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Geology of New England Passive Margin[1]

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Abstract The New England continental margin began to develop in the Middle Triassic, when rifting of Precambrian/Paleozoic terrane produced a complex arrangement of horsts and grabens. During the Late Triassic–Early Jurassic, these grabens were filled with terrigenous clastics, volcanics, and evaporites. When plate separation took place and seafloor spreading began approximately 195 to 190 m.y.B.P., the newly formed continental edge was uplifted and eroded, truncating preexisting rift structures.

As North America began to drift away from Africa, subsidence occurred along a series of normal faults now beneath the outer continental shelf. This "hinge zone" may represent the boundary between continental crust and a transitional zone of continental and oceanic crustal fragments.

Atop the faulted and subsiding crustal platform, thick sediments were deposited. The lower part of the drift sequence is an evaporite/carbonate unit of Early-Middle Jurassic age, and the upper part is a clastic wedge of Middle Jurassic to Cenozoic age. More than 80% of these sediments are Jurassic. Their total thickness may be as much as 13 km beneath the southeastern part of Georges Bank.

Beneath the outer shelf and upper slope is a Mesozoic reef/carbonate platform which was an effective sediment barrier until it was buried by prograding clastics in the early Late Cretaceous. Both the geographic position and steepness (5 to 8°) of the continental slope south of Georges Bank are a result of this carbonate buildup.

Emplacement of the drift sequence was disrupted by regressions during the Middle Jurassic, late Early Cretaceous, latest Cretaceous, late Eocene–Oligocene, late Miocene, and Pliocene-Pleistocene. The Middle Jurassic regression coincided with a westward jump of the Mid-Atlantic Ridge, whereas the late Early Cretaceous event was synchronous with the opening of the Bay of Biscay and the separation of Eurasia and North America. All of the more recent regressions were associated with continental glaciation.

INTRODUCTION

In 1975, the Woods Hole Oceanographic Institution conducted a geophysical investigation of the passive continental margin south of New England. Major objectives of the study were (1) to describe the crustal structures characteristic of the margin; (2) to estimate the lithology and thickness of the sediments underlying the continental shelf, slope, and upper rise; and (3) to reconstruct the margin's evolution through time within the broad framework of plate tectonics.

The New England margin was chosen for study for two reasons. First, it adjoins two well-known regions: the Scotian Shelf (King, 1967; McIver, 1972; Jansa and Wade, 1975) and the Gulf of Maine (Drake et al, 1954; Uchupi, 1965, 1966, 1970; Oldale et al, 1973, 1974; Ballard and Uchupi, 1975; and others). Second, previous geophysical work (Officer and Ewing, 1954; Drake et al, 1959; Maher and Applin, 1971; Schultz and Grover, 1974; Mattick et al, 1974; and others) indicated the presence of a major depocenter beneath Georges Bank (Fig. 1).

The field investigation (R/V *Atlantis II* cruise 91) was carried out in an area extending from the western Scotian Shelf to the shelf south of Cape Cod (Fig. 1). Seismic profiles were run using a sound source consisting of four air guns (300, 120, 80, and 40 cu in.; 4917, 1967, 1311, and 656 cc) fired simultaneously at 16 or 18-sec intervals at 1,850 psi (12,756 kPa). The receiving array, ap-

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proximately 1.2 km long, was composed of six channels, each containing 150 hydrophones. Reflected arrivals were digitally recorded (at 4 msec sampling rate) on magnetic tape for subsequent common-depth-point (CDP; Mayne, 1962) processing ashore. Seismic refraction data were collected using expendable sonobuoys, and the total magnetic field intensity was measured with a proton precession magnetometer. Navigation was by satellite and loran A and C.

ACOUSTIC STRATIGRAPHY

To establish the geologic significance of the seismic profiles, tie lines were run between the New England margin and Shell Mohawk B-93, an exploratory well drilled on the southwestern Scotian Shelf (Fig. 1). From the well's sonic and lithologic logs and the geophysical data, seven regionally prominent acoustic horizons were correlated with major velocity changes and/or lithologic variations at the well site (Fig. 2).

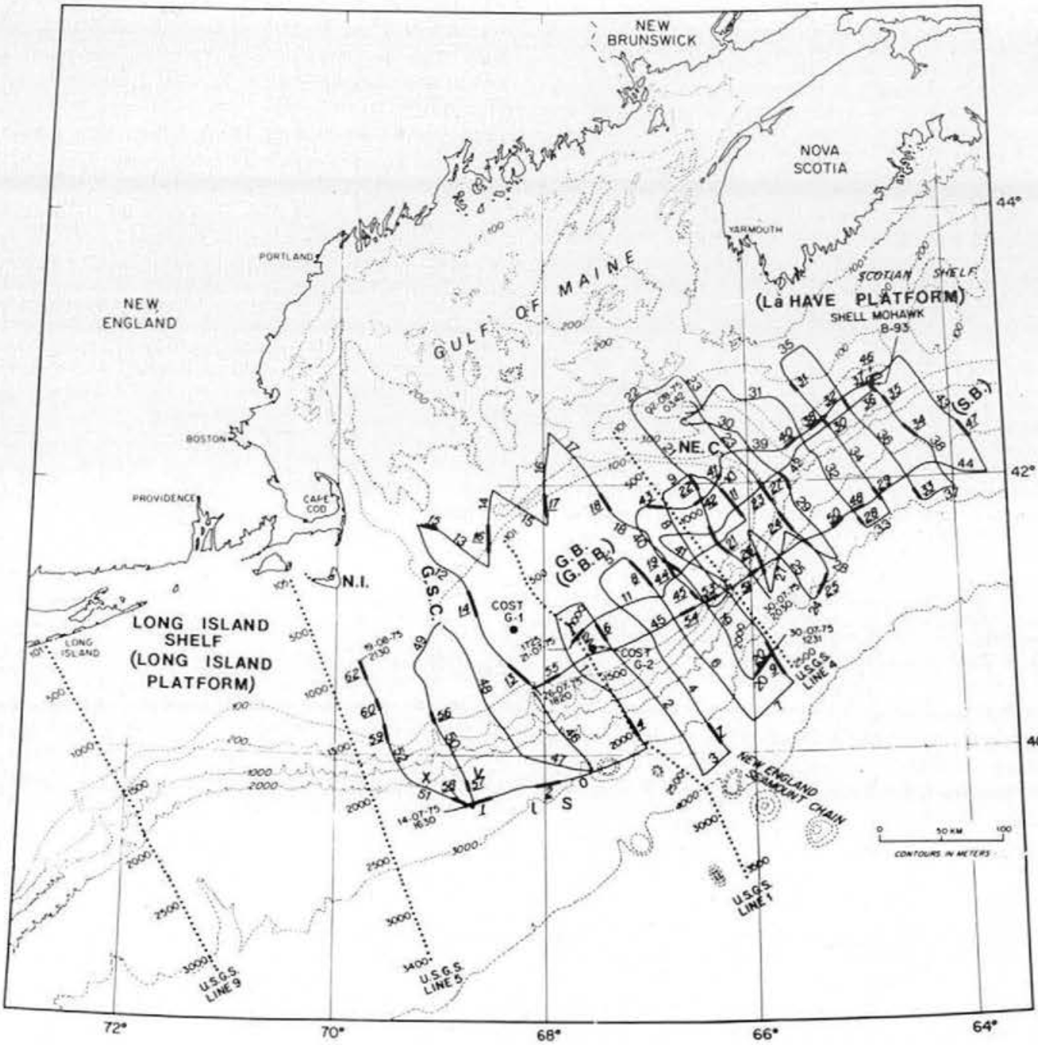

FIG. 1—Locations of seismic reflection profiles used in this study. Solid lines: AII-91 track lines (shelf, 6-channel; slope and rise, single-channel). Heavy short lines: AII-91 sonobuoys. Dotted lines: USGS multichannel lines. *N.I.:* Nantucket Island. *G.B.:* Georges Bank. *G.B.B.:* Georges Bank basin. *S.B.:* Scotian basin. *NE.C.:* Northeast Channel. *G.S.C.:* Great South Channel. On this and following maps, light-dashed contours show bathymetry.

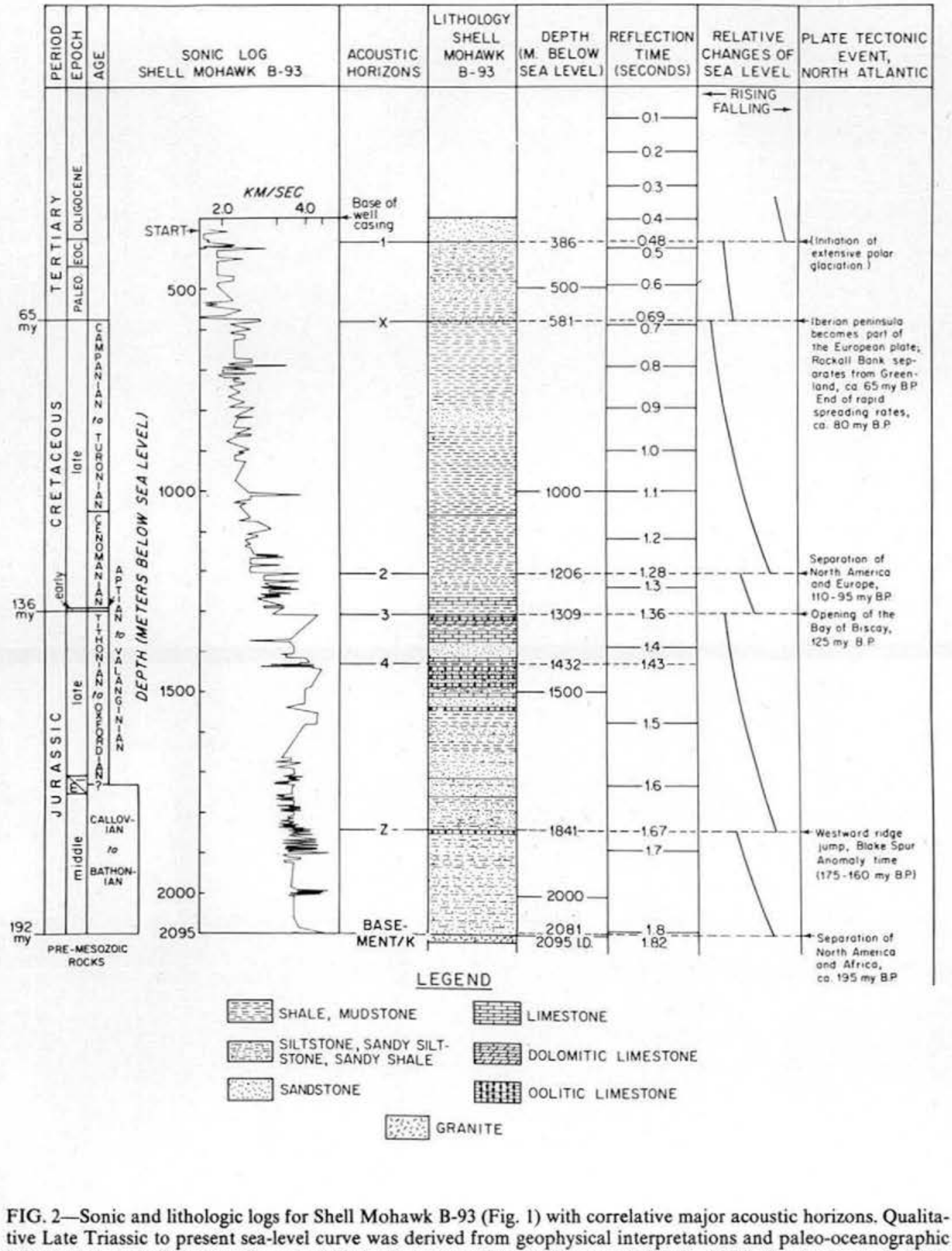

FIG. 2—Sonic and lithologic logs for Shell Mohawk B-93 (Fig. 1) with correlative major acoustic horizons. Qualitative Late Triassic to present sea-level curve was derived from geophysical interpretations and paleo-oceanographic information compiled on sediments drilled off eastern Canada (Jansa and Wade, 1975; Gradstein et al, 1975; Given, 1977). Although sea-level cycles are broadly similar to global curve of Vail et al (1977), no attempt was made to calibrate actual sea-level changes from one cycle to next. Major North Atlantic plate-tectonic events are from van Hinte (1976a,b), Sclater et al (1977), Klitgord and Schouten (1977). Reflector identifications K, Z, and X are after Schlee et al (1976).

