Tectonophysics, 59 (1979) 53—69

THE GEOLOGIC HISTORY OF THE PASSIVE MARGIN OFF NEW ENGLAND AND THE CANADIAN MARITIME PROVINCES

ELAZAR UCHUPI and JAMES ALBERT AUSTIN, Jr.

Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Mass 02543 (U.S.A.)
Woods Hole Oceanographic Institution/Massachusetts Institute of Technology Joint Program in Oceanography, Woods Hole, Mass. 02543 (U.S.A.)

(Received March 9, 1979)

ABSTRACT

Uchupi, E. and Austin, J.A., Jr. 1979. The geologic history of the passive margin off New England and the Canadian maritime provinces. In: C.E. Keen (Editor), Crustal Properties across Passive Margins. Tectonophysics, 59: 53—69.

The geologic history of the passive continental margin off the east coast of North America from New England to Newfoundland is described using all available geological and geophysical information. "Rift" and "drift" phases of the margin's evolution are recognized, with rifting initiated in Late Triassic and completed by Early Jurassic. The plate decoupling process created a complex block-faulted terrain as a result of uplift and tensional fracturing. The approximate plane of continental separation is marked by a "hinge zone" characterized by a pronounced steepening of basement gradients. Since the Early Jurassic, the margin has undergone continual subsidence in response to cooling and sediment loading. This "drift" sequence attains its maximum thickness in the vicinity of the continental slope, and thins both landward and seaward. On the shelf, this unit consists of Mesozoic evaporites, carbonates, and deltaic deposits. Overlying these sediments is a prograding wedge of Cenozoic clastics. On the rise, the Mesozoic sediments are evaporites, hemipelagic limestones and shales, and carbonaceous clays. The Cenozoic is dominantly terrigenous material. Separating these two sedimentary provinces is the continental slope, a site of major facies changes and a Mesozoic reef complex.

INTRODUCTION

In this report we summarize the results of our analysis of more than 10,000 line km of single and multi-channel seismic reflection profiles collected on the Laurentian Cone * and in the Georges Bank region by the Woods Hole Oceanographic Institution and Imperial Oil Ltd. (Austin, 1978; Uchupi and Austin, in press). We will trace the geological development of

* As used in this report, the term "cone" is a synonym for "fan". As similar features in the rest of the Atlantic and Gulf of Mexico have been termed cones, we will follow the terminology of the late B.C. Heezen and call the feature the Laurentian Cone.

the passive margin off New England and the Canadian Maritime Provinces using these profiles and all other available geological and geophysical data (Emery et al., 1970; Keen and Keen, 1974; Weed et al., 1974; Ballard and Uchupi, 1975; Jansa and Wade, 1975; Parsons, 1975; Hathaway et al., 1976; Schlee et al., 1976; Gradstein et al., 1977; Grant, 1977; Tucholke and Mountain, 1977; Uchupi et al., 1977; Wade, 1977, 1978; Ryan et al., 1978). Stratigraphic control is provided by wells drilled on the Scotian Shelf and the Grand Banks (Jansa and Wade, 1975; Given, 1977), samples recovered from the Gulf of Maine and the submarine canyons south of Georges Bank by dredge and submersible (Weed et al., 1974; Ballard and Uchupi, 1975; Ryan et al., 1978), and cuttings obtained during a shallow drilling program conducted by the United States Geological Survey on the northern and southwestern perimeter of Georges Bank (Hathaway et al., 1976). Lithologic interpretations are based on our correlation of well logs, on interval velocities calculated from sonobuoy profiles and CDP processing of multi-channel seismic reflection recordings.

This data set has provided new insight into the evolution of the continental shelf, slope, and rise off the northeast coast of North America. However, these data do not allow us to do more than speculate about the nature and exact geographic position of the boundary between oceanic and continental crust.

TECTONIC UNITS

An examination of all of the seismic reflection profiles supports the subdivision of the passive margin between Georges Bank and the Grand Banks into two major tectonic units. These units comprise the "rift" and "drift" phases of passive margin development, as described by Falvey (1974). Entrained within the Precambrian—Paleozoic basement terrain are a series of grabens and half-grabens (Figs. 1 and 2). Some of these rift structures are truncated by a prominent unconformity (Fig. 2, reflector "*K*"), which we believe is the "breakup unconformity" of Falvey. Overlying this unconformity is a sediment wedge (Figs. 2—8), deposited during the margin's drifting phase. This wedge displays its greatest thickness in the area of the outer shelf and upper continental slope, and is associated with a long period of gradual margin subsidence. Deformation of this drift sequence is restricted to halokinetic structures and associated growth faults, compaction over rifted basement blocks. and the reactivation of basement faults (Figs. 2—8). Using the terminology of Kay (1951), the drift sediments consist of two parts: a "miogeosyncline" encompassing all post-rift strate on the continental shelf, and the corresponding "eugeosyncline" consisting of coeval sediments composing the continental rise. The continental slope separates these two geosynclinal sequences, and is characterized on the seismic reflection profiles by confused acoustic returns associated with reefal growth and complex cut-and-fill topography (Figs. 2, 5, 6, and 8).

