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The Atlantic Continental Margin

Bruce C. Heezen

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BRUCE C. HEEZEN†

ABSTRACT

Turbidity currents, surface, and subsurface currents carry detritus from the land across the continental shelf to the adjacent continental slope where slumps and turbidity currents transport the sediment downslope for hundreds of miles to greater depths, and deep geostrophic contour currents transport it thousands of miles down-current in a direction parallel to the bathymetric contours. The combined effect of these processes has been to create a wide, thick, geosynclinal apron of sediment at the base of the continental slope.

Subsidence of the continental shelf has continued since mid-Mesozoic, carrying down Lower Cretaceous reefal limestones to depths of 5,000 meters off Florida. The subsidence of the Atlantic continental margin and the basement of the continental rise geosyncline apparently commenced in mid-Mesozoic time with the creation of abyssal depths in the steadily expanding Atlantic.

INTRODUCTION

What is a continental margin? First of all it is a transition which separates the two principal hypsometric levels of the earth. It is where the thick continental crust abruptly ends. To the continental drifter, it is either the broken edge at the rear of a drifting continent or the crumpled load ahead of a bulldozing continental mass. To the annular accretor, it is either the edge of the most recently consolidated ring or a filling geosyncline making ready for the next consolidation. What it is in a tectonic sense largely depends on the viewer's geophilosopy. However, there are some facts which must be fitted into any hypothesis.

The geological investigation of the Atlantic continental margin of the United States began with the early hydrographic surveys of the nineteenth century. The continental shelf was charted. Submarine canyons were discovered. Beginning in the 1880's, fishermen began bringing in rocks of Tertiary and Cretaceous age which they obtained on the continental slope, primarily in submarine canyons off the fishing banks. In the twentieth century, with the introduction of precision navigational systems, the United States Coast and Geodetic Survey did detailed, precision-controlled, bathymetric charting of the entire continental margin of the United States from Georges Bank to Cape Hatteras. These surveys revealed the detailed character of the submarine canyons and encouraged many investigators to make further studies.

Among these investigations are the important works of Shepard (1934) and Stetson (1936, 1938). Upon the founding of the Woods Hole Oceanographic Institution in the early 1930's, Stetson began an active program of dredging in the Georges Bank submarine canyons in order to determine the positions and depths of the outcrops of Tertiary and Late Cretaceous rocks. In his coring program on the continental slope between Georges Bank and Hudson Canyon, he recovered a few cores of Miocene and Eocene unconsolidated sediments, suggesting that outcrops were frequent on the continental slope (Stetson, 1949).

During the 1930's, an active geophysical program was begun by Maurice Ewing and his collaborators (1937-1956) which led to the publication of a series of ten papers entitled "Geophysical Investigations of the Emerged and Submerged Atlantic Coastal Plain". These papers, primarily based on seismic refraction and reflection investigations, revealed the structural form of the continental margin.

After World War II, the continental margin received much more attention. Over 400 sediment cores were taken in deep water (Ericson and others, 1961), thousands of miles of continuous seismic reflection profiles were obtained (Ewing and Ewing, 1964), and precision high resolution echo soundings revealed the detailed character of the morphology (Heezen and others, 1959).

The continental margin includes those physiographic provinces of the continents and of the oceans that are associated with the boundary between the two first-order, morphologic features of the earth (Fig. 1). Three categories of continental-margin provinces (Hee-

*Lamont Geological Observatory Contribution No. 1145

†Associate Professor of Geology, Department of Geology and Lamont Geological Observatory, Columbia University, Palisades, New York.
Regrettably the list of those whose efforts should be acknowledged is much too long to print here. I must, however, mention the particular contributions of the following: C. L. Drake, C. D. Hollister, R. J. Menzies, R. Sheridan, and Marie Tharp. The preparation of this paper was supported by the National Science Foundation Grant GA-580.

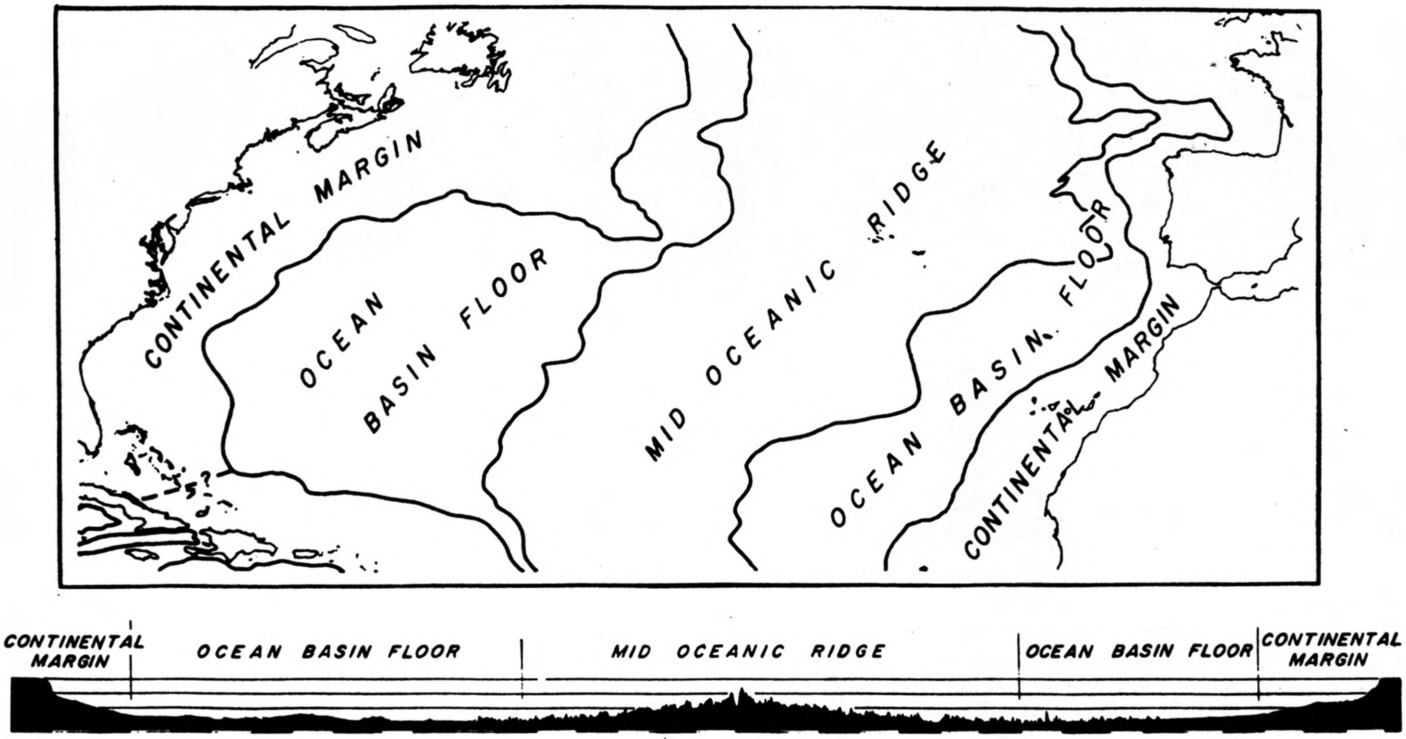

Fig. 1. The three major morphologic divisions of the ocean, illustrated by a trans-Atlantic profile from New England to the Spanish Sahara (after Heezen and others, 1959).

zen and others, 1959) can be distinguished: 1) submerged portions of the continental block; 2) the steep, seaward edge of the continental block; and 3) the margins of the ocean floor (Fig. 2). At first glance, the continental margin seems to have a great diversity of morphologic expression. On this basis, it has been generally inferred that radically different tectonic processes have been exerted from place to place along the continental margin. However, when comparing continental-margin profiles, it is found that this great diversity in morphological form is largely limited to the margins of the ocean floor (Fig. 3). This complexity largely disappears when the seismic-refraction results for this area are examined in more detail.

In their summary and synthesis of all geophysical investigations carried out on the eastern continental margin of North America be-

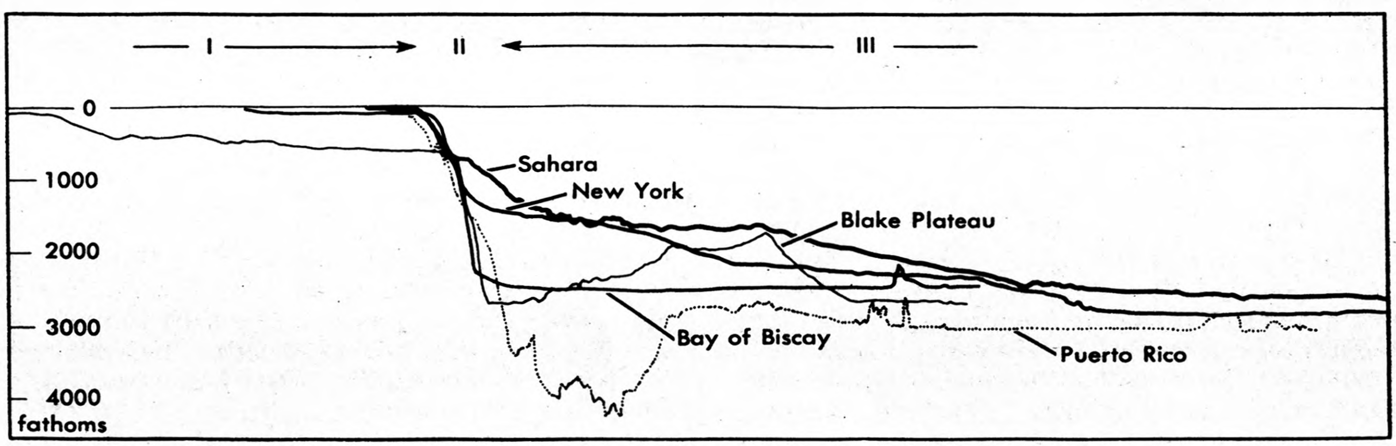

Fig. 2. Three categories of continental margin provinces. Representative profiles taken from various parts of the North Atlantic. Note the great similarity in form of the Category I provinces and the great diversity in expression in the Category III provinces, particularly in that portion of Category III closest to the boundary of the Category II provinces (after Heezen and others, 1959).

