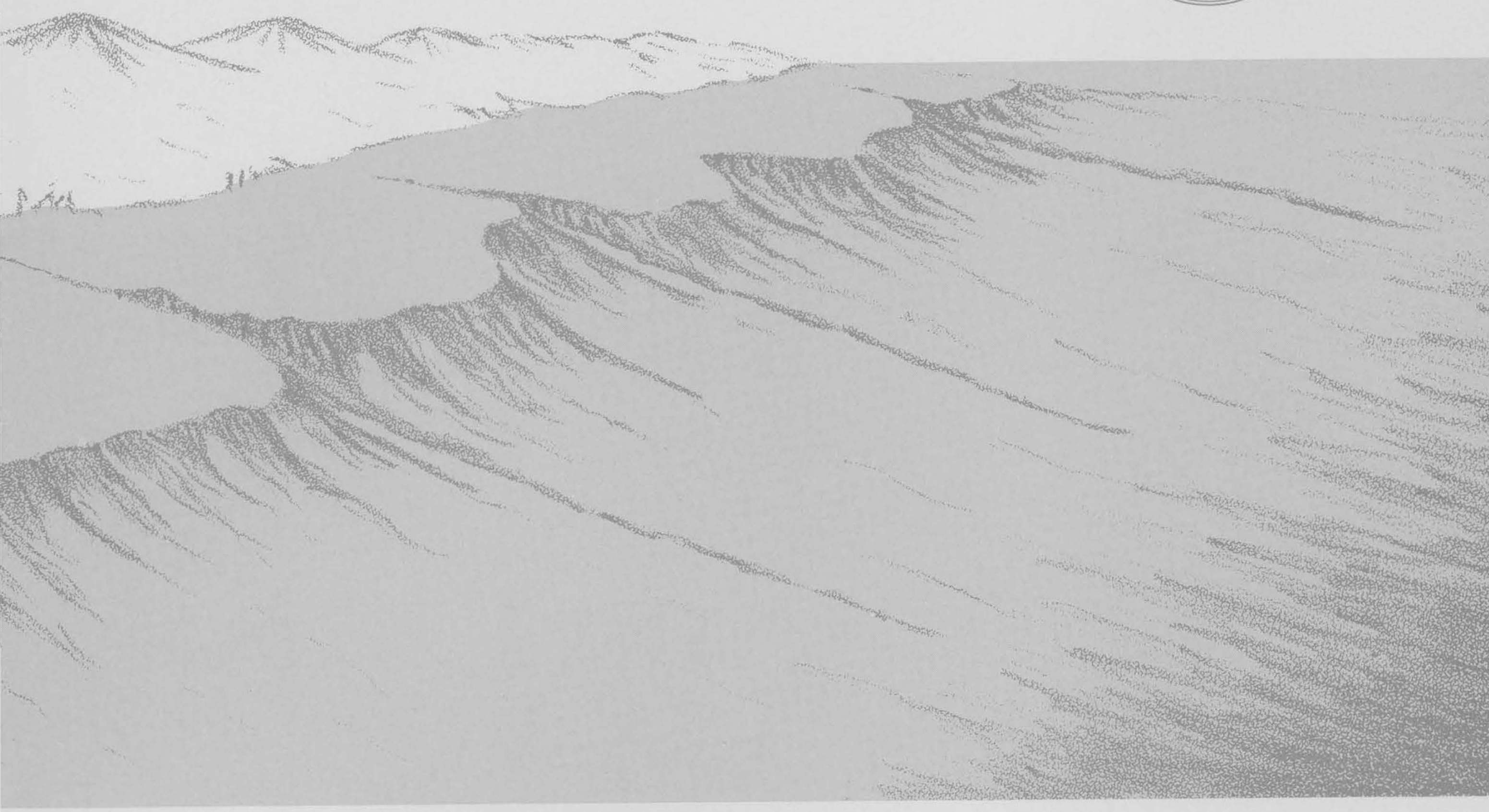
Atlantic Continental Shelf and Slope of the United States



Shallow Structure

GEOLOGICAL SURVEY PROFESSIONAL PAPER 529-I

Atlantic Continental Shelf and Slope of The United States—Shallow Structure

By ELAZAR UCHUPI

GEOLOGICAL SURVEY PROFESSIONAL PAPER 529-I

Description of the subsurface morphology of the shelf and slope (continental terrace) and some speculations on the evolution of the sedimentary framework of the terrace

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1970

UNITED STATES DEPARTMENT OF THE INTERIOR

WALTER J. HICKEL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price $1 (paper cover)

CONTENTS

ILLUSTRATIONS

ATLANTIC CONTINENTAL SHELF AND SLOPE OF THE UNITED STATES—SHALLOW STRUCTURE[1]

By Elazar Uchupi, Woods Hole Oceanographic Institute

ABSTRACT

The continental terrace (continental shelf and slope) off the east coast of the United States can be divided into two segments. North of Cape Hatteras, N.C., the shelf is immediately adjacent to the continental slope; south of Cape Hatteras, the shelf is either separated from the slope by a marginal plateau (Blake Plateau) or is cut in two by a marginal trough (Straits of Florida).

The northern segment of the continental terrace was formed by upbuilding on the shelf and outbuilding on the slope atop subsiding Triassic and Jurassic rocks and the Paleozoic basement. Strata on some sections of the shelf, in both the northern and southern segments, have been slightly worked into broad ridges at right angles and parallel to shore. Within the southern segment, the slope east of the Blake Plateau (Blake Escarpment) was formed by carbonate accretion or reef buildup. Carbonate accretion, possibly accompanied by folding and faulting, also formed the side slope of the Straits of Florida. The shelf and Florida-Hatteras Slope west of the Blake Plateau were formed by upbuilding on the shelf and outbuilding on the slope in the direction of the Blake Plateau.

The framework of the continental terrace was modified considerably during the Pleistocene. Proglacial fluvial and glacial erosion deepened the normally shallow shelf east of New York. Fluvial and marine erosion and deposition formed the channels, deltas, and terraces on the shelf's surface west of Georges Bank. Turbidity currents, slumping, and gravitational sliding deeply eroded and steepened the normally gentle continental slope north of Cape Hatteras. Erosion by the Gulf Stream modified the Blake Plateau and Florida-Hatteras Slope. Farther south, deposition by littoral drift from the north partly buried the carbonate side slopes of the Straits of Florida.

Other modifications of the shelf occurred during the last transgression in post-Wisconsin time. At that time, the glacial sediments on Georges Bank and Nantucket Shoals were modified to nearly their present shape by waves. Fine material winnowed from these glacial sediments was transported northward and deposited in the basins in the Gulf of Maine. The ridge and trough topography of the shelf west of Georges Bank was probably also formed during the last rise in sea level. Within the southern segment of the terrace, carbonate ridges were formed by calcareous algae on the shelf, near the present shelf-break, and on the Florida-Hatteras Slope. On most of the continental terrace, the Pleistocene relict surface is still recognizable, and it reflects the short time since sea level rose to its present position and the low volume of sediment that has been deposited on the shelf since then.

[1] Contribution 2098 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.

INTRODUCTION

The continental margin off the east coast of the United States is probably one of the best surveyed submarine areas in the world. Its bathymetry has been described in considerable detail (Garrison and McMaster, 1966; Heezen and others, 1959; Hurley, 1964; Hurley and others, 1962; Jordan and others, 1964; Jordan and Stewart, 1961; Murray, 1947; Pratt, 1968; Pratt and Heezen, 1964; U.S. Coast and Geod. Survey and U.S. Bur. Commercial Fisheries, 1967; Uchupi, 1965, 1966a–e; Veatch and Smith, 1939). Total sediment thickness atop the pre-Triassic basement has been determined for most of the margin by seismic-refraction methods (Antoine and Henry, 1965; Drake and others, 1959; Hersey and others, 1959; Sheridan and others, 1966). Systematic coring, dredging (Ericson and others, 1952, 1961; Gibson, 1965; Gibson and others, 1968; Heezen and Sheridan, 1966; Northrop and Heezen, 1951; Stetson, 1949), and drilling (Joint Oceanog. Inst. Deep Earth Sampling Program, 1965) have yielded data on the stratigraphy of the region. Recent surveys using seismic-reflection profilers have added considerable information on the subsurface of several segments of the margin (Emery and Uchupi, 1965; Ewing and others, 1966; Garrison, 1967; Hoskins, 1967; Hoskins and Knott, 1961; Jordan and others, 1964; Knott and Hoskins, 1968; Krause and others, 1966; McMaster and others, 1968; Roberson, 1964; Swift and Lyall, 1968; Tagg and Uchupi, 1966, 1967; Uchupi, 1966a,b,d, 1967a,b; Uchupi and Emery, 1967; Zarudzki and Uchupi, 1968.

From 1963 to 1966, continuous seismic profiles were recorded for more than 20,000 km (kilometers) on the continental margin. The work was done during a study of the Atlantic Continental Shelf and Slope by the Woods Hole Oceanographic Institution in cooperation with the U.S. Geological Survey. This report discusses the result of this survey. Data from these profiles, when augmented with information already available from the continental margin, make possible the reconstruction of the geologic history of the area.

ACKNOWLEDGMENTS

The writer wishes to express his appreciation to the officers and crew of the RV *Gosnold* of the Woods Hole Oceanographic Institution for their cooperation during the seismic survey. Part of the equipment used during the survey was designed and built by R. K. Paul and K. E. Prada of the Woods Hole Oceanographic Institution. Paul, Prada, and A. R. Tagg of the U.S. Geological Survey kept the equipment in operation during the cruises. To John Schlee, R. H. Meade, R. Brodie, Edward Bradley, and R. N. Oldale of the U.S. Geological Survey; P. F. McFarlin, K. E. Prada, John Watts, K. O. Emery, D. D. Caulfield, and R. M. Pratt of the Woods Hole Oceanographic Institution; B. M. Hand, R. Clark, C. Cunningham, Jr., K. Bryant, T. Owen, and W. Simmins of Amherst College; J. D. Smith of the University of Chicago; W. Sutphen of Wesleyan College; D. W. Folger of Lamont Geological Observatory; J. L. Laternauer of Duke University; P. Boyer of the University of Illinois; T. J. M. Schopf of the Marine Biological Laboratory at Woods Hole; and B. V. Shekhatov of the Institute of Oceanology, Moscow, the writer is indebted for standing watches. For the loan of profiles TW 8 and TW 9, the writer thanks J. R. Curray of Scripps Institute of Oceanography. Appreciation is also expressed to J. D. Milliman and K. O. Emery, of the Woods Hole Oceanographic Institution, R. L. McMaster of the University of Rhode Island, and L. E. Garrison and R. H. Meade of the U.S. Geological Survey for critical reading of the manuscript. The writer also wishes to thank A. A. Gioisa, Graphic Arts Dept., Woods Hole Oceanographic Institution, who drafted the illustrations used in this report.

TOPOGRAPHIC SETTING

The continental margin off the east coast of the United States can be divided into two sectors. In the northern sector, which extends from Nova Scotia to Cape Hatteras, the continental slope immediately adjoins the continental shelf (fig. 1). At the base of the slope is a well-developed apron, the continental rise. This northern sector in turn can be divided into two segments, a northern segment extending from Great South Channel to Nova Scotia, where the shelf is unusually deep because of fluvial and glacial erosion, and a southern segment from Great South Channel to Cape Hatteras, where the shelf is relatively smooth and less than 200 m (meters) deep.

The southern sector from Cape Hatteras to the Florida Keys can also be divided into two segments. In the northern segment, extending from Cape Hatteras to Cape Kennedy (fig. 1), the continental slope is separated from the shelf by an intermediate surface, the Blake Plateau. The plateau in turn is separated from the shelf by a gentle slope, the Florida-Hatteras Slope. The continental rise in this region is missing, and its position is occupied by a broad ridge, Blake Ridge, and an enclosed depression, Blake Basin. The southern segment from Cape Kennedy to the Florida Keys consists of a narrow shelf immediately off the mainland coast. This shelf is separated from the continental shelf's seaward extension, the Bahama Banks, by the Straits of Florida, a 700-km-long, arcuate trough 800 to 2,200 m deep. During the present survey, no data were obtained from the Bahama Banks, Blake Ridge and Basin, and most of the continental rise. Consequently, these areas will be omitted from the present discussion.

METHODS OF STUDY

From 1963 to 1966, more than 20,000 km of continuous seismic profiles were obtained from the continental margin off the east coast. Figure 2 shows the locations of the profiles. The sound source used during the survey was a sparker, consisting of a power supply to charge up a bank of energy-storage capacitors which were triggered at timed intervals into sudden discharge through an underwater electrode. The sparker, powered by a diesel-generator set, has a maximum energy of 10,500 j (joules) and will charge 840 mf (microfarads) to a potential of 5 kv (kilovolts) at a rate of 1 amp (ampere). Discharge is produced by control signals from a Precision Graphic Recorder (PGR) that dump the capacitor banks through ignitron-switch tubes into a transmission cable terminated by an underwater brass electrode. The electrode, towed 15 m behind the ship, discharges with maximum energy around 100 Hz (Hertz). Throughout most of the present survey, the sparker was used at maximum energy, 10,500 j, and was programmed to discharge every 5 seconds or 12.5 m apart when the ship was moving at 9 km/hr (kilometers per hour).

Signals from the bottom and subbottom were received by a five-element hydrophone array towed 20 m behind the ship, where a preamplifier conditioned the signals for transmission to the ship via the tow cable. Aboard the ship the return signals were amplified, and part of the signal was recorded on a four-channel tape recorder for later playback if necessary. The remainder of the signal was filtered, and signals generally between 20 and 150 Hz were fed to a PGR for further amplification and recording on paper.

Throughout most of the seismic survey, the ship's speed was about 9 km/hr. Navigation was by radar nearshore and Loran-A farther offshore. Fixes were usually taken every 4.5 km.

The final recording, generally the one obtained in

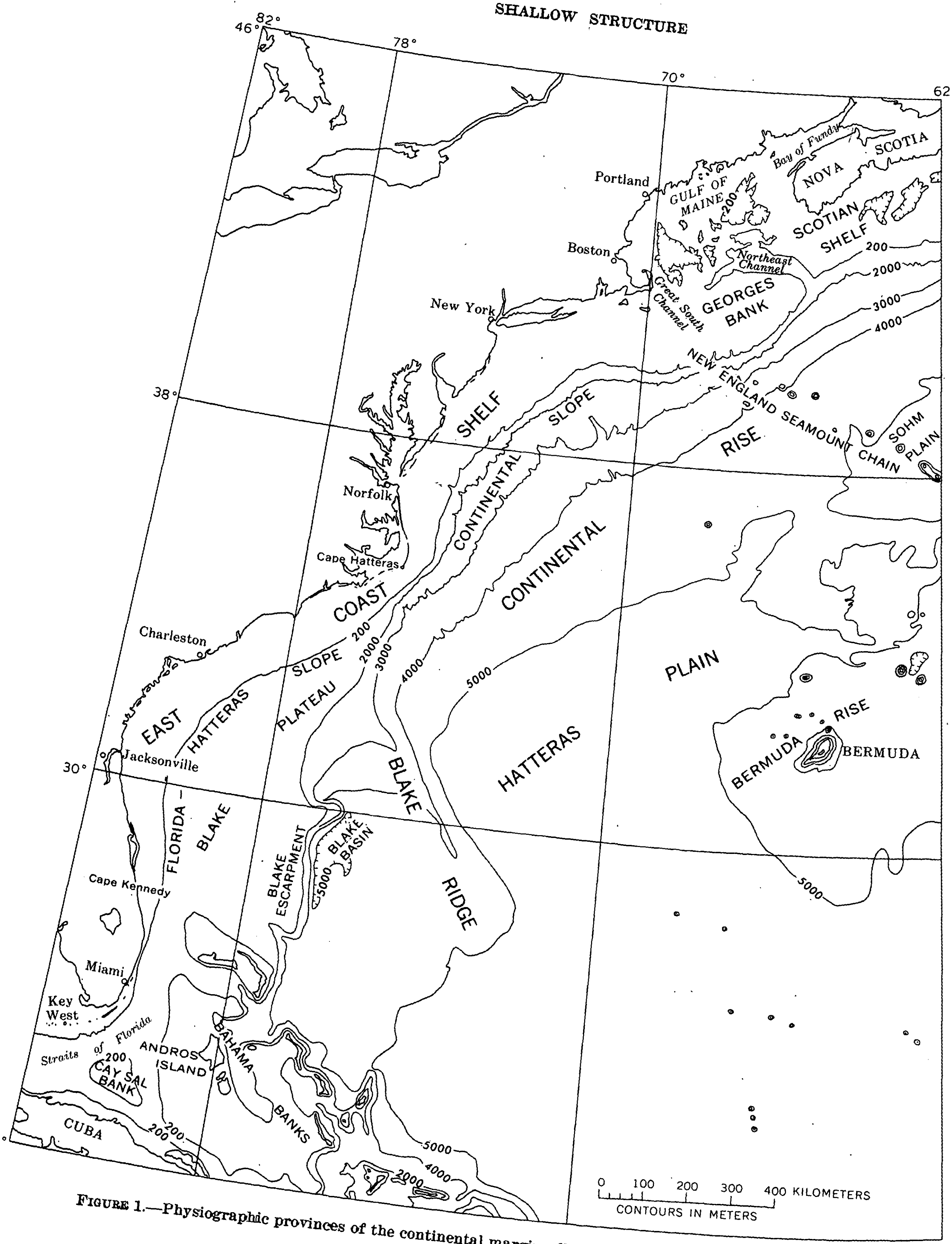


Figure 1.—Physiographic provinces of the continental margin off the east coast of the United States.

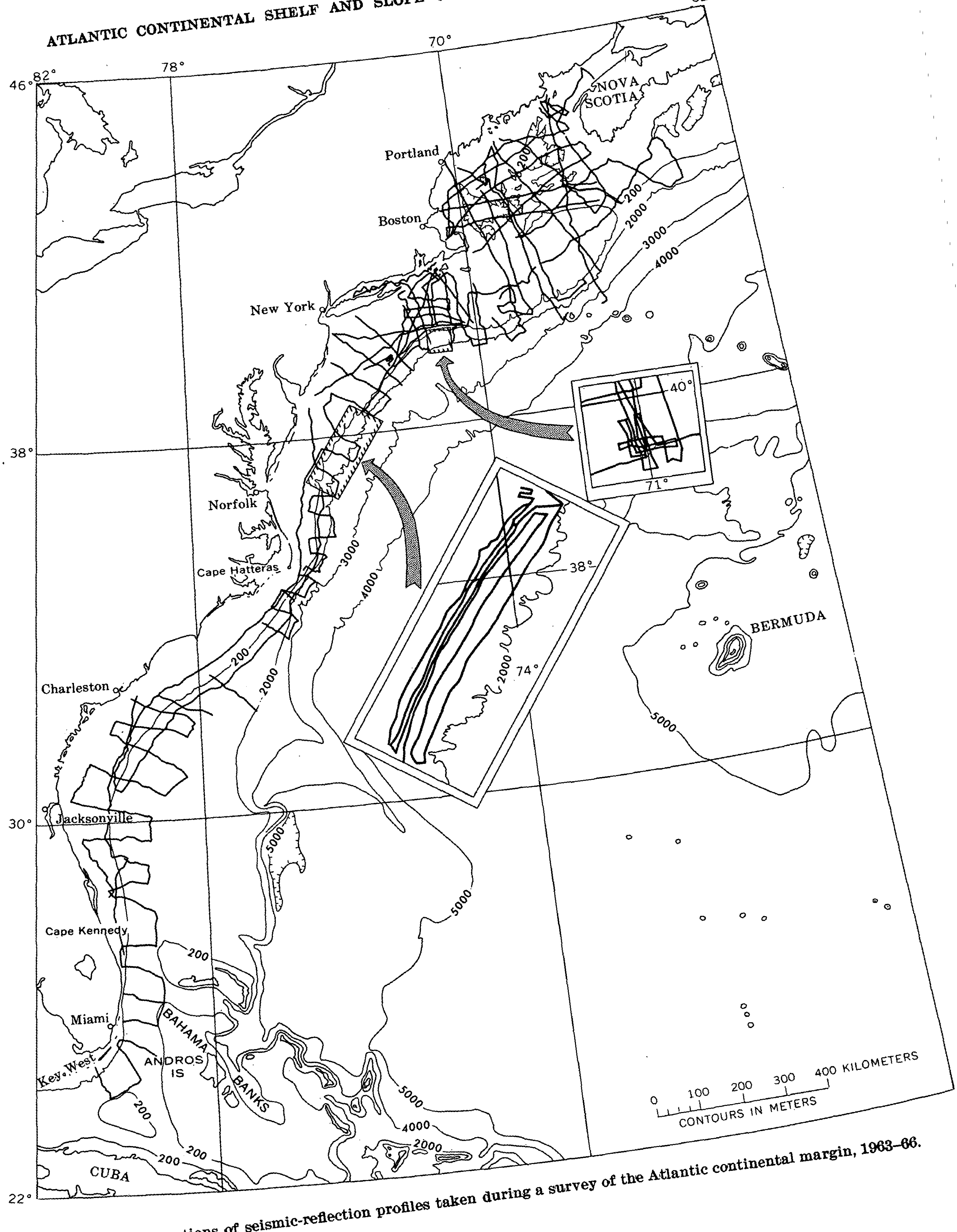


FIGURE 2.—Locations of seismic-reflection profiles taken during a survey of the Atlantic continental margin, 1963–66.

the field, was spread on a table and a transparent acetate overlay placed on top. Echos from the bottom and subbottoms were then traced with a grease pencil. The interpretation was then reduced to a common scale, using the following method. A transparent overlay with horizontal traveltime marks at 0.1-second intervals and vertical distance lines at 3-km intervals was placed over the acetate film. The grease-pencil lines were then transferred visually to a similar grid printed on paper. Profiles from the outer shelf and slope, Florida-Hatteras Slope, and the Straits of Florida were reduced about 80 percent. The resulting profiles had a vertical exaggeration of about 10, based on a sound velocity of 1,500 m/sec (meters per second). Because of the shallowness of the water and the small penetration, profiles from the rest of the shelf were reduced about 93 percent in a horizontal direction and 40 percent in a vertical direction. These profiles have a vertical exaggeration of about 30.

Identification of horizons shown by the recordings is based on rock samples dredged and cored offshore, drill data, seismic-refraction velocity determinations, and rock exposures along shore. On most of the profiles where the horizon marking the Tertiary and Cretaceous boundary has been identified, the discontinuity is marked with the letter A.

SCOTIAN SHELF AREA

Profiles across the Scotian Shelf, slope, and continental rise (profiles 34 and 36, fig. 3) show a thin sequence of reflecting horizons that parallel the present surface of the shelf and slope. Horizons on both profiles have an upbuilding-outbuilding type of structure with a seaward progradation of about 5 km; they can be traced from the shelf-break to the continental rise without any disruption. Reflectors within the rise show some irregularities which may be due either to slumping or to cut-and-fill structures that result from turbidity-current activity. Both profiles have a shallow and gradual transition from the slope to the rise. Such a shallow transition is believed by Uchupi and Emery (1967) to be due to Pleistocene glaciers that crossed the shelf and deposited a large volume of sediment at the base of the slope.

A more complete profile, extending from the continental rise to the shoreline, is depicted by profile 36 in figure 4. Horizons on this profile can be traced to the center of the shelf, where they terminate against the slope of one of the shelf basins. This profile clearly demonstrates that the depressions within the Scotian Shelf are erosional in origin. Uchupi (1968) has suggested that these depressions were formed by glacial erosion, possibly along preglacial fluvial valleys. The deep irregular reflector that extends to the present shoreline represents the top of the pre-Triassic rocks. No structure has been observed beneath this surface on any of the profiles.

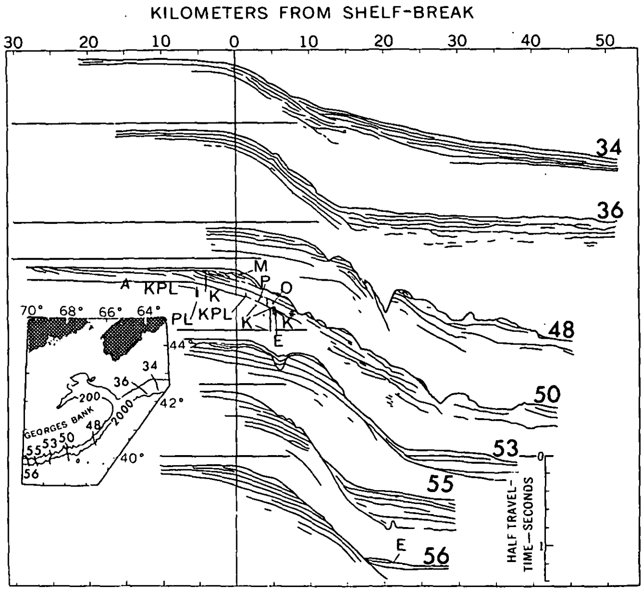


FIGURE 3.—Seismic profiles across the continental margin off Nova Scotia and the continental slope south of Georges Bank. Along profile 50 the lines and dots represent depth of rock samples dredged from the continental slope by Stetson (1949) and Gibson, Hazel, and Mello (1968). Ages of rock samples are as follows: K, Upper Cretaceous, P, upper Paleocene, E, Eocene, O, Oligocene, M, Miocene, PL, Pliocene. The letter A indicates Tertiary and Cretaceous boundary. Modified from Uchupi and Emery (1967, fig. 2). Vertical exaggeration, × 8 (assuming a velocity of 1,500 m/sec).

GULF OF MAINE AND BAY OF FUNDY

The Gulf of Maine is a broad depression off the New England coast which is separated from the open sea by Georges Bank and the Scotian Shelf (fig. 1). The gulf is analogous to the depressions on the Scotian Shelf and Long Island, although it is larger and deeper (fig. 4). Compressive velocities determined by seismic-refraction methods and from samples dredged offshore (Toulmin, 1957) and rock exposures along shore indicate that the deep irregular reflector present on all the seismic profiles of the Gulf of Maine (figs. 5, and 6) is the top of the Paleozoic. As in the Scotian Shelf, no structures were observed within the Paleozoic rocks on any of the profiles.