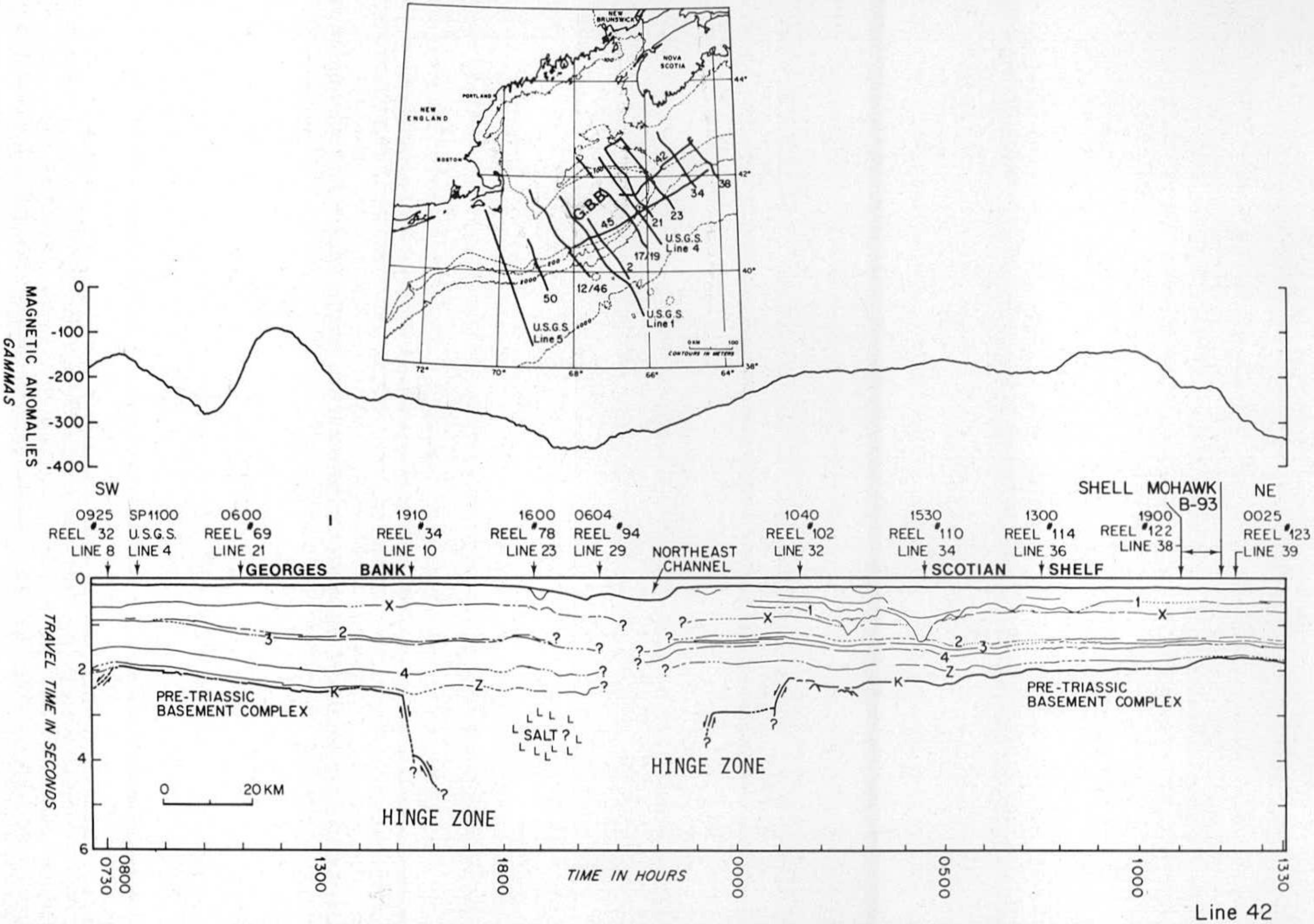

FIG. 3—Interpretation of line 42, 6-channel profile from Scotian Shelf across Northeast Channel to Georges Bank. Reflector identifications are summarized in Figure 2. Vertical exaggeration of bottom topography is 13:1. Cross-ties with other profiles are shown. Magnetic anomalies were calculated from total field measurements by systematically removing 1975 international geomagnetic reference field (Leaton, 1976). *L* pattern indicates known or inferred presence of evaporites. *G.B.B.* (inset map): Georges Bank basin.

Regional Correlations: Continental Shelf

LaHave platform (Fig. 1)—Lines 42 (Fig. 3), 38, and 34 (Fig. 4) illustrate the acoustic structure and stratigraphy of the southwestern Scotian Shelf. A zone of confused hyperbolic echoes beneath the outer shelf suggests a ridgelike feature which may be a basement structure. However, the presence of Early Jurassic salt in the Shell Mohican I-100 well drilled near the shelf break about 200 km east of line 38 implies instead that the ridge is composed of salt/shale diapirs.

Georges Bank basin (Fig. 1)—Five lines (Figs. 5, 6) show the geologic framework of the depocenter underlying Georges Bank. Acoustic basement appears as a series of faulted blocks truncated by an unconformity, horizon K (Schlee et al, 1976). Similar rift structures are present within the Triassic system of New England and Nova Scotia, and beneath the Bay of Fundy and the Gulf of Maine (Ballard and Uchupi, 1975).

Beneath the southeastern part of Georges Bank, basement is strongly downfaulted (Fig. 5). Beyond this hinge zone, sediment thickness increases drastically and diapirs may be present (Figs. 3, 5). The hinge zone is not observed west of line 17-19 (Fig. 6), but it may be masked by a shelf-edge high originally described by Drake et al (1959). This high, termed a "reef-ridge" by Schlee et al (1976), is acoustically identified by a zone of hyperbolic echoes accompanied by a general deterioration in reflection amplitudes (Fig. 7). From the west side of Northeast Channel to approximately 68°W, the reef-ridge appears to be continuous. Throughout its length, it forms the foundation of the continental slope south of the Georges Bank. The geophysical evidence (Schlee et al, 1976; Grow et al, 1979) and samples of Neocomian algal reef carbonate collected by submersible from near the top of this feature (Ryan et al, 1978; Fig. 5) suggest that the reef-ridge is a Mesozoic reef/carbonate platform. A magnetic high 6 to 8 km below present sea level could be the basement structure on which the carbonate buildup has formed (Klitgord and Behrendt, 1979).

The Jurassic (pre-reflector 3) sediment section is characterized by continuous reflectors of high amplitude beneath the outer part of Georges Bank, and discontinuous, bifurcating acoustic horizons of variable amplitude beneath the inner part. This significant transition coincides with the landward termination of reflector 4 (Figs. 2, 4, 5) and a large decrease in interval velocities. Schlee et al (1976) suggested that the acoustic transition is caused by a major facies change from carbonates on the outer shelf to clastics on the inner shelf.

Reflector X (Fig. 2) is the shallowest acoustic horizon which we can correlate regionally beneath Georges Bank. Reflector 1 (Fig. 2) cannot be traced beyond Northeast Channel (Fig. 3), although an unconformity is present beneath the Gulf of Maine (Figs. 5, 6) which could be correlative with 1.

Long Island platform (Fig. 1)—No reef-ridge is visible west of USGS line 1 (Fig. 6). Consequently, acoustic horizons can be traced across the shelf to the upper continental slope, where they are truncated by a major unconformity (Fig. 8). Erosion of this part of the slope occurred from the Middle Jurassic (reflector Z time) to the Cenomanian (reflector 2 time). Since then, outbuilding has taken place, associated with onlapping of the continental-rise prism (Fig. 8).

Continental Slope

The continental slope south of New England is steep (5 to 8°, Fig. 1), and its structure is complex. Numerous erosional episodes have cut canyons and created unconformities which prevent the correlation of reflectors from the shelf to the rise (Figs. 6, 8). However, slope outcrops sampled by dredge and submersible have supplied almost all of our present stratigraphic knowledge of the New England margin. These samples are as important as well control for verifying geophysical interpretations in this region.

Continental Rise

The continental rise south of Nova Scotia is a highly deformed area known as the Sedimentary Ridge Province (SRP; Jansa and Wade, 1975). The SRP is now considered to be the result of the migration of evaporites, on the basis of the recovery of Lower Jurassic salt from holes drilled on adjacent structures beneath the Scotian Shelf and the Grand Banks (Jansa and Wade, 1975; Jansa et al, 1977). The SRP contacts the reef-ridge at the base of the continental slope southeast of Georges Bank. West of this (65°50′W), no diapiric structures are observed (Uchupi et al, 1977; Figs. 5, 6).

South of Georges Bank, the acoustic stratigraphy of the rise is based on long-distance correlations with acoustic horizons identified in the western North Atlantic (Tucholke and Mountain, in press; Tucholke and Vogt, in press). Reflector J_2 coincides with the formation of the Blake Spur anomaly (K. Klitgord, personal commun.). Reflector J_1 marks the Jurassic-Cretaceous boundary. Where it has been sampled by the Deep Sea Drilling Project, horizon B separates Neocomian limestones from Aptian-Albian black shales. Horizon A^* ties to a calcareous unit deposited during

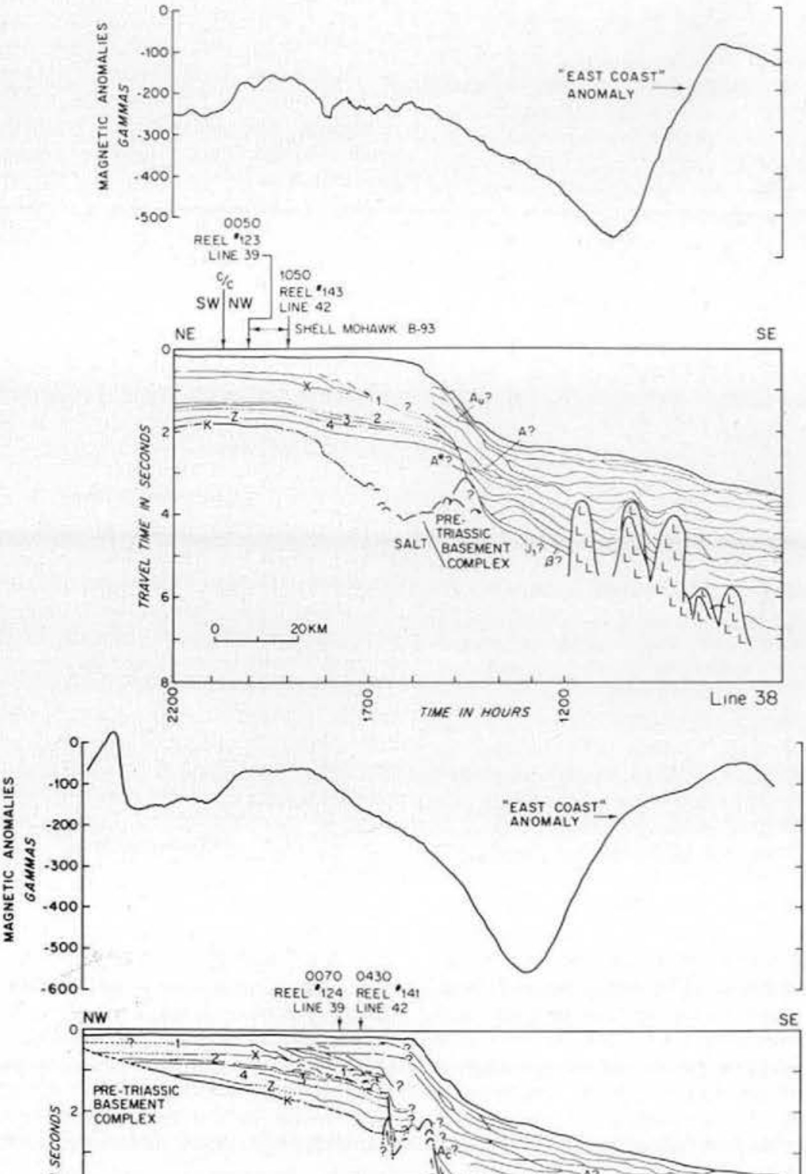

FIG. 4—Interpretations of lines 38 and 34, western LaHave platform. On shelf, these and following profiles are from 6-channel recordings except where indicated. On slope and upper rise, interpretations of AII-91 single-channel records are from Uchupi et al (1977). Vertical exaggeration of topography is 13:1. For locations, see Figure 3.

