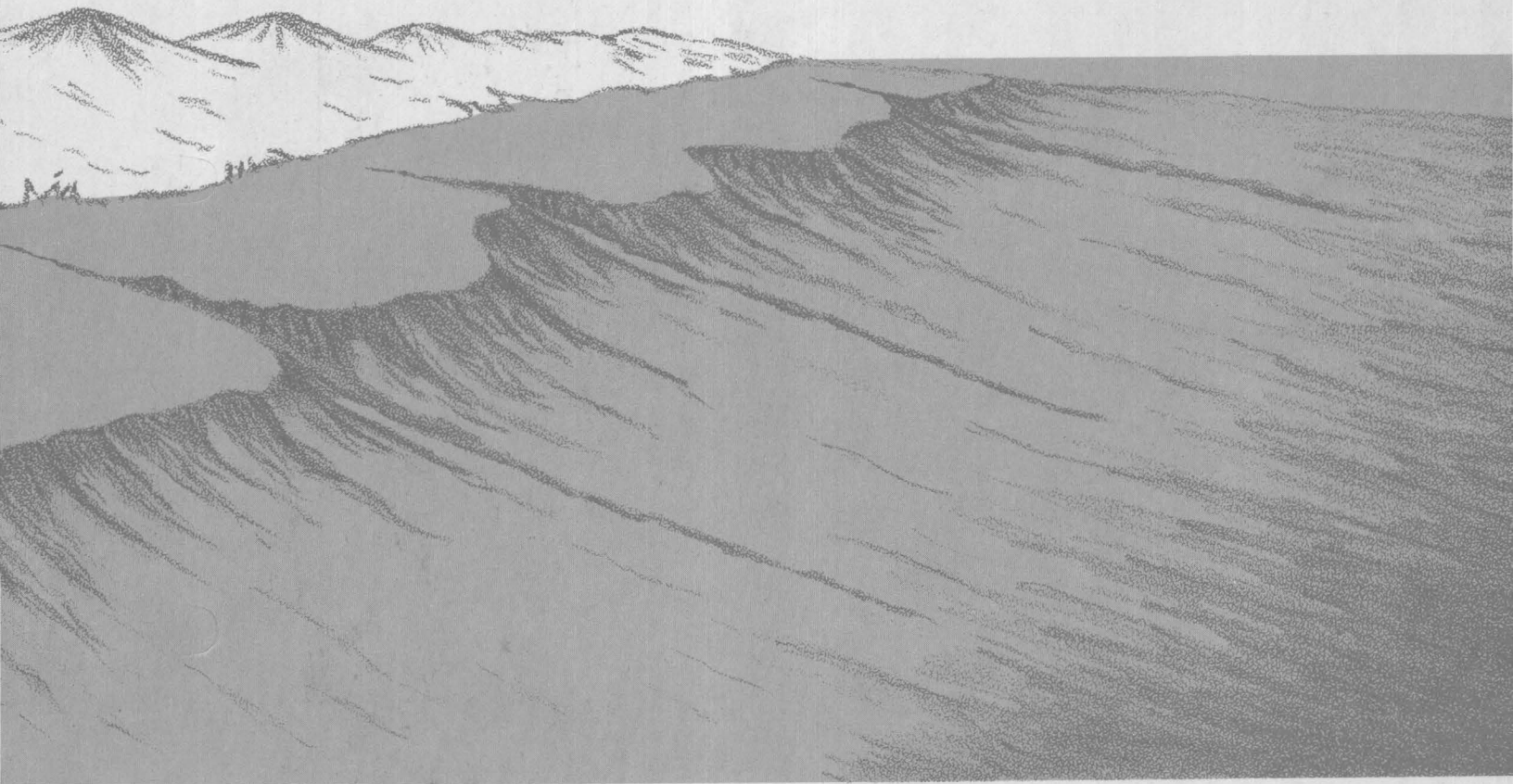


Atlantic Continental Shelf and Slope of the United States



Geologic Background

GEOLOGICAL SURVEY PROFESSIONAL PAPER 529-A

Atlantic Continental Shelf and Slope of The United States Geologic Background

By K. O. EMERY

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A background discussion for a comprehensive investigation of the marine geology and associated hydrology of the Atlantic continental margin



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THE ATLANTIC CONTINENTAL SHELF AND SLOPE OF THE UNITED STATES

GEOLOGIC BACKGROUND¹

By K. O. EMERY

ABSTRACT

This report is the first of a series that describe the geological, biological, and hydrological characteristics and the geological history of the continental shelf, slope, and rise off the Atlantic coast of the United States. The reports are the result of a 5-year program that is being conducted jointly by the U.S. Geological Survey and the Woods Hole Oceanographic Institution with extensive collaboration of the U.S. Bureau of Commercial Fisheries and other organizations. The geological work consists of field and laboratory investigations of topography, sediments, rocks, and structure. Mineralogy, paleontology, geochemistry, and economic geology are included. Complementing the geological work are studies of biology (the distribution and nature of pelagic and benthic organisms) and hydrology (the contribution to the ocean of fresh water by stream runoff and the processes by which this water becomes mixed with oceanic water).

Topographic charts constructed during the program reveal deep irregular topography in the Gulf of Maine and off Nova Scotia produced by glacial erosion and deposition. On the continental shelf most irregularities, such as terraces and sand waves, are formed by marine processes. In deeper water, submarine canyons, aprons superimposed upon the continental rise, and broad flat abyssal plains are caused or influenced by turbidity currents. Structural deformation is shown on the topographic charts by prominent bends of the continental slope.

A suite of well-distributed large bottom samples discloses a broad belt of coarse-grained relict sediment deposited during the transgression of the ocean across the shelf during post-glacial time. These sediments were contributed to the ocean by streams that carried glacial melt water in the north, or drained areas of weathered rock in the central and southern parts of the region. Modern coarse-grained detrital sediments are restricted to the nearshore zone, but modern fine-grained sediments largely blanket the deep Gulf of Maine and the still deeper continental slope and rise. Modern calcareous biogenic sediments dominate at the south on the continental shelf, on the Blake Plateau, and at greater depths.

Dredge and other samples from the ocean bottom show that the unconsolidated Pleistocene and Recent sediments overlie strata of Pliocene and Miocene age on most of the continental shelf. In areas of deeper water are discontinuous outcrops of rocks that are as old as middle Cretaceous on the continental slope and as old as Paleozoic in the Gulf of Maine.

Continuous seismic profiles reveal that the Pleistocene and Recent sediments are 10-60 meters thick throughout most of the shelf and that they unconformably overlie the older strata. Several reflecting horizons within the sediments indicate interruptions in deposition, possibly during times of glacially lowered sea level. The profiles also show local downwarping of Pliocene and Miocene strata at the top of the continental slope, a possible result of downwarping. Earlier and greater tectonic activity is indicated by structural trenches in the vicinity of the continental slope, those at the north being filled to over-

flowing with Cretaceous and later sedimentary strata and those at the south being incompletely filled. Clearly, the topography, sedimentology, lithology, and structure are closely interrelated and cannot be completely isolated one from the other.

INTRODUCTION

GENERAL PROGRAM

In September 1962 the U.S. Geological Survey and the Woods Hole Oceanographic Institution began a 5-year joint program to study the marine geology of the continental margin off the Atlantic coast of the United States. The Survey provides the financial support for the work, and the two organizations provide an approximately equal number of personnel for field and laboratory work. Several laboratories of the U.S. Bureau of Commercial Fisheries are also cooperating.

The geological work consists of field and laboratory investigations of topography, sedimentology, lithology, and structure. Mineralogy, paleontology, geochemistry, and economic geology are included among the geological investigations. Complementing the geology are studies of biology and hydrology.

This is the first comprehensive study of marine geology organized for the continental margin of such a large region. Studies by many individuals encompassed most aspects of marine geology off southern California (Emery, 1960), but the work was random and distributed throughout a long period, about 25 years for the most intense phase. A more direct and specifically organized study was conducted for the continental shelf of part of the Gulf of Mexico as a project of the American Petroleum Institute (Shepard, Phleger, and van Andel, 1960); however, the work was largely restricted to Recent sediments and associated biology. European and Asiatic studies of the continental shelf and slope are somewhat like those of southern California; the studies have been random and performed over a long period of time by many workers. The European studies are also limited by national boundaries. The varying intensity of effort has resulted in uneven knowledge of the marine geology of the continental shelves and slopes of the world. As indicated by figure 1, the best known (but not well known) continental shelves are those that border the most industrialized countries. Less is known about the adjacent continental slopes and still less about the continental rises that are farther seaward and deeper.

¹ Contribution No. 1772 of the Woods Hole Oceanographic Institution. Based on work done under a program conducted jointly by the U.S. Geological Survey and the Woods Hole Oceanographic Institution and financed by the U.S. Geological Survey.

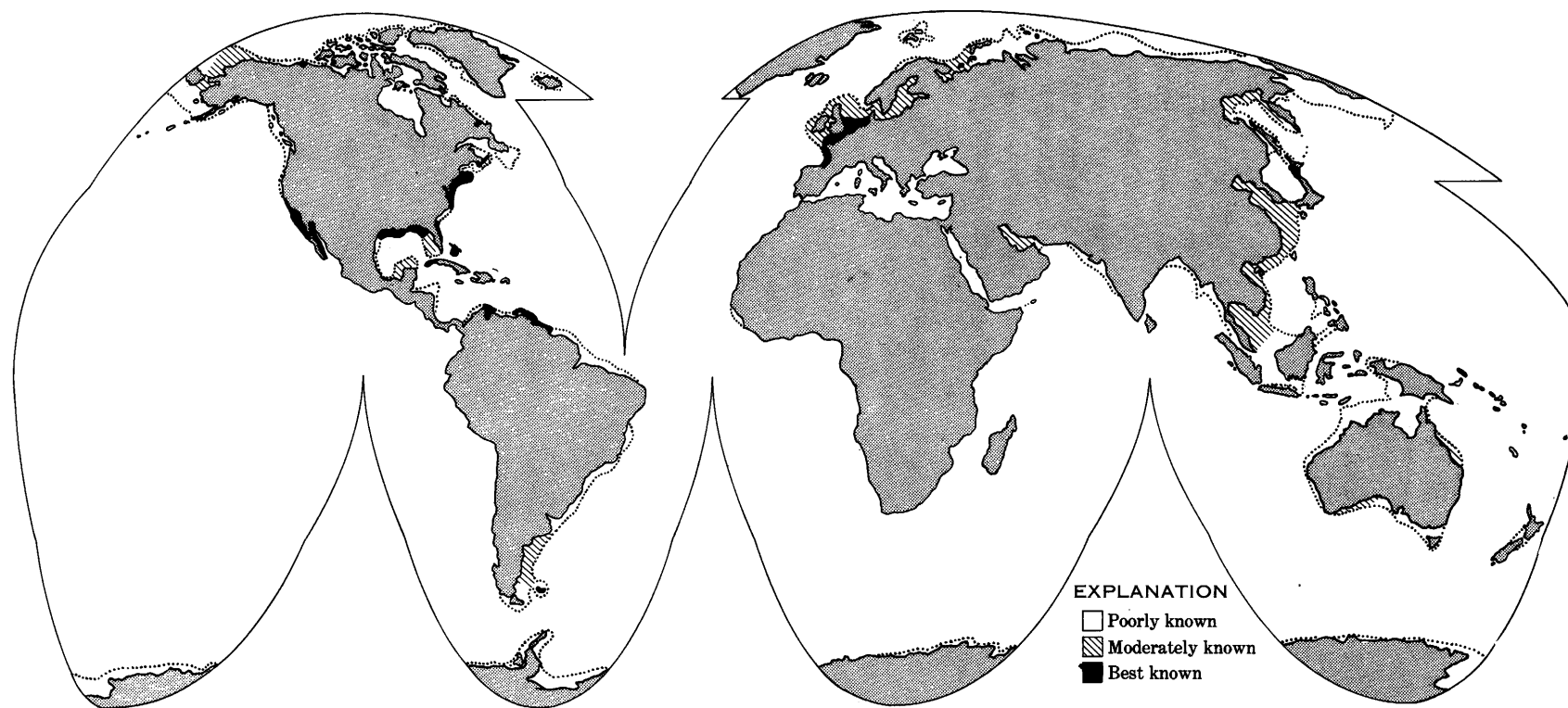


FIGURE 1.—Distribution of the wider continental shelves of the world and the comparative level of geological knowledge of them prior to 1962. Shelves indicated as poorly known have little other than general topographic information; those listed as better known have some additional information on sediments, on lithology, or on structure; those which are indicated as best known have some data in all four fields.