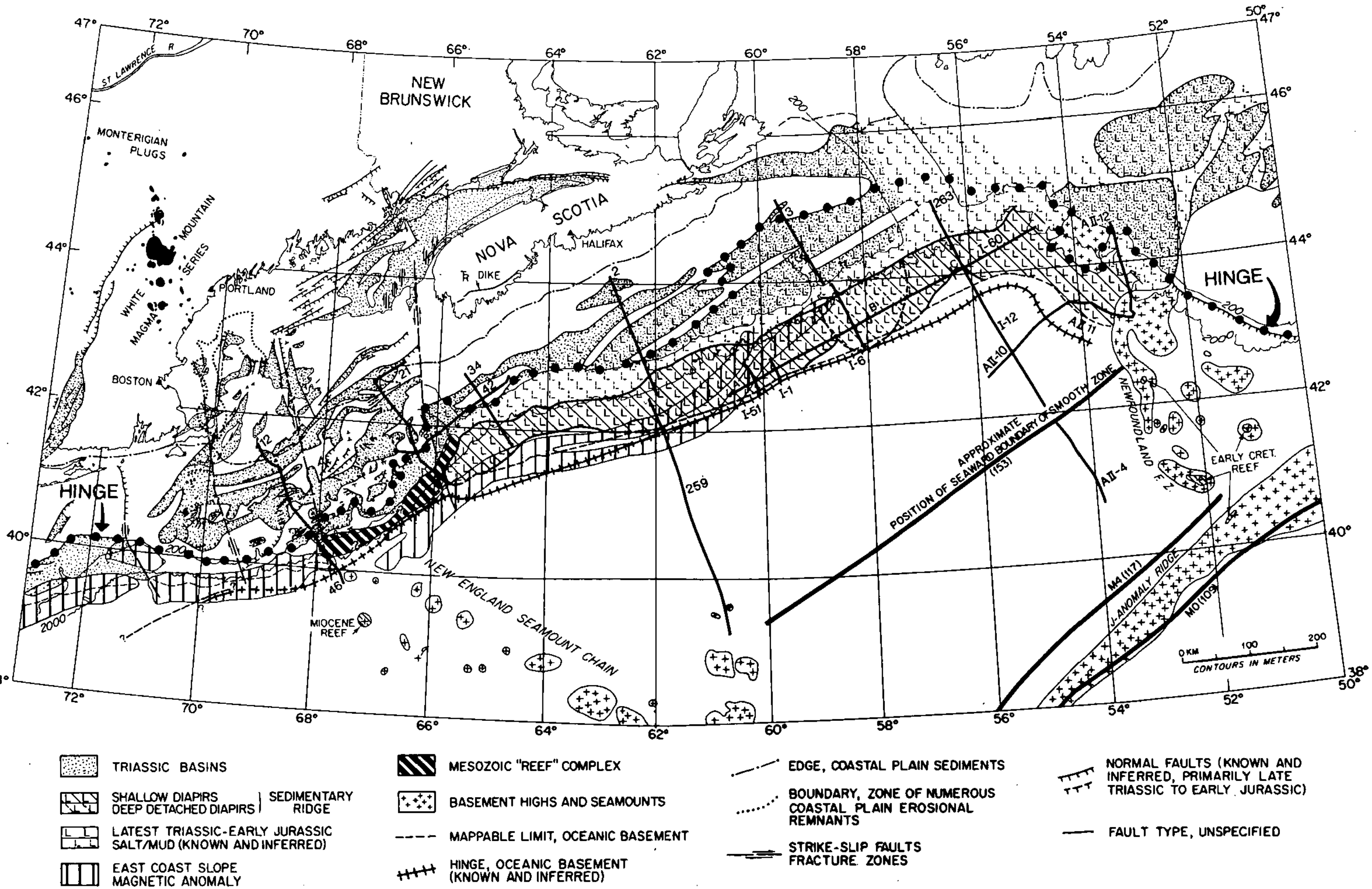
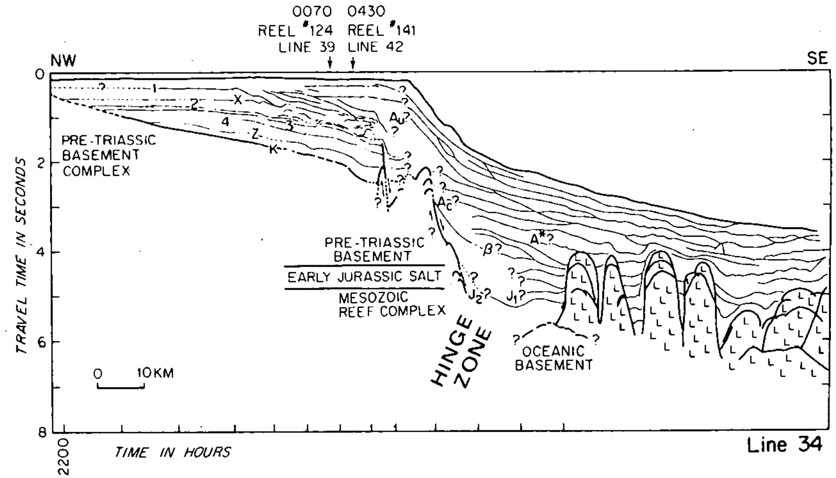
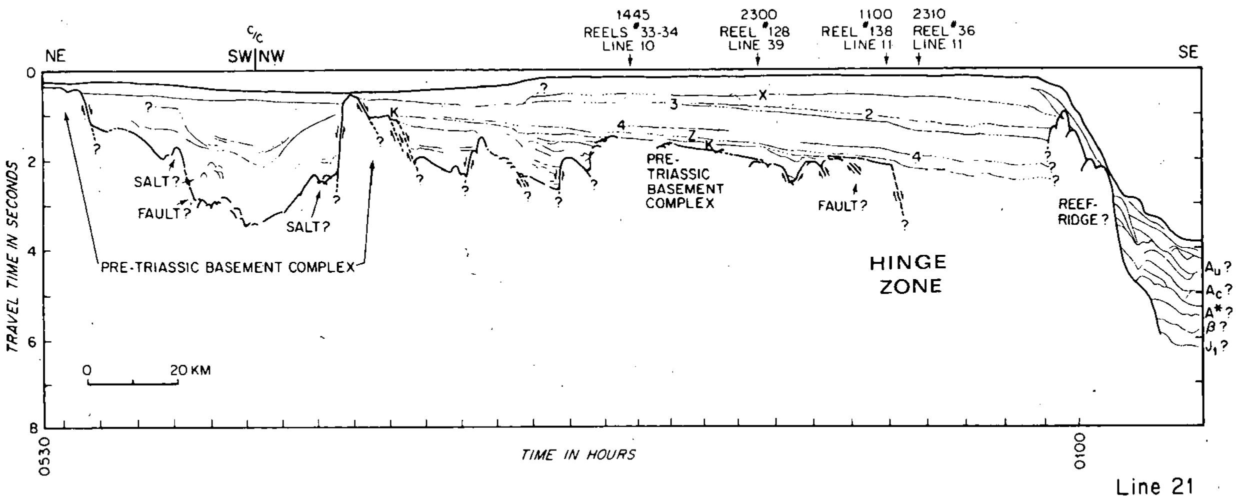


