

Two distinct types of barnacle-coralline algae sediments are recognized. On the upper slope and outermost shelf the sediments are coarse sand and gravel and are characterized by large amounts of encrusting algae, serpulids, bryzoans and shermatypic corals, plus fragments of algally-bound limestone. Locally the sediment is comprised of a pelecypod shell-hash, coated by coralline algae and barnacles. The upper slope sediments often contain significant amounts of very fine sands and glauconitic fillings of planktonic foraminifera. Sediments at shallower depths on the outer shelf tend to be medium to coarse sand, characterized by branching coralline algae and benthic foraminifera. Barnacles and mollusks are ubiquitous throughout the entire assemblage.

Barnacle-algal assemblage sediments in Onslow Bay have carbonate contents greater than 75 percent. The assemblages off both Long and Raleigh Bays generally have less carbonate; about 50 percent. The Raleigh Bay assemblage tends to be black in color and is diluted with large amounts of very fine sand and silt, apparently derived from Pamlico Sound.

Although positive barnacle identification was impossible due to lack of opercular valves, V. A. Zullo (1967, personal communication) felt that most might be Balanus calidus Pilsbry, a common species in outer shelf sediments off South Carolina (Zullo, 1966). Wells et al., (1964) found that Balanus amphitrite and B. calidus actively encrust scallop shells in 30 to 40 m depths in Raleigh Bay, illustrating that barnacles are presently living on the shelf.

R. K. S. Lee studied the algae from several sediment samples. He concluded (1968, personal communication) that dominant species on the outer portions of the assemblage are the massive species, Lithothamnion and Lithophyllum. The lack of reproductive structures and the fragmentary nature of the specimens did not permit species identification.

The barnacle-coralline algae assemblage is closely related to a ridge system that extends discontinuously along the upper slope and outer shelf edge. This complex apparently was formed (at least partially) by algal growth during previous low stands of Pleistocene sea level; an algal nodule recovered from the ridge was radiocarbon dated as 19,000 years by Menzies et al. (1966). Two carbon-14 analyses for algal rock samples dredged by I. G. Macintyre, Duke University Marine Laboratory, gave ages of 26,500 ± 900-800 years (Duke sample E-8193) and 12,270 ± 190 years (Duke sample E-8200) B.P.

The implication is that the barnacle-coralline algae sediments may be derived from the algal ridge. Most of the organisms comprising the assemblage require growth on a hard substrate. Also, in those areas in which the algal ridge is patchy or lacking, such as off Raleigh and Long Bays, the barnacle-coralline algae sediments are lacking. Apparently the outer, deeper assemblage represents sediments near or on the ridge, while the shallower sediments may have been washed in from the outer assemblage.

Branching Coralline Algae

Several shoal sediments in inner Onslow Bay contain large amounts of branching coralline algae (Figure 5). The samples from this assemblage average 62 percent coralline algae in the carbonate fraction. The dominant algal form is Neogoniolithon sp., probably N. strictum (Foslie) Setchell et Mason, (R. K. S. Lee, 1968, personal communication). The green color (probably chlorophyl) in many of the branches suggests a recent age. Mollusk and lithic fragments average 15 and 14 percent, respectively. The presence of lithic fragments, plus a need by coralline algae to grow on a hard substrate suggests that the algae were derived from modern colonies growing on nearby rock outcrops. From the distribution of this assemblage, the substrate is probably Miocene limestone. These outcrops with their luxurient epifauna and flora have been termed coral reefs (Radcliffe, 1914; Hoyt, 1920) when in fact, little or no hermatypic corals are presently growing, and the substrate is not coralline. Hoyt (1920) and Pearse and Williams (1951) reported on the biota from these outcrops.