A subjective breakdown of the sources of interest and effort that have produced data about the continental shelves and slopes of the world is given in figure 2. Probably the first need for knowledge about the continental shelf was for navigation in the Mediterranean Sea. For example, 2,400 years ago Herodotus mentioned that on approaching Egypt by ship sailors found mud bottom at a depth of 20 meters, about one day's sailing from shore. About 100 years ago, charting of the shelves reached a peak in lead line sounding, and a few decades ago other large advances resulted from application of electronics to echo sounding and precise positioning. General scientific studies of the continental shelves and slopes to learn the nature and distribution of marine plants and animals, the geological composition of the bottom, and the interrelationships of topography and water movements greatly increased about the time of the *Challenger* Expedition during the 1870's. Since then the studies have continued mostly in universities. During World War II, much information was obtained about the surfaces of continental shelves

owing to military requirements for predicting the behavior of sound during searches for submarines, for designing minefields, and for planning amphibious operations. Some of the findings were published shortly after the war, but most of them remained unpublished in the interest of military security. In recent years military investigations have largely been confined to the deep-sea floor.

A fourth field which has contributed to knowledge of the continental shelves is industry. Fishermen long ago recognized the ecological dependence of edible fish and mollusks upon bottom materials. The petroleum industry turned toward active exploration of the shelves only a little more than 15 years ago as the demand for oil increased. Probably the knowledge of stratigraphy and structure of the shelf that the petroleum industry gained during these years exceeds the gains from all other sources, but publication of results has been limited by proprietary considerations. From all sources, published knowledge (upon which future substantial advances depend) is presently at its highest level, and the number of full-time professional and semiprofessional investigators is greater than ever before. Nevertheless,

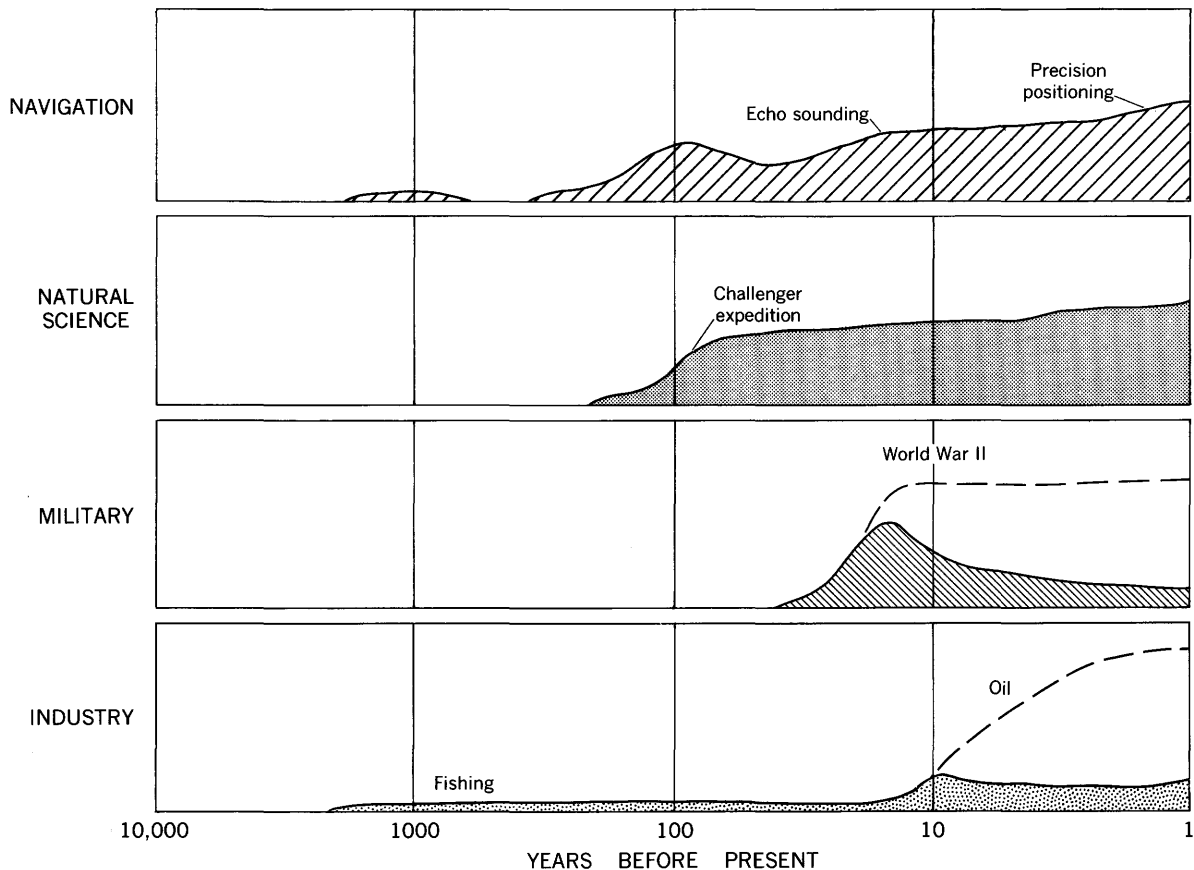


FIGURE 2.—Sources of contributions to geological knowledge of the continental margins of the world by those whose main interests are navigation, natural science, military, and industry. Dashed lines represent estimates of unpublished knowledge.

many gaps remain: What was the origin and geological history of the present continental shelves and slopes? Did similar features exist during early geological times? How uniformly do the strata from the adjacent land area extend seaward under the shelves?

The Atlantic continental margin was chosen as the site for concentrated effort of the Geological Survey-Woods Hole Oceanographic Institution program for many reasons. The region is important because it borders the most densely populated part of the country and thus is an area of considerable fishing and shipping activity. Nearness to markets also should promote active exploitation of any mineral resources that may be discovered or explored, such as petroleum, sand and gravel, phosphate, and manganese oxide. Many geological studies have been made of the adjacent land by government, industry, and university geologists whose results can be extrapolated seaward to aid in the interpretation of new marine data; in turn, the measurement of phenomena in the existing marine environment can be used to interpret depositional conditions of ancient sedimentary strata now on land. Many geological studies have been made in this marine region, even more than 100 years ago, but most of these studies were based upon methods, now obsolete, and most involved only small areas. A reconnaissance of the entire region will provide a general framework of knowledge into which the results of past and future detailed studies can be examined in proper perspective. Once the distribution of properties and the general geological history of the region is known, studies of processes will be easier to make and to evaluate. The increased attention being given to oceanography doubtlessly will result in the planning and making of many detailed studies during the future. As a matter of fact, one of the difficulties experienced throughout this general program was the temptation to divert too much effort into investigating interesting details, many of which can be solved by individuals or small groups having limited resources.

The area of this investigation (fig. 3), occupies a coastal belt about 2,500 kilometers long. Nearest shore is the continental shelf, which ranges in width from less than 1 kilometer off Florida to more than 420 kilometers off Maine; it averages about 135 kilometers. The total area is 420,000 square kilometers, of which one-fourth is within the Gulf of Maine north of Georges Bank. Adjoining the continental shelf off Florida is the Blake Plateau, an area of about 180,000 square kilometers. Ordinarily the continental slope borders the continental shelf, but off Florida it lies seaward of the Blake Plateau and is termed the "Blake Escarpment." Considered together, the continental slope and the Blake Escarpment have an average width of 30 kilometers and

an area of about 62,000 square kilometers. The total area of all the sea floor from shore to the base of the continental slope is about 662,000 square kilometers, about the same as the area of all 13 States northeast of North Carolina. Seaward of the Blake Escarpment is an irregular area containing the Blake Ridge; it extends to the 5,000-meter contour and encloses about 207,000 square kilometers. Elsewhere, the continental slope is boarded by the continental rise, a broad gently sloping plain which has a width as great as 500 kilometers and an area of nearly 700,000 square kilometers. Still farther seaward, the continental rise grades into a broad flat abyssal plain. Of necessity, the program of study is focused mostly upon the continental shelf with progressively less concentration on the continental slope, the Blake Plateau, and the continental rise and its associated abyssal plain.

Marine geology, the central field to be investigated in this program, consists of four main and closely inter-related subfields: topography, sedimentology, lithology, and structure. Knowledge of each subfield is necessary for an understanding of the origin of major features of the sea floor such as the continental shelf and slope and even for an understanding of many minor features. No longer can we say, as did Shepard in 1928 (p. 1157), "Coastal charts afford almost the only means by which we can study continental shelves."

The term "topography" includes both shoreline and ocean bottom configuration. By sedimentology is meant, broadly, the nature and origins of unconsolidated materials ranging from boulders through clay sizes, whether of detrital, biogenic, anthigenic, or other origins, and their contents of living organisms as well as dead or fossil remains. Lithology refers to the description of the consolidated rocks whether of sedimentary, igneous, or metamorphic origin and regardless of their age. Structure describes the attitude of the rocks with respect to each other and to overlying sediments, whether massive, bedded, folded, or faulted.

ACKNOWLEDGMENTS

The writer is indebted to the members of the staff assigned to this program of marine geology for information and discussion of the results of their work on different aspects of the program. One or two years of field and laboratory work was completed prior to the end of 1964 by the following: Elazar Uchupi, Woods Hole Oceanographic Institution, topography and structure; R. M. Pratt, Woods Hole Oceanographic Institution, deep-sea topography and sediments; John Schlee, U.S. Geological Survey, sediment texture and stratigraphy; Jobst Hülsemann, Woods Hole Oceanographic Institution, organic analyses of sediments; J. C. Hath-