Fig. 1. Basement tectonic map of the passive continental margin off New England and the Canadian Maritime Provinces. Compiled from Ballard and Uchupi (1975), Jansa and Wade (1975), Given (1977), Scientific Staff (1975), Austin (1978), and Uchupi and Austin (in press). Numbered lines are seismic reflection profiles discussed in the text. Large dots show the position of the "hinge zone" which represents the seaward boundary of continental crust.

Fig. 2. Line drawing of Multi-channel seismic reflection profiles from the western Scotian Shelf and Georges Bank collected with the Woods Hole Oceanographic Institution 6-channel seismic reflection profiling system in 1975. The "rift" and "drift" phases of margin development described by Falvey (1974) are clearly delineated. See Fig. 1 for locations of profiles.
Shelf reflectors: *K* = basal unconformity (Early Jurassic); *Z* = Bathonian; *4* = approx. Callovian (Scatarie Member, Abenaki Formation); *3* = Jurassic—Cretaceous boundary; *2* = Aptian—Albian; *X* = approx. Turonian; *1* = Oligocene (?). From Austin (1978).
Slope/upper rise reflectors: *J2* = Early Jurassic, 170—175 m.y. B.P. (Blake Spur Anomaly); *J1* = Late Jurassic, 145 m.y. B.P.; *B* = Hauterivian—Barremian: *A** = Maestrichtian; *Ac* = Upper-lower to lower-middle Eocene cherts; *Au* = Oligocene to earliest Miocene unconfirmity. The "*L*" pattern denotes salt diapirs of the sedimentary ridge. Tucholke and Vogt (in press).