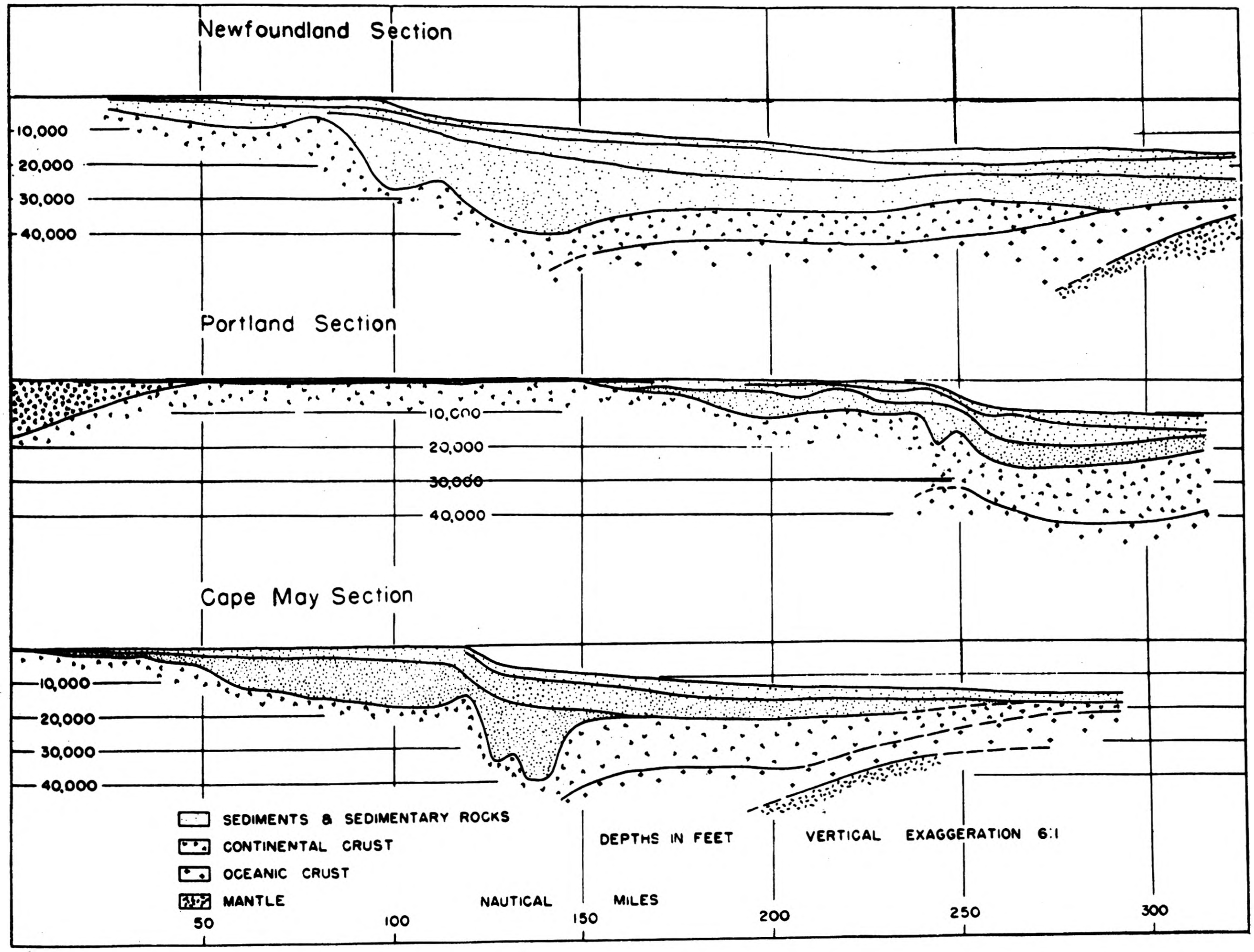

Fig. 3. Three structural profiles of the eastern continental margin of North America (after Drake and others, 1959).

tween 1936 and 1956, Drake and others (1959) delineated two thick linear accumulations of sediment. One of these sedimentary accumulations lies beneath the present continental shelf, the other was found beneath the upper continental rise, very close to the base of the continental slope. Thicknesses of 5 to 10 km (Figs. 3 and 4) were found in these two bands. Drake and others (1959) drew an analogy between these two sedimentary accumulations and the classic miogeosyncline and eugeosyncline as defined by Stille and Kay. In a now classic diagram (Fig. 5), they compared isopachous profiles of the present continental margin with the reconstructed profile of the Appalachian geosyncline worked out by Kay (1951). They inferred that the sedimentary accumulation beneath the continental shelf could be compared with the miogeosyncline and that the sediments contained in this geosynclinal accumulation must largely belong to the orthoquartzite suite which contains limestones and quartz-arenites and is largely devoid of volcanic rocks and graywackes. This inference was based in part on results of borings on the emerged coastal plain of the eastern United States and on dredgings on the continental slope where outcrops of older continental shelf sediments frequently occur. All the sediments found in the drill holes and outcrops range in age from Early Cretaceous to late Tertiary and can be ascribed more or less to the orthoquartzite suite. The assignment of the great sedimentary lenses at the base of the continental slope to the eugeosynclinal suite is more problematical. No drill holes have been made in this area of deep water, rocks rarely have been dredged from these depths, and sediment cores seldom penetrate through the Recent and Quaternary hemipelagic sedi-

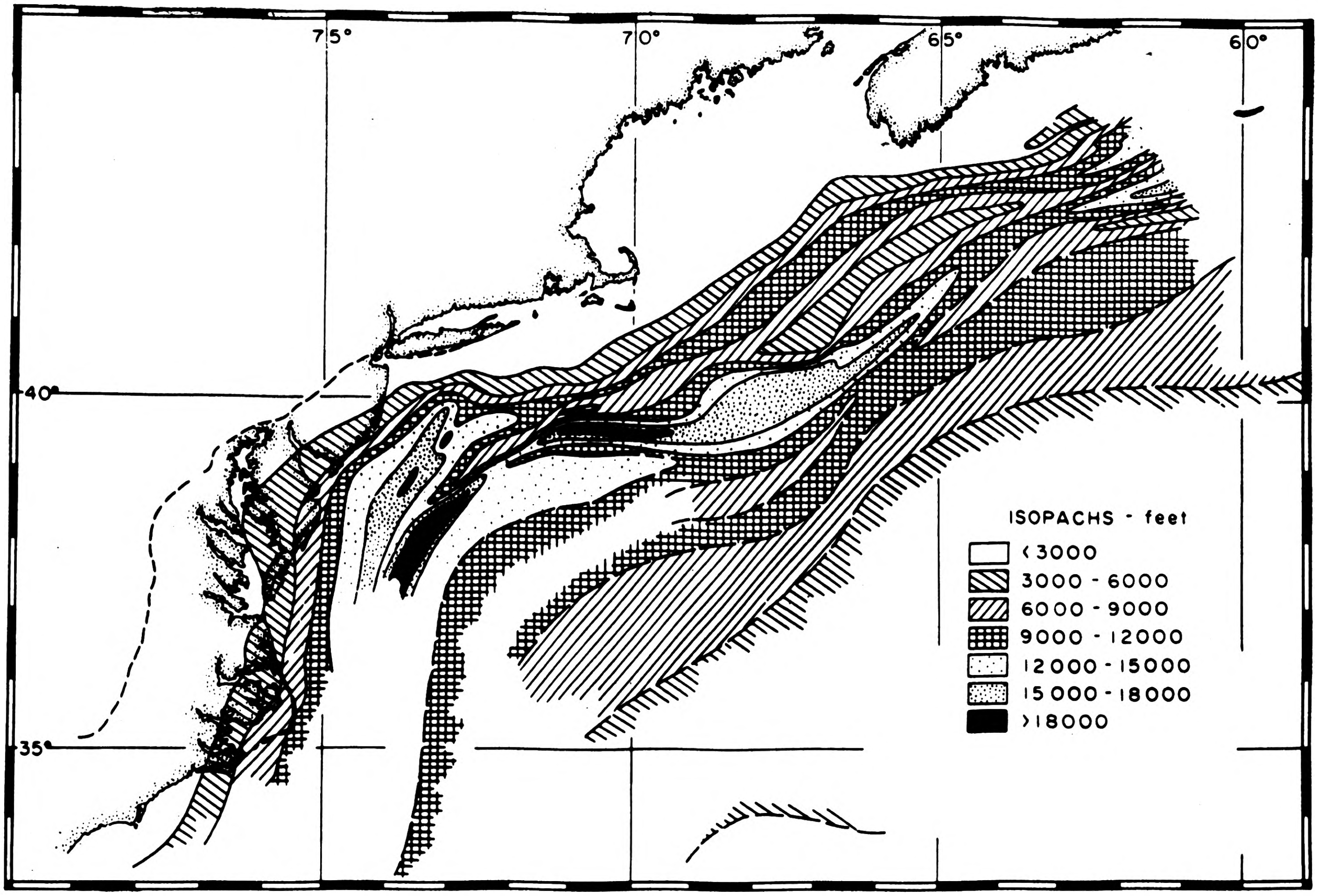

Fig. 4. Sediment thickness in the continental margin and ocean basin floor off northeastern North America (after Heezen and Drake, 1963).

ments. Occasionally, however, dredging on the walls of continental rise submarine canyons has revealed the existence of Miocene sediments which largely consist of green, pyritic, silty, foraminiferal lutites which can be described as hemipelagic.

Off New England, a line of seamounts crosses the continental margin and extends for several hundred miles out to sea. These seamounts were certainly ancient volcanoes, and during their active phase volcanic material must have spread considerable distances from their bases. Thus it seems likely that these volcanoes could have contributed the volcanic rocks which are characteristic of a eugeosyncline.

TURBIDITY CURRENTS

The flysch and graywackes which are characteristic of eugeosynclines have been interpreted as the products of turbidity current deposition, and flysch certainly bears a close similarity to many modern, deep-sea sediments (Nesteroff and Heezen, 1960). As early as the late nineteenth century, Forel suggested that the sablacustrine channel of the Rhone in Lac Leman was formed by a type of bottom current which might now be called a turbidity current. The mechanism he envisaged was that the cold, sediment-laden, river water which seasonally flows beneath the lake waters produces the characteristic leveed channel which occurs off the Rhone in eastern Lac Leman. Daly (1936) revived the turbidity current idea as an explanation for the submarine canyons which had up to that time been primarily interpreted as products of subaerial erosion at a time of lowered sea level. Daly's idea interested several investigators who made both model experiments and investigations in freshwater reservoirs and who found considerable evidence in favor of the hypothesis. However, for 10 or more years none of the experiments produced currents that could erode, and no evidence was found of the occurrence of turbidity currents in the ocean.

Sediment cores taken in 1947 and 1948 from submarine canyons and abyssal plains revealed detrital beds containing shallow-water Foraminifera, coarse silts and sands, and even gravel (Ericson and others, 1952). This material was first interpreted as evidence of a great eustatic lowering of sea level. However, it is not possible to lock up that much water in continental glaciers. Finally this idea had to be abandoned when it was found that normal pelagic sedimentation had gone on in shallower areas between canyons while vigorous transportation had been going on in the canyons. Thus a case for turbidity currents on the deep-sea floor emerged from the study of the sediment cores; however, many geologists and oceanographers remained unconvinced, and numerous alternative hypotheses were put forward. Obviously what was needed was evidence of modern, turbidity current activity on the deep-sea floor.

Heezen and Ewing (1952) inferred that the cable failures which occurred following the 1929 Grand Banks earthquake were due to the motion downslope of turbidity currents which converged from various sources near the epicenter and flowed along a broad front over 200 miles wide for a distance of more than 300 miles to the south.

A series of sediment cores later revealed an uppermost graded layer of sediment on the abyssal plain south of the epicenter. From the sequence and interval between the successive breaks, it was possible to determine the velocity of the current. The velocity turned out to be amazingly high, being over 50 knots on the continental slope and over 14 knots at the base of the continental rise. These high velocities were hard to comprehend and were not at first accepted. Some claimed that the sequence and pattern were merely coincidental. In 1954, an earthquake occurred in Algeria that produced a similar sequence of breaks in the Mediterranean and revealed similar velocities. A search through old records revealed that the 1908 Messina earthquake had produced one later cable break which suggested a current traveling at an average velocity of more than 10 knots over a distance of 100 miles (Ryan and Heezen, 1965).