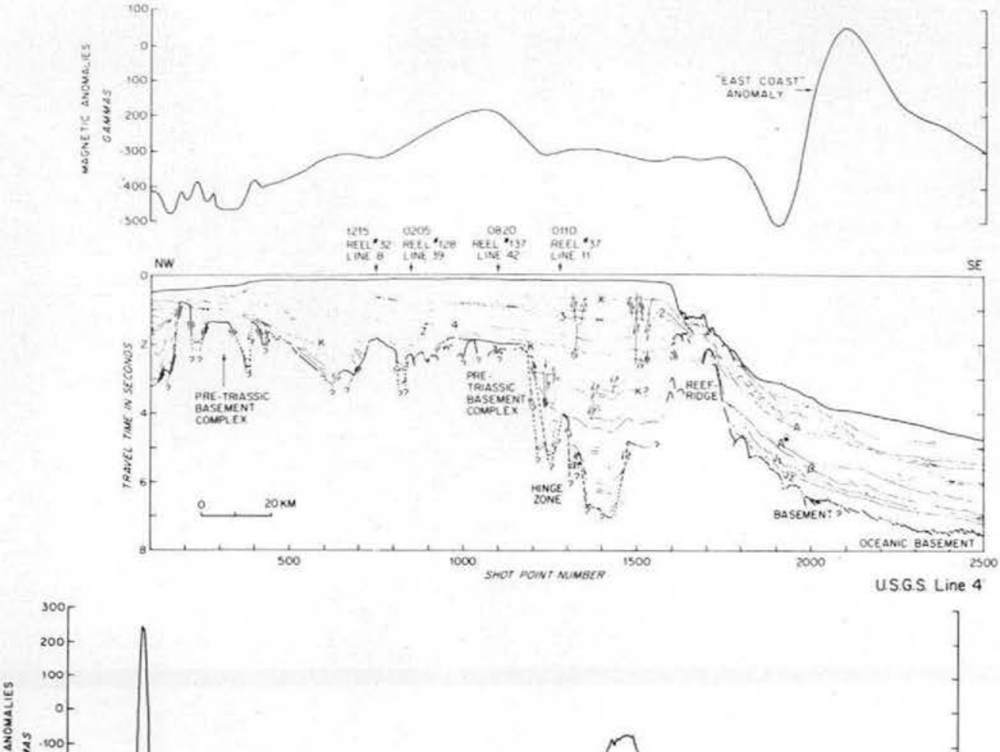

FIG. 5—Interpretations of USGS line 4 (48-channel) and line 17-19, eastern and central parts of Georges Bank. Star symbol on upper continental slope part of line 17-19 is approximate location of site in Heezen Canyon from which Neocomian reefal limestone was collected by Ryan et al (1978) from submersible DSRV *Alvin*. For locations, see Figure 3.

a late Maestrichtian depression of the carbonate compensation depth (Tucholke and Mountain, 1977, in press). Finally, the Horizon A complex or sequence is caused by the deposition of upper-lower to lower-middle Eocene cherts and cherty turbidites (A^C and A^T), and by a late Eocene–early Miocene regional unconformity (A^U; Tucholke and Mountain, 1977, in press).

GEOLOGIC MAPS

Interval velocities from AII-91 sonobuoys (Fig. 1) and CDP velocity analyses were used to convert travel-time data to actual layer thicknesses and depths beneath the New England continental shelf (Austin, 1978). USGS interval velocity information (Grow and Schlee, 1976; Schlee et al, 1976) was used for the same purpose in deep water.

Basement Tectonics

Basement is block faulted, with rifts generally trending northeast-southwest (Fig. 9). The faults seem to be normal, with individual throws ranging from less than a kilometer to several kilome-

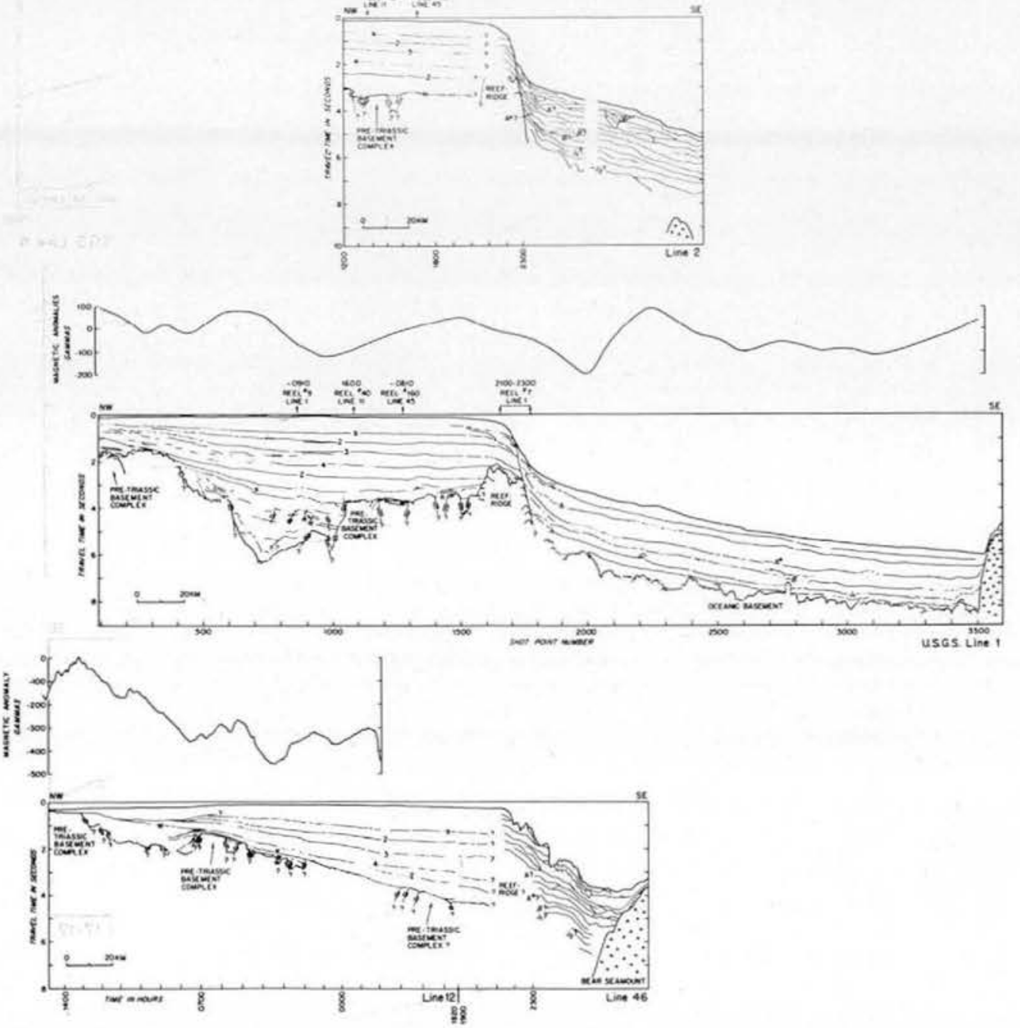

FIG. 6—Interpretations of lines 2, USGS 1 (24-channel), and 12-46, central and western parts of Georges Bank. For locations, see Figure 3.

ters, although the K unconformity bevels these structures and makes an accurate estimate of original basement relief impossible.

A large horst, the Yarmouth arch (Schultz and Grover, 1974), separates two major grabens underlying Georges Bank and warps the entire post-K sediment section. The basement hinge zone constitutes the boundary between the arch and the southwestern extension of the Scotian basin (Jansa and Wade, 1975; Fig. 1), the depocenter which includes the SRP. Diapirs may be present southeast of the Yarmouth arch beneath Georges Bank (Fig. 5).

The reef-ridge is shown (Fig. 9) because it must rest on some kind of basement foundation. The sharp contact between the reef-ridge and the SRP implies that the foundation may have prevented the deposition of evaporites south of Georges Bank.

Schouten and Klitgord (1977) have mapped Mesozoic magnetic anomalies and fracture-zone trends in the western North Atlantic. We show