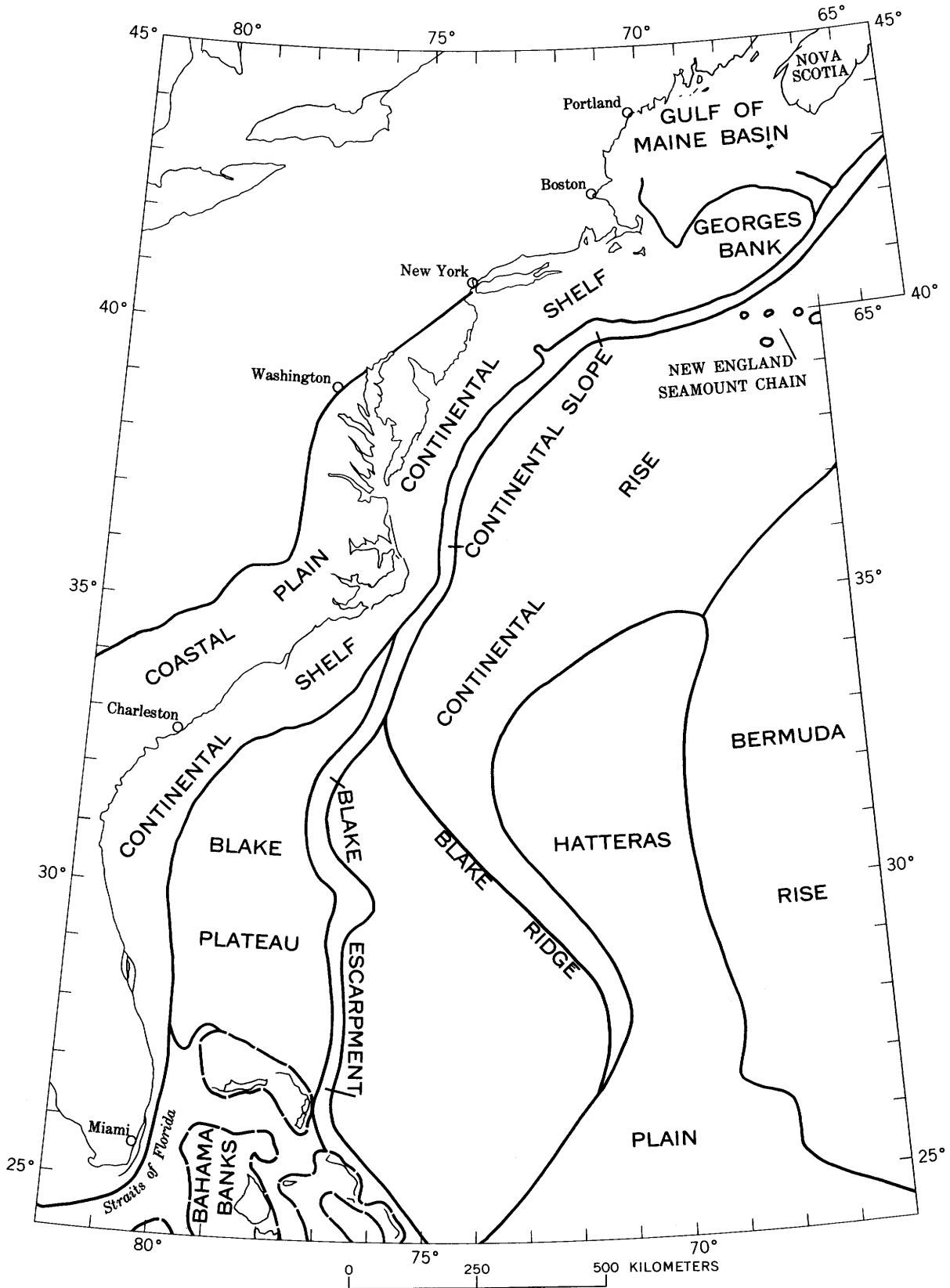


FIGURE 3.—Area of investigation in the joint U.S. Geological Survey—Woods Hole Oceanographic Institution program.

away, U.S. Geological Survey, mineralogy; James V. A. Trumbull, U.S. Geological Survey, sand fractions of sediments; R. K. Paul, Woods Hole Oceanographic Institution, and A. R. Tagg, U.S. Geological Survey, continuous seismic profiling; R. H. Meade, U.S. Geological Survey, hydrology; F. T. Manheim, U.S. Geological Survey, geochemistry; T. G. Gibson, U.S. Geological Survey, Foraminifera; and J. E. Hazel, U.S. Geological Survey, Ostracoda. Appreciation is also due cooperating investigators of benthic biology of the U.S. Bureau of Commercial Fisheries, R. W. Wigley (Woods Hole, Mass.), and A. S. Merrill (Oxford, Md.).

TOPOGRAPHY

The earliest records of marine geology along the Atlantic coast are the sagas of the Vikings, A.D. 1000–1006 (Thórdarson, 1930), which contain cryptic references to coastal forms and shore materials of Newfoundland and perhaps of Nova Scotia and the Gulf of Maine. Five centuries later, Columbus' four cruises, 1492–1504 (Morison, 1942) provided coastal charts much farther south, in the Caribbean Sea, and initiated a great period of discovery. One of the first charts of the entire Atlantic coast of the United States was drawn by Diego Ribero in 1529, from information largely obtained during a cruise of Estevan Gomez between Newfoundland and Cuba in 1524–1525. The map (fig. 4) contains many identifiable coastal features and even depicts the Gulf Stream, which had been discovered earlier by Ponce de Leon (Stommel, 1958, p. 1–2).

Continued exploration during the following three centuries contributed many details of coastal configuration, but the best charts were still inadequate for the growing shipping and fishing industries, and they led to many shipwrecks. Consequently, in 1807 Congress established the "Survey of the Coast" under the direction of Ferdinand Hassler (Roberts, 1957). In 1878 the name of the organization was changed to the Coast and Geodetic Survey, whose function in marine surveying until about 1960 was largely confined to waters bordering the United States and its territories. A parallel charting organization within the U.S. Navy was established in 1830 as the "Depot of Charts and Instruments" under the direction of Lt. Charles Wilkes. In 1842, command of the depot was assigned to Lt. Matthew Maury, who greatly expanded its functions so that in 1866 it became the Navy Hydrographic Office (now the U.S. Naval Oceanographic Office). This office chiefly charts deep waters and foreign coasts. Using precise triangulation, each organization produced charts of the shorelines as early as 1816. Aerial photography has accelerated and improved chart making. Still further gains are indicated through the future use of satellites,

which presently provide instructive but coarse-lined television pictures of the earth's surface (fig. 5); these pictures duplicate in a few minutes the coastal outlines which previously required many years of shipboard surveying.

Ease of access has led university faculty members to make many studies of the shoreline. One of the most industrious workers was N. S. Shaler, who described many aspects of coastal geology between 1860 and 1905 and completed a fine study of beaches and marshes (Shaler, 1895). Later, a classic book on shoreline features was written by Johnson (1925), and in it, he developed a classification of shore forms. Popular interest in the shore for building sites and for summer recreation during recent decades has led to an increase in engineering problems. Many of these problems have been studied by the Beach Erosion Board (now the Coastal Engineering Research Center, Corps of Engineers, U.S. Army) either directly or by contract with universities.

Most early soundings in the ocean were confined to the continental shelf, where lead lines sufficed. These records formed the basis for the first sounding chart published by the Survey of the Coast, the New York area, in 1835. In deeper water, sounding proved to be far more difficult, owing to uncertainty in determining the instant of arrival of the lead weight at the bottom. Several techniques were proposed by Maury (1855, p. 200–216) for making deep-sea soundings, but by 1912, Murray and Hjort (1912, p. 131) could report only 1,873 soundings greater than 1,000 fathoms in the entire North Atlantic Ocean. As a result, the charts of Maury (1855, pl. 11) and Murray and Hjort (1912, map II) show the deep-sea floor off the United States in only the most rudimentary fashion. Beginning in the early 1920's, sounding by acoustic echo became routine because of its speed and convenient underway operation. Later improvements through continuous recording (about 1935) and precision timing (about 1955) vastly increased the value of echo sounding. About 1,500,000 soundings on the continental shelf and slope off the eastern United States have been compiled on plotting (smooth) sheets of the Coast and Geodetic Survey, most of the soundings having been taken since 1930. Several tens of thousands of soundings in deep water farther seaward resulted mostly from expeditions of Lamont Geological Observatory and Woods Hole Oceanographic Institution, as well as from general compilations of the U.S. Naval Oceanographic Office.

Among the more significant studies of topography off the Atlantic coast based upon echo soundings are those of Veatch and Smith (1939) for the continental shelf and slope, and of Heezen, Tharp, and Ewing (1959)

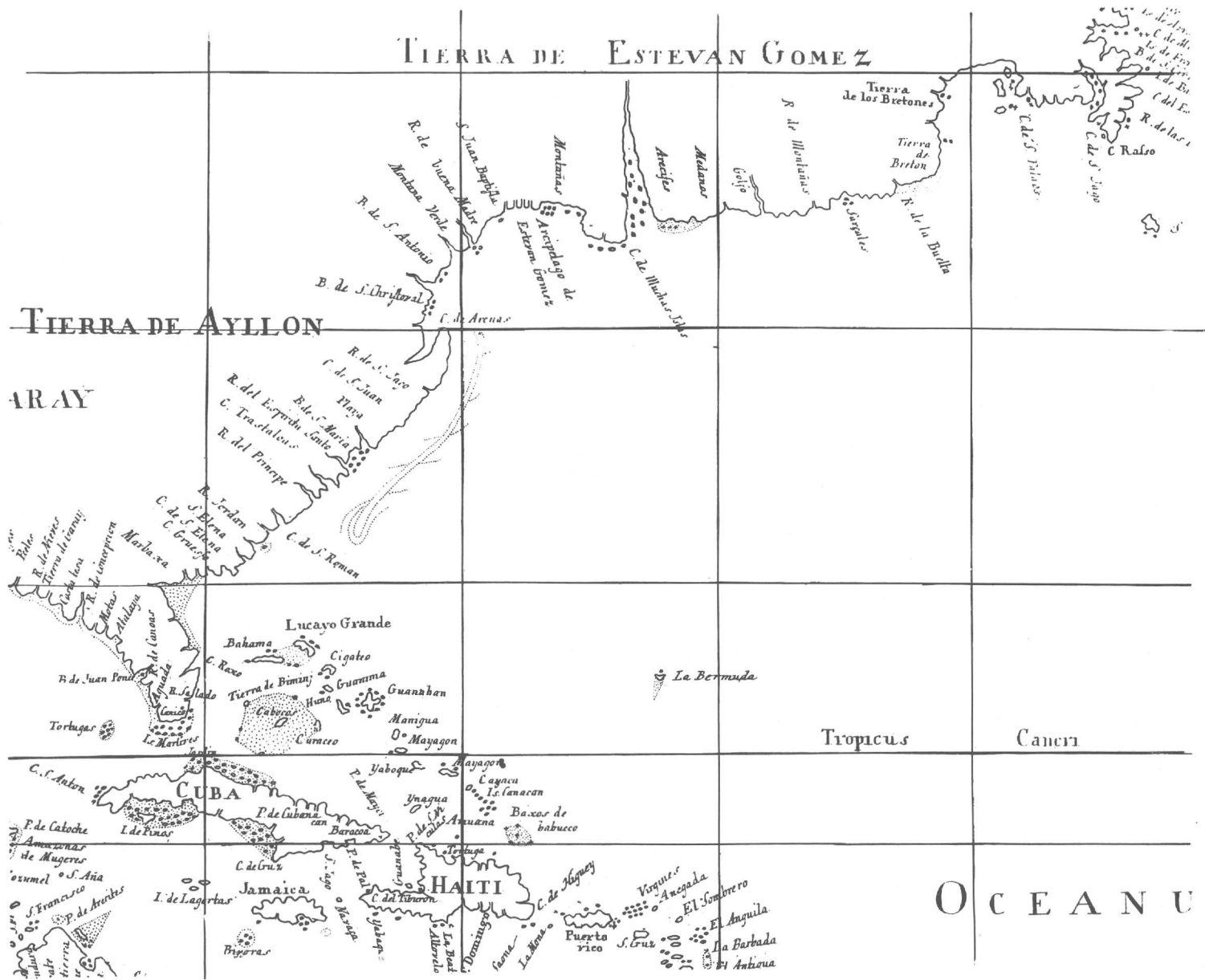


FIGURE 4.—Part of world map made by Diego Ribero in 1529. One of the first maps to show entire Atlantic coast of the United States. Easily identifiable points are irregular east coast of Newfoundland, Penobscot Bay (exaggerated scale, trending northward), Cape Cod (named appropriately Cabo de Arenas), and Florida. Reproduced from a copy in Yale University Library.