A number of major rivers of the world frequently produce turbidity currents at their

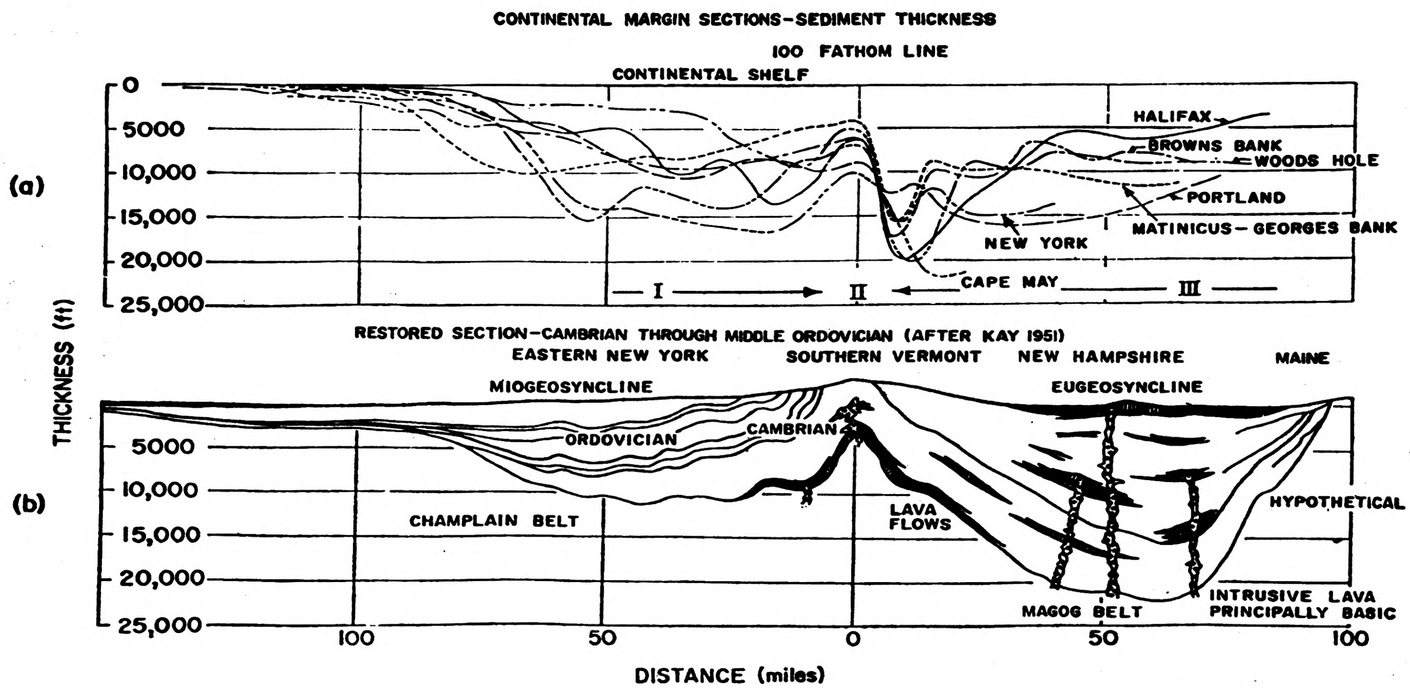

Fig. 5. Paleozoic and modern geosynclines: a) Isopachous sections off the east coast of North America (after Drake and others, 1959); b) Restored geosynclinal section of the Appalachian geosyncline in eastern North America (after Kay, 1951). Three categories of physiographic provinces are indicated in the top profile. Note that the inner, or miogeosynclinal thickness of sediment occurs below the continental shelf, that the basement ridge between the two troughs lies beneath the continental slope, and that the eugeosynclinal thickness correlates well with the deep trough on the landward margin of the continental rise. The typical orthogeosyncline as depicted in the restored profile of the Appalachian geosyncline seems to be duplicated in the sediment-filled troughs of the continental margin off eastern North America. Similar patterns have been found elsewhere in the continental margins in other parts of the world.

mouths. The most notable are the Congo and Magdalena, each of which cause some 50 individual flows per century. In terms of the formation of submarine canyons and deep-sea sediment cones and fans, the turbidity currents occurring off the mouths of rivers have a great importance. The river collects the sediment, brings the sediment to the river mouth, and may trigger the flow. In such favored locations, turbidity currents can occur at relatively short intervals, each from a single source, and, conceivably, can erode canyons in the continental slope and can build alluvial plains and deep-sea channels on the margin of the ocean floor.

It is now widely held that the continental rise was constructed at the foot of an originally faulted continental slope by a series of coalescing deep-sea fans or cones built by downslope, turbidity current transport at the mouths of submarine canyons (Menard, 1955) and by the seaward diffusion of very fine terrigenous lutite through the water column. This simple picture, although essentially correct, cannot be complete, for it fails to explain the nearly identical form of successive profiles across the continental rise and the characteristic lack of irregularities seen on profiles of the continental rise in most parts of the world, and it completely fails to explain the huge sediment drifts found east of the Bahamas, Florida, Georgia, and the Carolinas.

CONTOUR CURRENTS

Recent investigations indicate that contour-following bottom currents involved in the deep thermohaline circulation of the world ocean are perhaps the most important factor in the transportation and deposition of sediments on the continental rise and that the currents probably shape the continental rise and the associated sedimentary drifts (outer ridges).

The continental rise, a broad, uniform, gently sloping and smooth-surfaced wedge of sediments, 100 to 1,000 km wide and 1 to 10 km thick, is covered with—and may be largely composed of—monotonously homogeneous gray lutites. These terrigenous sediments were deposited at comparatively high rates. Postglacial rates ranged from 5 to 50 cm per 1,000 years, and even higher rates predominated during the Pleistocene. Identifiable turbidites constitute a small proportion of the glacial and postglacial sediments of the continental rise (Ericson and others, 1961; Heezen and others, 1959). Because hemipelagic lutites are derived almost entirely from the denudation of land, a seaward diffusion of lutite is generally assumed, but transporting mechanisms and direction of transport are difficult to infer.

The continental rise off the eastern United States merges south of Cape Hatteras with the broad, southeasterly plunging Blake-Bahama Outer Ridge. Seismic investigations (Katz and Ewing, 1956; Hersey and others, 1959; Ewing and Ewing, 1964) indicate that this southward extension of the continental rise is an undeformed sedimentary wedge similar in seismic velocity and geologic structure to the normal continental rise, sedimentary wedge found farther north.

The outer ridge is separated from the continent by the Blake-Bahama Basin and by the broad Blake Plateau (Fig. 6). Terrigenous sediments derived from southeastern United States are barred from the eastern Blake Plateau, the Blake Escarpment, and the western Blake-Bahama Basin by the vigorous northerly transport of the Gulf Stream which flows at velocities of 100 to 300 cm/sec along the western margin of the Blake Plateau. Thus the existence of the accumulation of a continental-rise-type sediment, 1,000 km seaward of Florida, suggests a north-to-south abyssal transport of terrigenous sediments.

The growing Gulf Stream draws over 12 million m^3/sec of the Antilles Current (Wüst, 1924, 1933, 1957; Stommel, 1965) across the Blake Plateau. Transportation by this westerly flow may account for the relatively thin veneer of Recent sediments and the frequent exposure of Tertiary and Mesozoic marls on the Blake Plateau and Blake Escarpment. Numerous unconformities were encountered in the reduced Tertiary carbonate section penetrated by five shallow drill holes (Bunce and others, 1965). This suggests that a vigorous but fluctuating westerly transport had persisted throughout the Tertiary. Some of this detritus, including all of the bedload, must be deposited somewhere near Cape Hatteras where the Gulf Stream flows into the deep Atlantic; but, there are no obvious topographic features directly east of Cape Hatteras which might represent a pile of detritus. Although the Gulf Stream apparently has locally eroded the Blake Plateau, the stream's main effect has been to prevent terrigenous deposition seaward and to inhibit deposition of the normally thin pelagic carbonate oozes.

Slope water off northeastern North America is bluish or grayish green, while the Gulf Stream and Sargasso Sea are a clear deep ultramarine. Slope water, which north of Hatteras lies at the surface between the Gulf Stream and the continental slope and laps up

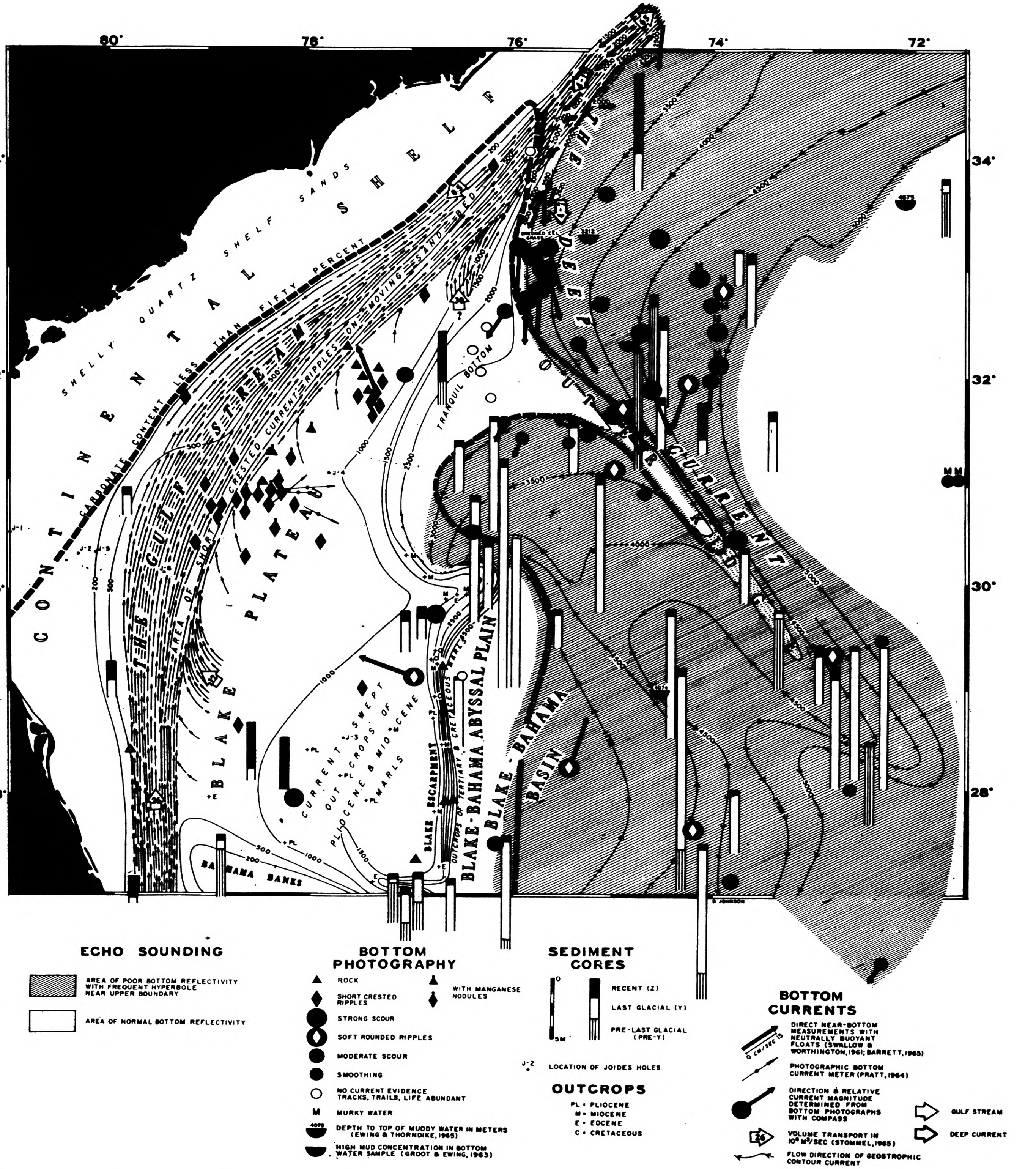

Fig. 6. Bottom currents and sediments on the Blake Plateau and Blake-Bahama Outer Ridge. Short-crested ripples, manganese nodules, and Tertiary outcrops are found beneath the Gulf Stream which acts as a barrier to seaward transport of terrigenous sediment. The outer ridge is formed by rapid deposition of lutite from the southerly flowing sediment-laden Western Boundary Undercurrent which flows parallel to the contours. Thirty-three additional photographic stations (not shown) obtained from R/V *Eastward* in March, 1966, further support the current pattern indicated (after Heezen and others, 1966).

on the continental shelf, not only supports a much richer biota than the Sargasso Sea, but it also contains at least an order of magnitude more suspended matter and is, therefore, a potentially significant intermediate source of terrigenous lutite. Bottom water velocities on the continental shelf almost always exceed those required for the erosion and transportation of silt and clay. Thus lutite, eroded from the continents, largely bypasses the continental