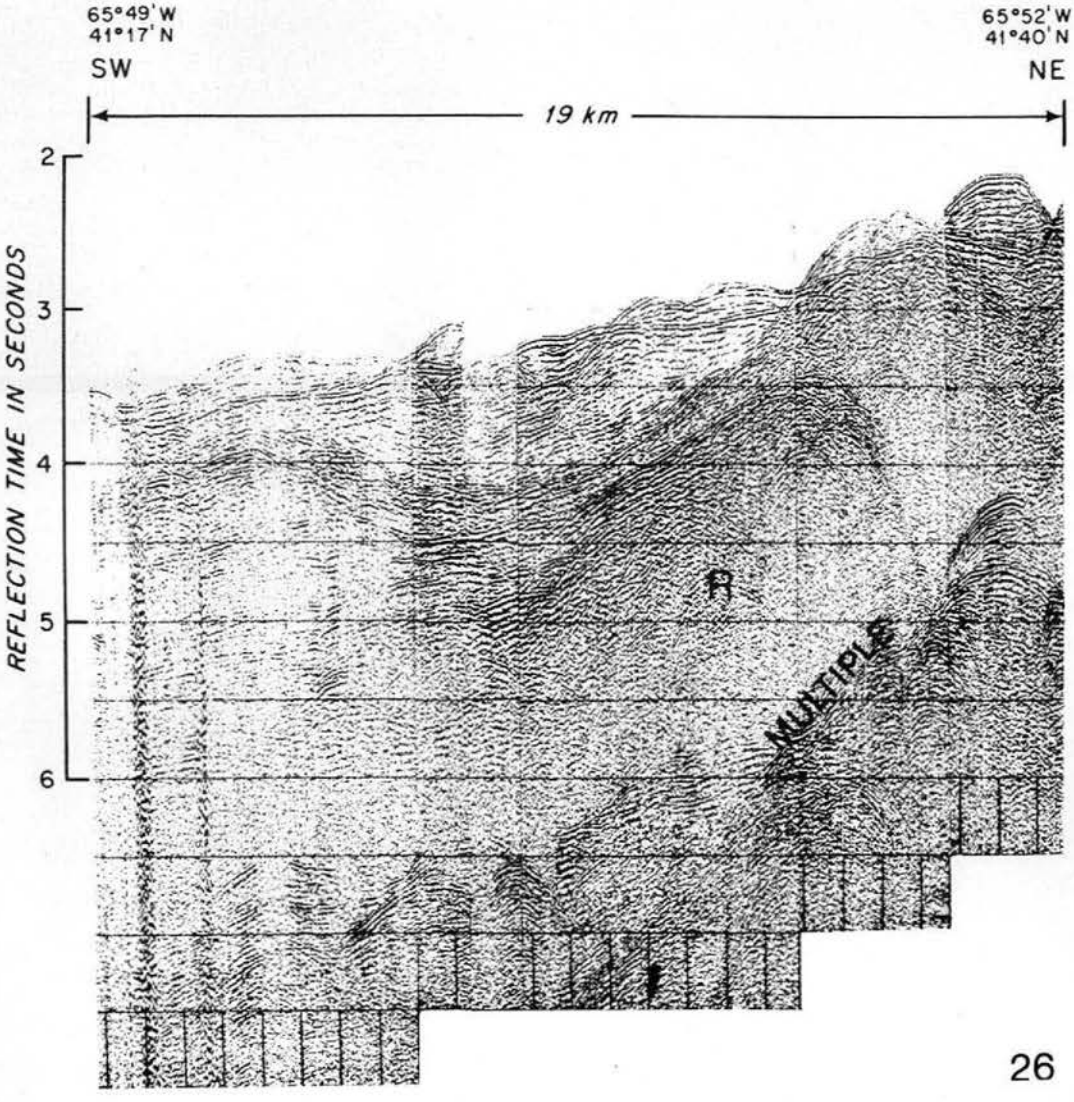

FIG. 7—Single-channel profile, part of line 26 (Fig. 1), originally published by Uchupi et al (1977). *R* is reef-ridge discussed in the text. Vertical exaggeration is approximately 9:1.

zones of crustal weakness that may have controlled the early development of these fracture zones (Fig. 9).

The westernmost zone intersects a north-south-striking basement dislocation, the New Shoreham fault, east of Long Island (McMaster, 1971; Fig. 9). Right-lateral motion along this fault is inferred from offsets in the spreading anomalies and in the "East Coast" anomaly (Fig. 9).

Another zone crosses the shelf break between 69 and 70°W. It is associated with a gap in the continental-slope magnetic basement ridge postulated by Klitgord and Behrendt (1979), and its trend parallels basement structures mapped east of Boston (Ballard and Uchupi, 1975). Right-lateral motion is again inferred from magnetic anomaly offsets.

A third zone bounds the reef-ridge at 68°W, and coincides with another gap in the magnetic basement ridge (Klitgord and Behrendt, 1979). This zone forms the western boundary of the large graben underlying the central part of Georges Bank (USGS line 1, Fig. 5; Fig. 9) and also parallels NNW-SSE-striking normal faults in the Gulf of Maine (Ballard and Uchupi, 1975). Right-lateral displacement is inferred both from offsets

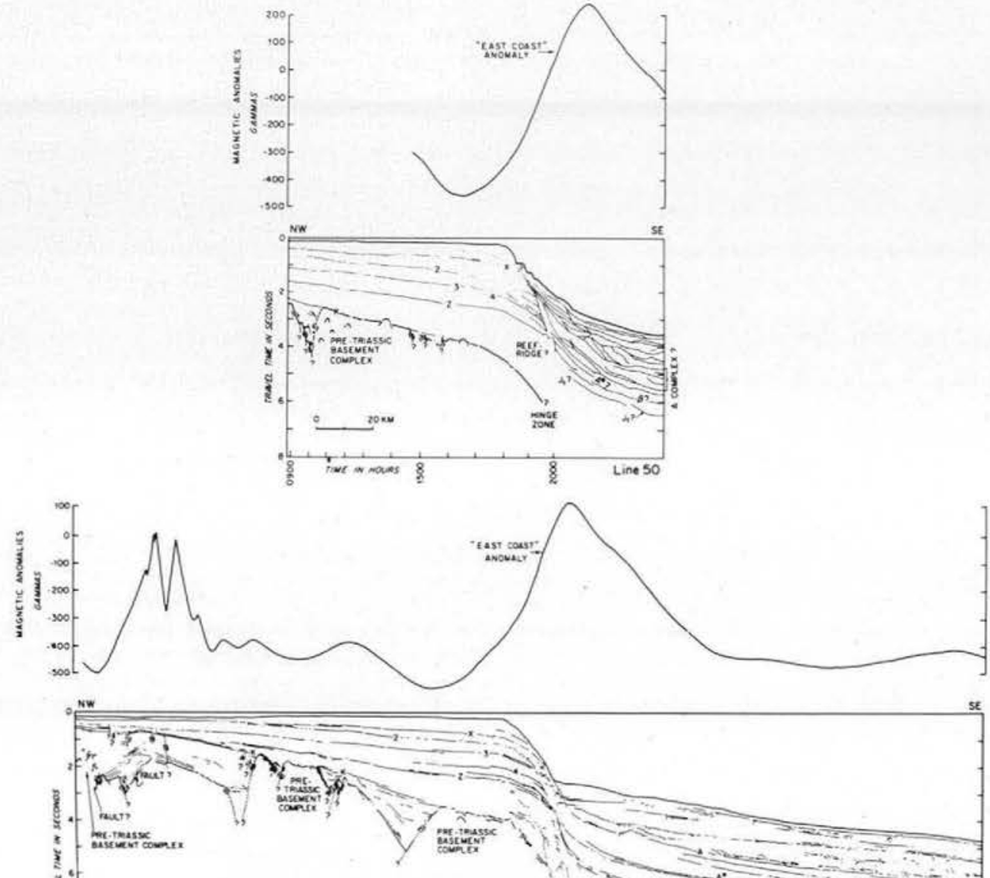

FIG. 8—Interpretations of lines 50 and USGS 5 (48-channel), Long Island platform. For locations, see Figure 3.

in the magnetics and from structural analysis of the Gulf of Maine (Ballard and Uchupi, 1975).

The easternmost zone forms the western side of the structural embayment underlying Northeast Channel (Figs. 1, 3, 9). This zone lines up with a left-lateral strike-slip fault offsetting Triassic basalts and diabases in the Bay of Fundy (Goldthwait, 1924), although the associated fracture zone offsets spreading anomalies in the opposite sense in the western North Atlantic (Klitgord and Schouten, 1977).

Isopachs

Pre-K—All pre-K sediments underlying the New England margin consist of graben fill. Although there is little interval-velocity information, maximum thicknesses are estimated to be more than 4 km (Fig. 10). Graben fill has been sampled by a well drilled in the Orpheus graben off Nova Scotia, where it consisted of Upper Triassic–Lower Jurassic red beds (Jansa and Wade, 1975; Given, 1977). Red beds also fill the structurally similar Triassic rifts in New England. Evaporites may also be present. Upper Triassic(?) halite has been sampled in the Carson subbasin beneath the eastern Grand Banks (Jansa et al, 1977), and there may be salt diapirs in the Georges Basin graben beneath the Gulf of Maine (Ballard and Uchupi, 1975; Fig. 10).

K-Z—The Early Jurassic sediment distribution

FIG. 9—Basement tectonic map. Reef-ridge must have formed on some basement foundation, but cannot be tied to possible basement structures mapped beneath outer part of the Scotian Shelf (Fig. 4). Additional information from Ballard and Uchupi (1975, Gulf of Maine), King and MacLean (1976, Bay of Fundy), Given (1977, Scotian Shelf), and Uchupi et al (1977, Sedimentary Ridge Province). *N.S.F.:* New Shoreham fault (McMaster, 1971).

reflects the influence of the Yarmouth arch (Fig. 11). Part of the arch may have been exposed at this time, together with the northern boundary of Georges Bank. Maximum sediment thicknesses southeast of the arch are over 10 km. The presence of a reef-ridge is inferred from seismic evidence, even though no Lower Jurassic carbonate rocks have been recovered from Georges Bank.

The present limits of the SRP (Fig. 11) represent the minimum extent of the Early Jurassic salt basin. Evaporites may also have been deposited in the structural lows under Northeast Channel and southeast of the Yarmouth arch.

Beneath the upper continental rise, no regional synthesis of Early Jurassic sediment thicknesses could be made because of insufficient velocity information. However, along the rise part of USGS line 5 (Fig. 8), the thickness of the Early Jurassic interval (basement-J_2) is approximately 7 km. This compares with a 2-km thickness for the same interval along USGS line 1 (Fig. 6), perhaps as a result of basement tectonism associated with emplacement of the New England Seamount Chain.

Z-3—Sedimentation rates were much lower during the Middle-Late Jurassic (15 cm/1,000 years) than during the Early-Middle Jurassic (21 cm/1,000 years; these rates are minimun estimates, as neither compaction nor erosion has been taken into account). Continental-shelf sedimentation continued to be influenced by the Yarmouth arch (Fig. 12).

Beneath the rise, the Middle-Late Jurassic interval (J_2-J_1) is thin, generally less than 1.5 km (USGS line 1, Fig. 6; 4, Fig. 5; and 5, Fig. 8). This interval could not be mapped in detail because of insufficient velocity data.

3-2—Early Cretaceous sediments are rarely thicker than 1.0 km beneath the shelf (Fig. 13), and beneath the rise they could not be mapped at all. Maximum thicknesses are near the shelf break

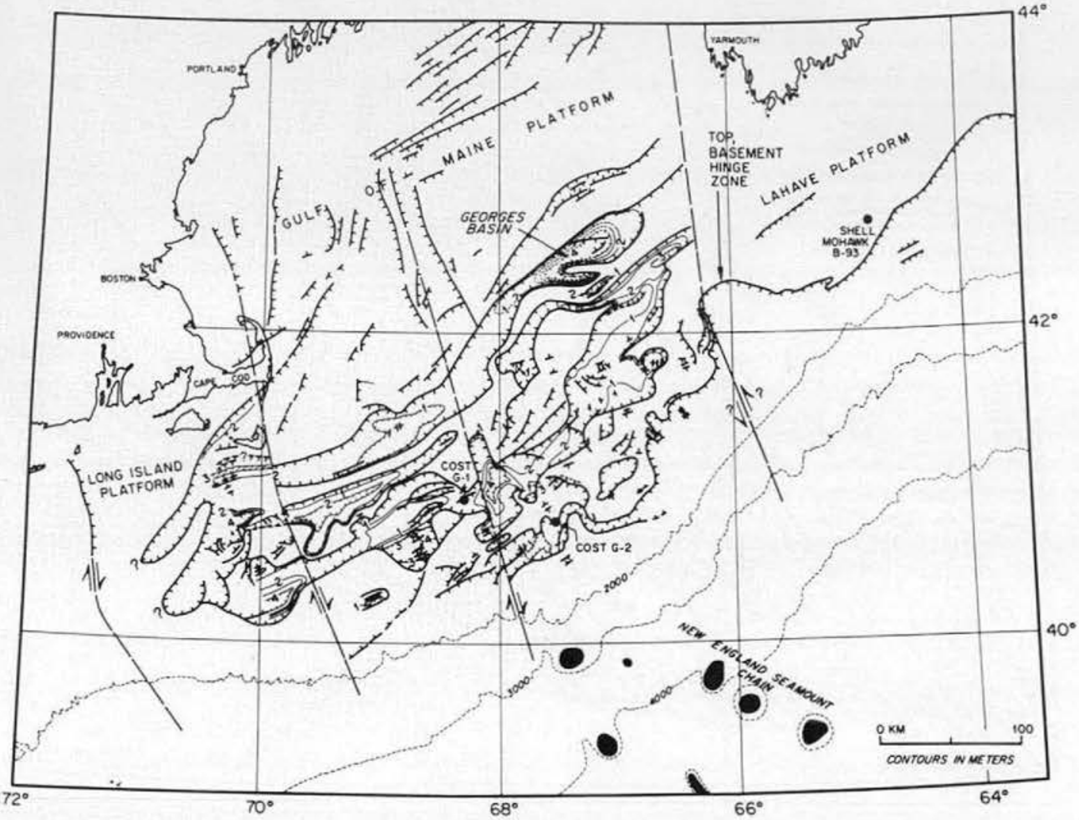

FIG. 10—Pre-K isopach map. Isopach (solid line) interval is 1.0 km. Graben-fill thicknesses are unknown beneath Gulf of Maine (north and west of Georges basin) and southeast of Yarmouth arch. *C.O.S.T.:* Continental Offshore Stratigraphic Test wells; drilling data are currently confidential.

in the axes of buried submarine canyons.