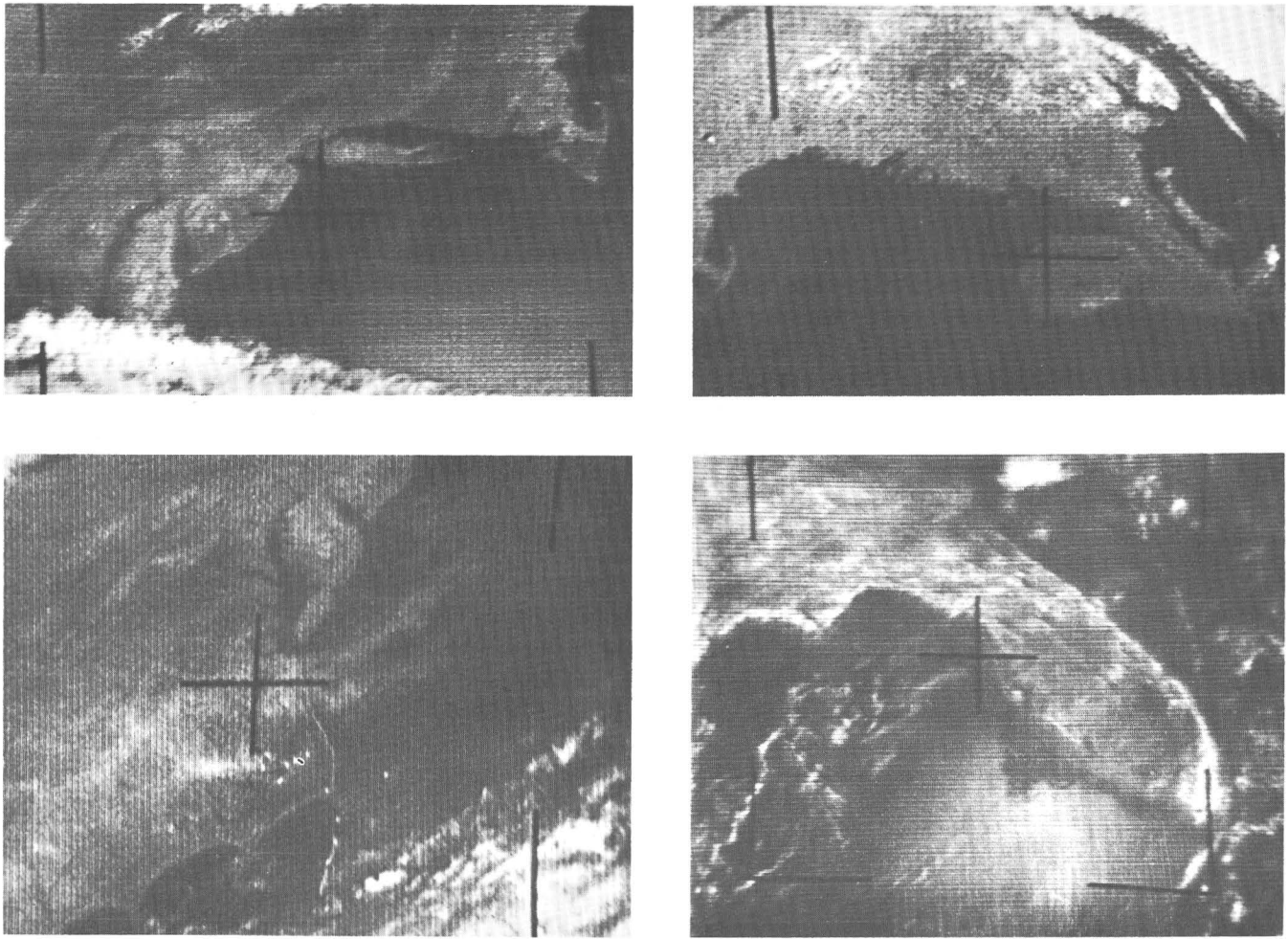


FIGURE 5.—Photographs of TIROS television transmissions showing sections of the Atlantic coast of the United States viewed from a height of about 650 kilometers during 1963. (From Goddard Space Flight Center, TIROS Station, Wallops Island, Va.)

for the continental slope, continental rise, and abyssal plains. A great deal of attention has been given the numerous submarine canyons that indent the continental shelf and extend to the base of the continental slope and beyond; important contributions were made by Shepard (1934), Veatch and Smith (1939), and Heezen, Tharp, and Ewing (1959). Interpretations of topography also have been made for Georges Bank (Shepard, Trefethen, and Cohee, 1934), the Gulf of Maine (Johnson, 1925, p. 255-314; Murray, 1947), and the Bay of Fundy (Shepard, 1930).

The most pressing need at the beginning of the program was a general topographic chart for the entire region between Nova Scotia and the tip of Florida. Accordingly, charts were constructed on the basis of all pertinent smooth sheets of the Coast and Geodetic Survey and of the Canadian Hydrographic Service for the continental shelf and slope and of the many unpublished sounding lines of Woods Hole Oceanographic Institu-

tion and Lamont Geological Observatory for the continental slope, the Blake Plateau, the continental rise, and the deep sea. A general chart of the region (scale 1:5,000,000) was compiled by Pratt (unpub. data) to depict the relation of the continental margin to the deep sea. A set of three more detailed sheets (scale 1:1,000,000) was drawn by Uchupi (1965; unpub. data) for the continental shelf, slope, and rise. Secondary charts, still more detailed and of larger scale, illustrate certain features such as basins, sand waves, and terraces. All these charts are sources of information for making inferences about the sediment, lithology, and structure of the region and thence of its geological history, and some of them also serve as bases for plotting information obtained from samples and other benthic data.

Most of the continental shelf off the Atlantic coast fits the classical concept of a shelf as a region of low relief sloping gently seaward. The depth of its outer edge varies between 80 and 140 meters, spanning the

world average of 132 meters (Shepard, 1963, p. 257) and lying close to the estimate of 159 meters for the maximum lowering of sea level during Pleistocene glaciations (Donn, Farrand, and Ewing, 1962). Most of the area of the shelf is well below present wave base, which is about 20 meters, as estimated from the position at which waves begin to refract and transmit energy to the sea bottom. The rising sea level of interglacial and postglacial times left several terraces of both erosional and depositional origin and many submerged bars which once may have separated long lagoons from the open sea. Transverse to the shelf are channels cut by streams during the low stages of sea level; one channel off the Hudson River has remained partly open, but others are completely filled. Elsewhere between Nova Scotia and Cape Hatteras, the shelf edge is indented by the heads of submarine canyons. In the north, particularly within the Gulf of Maine, very irregular topography remains from direct erosion and deposition by Pleistocene glaciers.

The continental slope is steeper than the continental shelf, but most of it is gentler than 5° . North of Cape Hatteras the slope is deeply cut by submarine canyons, and south of the cape it is interrupted by the broad Blake Plateau, whose surface is at depths of 500–1,100 meters (Pratt and Heezen, 1964). Blake Plateau was probably shaped by faults, as was the offset of the continental slope between New York and a point southeast of Boston (fig. 3). Although sediments mantle the continental slope, numerous outcrops of rock on the slope or on the sides of its submarine canyons indicate that structural deformation of some sort probably played a large role in shaping it. The seaward limit of the continental slope gradually deepens from 1,400 meters off Nova Scotia to 2,500 meters off Cape Hatteras; farther south off the Blake Plateau the slope extends to a depth of 5,000 meters.

At the base of the continental slope is the continental rise, a depositional apron sloping seaward at a declivity generally between $0^\circ35'$ and $0^\circ05'$. Its base is near the 5,000-meter-depth contour, which is as far as 500 kilometers beyond the base of the continental slope. Crossing the continental rise are many prolongations of the submarine canyons that occur on the continental slope. At a depth of about 5,000-meters the continental rise merges with the abyssal plains, which are among the flattest large physiographic features of the earth. Topographic, sedimentary, and stratigraphic evidence indicate that the continental rises and abyssal plains formed by deposition of sediments from turbidity currents.

Continued development of sounding devices may eventually render ordinary echo sounding as obsolete as lead line sounding is today. Water is nearly opaque

to light and radio frequencies as compared with sound; therefore, increased attention is being given to special uses of sound in exploration. Typical new (since 1955) devices are sideways pingers used for acoustically sweeping a broad area of sea floor parallel to the ship's track, narrow-beam sound sources for reducing side echoes and obtaining true slopes, and high-energy sound sources for gaining knowledge of subbottom structures.

SEDIMENTOLOGY

Study of the sediments on the sea floor serves chiefly to illuminate processes of deposition and the geological history of Pleistocene and post-Pleistocene times. Understanding of these sediments requires a knowledge of both horizontal and vertical distribution patterns. Simpler of the two patterns to investigate is the horizontal one; it is also the more important from the viewpoint of simultaneously revealing the distribution and density of benthic animals that contribute to the sediments and partly rework them.

Small samples of the sediments from the ocean bottom were obtained during the past century by the tallowed lead originally used for making shallow soundings. Using some of these samples, Pourtales (1850) first described the sediments off New Jersey, and later, using 9,000 samples, he made a map showing the types of sediments along the entire coast (Pourtales, 1870, 1872). Supplementary information for Blake Plateau was provided by Agassiz (1888). About 700 lead line and small snapper samples were examined and 200 were analyzed by Shepard and Cohee (1936) to determine the characteristics of sediment on the continental shelf off the Middle Atlantic States. With the advent of echosounding methods, the collection of small ocean bottom samples largely ceased; however, navigational charts commonly retain bottom notations inherited from early surveys. These notations served as the basis for drawing bottom-sediment charts of the Gulf of Maine by Shepard (1939) and for much of the Atlantic coast by the Oberkommando der Kriegsmarine (1943).

Special snapper samples were collected by Stetson (1938) along 13 profiles and analyzed in the laboratory to learn more of the distribution patterns. Still other snapper and larger samples were obtained by the U.S. Bureau of Commercial Fisheries during fisheries studies. One set of samples is from Georges Bank (Wigley, 1961b) and the Gulf of Maine; another is from the shelf off Florida and Georgia (Moore and Gorsline, 1960). Sediments of small bays have been studied by many workers associated with universities. The Woods Hole Oceanographic Institution and the Lamont Geological Observatory have also made major contributions to knowledge of sediments on the con-

tinental slope, the Blake Plateau, and the deep-sea floor, mostly through coring operations (Stetson, 1949; Ericson, Ewing, Wollin, and Heezen, 1961).

A general distribution map of the sediments on the continental shelf was compiled by Uchupi (1963) from past publications. This map revealed patterns due to regional differences in sources and environment, but these patterns are complicated and partly obscured by differences in sampling devices and density of sampling and by differences in intensity of study of the samples. In the present program, a new set of samples was needed for studies using modern and uniform techniques. To cover the entire region with a reasonable number of samples, a grid was so chosen that samples were obtained at intervals of about 18 kilometers (10 nautical miles). Thus there is one sample for each 300 square kilometers, or a total of about 1,400 samples for the continental shelf. Samples of the continental slope and the Blake Plateau are more widely spaced owing to greater depth (longer time required for sampling) and to a presumed more uniform distribution pattern of sediments; these comprise about 600 samples. During 1960 and 1961, samples at about 400 of the grid points within the Gulf of Maine, Georges Bank, and Nantucket Shoals were obtained by the Bureau of Commercial Fisheries Biological Laboratory at Woods Hole as part of a study of the relation of benthic animals to bottom materials; these samples are available for the sediment studies. Collection of the additional necessary 1,600 surface samples was completed by the summer of 1965.