Strata above the Paleozoic rocks can be divided into two sequences: an upper poorly stratified unit and a

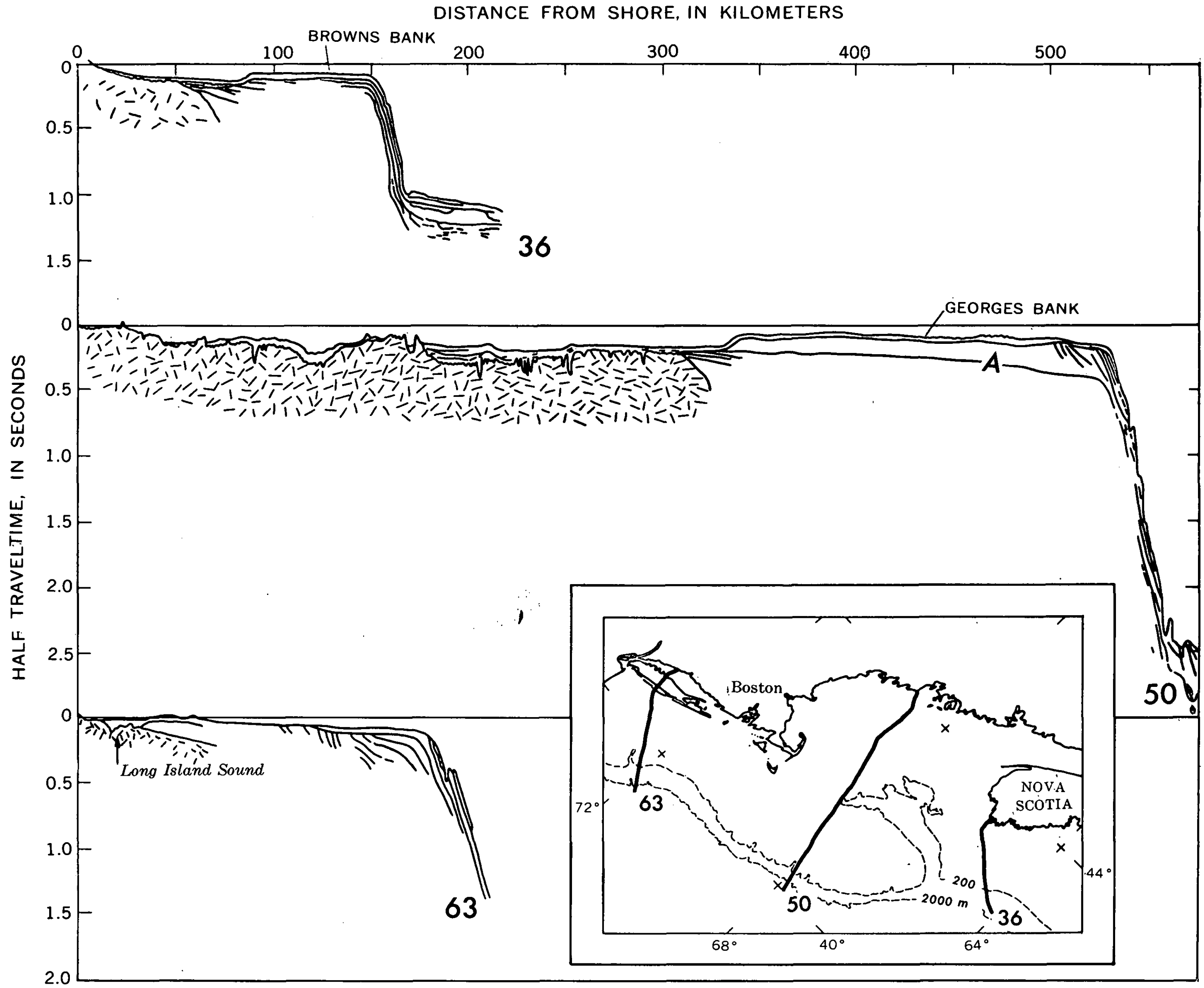


FIGURE 4.—Seismic profiles of the continental margin off Nova Scotia, Maine, and Long Island. Vertical exaggeration, about × 45 (assuming a velocity of 1,500 m/sec). *A* indicates Tertiary and Cretaceous boundary.

lower well-bedded unit (fig. 5). The upper unit, presumably all of Quaternary age, consists of two subunits: an upper acoustic transparent layer, and a lower unit made of stronger reflecting material (fig. 7). Bottom samples indicate that the upper unit consists of fine-grained silt and clay with a high water content, and the lower layer consists of glacial till and outwash. The fine-grained layer presumably is made up of fines winnowed from the glacial sediments.

The stratified sequence immediately above the Paleozoic rocks consists of sediments of presumed Tertiary, Cretaceous, and Triassic age. Recovery of Eocene marine fossils from one of the banks west of Cape Cod (Schlee and Cheetham, 1967), the occurrence of Eocene continental rocks in the subsurface on Cape Cod (Zeigler and others, 1960), and the presence of marine Eocene fossiliferous boulders within the glacial sediments of Cape Cod (Crosby, 1879) suggest that the strata east of Cape Cod are Tertiary in age. Tertiary sediments in nearby Martha's Vineyard are highly glauconitic, and the presence of glauconite in most of the Gulf of Maine sediments suggests that the Tertiary sediments were more widely spread in the past. The well-bedded sediments north of Georges Bank can be traced across Georges Bank to the continental slope where they crop out. Rock samples dredged by Stetson (1949) from the slope indicate that strata north of Georges Bank are Late Cretaceous in age. Sediments of Late Cretaceous(?) age may also be present in Cape Cod Bay.

Some of the seismic profiles from this area show ero-

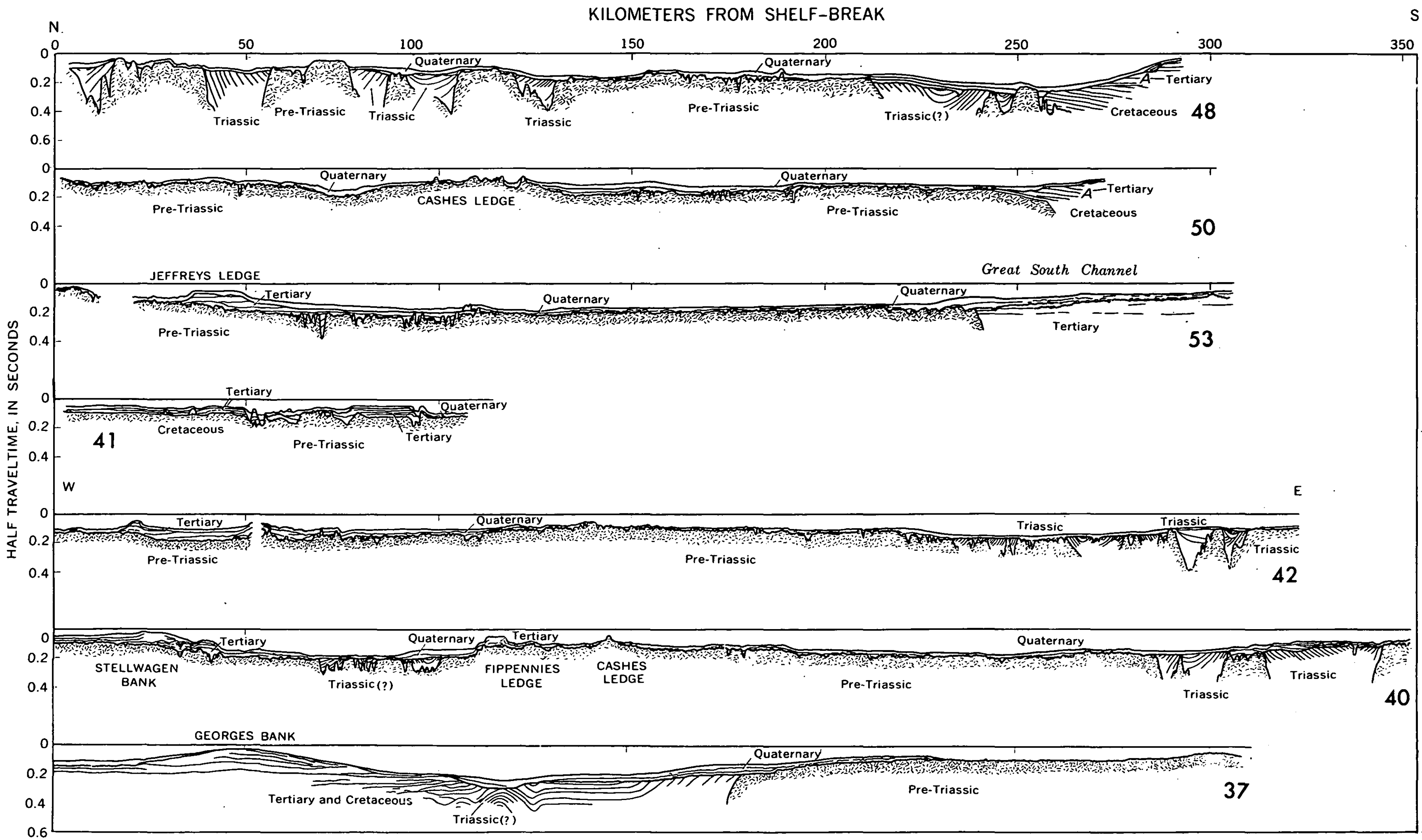


Figure 5.—Seismic profiles in the Gulf of Maine (modified from Uchupi, 1966b, figs. 4, 5). See figure 6 for locations of profiles. Vertical exaggeration, × 28 (assuming a velocity of 1,500 m/sec). The letter *A* indicates Tertiary and Cretaceous boundary.

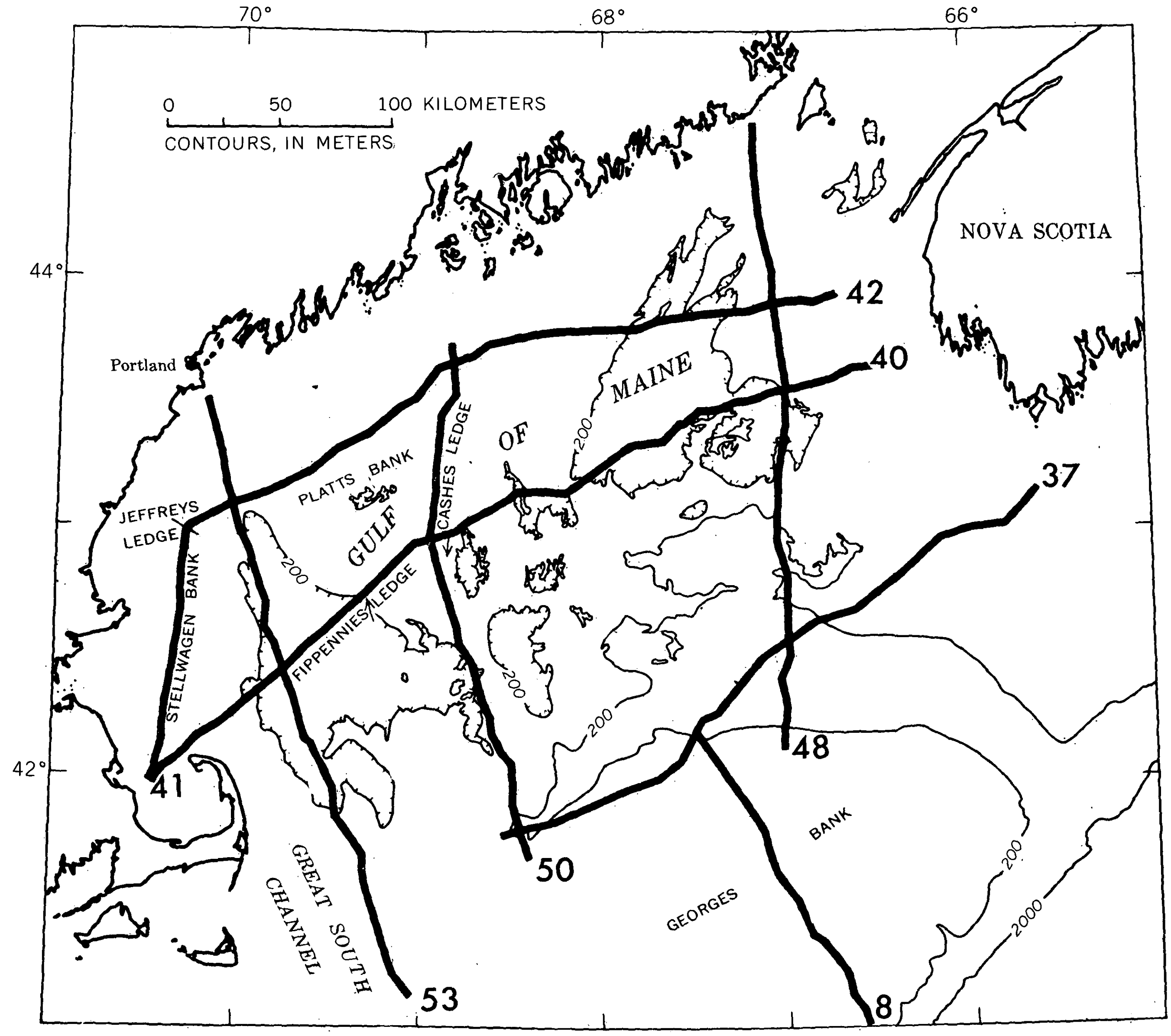


Figure 6.—Locations of seismic profiles shown in figure 5.

sional remnants beneath the Tertiary strata (fig. 8). Hoskins and Knott (1961), who first described the remnants, suggested that they may consist of Upper Cretaceous sediments, as they have compressive velocities similar to possible Upper Cretaceous sediments off Nonamesset Island. Velocity determinations on Gay Head, Martha's Vineyard, where Upper Cretaceous strata are exposed, only gave values between 1.5 and 2.4 km/sec (kilometers per second) (Oldale, 1969, p. B124). Values reported by Hoskins and Knott (1961) (4 km/sec) are more typical of Triassic sediments. Tuttle, Koteff, and Hartshorn (1960), for example, reported such velocities from the Triassic strata in the Connecticut Valley. Possibly, the erosional remnants in Cape Cod are not Cretaceous but are Triassic in age. A third explanation is that the sediments are not Cretaceous or Triassic, but Carboniferous. Birch and Dietz (1962) stated that Carboniferous deposits in Narragansett Bay, R.I., have velocities of 4.08 to 4.48 km/sec, velocities similar to those from the erosional remnants in Cape Cod. Rock exposures alongshore indicate that the strata within the Bay of Fundy are Triassic in age. Uchupi (1966b) and Tagg and Uchupi (1966) have traced these sediments 120 km into the Gulf of Maine. The folded sediments north of Georges Bank (profiles 48 and 37, fig. 5) and east of Cape Cod (profile 42, fig. 5) may also be Triassic, but this has not been verified by sampling.

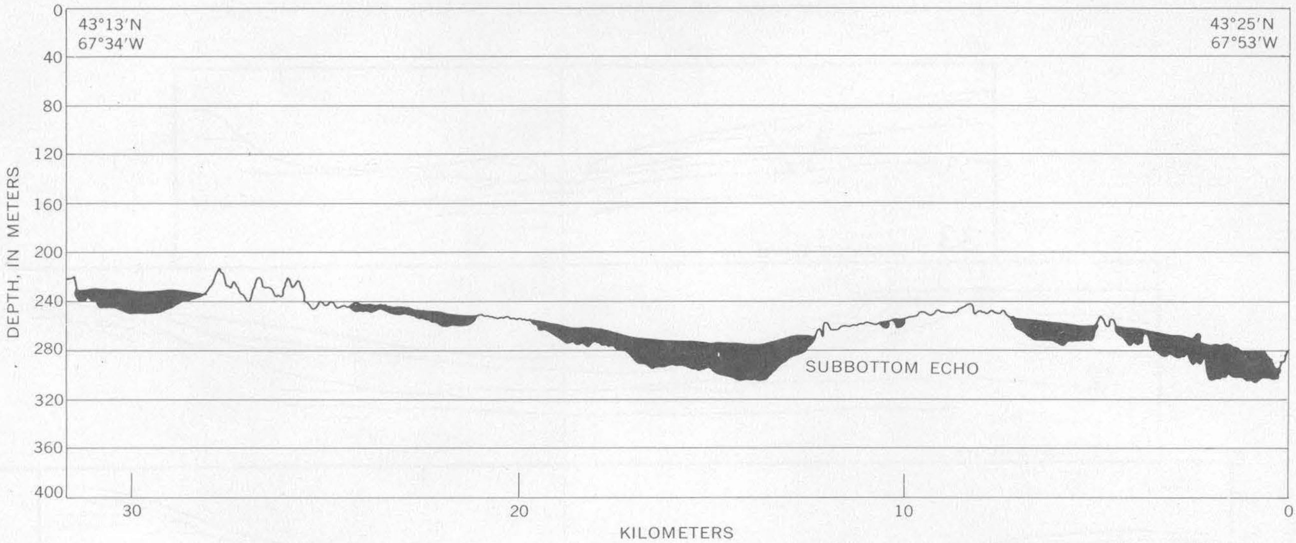
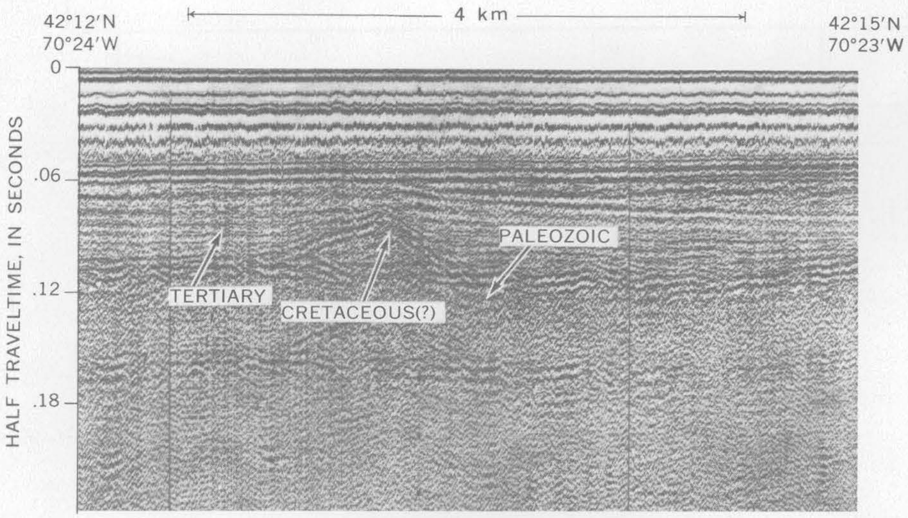


FIGURE 7.—Profile taken with a 12-kc (kilocycles per second) echo-sounder in the Gulf of Maine. The shaded area is the silt-clay deposits, and the strong reflector is the top of the glacial till and outwash sediments (modified from Uchupi, 1968, fig. 8). Vertical exaggeration, × 33.



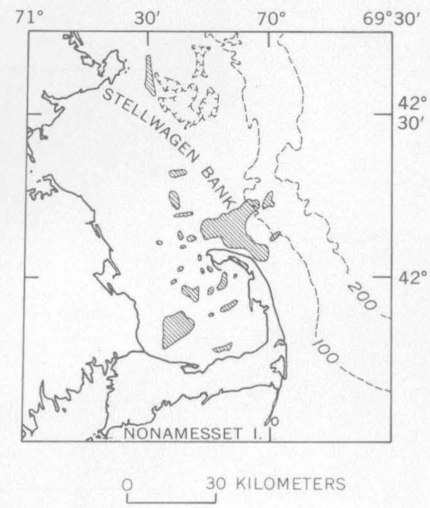


FIGURE 8.—Buried erosional remnants of Cretaceous(?) material. Map shows distribution of Cretaceous deposits in Cape Cod Bay. Dashed lines are depth contours in meters. Left, a typical seismic-profiler record. Vertical exaggeration, × 10 (assuming a velocity of 1,500 m/sec). Gay Head, Martha's Vineyard (off the map) is located 25 km southwest of Nonamesset Island.

Johnson (1925, p. 264–286), first described the surface morphology of the Gulf of Maine, suggested that the gulf was a lowland carved out of the shelf strata by fluvial erosion. Later, Shepard, Trefethen, and Cohee (1934) and Chadwick (1948, 1949) suggested that the gulf was formed by a combination of fluvial erosion that first formed a lowland and glacial erosion that deepened and broadened it. Seismic profiles taken during the present survey show that the gulf is erosional in origin, and the presence of glacial sediments on most of the Gulf of Maine indicate that ice erosion has played a significant role in the forming of the gulf.

NORTHEAST AND GREAT SOUTH CHANNELS

Northeast and Great South Channels form deep-water passageways into the Gulf of Maine. Northeast Channel is between Georges Bank and the Scotian Shelf, and Great South Channel separates Georges Bank from Nantucket Shoals (fig. 12). Both channels may represent the water gaps of the fluvial system that

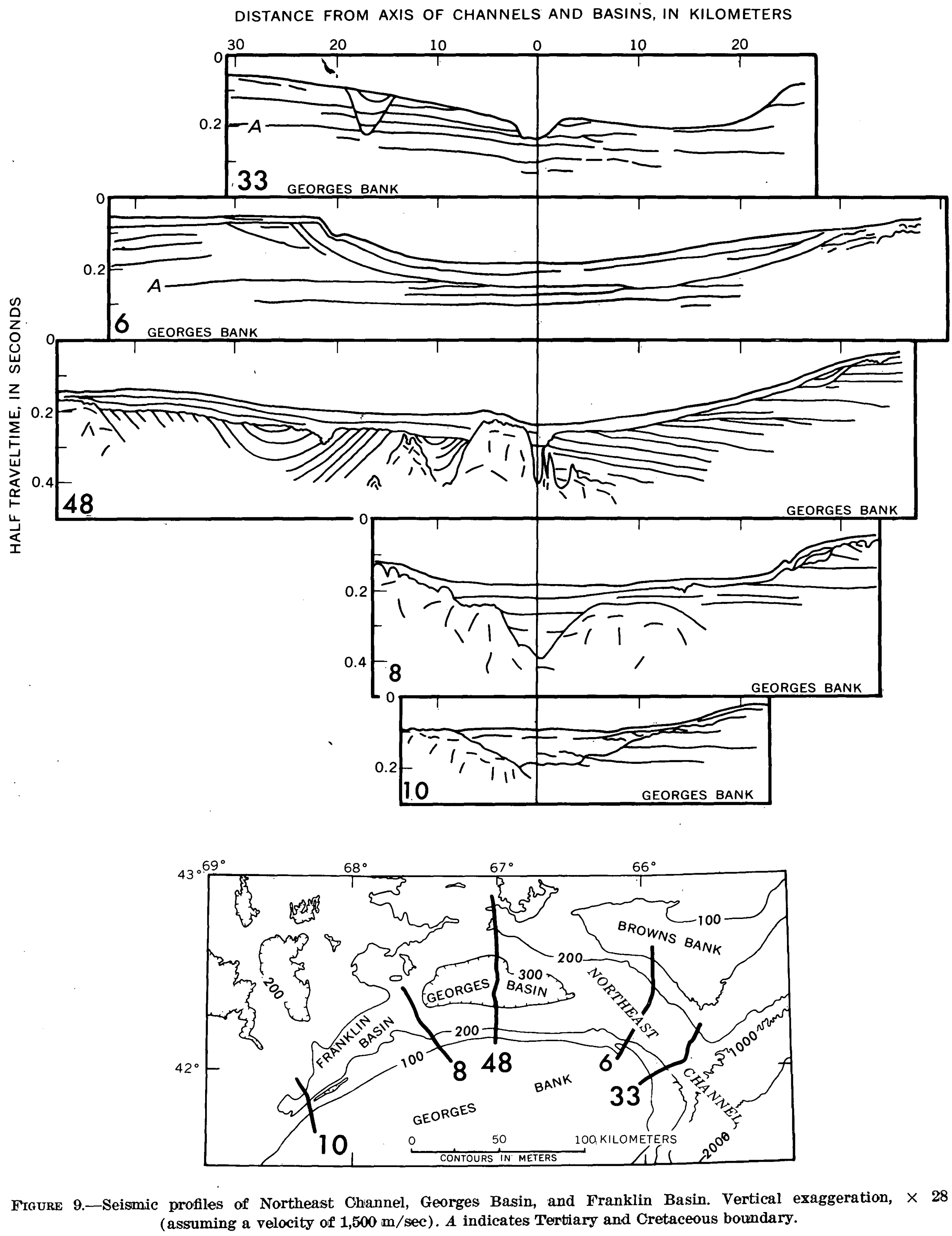


FIGURE 9.—Seismic profiles of Northeast Channel, Georges Basin, and Franklin Basin. Vertical exaggeration, × 28 (assuming a velocity of 1,500 m/sec). *A* indicates Tertiary and Cretaceous boundary.

formed the Gulf of Maine. Torphy and Zeigler (1957) and Uchupi (1966a) have suggested that Northeast Channel was widened and deepened by glacial erosion during the Pleistocene. A similar development has been suggested by Knott and Hoskins (1968) for Great South Channel. Most of the detritus eroded by ice from the Gulf of Maine appears to have reached the open sea by way of these channels, as the continental rise seaward of the channels is unusually thick, next to the continental slope.

At present, Northeast Channel has a maximum depth of about 240 m. Profile 6 (fig. 9) shows, however, that in the past the channel was 0.07 seconds or 126 m. (assuming a sediment velocity of 1,800 m/sec) deeper. Northeast Channel and Georges and Franklin Basins seem to form one continuous feature; this suggests that the ice was stopped by Georges Bank and was forced to flow parallel to the northern slope of the bank, reaching the open sea by way of Northeast Channel. At present, the side slopes of this glacial trough are partly masked by and the trough partly filled with sediments presumably derived from Georges Bank during the last transgression during the Holocene.

Profiles across Great South Channel also show that this trough may have been deeper in the past. The inclined reflector (fig. 10, profile 11C; reflector 1) may mark the western side slope of this filled trough. After this deeper channel was filled, several others appear to have been cut, and they too were filled in turn (fig. 10, profile 11C).

GEORGES BANK

Georges Bank is an immense barrier separating the Gulf of Maine from the open sea. Profiles across the northern slope show several reflecting horizons (fig. 5). The deepest horizon has an irregular surface and probably represents the top of the pre-Triassic rocks that form the foundation of the Gulf of Maine. This Paleozoic terrain is blanketed by smoother horizons consisting of sedimentary strata of possible Cretaceous and Terti-

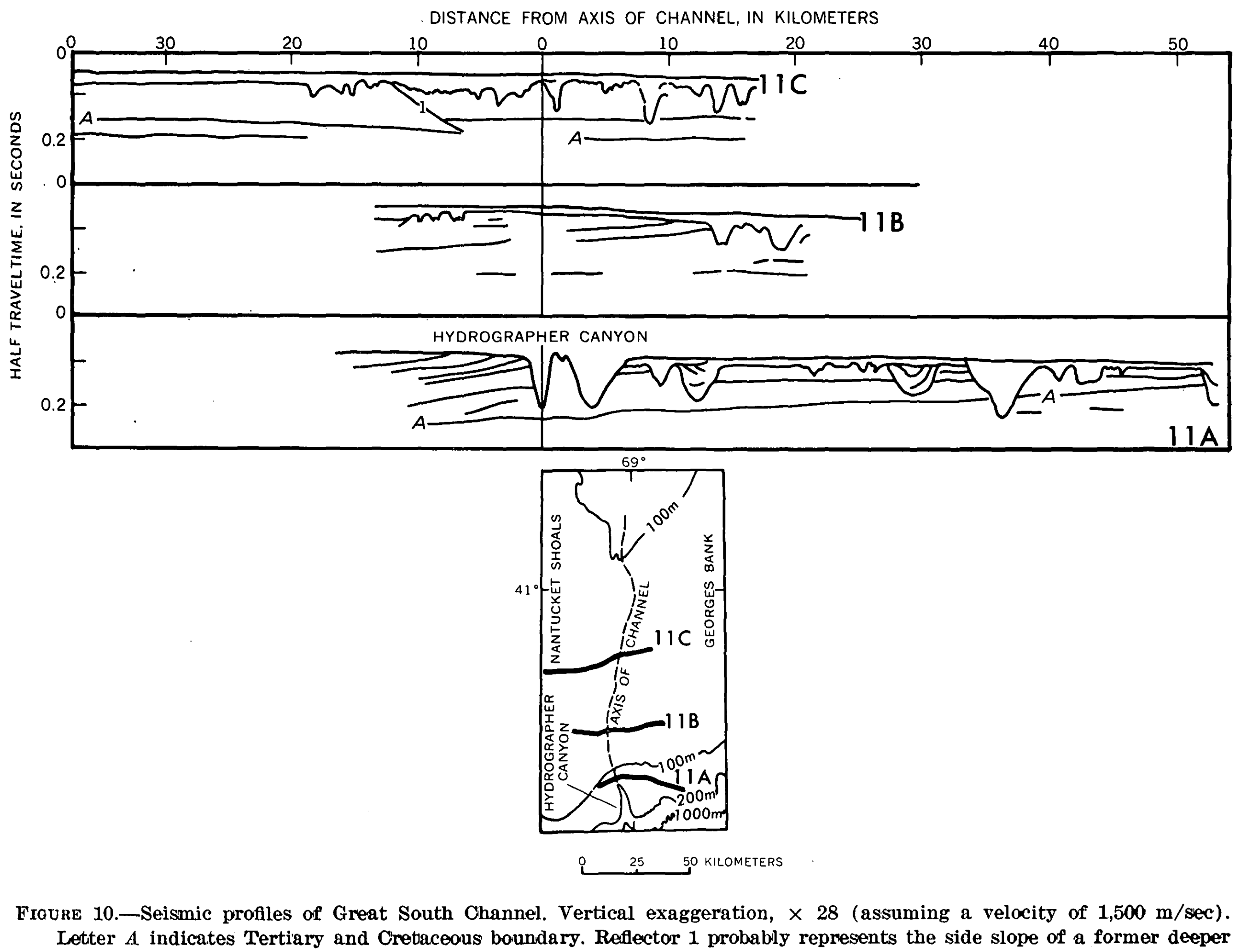


FIGURE 10.—Seismic profiles of Great South Channel. Vertical exaggeration, × 28 (assuming a velocity of 1,500 m/sec). Letter *A* indicates Tertiary and Cretaceous boundary. Reflector 1 probably represents the side slope of a former deeper channel.

ary age. These sedimentary deposits extend beneath Georges Bank to the southern slope (continental slope) of the bank. To the north they are truncated by the in-face slope of the bank and are blanketed by a thin veneer of sediment, presumably derived from the top of the bank. Seismic profiles across this northern slope (fig. 5) clearly show that it is erosional in origin. Profile 37 (fig. 5), parallel to the slope, and profile 48 (figs. 5 and 9), at right angles to it, show some indication of folding. These rocks are probably Triassic, as on seismic-profiler recordings they resemble known Triassic rocks in the Bay of Fundy. By using higher resolution equipment, Knott and Hoskins (1968) found several buried channels on the northern slope of the bank that appear to drain into the Gulf of Maine from Georges Bank. The axes of the channels can be traced to depths exceeding 350 m. As this depth is greater than the maximum lowering of sea level during the Pleistocene (Donn and others, 1962), Knott and Hoskins (1968) suggested that the channels were probably formed by a combination of subaerial and submarine processes.