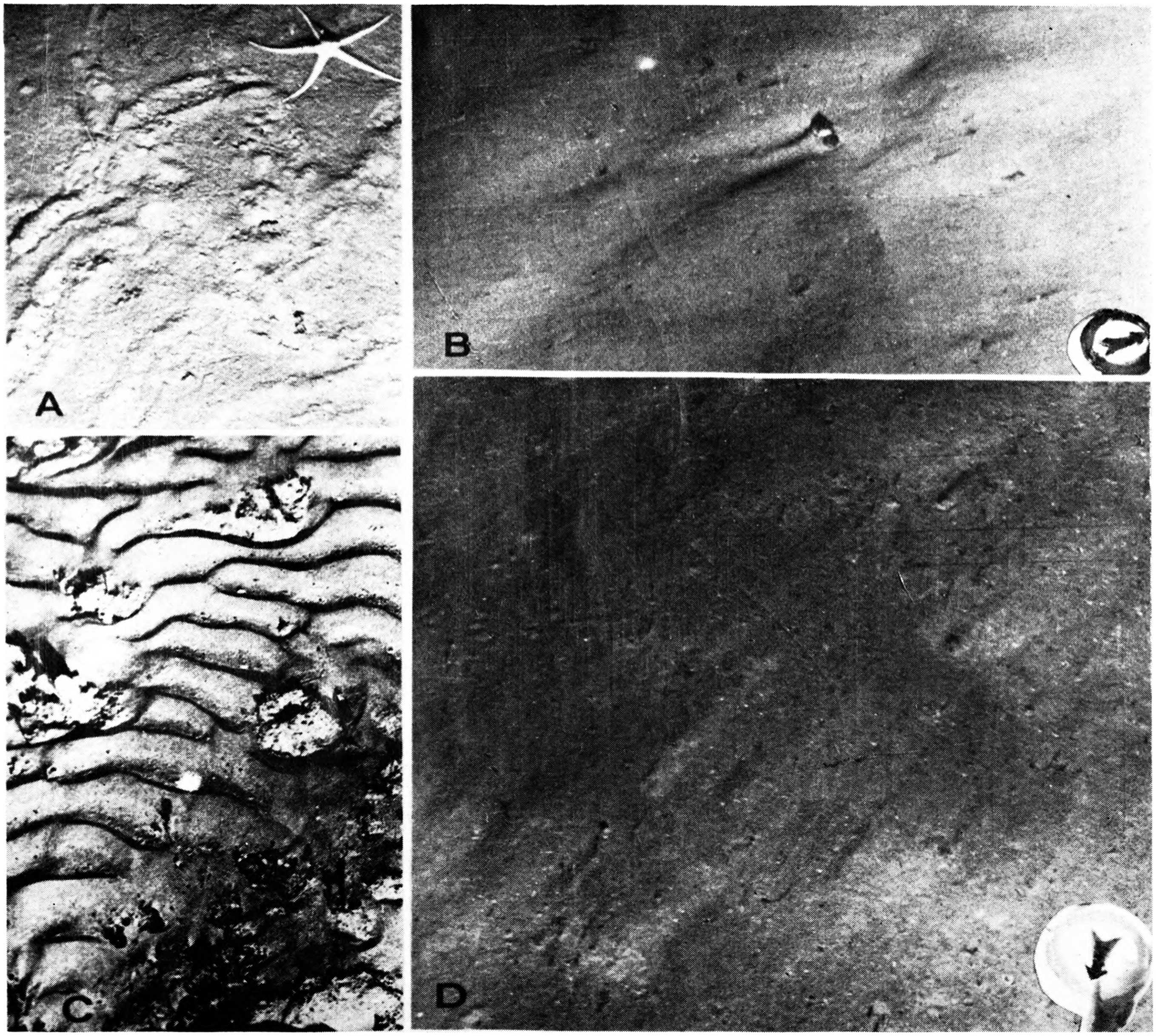

Fig. 7. Bottom photographs of the Blake Plateau and Blake-Bahama Outer Ridge. (A) Tranquil bottom on crest of outer ridge near base of continental slope. In this area, four stations reveal abundant life and no current evidence. E41-58-1; 2,164 m; 32° 24′ N., 76° 18′ W. (B) Current lineation east of crest of the outer ridge. At 14 stations from both the eastern side of the outer ridge between 3,000 and 5,000 m and from the base of the continental slope off North Carolina, abundant lineations indicate a southerly current flowing precisely parallel to the contours. The compass is 10 cm in diameter. E41-49-8; 3,975 m; 31° 42′ N., 74° 49′ W. (C) Short-crested current ripples beneath the Gulf Stream on the Blake Plateau. Surface of the Blake Plateau is characterized by rippled sand, manganese nodules, or manganese-encrusted tabular outcrops of Tertiary sediment. E19-D; 872 m; 30° 52′ N., 78° 41′ W. (D) Current lineations made by the southerly flowing Western Boundary Undercurrent east of the crest of the outer ridge near the base of the continental slope. Direct current measurements nearby indicate a southerly flowing near-bottom current of up to 18 cm/sec (Swallow and Worthington, 1961). E41-61-17; 3,183 m; 32° 51′ N., 75° 45′ W.

shelf where sand and gravel are the predominant sediment. Upon reaching the slope water, much of this fine material remains in suspension and drifts to greater depths.

The pronounced seaward dip of near-bottom isotherms frequently observed on the continental slope and continental rise constitutes the first evidence of relatively strong, deep contour-following, geostrophic currents (Stommel, 1965). Pressure gradients indicated by the inclined isopycnals must be opposed by an opposite and equal force which would seem to be provided by a current on which the Coriolis forces are acting normal to the direction of motion (to the right in the northern hemisphere). These contour currents flow along isopycnals which are approximately parallel to the bathymetric contours.

Near-bottom velocities up to 18 cm/sec have been observed in the southerly flowing Western Boundary Undercurrent east and southeast of Cape Hatteras, east of Cape Cod, and off Greenland and Labrador (Swallow and Worthington, 1961). These measured velocities are competent to transport all the sediment sizes generally found on the continental rise (Heezen and Hollister, 1964). However, most measured or calculated current velocities in the deep sea are closer to the minimum values required for transportation of continental rise sediments.

During cruises of Duke University's RV *Eastward,* we have investigated the nature and orientation of the effects of geostrophic contour currents on bottom sediments of the continental rise and the Blake-Bahama Outer Ridge. Deep-sea cameras, equipped with punch core and compass, and a precision echo sounder have been the principal tools used (Heezen and others, 1966).

Along the base of the continental slope off North Carolina and along the eastern flank of the outer ridge, current lineations consisting of streamers of sediment deposited in the lee of burrow mounds and other objects on the bottom were observed. In depths between 3,000 and 5,000 m, abundant lineations indicate a southerly current which flows parallel to the local contours (Figs. 6 and 7). Where current lineations are abundant, the bottom is smooth and remarkably free of benthic life, and the water appears muddy.

On the Blake Plateau, the Recent is variable in thickness and consists of reworked, shelly green-sand and phosphorite on the landward side of the Gulf Stream, reworked coral sand and manganese nodules beneath the Gulf Stream, and globigerina ooze on the outer part of the plateau. Near the seaward edge of the Blake Plateau, the Pleistocene is absent, and Pliocene or Miocene marl is either exposed at the surface, covered by a few centimeters of ooze, or coated with a maganese crust (Ericson and others, 1961; Heezen and others, 1959). The outer ridge, on the other hand, is covered by a thick sequence of Quaternary sediments.

The thickness of the Recent (Ericson and others, 1961; Heezen and others, 1959) increases from the Hatteras Abyssal Plain toward a maximum of over 1 m on the eastern flank of the outer ridge then decreases markedly and reaches a minimum beneath the Western Boundary Undercurrent on the east flank of the ridge crest. West of the crest, the thickness of the Recent ranges from 30 to 80 cm and decreases to 20 cm on the Blake-Bahama Abyssal Plain (Fig. 8). To the east, numerous thin laminae of silt and fine sand are intercalated in grayish-brown and rose colored lutites, whereas, to the west silts are absent, and the rose-gray hue becomes increasingly diluted and is not observed in the westernmost cores.

Ericson first discovered rose and rose-gray lutites in glacial age sediments on the continental slope and continental rise off eastern North America. Subsequently, red and brick-red marine tills were described from the Cabot Strait and adjacent continental slope (Heezen and Drake, 1964). Deposition of these red detrital sediments ceased before the end of the last glaciation (Y). Thus the rose, rose-gray, and light rose-gray lutites found on the outer ridge may have been derived from Triassic and Paleozoic red sediments of the Gulf of St. Lawrence and transported 3,000 km to the south by the southerly flowing Western Boundary Undercurrent. The rose-gray sediment is also found in earlier glacial (W and U) sediments but not in interglacial sediments.

In a water sample collected 200 m above the east flank of the Blake-Bahama Outer Ridge (Groot and Ewing, 1963), suspended sediment was found in a concentration of about 1×10^{-6} g/cm^3. Subsequently, a near-bottom layer of muddy water a few hundred meters thick was found between the continent and the abyssal plain. A rough calculation suggests that approximately an order of magnitude more sediment was transported past the outer ridge in postglacial times than was deposited on it. These rough calculations show that the transport of lutite in the Western Boundary Undercurrent is adequate to build the Recent and

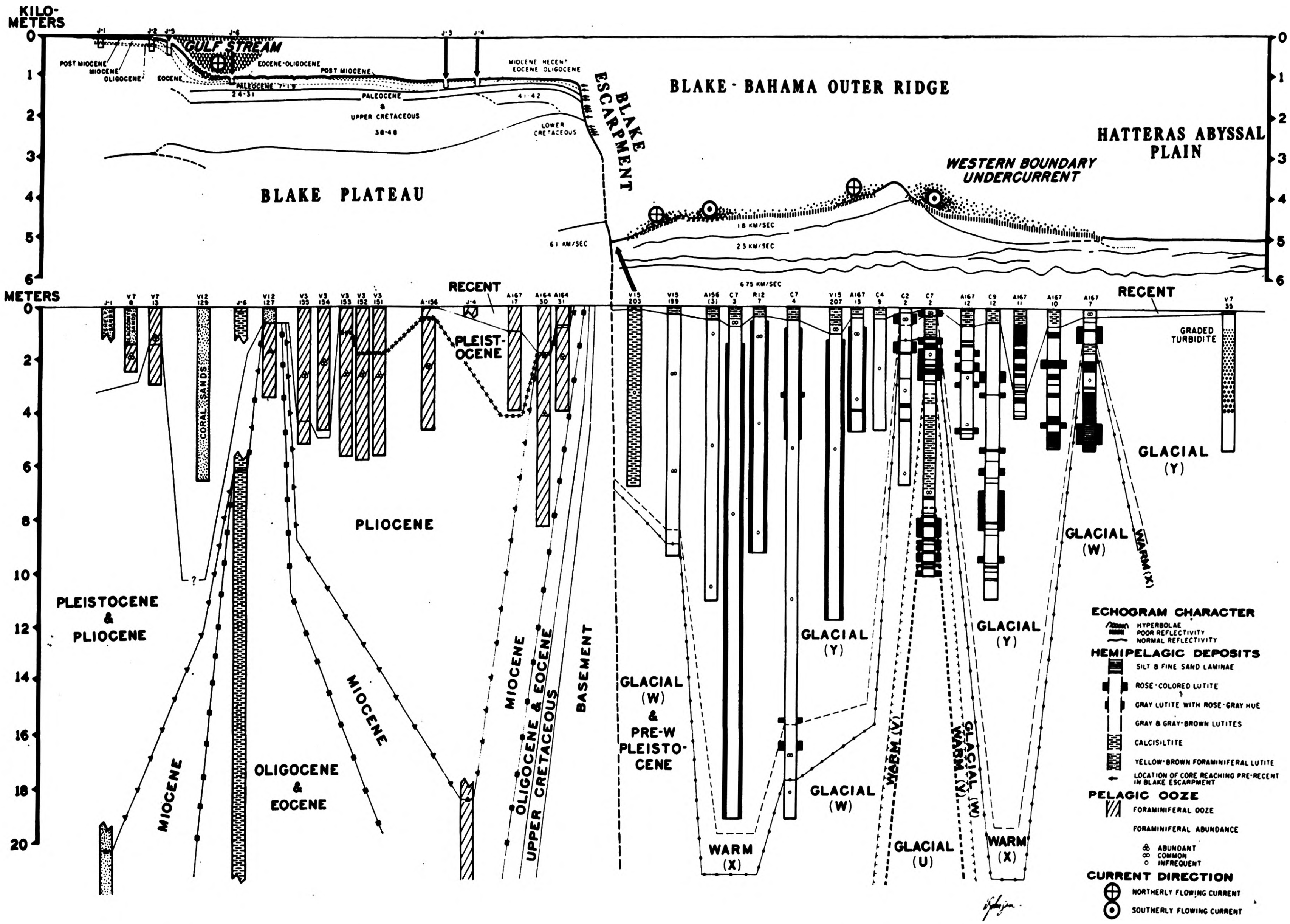

Fig. 8. Profile across Blake Plateau and Blake-Bahama Outer Ridge (after Heezen and others, 1966). Thick Pleistocene and Recent wedges of lutite on the Blake-Bahama Outer Ridge thin eastward toward the Hatteras Abyssal Plain and westward toward the Blake-Bahama Abyssal Plain in response to decreased volume transport of the Western Boundary Undercurrent (Katz and Ewing, 1956; Hersey and others, 1959; Ewing and Ewing, 1964; Bunce and others, 1965). The greatest water depth west of the outer ridge occurs at the base of the Blake Escarpment, precluding any significant seaward sediment dispersal. Climatic zones are based on foraminiferal assemblages (Ericson and others, 1961).