The samples of the Bureau of Commercial Fisheries were obtained with a Smith-McIntyre grab (Smith and McIntyre, 1954) which recovers material from an area of 0.1 square meter. Within the present program, sampling was done with the much larger Campbell grab, which samples 0.6 square meter. Fitted into the interior of the grab is a light and a camera that takes a photograph of the bottom while the grab is being lowered and when it is 1 meter above the bottom (Menziés, Smith, and Emery, 1963). Representative parts of each sample were removed aboard ship for later sediment analyses in the laboratory (color, coarse fractions, granulometry, clay and other mineralogy, and contents of calcium carbonate and organic matter), and for study of enclosed foraminifers and ostracodes. The remainder of the sample was screened on a sieve having 1-millimeter openings. Fine material that passed through the sieve was discarded overside and the coarse fraction preserved in formalin for later sorting and removal of all organisms at the Bureau of Commercial Fisheries Biological Laboratory at Woods Hole. Gravels were also retained to complete the information on grain-size distribution.

In addition to sampling from aboard ship, collections of beach sediments and observations of beach slope and other characteristics were made at 18-kilometer intervals along the entire coast. This work, under the direction of John M. Zeigler of the Woods Hole Oceanographic Institution, is being coordinated with the offshore program to gain maximum benefit for both studies.

Preliminary inspection of the samples enabled the construction of distribution maps of texture (granulometry), contributing agent, and age (fig. 6). The map of texture shows irregularity of pattern, but sands dominate throughout most of the shelf southwest of the Gulf of Maine. In the Gulf of Maine the rugged coast and irregular sea floor are accompanied by rock and boulder bottoms, but deep areas are thickly covered by silt and clay which remain because of the protection from wave action provided by the broad embayment and the lee of the shallow Georges Bank (Hathaway, Hülsemann, Schlee, and Trumbull, 1965). The continental slope along the entire coast appears to be mantled with clay and silt. Sediments on the continental rise and abyssal plains are clays interbedded with fine sands and coarse silts.

Several different sediment sources are represented on the continental shelf off the Atlantic coast, as they are on many other continental shelves of the world. Near Miami the warm water is conducive to deposition of biogenic calcium carbonate; thus shell sands dominate on the southwestern end of the continental shelf. Similarly, foraminifer sands or silts characterize the top of Blake Plateau, and reef corals and algae are present on the nearby Bahama Islands. On most of the continental shelf, river-contributed detrital sands and silts are the chief sediment, although between New York and Georges Bank the rivers probably consisted mostly of glacial melt water. True glacial and ice-rafted sediments having a wide range of grain sizes are typical of the continental shelf off Nova Scotia and bank tops in the Gulf of Maine. The continental slope and rise receive sediments from the same sources as the shelf but after considerable mixing, particularly at great depth and on the abyssal plains. Accordingly, we can expect a south-to-north change of sediment source from biogenic to fluvial to glacial, each somewhat blurred by subsequent reworking by marine agents (fig. 6).

Comparison with other regions indicates that the sediments vary transversely from shore to deep water owing to differences in extent of reworking by waves and currents and to differences in age (Emery, 1960). Continental shelves whose sediments have been studied carefully have a generally narrow belt of modern sediment that shows a seaward decrease in grain size from

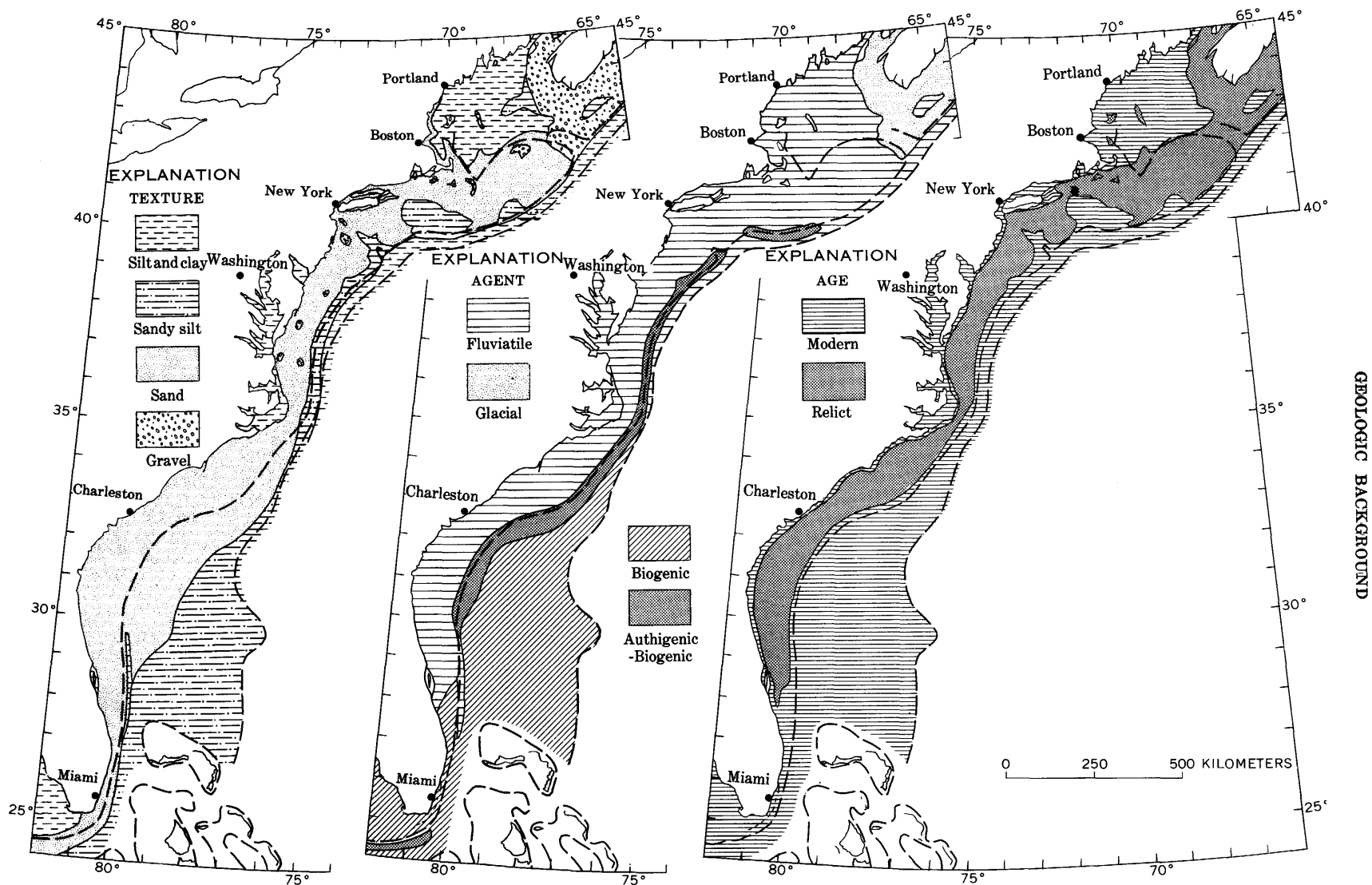


FIGURE 6.—Sediments off the Atlantic coast of the United States classified by texture, contributing agent, and age. The charts are based upon inspection of about 1,600 samples prior to detailed laboratory analyses.

gravels or coarse sands on the beaches to fine sands offshore. On open shelves, such as occur along most of the Atlantic coast, this belt of sediments extends to depths of about 20 meters and is usually only a few kilometers wide. Within areas protected by coastal configuration (estuaries and lagoons) and areas protected by submerged barriers (Gulf of Maine), the belt is wider, extends to deeper water, and contains sediments as fine as clay sizes (fig. 6). Sediments on the main expanse of the continental shelf are commonly coarse grained and iron stained and contain shells of animals that lived in water shallower than that at the sampling site. These sediments evidently are relict, deposited at a time of glacially lowered sea level. More than a single relict age can be represented, as shown for example by thick sands overlying gravels. Modern sediments have failed to cover these older ones, mainly because insufficient time has elapsed since sea level reached its present position (about 5,000 yr ago) for sediments derived from rivers or from erosion of sea cliffs to fill estuaries and prograde very far seaward. Corroboration of the antiquity of these sediments is provided by the recovery and radiocarbon dating (8,000–11,000 yrs before the present) of shallow-water mollusks and intertidal peat from the continental shelf (Merrill, Emery, and Rubin, 1965; Emery, Wigley, and Rubin, 1965).

Waves and currents atop the continental shelf provide enough turbulence to cause much of the clay and fine silt components of the modern sediment to bypass the outer half of the shelf and reach deeper water sites of deposition. Owing to lack of burial under detrital sediments, accumulations of slowly deposited authigenic glauconite, phosphorite, and manganese oxide are common near the outer edge of the continental shelf. The same conditions of slow deposition allow residual sediments (reworked from outcrops of older strata) to compose a recognizable percentage of the total sediment. This residual component tends to concentrate the more resistant grains, such as quartz but also locally glauconite and phosphorite. A last type of sediment, biogenic, can be deposited any place on the continental shelf and is not related to distance from shore.

The fine-grained components of modern sediments that bypass the continental shelf are deposited partly on the continental slope, giving rise to massive deposits containing little evidence of bedding. Those components that reach even deeper water may become interbedded with coarser sediments contributed by turbidity currents. These currents bring coarse-grained nearshore sediments to deep water especially in areas where submarine canyons reach close inshore (Emery, 1960, p. 217–219). Submarine canyons off the Atlantic coast

have heads that are now far from shore and inaccessible to nearshore sediments. Therefore, turbidity currents probably contribute far less sediment to this deep-sea region now than during glacial times of lower sea level, when the shore was closer to the heads of the canyons and when the extensions of the canyons across the continental shelf were free of their present fills of sediment.

Once the provinces of surface sediments have been outlined and the controlling agencies inferred, the positions for collection of long cores can be established. These cores require considerable effort, both in the field and in the laboratory; thus positions for them must be carefully selected for maximum scientific information. Piston coring is most productive in areas of fine-grained sediments (basins in the Gulf of Maine, the protected Long Island Sound, a few areas of the open continental shelf, the continental slope, and the continental rise). Cores may be as long as 10 meters and have diameters of 6–15 centimeters depending upon the kind of sediments and the use intended for particular cores. Some short (1– to 2-m) cores are available from earlier sampling with open-barrel gravity corers by staff members of Woods Hole Oceanographic Institution. Areas of sandy sediment on the continental shelf cannot be sampled satisfactorily with such corers, but they may be cored with a vibropiston corer (Kudinov, 1957). Most cores will undergo analyses similar to those of the surface sediments, plus radiocarbon dating to determine rates of deposition, and analyses of interstitial waters to investigate possible diagenesis of the sediments and their included waters. A box sampler (Reineck, 1963) is also being used to examine minor features of stratification and effects of burrowing animals; this sampler is essentially a corer 30 centimeters in diameter.

LITHOLOGY

Rocks cropping out on the continental margin have been sampled mostly by university research workers, but because of the high cost, both in time and money, the study is still in its infancy. Among the earliest reports of rock outcrops is that of Shepard, Trefethen, and Cohee (1934), who reported its recovery from Georges Bank on anchors. Later, Stetson (1949) dredged rocks from the sides of New England submarine canyons. Cores from the Blake Escarpment and the Blake Plateau have included rock and also sediments containing Foraminifera reworked from older sedimentary strata (Ericson, Ewing, Wollin, and Heezen, 1961). Borings made by Zeigler, Hoffmeister, Giese, and Tasha (1960) along the shores of Cape Cod penetrated Eocene nonmarine strata. Other wells were drilled by engineering firms to test foundations for light towers and radar towers at many places along the

coast; many of these test wells penetrated late Tertiary sedimentary strata.