Mixed Assemblage

Some sediments in the study area contain significant amounts of both barnacle-coralline algae components and oolite. On the outer shelf these samples lie between oolite and barnacle-coralline algae assemblages (Figure 5), and probably represent a transition between the two. Several occurrences of mixed assemblages also occur on the middle portion of Onslow Bay. The barnacles and coralline algae are assumed to have been derived from outcrops on which they live (see above) and deposited in surrounding oolitic sands. The presence of lithic fragments and phosphate pebbles in the sediments support this assumption.

Foraminifera

Benthonic foraminifera are a common carbonate component. Yet, except for one isolated area near Frying Pan Shoals, designated as the benthic foraminifera assemblage, shelf sediments rarely contain more than 10 percent foraminifera.

Planktonic foraminifera dominate the sediments on the upper slope and portions of the outer shelf off Raleigh Bay (Figure 5). Planktonic foraminifera are also present in the finer-size fractions of the outermost barnacle-coralline algae assemblage. For the most part these foraminifera appear to be recent forms, although off Long and Raleigh Bays some tests are filled with glauconite, suggesting a relict sediment.

PARTICLE CHARACTERISTICS

Although carbonates are ubiquitous constituents of most shelf sediments, previous studies have only reported on carbonate abundance plus some information on the nature of the constituents. A largely ignored aspect of the carbonate fraction has been the nature and environmental significance of the individual particle characteristics. These include such properties as size distribution, roundness, staining and degree of fragmentation. Since these and other characteristics reflect the sediment history in a similar fashion to properties of grains of terrigenous origin, they should also be of value in interpretation of shelf history. In the following sections, the carbonate fraction is discussed from a sedimentary particle viewpoint.

Fragmental Shells

Stratigraphers have used the presence of broken shells as an indicator of relict shorelines. However, no distinct strand lines are seen on the Carolina Shelf (Figure 7). The distribution of broken and fragmental shells in the 2-4 mm size fraction is extremely patchy. This complicated pattern no doubt reflects the dual origin of fragmentation: either by physical means in the surf zone or biological fragmentation by skates, rays and various invertebrates. In environments with high rates of sedimentation, biological fragmentation would be expected to be less efficient, and the degree of fragmentation would correspond more closely with physical conditions.

Worn Shells

A large portion of the shell material in shelf sediments exhibits varying degrees of abrasion, solution, burrowing and loss of coloration. The degree of wear should be a function of the duration of exposure to subaqueous and perhaps subaerial "weathering" processes, as well as biological erosion. Thus relict or slowly deposited sediments should exhibit a more highly worn carbonate fraction than Recent or rapidly deposited materials. Pilkey (1964) noted that within some samples two distinct "populations" of shells are often present, one worn and the other fresh.

From Figure 8 it is apparent that most of the 2 to 4 mm size carbonate materials are worn. The distribution is very patchy, but there is some tendency toward fresh shells on the outer shelf and upper slope,