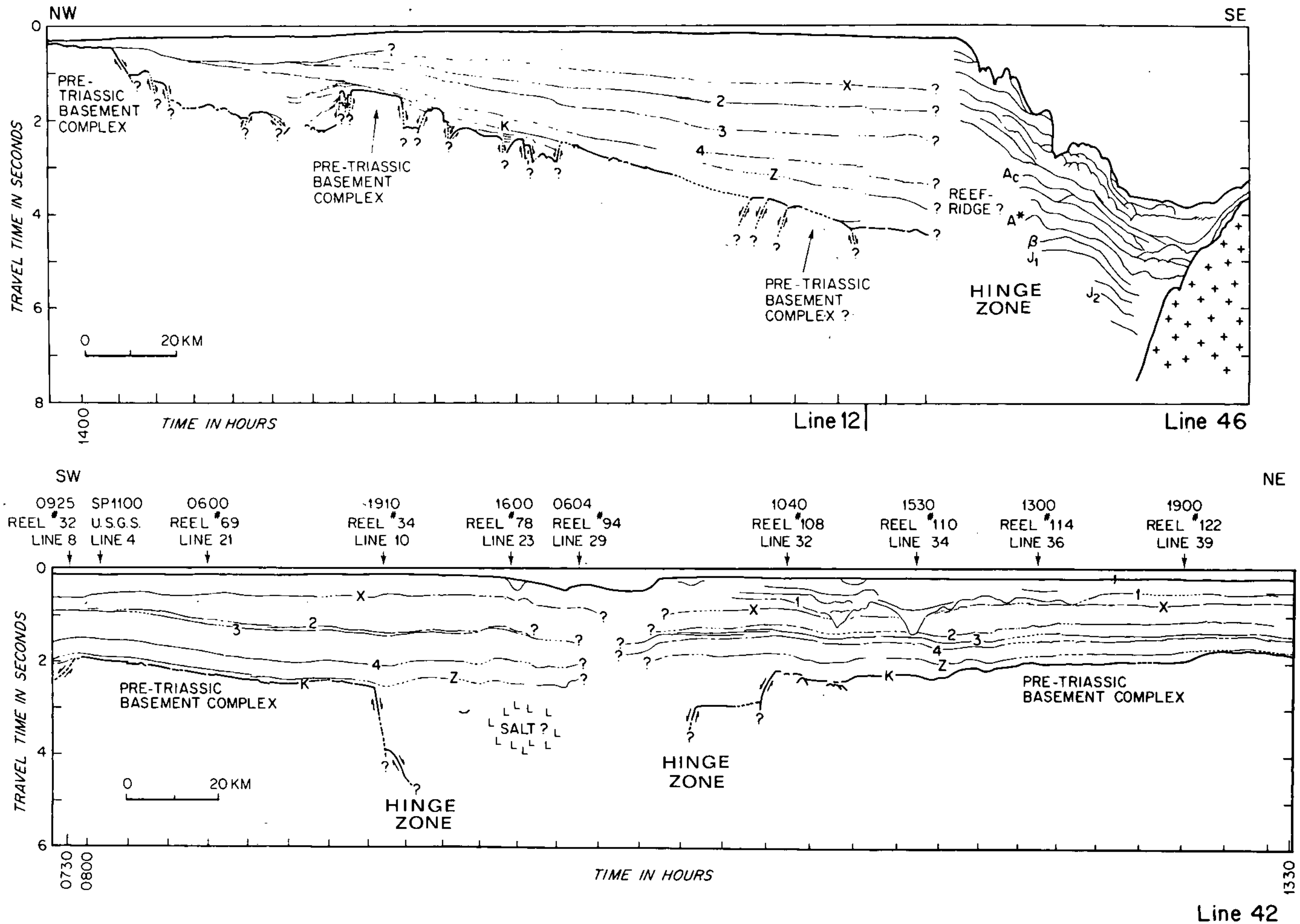


Fig. 3. Line drawings of multi-channel seismic reflection profiles from the western Scotian Shelf and Georges Bank. See Fig. 1 for location of profiles and Fig. 2 for reflector identification.