2-X—The Late Cretaceous sections is not distinguished by significant regional trends (Fig. 14). Slow margin subsidence resulted in maximum average sedimentation rates of approximately 1.0 cm/1,000 years. Neither the Yarmouth arch nor the reef-ridge exerted significant influence on regional sedimentation patterns after the Cenomanian (reflector 2 time).

X-present—Upper Cretaceous and younger sediments are thickest in the axes of filled submarine canyons near the present shelf break (Fig. 15). The largest of the paleocanyons underlies the present axis of Oceanographer Canyon (just west of 68°W, Figs. 1, 15), indicating that some reexcavation has occurred there. Ryan et al (1978) showed that at least four erosional episodes have affected the development of the submarine canyons south of Georges Bank: one during the late Early Cretaceous, another during the post-Eocene, and two or more during the Pliocene-Pleistocene.

North of the 250-m isopach in the Gulf of Maine (Fig. 15), the thickness of Upper Cretaceous and younger sediments varies. Within some of the gulf's enclosed basins (see Fig. 1), up to 150 m of reworked coastal plain and glacial sediment are present (Austin, unpub. data). Cretaceous and Tertiary (coastal plain) erosional remnants have been mapped in the northwestern Gulf of Maine (Oldale et al, 1973), but they probably are scattered throughout the gulf in complex stratigraphic association with younger deposits.

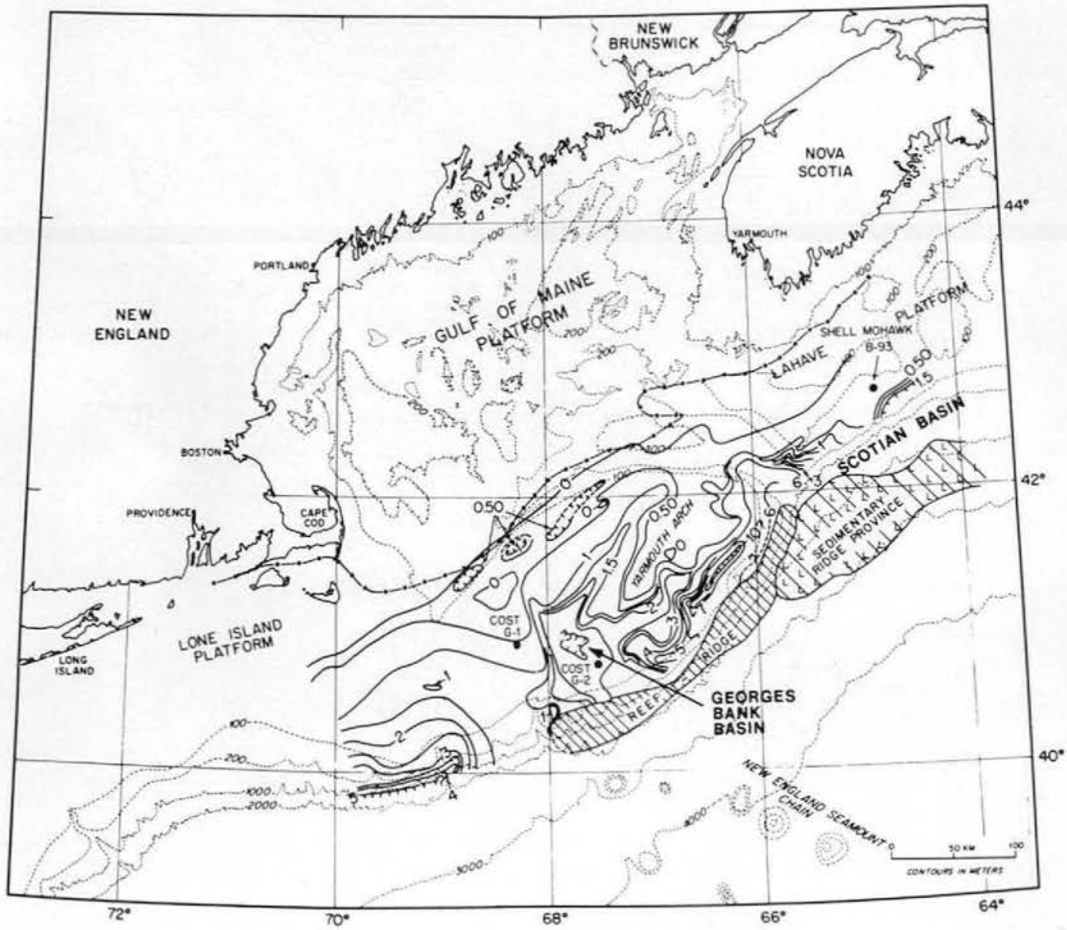

FIG. 11—K-Z (Early Jurassic) isopach map. Isopach (solid line) interval is 0.5 km to 4.0 km, then 1.0 km. Equivalent continental-rise sequence is not included. In this and subsequent isopach maps, dot-dash symbol marks approximate edge of Cretaceous/Tertiary sediments (coastal plain).

Depths

Basement—On the New England continental shelf, the maximum depth to pre-Triassic basement may be more than 13 km southeast of the Yarmouth arch. Abrupt changes in basement relief indicate that the zones of crustal weakness previously described are sites of dip-slip as well as strike-slip motion (Fig. 16).

Off the shelf, the maximum depth to basement is at the base of the continental slope along USGS line 5 (Figs. 8, 16). We interpret basement at slightly more than 12 km there, although Klitgord and Behrendt (1979) and Grow et al (1979) estimated it at 10 to 11 km. Beneath the SRP, basement may also be over 12 km deep (Keen and Keen, 1974).

K unconformity—The maximum post-K sediment thickness is approximately 8 km in the southwestern Georges Bank basin (Fig. 17). The Yarmouth arch separating the Georges Bank basin from the Scotian basin is clearly an extension of the LaHave platform beneath Georges Bank. The original K unconformity is not present beneath the Gulf of Maine, where it has been modified by subsequent erosional episodes.

Jurassic-Cretaceous boundary—Figure 18 shows the depth to reflector 3 beneath the shelf and upper slope, and the depth to reflector J_1 beneath the rise. The influence of the Yarmouth arch is still evident, despite lower sedimentation/subsidence rates after the Jurassic.

The Cretaceous-Cenozoic section remaining in the Gulf of Maine consists of isolated erosional remnants (Oldale et al, 1973). If Jurassic sedi-

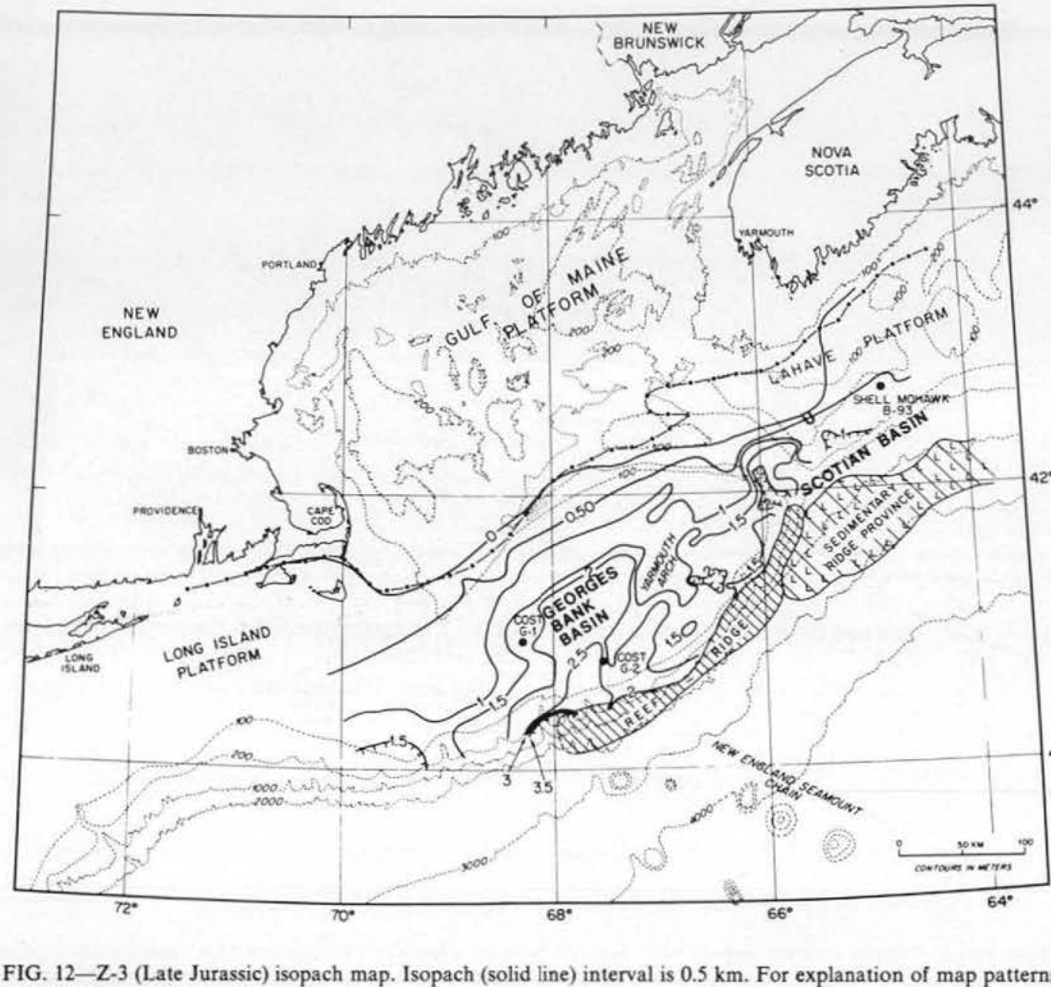

FIG. 12—Z-3 (Late Jurassic) isopach map. Isopach (solid line) interval is 0.5 km. For explanation of map patterns and symbols, see Figure 11.

ments ever extended north of Georges Bank, they have since been removed by erosion.

Velocities/Lithofacies

Maps of interval velocities were prepared for the following intervals: Early Jurassic (K-Z), Late Jurassic (Z-3), Early Cretaceous (3-2), and Late Cretaceous (2-X; Figs. 19-22). The velocity distribution of graben fill (pre-K) could not be mapped because of insufficient data, and the velocities within the X-present interval showed no regional trends. All four maps showed general seaward increases in interval velocity (see also Schlee et al, 1976; Grow et al, 1979).