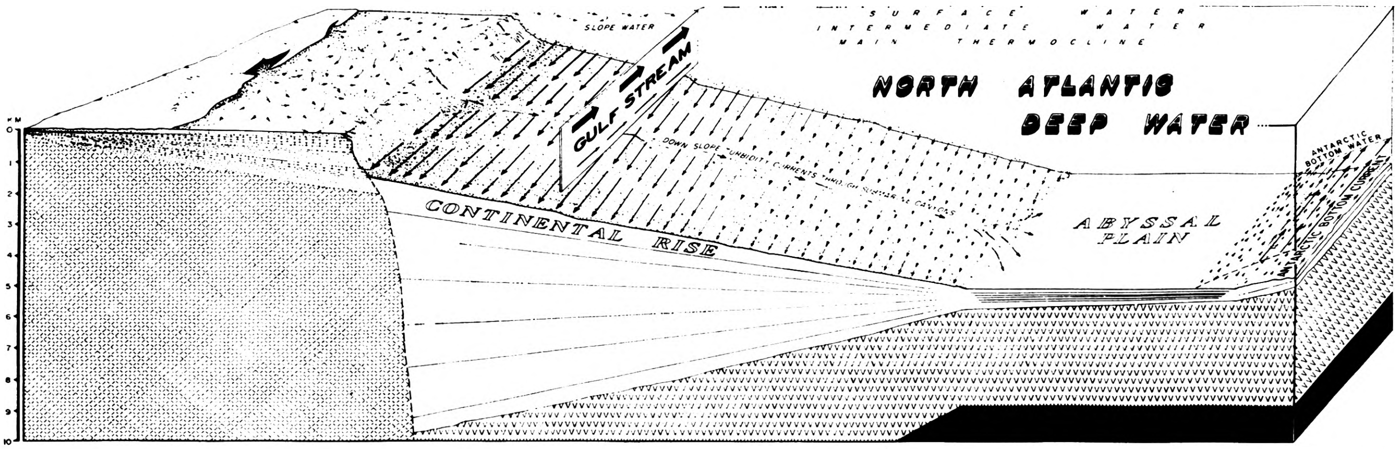

Fig. 9. Shaping of the continental rise by geostrophic contour currents. Arrows indicate prevailing bottom currents. Continental and oceanic crust is shown by patterns; mantle is solid black. Sedimentary rock is shown by conventional symbols, turbidites by horizontal ruling, and rise deposits by open wedges. In addition to the measurements reported here, the transport directions are supported by further oriented photographs of current lineations obtained in November, 1965, on the continental rise off Nova Scotia and on the western Bermuda Rise. With the exception of the shifting position of the Gulf Stream, this schematic diagram, drawn on the basis of an average section off eastern North America, is intended to illustrate the principal processes shaping a "normal continental rise" in any part of the world.

last glacial (Y) thicknesses observed on the outer ridge. Turbidity currents account for the sands and gravels which underlie the perfectly flat, strongly reflecting abyssal plains. They also account for the gravel and sand in submarine canyons and for the finer sediments in natural levees and abyssal cones, but they fail to account for the uniform shape and stratification of the enormous accumulation of continental rise lutite. Massive transport of continental rise sediment parallel to the contours for at least 1,500 km is demonstrated by the construction of the Blake-Bahama Outer Ridge. This illustrates the powerful smoothing potential of deep geostrophic contour currents in the shaping of the continental rise (Fig. 9). The characteristic, downslope thinning wedges of sediment, which when stacked one upon another comprise the continental rise, appear to gain their shape through controlled deposition by deep, geostrophic contour currents.

GRAVITY TECTONICS

In 1961, C. L. Drake, aboard RV *Vema,* made a seismic reflection profile from Cabot Strait southeastward across the area affected by the Grand Banks earthquake. This profile, illustrated in Figures 10 and 11, is extremely instructive. It reveals what appears to be a large gravitational slump which is 1,200 feet thick and over 60 miles long, and is possibly of greater width (Heezen and Drake, 1964).

These data add some significant points to the sequence of events which occurred in 1929. The epicenter of the 1929 Grand Banks earthquake was on the continental slope. A number of cables on the continental slope broke instantly. The first delayed break occurred 59 minutes later, approximately 60 miles south of the epicenter, and thence a sequence of breaks occurred for the next 12 hours. A difficult point to explain—and, in fact, a point not explained in the original paper by Heezen and Ewing (1952)—was that the cable which broke 59 minutes later lay but 10 miles south of a cable which broke at the instant of the quake. This seems difficult to reconcile with the fact that a tangent to the travel-time curve drawn through the 59-minute point indicates a velocity exceeding 50 knots. Thus, if the turbidity current had originated from the foot of the slump or slumps, it certainly would not have taken an hour to traverse less than 10 miles. It, therefore, has to be assumed that the origin of the turbidity currents lay somewhere within the epicentral area; that is, in that area in which all the cable breaks occurred instantaneously. In fact, by extrapolating the travel-time curve, the most reasonable position for the point of generation of the turbidity currents seems to have been near the instrumentally located epicenter. The seismic reflection profile indicates that the sole plane of the gravitational slide crops out a few miles upslope from the cable which broke with a delay of 59 minutes. Thus, it appears that the earthquake triggered a gravitational slide of unknown magnitude, that this slide broke the cables in the so-called epicentral area, and that the earthquake also generated other slides which transformed into turbidity currents and flowed around and in part over the gravitational slide and subsequently traveled on to the abyssal plain to the south.

The fact that the cable 5 miles upslope from the outcrop of the gravitational slide broke instantaneously indicates that the gravitational slide could not have moved more than 5 miles; otherwise, the break of that cable would not have been instantaneous. We certainly have no indication how much movement did occur, except that it was probably at least several feet in order to cause the appropriate damage to the cables which failed instantaneously within and along the margin of the slump.

Thus from one single trigger mechanism, the Grand Banks earthquake, we observe two types of gravitational phenomena: 1) the turbidity currents which caused the sequence of delayed breaks and 2) the gravitational slump which produced the instantaneous failure of many cables over a wide but smaller area. Both phenomena occurred on the continental rise above a thick geosynclinal pile of sediment. Such phenomena can certainly be assumed to have occurred throughout the deposition of this thick accumulation. We thus have a significant indication that the modern "geosyncline" which lies beneath the continental rise contains gravitational overthrusts which occurred as sedimentation continued. Because these geosynclinal lenses show no evidence of being affected by compression or uplift, the thrusting must have occurred during the sedimentation stage and be purely a gravitational phenomenon not involved in the orogenic deformation of the geosyncline.

SUBMARINE OUTCROPS

Cretaceous and Tertiary rocks crop out on the continental slope off eastern North America. These outcrops, originally discovered by fishermen in the late nineteenth century, were investigated more thoroughly by Henry Stetson on board the RV *Atlantis* during the early 1930's. Although the outcrops are most conspicuous on the walls of the submarine canyons, they apparently occur also on the continental slope in inter-canyon areas. A study

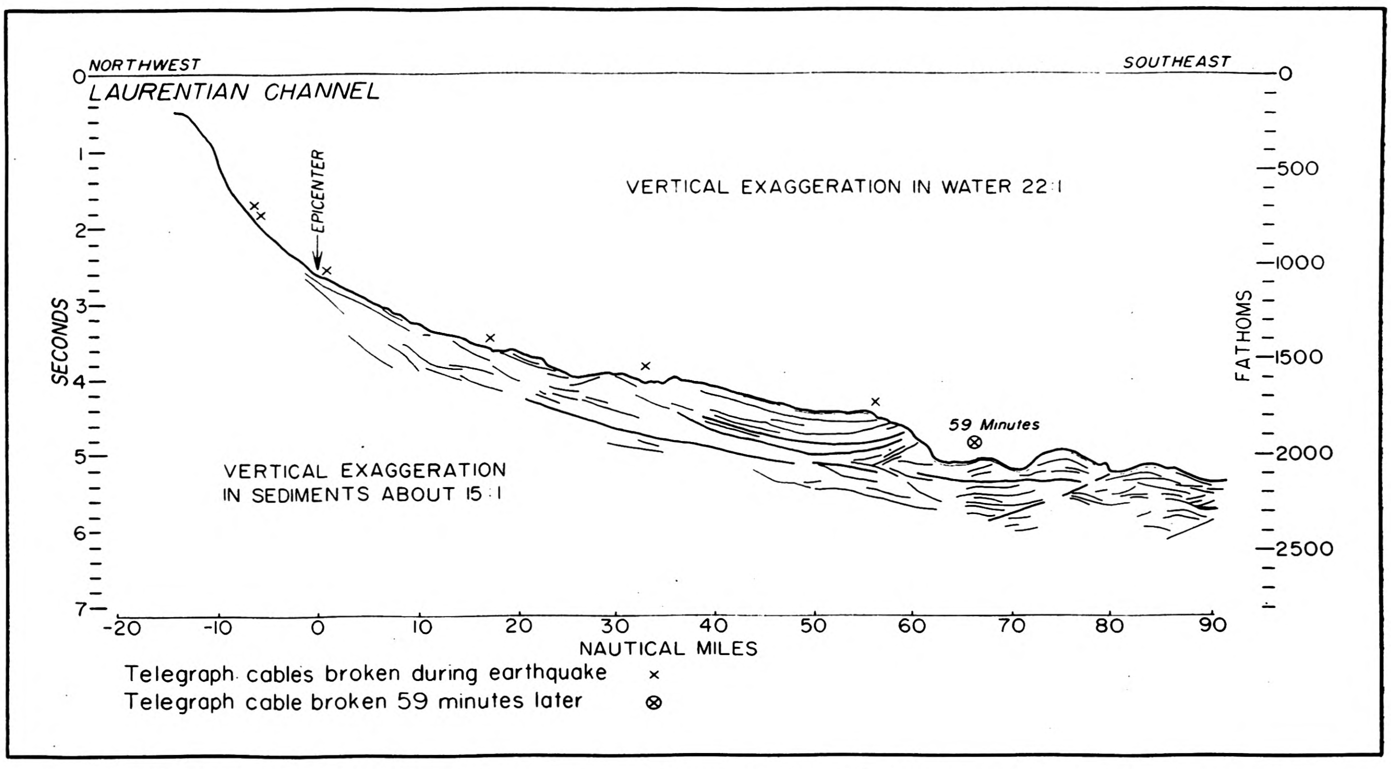

Fig. 10. Grand Banks slump. This profile is a tracing of the seismic reflection records made along a profile from the Laurentian Channel across the continental slope and continental rise south of the Grand Banks. Shots were fired at approximately one-half mile intervals. The charges were floated above the critical depth to avoid the bubble pulse phenomenon. The location of this profile is shown by the dotted line in Figure 11. Note that the sole plane of the slump crops out approximately 10 miles upslope from the first delayed cable break and that all cables crossing the area of the slump were broken at the instant of the earthquake (after Heezen and Drake, 1964).