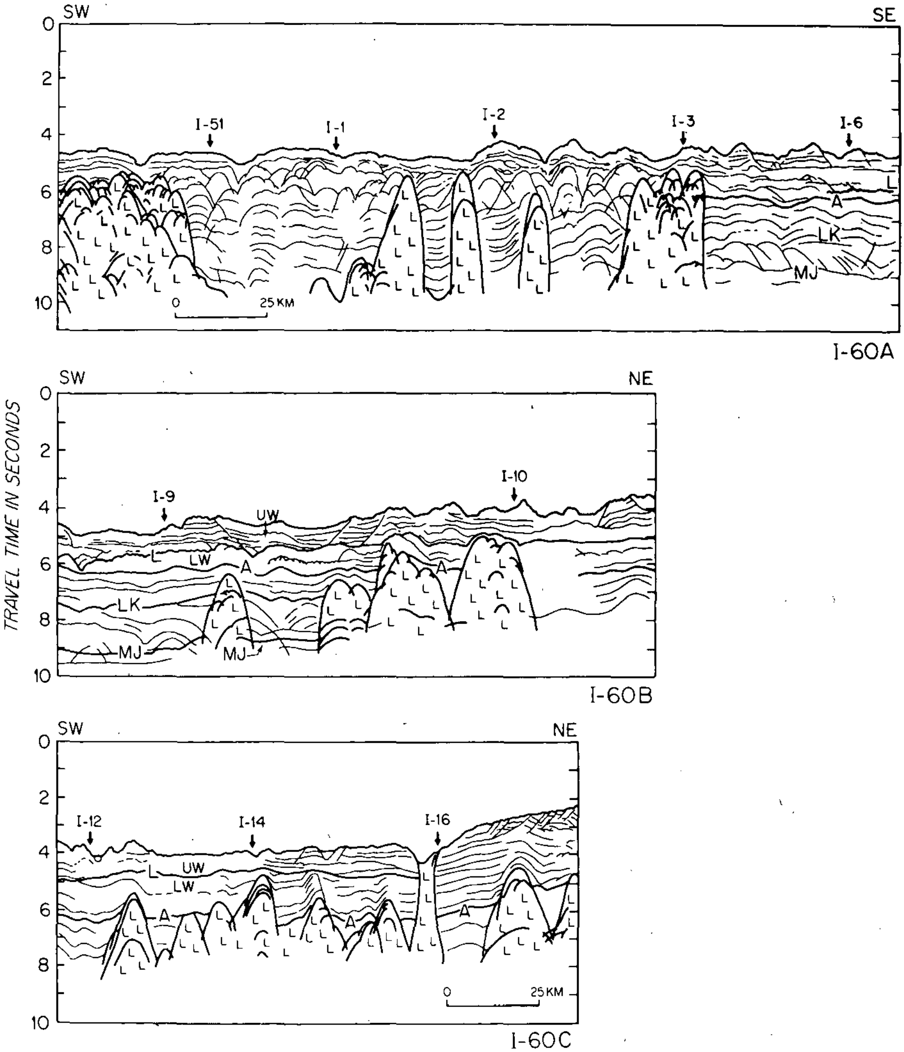


Fig. 4. Line drawings of multi-channel seismic reflection profiles of the sedimentary ridge provided by Imperial Oil Ltd. The profile parallels the long axis of the ridge. From Uchupi and Austin, in press). For location of the profile, see Fig. 1. Seismic markers; *MJ* = Middle Jurassic (Parsons, 1975); *LK* = Lower Cretaceous (Parsons, 1975): *A* = Horizon A; *L* = Plio-Pleistocene (Uchupi and Austin, in press); *LW* and *UW* = lower and upper wedges of the Laurentian Cone.

RIFT PHASE

The breakup of the North American and African continents began during the Late Triassic and was completed by the Early Jurassic with the separation of the two continents. Along the southwestern side of the Grand Banks,

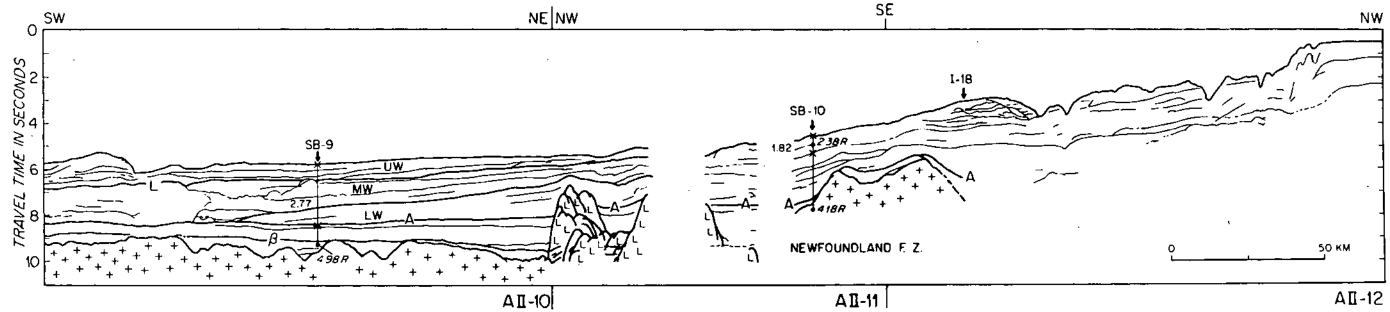


Fig. 5. Line drawing of single-channel seismic reflection profile across the western slope of the Grand Banks. The basement high on the northwestern end of the profile is located along the Newfoundland fracture zone. The plus (+) pattern denotes oceanic basement, and the letters *UW*, *MW* and *LW*, the three wedges of the Laurentian Cone. *SB* stands for sonobuoy with the vertical numbers representing a reflection velocity, and the slanted numbers with the letter *R*, a refraction velocity. From Uchupi and Austin (in press). For location of profile, see Fig. 1.

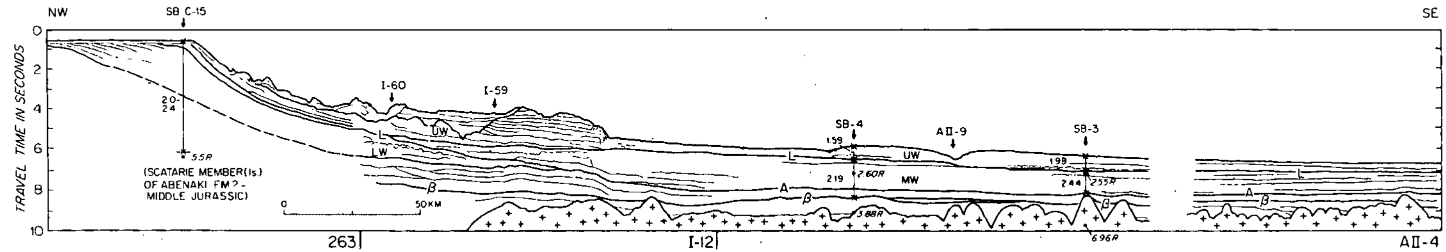


Fig. 6. Line drawing of composite single and multichannel profile of the Laurentian Cone seaward of the Laurentian Channel. Symbols are the same as for previous figures. *I-12* is a multi-channel provided by Imperial Oil Ltd. See Fig. 1 for location of the profile.