From geologic information available from Georges Bank and Canadian margin drill holes, lithofacies were assigned to the velocity distributions. All velocities greater than 5.0 km/sec were interpreted as dolomites or dolomitized limestones. Volcanic rocks have similar velocities, but no post-K volcanic rocks have been sampled beneath the New England or Scotian Shelves.

Velocities of 4.0 to 5.0 km/sec were interpreted as limestones. The reef-ridge is probably limestone, too, on the basis of geophysical data and the samples collected by Ryan et al (1978).

Velocities of 3.0 to 4.0 km/sec were interpreted as marls, and velocities less than 3.0 km/sec were considered indicative of mixed sandstones and shales. By the end of the Cretaceous, noncarbonate lithologies were widespread on the New England margin.

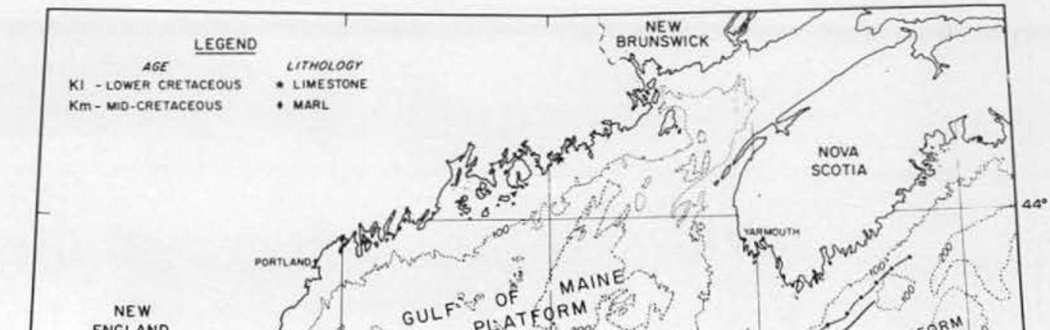

FIG. 13—3-2 (Early Cretaceous) isopach map. Isopach (heavy dashed/solid line) interval is 0.25/0.5 km. Symbols in legend refer to samples collected by Ryan et al (1978). For other symbols, see Figure 11.

GEOLOGIC HISTORY OF NEW ENGLAND CONTINENTAL MARGIN

Middle to Late Triassic: Continental Rifting

The separation of Africa and North America began with rifting in Morocco during the Middle Triassic (Manspeizer et al, 1978) and in New England during the Late Triassic (Cornet and Traverse, 1975; Fig. 23). The graben fill is composed of Middle Upper Triassic clastics, evaporites, and volcanic rocks in Morocco (Manspeizer et al, 1978), and similar deposits of Late Triassic–Early Jurassic age in New England and Nova Scotia (Cornet and Traverse, 1975; Given, 1977).

During the rifting phase, evaporites were deposited progressively from east to west in response to a Tethyan marine transgression (Jansa and Wade, 1975; Van Houten, 1977). Original thicknesses may never be ascertained because of diapir activity.

Graben-fill thicknesses exceed 4.0 km in Georges basin beneath the Gulf of Maine (Fig. 10). Thicker accumulations are possible seaward of the hinge zone beneath the southeastern part of Georges Bank.

Latest Triassic to Earliest Jurassic: Continental Separation and Formation of the K or Break-Up Unconformity

During the latest Triassic–earliest Jurassic (approximately 205 to 190 m.y.B.P.), widespread tholeiitic volcanism and the intrusion of mafic dikes and sills began on both the North American and African margins (Cousminer and Manspeizer,

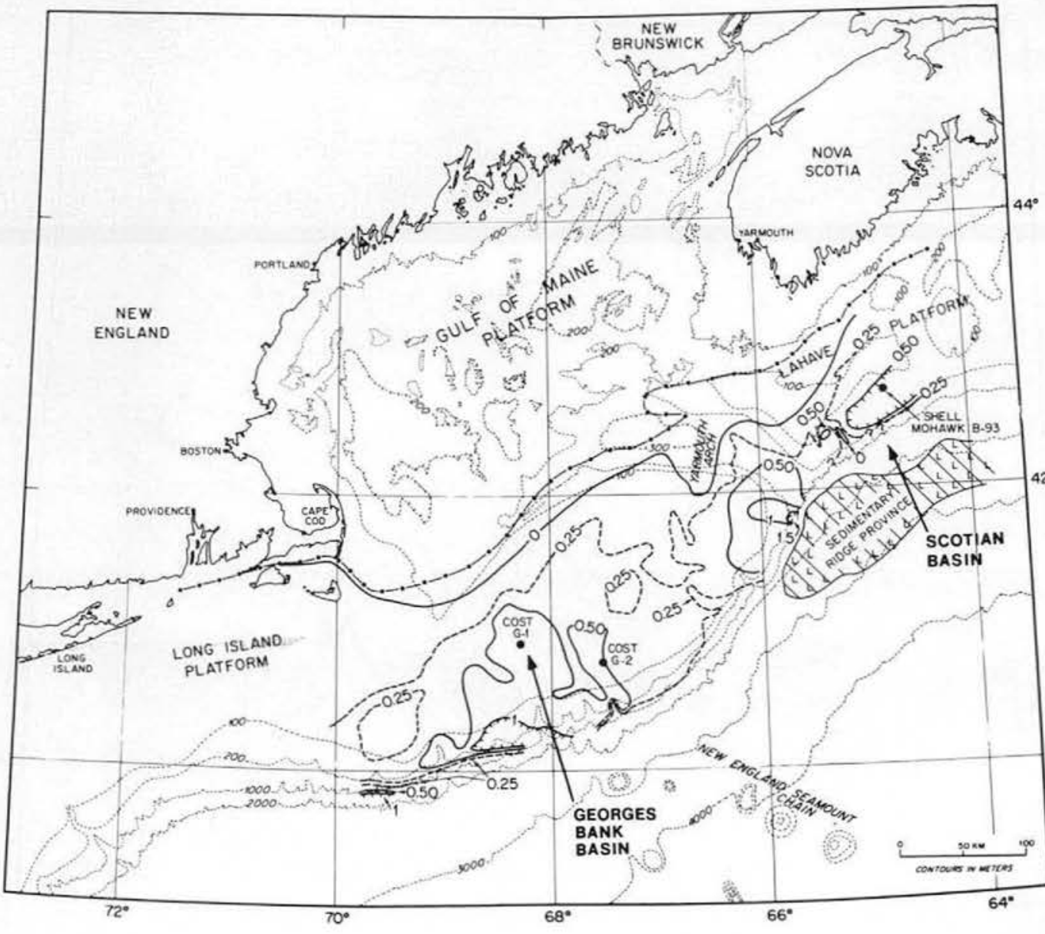

FIG. 14—2-X (Late Cretaceous) isopach map. Isopach (heavy solid/dashed line) interval is 0.25 km. For explanation of symbols, see Figure 11.

1976; Manspeizer et al, 1978; McHone, 1978; Fig. 23). Continental separation and the initiation of seafloor spreading may have occurred near the peak of this activity, 195 to 190 m.y.B.P. (Scrutton, 1973). We believe that separation took place along the basement hinge zone. If this hypothesis proves to be correct, then the hinge zone represents the boundary between normal continental crust and a crust consisting of a mosaic of continental and oceanic fragments, and the slope anomaly would mark the boundary between this transitional crust and an oceanic one (Grow et al, 1979).

Subaerial erosion created the K unconformity prior to final subsidence of the New England margin. We consider K to be equivalent to Falvey's (1974) "break-up" unconformity. Therefore, its age correlates with the start of seafloor spreading (195 to 190 m.y.B.P.).

Early Jurassic to Present: Drift Sedimentation

K-Z (190 to 160 m.y.B.P.)—After the formation of the K unconformity, rapid margin subsidence caused an Early Jurassic marine transgression that inundated the truncated rift structures. Early Jurassic stratigraphy consists of evaporites, sabkha tidal-flat dolomites, lagoonal limestones, and marls (Given, 1977; Fig. 19). These platform carbonate rocks were laid down at least in part on altered continental and/or oceanic crust. If Lower Jurassic evaporites extend beyond the present boundary of the SRP to the rise south of Georges Bank, then they are either too thinly bedded to produce diapirs or they are prevented from verti-

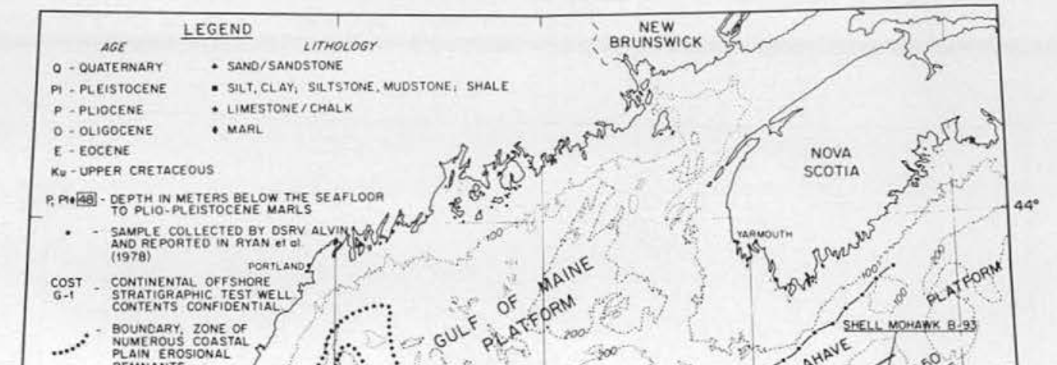

FIG. 15—X-present (Cenozoic) isopach map. Isopach (heavy solid line) interval is 0.25 km. Sample location and age data from Emery and Uchupi (1972); Oldale et al (1973); Weed et al (1974); Hathaway et al (1976); Ryan et al (1978). For explanation of symbols not contained in legend, see Figure 11.

cal migration by competent overlying sediments, perhaps fore-reef carbonate rocks associated with the reef-ridge (Fig. 19).

Landward of the carbonate rocks, a major change to marls and clastics (probably red beds) is inferred (Fig. 19) from similar transitions in the Lower Jurassic section off eastern Canada and Morocco (Jansa and Wade, 1975; Van Houten, 1977).

Z-3 (160 to 136 m.y.B.P.)—During the Middle Jurassic, the margin off eastern North America was subjected to a large influx of clastics in response to uplift and the consequent rejuvenation of source areas (Wade, 1978). We interpret this tectonism to be a result of a jump of the Mid-Atlantic Ridge westward toward the margin (Luyendyk and Bunce, 1973; Sclater et al, 1977) at the time of formation of the Blake Spur anomaly 175 to 160 m.y.B.P. (van Hinte, 1976a; Klitford and Schouten, 1977).

Following the ridge jump, margin subsidence continued (Keen, 1979). Limestones were deposited on the outer shelf (Fig. 20). Their regional extent is indicated by reflector 4 (Fig. 2), whose northern limit mimics the transition from limestones to marls on Figure 20. Although open marine conditions prevailed on the outer shelf (Wade, 1978), the reef-ridge must have been at least a partial barrier to the seaward transport of sediments during the latter half of the Jurassic.

3-2 (136 to ~95 m.y.B.P.)—Reflector 3 (the approximate Jurassic-Cretaceous boundary) records the facies change associated with the progradation of deltaic sediments across the carbonate platform during the latest Jurassic–earliest Cretaceous. As clastics inundated the reef-ridge, it became little more than a series of patch reefs near the present shelf break (Fig. 21).