In profile 8 (fig. 11) across Georges Bank, at least two erosional surfaces can be recognized. By using higher resolution equipment, Knott and Hoskins (1968) were able to distinguish five erosional surfaces atop the bank. Each surface onlaps the one immediately beneath it, and the surfaces pinch out progressively farther south. Sediments within this depositional sequence appear to be disturbed along the northern edge of the bank, probably by ice that overrode the bank's northern edge. Each erosional surface is characterized by well-developed channels that were first cut and then filled; later channels were then cut and filled above them. The recordings taken by Knott and Hoskins (1968) suggest an upbuilding of the bank during the Pleistocene of more than 70 m (assuming a sediment velocity of 1,800 m/sec.). As this upbuilding requires more sediment than could be derived from the bank itself, Knott and Hoskins suggested that the sediment was transported to the bank from the Gulf of Maine, presumably by ice. This would imply that the Gulf of Maine was covered by ice five times. Melt-water runoff from the ice supposedly cut the channels and deposited the sediments as a terminal moraine and outwash plain. Later, as the ice retreated and sea level rose, the channels were filled. Sediments deposited during the last ice advance are represented by the sand shoals and ridges near the crest of Georges Bank and in Nantucket Shoals (fig. 12). These sediments were reworked into their present form by wave action during the last transgression and by tidal currents since then. Tertiary vertebrate and invertebrate fossils, which are rather common within these sediments, probably were reworked from the Tertiary strata exposed along the northern slope of the bank and were transported to their present site by ice.

Reflectors beneath Georges Bank increase in dip as they approach the southern slope of the bank (the continental slope). Although they have undergone considerable erosion, most of the reflecting horizons can be traced to the base of the slope. Erosion on the upper part of the slope was probably due to melt water from glaciers that overrode the northern edge of Georges Bank. Turbidity currents initiated by the melt waters extended the erosion to the continental rise. Profiles 53, 55, and 56 (fig. 3) show that turbidity-current deposits have buried the lower segment of the slope. Rock samples dredged from canyons (Stetson, 1949; Gibson and others, 1968) shown on either side of profile 50 have been projected onto that profile (fig. 3). As suggested by the distribution of these rock samples, the sedimentary sequence shown by the recordings probably represents the entire Tertiary, and the deepest reflector, marked "*A*" (figs. 3, 11), is probably the top of the Upper Cretaceous.

LONG ISLAND, BLOCK ISLAND, RHODE ISLAND, AND VINEYARD SOUNDS, AND BUZZARDS BAY

Profiles across Long Island Sound and the other sounds off the southern New England coast and Buzzards Bay show a strong reflecting horizon 16–200 m (assuming a sediment velocity of 1,800 m/sec) below sea

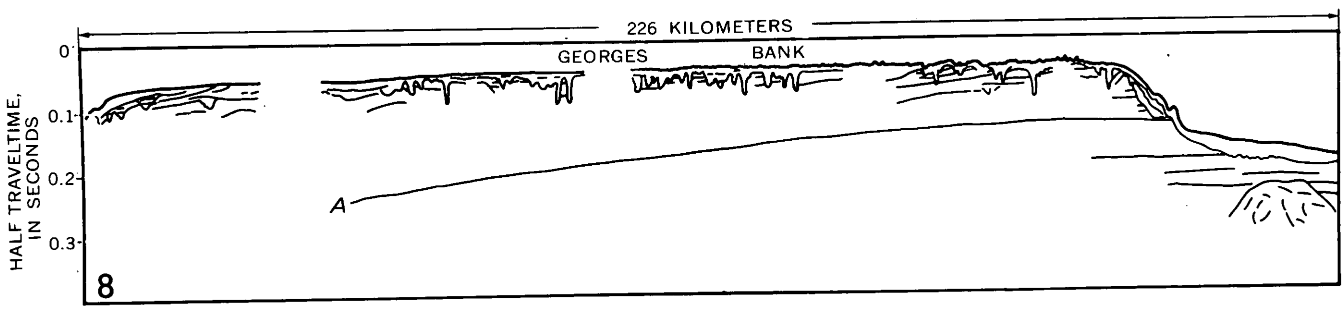


FIGURE 11.—Seismic profile across Georges Bank from the Gulf of Maine (on the right) to the continental slope (on the left). Reflector *A* is probably at or near the Tertiary and Cretaceous boundary. Two erosional surfaces can be recognized in this profile. Vertical exaggeration, × 80 (assuming a velocity of 1,500 m/sec).

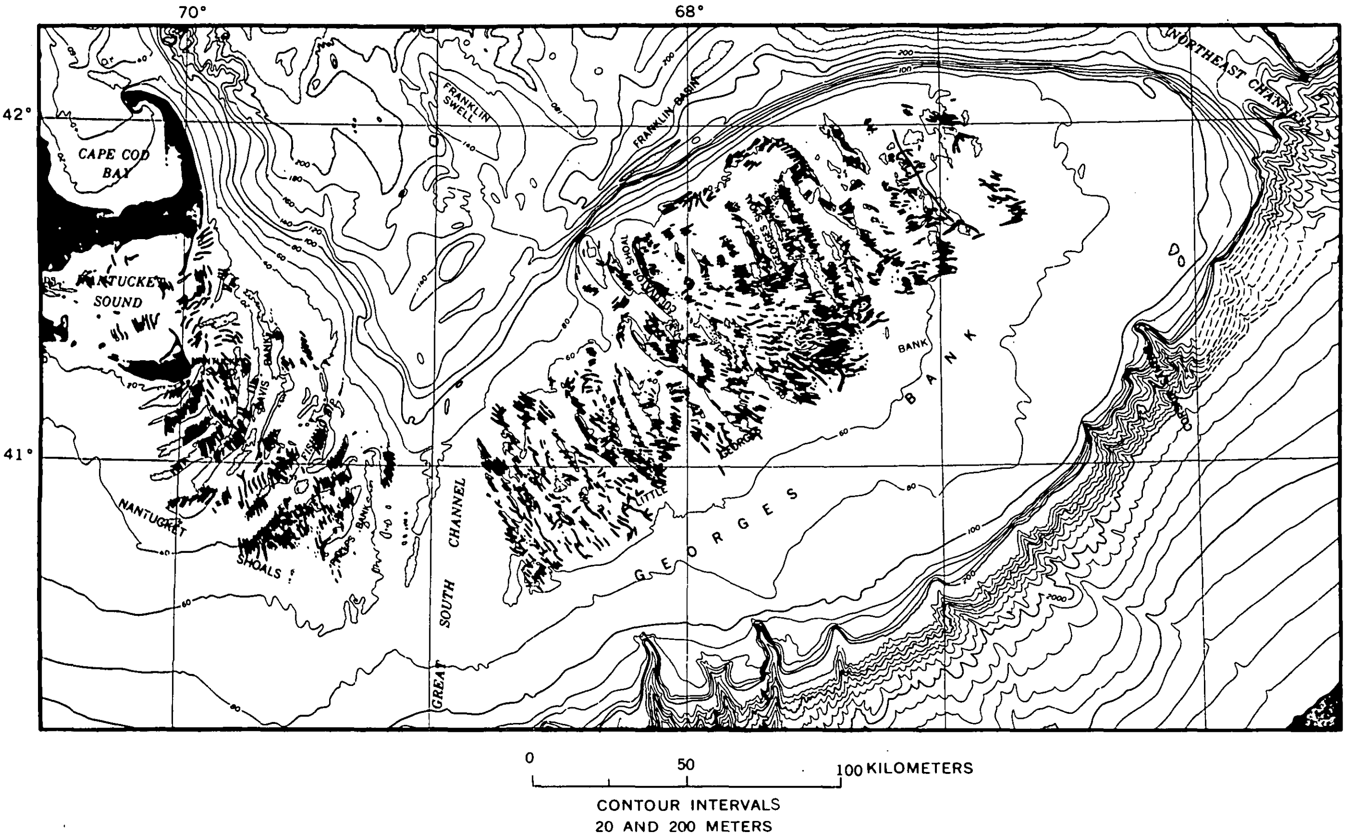


FIGURE 12.—Sand ridges and shoals on Georges Bank and Nantucket Shoals. This dunelike topography is believed to have been formed from sediments deposited by ice and reworked to their present form by wave and tidal currents. Based on soundings from the U.S. Coast and Geodetic Survey hydrographic surveys. Depth contours in meters.

level (fig. 13). Outcrops alongshore and seismic-refraction data from Long Island Sound (Oliver and Drake, 1951) suggest that this reflector delineates the top of the Paleozoic. On most of the profiles, discontinuities above the strong reflector are weak or absent. No indication of Tertiary or Cretaceous sediments was found throughout most of the sounds or Buzzards Bay. Except for the deep channel southeast of Narragansett Bay, the pre-Triassic rocks have very little relief. The channels along profile 165 (fig. 13) may be the seaward extensions of the channels described by J.B. Hersey, A. H. Nalwalk, and D. R. Fink (written commun., 1961) at the entrance to Narragansett Bay. The greatest relief shown by the pre-Triassic rocks is in the western end of Long Island Sound where U-shaped troughs are more than 100 m deep. In a more detailed survey of this segment of the sound by Smith (1963), the troughs appear to have closure to the south. These troughs are believed to be due in part to glacial erosion, probably along preglacial fluvial valleys.

Near the southwestern margin of Vineyard Sound and between Long Island and Block Island, the seismic profiles show the inface slope of a cuesta buried by shelf sediments. This slope can be traced from the New York shore to the shelf off Nova Scotia (figs. 14, 15). The lowlands (the sounds, Gulf of Maine, and the Scotian Shelf basins) and the cuesta (Long Island, Block Island, Martha's Vineyard, Georges Bank, and the banks on the Scotian Shelf) were carved out of the shelf strata by fluvial erosion. McMaster, Lachance, and Garrison (1968) came to the same conclusion in a more detailed survey of Block Island and Rhode Island Sounds. After the formation of the lowland and cuesta, the area was glaciated and the lowland widened and deepened. Deposition of glacial sediments and compression by ice pressure (Kaye, 1964) thrust some segments of the cuesta above sea level to form the islands.

CONTINENTAL SHELF FROM CAPE COD TO VIRGINIA

Compared with the shelf east of Cape Cod, the shelf from Georges Bank to Chesapeake Bay is relatively smooth. As shown on plate 1, however, this section of the shelf is far from being a smooth plain. Along the shelf-break are four well-developed terraces having their seaward edges at depths of 60, 80, 120, and 140 m. Four channels incise the shelf's surface, a poorly developed channel off Chesapeake Bay and better

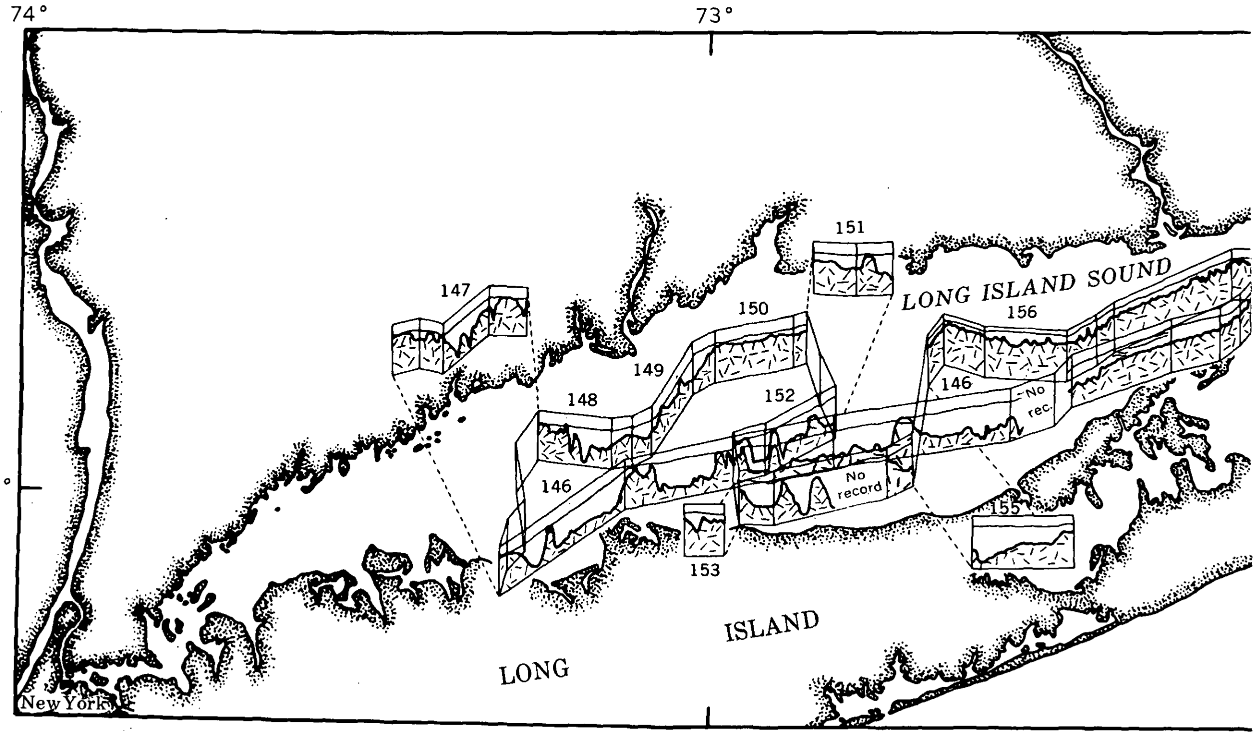


FIGURE 13.—Seismic profiles of Long Island Sound and other sounds off New England and Buzzards Bay showing a strong reflecting horizon 16–200 m below sea level (modified from Tagg and Uchupi, 1967, fig. 1). Vertical exaggeration, × 24 (assuming a velocity of 1,500 m/sec).

formed ones off Delaware Bay, Hudson River, and Block Island. The channels off Delaware and Chesapeake Bay only extend to the center of the shelf, but the other two can be traced to the shelf-break. Along the banks of Hudson Channel (the name given by Veatch and Smith (1939, p. 14) to the channel off the Hudson River) and the channels farther south are other terraces. Schlee (1964) found that the 60-m terrace along Hudson Channel is capped by gravel that he believes was deposited as an alluvial apron by the Hudson River during a lower stand of sea level. Between the channel areas are ridges that trend at an oblique angle to the present shoreline, and that are separated by elongate depressions. These features may represent offshore bars and lagoons formed during the last transgression during the Holocene. The lagoonlike features south of Long Island are open to the east and indicate that littoral drift at that time was to the east. Seismic profiles from the shelf seem to substantiate this interpretation, as they show progradation toward the east. At present, littoral drift along the south shore of Long Island is to the west (Taney, 1961, p. 27, 44).

Seaward of Hudson Channel and Block Channel (the name given by Garrison and McMaster (1966) to the channel south of Block Island) are two prominent deltas. The one at the mouth of Hudson Channel was named the Hudson Apron by Veatch and Smith (1939, p. 14), and the one off Block Channel was named the Block Delta by Garrison and McMaster (1966). During the Pleistocene, Hudson Channel was apparently the main stream that carried runoff from the New York-New Jersey region, and Block Channel served Cape Cod and Long Island Sound and other sounds north of Block Island.

Hudson Apron is the only one of the submerged deltas that has been surveyed in any detail with a seismic profiler (Knott and Hoskins, 1968; Ewing, and others, 1963). Knott and Hoskins (1968) found that Hudson Apron consists of five deltaic depositional sequences separated by prominent erosional surfaces. The outer edge of this depositional prism is cut by two terraces and is deeply entrenched by Hudson Canyon. The apron apparently was deposited by the Hudson River during a lower sea-level stand. Maximum thickness within the

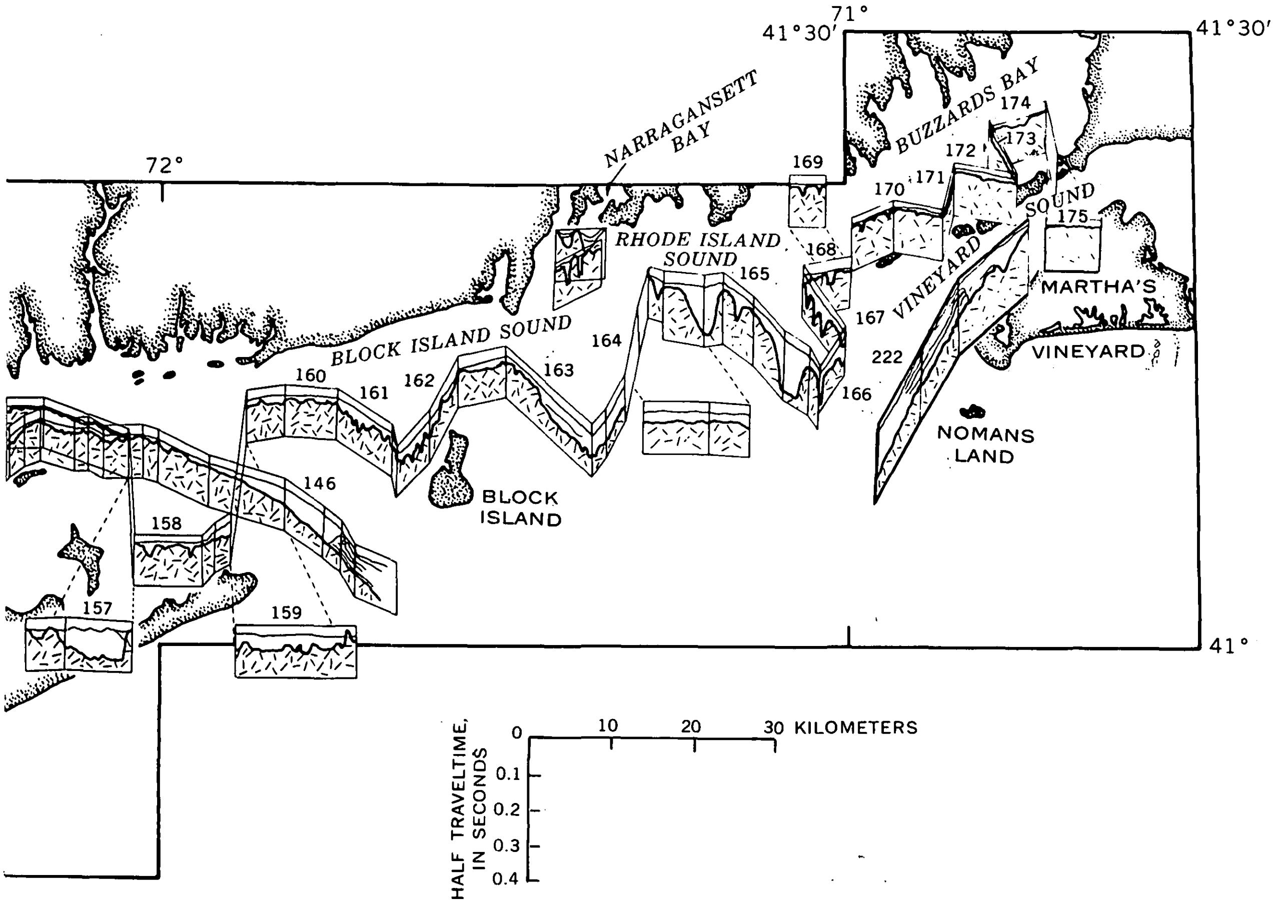


FIGURE 13.—Continued.

delta is near the present shelf-break and indicates an upbuilding of about 70 m.

Seismic profiles from the shelf south of Martha's Vineyard (figs. 16, 17) indicate that the shelf strata are folded and thrust faulted, probably as a result of ice pressure. The front of this disturbed zone is lobate and can be followed as far west as long 71°30′. Approximately 20 km south of the folded sediments is a bermlike ridge that may be a moraine. Both features probably mark the southern extension of glaciation on the shelf.

CONTINENTAL SLOPE FROM GEORGES BANK TO CAPE HATTERAS

Profiles across the outer edge of the shelf and continental slope between Georges Bank and New Jersey show structures intermediate in character between those off Nova Scotia and those off Georges Bank (fig. 18). Along profile 58, the shallow reflectors mantle a strong reflecting horizon that appears to crop out near the base of the continental slope. Strata on the upper slope are truncated and covered by a thin veneer of sediment. A similar structure was found farther east along profile 2. A complex structure of cut and fill is shown by profile 60 on the shelf, but the deeper reflectors are continuous from the outer shelf to the base of the continental slope.

Profile 1, in the center of a broad reentrant between Block and Atlantis Canyons (pl. 1), shows several interesting features. Within the reentrant itself, no reflecting horizons were found. This structureless zone is flanked on the landward side by a reflector that is at a high angle to the shelf's surface. Layers on the upper slope are slightly crenulated, as though they have slid in a seaward direction. At the base of the slope are two rectangular blocks which probably slumped from farther up the slope. A detailed survey of this area of the slope (Uchupi, 1967a) revealed considerable evidence of massive slumping. With the exception of some slight folding, strata within each slump block are hardly disturbed (figs. 19, 20; for locations of profiles, see fig. 21). The surface of the slump mass itself is broken by swales and rectangular blocks representing one slump mass superimposed upon another. Sediments along the base of the slump mass show a high degree of distortion, which was probably caused during their displacement

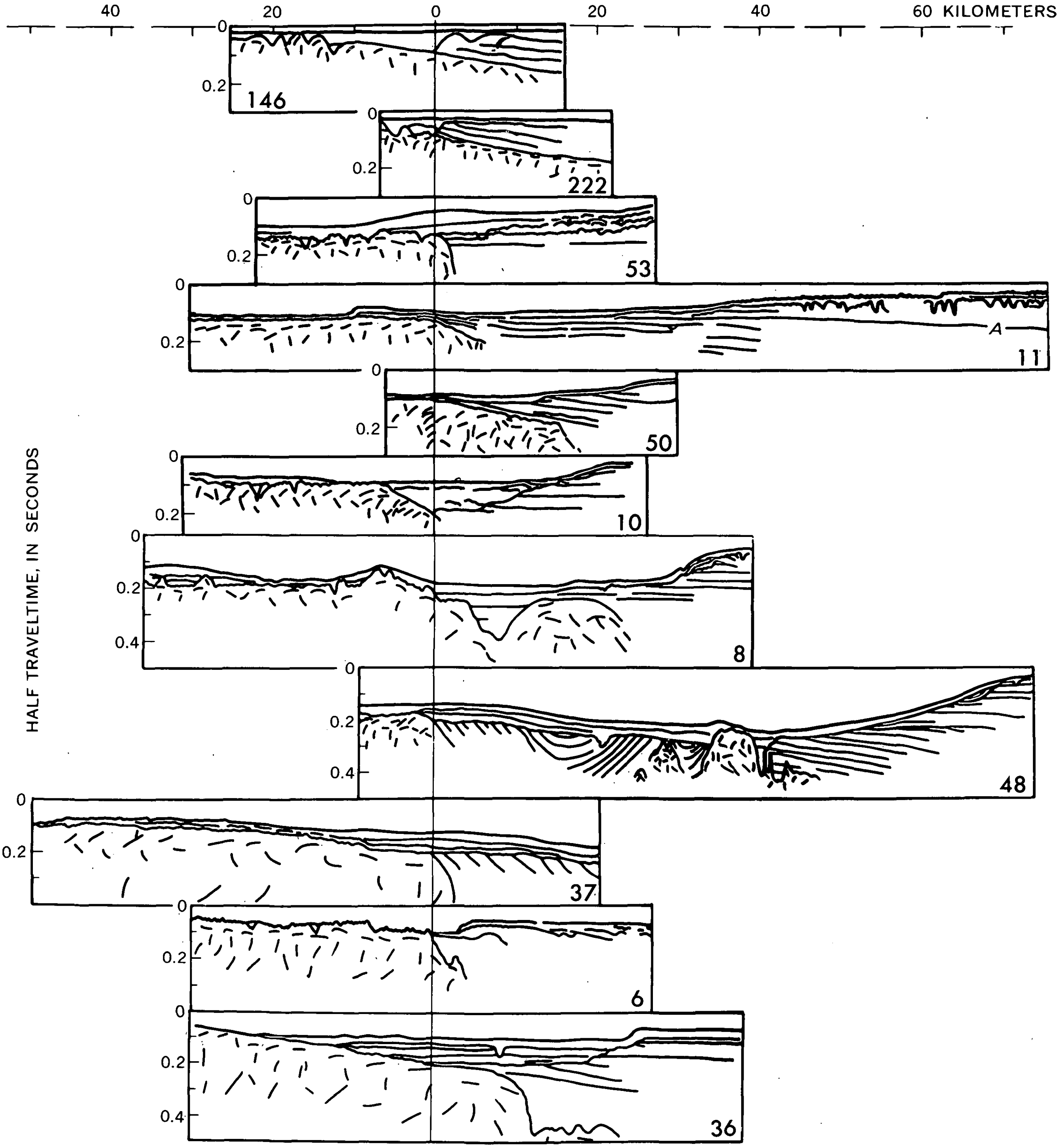


FIGURE 14.—Seismic profiles across the inface slope of the cuesta extending from New Jersey to the Scotian Shelf. Locations of profiles shown in figure 15. Right end of profiles is seaward. Vertical exaggeration, × 28 (assuming a velocity of 1,500 m/sec). Letter *A* indicates Tertiary and Cretaceous boundary.