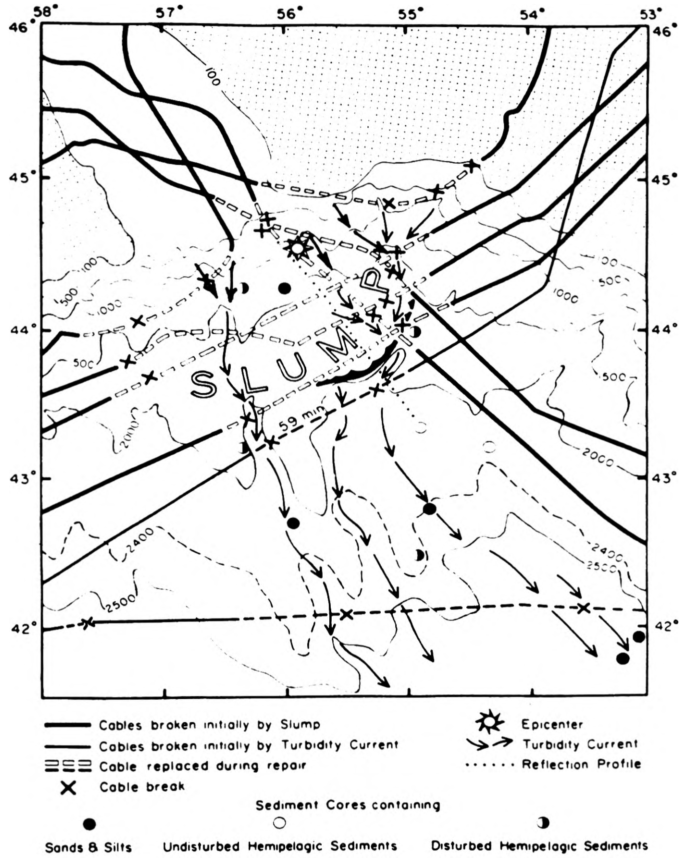

Fig. 11. Map of the Grand Banks slump. All cables within about 60 miles south of the epicenter of the Grand Banks earthquake broke at the instant of the earthquake. A sequence of later cable failures occurred to the south, the first one occurring 59 minutes after the earthquake. The first two of the cables to break following the earthquake are indicated in this chart. The outcrop of the sole plane of the slump is indicated in the conventional manner. Within the area of this map, turbidity currents seem to have been concentrated into at least three separate channels. Sediment cores taken between the channels indicate undisturbed or slightly disturbed hemipelagic sediments, while cores taken along the axes of these channels revealed turbidity current deposited sands and silts (after Heezen and Drake, 1964).

of the structural benches in the topographic profiles off the eastern United States together with the results of the dredging operations of Stetson and others has led Heezen and others (1959) to propose that the beds within the continental shelf crop out on the continental slope and that these beds were truncated on the seaward slope by erosion.

The Blake Escarpment, a precipitous declivity which separates the 1,000 m depth of the Blake Plateau from the 5,000 m depth of the Blake-Bahama Basin (Heezen and others, 1959), extends from 27° to 30° North latitude as a uniform and nearly straight north-south feature (Fig. 13). Prominent benches occur at 1,400 m and at 3,000 m (Fig. 12). The gradient below 3,000 m often exceeds 1:3.

Miocene and Eocene marls were discovered on the Blake Plateau in 1949 and 1950 (Ericson and others, 1952). In 1951, I conducted a coring program on the escarpment in an attempt to find outcrops of still older sedimentary units. The Upper Cretaceous and Tertiary rocks of the coastal plain were found to crop out along the escarpment where they seem to form prominent benches (Pratt and Heezen, 1964). Cores taken low on the escarpment included within Recent sediments fragments of limestone and dolomite thought to be debris from outcropping Cretaceous rocks. In several instances, after hitting the scarp below 2,400 m, the coring apparatus came up empty and badly damaged through impact with hard rock.

Seismic methods (reflection and refraction) have been used on the Blake Plateau to trace distinct seismic horizons from wells in Florida and the Bahamas to the benches of the Blake Escarpment (Ewing and others, 1966a; Sheridan and others, 1966). The bench at the 1,400 m depth is formed by the cropping out of a reflector within the Upper Cretaceous (#4, Fig. 12). The observed relatively high velocities, which could be confused with crystalline basement velocities, are very similar to those found in the Lower Cretaceous limestones, dolomites, and evaporites of southern Florida and the Bahamas. Extrapolations from the Andros Island deep test hole suggest that the top of the Lower Cretaceous dolomites may crop out in depths of 3,000 to 3,500 m on the walls of the nearby Northeast Province Channel (Maher, 1965) and may form the 3,000 m bench found on the Blake Escarpment.

The velocities observed (5.1 to 5.2 km/sec) are indicative of well consolidated rocks which can not normally be sampled by deep-sea coring apparatus. We first dredged on the Blake Escarpment early in 1966 from Duke University's RV *Eastward*. Of 13 dredge lowerings made on the escarpment in depths of 2,300 to 4,800 m, four hauls were productive (Fig. 13). All the rocks recovered were carbonates and resembled the formations of the coastal plain sequence of Florida and the Gulf Coast. The rocks obtained on the steep escarpment in depths of 3,000 to 4,800 m are shallow water, algal calcarenites, Aptian to Neocomian in age. In depths less than 2,400 m, deeper water calcilutites of Albian age were obtained (Heezen and Sheridan, 1966).

The Neocomian algal limestones recovered from the Blake Escarpment are the oldest in-place rocks so far dredged from the floor of the deep Atlantic. Bottom photographs of the escarpment reveal that the limestones crop out both as ledges of bedded strata and as massive rocks (Fig. 14). The steepness of the slope is apparent in the compass-oriented photographs which show the bottom dropping off sharply to the east.

Velocities of compressional elastic waves measured on a few rocks from each dredge haul are reasonable for limestones and dolomites of relatively low porosity and can be compared favorably, for the most part, with those determined in nearby refraction profiles (Sheridan and others, 1966).

Important geologic implications are obvious from the discovery of these Lower Cretaceous rocks on the Blake Escarpment. The similarity of the lithologies and fauna to the Lower Cretaceous of southern Florida indicates that the same shallow water environment extended as far east and north as the Blake Nose. The abundance of algal fragments in the calcarenites requires a source that was reasonably nearby. During the Early Cretaceous, algal and perhaps coral banks formed a barrier reef which extended north of the Bahamas (Newell, 1959). It has been suggested that the zone of rough relief on reflection #4 (Fig. 12) represents a reef built on an arched foundation (Ewing and others, 1966a). Contours on the 5.1 to 5.2 km/sec horizon (the horizon near the top of the Lower Cretaceous) indicate a north-south trending arch near the eastern edge of the Blake Plateau (Sheridan

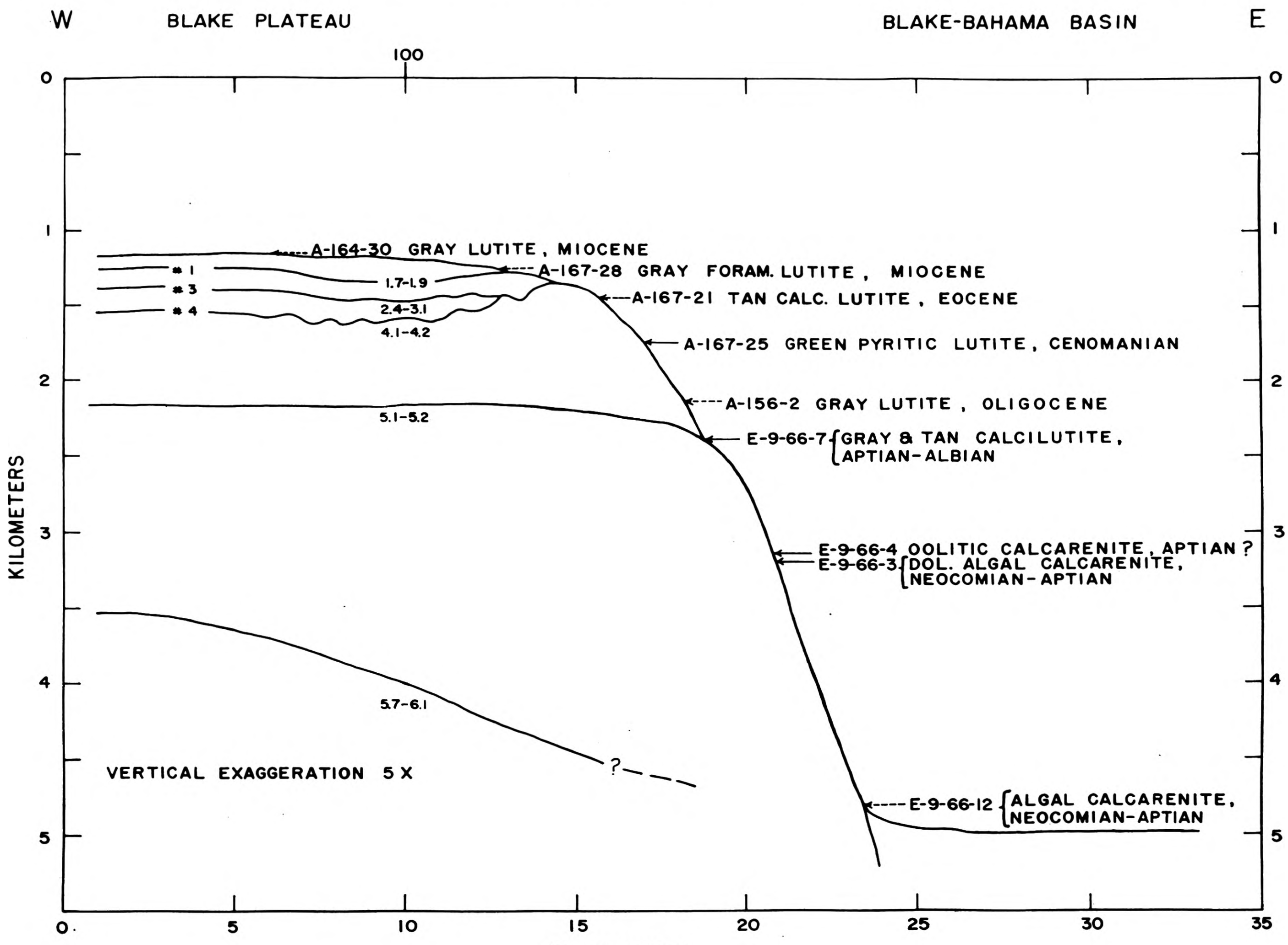

Fig. 12. Detailed structure section across the Blake Escarpment at 29° N. latitude. Prominent reflecting horizons are labeled as #1, #3, and #4 (Ewing and others, 1966b) and velocity layers are indicated by the velocity range observed, such as 5.1 to 5.2 km/sec (Sheridan and others, 1966). Dashed arrows are used to locate data which are extrapolated significant distances to the section shown.