On the inner shelf, widespread erosion occurred at this time. The entire Lower Cretaceous section is only 4 m thick in the Shell Mohawk B-93 well, where a hiatus separates Aptian from

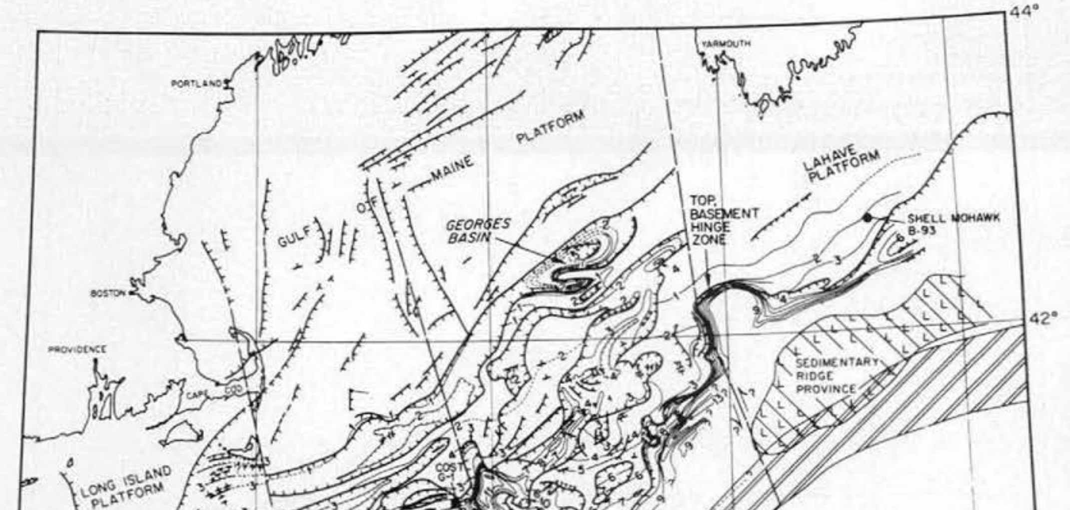

FIG. 16—Depth to acoustic basement. Datum is sea level. Contour interval is 1.0 km. Near New England Seamount Chain, contours are generalized because of insufficient seismic coverage. For explanation of labels and symbols, see Figures 3 and 9.

Cenomanian sediments (Fig. 2). We interpret reflector 2 as the Early Cretaceous unconformity beneath the New England margin, and we attribute the regression which caused the erosion to the opening of the Bay of Biscay 125 m.y.B.P. (Jansa and Wade, 1975; Sclater et al, 1977) and to the separation of Europe and North America 110 to 95 m.y.B.P. (Sclater et al, 1977).

2-X (~95 to ~75 m.y.B.P.)—Margin subsidence continued at a much reduced rate during the Late Cretaceous (Gradstein et al, 1975). Evidence from the adjacent Canadian margin suggests that slow transgression continued until the Maestrichtian (Jansa and Wade, 1975; Given, 1977; Wade, 1978). Although most of the New England margin was blanketed by terrigenous clastics (Fig. 23), limestone and chalk were deposited in a deep basin occupying the southwestern Scotian Shelf from Turonian to Campanian time. These carbonate rocks produce reflector X (Fig. 2), and because X can be traced across Georges Bank, the presence of Upper Cretaceous carbonate rocks can be inferred there even though Figure 23 does not indicate their presence.

X-present (75 to 0 m.y.B.P.)—Renewed erosion of the inner parts of the Scotian Shelf was taking place by the latest Cretaceous, as is evidenced by an early Campanian–Paleocene hiatus in the Shell Mohawk B-93 well (Fig. 2). This regressional cycle coincides with a major North Atlantic plate reorganization (Sclater et al, 1977; Fig. 2), a decrease in spreading rates (van Hinte, 1976b), and a decline in bottom-water temperatures (Savin et al, 1975) perhaps signaling the onset of continental glaciation.

Since the Campanian, clastics have dominated

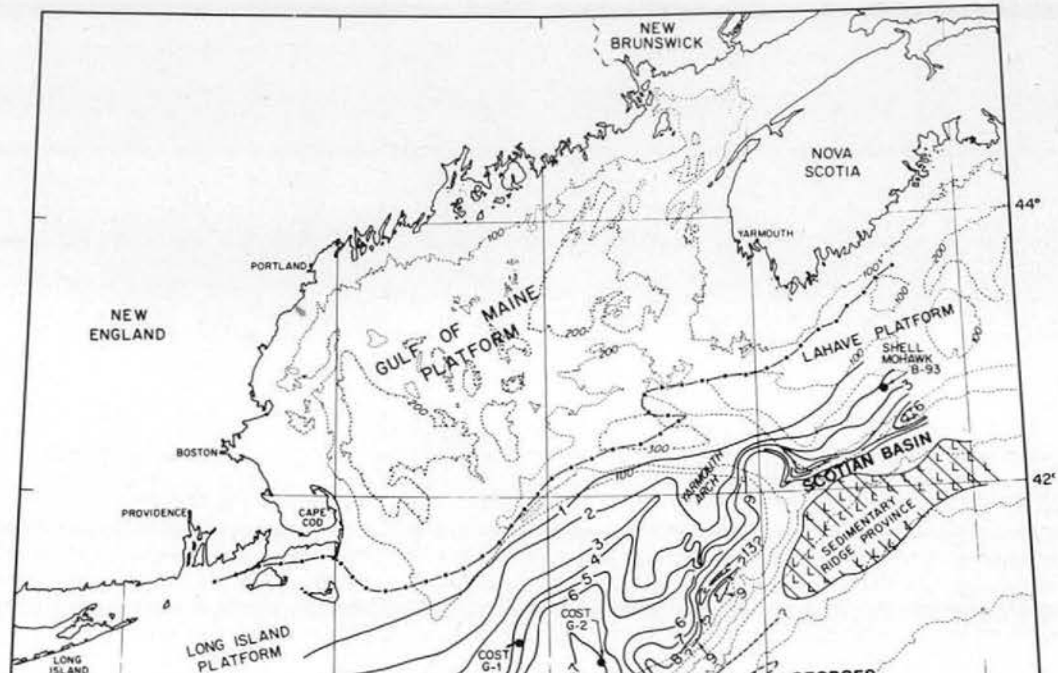

FIG. 17—Depth to K unconformity. Contour interval is 1.0 km. Beneath rise, depth to K is same as depth to acoustic basement (Fig. 16). For explanation of labels and symbols, see previous figures.

on the New England margin (McIver, 1972; Jansa and Wade, 1975; Given, 1977). Carbonate deposition in the early Tertiary was restricted to parts of the outer shelf (Ryan et al, 1978; Fig. 15).

A spectacular erosional episode occurred during the Oligocene, when a major regression, perhaps accompanying the onset of continental glaciation (Savin et al, 1975; Ingle et al, 1976; Haq et al, 1977), resulted in massive downcutting of the central and outer parts of the Scotian Shelf. Reflector 1 (Fig. 2) marks this event (Figs. 3, 4), which has been recognized on many margins around the world (Vail et al, 1977, in press). According to Vail and his colleagues, sea level may have dropped about 250 m below its present level during the Oligocene. If so, the present shelf was exposed, and the now filled canyons along line 42 (Fig. 3) were cut in part subaerially.

Reflector 1 cannot be correlated regionally beneath Georges Bank. However, an unconformity probably coeval with 1 has been identified by Uchupi et al (1977) on a series of single-channel profiles of Corsair Canyon (just west of 66°W, Fig. 15). The Tertiary unconformity beneath the Gulf of Maine (Figs. 5, 6) may also have been produced during the Oligocene. Much of the erosion which left the gulf as an interior lowland (Fig. 1) could have taken place at this time (Oldale and Uchupi, 1970).

Sediments eroded from the shelf during the Oligocene must have been deposited in deep water. However, no large accumulations of Oligocene sediments have been drilled in the western North Atlantic basin, perhaps because extensive sam-

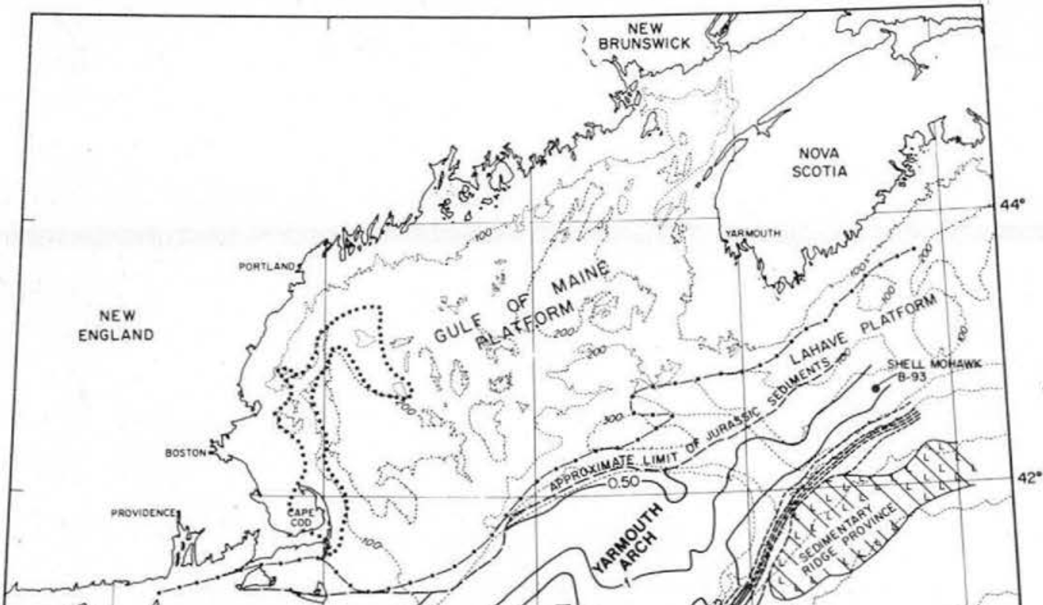

FIG. 18—Depth to Jurassic-Cretaceous boundary (reflector 3 beneath continental shelf and upper slope, and reflector J_1 beneath continental rise). Contour interval is 0.1 km. Dotted line north of Cape Cod encloses region of coastal plain erosional remnants.

pling of the continental slope and rise has not taken place.

From the latest Miocene through the Pleistocene, continental glaciation modified the morphology of the New England margin. The Gulf of Maine and the northern edge of Georges Bank were directly glaciated (Oldale and Uchupi, 1970). Ice may have reached the shelf edge through Northeast and Great South Channels (Fig. 1), which also acted as conduits for the seaward transport of sediments. Such transport explains both the large thickness of Pleistocene material sampled by USGS drill hole 6013B (Hathaway et al, 1976; Figs. 1, 15), and the filling of submarine canyons on the Scotian Shelf (Fig. 3). On Georges Bank, Miocene sediments were exposed by stream erosion (Emery and Uchupi, 1972; Fig. 15).

During the Holocene transgression, winnowing of the fine-grained components of glacial and periglacial deposits left the sands that now veneer Georges Bank and adjacent areas. Rising sea level prevented off-shelf sediment transport, which now occurs sporadically in the submarine canyons south of Georges Bank (Ryan et al, 1978). By 2000 years B.P., the New England margin had assumed its present form (Oldale and O'Hara, 1978).