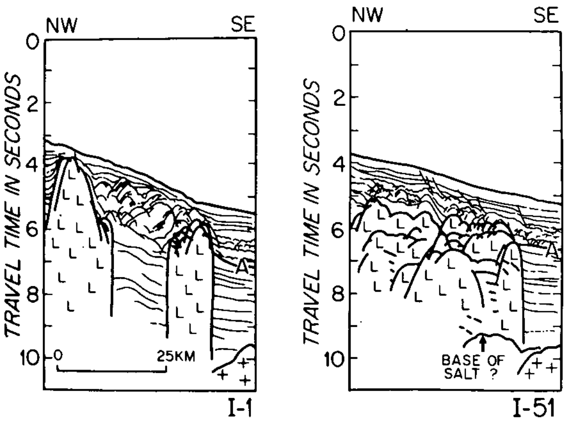


Fig. 7. Line drawing of multi-channel seismic reflection profiles from the sedimentary ridge's western zone. Profiles were provided by Imperial Oil Ltd. See Fig. 1 for locations of profiles.

translational motion occurred, while divergence was dominant from the vicinity of the Laurentian Channel to Georges Bank (Fig. 1). During the initial stages, continental basement underwent a taphrogenic episode. The resulting rift structures trend northeast-southwest beneath Georges Bank and the western Scotian Shelf, roughly paralleling the Paleozoic structural grain (Fig. 1). At the eastern end of the Scotian Shelf, these structures turn eastward, aligning themselves with the Glooscap fault system (King et al., 1975; Fig. 10). In the Gulf of Maine, the trends of observed rift structures range from northeast—southwest in the eastern part to north—south in the western part (Ballard and Uchupi, 1975; see Fig. 1).

All of these grabens and half-grabens are filled with sediment and volcanics. Where this graben-fill has been sampled, such as in the valley of the Connecticut River in southern New England, the sediments consist predominantly of coarse-grained fanglomerates and fine-grained lacustrine and flood-plain deposits of Late Triassic—Early Jurassic age (Hubert et al., 1976). Partly coeval deposits on the Canadian margin have been termed the Eurydice Formation (Jansa and Wade, 1975). Some evaporites also appear to be present, as evidenced from diapiric structures in some of these basins (Fig. 2). Jansa et al. (1977) have interpreted the salt recovered from a well (Osprey H-84) drilled in the Carson Sub-basin beneath the eastern Grand Banks to be a part of the European Triassic system. The occurrence of a possible halokinetic structure within the Triassic (?) fill underlying Georges Basin in the Gulf of Maine (Ballard and Uchupi, 1975, p. 1059) suggests that an initial marine incursion in the Late Triassic may have extended as far west as the Gulf of Maine. However, as these structures are rare, such an incursion must have been of limited extent.