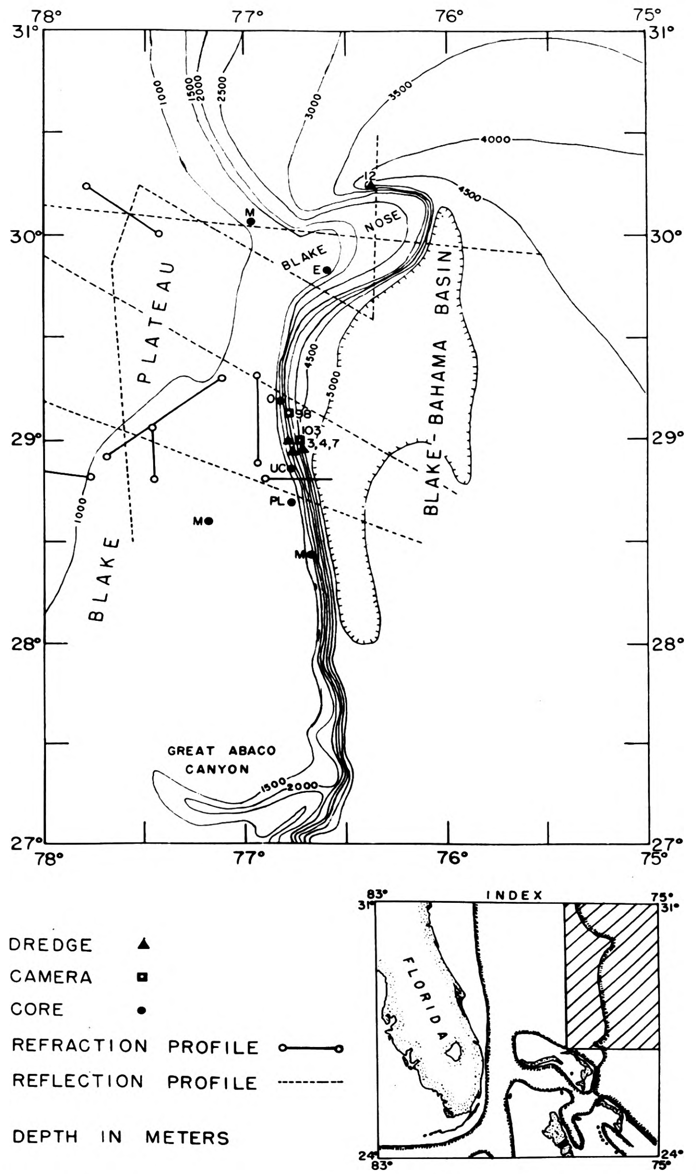

Fig. 13. Location map showing sites of dredge and camera lowerings made from R/V *Eastward* (after Heezen and Sheridan, 1966). Also shown are supporting data of deep-sea cores (Ericson and others, 1961), refraction profiles (Sheridan and others, 1966), and reflection profiles (Ewing and others, 1966a).

and others, 1966). This arch might represent an Early Cretaceous barrier reef which built the foundations of the Blake Escarpment at that time. The arch structure in the three deepest seismic horizons along the eastern edge of the Blake Plateau may provide a structural trap for any oil present. The back-reef facies would be deposited west of the Cretaceous barrier reef in a gently subsiding trough, resulting in very slight westward dips and possible stratigraphic pinch-outs along the arch on the east. In the future, deep-sea drilling operations may allow the tapping of potential oil reserves in this area.

The algal calcarenites found along the deepest part of the Blake Escarpment were probably deposited in only a few meters' depth. Most algae live in strong light and are restricted to depths of less than 25 m (Johnson, 1961). The well rounded grains and the miliolid and arenaceous Foraminifera, which have resilent tests, could even have been deposited near a beach. The pure carbonate deposits accumulated only because there was subsidence to allow room for reef growth, but the subsidence was not the result of sediment loading. The Lower Cretaceous sedimentary rocks are all of relatively shallow water facies, whereas the Tertiary rocks have an increasingly pelagic character, suggesting gradually deepening water. Thus the rocks forming the base of the escarpment in 5,000 m depth, represent sediments deposited near sea level, whereas the rocks from 2,000 to 3,000 m depth represent sediments laid down in depths approaching those in which the Blake Plateau now lies. Thus, 5 km of gentle, uniform subsidence over a wide area of the continental margin is well substantiated, both by the wells in the Bahamas and Florida and by the dredgings from the edge of the Blake Escarpment.

The unconsolidated sediments beneath the Blake-Bahama Basin immediately adjacent to the dredge sites are 0.6 to 0.7 km thick. If the 4.5 km/sec "basement" underlying these unconsolidated sediments is pre-Neocomian in age, we must conclude that the depth of this portion of the Atlantic in Neocomian time was less than about 600 m. Because the present depth in this region is approximately 5,000 m, we must assume either a 5 km subsidence of the entire abyssal floor of the Atlantic, huge complex vertical faults throughout the Blake-Bahama region, or a downwarp by nearly 5 km of the primoridal continental slope structure into a continental rise sedimentary trough basin (Drake and others, 1959).

THE CRUSTAL EVOLUTION OF THE ATLANTIC OCEAN

The Mid-Atlantic Ridge (a segment of the world-encircling Mid-Oceanic Ridge) is a symmetrical, median, mountainous swell which occupies the middle third of the Atlantic Basin. By comparing transoceanic profiles, it is readily observed that the width of the Mid-Atlantic Ridge, as well as the width of the ocean basin floor, is a function of the total width of the ocean (Fig. 15). A seismically active median valley follows the crest of the ridge. The

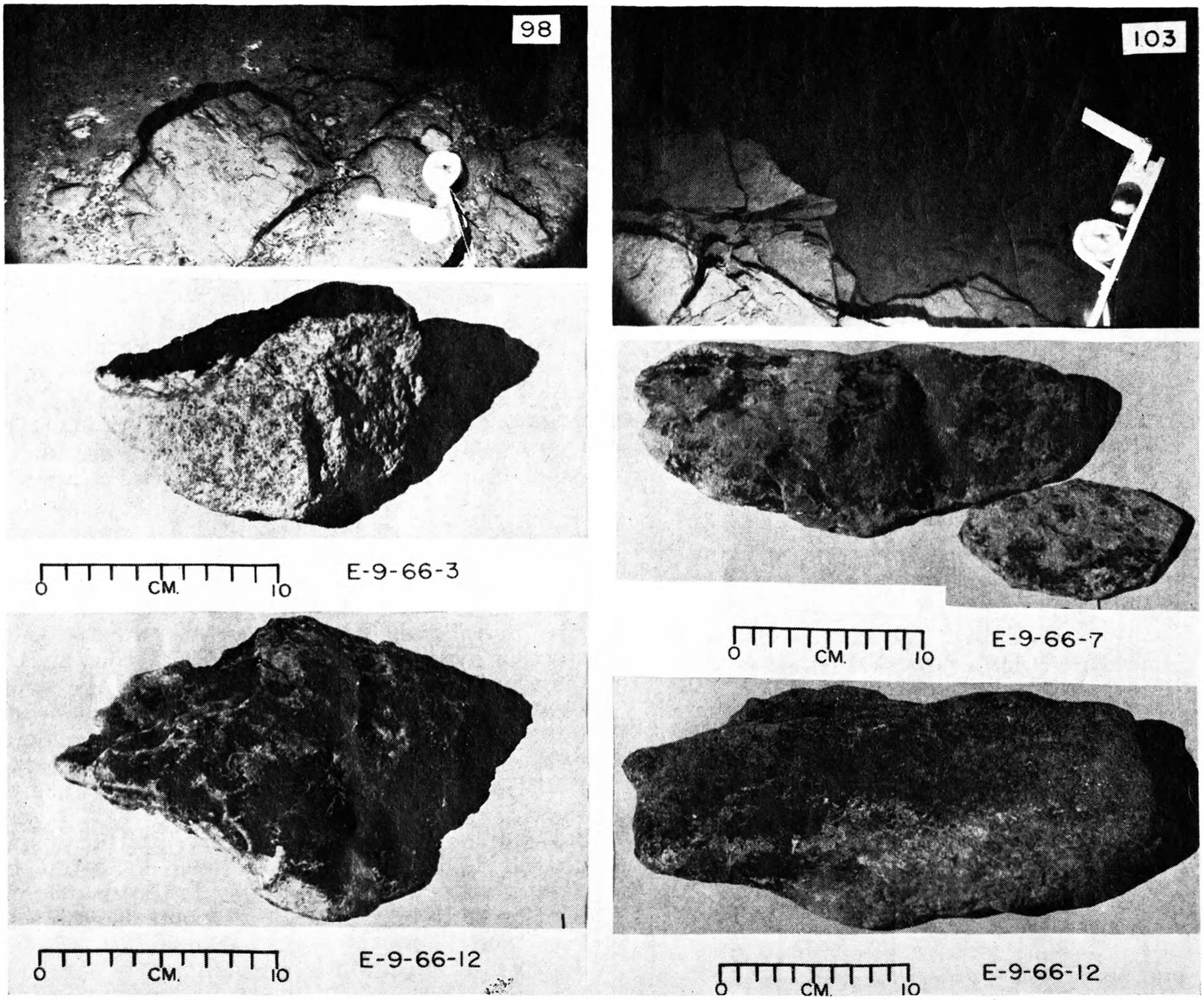

Fig. 14. Two bottom-photographs taken on the escarpment near the location where the rocks were dredged (98 and 103) and some of the Lower Cretaceous rocks. The photo from station E-9-66-98 (29° 09′ N., 76° 45′ W.) shows massive boulders cropping out and the escarpment dropping off to the east. The compass in the photo is 10 cm in diameter. On the sample from dredge E-9-66-3, the freshly broken surface contrasts markedly with the older manganese coated surface. The platy, angular shape of the rocks from dredge E-9-66-7 can be compared to the similar platy rocks shown in the photograph 103.

identification of this median valley as a rift valley, combined with a study of the comparative morphology and geology of the Mid-Oceanic Ridge along transoceanic traverses of widely different widths, and a review and study of landward extensions led me to the conclusion that the Mid-Oceanic Ridge is growing wider through the continuing emplacement of mantle material in a succession of widening, median, mid-oceanic, rift valleys (Heezen, 1957, 1959b, 1960). Hess (1962), Dietz (1961), Wilson (1963), Vine and Matthews (1963) and others have adopted my model of oceanic crustal evolution and have provided additional hypotheses as to the driving forces and have given details of various specific hypothetical processes which may have caused or may have resulted from the crustal growth. Most of these hypotheses involve convection currents which are imagined to have transported the oceanic crust away from the axis of the Mid-Oceanic Ridge towards the continents. The horizontal limbs of these convection currents are thought to turn downward beneath an appropriately deformed area such as a folded mountain range or an island arc. With the exception of the antillian

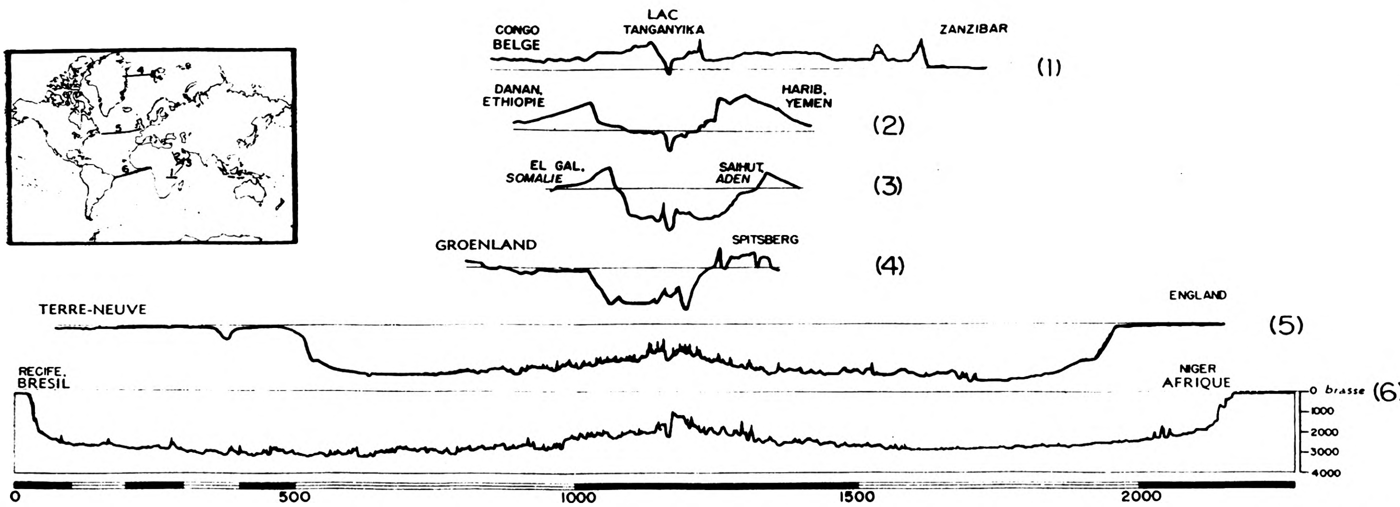

Fig. 15. Six profiles across the Mid-Oceanic Ridge. Note the marked similarity of each profile, despite the large difference in profile lengths. This sequence could represent a genetic series in which the rift valleys of Africa represent an early stage in the development of an ocean, and the Atlantic shown in profiles 5 and 6 represents later stages (after Heezen, 1959a).

arcs, no Tertiary deformation is observed on the continental margins of the Atlantic either beneath the sea or at the margin of the continents. Therefore, if the convection cell theory is to be adopted for the Atlantic, it must be assumed that the continents bounding the Atlantic traveled at precisely the same speed as the adjacent deep-sea floor.