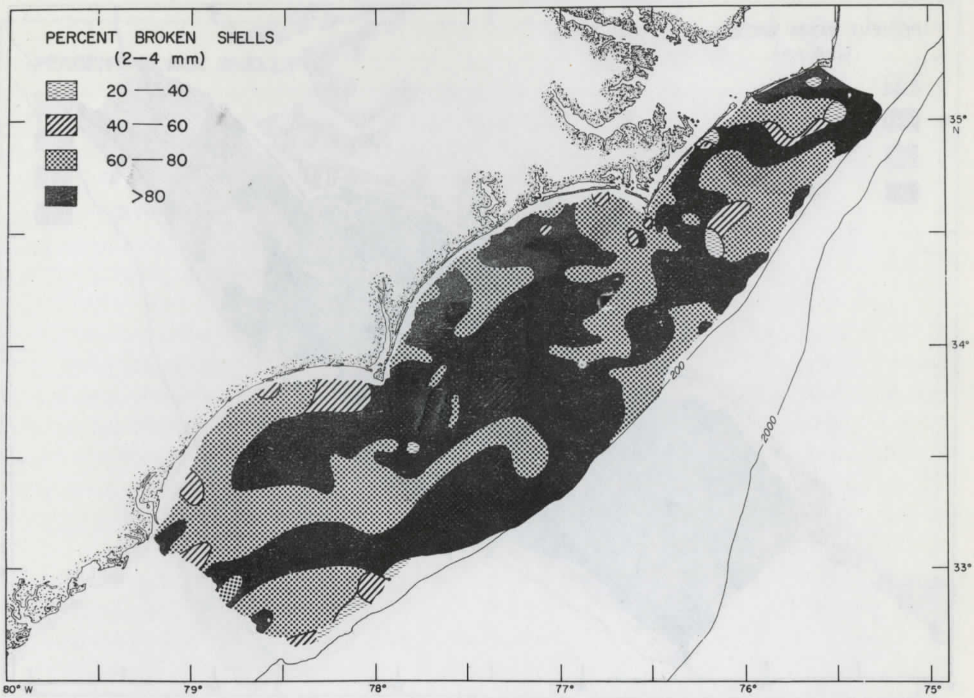

Figure 7. Areal distribution of fragmental (broken) shells in the 2 to 4 mm size fraction.

Black Shells

Black shells are a common constituent of the carbonate fraction of both beach and shelf sediments in the study area. Doyle (1967) has studied the origin and environmental significance of black shells. The origin of the black color is unknown, although it appears to result from the reduction of iron; black shells contain finely divided pyrite (Doyle, 1967). This blackening process may also involve the formation of some organic compound, perhaps alteration of shell conchiolin (Houbolt, 1957).

Apparently blackening results from burial in reducing conditions, and can occur after only a few weeks of burial (Doyle, 1967). At present such conditions are found only in muddy nearshore and lagoonal environments. The remainder of the shelf is essentially devoid of muddy sediments in which a strongly reducing condition could form. Therefore the presence of black shells on the present-day shelf can be considered an indication of former shore lines.

The outer shelf of both Onslow and Long Bays is nearly devoid of black shells perhaps corresponding to the absence of shallow-water molluscan fauna (Figure 9). Most of Raleigh Bay sediments contain

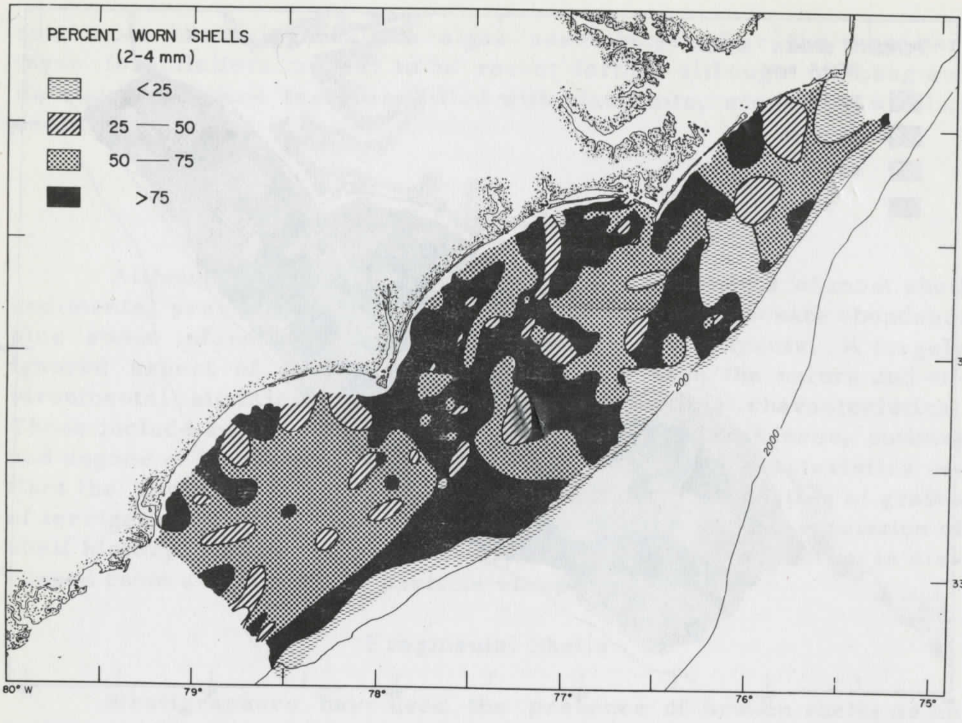

Figure 8. Areal distribution of worn shells in the 2 to 4 mm size fraction.