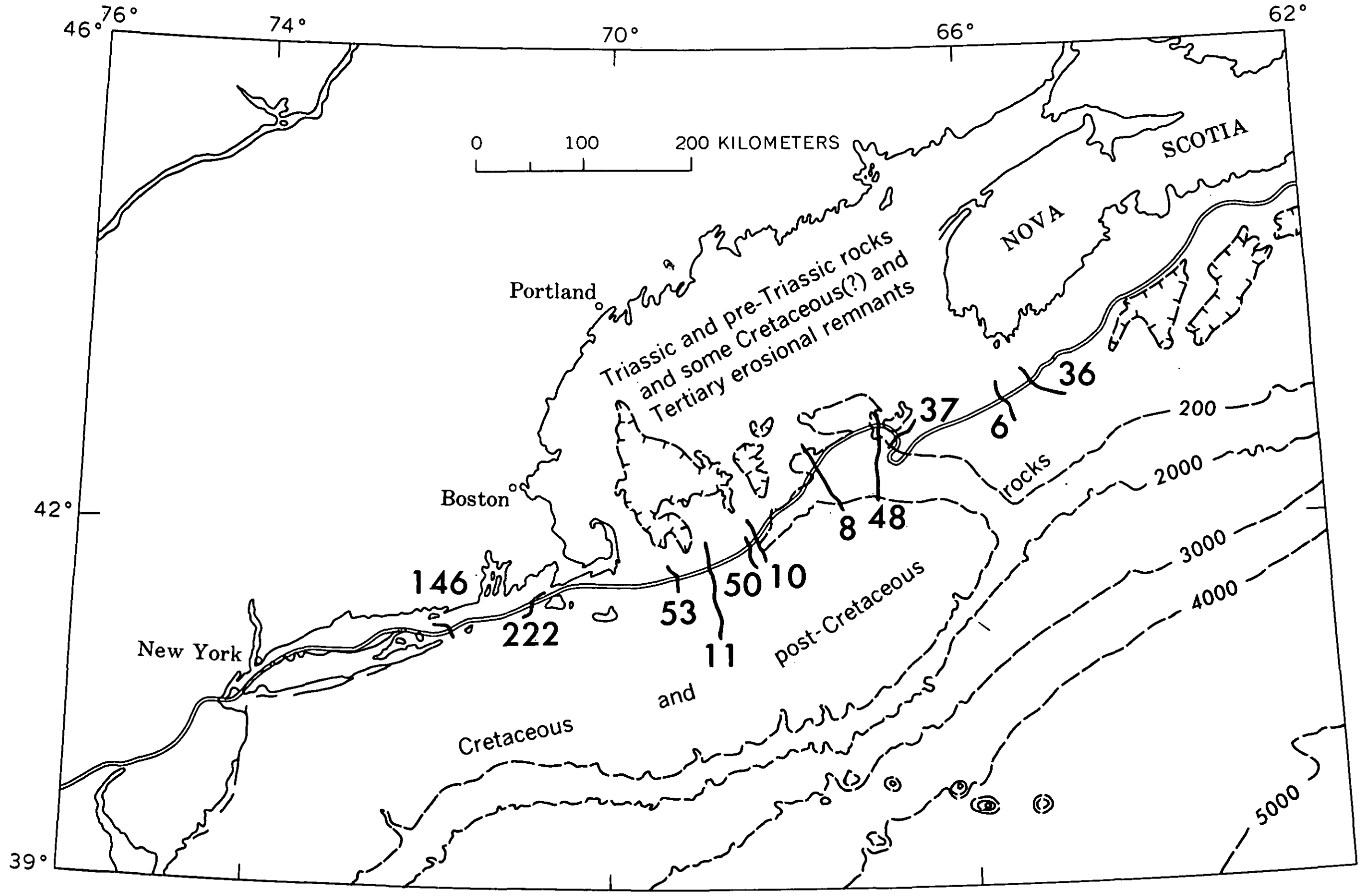
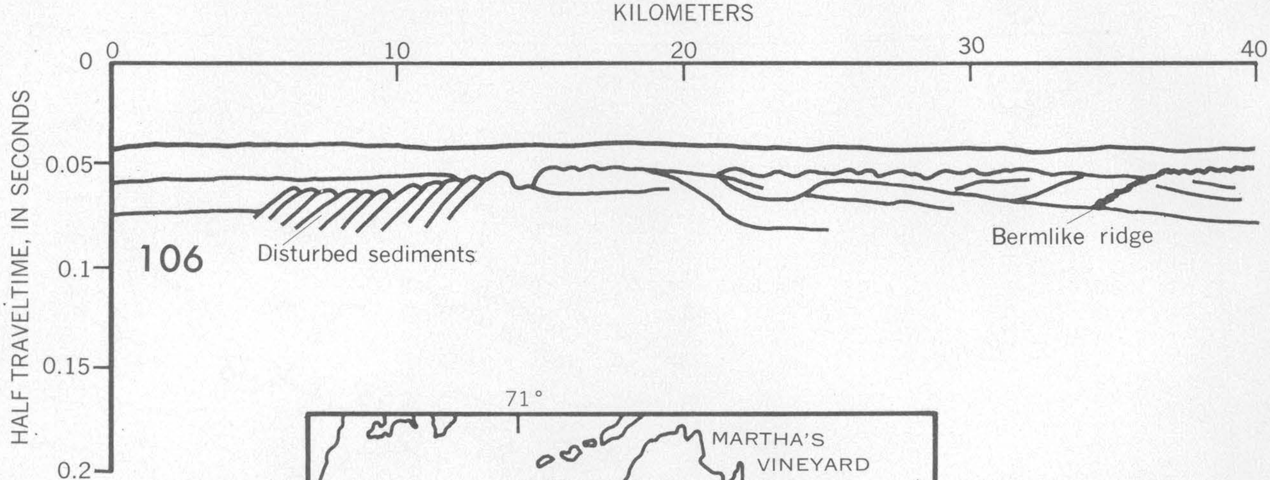


FIGURE 15.—Locations of the seismic profiles shown in figure 14. The double line is along the base of the inface cuesta. Dashed lines are depth contours in meters.

from the slope to the rise. Strata within the upper continental slope show evidence of folding due to sliding of the strata in a seaward direction. Uchupi (1967a) suggested that sediments from the lower slope were first displaced and thus the support was removed from the sediments farther up the slope and they also slid seaward. The reentrant between Block and Atlantis Canyons probably formed in this manner. The age of the slumping and sliding is probably Pleistocene. During the Pleistocene, the shoreline was near the present shelf-break, and deposition was directly on the slope. Such drastic increase in deposition probably triggered the downslope movements.

Structure of the continental slope along profile 63 (fig. 18) is much simpler than along the other profiles in this section of the slope. The layers are truncated by the shelf but can still be traced to the base of the slope. West of Hudson Canyon, a prominent reflector may extend from the inner edge of the shelf to the base of the continental slope (profile 65, fig. 18). Rock samples dredged from the Hudson Canyon area (Stetson, 1949; Gibson and others, 1968) suggest that the deepest reflector cropping out on the slope is at or near the Tertiary and Cretaceous boundary. Atop this horizon, the reflectors have a deltaic structure that indicates an upbuilding of about 1.4 km and a seaward progradation of more than 30 km.

The continental slope between New Jersey and Cape Hatteras, N.C., has more structural types than any other sector of the slope. Along profiles 113, 115, 126, and 130, the strata are truncated by the slope (figs. 22, 23). On profile 140 (fig. 23), on the other hand, most of of the reflectors can be traced to the base of the slope. Only the deeper horizons are truncated by the slope on profile 138; the shallower layers parallel the slope. The most complex structure in this sector of the slope is along profiles 118, 120, and 126. All three of the profiles show evidence of renewed deposition after truncation. During the renewed cycle of deposition, the sediments on the rise onlapped the slope in the manner suggested by Dietz (1963b). The cycle of deposition was followed by another erosional one that resulted in the present morphology of the slope.



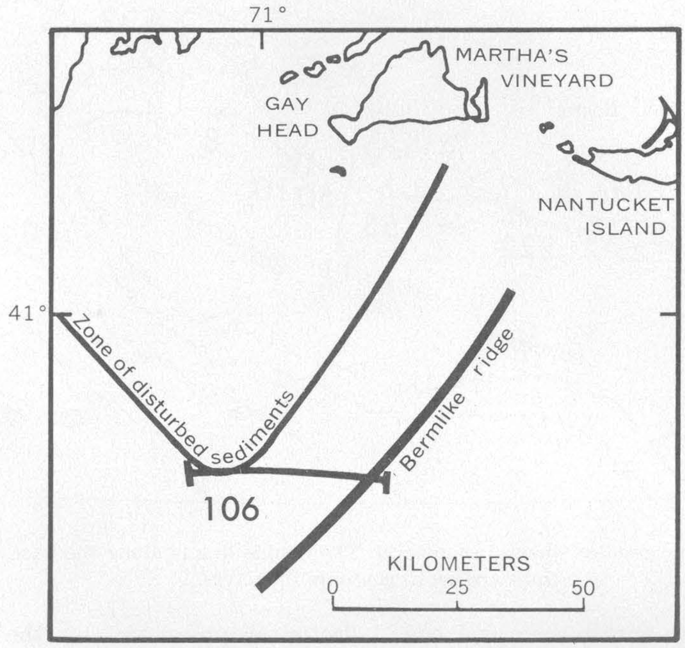


FIGURE 16.—Seismic profile across the zone of disturbed sediments and the bermlike ridge on the shelf south of Martha's Vineyard. Vertical exaggeration, × 28 (assuming a velocity of 1,500 m/sec).

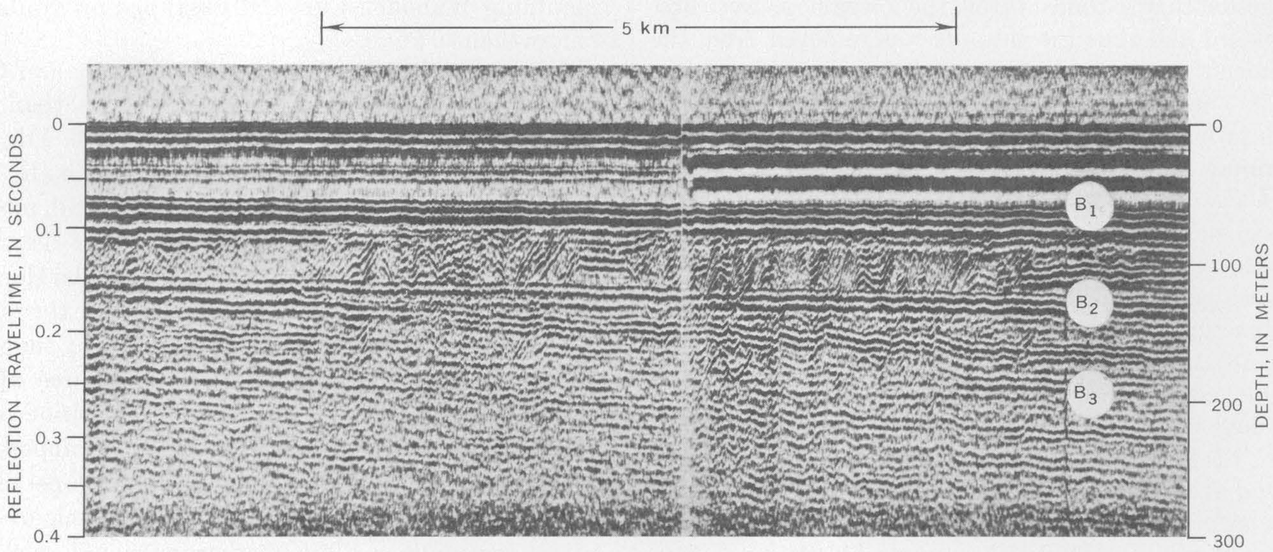


FIGURE 17.—Photograph of an actual recording across the zone of disturbed sediments south of Martha's Vineyard. Note that the layers between B_1 and B_2 are folded and faulted. These structures are believed to be the result of ice pressure (Knott and Hoskins, 1968, fig. 13). Vertical exaggeration, × 8 (assuming a velocity of 1,500 m/sec).

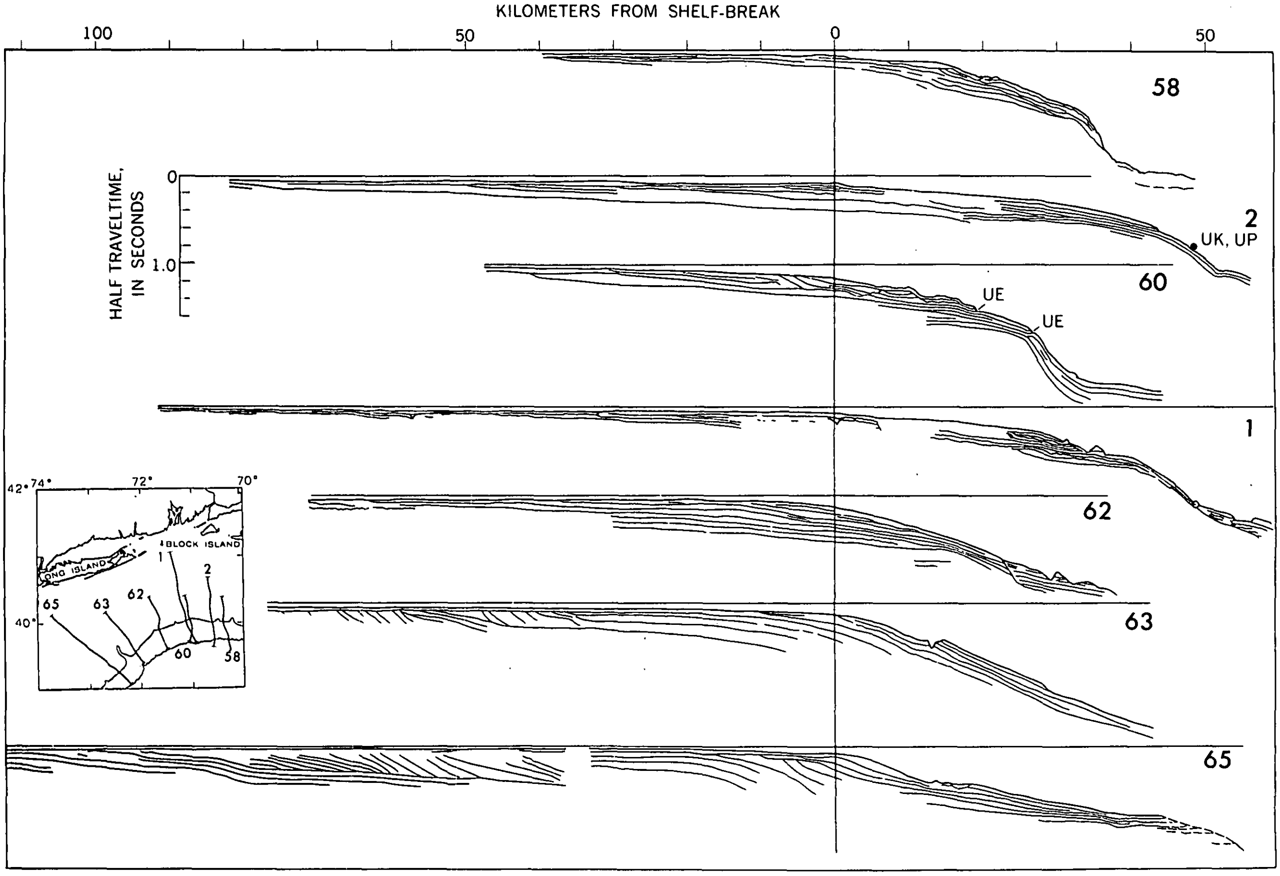


FIGURE 18.—Seismic profiles of the outer continental shelf and slope between Georges Bank and western Long Island (modified from Uchupi and Emery, 1967, fig. 3). The letters UK, UP, and UE show the positions of Upper Cretaceous, upper Paleocene, and upper Eocene sediments dredged by Stetson (1949), Northrop and Heezen (1951), and Gibson, Hazel, and Mello (1968). Vertical exaggeration, × 8 (assuming a velocity of 1,500 m/sec).

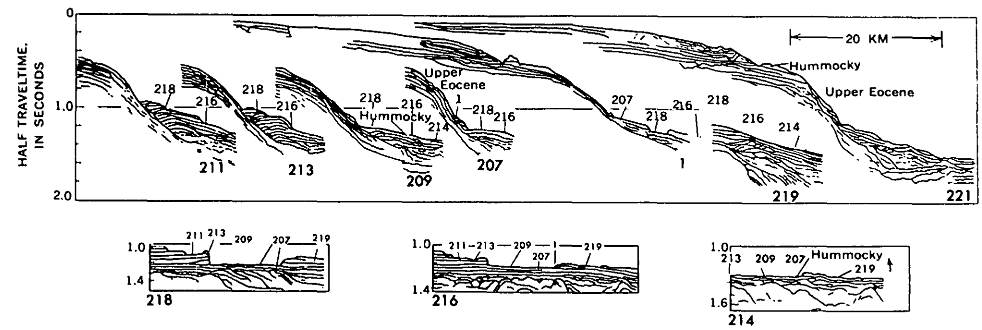


FIGURE 19.—Seismic profiles of the lower continental slope and rise between Block and Atlantis Canyons. Most of the structures present on the lower slope and upper rise are believed to be due to slumping. From Uchupi (1967a, fig. 3). For locations of profiles, see figure 21. Vertical exaggeration, × 8 (assuming a velocity of 1,500 m/sec).

CONTINENTAL SHELF FROM CAPE HATTERAS TO CAPE ROMAIN

Most of the profiles taken on the shelf show no evidence that strata are folded or faulted. In contrast, a profile (fig. 24) parallel to the shoreline north of Cape Romain, S.C., suggests that the strata on this section of the shelf are warped. Four structural highs can be recognized in this profile, one north of Cape Hatteras and three others off Capes Hatteras, Lookout, and Fear. Similar structures also occur off Georgia and in the Blake Plateau. Some of these structural ridges are probably seaward extensions of the ones described by Gibson (1967) from the Coastal Plain.

BLAKE PLATEAU AREA

Seismic profiles in figures 25–29 show the subsurface morphology of the outer shelf, Florida-Hatteras Slope,

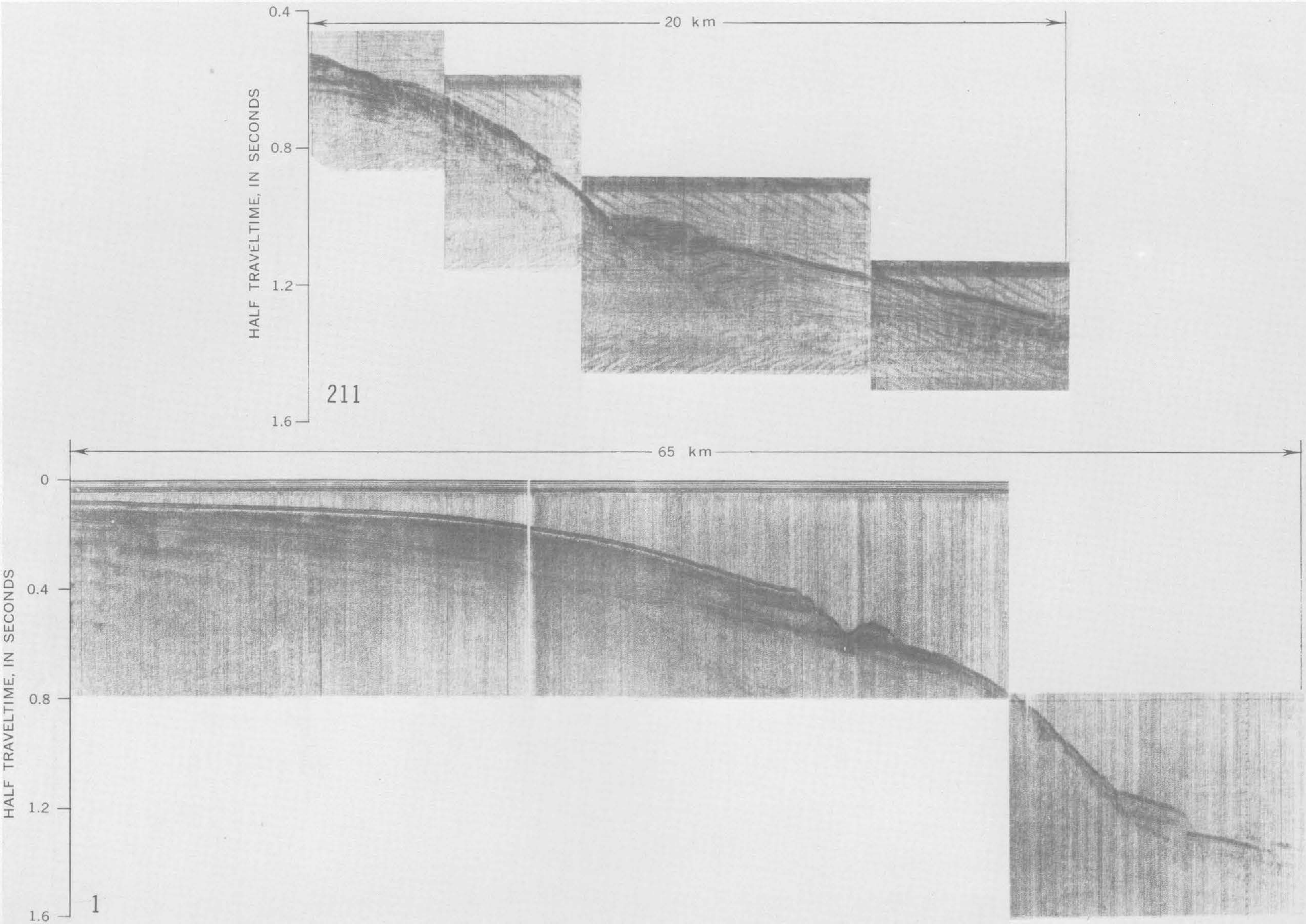


FIGURE 20.—Photographs of two actual seismic-reflection profiles. The sedimentary prism in the upper profile and the smaller blocks in the lower profile represent slump blocks displaced from farther up the slope. Locations of profiles shown in figure 21. Vertical exaggeration: profile 211, × 8; profile 1, × 10 (assuming a velocity of 1,500 m/sec).

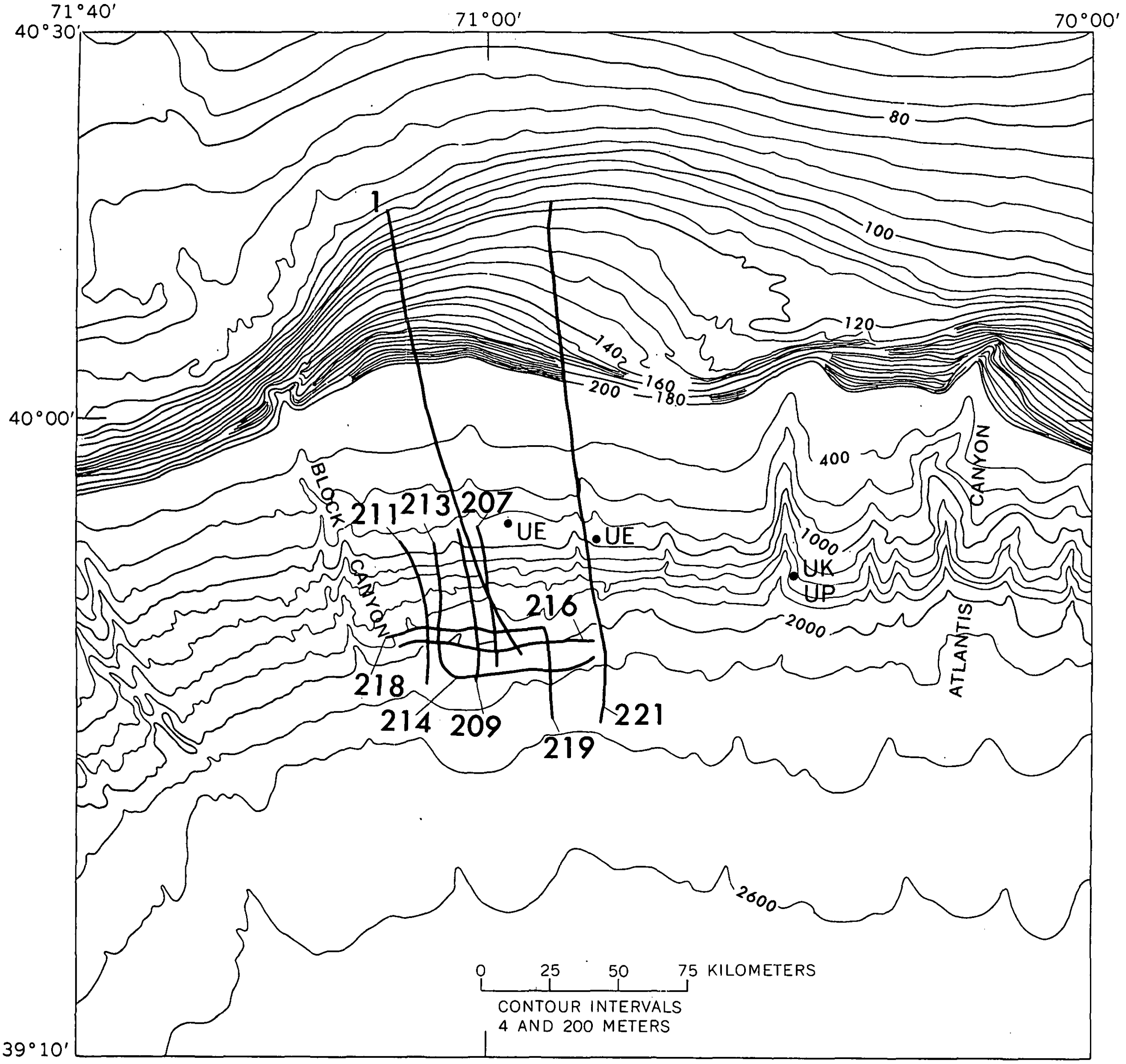


FIGURE 21.—Locations of seismic profiles shown in figures 19 and 20 (from Uchupi, 1967a, fig. 2). Letters UK, UP, and UE show positions of Upper Cretaceous, upper Paleocene, and upper Eocene sediments recovered from the continental slope by Stetson (1949), Northrop and Heezen (1951), and Gibson, Hazel, and Mello (1968).

and the Blake Plateau. Profiles 136, 134, and TW 8 (fig. 25) are in the transitional zone between the broad plateau to the south and the continental slope to the north. In all three profiles, the shallow layers have prograded the width of the plateau, a distance ranging from 20 km in profile 136 to more than 100 km in TW 8. In profiles 136 and 134, the deeper reflectors are truncated by the continental slope.

The structure along TW 9 (fig. 25) is more typical of the Blake Plateau area. Within the plateau itself, the strata dip gently seaward and are deeply eroded along the present surface of the plateau. This and other profiles clearly demonstrate that the surface irregularities on the plateau are erosional in origin. The erosional nature of the plateau's surface is best illustrated in figure 26*A*. This profile, taken with a high-resolution boomer, shows that the layers beneath the depression are continuous and that the upper layers are truncated by the side slopes. Along the margins of the depression are low conical banks formed by deep-water corals. These organic structures are found scattered throughout most of the plateau, but are especially concentrated beneath the Gulf Stream's axis. Similar structures, in different stages of burial are also shown on profiles 86,

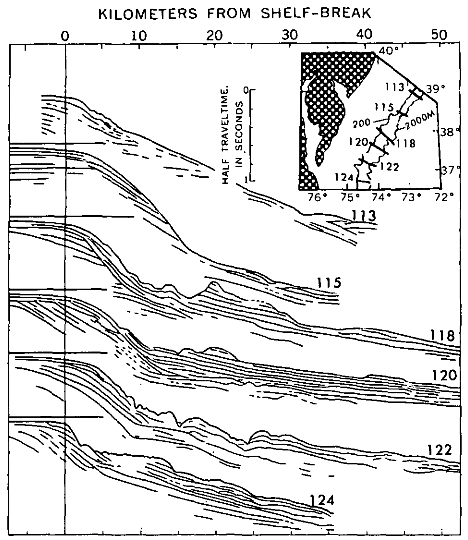


FIGURE 22.—Seismic profiles of the outer continental shelf, slope, and upper rise between New Jersey and Chesapeake Bay. From Uchupi and Emery (1967, fig. 4). Vertical exaggeration, × 8 (assuming a velocity of 1,500 m/sec).