In selecting a working hypothesis for the geological exploration or explanation of the Atlantic floor, it makes little difference if we choose a mechanism involving convection cells, a general continental drift towards the Pacific, or an expansion of the mantle, for the resulting geologic and tectonic patterns left in the deep sea floor would be nearly identical.

M. Ewing and others (1964) have shown that the Mid-Atlantic Ridge lacks a prominent sedimentary layer which is found throughout the adjacent basins (Fig. 16). By extrapolating modern rates of deposition, I concluded that the top of this layer was formed approximately 75 million years ago (Heezen, 1962). Subsequently, by coring outcrops of this horizon (referred to as "Interface 1" or "layer A"), J. Ewing and others (1966b) established its age as Maestrichtian (63 to 72 m.y.). Thus, there appears to be no real discrepancy between modern rates of deposition and the age of the underlying basement, and additional support is given for the post-Cretaceous age of the existing Mid-Oceanic Ridge.

Where the Mid-Atlantic Ridge is 1,400 km wide, the average rate of the expansion of the

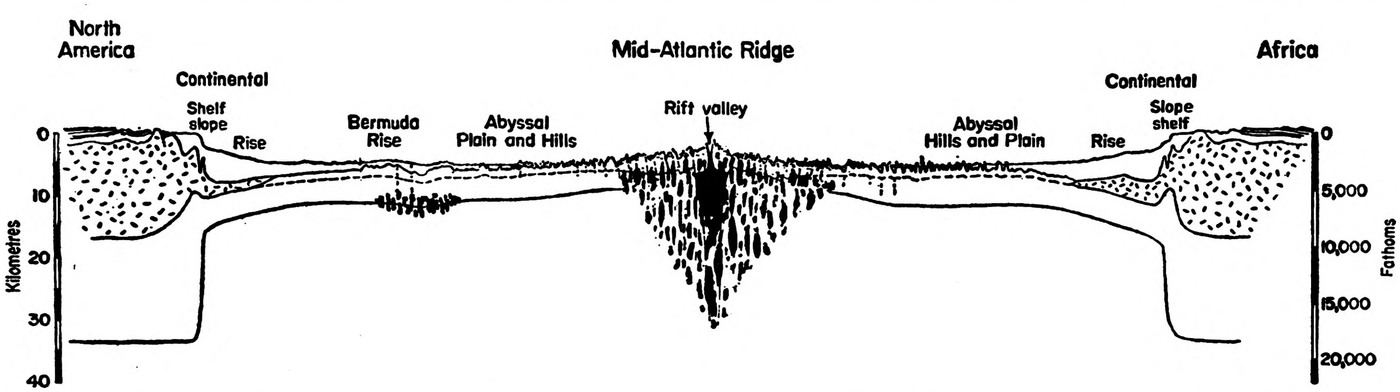

Fig. 16. Crustal section across the North Atlantic. The dark shaded area represents the 7.2 to 7.4 km/sec material which lies beneath the crest of the Mid-Atlantic Ridge. The first layer under the oceans represents sediments; the second, possibly lithified sediments or, more probably, volcanic rocks; and the third is the oceanic crustal layer. Beneath this layer lies the mantle. This illustration is based on the correlation of crustal thickness measurements and physiography throughout the North Atlantic (after Heezen and others, 1959).

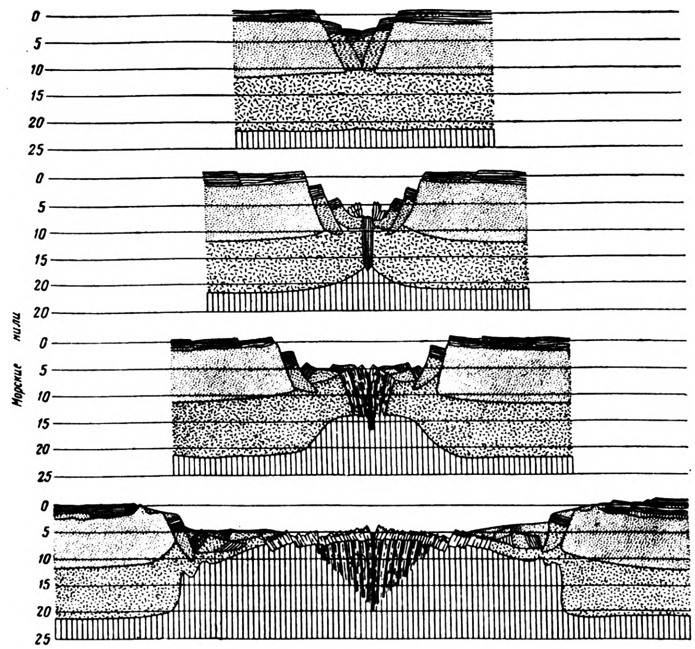

Fig. 17. Evolution of the ocean floor. Top profile represents an initial continental rift such as the modern East African rift valleys or the Triassic Atlantic. The second profile represents a young rift ocean such as the modern Red Sea or the Jurassic Atlantic. The third profile represents an ocean in a later stage of expansion such as the modern Gulf of Aden or the Neocomian Atlantic. The fourth profile indicates a still later stage which might be represented by the Norwegian Sea or the Cenomanian Atlantic (after Heezen, 1960).

ridge (assuming the above 70 m.y. date) would have to be 2 cm/yr., and where the ridge reaches 2,800 km in width the rate of growth would have to be 4 cm/yr. If we lineally extrapolate these rates backward in time, we arrive at a zero width for the Atlantic at about 200 million years ago. According to this reasoning, the Atlantic was born during the Triassic Period. But if the rate of expansion has varied with time, we might be badly misled by such an extrapolation.

EVOLUTION OF THE ATLANTIC CONTINENTAL MARGIN OF NORTH AMERICA

Let us for a moment accept the evidence for the expansion of the Atlantic and try through modern analogy to interpret the meager but simple data in order to construct a history of the Atlantic continental margin.

The Triassic in eastern North America was a period when basic sills, dikes, and flows were emplaced in predominantly nonmarine sediments. The paleotectonic events of the Triassic along the continental margin of North America may have been somewhat similar to the recent history of the Gregory Rift of Kenya (Fig. 17). The extensive basic dikes and sills in the Triassic of the eastern United States may well mark the beginning of rifting which led to the birth of the Atlantic. During the Jurassic, the width of the Atlantic grew to over 1,000 km, and the sea invaded the deeper portions of the evolving basin. As the ocean grew wider, the newly formed margins of the continents were upturned at least in part by isostatic effects on the toes of the continental blocks. If we reason by analogy with the modern ocean, we would expect this narrow early Mesozoic Atlantic to be relatively shallow. The Jurassic Atlantic must have greatly resembled the modern Red Sea, but it may not have become so choked with coral reefs. The lack of Jurassic deposits along the continental margin of eastern North America probably indicates that the continental blocks still stood relatively high and may have in fact tectonically resembled the eroded and upturned Arabian and African margins of the Red Sea.

The oldest sedimentary rocks recovered to date from the abyssal depths of the Atlantic are the Neocomian algal reef beds at the base of the Blake Escarpment. These consolidated limestones and marbles were obtained from a re-excavated reef at a point only a few kilometers distant and only 600 meters higher in elevation than the 4.5 km/sec basement layer. In other words, unless we are to hypothesize the presence of a large ancient fault between the Neocomian outcrops and the Blake-Bahama Basin, we must conclude that the Atlantic Basin east of the Lower Cretaceous Blake Reef was no more than 600 meters deep. Because the 4.5 km/sec layer is probably at least somewhat older than the Neocomian Reef, there should have been some Atlantic sediments deposited in front of the reef. Thus, the floor of the Neocomian Atlantic east of the Blake Reef was not significantly deeper than the modern shelf seas.

The Atlantic must have been at least 2,000 km wide by the end of Neocomian time, and the adjacent continental margins must have then begun to escape the influence of the ~2,000 km wide central elevation which characterizes the Mid-Oceanic Ridge welt. Although other parts of the basin could have been deeper, our single data locally suggest that up to the beginning of the Cretaceous the sea was only a few hundred meters deep and that the Atlantic was still in a Gulf of Aden "phase". Throughout the Early Cretaceous, the edge of the continent warped downward towards a rapidly deepening Atlantic.

Comparative morphologic studies suggest

that as the ocean widens it steadily deepens until it reaches a width of 2,000 or 3,000 km at which point its subsidence slows and its basin floor approaches a depth of 5 or 6 km. Bermuda is an extinct volcano which was truncated in Late Cretaceous or early Tertiary time and has not subsided since. The depth of the Atlantic in the vicinity of Bermuda could not have been very much different in Late Cretaceous time than the present 5 to 6 km. Thus, Bermuda testifies that the subsidence of the Atlantic floor had been entirely accomplished in this region prior to the Tertiary. The Kelvin Seamounts are truncated at depths approximating 1,000 to 1,500 meters. The age of truncation is not well determined, but the occurrence of some fragments of Late Cretaceous shallow water fossils may indicate a gentle subsidence of the basin floor of about 1,000 to 1,500 meters during the same interval that Bermuda remained stable. Alternately, the Kelvin Seamounts might be slightly older than Bermuda and have been formed before the ocean basin had reached its present depth. However, the difference in depth between the base of Bermuda and the base of the Kelvin Seamounts is approximately equal to the summit depth of the seamounts, and thus perhaps we can appeal to a Tertiary subsidence of the basin relative to a more stable Bermuda rise.

The uplifted edges of the rifted continents were eroded, and the Cretaceous seas invaded the edges of the eroded and subsided continents. What has happened since is more fact than hypothesis and is clearly described in great detail in many works. In brief, however, the margin continued to subside, sediment continued to be deposited on the continental shelf which was created in Middle Cretaceous time after the final filling of the former linear epicontinental basins which now lie beneath the continental shelf. The continental rise began to grow at the base of the continental slope by the accumulation of sediment injected into the sea through the water column and carried in along the bottom by turbidity currents. These sediments were then transported parallel to the continent by geostrophic bottom currents which in turn shaped the great sediment wedges which constitute the continental rise. The outer ridge sedimentary drifts began to build upward in the Tertiary, signalling the commencement of a vigorous, thermohaline, abyssal circulation in the modern pattern. Although these drifts probably steadily evolved, there was certainly repeated filling and recutting as the vigor of the thermohaline circulation of the Atlantic fluctuated and as local geologic events altered the path of flow. Although submarine canyons probably have existed throughout the history of the Atlantic, the late Cenozoic regression brought a great influx of clastics which were transported to abyssal depths through the submarine canyons and poured out on to the abyssal floor causing the abyssal plains to reach their maximum Tertiary extension.

Thus, the Atlantic continental margins were created and uplifted during a Triassic taphrogenic phase. Later they were eroded and subsided and finally transgressed by Late Cretaceous and Teritary seas as the Atlantic grew to its present width and depth. If we accept this history, we then cannot speak of a Paleozoic North Atlantic, nor should we expect to find deep-sea deposits older than Cretaceous in the Atlantic (Menzies and Imbrie, 1958).

We should dredge the many bare rock scarps of the Atlantic floor. The discovery of Paleozoic or lower Mesozoic rocks in the deep Atlantic would allow someone to build a wonderful new hypothesis, for as Mark Twain once observed: "There is something fascinating about science. One gets such a wholesale return of conjecture out of such a trifling investment of facts."

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