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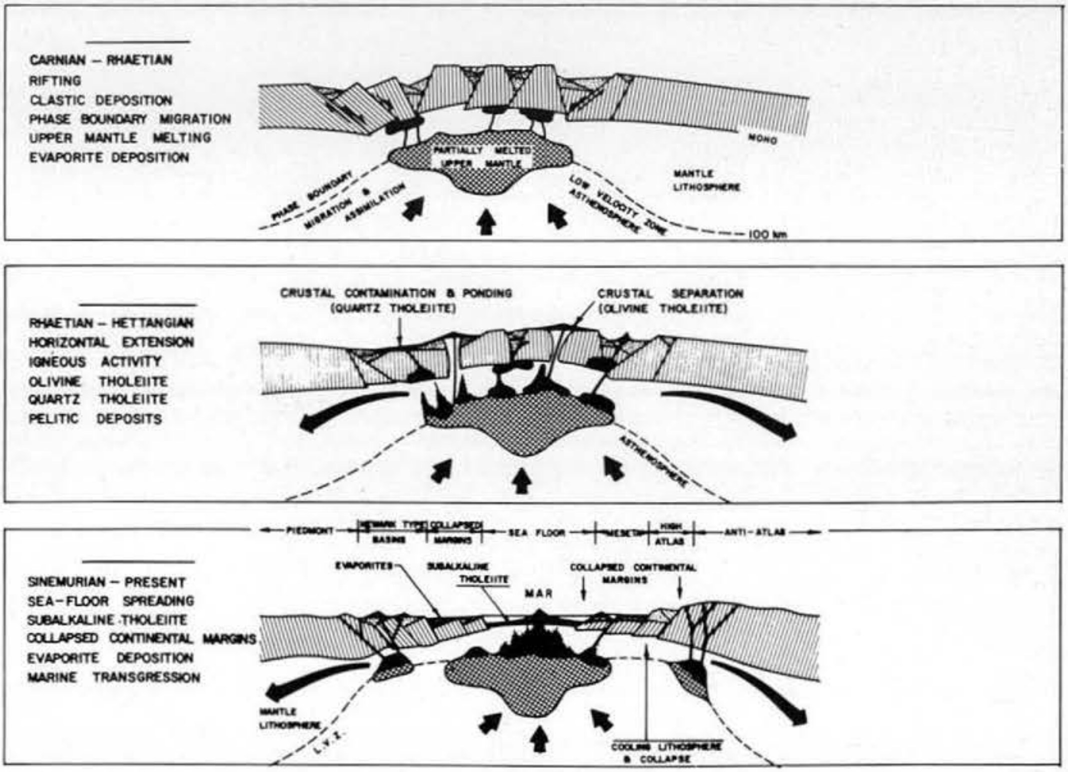

FIG. 19—Model of North Atlantic passive margin formation. Modified from Manspeizer et al (1978).

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FIG. 20—K-Z (Early Jurassic) interval velocity–lithofacies distribution. In this and subsequent maps, velocity contour (heavy lines) interval is 1.0 km/sec.

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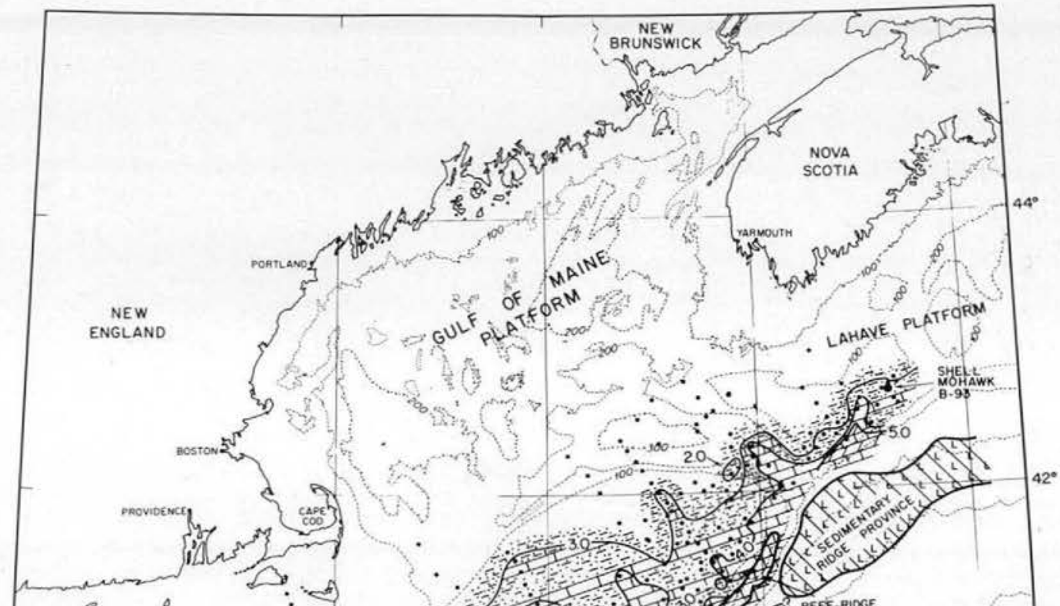

FIG. 21—Z-3 (Late Jurassic) interval velocity–lithofacies distribution. For explanation of labels and symbols, see Figure 20. Outline of reef-ridge is approximate.

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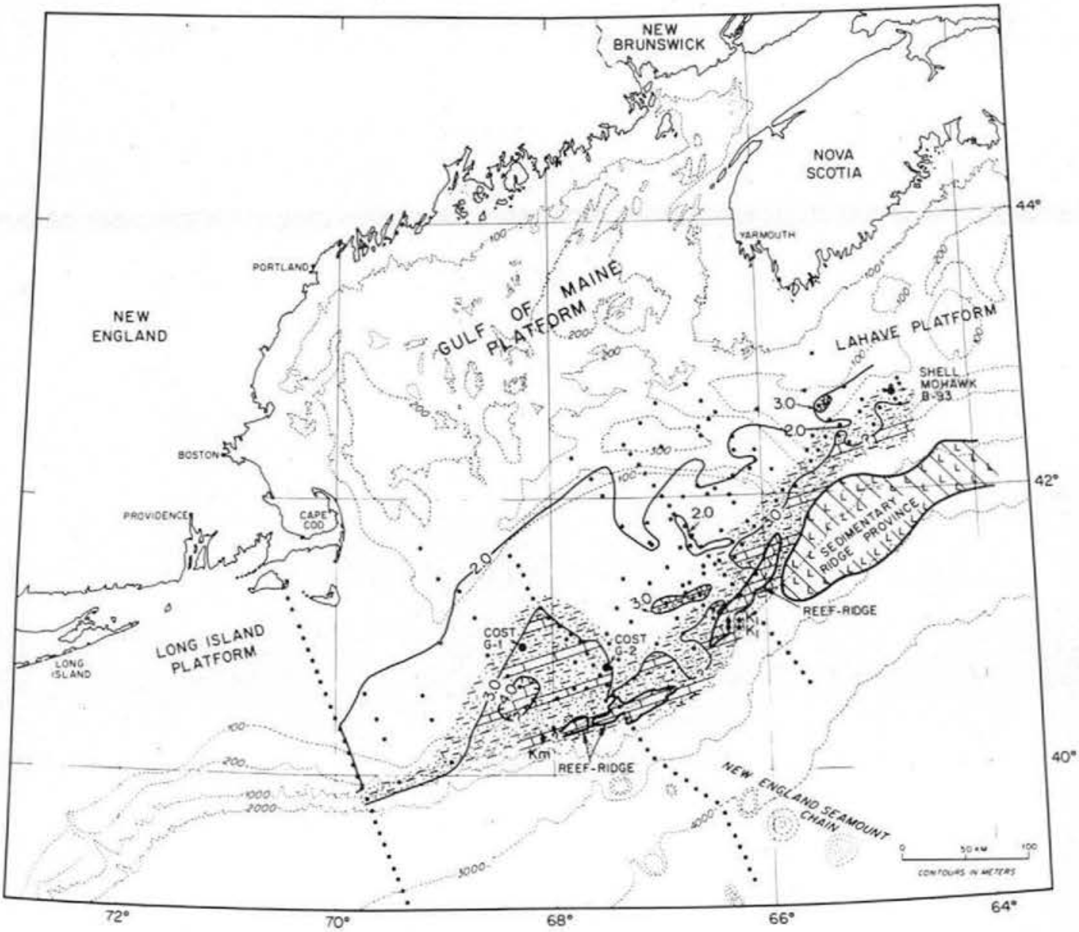

FIG. 22—3-2 (Early Cretaceous) interval velocity–lithofacies distribution. For explanation of symbols and labels, see Figure 20. Although outline of reef-ridge is same as that shown on Figure 21, its extent was reduced during Early Cretaceous.

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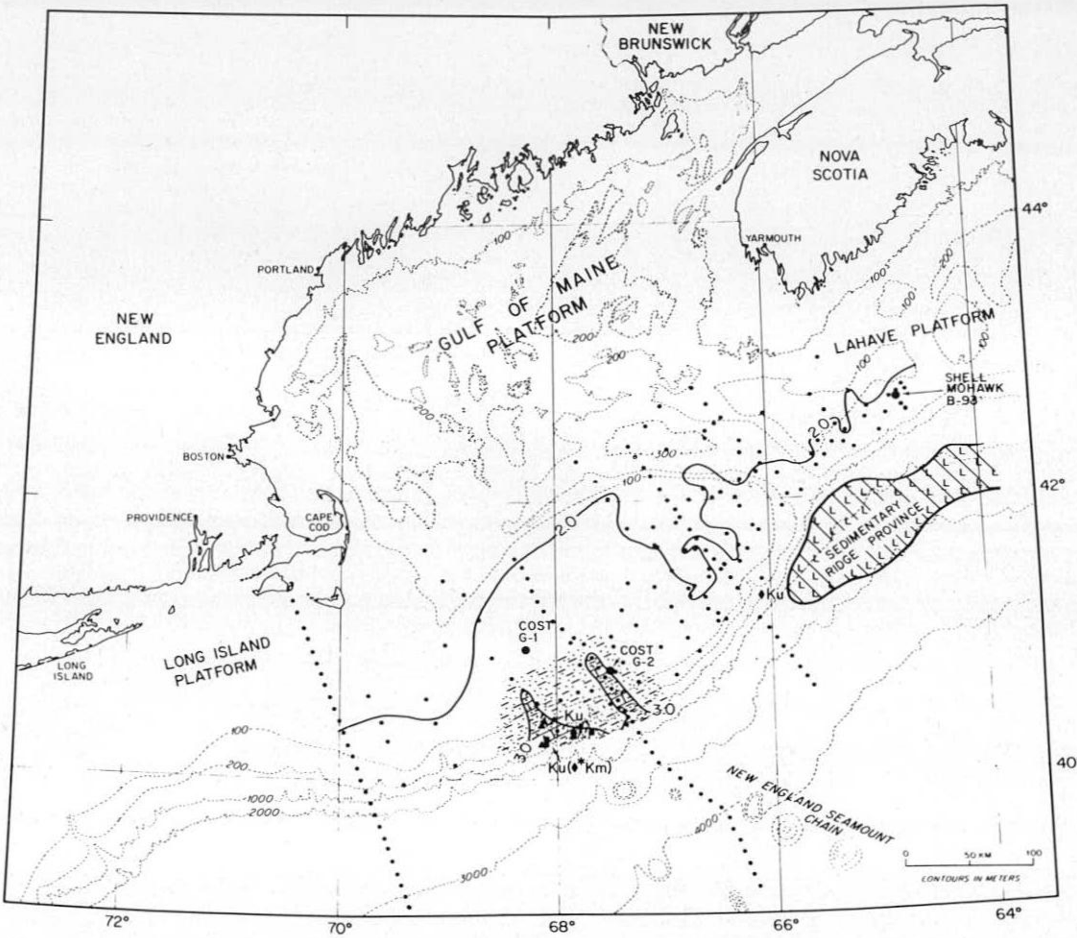

FIG. 23—2-X (Late Cretaceous) interval velocity–lithofacies distribution. For explanation of labels and symbols, see Figure 20.

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