large amounts of black shells. Greatest concentrations are found in Onslow Bay near Cape Lookout and Raleigh Bay off Pamlico Sound.

The overall distribution of black shells is very patchy, with no obvious lineation related to fossil strand lines. However, correlation of blackened shells and ooids, with bleached quartz grains (reduced iron-stained grains) may prove an interesting technique for delineating fossil shorelines (Pilkey and Milliman, in preparation).

SEQUENCE OF EVENTS

Using carbon-14 ages, plus petrographic and mineralogic data, we can construct a sequence of events for shelf carbonate sedimentation in the study area. Most carbonates on the continental shelf between Cape Hatteras and Cape Romain were deposited during or after the Wisconsin glaciation. Miocene outcrops that cover much of Onslow Bay and possibly some Pliocene rock outcrops (Richards, 1936, Wells and Richards, 1962) are probably the only Pre-Sangamonian carbonates on the shelf. Pleistocene beachrock outcrops along the shore and nearshore were probably formed during the Sangamonian high stand of sea

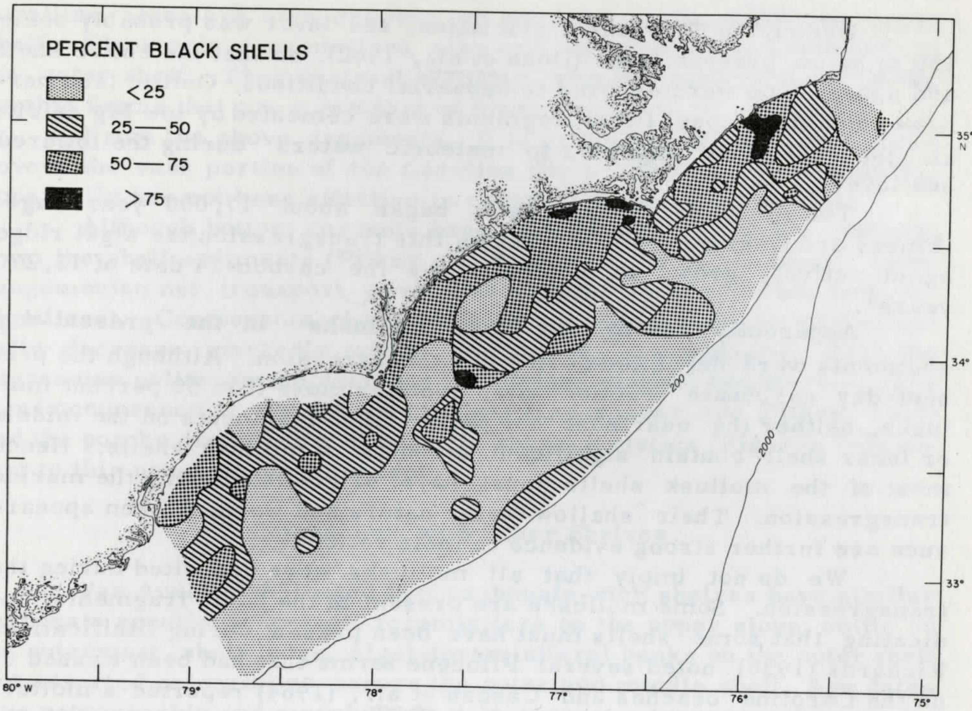

Figure 9. Areal distribution of blackened shell fragments in the 2 to 4 mm size fraction.

level (Wells and Richards, 1962; Du Bar and Johnson, 1964).