In the future a great advance over the largely hit-or-miss dredging method is likely to result through the proper use of two new tools, manned submersibles and oceanic drilling from ships. Both are in early stages of development, but even so they have made significant contributions to the knowledge of the lithology of the sea floor. The submersible can bring a trained observer to outcrops to map strata and select specimens (Moore, 1963; Terry, 1964). Deep-sea drilling has been accomplished in experimental borings off California and Mexico (National Research Council, AMSOC Committee, 1961), the first experimental drilling from a ship since that at Funafuti in 1896-98 (Halligan, 1904). Eventually, the drill method of sampling rock may become relatively inexpensive and available for nearly routine use to recover rock from considerable depth beneath the ocean floor even in great depths of water.

Existing dredge and drill samples generally show seaward extensions of strata found in oil wells and outcrops of the adjacent land, as shown by the Geologic Map of the United States (Stose, 1932) and by the various State geologic maps, and as summarized by Murray (1961). Also, as on land, the rocks of the continental shelf are highly varied. A collection by a diver, John M. Zeigler, showed that least one of the shallow banks in the Gulf of Maine is a massive outcrop of Paleozoic granite (Toulmin, 1957). Other dredgings and photographs of the Gulf bottom reveal widespread boulders of igneous, metamorphic, and sedimentary rocks deposited by Pleistocene glaciers or by icebergs. Elsewhere on the shelf, Pleistocene and Recent marine sediments form a surface cover largely concealing older strata.

The results of all known offshore collections of rock are summarized in a geologic map (fig. 7) that shows the age of rock immediately underlying the Quaternary cover of glacial till and marine sediments. This map is a simple one commensurate with the paucity of data. However, it does indicate Pliocene and Miocene strata atop most of the continental shelf, Miocene on the Blake Plateau, and rocks only of Eocene or greater age in the Gulf of Maine. Rock samples recovered through 1964 from the continental slope and from submarine canyons cut into it include strata of Pliocene, Oligocene, Eocene, Paleocene, and Cretaceous age. The Pliocene rocks are mainly from near the top of the continental slope and the older rocks are from greater depths, but there is considerable overlap in depth. This overlap may result from a sampling of talus or it may reflect a downwarp of the continental slope. A downwarp could mean that Miocene and Pliocene strata conceal older rocks except where they have been removed by erosion

of submarine canyons or by mass movements at the face of the continental slope. A downwarp is also suggested by some continuous seismic profiles, but it may be absent locally if irregular terraces on the continental slope represent the outcropping edges of resistant strata, as suggested by Heezen, Tharp, and Ewing (1959).

Beyond the base of the continental slope (on the continental rise, Blake Ridge) samples obtained to 1964 consist only of post-Pleistocene sediments. At some presently unknown depth there should be a buried blanket of Pliocene sediments, underlain by Miocene strata. The tops of the seamounts of the New England Seamount Chain which protrude through these layers are capped by Eocene calcareous sediment (Northrop, Frosch, Frassetto, and Zeigler, 1959).

STRUCTURE

The structure of the continental margin is so closely associated with its origin that if the structure is known, the origin should be apparent. Two classes of structural data are needed, deep and shallow, and these two classes require different methods of measurements. At present the most successful method for investigating deep structure is seismic refraction, followed by magnetic and gravity measurements. For detailed study of shallow structure the best method is continuous seismic profiling.

Gravity measurements constitute the coarsest geophysical method to be considered here. Bouguer anomalies measured aboard a submarine were computed and reported by Ewing, Worzel, and Shurbet (1957). A plot of their results indicates an increase from between -25 and +50 milligals at the shore between Maine and Cape Hatteras through about +100 milligals near the edge of the continental shelf to about +300 milligals on the upper continental rise. This relation merely indicates a seaward thinning of the crust (Airy theory), a seaward increase in density of the crust (Pratt theory), or both (Heiskanen theory), with thickness or density contours approximately paralleling the shelf edge. The change in thickness of the crust is reflected by a decrease in depth of the Mohorovičić discontinuity from about 32 kilometers below sea level under the land and most of the continental shelf to between 10 and 15 kilometers below sea level in the deep sea.

Magnetic measurements compiled by Drake, Heitzler, and Hirshman (1963) show several parallel belts of positive anomalies alternating with belts of negative anomalies and extending along the continental shelf, slope, and rise of the entire coast. Off New Jersey these belts are offset as though by right-lateral strike-slip faulting (fig. 8). Supplementary evidence of this faulting is provided by displacement of Triassic and earlier structures on land to the west and by numerous extinct

ATLANTIC CONTINENTAL SHELF AND SLOPE OF THE UNITED STATES

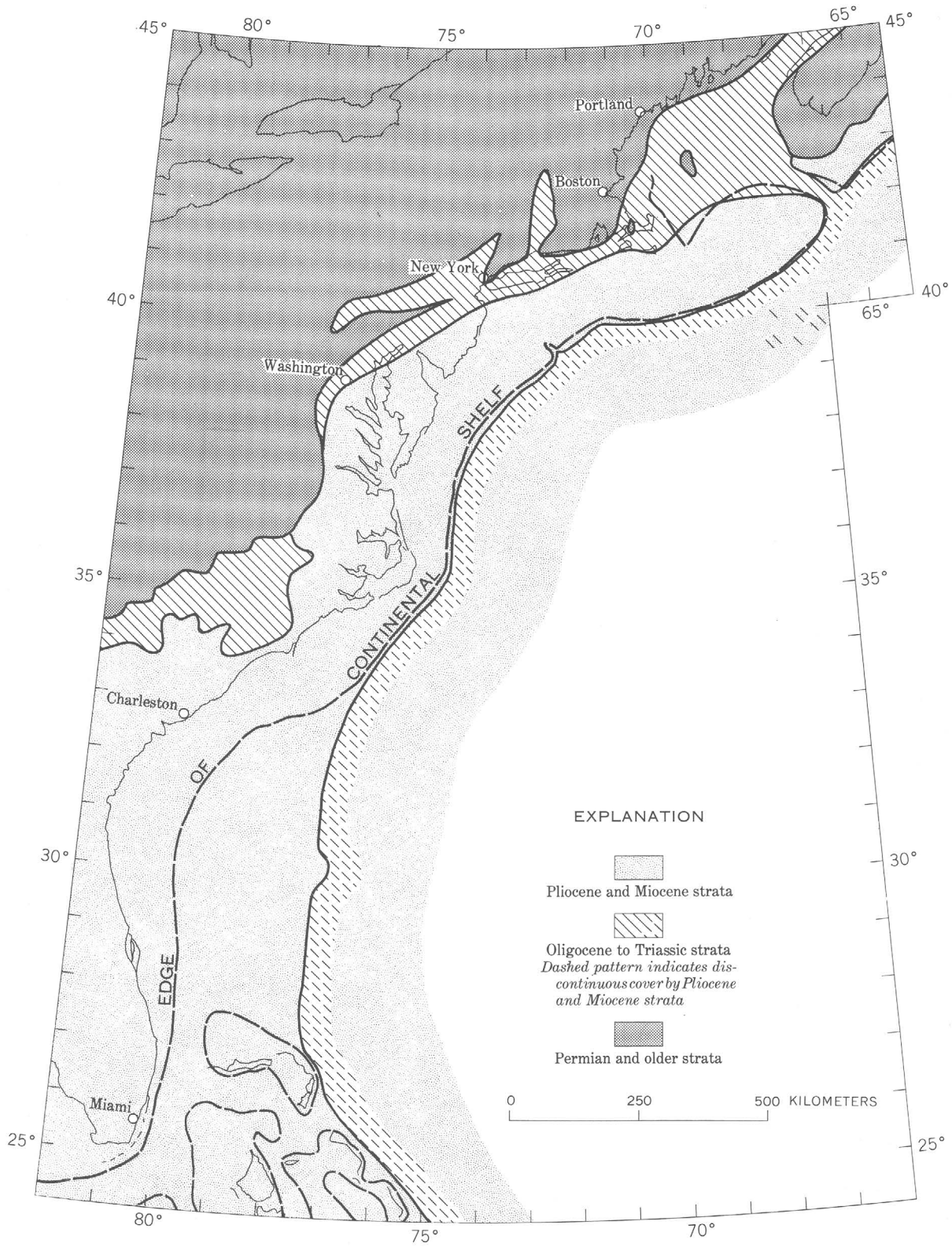


FIGURE 7.—Map of continental shelf and slope showing distribution of pre-Pleistocene strata.

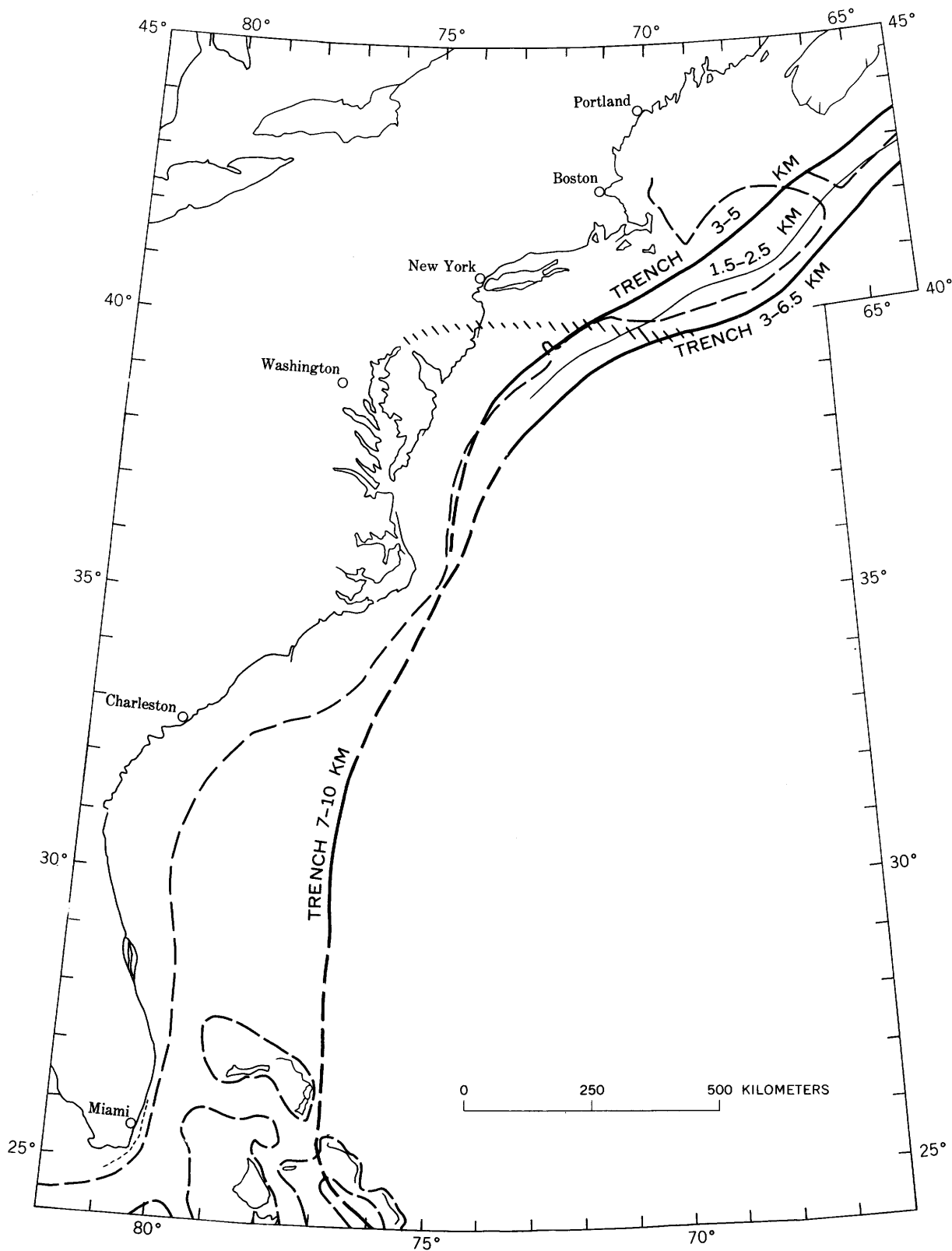


FIGURE 8.—Axes of trenches. Numbers indicate thickness of sedimentary fill atop basement rocks that have compressional velocities of 5.0–6.4 km per sec. Crosshatched band south of New York marks a zone in which magnetic anomalies are offset and suggestive of strike-slip faulting. Data from Drake, Ewing, and Sutton (1959); Hersey, Bunce, Wyrick, and Dietz (1959); and Drake, Heirtzler, and Hirshman (1968).

volcanoes in the New England Seamount Chain to the east. The fault is associated with the bend in the Appalachian Mountains shown by the TIROS photograph of the New York region (fig. 5). The offset of the continental slope is approximately parallel to that of the Appalachian Mountains, and it amounts to about 220 kilometers, somewhat less than the movement along strike-slip faults off the Pacific coast inferred from displacement of belts of magnetic anomalies (Vacquier, Raff, and Warren, 1961).