Ballard and Uchupi (1975) believe that the rift structures in the Gulf of

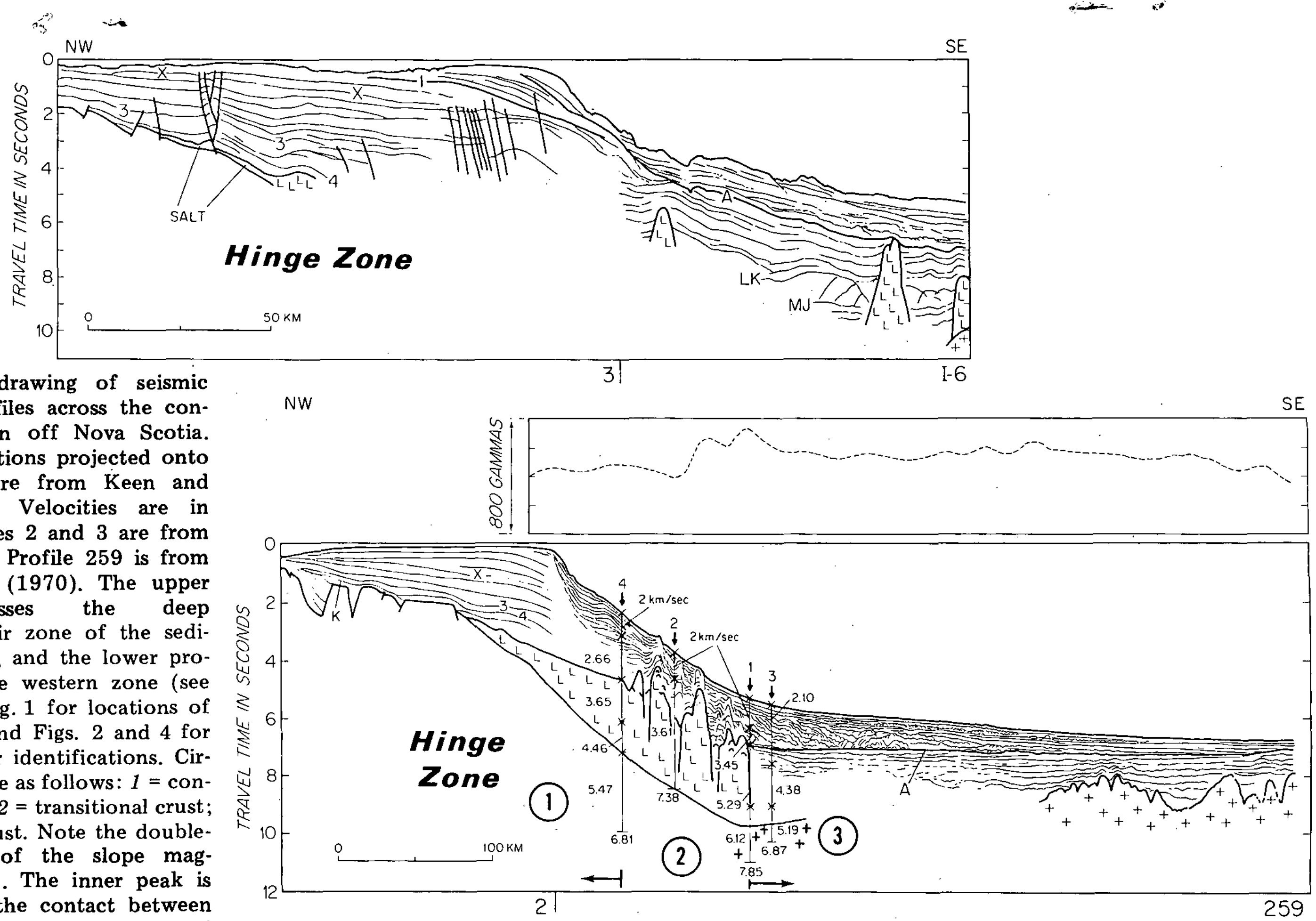


Fig. 8. Line drawing of seismic reflection profiles across the continental margin off Nova Scotia. Refraction stations projected onto profile 259 are from Keen and Keen (1974). Velocities are in km/sec. Profiles 2 and 3 are from Given (1977). Profile 259 is from Emery et al. (1970). The upper profile crosses the deep detached diapir zone of the sedimentary ridge, and the lower profile crosses the western zone (see Fig. 1). See Fig. 1 for locations of the profiles, and Figs. 2 and 4 for seismic marker identifications. Circle numbers are as follows: *1* = continental crust; *2* = transitional crust; *3* = oceanic crust. Note the double-peak nature of the slope magnetic anomaly. The inner peak is located near the contact between the continental and transitional crust at the base of the continental basement hinge. The outer peak is located near the contact of the transitional and oceanic basements at the oceanic basement hinge.

Maine are the result of regional uplift and the intrusion of basalts from the upper mantle during the Late Triassic. They postulate a stress field approximated by a left-lateral shear couple to account for the exhibited tensional fracturing. Apparently, faulting was deep enough to tap upper mantle magma sources of sufficient size to produce the sills and lava flows characteristic of the coeval Newark Group onshore. During the latest Triassic, when the stress field changed from a left-lateral shear couple to simple tension, faulting was renewed and rift sediments were warped into synclinal forms. Continental separation in the Early Jurassic was accompanied by the formation of new tensional fractures along which basaltic dikes and the White Mountain magma series were intruded. Following decoupling, considerable erosion of the rifted arch sent large quantities of sediment to depositional sites seaward of what is now the continental slope. Reflector "*K*" (Fig. 2) represents the unconformity formed by this erosional episode. This unconformity is well-developed on structural highs (Fig. 2), but is missing from some of the grabens, implying that deposition was continuous in these lows throughout the decoupling process.

The plane of original continental separation was probably along a "hinge zone" (Fig. 1) marked by a considerable steepening in basement gradient (Figs. 2 and 8). This zone, we believe, is the seaward boundary of continental crust. In most of the seismic reflection profiles, this drop in the basement surface is so sudden that it is difficult to trace (Fig. 2). According to Keen and Keen (1974), compressive velocities landward of the continental basement hinge are characteristic of continental crust, and those seaward of the oceanic basement hinge are typical of oceanic crust. Basement rocks between the two hinges have a velocity of 7.4 km/sec (Fig. 8). Keen et al. (1975) have proposed that this high velocity crust represents material of gabbroic composition intruded under thick sediments. Thus, this crustal type emplaced during the earliest stages of drifting forms a transitional zone from continental to a normal oceanic crust (Keen et al., 1975). Associated with this change from continental to transitional to oceanic crust is the east coast or slope magnetic anomaly. Off Nova Scotia the anomaly is double-peaked (Figs. 1 and 8), with one peak overlying the contact between the oceanic and transitional crusts and the other with the contact between the transitional and continental basement. According to Keen and Keen (1974), the juxtaposition of these types of crusts, continental, a transitional crust with a lower magnetization than oceanic basalts, and oceanic crust has produced the double-peak slope anomaly. To the southwest where the slope anomaly consists of a single peak (Fig. 1), we feel it probably marks the seaward edge of transitional crust.