The oldest datable carbonate sediment on the shelf is the Onslow Bay oolite, at 25 to 27 thousand years (Terlecky, 1967; this paper). Since ooids precipitate in very shallow water (Newell et al., 1960) the shelf oolite presently at depths of 25 to 40 m, must have formed at lower sea level. A sea level of -25 to -40 m at 25 to 27 thousand years B.P. would correspond to the Wisconsin regression (Curray, 1965). During the regression oolite precipitation was limited to Onslow Bay and a few scattered areas on the outer shelf of Long Bay. The minor influence of Piedmont rivers in these areas probably permitted slow oolite precipitation without threat of burial. Preliminary δO^{18} values suggest that the oolite was formed in a restrictive environment perhaps lagoons behind offshore bars.

As the sea level subsided further, the algal "ridge" on the shelf edge and upper slope was actively growing; the carbon-14 date of 26,250 years for a piece of algal rock (collected by I. G. Macintyre) corresponds to the Wisconsin regression curve of Curray (1965). The lowered sea level, with resulting increased light and wave energy no doubt benefited the growth of the coralline algae comprising the "ridge".

During the Wisconsin glaciation, sea level was probably some 150 m below present level (Donn et al., 1962), so that the entire shelf and upper slope were exposed to subaerial conditions. Oolitic (and perhaps some quartzose) lithic fragments were cemented by low Mg calcite as the result of exposure to meteoric waters during the lowered sea level.

The Holocene transgression began about 17,000 years ago (Emery and Garrison, 1967). During this transgression the algal ridge again actively grew, as evidenced by the carbon-14 date of 12,270 years[1].

Apparently many of the mollusks in the present-day sediments were deposited during the transgression. Although the present-day carbonate fraction often contains more than 50 percent mollusks, neither the quartzose nor oolitic lithic fragments on the middle or inner shelf contain significant amounts of mollusk shells. Hence most of the mollusk shells must have originated during the marine transgression. Their shallow-water nature and worn, broken appearance are further strong evidence to their relict age.

We do not imply that all mollusks were deposited during the transgression. Some mollusks are present in the lithic fragments, indicating that some shells must have been present during lithification. Richards (1936) noted several Pliocene forms that had been washed up on the Carolina beaches and Cazeau et al., (1964) reported a mollusk from the inner shelf that is 33,000 years old. Also, as noted by the presence of fresh shells in nearshore sediments (Pilkey, 1964), mollusks are presently living on the shelf; prolific scallop beds are reported in depths of 35 to 40 m in Raleigh Bay (Cummins et al., 1962).

Other carbonate forms accumulated during and after the transgression. Probably the barnacles grew on the ridge after sea level was high enough to inhibit rapid reef accumulation; they require a relatively inactive substrate on which to grow (Zullo, 1967, personal communication). Barnacles no doubt are still living on the outer shelf (Ross et al., 1962; Wells, et al., 1964; Zullo, 1966). In addition, branching coralline algae, together with numerous bryzoans and serpulids, are presently living on the outer shelf. These carbonate organisms are being eroded from substrates and being deposited in the barnacle-coralline algae assemblage on the outer shelf. Branching

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1 Algal ridges apparently are common features on the shelf break of many tropical and semi-tropical areas, such as the Caribbean (Nota, 1958; Koldewign, 1958) and (discontinuously) from the Gulf of Mexico around Key West to Cape Hatteras (Stetson, 1953; Ludwick and Walton, 1957; Zarudzki and Uchupi, 1968; Menzies, et al., 1966; I. G. Macintyre, personal communication). Available age dates suggest that all these features were actively growing 11 to 13 thousand years ago, during the Holocene transgression.

coralline algae are also growing on outcrops on the middle and inner shelf. Planktonic foraminifera also are being added to sediments on the outer shelf. They contrast strongly with the relict shallow-water benthic forms that are a remnant of lower sea level.