Seismic refraction surveys were begun off the Atlantic coast in 1937 (Ewing, Woollard, Vine, and Worzel, 1946), and subsequently many traverses have been run at about right angles to the New England coast by Ewing and his associates. All these refraction data were compiled and summarized by Drake, Ewing, and Sutton (1959). Clearly shown in their compilation are two trenches formed in basement rocks having 5.0–6.0 kilometers per second compressional velocity. The trenches contain fills of 3.0–6.5 kilometers of materials having compressional velocities similar to those of sedimentary rocks overlain by unconsolidated sediments. Between the trenches is a ridge which is much shallower and nearly reaches sea level at Sable Island off eastern Nova Scotia.

Many other scattered refraction stations were obtained by Hersey, Bunce, Wyrick, and Dietz (1959) farther south on the Blake Plateau and the nearby continental shelf. These stations reveal a single broad trench in which as much as 10 kilometers of sedimentary rocks and sediments rest atop basement rocks having a higher compressional velocity (5.8–6.4 km per sec) than was reported off New England. In figure 8 this trench is shown as possibly being a union of the two northern trenches, and its axis is along the Blake Escarpment. If the trench continues beyond the Blake Plateau, it probably bends southeastward to join the Puerto Rico Trench (Ewing and Worzel, 1954), where a smaller supply of sediment may account for its incompletely filled condition. The surface of basement rocks off the entire coast probably represents a submerged extension of the Fall Zone peneplain of pre-Cretaceous age. A velocity discontinuity within the sedimentary fill is considered to be the top of Lower Cretaceous strata on the basis of continuity with outcrops and logs of wells drilled on land (Ewing, Worzel, Steenland, and Press, 1950). As shown by the composite cross section of figure 9, Lower Cretaceous rocks (semiconsolidated) compose the bulk of the fill within the trenches.

During the past, shallow structural features of the continental shelves had to be inferred from physiography, as was done by Shepard (1930) for the Bay of Fundy and by Shepard, Trefethen, and Cohee (1934)

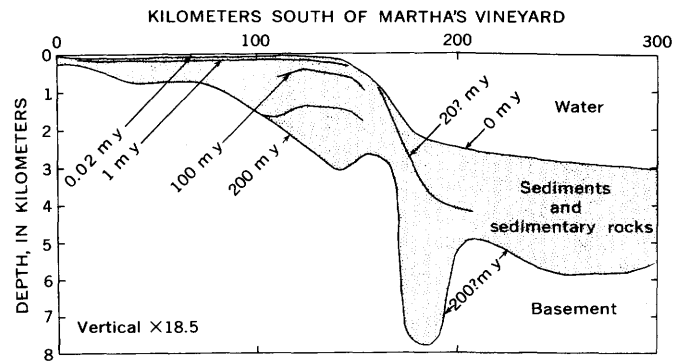


FIGURE 9.—Structural section inferred from seismic data for continental shelf, slope, and rise south of Massachusetts. Data are from Ewing, Worzel, Steenland, and Press (1950); Drake, Ewing, and Sutton (1959); and unpublished profiles of various dates by S. T. Knott, D. D. Caulfield, and Hartley Hoskins of Woods Hole Oceanographic Institution. The abbreviation "my," stands for million years. Inferred ages are based on correlation with geology from adjacent land areas.

for Georges Bank. Where data were available from rock dredgings and from wells or outcrops on shore, structural cross sections could be inferred by interpolation beneath the shelf (Heezen, Tharp, and Ewing, 1959). In the first systematic acoustic study, Murray (1947) mapped shallow features beneath acoustically highly transparent sediments of the Gulf of Maine using records of ordinary echo sounders. His work revealed basin fillings of Recent sediments resting atop Pleistocene glacial till and perhaps on older strata.

Since about 1955, rapid development of high-energy low-frequency sound sources has allowed the recording of subbottom echoes that can be related to strata as old as Cretaceous and as deep as 2,000 meters (Ewing, Luskin, Roberts, and Hirshman, 1960; Ewing, Le Pichon, and Ewing, 1963; Hersey, 1963). A continuous seismic profiler was built especially for this program by R. K. Paul assisted by A. R. Tagg and advised by members of the Department of Geophysics at Woods Hole Oceanographic Institution. This device uses a 10,000-joule spark source of low-frequency acoustic energy. The data are printed aboard ship on rolls of chemical paper about 45 centimeters wide. Recordings on magnetic tape are also made as a source of base data for closer study in the laboratory, using various filters to amplify the signal over background noise. The average spacing of profiles on the continental margin is about 50 kilometers, but closer spacing is provided for detailed study of certain features such as basins, submarine canyons, and embayments.

The seismic profiles show unconformities, faults, buried hills and valleys, and depositional irregularities. Profiles across Georges Bank show 10–30 meters of hori-

zontally bedded sediment (probably glacial outwash) resting unconformably atop seaward-dipping strata (probably Pliocene shales) with some prograding on the continental slope. The same unconformity is common beneath other kinds of Pleistocene and post-Pleistocene sediments of the continental shelf between Georges Bank and Florida (fig. 9). In a general way, the post-unconformity sediments change from dominantly up-building to dominantly out-building in a southwesterly direction, as though controlled by the greater supply of sediments and the generally shallower surface of the shelf toward the southwest. The postunconformity sediments extend horizontally to outcrops on the sides of submarine canyons, indicating that canyon cutting was subsequent to deposition of these sediments; only locally do the sediments dip down the sides of canyons as though these sediments were deposited after the canyons had formed.

Widespread application of continuous seismic profiling is expected to provide much new information on the late geological history of the continental margin, as well as upon general conditions of deposition of sediments, in these areas. It supplements seismic refraction studies, which are more apt to yield data on deep structures, including the shapes of the trenches in which thick prisms of sediments have accumulated along the coasts of both the Atlantic Ocean and the Gulf of Mexico. Striking similarities have been shown by Drake, Ewing, and Sutton (1959) between the trenches under the present Atlantic continental shelf and slope and those containing Paleozoic sedimentary rocks of the Appalachian Mountains. Further speculations about the nature of continental accretion by Hess (1962) and Dietz (1963) can be tested by these seismic techniques as well as by deep oceanic drilling.

WATER AND BIOLOGY

The water overlying a marine environment is probably the chief factor governing the distribution and kinds of organisms and the nature of the sediments; accordingly, study of the water and biology is warranted in this program. A compilation by the author of unpublished data in the files of Woods Hole Oceanographic Institution reveals a large seasonal change in both salinity and temperature of the waters off New England, in contrast with great uniformity of salinity and temperature in waters off Florida (fig. 10). These seasonal changes are the result of greater extremes in solar heating, precipitation, and runoff at the north. Cape Hatteras constitutes an obvious barrier separating waters of these two regions. Cape Cod farther north and the tip of Florida at the south are less important barriers.

Warm salty waters of the Florida Current pass sea-

ward of Cape Hatteras to become the Gulf Stream, as noted by Franklin (1786), but masses of this warm water break away and intrude the region of the continental shelf (Stommel, 1958). A coastal countercurrent landward of the Gulf Stream consists of water partly derived from the Gulf Stream and partly from land runoff. Seasonal changes and year-to-year variations in runoff and coastal winds produce changes in the currents atop the continental shelf, particularly in the countercurrents. Studies of these changes are based upon drift bottles (Bumpus and Lauzier, 1964), current-meter records, and water properties (Bigelow, 1927). A good example of the effectiveness of water properties as tracers is given by the fact that the near-shore countercurrent brings low salinity water from runoff as far south as Cape Hatteras.

Data from the files of the U.S. Geological Survey on seasonal and annual stream discharge permit the construction of a water budget for the coastal region. Measurements of salinity and related chemical characteristics of streams, estuaries, and shelf waters are being compiled from many sources for their possible aid as tracers of water movement.

A direct effect of water properties upon sediments of the continental shelf is their control of biogenic calcium carbonate. The warm saline waters south of Cape Hatteras result in high concentration (commonly more than 70 percent) of calcareous sediments such as shells, foraminiferal tests, algae, and corals, whereas the cool, more dilute waters of the north are underlain by sediments low in calcium carbonate (commonly about 5 percent). The speed of the Florida Current is so great that it has swept parts of the Blake Plateau nearly clean of loose sediments, but it does little more than impinge upon the continental shelf, and its side eddies and countercurrents are too slow to have much effect upon sediments of the shelf. Instead, the sediments are controlled by the faster currents produced by tides, internal waves, and surface waves, listed in their order of importance from deep to shallow water; these currents appear to be sufficiently great to be able to transfer the finest sediments contributed by streams and shore erosion to deeper water beyond the continental shelf.

Diatoms and other phytoplankton serve as the food base for the animals that live in the ocean. Some of the organic matter which they produce by photosynthesis escapes ingestion by animals or decomposition by bacteria and is incorporated within the sediments. The concentration of this material in the sediments depends not only upon its rate of production in the overlying water, but also upon its rate of burial in the sediments and the rate at which it can be oxidized by the overlying waters (Emery, 1960). Analyses of the content of organic carbon and nitrogen in the sediments range from