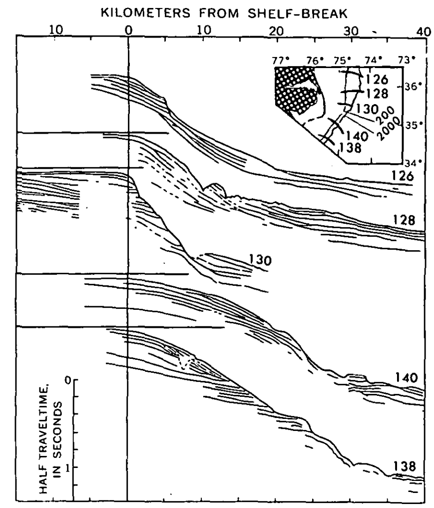


FIGURE 23.—Seismic profiles between Chesapeake Bay and Cape Lookout. From Uchupi and Emery (1967, fig. 5). Vertical exaggeration, × 8 (assuming a velocity of 1,500 m/sec).

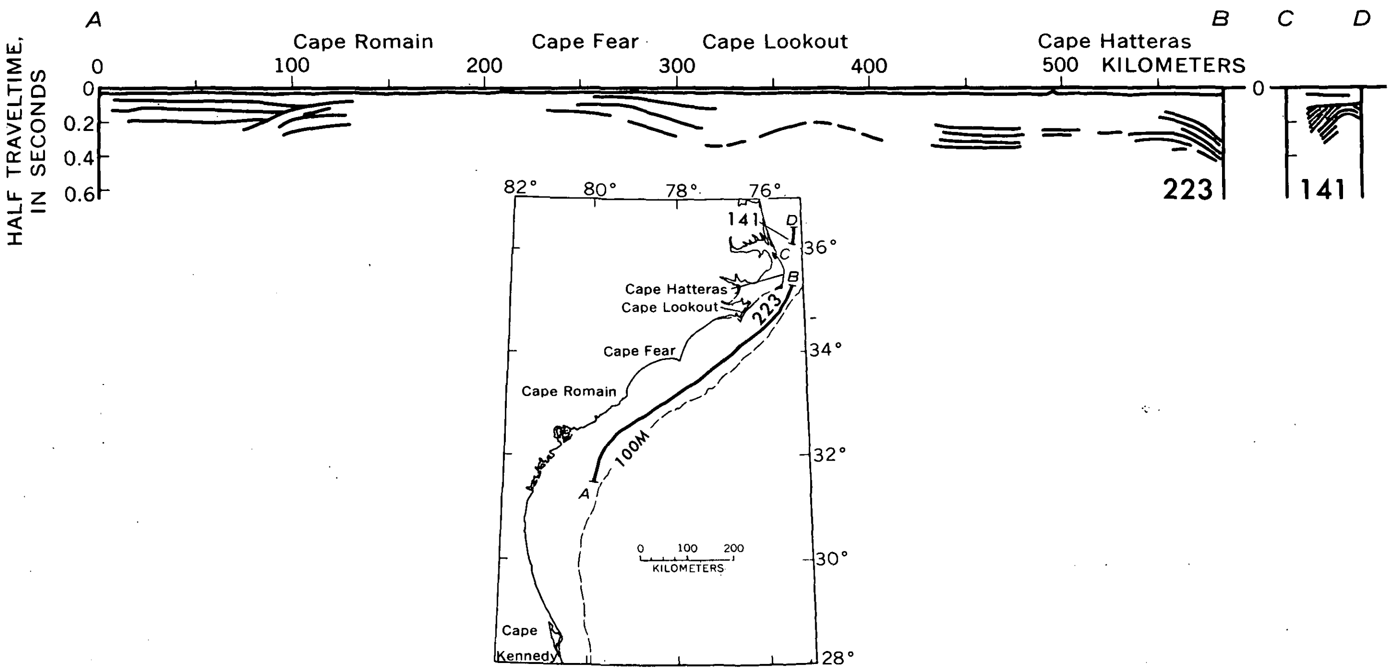


FIGURE 24.—Seismic profile parallel to shore from Norfolk, Va., to Cape Romain, S.C. Vertical exaggeration, × 50 (assuming a velocity of 1,500 m/sec).

84, and 224 (fig. 28). A systematic survey of Florida-Hatteras Slope by Zarudzki and Uchupi (1968) indicated that these deep-water coral banks may also be present beneath the Florida-Hatteras Slope. The banks beneath the slope form a ridge about 30 km long and suggest that, in part, the Florida-Hatteras Slope was formed by carbonate accretion (fig. 27).

Deep hollows similar to those present on the Blake Plateau beneath the axis of the Gulf Stream also occur beneath the Florida-Hatteras Slope (fig. 27; fig. 28, profiles 94 and 92). Pratt (1966) and Pratt and Heezen (1964) have suggested that the depressions on the plateau were formed by erosion by the Gulf Stream. Uchupi and Emery (1967) and Uchupi (1967b) extended

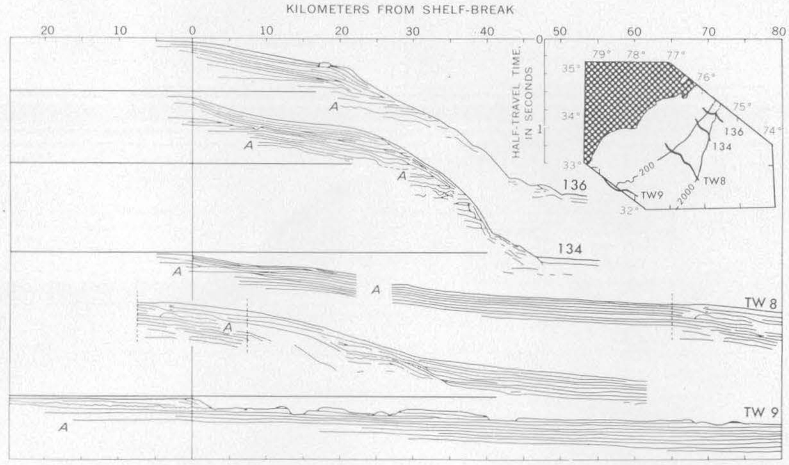


FIGURE 25.—Profiles of the shelf, Blake Plateau, and continental slope between Cape Lookout and Cape Fear. From Uchupi and Emery (1967, fig. 6). Vertical exaggeration, × 8 (assuming a velocity of 1,500 m/sec). The letter *A* indicates Tertiary and Cretaceous boundary.

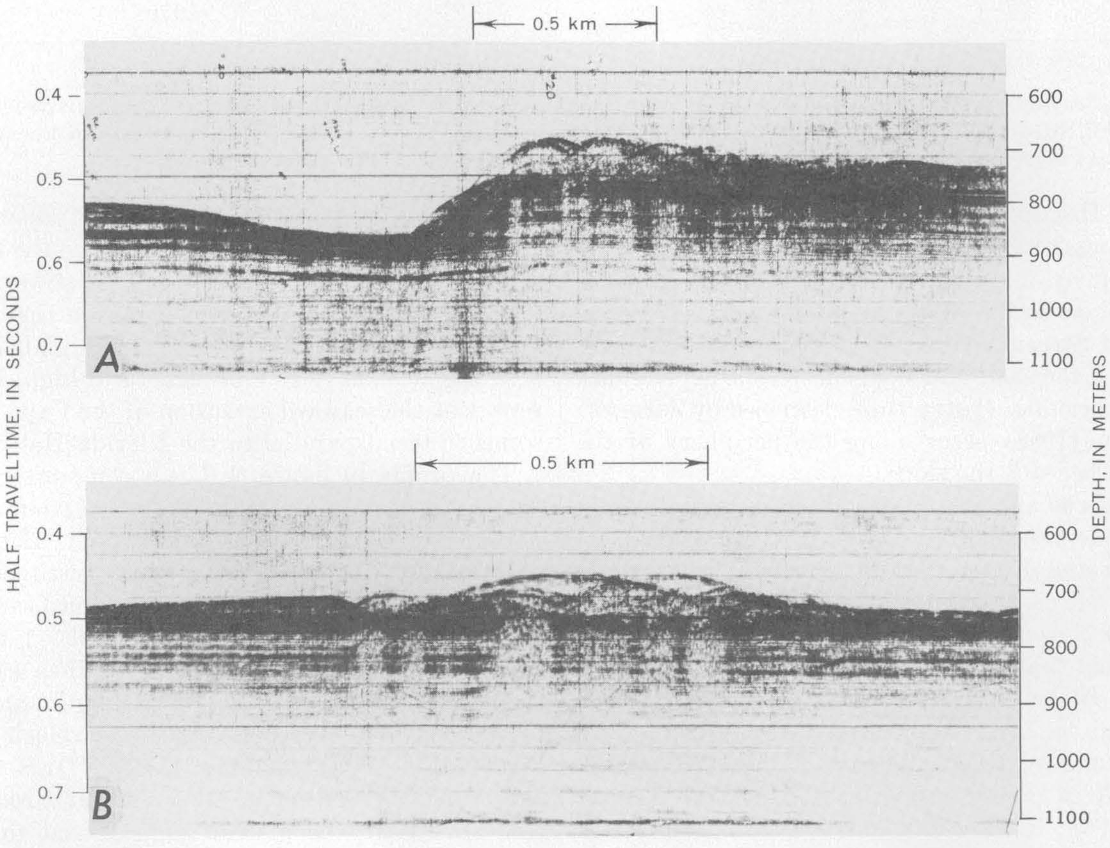


FIGURE 26.—Seismic-reflection profiles across one of the depressions on the Blake Plateau (*A*, lat 31°50′ N.; long 77°30′ W.) and a coral bank (*B*, lat 31°48′ N.; long 77°44′ W.). Photograph, courtesy of T. R. Stetson, Woods Hole Oceanographic Institution. Vertical exaggeration, × 2 (assuming a velocity of 1,500 m/sec).

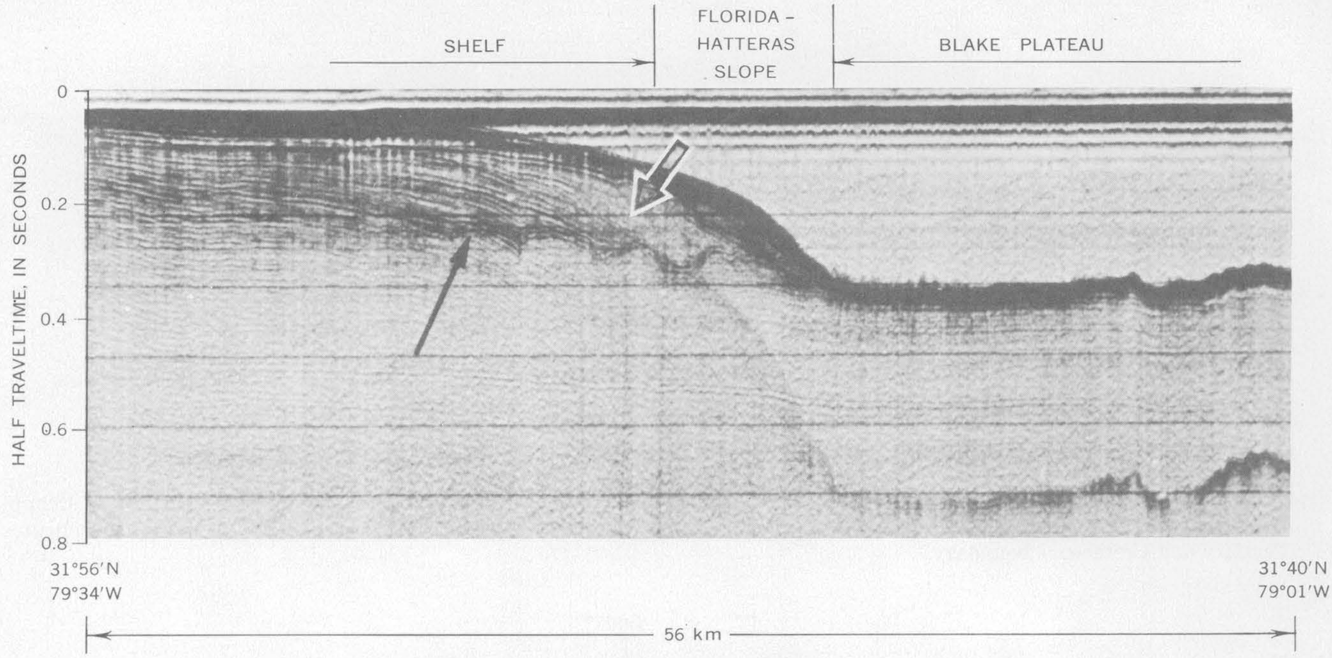


FIGURE 27.—Seismic profile across the Florida-Hatteras Slope showing the buried erosion surface (solid arrow) eroded by the Gulf Stream and the presumed coral bank (open arrow) on the erosion surface. From Zarudzki and Uchupi (1968). Vertical exaggeration, × 25 (assuming a velocity of 1,500 m/sec).

Pratt's and Heezen's suggestion to account for the origin of the depressions beneath the slope. They suggested that erosion by the Gulf Stream forced the Florida-Hatteras Slope to the west and cut the hollows. Later, as the Gulf Stream shifted its course to the east, progradation by the shelf and slope buried the depressions. The buried organic(?) structures described by Zarudzki and Uchupi (1968) occur along the periphery of the depressions beneath the slope.

On profiles 90 and 88 (fig. 28), there is no indication of renewed deposition after erosion of the Florida-Hatteras Slope and Blake Plateau. Farther south, along profiles 86, 84, 82, 81–80, deposition was continuous on the Florida-Hatteras Slope, and there is no indication of the erosion that took place farther north. Drill-hole data on the Blake Plateau and dredge and core samples (Joint Oceanog. Inst. Deep Earth Sampling Program, 1965; Ericson and others, 1961; J. D. Milliman, F. T. Manheim, R. M. Pratt, and E. F. K. Zarudzki, written commun., 1968; R. M. Pratt, oral commun., 1968) suggest that the irregular horizon in profile 81–80 above reflector *A* may mark the top of the Paleocene (Uchupi, 1967b). This reflector shows the same type of morphology as the present surface of the Blake Plateau. If erosion of this surface was also due to the Gulf Stream, it may indicate the time when the stream migrated to the Blake Plateau.

Profile 98 (figs. 29, 30) parallels the Florida-Hatteras Slope, crosses the pleateau's irregular surface between lats 31° and 32°, and extends to the transitional zone farther north. The shallow layers within the rough zone are so deeply eroded that Cretaceous strata have been exposed. There is also some suggestion that the layers are warped, the axis of the structural high being located near the 300–km tick. This structural high, which may represent the seaward extension of the Cape Fear arch, seems to trend parallel to the Florida-Hatteras Slope.

The profile in figure 30*B* is a composite of profiles 88 (this report) and profile Z1 (taken from a paper by Emery and Zarudzki, 1967). It extends along the line of JOIDES (Joint Oceanographic Institutions' Deep Earth Sampling Program) holes (Joint Oceanog. Inst. Deep Earth Sampling Program, 1965) 1 to 6, from there northwestward to hole 4, and then eastward to the base of the continental slope. In figure 31, this same profile has been corrected for sound velocity, and the stratigraphic units found in the JOIDES holes have been superimposed on it. Drill data and rock samples recovered from the plateau suggest that the reflector marked "A" (fig. 30) on this and other profiles in the area marks the top of the Cretaceous. On profile 88, the possible extension of this reflector beneath the shelf may be warped. This high may be structural in origin or may represent a carbonate ridge, as Emery (1967) reported that Eocene sediments in JOIDES hole 2 contain algal fragments.

On profile Z1 (fig. 30), the shallow strata above reflector *A* on the plateau are relatively thin and show

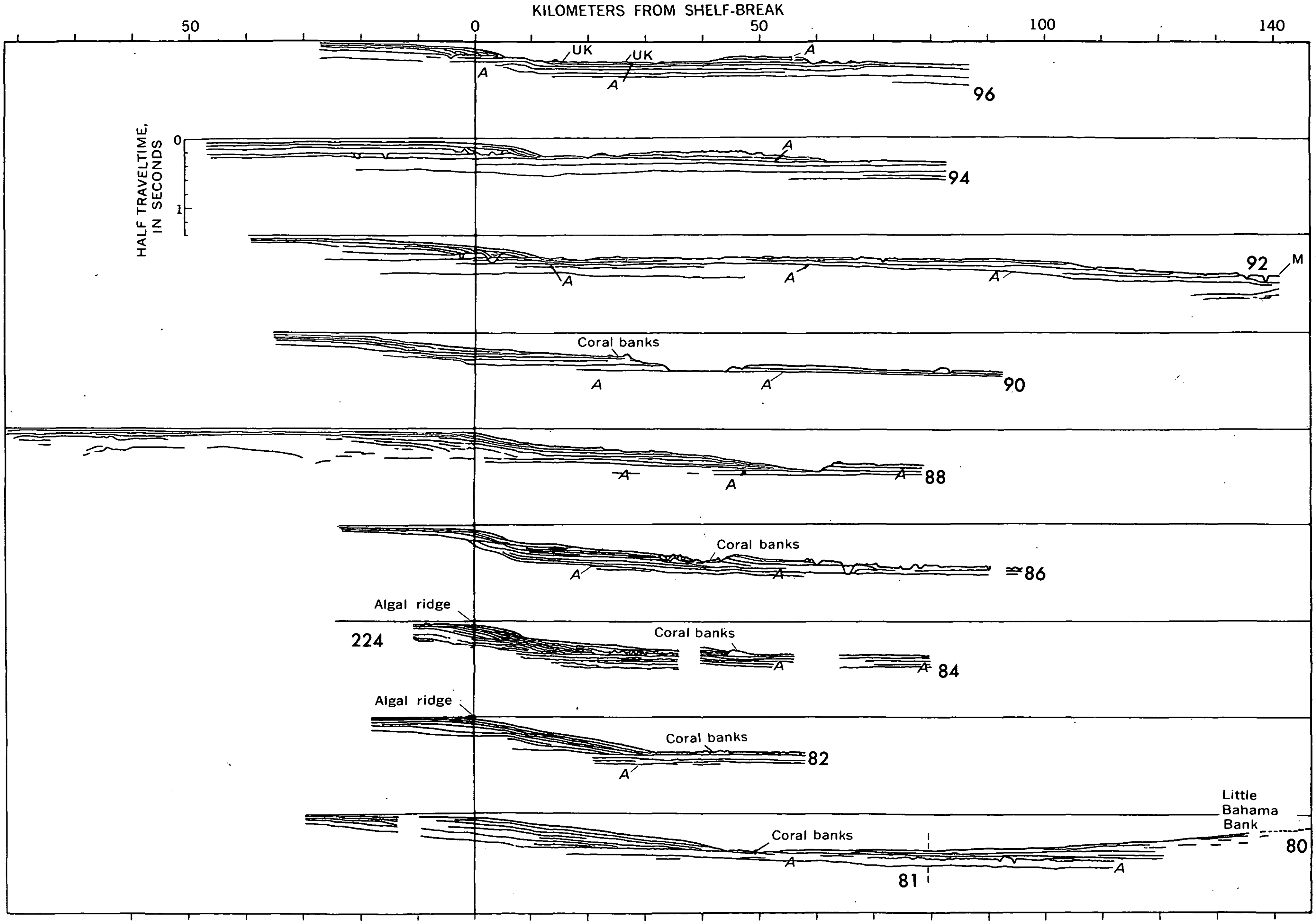


FIGURE 28.—Seismic profiles across the shelf, Florida-Hatteras Slope, and western margin of the Blake Plateau from Charleston to Cape Kennedy. Letters UK and M show positions of Upper Cretaceous and Miocene sediments dredged from the Blake Plateau (J. D. Milliman, F. T. Manheim, R. M. Pratt, and E. F. K. Zarudzki, written commun., 1968; R. M. Pratt, oral commun., 1968). Locations of profiles shown in figures 29. From Uchupi (1967b, fig. 6). Vertical exaggeration, × 8 (assuming a velocity of 1,500 m/sec). *A* indicates Tertiary and Cretaceous boundary.

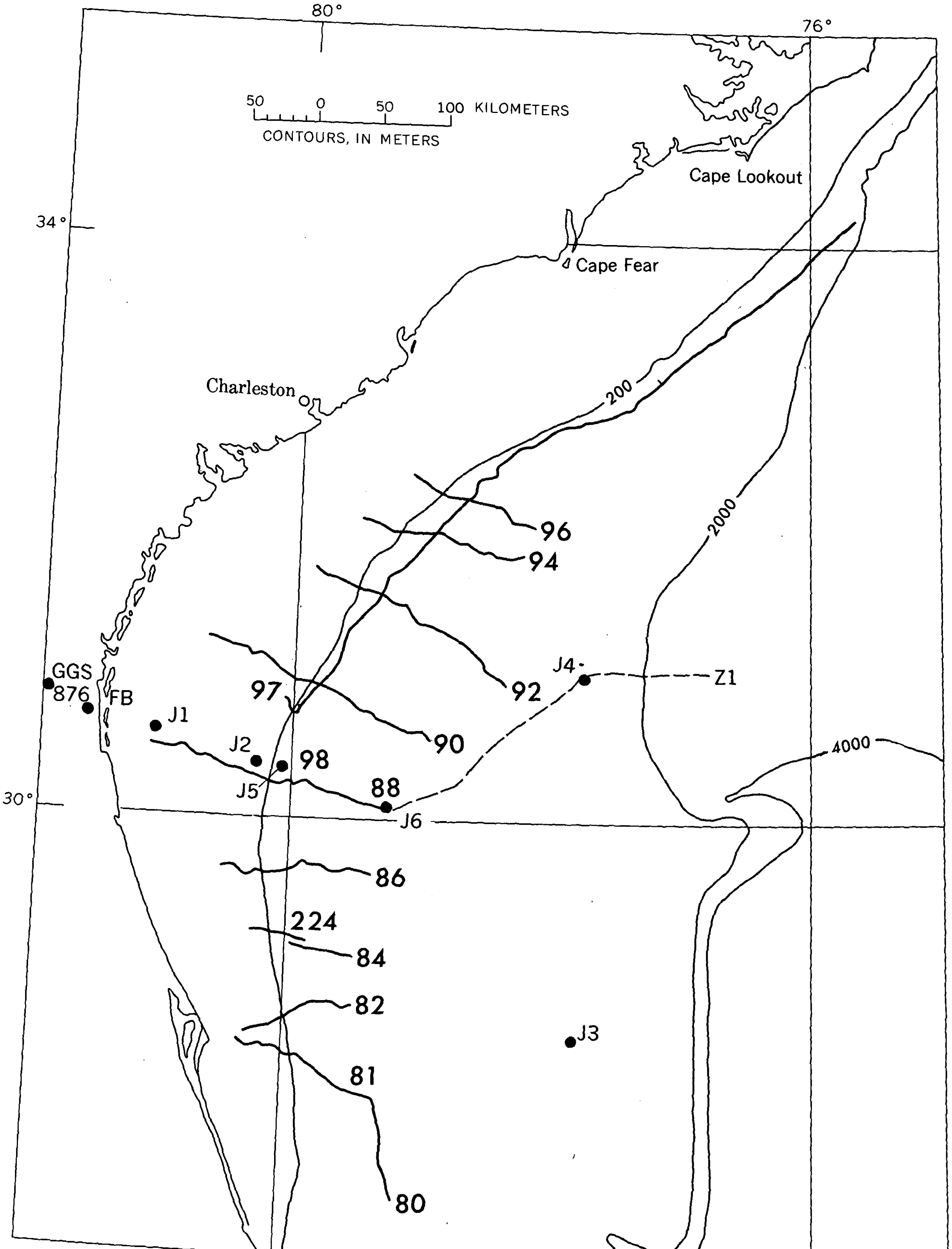


FIGURE 29.—Locations of seismic profiles shown in figures 28, 30, and 31. J1 to J6 are the JOIDES drill sites, and FB and GGS876 are wells on land. Line Z1 (dashed line) extends from drill site J1 to J4 and from there eastward across the continental slope.

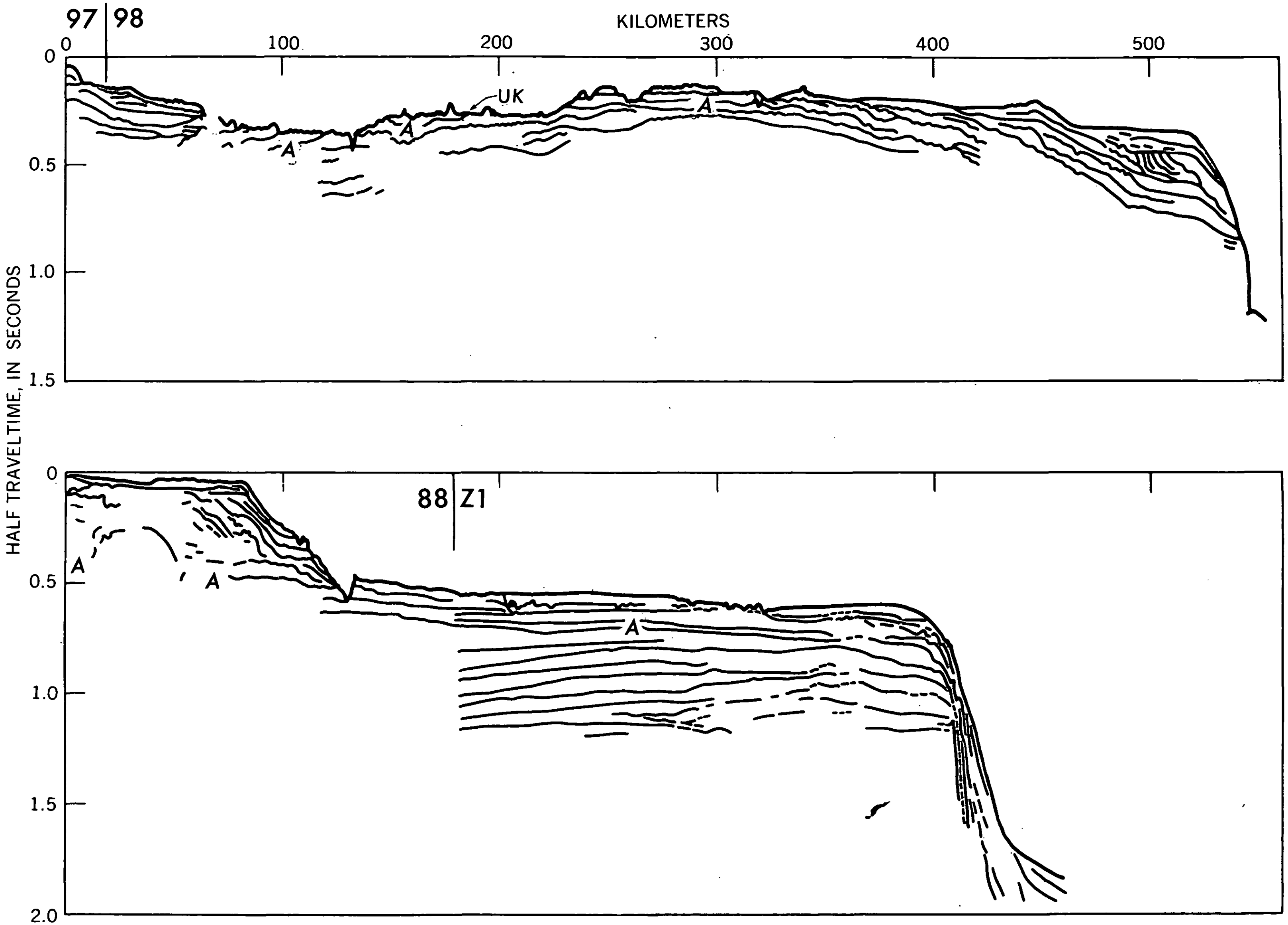


Figure 30.—Seismic profiles along the base of the Florida-Hatteras Slope and from JOIDES holes 1 to 6 and then northwest (to J4). Upper panel, from Uchupi (1967b, fig. 8) ; lower panel is a composite of profile 88 (this report) and profile Z1 (Emery and Zarudzki, 1967, fig. 3). Locations of profiles shown in figure 29. Vertical exaggeration, × 60 (assuming a velocity of 1,500 m/sec). The letters UK along profile 98 show position where Upper Cretaceous rocks were dredged from the Blake Plateau (J. P. Milliman, F. T. Manheim, R. M. Pratt, and E. F. K. Zarudzki, written commun., 1968; R. M. Pratt, oral commun., 1968.) *A* indicates Tertiary and Cretaceous boundary.