From the above arguments, it is concluded that relict material covers the vast portion of the Carolina Shelf. Holocene sedimentation apparently has not been effective in covering the relict sediment.

Although bottom currents have continued to winnow fine material from the shelf sediments (Pilkey and Milliman, in preparation), post-Sangamonian net transport of sand and gravel apparently has been insignificant. Components characterizing one carbonate assemblage usually decrease markedly within neighboring assemblages. Even the regressive oolite assemblage has maintained distinct boundaries. The local occurrence of phosphorite pellets (Luternauer and Pilkey, 1967) and the patchy distribution of particle characteristics (Figures 7-9) attest to this non-transport concept.

Comparison with Other Shelves

Van Andel (1965) noted that carbonate-rich shelves have similar carbonate zonations: pelagic foraminifera on the upper slope, oolite on the outermost shelf edge, algal-foraminiferal banks on the outer shelf and assorted calcarinites across the outer and middle shelf. Age dates plus petrographic and morphologic data suggest a transgressive age for most shelf carbonates (Van Andel, 1965, Van Andel and Veevers, 1967).

The carbonate assemblages off North Carolina closely resemble the deposits on carbonate-rich shelves, even though they were deposited in a high-latitude "non-carbonate" environment. Essential faunal differences appear to be the presence of barnacles and absence of coral and Halimeda on the Carolina shelf[2].

The basic departure from other studied world shelves is the arrangement of zonations and the sequence of events on the Carolina Shelf. The Carolina oolitic sands lie landward on the algal ridge, on the middle shelf, not on the shelf edge. With ages of 25,000 to 27,000 years, the North Carolina oolites were deposited during the regression, unlike the shelf oolites off Florida (Gould and Stewart, 1953; Terlecky, 1967), Campeche (Williams, 1963; Harding, 1964), Australia (Van Andel and Veevers, 1967), and India (Rao, 1964), all of which apparently were deposited during the last transgression.

Van Andel (1965, 1967) has theorized that during the lowered sea level oolite formed near the shelf edge in response to the upwelling

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2 Chave (1967) noted the abundance of bryzoans in non-tropical shelf sediments. While bryzoans are abundant on the Carolina Shelf, they seldom contribute more than 5 to 10 percent of the carbonate fraction.

and subsequent warming of slope waters. Such was not the origin of the Carolina oolite, which apparently was formed in a semi-restricted environment. During the peak of the Wisconsin glaciation, temperatures near the Carolinas might have been too cool for oolite precipitation.

CONCLUSIONS

1. The abundance of calcium carbonate in the shelf sediments between Cape Hatteras and Cape Romain is inversely related to the rate of terrigenous sedimentation. Thus Onslow Bay, with its small influx of terrigenous sediments, has the highest percentages of carbonate.

2. Three types of carbonate components contribute to the shelf sediments: residual lithic fragments, oolites and skeletal fragments. These components, in various ratios, comprise three dominant carbonate assemblages (mollusk, oolite and barnacle-coralline algae), and three minor assemblages (lithic outcrops, branching coralline algae and mixed). Planktonic foraminifera produce the bulk of the continental slope sediments.

3. Most carbonate sediments on the Carolina Shelf are relict. Evidence for this includes the worn physical appearance, abundant black shells, the widespread shallow-water fauna, the presence of oolite, radio-carbon dates and limestone outcrops. Carbon-14 dates, mineralogic and petrographic data indicate that most of the carbonate was deposited during and after the last glaciation; minor contributions come from Miocene strata cropping out across Onslow Bay.

4. The relatively distinct assemblage boundaries and the patchy areal distribution of the various carbonate parameters indicates that homogenization processes, either by transgressing shorelines or present-day waves and currents, have been inefficient.

5. Although these carbonate sediments were deposited in a non-carbonate area, their composition and distribution are similar to those deposited in more tropical, carbonate-rich areas.