ATLANTIC CONTINENTAL SHELF AND SLOPE OF THE UNITED STATES

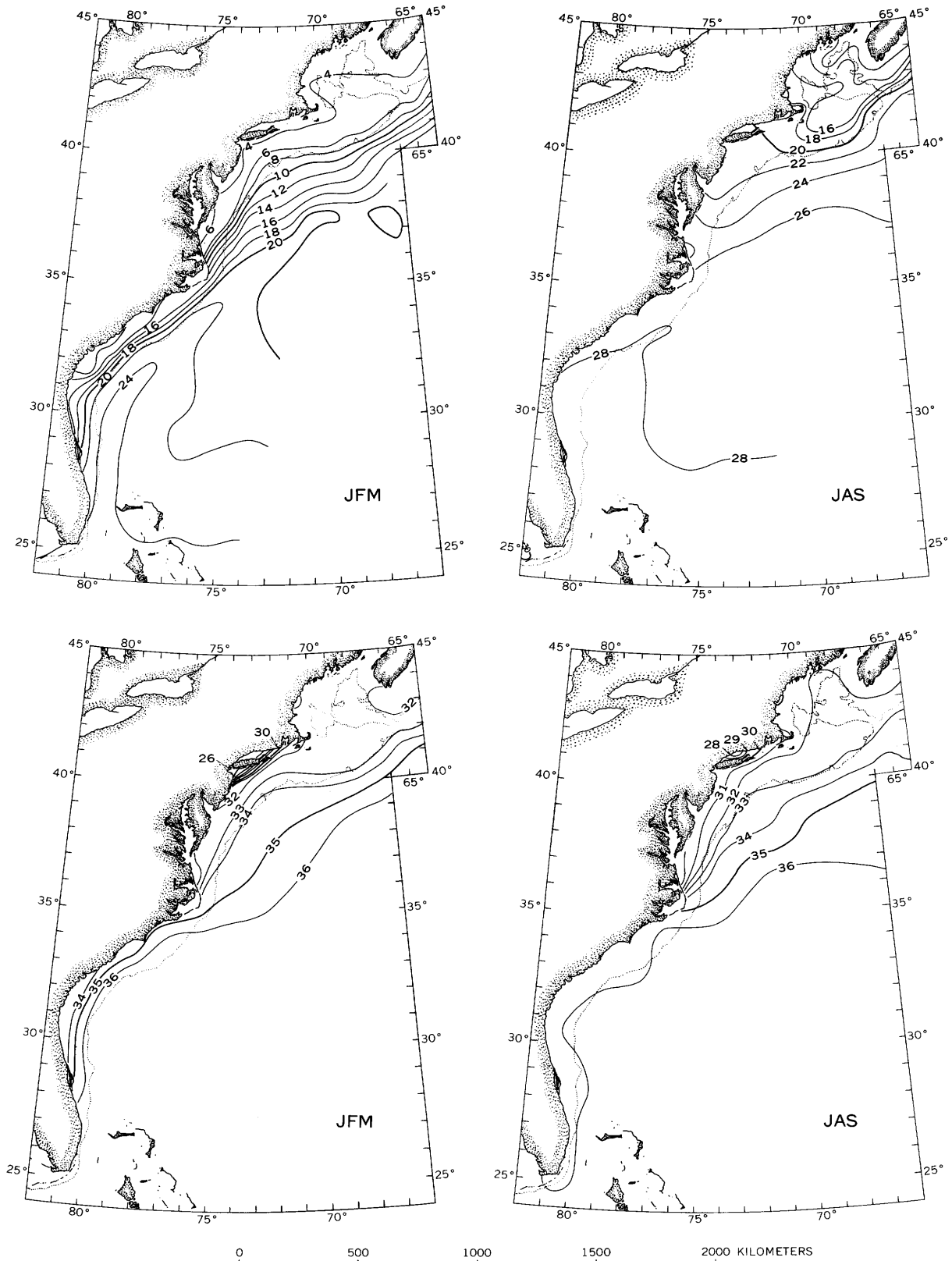


FIGURE 10.—Isotherms (top) and isohalines (bottom) of winter (JFM) and summer (JAS) seasons for surface waters off the Atlantic coast. Units are °C and salinity (‰). Based upon unpublished data in files of Woods Hole Oceanographic Institution from about 1940-61.

almost zero in the coarse sands of Georges Bank to commonly about 2 percent carbon and 0.3 percent nitrogen in the clays and silts of the Gulf of Maine and the continental slope. When complete, these measurements will be compared to rates of deposition, measurements of primary productivity, and specific organic constituents such as hydrocarbons, amino acids, and pigments in the sediments. Some of the data needed for comparison are available in the literature, but most will be obtained by various workers of several organizations as parts of small cooperative studies.

The animals living in the water and on the bottom are closely interrelated with the characteristics of the water and of the sediments. As shown long ago by Bigelow (1926), the nature and distribution of zooplankton contribute to an understanding of the circulation pattern and rate of movement of waters in the Gulf of Maine. Pelagic fishes also serve as indicators of topography through the indirect control of topography upon overlying waters. Examples are the locations of fishing grounds for cod and other commercial fishes above banks in the Gulf of Maine (Rich, 1929), and the recent finding and development of an all-year fishery for tuna and swordfish by long-line methods in the heads of submarine canyons off New England (Mather and Bartlett, 1962).

During the past, little information has been available concerning the relative abundance of pelagic Foraminifera in waters atop the continental shelves as compared with those of the deep sea, although speculation about their distribution has served as a basis for some paleoecological interpretations of ancient strata. As a partial remedy, about 100 large plankton hauls have been made for study of the relations of pelagic Foraminifera in the water with respect to their remains in the sediments. Pelagic species average less than 1 percent of total Foraminifera nearshore, but more than 90 percent of the total in deep water of the continental slope. Also reasonably common in the sediments of the continental shelf are the remains of diatoms and ostracodes, particularly in northern areas. The ostracodes appear to be abundant in areas of dilute sea water off the mouths of rivers; thus they may serve as indicators of large contributions of fresh water to the ocean.

Benthic Foraminifera are among the most ubiquitous animals in the sediments. Abundance of their tests shows regional zonations that are controlled by temperature, salinity, or other factors. A very sharp boundary occurs between warm-water benthic forms on the continental shelf and cold-water forms within the Gulf of Maine. On the shelf there is a marked increase in concentration of Foraminifera with bottom depth, an increase from an average of less than 1 test per gram of

sediment near shore to more than 1,000 per gram on the continental slope. Foraminifera are also much more abundant on the southern part of the shelf than on the northern part. A marked increase in living fauna (identified by stains) occurs below 40 meters, and a major increase is at 90–100 meters; changes of many species occur at the same depths. Breaks of this sort will permit identification of faunas of dead Foraminifera displaced by currents or mass movements.

The resistant remains of such animals as mollusks, corals, and foraminiferans are common constituents of the calcareous sediments south of Cape Hatteras, and they are present in the sediments farther north. Still other animals, including some sponges, fishes, holothurians, and worms destroy calcareous materials by their boring, comminution, or digestive activities. From another point of view, the sediments control the distribution patterns of the animals. Examples are the general restriction of most brachiopods, bryozoans, tunicates, and sponges to bottom areas of rock or boulders. Many polychaete worms and certain crustaceans and heart urchins are typical of mud bottom, and sand dollars and many brittle stars are restricted to sand. The distribution patterns and biomasses of these and other animals are being studied by the U.S. Bureau of Commercial Fisheries (Wigley, 1961a) as a cooperative part of the program. Studies of these larger benthic animals will require several years to complete, but a preliminary compilation of 37 stations between Nova Scotia and New York (Emery, Merrill, and Trumbull, 1965) shows that the greatest number of specimens and the highest biomass per unit area occur with gravel and boulders and the lowest number are in shell hash. If weighted for the area covered by each different kind of sediment between Nova Scotia and New York, the average biomass is about 120 grams per square meter, about 60 percent of the world average for continental shelves. At most stations, either crustaceans or annelid worms are dominant in terms of number of specimens, but at some stations echinoderms, mollusks, or bryozoans are dominant. Lack of hard parts in some organisms or their early disintegration produces a poor correlation between dominant living organisms and potentially dominant fossil forms. Comparison of faunas in the nearly simultaneous photographs and samples from the ocean bottom also yielded a poor correlation, indicating that many organisms transgress the simple classification of epifauna and infauna.

METHODS OF STUDY

A small converted Army freighter, R/V *Gosnold* (fig. 11), was outfitted by the Woods Hole Oceanographic Institution and used an average of 100 days per



FIGURE 11.—The research vessel *Gosnold*, used mainly for geological investigations.

year to accomplish most fieldwork. *Gosnold* is steel hulled, is 30 meters long, and has a 6.4-meter beam and a 2.5-meter draft; her gross tonnage is 250 (Emery and Schlee, 1963). Diesel powered (250 hp) with a variable pitch propeller, the ship can cruise at 7.5 knots (14 km per hr) but can maintain steerageway at 3 kilometers per hour. Navigation equipment includes Loran A, radar, radio direction finder, and gyropelorus. The low midship working area is sheltered at the forward end by the forecandle and at the after end by the superstructure which houses the bridge, electronics room, and most of the living quarters. A portable van is bolted to the deck adjoining the superstructure. Sample processing and chemical analyses, together with other shipboard laboratory work, are conducted here. The van opens into the forward room of the permanent deck structure of the ship where most electronic equipment needed for the geologic work is located. For collecting large grab samples, dredgings, and cores, a trawl winch containing 3,000 meters of 12-millimeter nontwist cable of 13-ton breaking strength is installed. Lighter cable (6,000 m of 6-mm stainless steel) on a separate drum of the same winch is used for lighter work. For near-shore work in shallow waters, R/V *Asterias*, about 13 meters long, was used about 30 days per year.

Work was done aboard ship and in laboratories ashore in each of the four subfields of marine geology: topography, sedimentology, lithology, and structure. In addition studies of water and biology were undertaken concurrently with geological sampling at sea. First priority was given to the construction of topographic charts because they are needed for all other investigations (fig. 12). Study of the sediments was advanced by the contribution from the U.S. Bureau of Commercial Fisheries of 400 suitable surface samples from the Gulf of Maine. Laboratory study of these samples was largely finished while R/V *Gosnold* was being outfitted. Subsequently, an additional 1,600 surface samples were collected. Completion of the sample studies enabled the selection of the best sites for more detailed work and for cores.

Rock specimens were included within many of the sediment samples, but the major effort in rock dredging was withheld until special cruises during the third and fourth years, which in turn were followed by intensive laboratory studies of lithology and stratigraphy. Structural geology, largely inferred from continuous seismic profiling, required a larger amount of ship time and of equipment preparation than most of the other subfields of marine geology. Accordingly, its fieldwork was spread throughout the 1963-66 period with a year-to-year increase from the first to the third year. Interpretation of results of the profiling constituted the major effort of the structure program in the fourth year.

The shipboard work was concentrated in the first 4 years, leaving the fifth year for cleanup of remaining work. Laboratory analyses and report writing continued throughout the period, with preparation of final reports spread throughout the entire period.

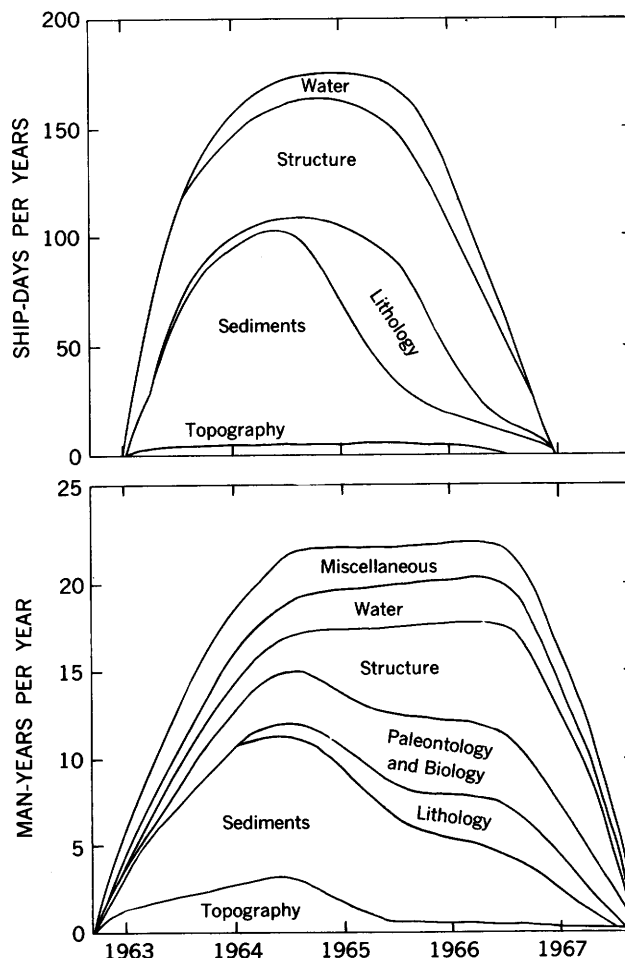


FIGURE 12.—Schematic distribution of ship time (ship-days per year) and of laboratory time (man-years per year) among the subfields of marine geology being applied to the study of the continental shelf and slope off the Atlantic coast of the United States.

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