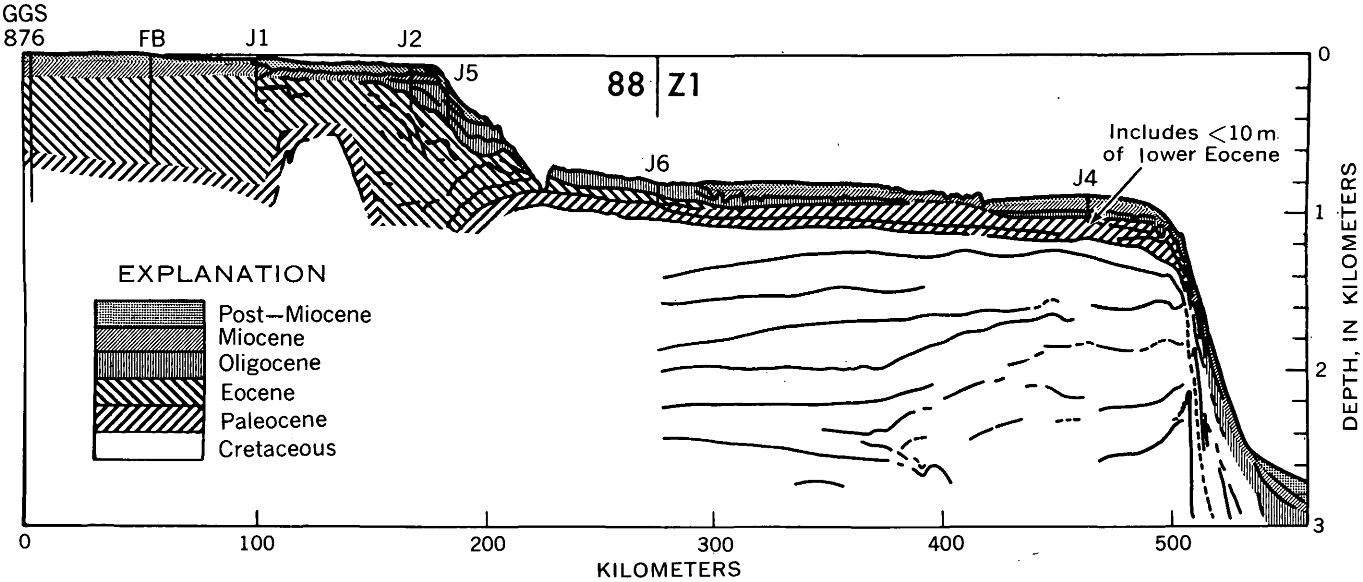


FIGURE 31.—Seismic profile across the continental shelf, Florida-Hatteras Slope, Blake Plateau, and Blake Escarpment. Modified from Emery and Zarudzki (1967, figs. 2, 3). Profile has been corrected for sound velocity and stratigraphic data from JOIDES holes superimposed on profile. Vertical exaggeration, × 70. J1 to J6 are the JOIDES holes and FB and GGS876 are wells on land. See figure 29 for location of wells and profile.

some evidence of erosion. The reflectors beneath layer A dip westward and terminate to the east on a subbottom ridge near the Blake Escarpment (fig. 1). This ridge becomes progressively shallower to the south and appears to form the core of the Blake Escarpment. Ewing, Ewing, and Leyden (1966) believed that this structure represents a ridge or banks of algae that flourished during most of the Cretaceous and suggested that the Blake Escarpment was formed by reef buildup or carbonate accretion. The recovery by Heezen and Sheridan (1966) of Lower Cretaceous algal limestone from the scarp seems to verify this interpretation. This algal ridge or banks along the eastern margin of the Blake Plateau may be part of the carbonate ridge system described by Uchupi and Emery (1968) from the Gulf of Mexico.

During the Early Cretaceous when the algal banks or ridges along the eastern margin of the Blake Plateau were active, a thick sequence of shallow-water deposits accumulated west of the banks. The algal banks apparently died out at the end of the Cretaceous, as Upper Cretaceous and Tertiary sediments from the area consist of deep-water carbonate oozes (Joint Oceanog. Inst. Deep Earth Sampling Program, 1965; Ericson and others, 1961). As suggested previously, some evidence indicates that the Gulf Stream invaded the Blake Plateau during the Paleocene by way of the Straits of Florida. The Bahama Banks are also believed to have been separated from the Florida peninsula at this time (Chen, 1965, figs. 43 and 44). During the early Tertiary, the locus of deposition shifted to the area near the present shelf-break where at least 800 m of shallow-water carbonate sediments accumulated (Uchupi, 1967b). The rate of deposition decreased rather rapidly along the western margin of the Blake Plateau, a rate indicating that the Gulf Stream has been an effective barrier to sediment transport to the plateau from the mainland. In consequence, the Tertiary section on the Blake Plateau is only about one-third as thick as that on the shelf.

During the Pleistocene, the Blake Plateau and Florida-Hatteras Slope appear to have been considerably eroded. During interglacial periods when sea level was higher than now, the Gulf Stream migrated westward and impinged on the Florida-Hatteras Slope, thus forcing the slope to retreat westward. During glacial periods when sea level was lower, the stream migrated eastward and eroded large areas of the plateau. During this shift of the stream to the east, progradation by the shelf sediments buried the erosion surfaces along the western margin of the Blake Plateau. Sediments eroded by the Gulf Stream were transported northward and onto the Blake Ridge (fig. 1).

An unusual feature shown by some of the seismic profiles (224, 82, figs. 28 and 29) is a ridge about 10 m high near the shelf-break. This ridge can be traced from Cape Hatteras as far south as Miami. The echo-sounding profiles (fig. 32) indicate that it is not continuous but is cut by numerous gaps. Other ridges also occur along the upper part of the Florida-Hatteras Slope at depths of 80 m and in the center of the shelf, at depths of 20–40 m. The ridges appear at different depths and

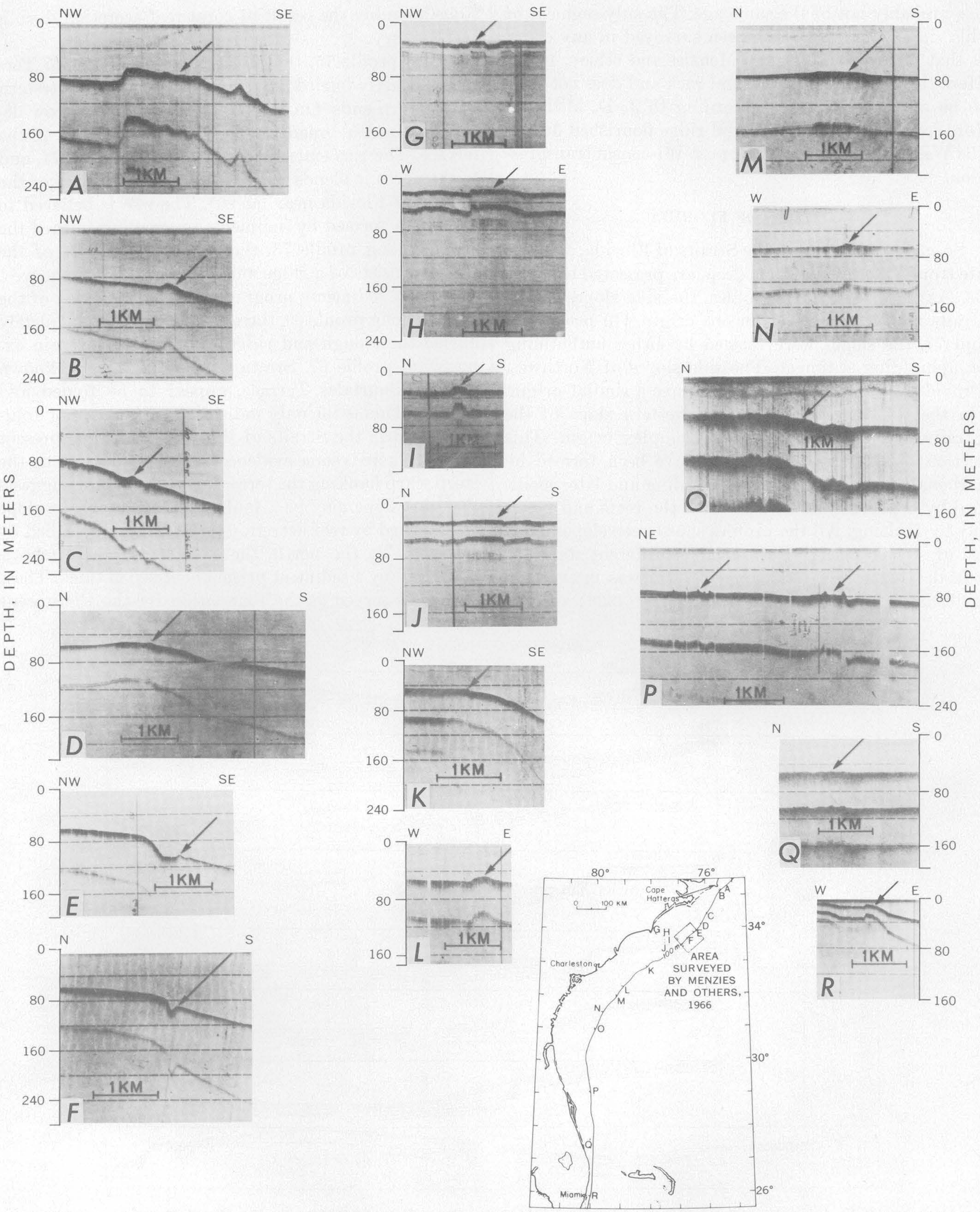


FIGURE 32.—Echo-sounding profiles across the algal ridge along the shelf-break. From Zarudzki and Uchupi (1968). Vertical exaggeration, about ×20.

are probably not of the same age. The only segment of this ridge system that has been surveyed in any detail is that off North Carolina (Menzies and others, 1966). Here the ridge consists of algal rock and does not seem to be active at present. According to J. D. Milliman (oral commun., 1968), the algal ridge flourished during the Wisconsin regression and post-Wisconsin transgression.

STRAITS OF FLORIDA

Seismic profiles across the Straits of Florida, an arcuate trough more than 800 m deep, are presented in figure 33. As shown by these profiles, the side slopes of the straits may have more than one origin. On profiles 79 and 77, the slopes were formed by either outbuilding or upbuilding sediment. The side slopes of Northwest Providence Channel (profile 76) have a similar origin. On the rest of the profiles, the western slope of the Straits of Florida has a more complex origin. This section of the slope appears to have been formed by carbonate accretion or by reef building and later modified by deposition of detritus over the reefs and possibly by faulting. All the profiles show steep slopes made up of strong reflecting material in different stages of burial. This strong reflecting material was interpreted by Uchupi (1966c) and Rona and Clay (1966) as limestone, possibly the result of coral-reef accretion during the Tertiary.

Along profile 75, the terrace, known as Miami Terrace, is partly buried by sediments both on the western and eastern ends. On profile 73 (fig. 33), a narrow depression and a broad sediment rise occur east of the terrace. The rise extends as far south as profile 71, and to the north it blends with the western side slope of the Straits of Florida near lat 26°. The rise is believed to have been formed by sediments prograding toward the south. Along profile 73, the western side slope of the straits consists of a ridge and a filled trough to the west capped by sediments prograding in the direction of the ridge. Along profile 69, these sediments have completely buried the trough and ridge. The terrace is again exposed on profile 67. Strata within the terrace, known here as Pourtales Terrace, appear to be folded and faulted. This is the only indication of faulting or folding found in the Straits of Florida during the present survey. There is some evidence of drag folding along the steep scarp flanking the terrace on the south; it suggests that this slope may be a fault scarp. Possibly the slope was formed by reef accretion and was later modified by faulting. To the north, the surface of the terrace is blanketed by a sediment prism about 200 m thick. These sediments served as the foundation for the Pleistocene

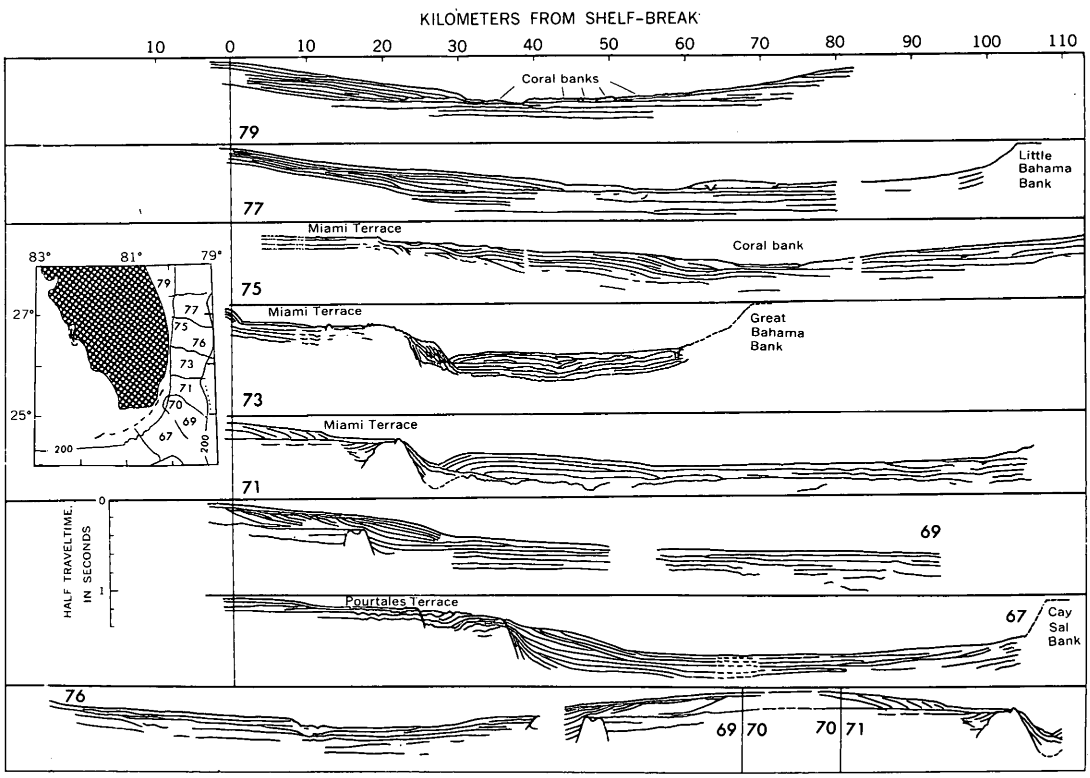


FIGURE 33.—Seismic profiles of the Straits of Florida. Modified from Uchupi (1966c, fig. 2). Vertical exaggeration, × 8 (assuming a velocity of 1,500 m/sec).

Florida Keys reef that flourished 97,000 years ago (Broecker and Thurber, 1965).

No data were obtained from the north slope off Cuba, the western slopes of Great and Little Bahama Banks, or Cay Sal Bank during the present survey. The slope north of Cuba seems to have been formed by folding and faulting and was later modified by carbonate accretion (Furrazola-Bermúdez and others, 1964, fig. 112). The side slopes of Cay Sal Bank may have been formed by reef buildup (Furrazola-Bermúdez and others, 1964, fig. 112). Probably, the steep side slopes of the Bahamas were also formed by carbonate accretion, as has been suggested by Hess (1933) and Newell (1959).

From the profiles taken during the present survey, it appears that faulting has played a minor role in the formation of the Straits of Florida. The side slopes seem to have been formed by reef accretion or by deltaic deposition or by a combination of both. The lower elevation in the center of the straits is due to decrease in deposition beneath the Gulf Stream, not to faulting. Faulting or folding has played a significant role only in the molding of the side slopes off Cuba and possibly of the slope immediately south of the Florida Keys.

GEOLOGIC MAP

Data from the seismic-reflection profiles described in this and other reports (Ewing, Ewing, and Leyden, 1966; Ewing, Worzel, Ewing, and Windisch, 1966), supplemented by information from seismic-refraction studies (Antoine and Henry, 1965; Drake and others, 1959; Hersey and others, 1959; Sheridan and others, 1966) and dredging, coring, and drilling (Joint Oceanog. Inst. Deep Earth Sampling Program, 1965; Ericson and others, 1952; Ericson and others, 1961; Gibson, 1965; Gibson, Hazel, and Mello, 1968; Gibson and Schlee, 1967; Heezen and Sheridan, 1966; McClelland Engineers, Inc., 1963a, b, c; [1] Northrop and Heezen, 1951; Pearse and Williams, 1951; Roberts and Pierce, 1967; Stetson, 1949) were used to compile the geologic map shown in figure 34. This map shows the distribution of pre-Pleistocene rocks.

Rocks of pre-Triassic age occur in the Gulf of Maine, off Nova Scotia, Buzzards Bay, and Long Island Sound and other sounds off southern New England. Triassic strata were only recognized in the Bay of Fundy and in the Gulf of Maine. Triassic sediments may also occur on the western end of Long Island Sound (Sanders, 1960; Zurflueh, 1962).

The Acadian Triassic basin in the Bay of Fundy extends 120 km into the Gulf of Maine—not as far westward as Johnson (1925) or Drake, Worzel, and Beckmann (1954) believed. The strata having velocities of about 4.0 km/sec reported by Drake, Worzel, and Beckmann (1954) from the center of the Gulf of Maine probably are low-grade metamorphic or well-indurated rocks of pre-Triassic age rather than Triassic sediments. Seismic-reflection profiles in the area where these deposits occur show only a strong reflecting horizon mantled by a thin veneer of sediment. The strong reflector supposedly marks the top of the Paleozoic. It is of interest to note that the deposits in Cape Cod Bay, suggested by Hoskins and Knott (1961) to be of Late Cretaceous age, have velocities similar to those of the strata suggested by Drake, Worzel, and Beckmann (1954) to be Triassic. In addition, Oldale and Tuttle (1964) also reported strata having similar velocities from the subsurface of Cape Cod. The strata in Cape Cod seem to occur in a deep trough that could possibly be a graben. If the strata in the center of the Gulf of Maine, Cape Cod, and Cape Cod Bay are Triassic, then the Acadian Triassic basin extends from the head of the Bay of Fundy across the Gulf of Maine to the eastern coast of Massachusetts. Possibly, the basin may extend farther west, as deposits having similar compressive velocities have been reported from the subsurface in Block Island by Tuttle, Allen, and Hahn (1961). As explained previously (p. I8), however, Carboniferous deposits in Rhole Island also have similar velocities. This would suggest that some of the above deposits may be Carboniferous rather than Triassic in age.

Johnson (1925, p. 291–294) and Koons (1941, 1942) suggested that the Acadian Triassic basin is flanked to the northwest by a fault, which Johnson named the Fundian fault. The conspicuous scarps along the New Brunswick-Maine coast were cited by them as evidence for the existence of the fault. In contrast, Shepard (1930, 1942) suggested that the linearity of the shoreline was erosional, not tectonic in origin. Magnetic data (Malloy and Harbison, 1966) seem to verify Johnson's interpretation of the origin of the western margin of the Triassic basin. Subbottom-profiler data (Swift and Lyall, 1968) suggest that the Bay of Fundy northeast of Grand Manan Island is a broad syncline. The basin's southeast margin consists of an unconformable contact between Triassic and pre-Triassic rocks; the northwest margin consists of a zone of normal faults closely resembling the Fundian fault. The faults within this zone, however, are relatively minor and do not seem to delineate a fault zone of the magnitude suggested by John-

[1] Unpublished reports to Commandant, U.S. Coast Guard, Washington, D.C., by McClelland Engineers, Inc., Soil and Foundation Consultants, Houston, Tex.: 1963a, Fathometer survey and foundation investigation—Chesapeake Bay entrance offshore structure, Cape Henry, Virginia, 13 p.; 1963b, Fathometer survey and foundation investigation—Frying Pan Shoals offshore structure, Cape Fear, North Carolina, 12 p.; 1963c, Fathometer survey and foundation investigation—Diamond Shoal offshore structure, Cape Hatteras, North Carolina, 11 p.

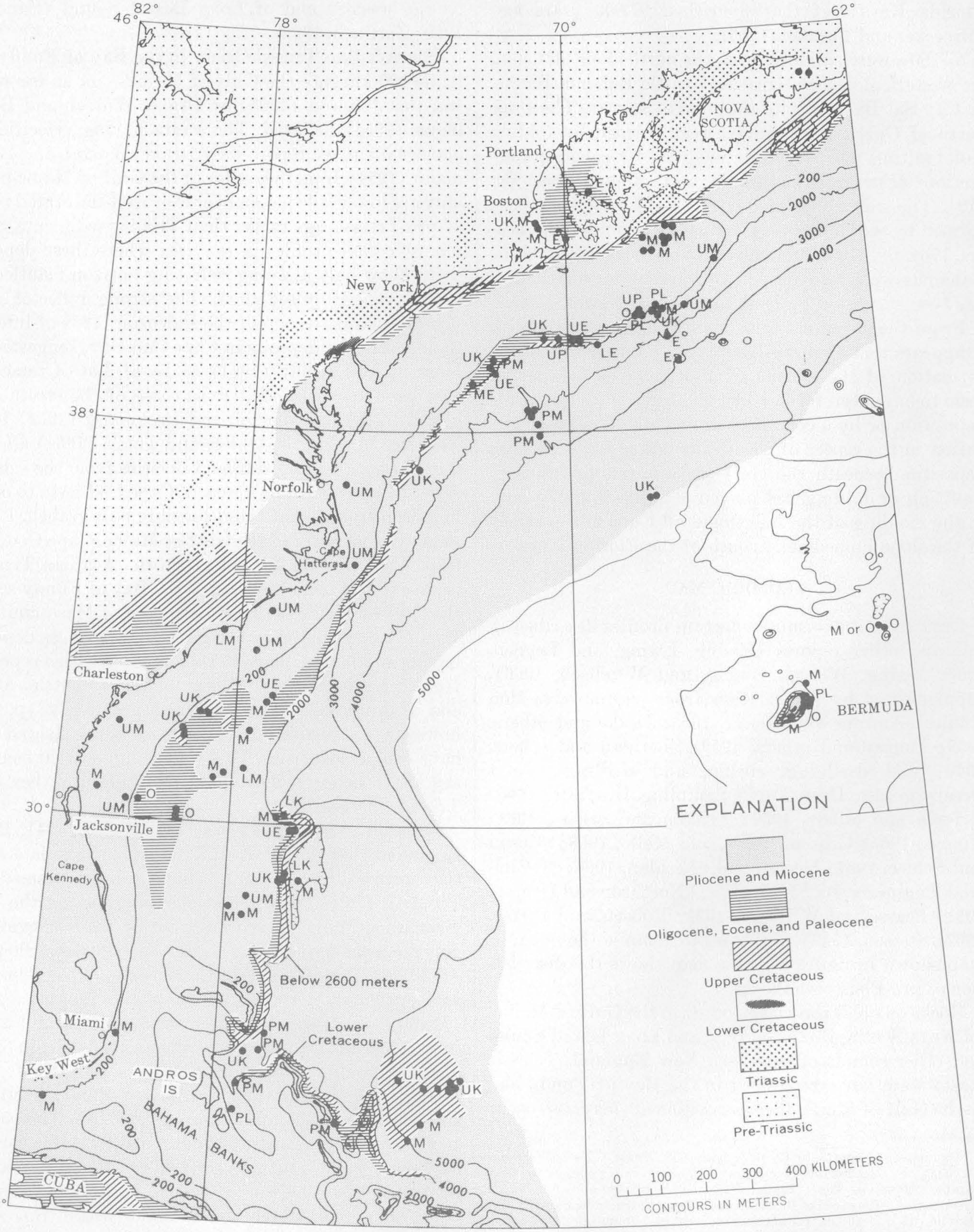


FIGURE 34.—Pre-Quaternary geologic map of the continental margin off the east coast of the United States. Onshore geology from: North Am. Geol. Map Comm. (1965); Emerson (1917); Stevenson and McGregor (1963); and Zeigler, Hoffmeister, Giese, and Tasha (1960). Bottom notations (sites where pre-Pleistocene sediments have been recovered by dredging, coring, or drilling) are as follows: LK, Lower Cretaceous, UK, Upper Cretaceous, UP, upper Paleocene, LE, lower Eocene, ME, middle Eocene, UE, upper Eocene, O, Oligocene; LM, lower Miocene, UM, upper Miocene, M, Miocene, PM, Pliocene and Miocene, PL, Pliocene.

son (1925). Several profiles were recorded across the location of the Fundian fault during the present survey (fig. 35). Results, unfortunately, proved to be inconclusive. The basin does seem to be bordered by relatively steep scarps on the northwest and southeast. Because of the poor resolution of the seismic profiles, the relationship of these scarps and the sediments between them could not be determined. Along some lines, the contact between the Triassic strata and the Paleozoic rocks appears to be depositional in origin; in others, it may be a fault. The fault does not seem to extend as far west as Johnson (1925) believed, but if the rocks on either side are strong reflectors, the seismic profiler would be incapable of seeing the faulting.

To date, no sediments of Jurassic age have been dredged from the shelf and slope off the east coast. The occurrence of Jurassic(?) deposits in the subsurface in Cay Sal Bank (Furrazola-Bermúdez and others, 1964), southern Florida, and Cape Hatteras, N.C. (Maher, 1965), suggests, however, that Jurassic sediments probably are present beneath the shelf and slope off the east coast.

Algal limestone of Early Cretaceous age was recovered from several areas on the Blake Escarpment. Sediments of similar age may also occur on the steep scarp along the eastern margin of the Bahamas, but this has not been verified by sampling. Upper Cretaceous strata occur on the deep sea bottom off the Bahamas in the area where Horizon A crops out (Ewing, Worzel, Ewing, and Windisch, 1966), on the Blake Escarpment, along the western margin of the Blake Plateau, on the continental slope and canyons from Cape Hatteras to Georges Bank, and possibly in the Gulf of Maine.

Paleocene, Eocene, and Oligocene strata are exposed along the western margin of the Blake Plateau beneath the axis of the Gulf Stream, near the Blake Escarpment, on the slope and submarine canyons north of Cape Hatteras, and in the Gulf of Maine. Sediments of Miocene and Pliocene age blanket most of the area studied.

ISOPACH MAPS

Data from this report, from other seismic reflection and refraction studies (Antoine and Henry, 1965; Drake and others, 1959; Emery and others, 1969; Houtz and Ewing, 1963, 1964; Katz and Ewing, 1957; Sheridan and Drake, 1968; Sheridan and others, 1966), and drill and other geologic data on land (Chen, 1965; Eardley, 1962, p. 128–134; Klein, 1962; Maher, 1965) were used by the writer (*in* Emery and others, 1969) to compile an isopach map of the total sediment thickness on the continental margin off the east coast of North America (fig. 36). More than 11 km of sediment are present in an east-west-trending basin called the South Florida embayment, extending from southern Florida to the Bahama Islands. This basin is flanked on the north by a ridge, an extension of the Peninsular arch, extending from Cape Kennedy to Little Bahama Bank, where the sediments decrease to less than 2 km in thickness. North of the ridge is another basin that underlies the Blake Plateau and that contains more than 8 km of sediment. This basin is bordered on the east and on the north by a ridge that may extend from Little Bahama Bank to Charleston, S.C. The algal banks that presumably flourished along the eastern margin of the Blake Plateau during the Cretaceous were along the crest of this ridge. Farther north is another basin that extends almost continuously to the Scotian Shelf. East of New York, the basin is bordered on the seaward side by a ridge that is near the present shelf-break. Both the ridge and the basin are disrupted by what may be a right-lateral fault along lat. 40°, which has a possible displacement of about 140 km. The New England Seamount Chain south of Georges Bank is along the seaward extension of this fault. Drake and Woodward (1963, p. 59), who named this fault the Kelvin fault, have stated that major movement took place in pre-Mississippian or perhaps Late Devonian time. Evidence in dating the fault is rather tenuous, however, and it could just as well be Triassic in age. The basin on the shelf east of New York may be analogous to the Triassic basins on land. The outer ridge may mark a marginal fault, both ridge and basin being displaced by a strike-slip fault.