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SEDIMENTARY FRAMEWORK OF THE CONTINENTAL TERRACE OFF THE EAST COAST OF THE UNITED STATES

By

Elazar Uchupi
Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

SUMMARY

Data from 20,000 km of continuous seismic profiles supplemented by information from dredgings, coring, drilling and seismic refraction profiles were used to compile a geologic map, isopach maps and reconstruct the evolution of the sedimentary framework of the continental terrace between Nova Scotia and the Florida Keys (Figure 1).

Paleozoic igneous and metamorphic rocks occur along the inner margin of the Scotian Shelf, the Gulf of Maine and Long Island Sound and other sounds and bays off southern New England. Triassic rocks are restricted to the Bay of Fundy and the Gulf of Maine. Lower Cretaceous limestones crop out along the lower part of the Blake Escarpment. Upper Cretaceous strata are exposed on the upper Blake Escarpment, the western edge of the Blake Plateau beneath the Gulf Stream, in the submarine canyons north of Cape Hatteras and in the Gulf of Maine. Paleocene, Eocene and Oligeocene sediments have been recovered from the eastern and western margins of the Blake Plateau, in the submarine canyons north of Cape Hatteras and in the Gulf of Maine. Miocene - Pliocene deposits are the most extensive, blanketing most of the continental terrace between Nova Scotia and the Florida Keys.

East of New England, Tertiary strata are relatively uniform in thickness ranging from 200 to 400 meters. A narrow basin extending from Martha's Vineyard to Cape Hatteras contains as much as 1200 meters of Tertiary sediments. This basin is not continuous throughout its length, but is divided by ridges at right angles to the present shoreline into a series of embayments such as the Salisbury Embayment in Maryland. A broad structural high extending from Cape Hatteras to Cape Fear borders this basin on the southwest. This structural high consists of three ridges, one off Cape Hatteras and the others off Capes Lookout and Fear, separated by shallow troughs. Less than 400 meters of Tertiary strata occur on these structural highs suggesting that they were active throughout most of the Tertiary. Between 400 to 1400 meters of Tertiary sediments are present on the shelf south of Cape Romain. Owing to erosion and non-deposition caused by the Gulf Stream, Tertiary strata on the Blake Plateau are less than 400 meters thick.

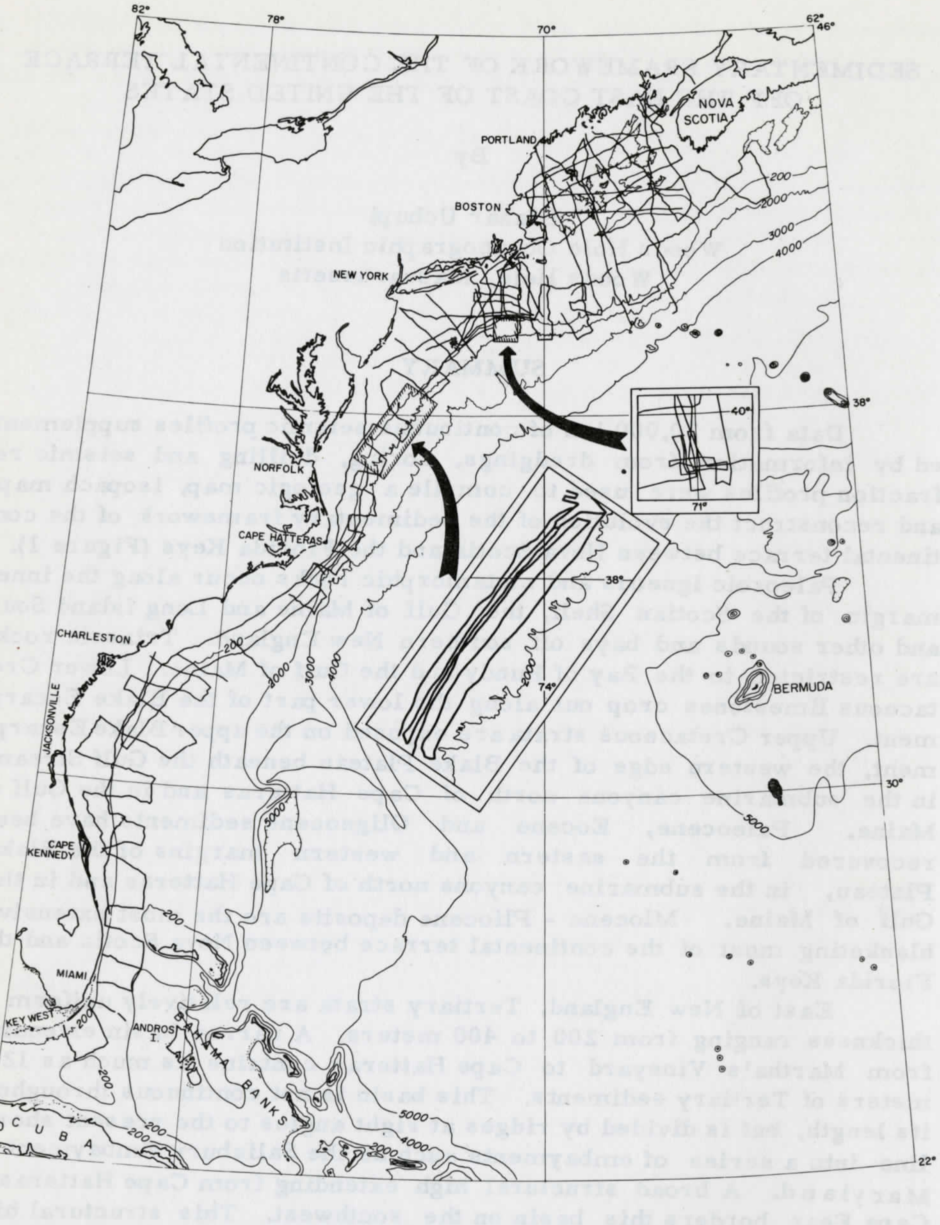

Figure 1. Locations of seismic profiles used in the present study. From Uchupi, (in preparation, Figure 2).

Pleistocene sediments, where they can be distinguished from the underlying Tertiary strata, are less than 70 meters thick. In large segments of the shelf, as for example between Cape Hatteras and Cape Romain, the Pleistocene is probably less than 10 meters thick. Recent sediments (sediments deposited since the beginning of the last transgression 10,000 years ago) are generally less than 5 meters thick. Only in such protected areas as the Gulf of Maine do greater accumulations occur.

The continental terrace north of Cape Hatteras, North Carolina, was generally formed by upbuilding on the shelf and outbuilding on the slope. The shelf and Florida-Hatteras Slope west of the Blake Plateau were formed in a similar manner, although carbonate accretion or reef build up may have played a role in molding the Florida-Hatteras Slope. Carbonate accretion or reef build up formed the Blake Escarpment east of the Blake Plateau and the side slopes of the Straits of Florida. The above framework has been modified by folding and faulting in some areas, for example in the Straits of Florida and the shelf between Cape Hatteras and Cape Romain.

Other modifications of the sedimentary framework of the continental terrace off the East Coast occurred during the Pleistocene. Preglacial fluvial and glacial erosion deepened the normally shallow shelf off New England. Turbidity-current action, slumping and gravitational sliding deeply eroded the slope north of Cape Hatteras. Erosion by the Gulf Stream and deposition by deep-water corals and shallow water calcareous algae have altered the framework of the Blake Plateau, Florida-Hatteras Slope and the shelf south of Cape Hatteras. Emplacement of large volumes of carbonate sediment has partially buried the carbonate accreted side slopes of the Straits of Florida.

REFERENCES CITED

Uchupi, Elazar, Atlantic Continental Shelf and Slope of the United States: Shallow Structure: U. S. Geol. Survey Prof. Paper 529, in preparation.