An isopach map of the Tertiary sediments (fig. 37) was compiled by the writer (in Emery and others, 1969) using data from the seismic-reflection profiles described in this report, from seismic data from Blake Ridge (Bryan and Markl, 1966), and the continental rise (Emery and others, 1969), from drill, dredge, and coring information offshore, and from drilling data on the Coastal Plain (Maher, 1965). In several areas beneath the Gulf Stream along the western margin of the Blake Plateau, on the Blake Escarpment, in segements of the slope and canyons north of Cape Hatteras, and in large areas of the shelf east of New York (shaded areas in fig. 37), Tertiary sediments are absent or are less than 20 m thick. Slightly greater thicknesses occur on Georges Bank and in the vicinity of Nantucket Shoals and on structural ridges between Cape Hatteras and Charleston, S.C. Thicknesses of about 400 m occur on the shelf west of Blake Plateau. Maximum sediment thicknesses, in places exceeding 1,200 m, occur in southern Florida, on the Blake Ridge, and on a narrow trough north of Cape Hatteras.

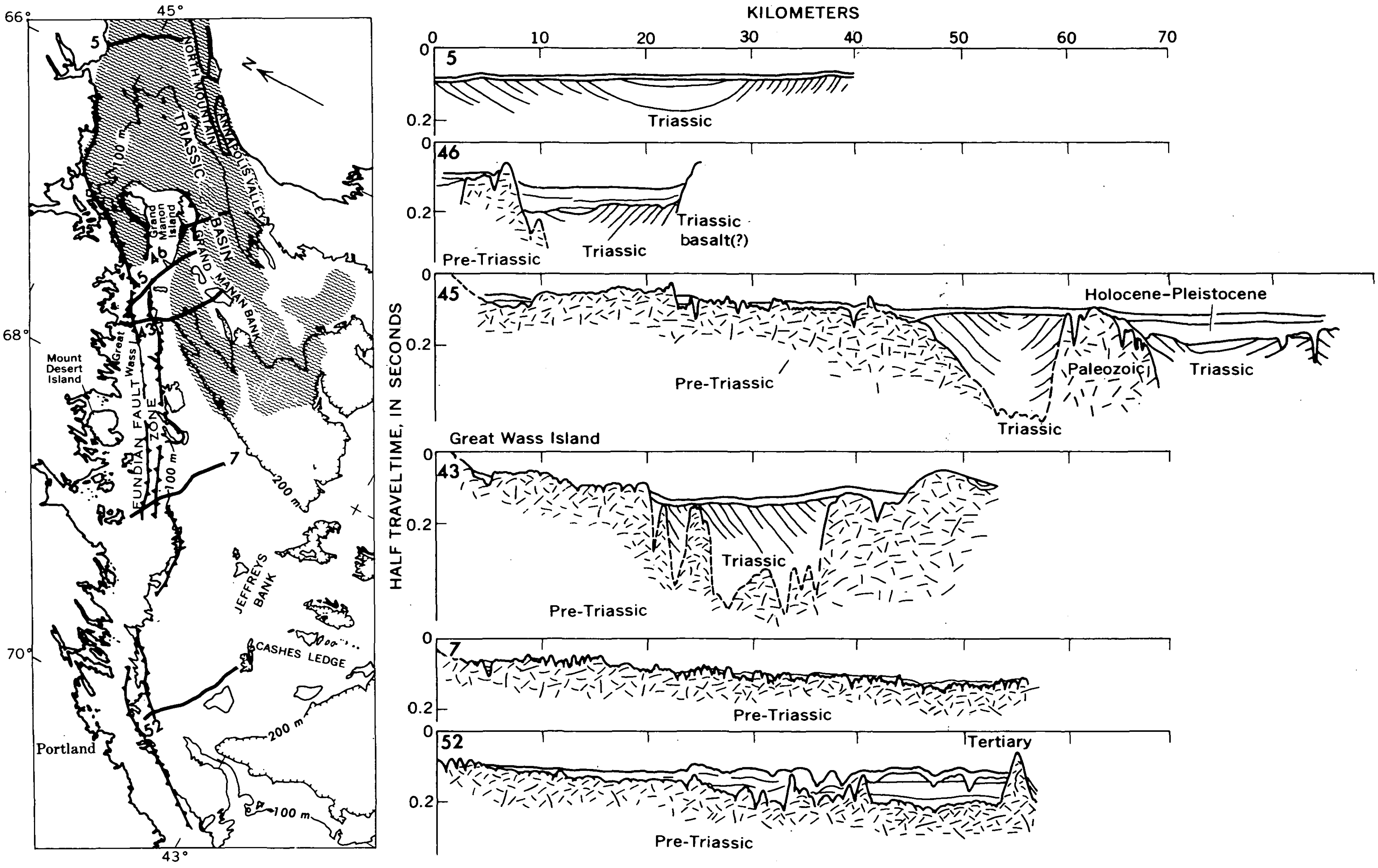


FIGURE 35.—Location of the Fundian fault zone according to Johnson (1925, fig. 144). The numbered heavy black lines are the seismic profiles taken across the fault zone (from Uchupi, 1966b, fig. 8). Seaward end of the profiles is at the right. Vertical exaggeration, × 28 (assuming a velocity of 1,500 m/sec).

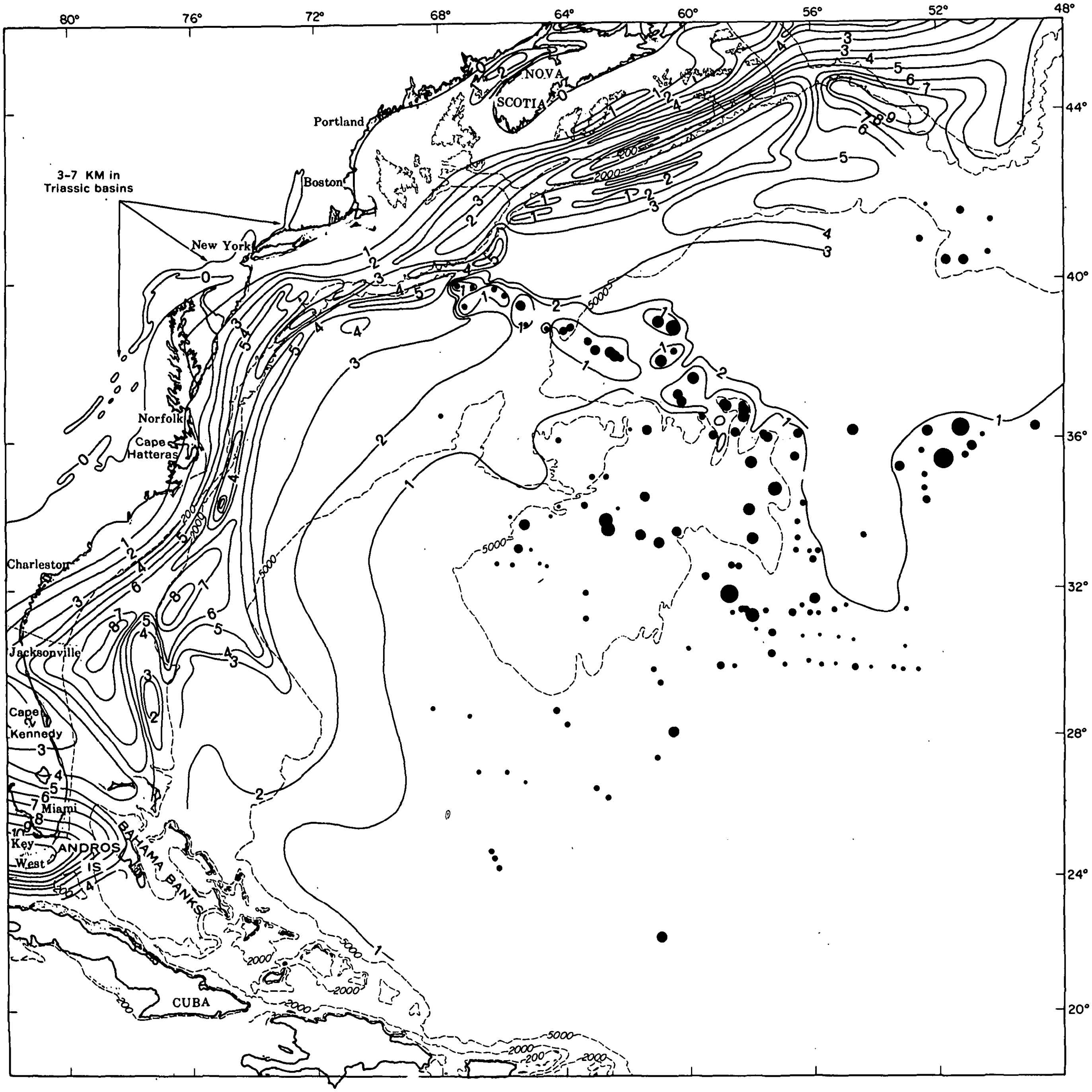


FIGURE 36.—Isopach map showing total thickness of inferred Triassic and post-Triassic sediments on the Coastal Plain and on the continental shelf, slope, and rise. From Emery and others (1969, fig. 59). Heavy contours indicate sediment thickness in kilometers; contour interval, 1 km. Dashed contours indicate depth of water in meters. Circles are seamounts.

Throughout most of the continental margin, Pleistocene strata cannot be distinguished from the underlying Tertiary deposits. In areas where this distinction can be made, either through high-resolution seismic profiling or drill data, the Pleistocene ranges in thickness from less than 5 to more than 100 m, maximum thicknesses being present near the shelf's edge north of Cape Hatteras. According to Knott and Hoskins (1968), the Pleistocene may be as thick as 200 m on the slope south of Martha's Vineyard.

Holocene sediments (sediments deposited since the beginning of the last transgression of the sea) are very

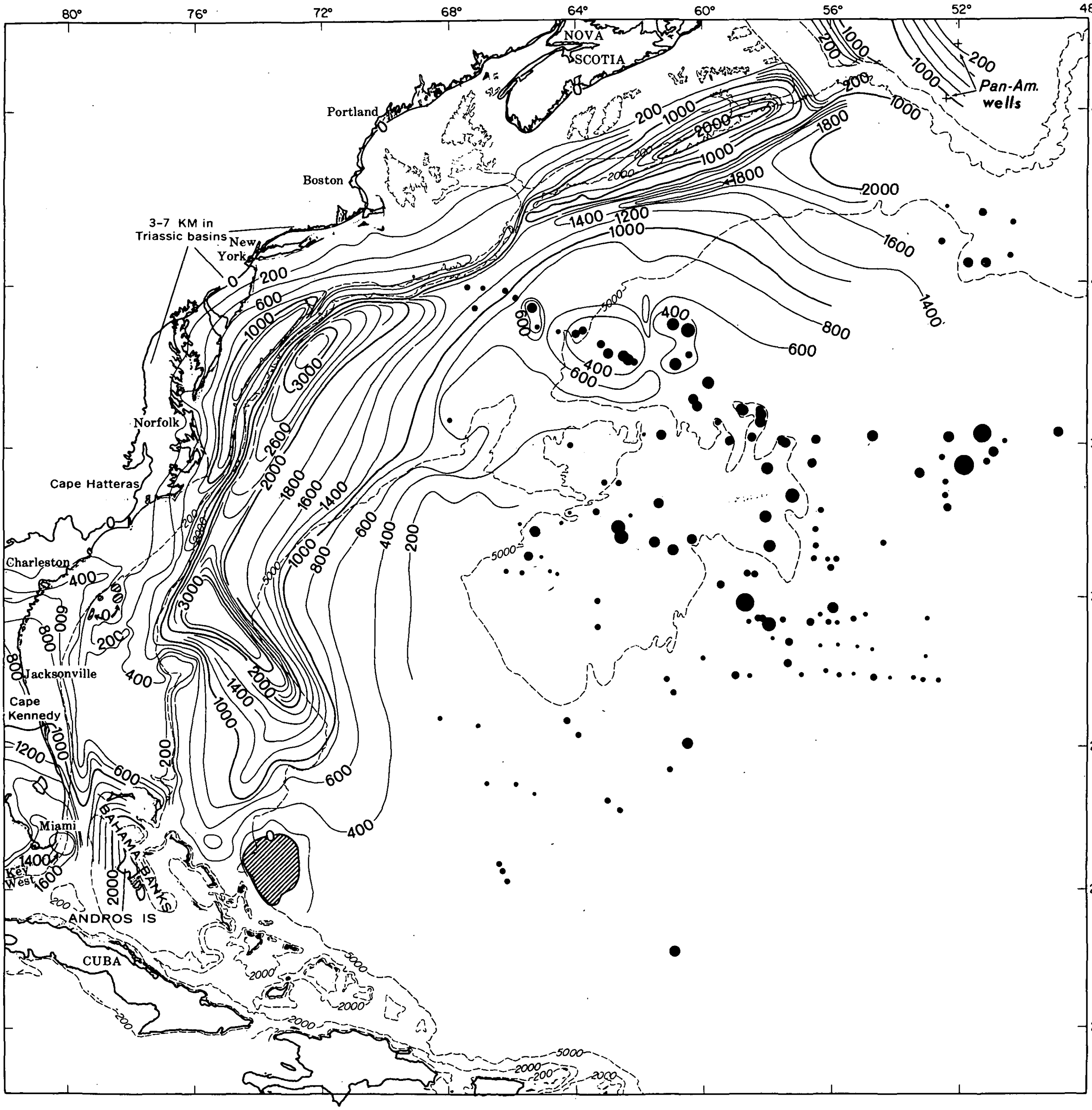


FIGURE 37.—Isopach map of Tertiary sediments on the Coastal Plain and on the continental shelf, slope, and rise. From Emery and others (1969, fig. 60). Heavy contours are isopachs in meters; dashed contours indicate water depth in meters. Circles are seamounts.

spottily distributed throughout most of the shelf and slope. In such areas as the Blake Plateau, which is constantly being swept by the Gulf Stream, Holocene sediments are probably only a few meters thick. In other areas, such as in the Gulf of Maine and Long Island Sound, appreciable amounts have accumlated. The Holocene sediments in the Gulf of Maine are highly transparent to sound, and their thickness can easily be determined with the aid of a 12-kc echo sounder, as illustrated by Murray (1947). Values of this transparent layer in the Gulf of Maine range from a high of 30 m to zero and average about 10 m (fig. 38). The Holocene sedi-

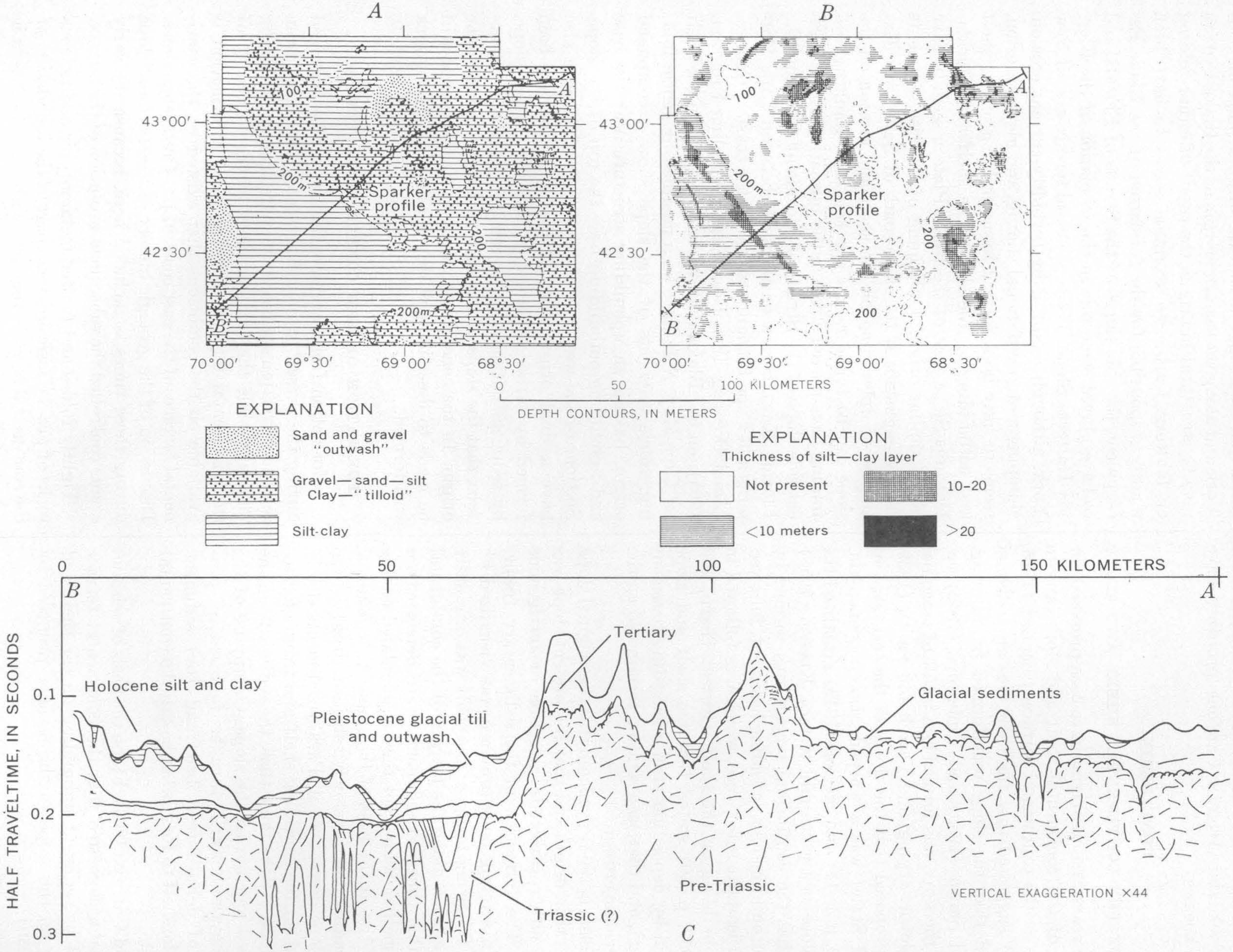


FIGURE 38.—*A*, Sediment map of a segment of the Gulf of Maine (modified from John Schlee, unpub. data). *B*, Isopach map of the transparent (to sound) layer, based on data from U.S. Coast and Geodetic Survey Hydrographic Survey H–6465. *C*, Seismic-reflection profile showing the patchy distribution of the transparent Holocene silt-clay layer (from Uchupi 1966b, fig. 14).

ments on Long Island Sound and in the broad reentrant between Block and Atlantis Canyons probably have similar thicknesses.

CONCLUSION

NATURE OF THE CONTINENTAL SHELF AND SLOPE

Over the years various origins have been proposed for the origin of the continental shelf and slope, known collectively as the continental terrace. Shepard (1948, p. 157–206) suggested that the shelf was an erosional surface and that the slope was formed by faulting. Veatch and Smith (1939) and Umbgrove (1946) believed that the slope was formed as a result of marginal flexing or downwarping, and Veatch and Smith (1939, p. 33–41) proposed that the slope off the east coast of the United States was a warped Miocene peneplain. Daly (1942, p. 9–11) and Stetson (1949) visualized the shelf and slope as a wave-built terrace. Kuenen (1950) indicated that the continental terrace was formed by sediment outbuilding on a subsiding basement, followed by regional isostatic subsidence, which was followed in turn by upbuilding on the shelf. Heezen, Tharp, and Ewing (1959, p. 50) stated that the shelf and slope were formed by deposition atop a subsiding basement (upbuilding), and that each stratum terminated on the slope by periodic erosion.

Dietz (1963a, b, 1964) proposed that the original slope was structural in origin and that the present slope was formed by either carbonate accretion or terrigenous deposition. The formation of the sedimentary framework within a terrigenous province was visualized by him in the following manner: the shelf was originally formed by erosion along the margin of the continental block. At this time, no sediments were deposited on either the shelf or slope, but they accumulated on the continental rise at the base of the slope. As a result of sediment loading, the rise slowly subsided, dragging the shelf and slope down with it. Paralic sediments slowly accumulated on the subsiding shelf and prograded toward the slope. At the same time, the sediments on the rise onlapped and buried the slope. Onlapping of the slope by the rise may in turn be followed by progradation of delta foreset beds and (or) sediment bypassing the shelf to form what he called a continental embankment.

Moore and Curray (1963a, b), on the basis of seismic-reflection data, suggested that the continental terrace was formed by sediment upbuilding on the shelf and outbuilding on the slope in the manner proposed by Kuenen (1950).

Seismic-reflection profiles taken during this survey and seismic-refraction data already published have examples of most of the ideas proposed above. Seismic-refraction data suggests that the original slope off New York and along the eastern margin of the Blake Plateau may be structural in origin, the result of either folding or faulting. Carbonate accretion seems to have been mainly responsible for the formation of the Blake Escarpment, the side slopes of the Straits of Florida, and to have played some role in the formation of the Florida-Hatteras Slope. The continental terrace east of New York, although modified by turbidity-current erosion, slumping and gravitational sliding, and glacial erosion, seems to have been formed by upbuilding on the shelf and outbuilding on the slope. The shelf and Florida-Hatteras Slope west of the Blake Plateau seem to have had a similar origin. Onlapping of the rise sediments formed segments of the slope south of New York. Examples of upbuilding on the shelf and erosion on the slope can be found near Cape Hatteras. Faulting and folding have played a role in the formation of the present side slope of the Straits of Florida off Cuba and the Florida Keys. Strata on the shelf between Cape Hatteras and Cape Romain, parallel to the coast of Georgia (Joint Oceanog. Inst. Deep Earth Sampling Program, 1965), on the Blake Plateau, and possibly on the shelf off Cape May, N.J., have been modified by gentle folding. Some segments of the slope show a compound origin, having an upbuilding structure near the base and upbuilding-outbuilding near the top of the slope. Sections of the west side of the Straits of Florida also have a dual origin, the original slope having been formed by carbonate accretion and the present slope, by sediment outbuilding. It can clearly be seen, therefore, that the slope off the east coast has more than one origin. In the concluding paragraphs, an attempt will be made to describe how this sedimentary framework was formed.

FORMATION OF THE CONTINENTAL TERRACE

Information from seismic-reflection profiles obtained during the present survey, augmented with data from seismic-refraction studies, coring, dredging, and drilling makes possible the reconstruction of the formation of the continental terrace. To date, little information is available on the conditions that existed on the continental terrace off the east coast in pre-Cretaceous times. Discussion of the geologic history of the shelf and slope during those times is included here, because the early events controlled the subsequent evolution of the terrace.

Tightly folded and faulted metamorphic and igneous rocks of pre-Triassic age form part of the foundation of the continental terrace. Included within this basement is a belt of Triassic sediments deposited in a taphrogeosyncline, a tilted geosyncline bounded on one or both sides by high-angle faults. On land, the belt of Triassic strata extends from the Bay of Fundy to at least South Carolina and may extend as far south as Florida. The deep filled trough near the present shelf-break east of New York and the basin beneath the Blake Plateau may be offshore equivalents of these land taphrogeosynclines, the ridge along the seaward side representing the marginal fault. The ridge extending from Cape Kennedy to Little Bahama Bank and the east-trending basin south of this ridge may have a similar origin. Sediments within these basins probably consist of continental and paralic deposits and may include evaporites. The strata forming the upper segment of the continental terrace (Cretaceous and younger sediments) (fig. 39) were deposited atop these strata.

North of Cape Hatteras, the shelf and slope were formed by a combination of shelf upbuilding and slope outbuilding. South of Cape Hatteras, the margin was formed by carbonate accretion or reef buildup atop the ridge along the seaward side of the taphrogeosyncline and by the accumulation of shallow lagoonal sediments landward of the algal ridge. The lagoon occupied the area of the present Blake Plateau and the shelf to the west, Florida, the Bahamas, and the Straits of Florida. The northern terrigenous province was separated from the carbonate province to the south by the Suwannee Channel. Slightly north of the channel was a structural ridge system extending to Cape Hatteras. Similar ridges also occur north of Cape Hatteras, within the Blake Plateau, and parallel to the Georgia coast. These structural ridges appear to have been active during the Cretaceous and throughout the Tertiary.

Subsidence of the continental terrace continued during the Tertiary. East of New York, however, subsidence was relatively small, and less than 800 m of sediment was deposited in this area. Between New York and Cape Hatteras, subsidence was greater, especially near the present shelf-break where more than 1,400 m of sediment was deposited. The narrow basin south of New York seems to be separated into a series of embayments, such as the Salisbury embayment in Maryland, by ridges at right angles to the present shoreline. The structural high or highs between Cape Hatteras and Cape Romain, parallel to the Georgia coast, and in the Blake Plateau were also active during this time.

In the Blake Plateau region, the reefs along the seaward edge of the plateau died out toward the end of the Cretaceous. Soon after the reefs died, the Gulf Stream extended its course into the plateau by way of the Straits of Florida. Opening of the straits may have been due to diastrophic movements in Cuba, as this island seems to have been very active during the latter part of the Cretaceous and early Tertiary (Furrazola-Bermúdez and others, 1965). In the Blake Plateau region, the locus of deposition shifted to near the present shelf-break during the early Tertiary, and at least 800 m of sediment was deposited. Farther south, in the Straits of Florida, coral or algal reefs began to flourish along the edges of the Gulf Stream and formed the steep slopes of the Straits of Florida. These organic structures may have extended as far north as Jacksonville, Fla.; Eocene sediments in JOIDES hole 2 contain appreciable quantities of algal debris. Deposition in the center of the Straits of Florida and the Blake Plateau during the Tertiary was small because the Gulf Stream prevented the accumulation of any large volume of sediment.

During the late Tertiary or early Pleistocene, a lowland and cuesta were carved out of the shelf strata east of New York by fluvial erosion. This lowland and cuesta extended from New Jersey as far east as the Scotian Shelf. The region was later glaciated during the Pleistocene. Glacial erosion deepened and widened the lowland, and the cuesta was built up by deposition and by folding and faulting of the strata within the cuesta by ice pressure. In some areas of the cuesta, this buildup raised it above sea level to form islands. At the time that the lowlands and cuesta were modified by glacial erosion and deposition, the rest of the shelf was modified by fluvial deposition (emplacement of Hudson Apron and Block Delta) and marine erosion (formation of terraces along the shelf-break). At the same time, direct deposition on the slope by the streams that extended their courses across the shelf during low stands of sea level led to formation of turbidity currents and subsequent canyon cutting. Such rapid deposition on the slope also led to unstable conditions that caused slumping and gravitational sliding and further modification of the slope.

South of Cape Hatteras, the Blake Plateau and Florida-Hatteras Slope underwent considerable erosion by the Gulf Stream. During interglacial periods, when sea level was higher than now, the Gulf Stream impinged on the Florida-Hatteras Slope and forced its retreat westward. During glacial stages, when sea level was lower than now, the Gulf Stream migrated eastward and cut the deep depressions on the Blake Plateau. As the stream migrated to the east, the Florida-Hatteras Slope prograded eastward over the erosional surface eroded by the stream.

Off southern Florida, sediment transported by littoral drift partly buried the carbonate slopes along the margins of the Gulf Stream in the Straits of Florida. In addition, carbonate accretion or reef buildup formed the present Florida Keys during an interglacial period 97,000 years ago when sea level was higher than now (Broecker and Thurber, 1965). The limestone blanketing most of the area south of Miami was deposited in the lagoon behind the reef delineated by the Florida Keys (Hoffmeister and others, 1967).

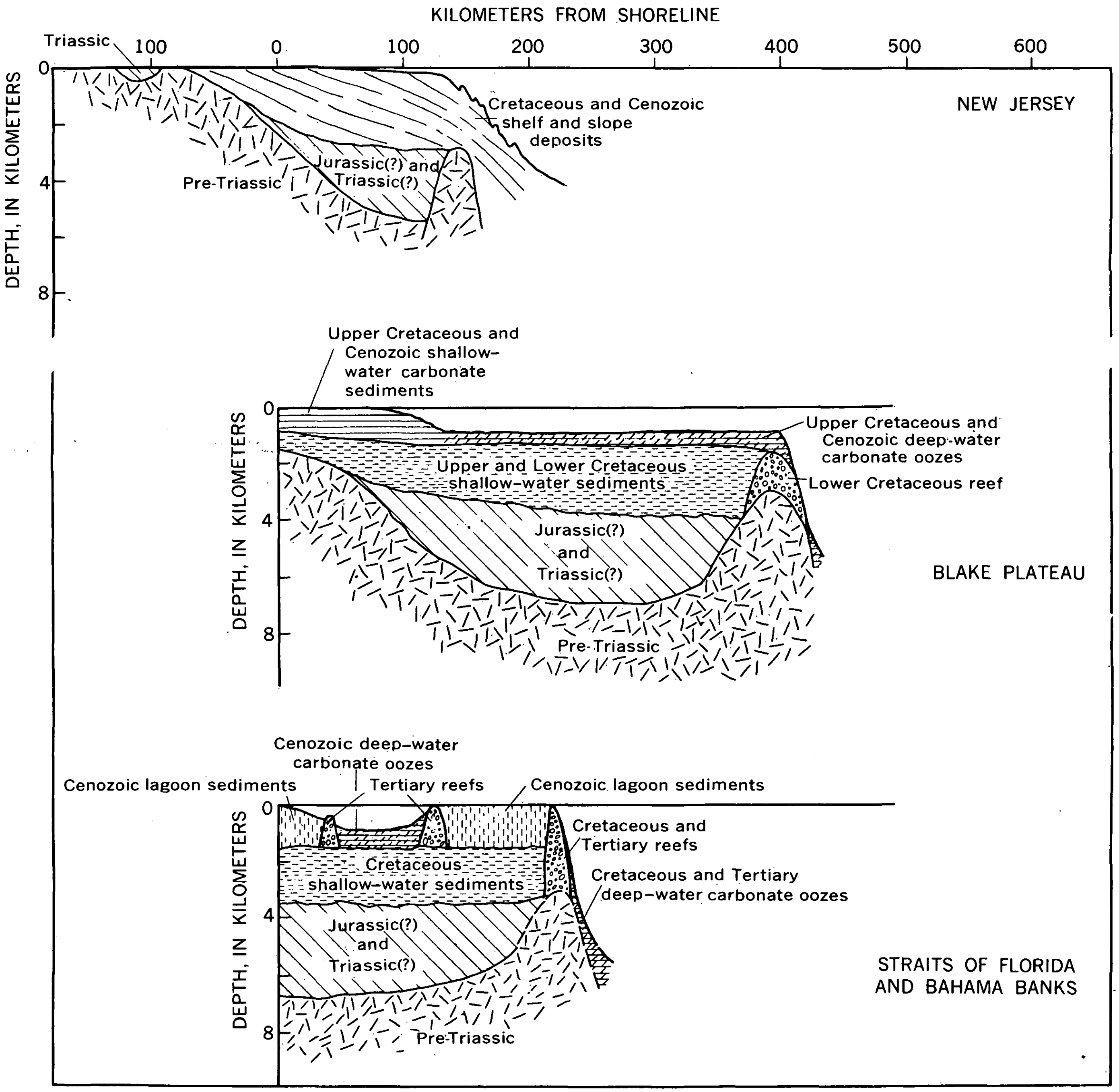


FIGURE 39.—Schematic diagrams showing structural cross-sections off New Jersey, Blake Plateau, and Straits of Florida.

The presence of salt-water and fresh-water peat, oyster fragments, and the remains of such mammals as mastodon, mammoth, and musk ox (Whitmore and others, 1967), and the lagoonal–outer-ridge–estuarine-type topography of the shelf suggest that most of the shelf prior to the last transgression looked much like the present Coastal Plain. As the Wisconsin glaciers retreated north, this coastal plain slowly submerged. Submergence began 15,000 years ago and ended about 3,000 years ago when sea level reached its present position (Milliman and Emery, 1968). During this transgression, the sediments deposited on Georges Bank and Nantucket Shoals during the last glacial advance were reworked by waves to essentially their present form. Tidal action since then has further modified these deposits. The fines winnowed out of the glacial deposits blanket the side slopes of Georges Bank and form the acoustically transparent layer in the Gulf of Maine basins. The lagoon–offshore-ridge–estuarine-type topography on the shelf was probably formed during this transgression. The algal ridge between Cape Hatteras and Miami also seems to have flourished along the western edge of the Gulf Stream during the last transgression.

The topography formed on the shelf in pre-Wisconsin time and during the Wisconsin regression and post-Wisconsin transgression is still recognizable throughout most of the continental terrace. That such topography is still well preserved is a reflection of the small volume of sediment that is reaching the shelf at present and of the short time that has elapsed since sea level was established at its present level.

REFERENCES CITED

Antoine, J. W., and Henry, V. J., Jr., 1965, Seismic refraction study of shallow part of continental shelf off Georgia coast: Am. Assoc. Petroleum Geologists Bull., v. 49, no. 5, p. 601–609.

Birch, W. B., and Dietz, F. T., 1962, Seismic refraction investigations in selected areas of Narragansett Bay, Rhode Island: Jour. Geophys. Research, v. 67, no. 7, p. 2813–2821.

Broecker, W. S., and Thurber, D. L., 1965, Uranium-series dating of corals and oolites from Bahaman and Florida Key limestones: Science, v. 149, no. 3679, p. 58–60.

Bryan, G. M., and Markl, R. G., 1966, Microtopography of the Blake-Bahama region: Columbia Univ., Lamont Geol. Observatory, Tech. Rept. 8, 26 p.

Chadwick, G. H., 1948, Peneplains in Maine [abs.]: Geol. Soc. America Bull., v. 59, no. 12, pt. 2, p. 1315–1316.

———1949, Glacial moulding of the Gulf of Maine [abs.] Geol. Soc. America Bull., v. 60, no. 12, pt. 2, p. 1967.

Chen, C. S., 1965, The regional lithostratigraphic analysis of Paleocene and Eocene rocks of Florida: Florida Geol. Survey Geol. Bull. 45, 105 p.

Crosby, W. O., 1879, On the occurrence of fossiliferous boulders in the drift of Truro on Cape Cod, Massachusetts: Boston Soc. Nat. History Proc., v. 20, p. 136–140.

Daly, R. A., 1942, The floor of the ocean, new light on old mysteries; The Page-Barbour Lectures at the University of Virginia, 1941: Chapel Hill, Univ. North Carolina Press, 177 p.

Dietz, R. S., 1963a, Collapsing continental rises—An actualistic concept of geosynclines and mountain building: Jour. Geology, v. 71, no. 3, p. 314–333.

———1963b, Wave-base, marine profile of equilibrium, and wave-built terraces—A critical appraisal: Geol. Soc. America Bull., v. 74, no. 8, p. 971–990.

———1964, Origin of continental slopes: Am. Scientist, v. 52, no. 1, p. 50–69.

Donn, W. L., Farrand, W. R., and Ewing, Maurice, 1962, Pleistocene ice volumes and sea-level lowering: Jour. Geology, v. 70, no. 2, p. 206–214.

Drake, C. L., Ewing, Maurice, and Sutton, G. H., 1959, Continental margins and geosynclines; the east coast of North America north of Cape Hatteras, *in* Ahrens, L. H., and others, eds., Physics and chemistry of the earth [v.]3: London, Pergamon Press, p. 110–198.

Drake, C. L., and Woodward, H. P., 1963, Appalachian curvature, wrench faulting, and offshore structures: New York Acad. Sci. Trans., ser. 2, v. 26, no. 1, p. 48–63.

Drake, C. L., Worzel, J. L., and Beckmann, W. C., 1954, Gulf of Maine, Part 9 *of* Geophysical investigations in the emerged and submerged Atlantic Coastal Plain: Geol. Soc. America Bull., v. 65, no. 10, p. 957–970.

Eardley, A. J., 1962, Structural geology of North America: 2d ed., New York, Harper and Row, 743 p.

Emerson, B. K., 1917, Geology of Massachusetts and Rhode Island: U.S. Geol. Survey Bull. 597, 289 p.

Emery, K. O., 1967, The Atlantic continental margin of the United States during the past 70 million years, *in* Neale, E. R. W., and Williams, Harold, eds., Collected papers in geology of the Atlantic region: Geol. Assoc. Canada Spec. Paper 4, p. 53–70.

Emery, K. O., and Uchupi, Elazar, 1965, Structure of Georges Bank: Marine Geology, v. 3, no. 6, p. 349–358.

Emery, K. O., Uchupi, Elazar, Phillips, J. D., Bowin, C. O., Bunce, E. T., and Knott, S. T., 1969, The continental rise off eastern North America: Am. Assoc. Petroleum Geologists Bull., v. 54. In press.

Emery, K. O., and Zarudzki, E. F. K., 1967, Seismic reflection profiles along the drill holes on the continental margin off Florida: U.S. Geol. Survey Prof. Paper 581–A, 8 p.

Ericson, D. B., Ewing, Maurice, Heezen, B. C., 1952, Turbidity currents and sediments in North Atlantic: Am. Assoc. Petroleum Geologists Bull., v. 36, no. 3, p. 489–511.

Ericson, D. B., Ewing, Maurice, Wollin, Goesta, and Heezen, B. C., 1961, Atlantic deep-sea sediment cores: Geol. Soc. America Bull., v. 72, no. 2, p. 193–285.

Ewing, John, Ewing, Maurice, and Leyden, Robert, 1966, Seismic-profiler survey of Blake Plateau: Am. Assoc. Petroleum Geologists Bull., v. 50, no. 9, p. 1948–1971.

Ewing, John, Le Pichon, Xavier, and Ewing Maurice, 1963, Upper stratification of Hudson Apron region: Jour. Geophys. Research, v. 68, no. 23, p. 6303–6316.

Ewing, John, Worzel, J. L., Ewing, Maurice, and Windisch, Charles, 1966, Ages of horizon A and the oldest Atlantic sediments: Science, v. 154, no. 3753, p. 1125–1132.

Furrazola-Burmúdez, Gustavo, Judoley, C. M., Mijailóvskaya, M. S. Miroliúbov, Y. S., Novojatsky, I. P., Núnez-Jimenez, Antonio, and Solsona, J. B., 1964, Geología de Cuba: Havana, Inst. Cubano Recursos Minerales, 239 p.; English text (Translations on Cuba, no. 311), Washington, D.C., U.S. Dept. Commerce Clearinghouse Federal Sci. and Tech. Inf. (JPRS 32,325), 254 p., [1965].

Garrison, L. E., 1967, Cretaceous-Cenozoic development of the continental shelf south of New England: Providence, Univ. Rhode Island, Ph.D. thesis, unpub., 100 p.

Garrison, L. E., and McMaster, R. L., 1966, Sediments and geomorphology of the continental shelf off southern New England: Marine Geology, v. 4, no. 4, p. 273–289.

Gibson, T. G., 1965, Eocene and Miocene rocks off the northeastern United States: Deep-Sea Research, v. 12, p. 975–981.

———1967, Strategraphy and paleoenvironment of the phosphatic Miocene strata of North Carolina: Geol. Soc. America Bull., v. 78, no. 5, p. 631–650.

Gibson, T. G., Hazel, J. E., and Mello, J. F., 1968, Fossiliferous rocks from submarine canyons off the northeastern United States: U.S. Geol. Survey Prof. Paper 600–D, p. D222–D 231.

Gibson, T. G., and Schlee, John, 1967, Fossiliferous rocks from the eastern side of the Tongue of the Ocean, Bahamas: Deep-Sea Research, v. 14, p. 691–702.

Heezen, B. C., and Sheridan, R. E., 1966, Lower Cretaceous rocks (Neocomian-Albian) dredged from Blake Escarpment: Science v. 154, no. 3757, p. 1644–1647.

Heezen, B. C., Tharp, Marie, and Ewing, Maurice, 1959, The floors of the oceans. I, The North Atlantic: Geol. Soc. America Spec. Paper 65, 122 p.

Hersey, J. B., Bunce, E. T., Wyrick, R. F., and Dietz, F. T., 1959, Geophysical investigation of the continental margin between Cape Henry, Virginia, and Jacksonville, Florida: Geol. Soc. America Bull., v. 70, no. 4, p. 437–466.

Hess, H. H., 1933, Interpretation of geological and geophysical observations: U.S. Hydrographic Office, Navy-Princeton Gravity Expedition to the West Indies in 1932, p. 27–54.

Hoffmeister, J. E., Stokman, K. W., and Multer, H. G., 1967, Miami limestone of Florida and its Recent Bahamian counterpart: Geol. Soc. America Bull., v. 78, no. 2, p. 175–190.

Hoskins, Hartley, 1967, Seismic reflection observations on the Atlantic continental shelf, slope, and rise southeast of New England: Jour. Geology, v. 75, no. 5, p. 598–611.

Hoskins, Hartley, and Knott, S. T., 1961, Geophysical investigation of Cape Cod Bay, Massachusetts, using the continuous seismic profiler: Jour. Geology, v. 69, no. 3, p. 330–340.

Houtz, R. E., and Ewing, J. I., 1963, Detailed sedimentary velocities from seismic refraction profiles in the western North Atlantic: Jour. Geophys. Research, v. 68, no. 18, p. 5233–5258.

———1964, Sedimentary velocities of the western North Atlantic margin: Seismol. Soc. America Bull., v. 54, p. 867–895.

Hurley, R. J., 1964, Bathymetry of the Straits of Florida and the Bahama Islands; Part III, Southern Straits of Florida: Bull. Marine Sci. Gulf and Caribbean, v. 14, no. 3, p. 373–380.

Hurley, R. J., Siegler, V. B., and Fink, L. K., Jr., 1962, Bathymetry of the Straits of Florida and the Bahama Islands; Part I, Northern Straits of Florida: Bull. Marine Sci. Gulf and Caribbean, v. 12, no. 3, p. 313–321.

Johnson, D. W., 1925, The New England-Acadian shoreline: New York, John Wiley & Sons, 608 p.

Joint Oceanographic Institutions' Deep Earth Sampling Program, 1965, Ocean drilling on the continental margin: Science, v. 150, no. 3697, p. 709–716.

Jordan, G. F., Malloy, R. J., and Kofoed, J. W., 1964, Bathymetry and geology of Pourtales Terrace, Florida: Marine Geology, v. 1, no. 3, p. 259–287.

Jordan, G. F., and Stewart, H. B., Jr., 1961, Submarine topography of the western Straits of Florida: Geol. Soc. America Bull., v. 72, no. 7, p. 1051–1058.

Katz, Samuel, and Ewing, Maurice, 1956, Seismic refraction measurements in the Atlantic Ocean; Part VII, Atlantic Ocean basin west of Bermuda: Geol. Soc. America Bull., v. 67, no. 4, p. 475–510.

Kaye, C. A., 1964, Outline of Pleistocene geology of Martha's Vineyard, Massachusetts: U.S. Geol. Survey Prof. Paper 501–C, p. C134–C139.

Klein, G. de V., 1962, Triassic sedimentation, Maritime Provinces, Canada: Geol. Soc. America Bull., v. 73, no. 9, p. 1127–1146.

Knott, S. T., and Hoskins, Hartley, 1968, Evidence of Pleistocene events in the structure of the continental shelf off the northeastern United States: Marine Geology, v. 6, p. 5–43.

Koons, E. D., 1941, The origin of the Bay of Fundy and associated submarine scarps: Jour. Geomorphology, v. 4, no. 3, p. 237–249.

———1942, The origin of the Bay of Fundy: A discussion: Jour. Geomorphology, v. 5, no. 2, p. 143–150.

Krause, D. C., Chramiec, M. A., Walsh, G. M., and Wisotsky, Serge, 1966, Seismic profile showing Cenozoic development of the New England continental margin: Jour. Geophys. Research, v. 71, no. 18, p. 4327–4332.

Kuenen, Ph. H., 1950, The formation of the continental terrace: Adv. Sci., v. 7, no. 25, p. 76–80.

McMaster, R. I., Lachance, T. P., and Garrison, L. E., 1968, Seismic-reflection studies in Block Island and Rhode Island Sounds: Am. Assoc. Petroleum Geologists Bull., v. 52, no. 3, p. 465–474.

Maher, J. C., 1965, Correlations of subsurface Mesozoic and Cenozoic rocks along the Atlantic Coast: Tulsa, Okla., Am. Assoc. Petroleum Geologists, 18 p.

Malloy, R. J., and Harbison, R. N., 1966, Marine geology of the northeastern Gulf of Maine: U.S. Coast and Geod. Survey Tech. Bull. 28, 15 p.

Menzies, R. J., Pilkey, O. H., Blackwalder, B. W., Dexter, D., Huling, P., and McCloskey, L., 1966, A submerged reef off North Carolina: Internat. Revue gesamten Hydrobiologie, v. 51, no. 3, p. 393–431.

Milliman, J. D., and Emery, K. O., 1968, Sea level during the past 35,000 years: Science, v. 162, no. 3858, p. 1121–1123.

Moore, D. G., and Curray, J. R., 1963a, Structural framework of the continental terrace, northwest Gulf of Mexico: Jour. Geophys. Research, v. 68, no. 6, p. 1725–1747.

———1963b, Sedimentary framework of the continental terrace off Norfolk, Virginia, and Newport, Rhode Island: Am. Assoc. Petroleum Geologists Bull., v. 47, no. 12, p. 2051–2054.

Murray, H. W., 1947, Topography of the Gulf of Maine, field season of 1940: Geol. Soc. America Bull., v. 58, no. 2, p. 153–196.

Newell, N. D., 1959, The coral reefs—Pt. 1, Questions of the coral reefs; Pt. 2, Biology of the corals: Nat. History, v. 68, no. 3, p. 119–131; no. 4, p. 226–235.

North American Geologic Map Committee, 1965, Geologic map of North America: Washington, D.C., U.S. Geol. Survey, 2 sheets, scale 1:5,000,000.

Northrop, John, and Heezen, B. C., 1951, An outcrop of Eocene sediment on the continental slope: Jour. Geology, v. 59, no. 4, p. 396–399.

Oldale, R. N., 1969, Seismic investigations on Cape Cod, Martha's Vineyard, and Nantucket and a topographic map of the basement surface from Cape Cod Bay to the islands: U.S. Geol. Survey Prof. Paper 650–B, p. B122–B127.

Oldale, R. N., and Tuttle, C. R., 1964, Seismic investigations on Cape Cod, Massachusetts: U.S. Geol. Survey Prof. Paper 475–D, p. D118–D122.

Oliver, J. E., and Drake, C. L., 1951, Geophysical investigations in the emerged and submerged Atlantic Coastal Plain; Part VI, The Long Island Sound area: Geol. Soc. America Bull., v. 62, no. 11, p. 1287–1296.

Pearse, A. S., and Williams, L. G., 1951, The biota of the reefs off the Carolinas: Elisha Mitchell Sci. Soc. Jour., v. 67, p. 133–161.

Pratt, R. M., 1966, The Gulf Stream as a graded river: Limnology and Oceanography, v. 11, no. 1, p. 60–67.

———1968, Atlantic Continental Shelf and Slope of the United States—Physiography and sediments of the deep-sea basin: U.S. Geol. Survey Prof. Paper 529–B, 44 p.

Pratt, R. M., and Heezen, B. D., 1964, Topography of the Blake Plateau: Deep-Sea Research, v. 11, no. 5, p. 721–728.

Roberson, M. I., 1964, Continuous seismic profiler survey of Oceanographer, Gilbert, and Lydonia submarine canyons, Georges Bank: Jour. Geophys. Research, v. 69, no. 22, p. 4779–4789.

Roberts, W. P., and Pierce, J. W., 1967, Outcrop of the Yorktown Formation (upper Miocene) in Onslow Bay, North Carolina: Southeastern Geology, v. 8, no. 3, p. 131–138.

Rona, P. A., and Clay, C. S., 1966, Continuous seismic profiles of the continental terrace off southeast Florida: Geol. Soc. America Bull., v. 77, no. 1, p. 31–44.

———1967, Stratigraphy and structure along a continuous seismic reflection profile from Cape Hatteras, North Carolina, to the Bermuda Rise: Jour. Geophys. Research, v. 72, no. 8, p. 2107–2130.

Sanders, J. E., 1960, Structural history of Triassic rocks of the Connecticut Valley belt and its regional implications: New York Acad. Sci. Trans., ser. 2, v. 23, no. 2, p. 119–132.

Schlee, John, 1964, New Jersey offshore gravel deposit: Pit and Quarry, v. 57, no. 6, p. 80–81.

Schlee, John, and Cheetham, A. H., 1967, Rocks of Eocene age on Fippennies Ledge, Gulf of Maine: Geol. Soc. America Bull., v. 78, no. 5, p. 681–684.

Shepard, F. P., 1930, Fundian faults or Fundian glaciers: Geol. Soc. America Bull., v. 41, no. 4, p. 659–674.

———1942, Origin of the Bay of Fundy—A reply: Jour. Geomorphology, v. 5, p. 137–142.

———1948, Submarine geology: New York, Harper & Brothers, 348 p.

Shepard, F. P., Trefethen, J. M., and Cohee, G. V., 1934, Origin of Georges Bank: Geol. Soc. America Bull., v. 45, no. 2, p. 281–302.

Sheridan R. E., and Drake, C. L., 1968, Seaward extension of the Canadian Appalachians: Canadian Jour. Earth Sci., v. 5, no. 3, pt. 1, p. 337–373.

Sheridan, R. E., Drake, C. L., Nafe, J. E., and Hennion, J., 1966, Seismic-refraction study of continental margin east of Florida: Am. Assoc. Petroleum Geologists Bull., v. 50, no. 9, p. 1972–1991.

Smith, M. C., 1963, The Long Island Sound sub-bottom topography in the area between 73°00′ W and 73°30′ W: New York, Columbia Univ., Fac. Pure Sci., unpub. M.S. thesis, 25 p.

Stetson, H. C., 1949, The sediments and stratigraphy of the east coast continental margin—Georges Bank to Norfolk Canyon: Massachusetts Inst. Technology and Woods Hole Oceanog. Inst., Papers in Physical Oceanography and Meteorology, v. 11, no. 2, p. 1–60.

Stetson, T. R., Squires, D. F., and Pratt, R. M., 1962, Coral banks occurring in deep water on the Blake Plateau: Am. Mus. Novitates, no. 2114, 39 p.

Stevenson, I. M., and McGregor, D. C., 1963, Cretaceous sediments in central Nova Scotia, Canada: Geol. Soc. America Bull., v. 74, no. 3, p. 355–356.

Swift, D. J. P., and Lyall, A. K., 1968, Reconnaissance of bedrock geology by sub-bottom profiler, Bay of Fundy: Geol. Soc. America Bull., v. 79, no. 5, p. 639–645.

Tagg, A. R., and Uchupi, Elazar, 1966, Distribution and geologic structure of Triassic rocks in the Bay of Fundy and the northeastern part of the Gulf of Maine: U.S. Geol. Survey Prof. Paper 550–B, p. B95–B98.

———1967, Subsurface morphology of Long Island Sound, Block Island Sound, Rhode Island Sound, and Buzzards Bay: U.S. Geol. Survey Prof. Paper 575–C, p. C92–C96.

Taney, N. E., 1961, Geomorphology of the south shore of Long Island, New York: U.S. Army Corps Engineers Beach Erosion Board Tech. Mem. 128, 91 p.

Torphy, S. R., and Zigler, J. M., 1957, Submarine topography of Eastern Channel, Gulf of Maine: Jour. Geology, v. 65, no. 4, p. 433–441.

Toulmin, Priestley, III, 1957, Notes on a peralkaline granite from Cashes Ledge, Gulf of Maine: Am. Mineralogist, v. 42, nos. 11–12, p. 912–915.

Tuttle, C. R., Allen, W. B., and Hahn, G. W., 1961, A seismic record of Mesozoic rocks on Block Island, Rhode Island: U.S. Geol. Survey Prof. Paper 424–C, p. C254–C256.

Tuttle, C. R., Koteff, Carl, and Hartshorn, J. H., 1960, Seismic investigations in the Connecticut River Valley, southern Massachusetts [abs.]: Geol. Soc. America Bull., v. 71, no. 12, pt. 2, p. 1994.

Uchupi, Elazar, 1965, Map showing relation of land and submarine topography, Nova Scotia to Florida: U.S. Geol. Survey Misc. Geol. Inv. Map I–451, 3 sheets, scale 1: 1,000,000.

———1966a, Topography and structure of Northeast Channel, Gulf of Maine: Am. Assoc. Petroleum Geologists Bull., v. 50, no. 1, p. 165–167.

———1966b, Structural framework of the Gulf of Maine: Jour. Geophys. Research, v. 71, no. 12, p. 3013–3028.

———1966c, Shallow structure of the Straits of Florida: Science, v. 153, no. 3735, p. 529–531.

———1966d, Topography and structure of Cashes Ledge, Gulf of Maine: Maritime Sediments, v. 2, p. 117–120.

———1966e, Map showing relation of land and submarine topography, DeSoto Canyon to Great Bahama Bank: U.S. Geol. Survey Misc. Geol. Inv. Map I–475, scale 1: 1,000,000.

———1967a, Slumping on the continental margin southeast of Long Island, New York: Deep-Sea Research, v. 14, no. 5, p. 635–638.

———1967b, The continental margin south of Cape Hatteras, North Carolina—Shallow structure: Southeastern Geology, v. 8, no. 4, p. 155–177.

———1968, The Atlantic Continental Shelf and Slope of the United States—Physiography: U.S. Geol. Survey Prof. Paper 529–C, 30 p.

Uchupi, Elazar, and Emery, K. O., 1967, Structure of continental margin off Atlantic coast of United States: Am. Assoc. Petroleum Geologists Bull., v. 51, no. 2, p. 223–234.

———1968, Structure of continental margin off Gulf Coast of the United States: Am. Assoc. Petroleum Geologists Bull. v. 52, no. 7, p. 1162–1193.

U.S. Coast and Geodetic Survey and U.S. Bureau of Commercial Fisheries, 1967 [Bathymetric maps of the Atlantic Continental Shelf and Slope from Delaware to outer Cape Cod]: U.S. Coast and Geodetic Survey, C & GS 0807N–51 through 57, 0808N–51 through 55, 0708N–51 through 53, 15 sheets, scale 1:125,000.

Umbgrove, J. H. F., 1946, Origin of continental shelves: Am. Assoc. Petroleum Geologists Bull., v. 30, no. 2, p. 249–253.

Veatch, A. C., and Smith, P. A., 1939, Atlantic submarine valleys of the United States and the Congo submarine valley: Geol. Soc. America Spec. Paper 7, 101 p.

Whitmore, F. C., Jr., Emery, K.O., Cooke, H. B. S., and Swift, D. J. P., 1967, Elephant teeth from the Atlantic Continental Shelf: Science, v. 156, no. 3781, p. 1477–1481.

Zarudzki, E. F. K., and Uchupi, Elazar, 1968, Organic reef alignments on the continental margin south of Cape Hatteras: Geol. Soc. America Bull., v. 79, no. 12, p. 1867–1870.

Zeigler, J. M., Hoffmeister, W. S., Giese, Graham, and Tasha, Herman, 1960, Discovery of Eocene sediments in subsurface of Cape Cod: Science, v. 132, no. 3437, p. 1397–1398.

Zurflueh, E. G., 1962, A magnetic map of the Long Island Sound and the southward continuation of geologic units in Connecticut [abs.]: Am. Geophys. Union Trans., v. 43, no. 4, p. 435.

U. S. GOVERNMENT PRINTING OFFICE : 1969 O - 359-634