The locus of maximum basin subsidence is situated in the area of the outer shelf—upper slope at the continental-transitional contact. Initially this subsidence was due to thermal cooling, following uplift caused by thermal expansion and subaerial erosion (Sleep, 1971). Gravitational outflow of crustal material (Bott, 1971), deep crustal metamorphism (Falvey, 1974), and crustal stretching during continental separation also may have been important in the subsidence of the edge of the continental plateau. Emplacement of a large volume of sediment at the base of the continental slope in the early stages of the drifting phase also may have contributed to the subsidence of the shelf (Dietz, 1963). The sediment loading caused the transitional crust to subside, and in the course of this subsidence the adjacent continental crust was dragged down. Subsequently, sediment loading contributed to continued gradual subsidence. Seismic data indicate that more than 70% of the subsidence beneath parts of Georges Bank had taken place by the end of the Jurassic (Austin, 1978). Sedimentation kept pace with subsidence on the outer shelf, but it was not able to do so on the slope and upper rise as the North Atlantic widened and deepened during the Jurassic.

DRIFT PHASE

Jurassic

As described above, continental separation was completed by the end of the Early Jurassic. The earliest depositional unit of the margin's drifting phase consisted of detritus eroded from the thermally uplifted crust along the newly forming continental edge, and deposited in topographic lows on the shelf and in a structural low seaward of the continental basement hinge zone. Seismic evidence for the presence of this unit at the base of the rise sequence may occur on profile I-51 (Fig. 7), where the base of Early Jurassic salt does not appear to coincide with the interpreted plunging oceanic basement horizon.

As the lithosphere continued to cool and subside, part of it sank below sea level. The first marine incursion in the Jurassic is marked by the evaporites of Early Jurassic age beneath the Scotian Shelf, the Grand Banks, and the continental rise. The source of these evaporites, termed the Argo Formation (McIver, 1972), was presumably seawater from the Tethys by way of the Newfoundland fracture zone. Beneath the lower continental slope and upper continental rise, halokinesis has resulted in the formation of a 40—220 km wide and approximately 1000 km long sedimentary ridge (Fig. 1). The ridge displays several styles of deformation: an eastern area where diapirs are small but abundant, a zone near 58°W characterized by deep, detached structures exhibiting large closure, and a highly deformed western zone where the structures are very large, but occur less frequently (Parsons, 1975; Figs. 1, 4, 5, 7, 8). A number of gaps appear in the morphologic expression of this feature. For example, the profile reproduced as Fig. 6 shows no evidence of diapiric activity. In a number of locations, the southern terminus of the ridge abuts against a hinge in oceanic basement, and basement appears to plunge beneath the evaporites (Fig. 7). Early Jurassic salt extends southwestward at least as far as Northeast Channel, which separates the Scotian Shelf from Georges Bank (Austin, 1978). The sedimentary ridge terminates in deep water at 66°W against either a reef complex or its basement foundation southeast of Georges Bank (Fig. 1). The recovery of Neocomian reefal limestones from Heezen Canyon coupled with the unusual high compressive velocity (as high as 6 km/sec) of the sediments along the southern margin of Georges Bank suggest that the coeval shelf strata to the west and southwest of the sedimentary ridge consist of reefal carbonates and lagoonal limestones and dolomites (Schlee et al., 1976; Ryan et al., 1978; Austin, 1978). These lagoonal carbonates probably grade northward across the hinge in continental basement (Fig. 1) to marls, shales, and sandstones (Austin, 1978). South of Georges Bank, Early Jurassic sediments beneath the upper rise probably consist of fore-reef deposits and pelagic limestones and shales (Austin, 1978). Salt deposition came to an end everywhere on this margin by the end of the middle Early Jurassic and conditions favorable for carbonate deposition extended from southern Georges Bank to the Grand Banks (Given, 1977).

In the Middle Jurassic, an abrupt change in depositional regime occurred on the Scotian Shelf. Carbonates and associated anhydrite were replaced by continental clastics. Jansa and Wade (1975) and Wade (1977, 1978) ascribe this change to the initiation of sea-floor spreading between North America and Africa. We believe that a westward ridge jump, postulated by P. Vogt (1973), accounts for this change, rather than an initiation of spreading. If our view is correct, the resulting plate rearrangement had little effect on the Georges Bank region (Austin, 1978). Effects on the Grand Banks also appear to have been minor, except for a change from marine shales to shallow water carbonates in the Whale Sub-basin (Jansa and Wade, 1975).

By the upper Middle Jurassic, unrestricted marine conditions prevailed all along the passive margin off New England and the Canadian Maritime Provinces (Wade, 1978). Sedimentary sequences range from clastics to shelf carbonates and marine shales. The reef complex along the seaward edge of Georges Bank probably was still active (Fig. 1). Coeval deposits in deeper water continued to consist of fore-reef deposits off Georges Bank and pelagic limestones and claystones elsewhere (Austin, 1978).

Cretaceous

At the end of the Jurassic, another tectonic episode began which affected much of the margin. This long period of diastrophism was the result of the opening of the Bay of Biscay and the South Atlantic approximately 125 m.y. B.P., and the separation of the North American and European plates about 110 m.y. B.P. (H. Schouten, personal communication, 1978). A large portion of the Grand Banks was uplifted (Avalon Uplift) and northeast—southwest trending basins separated by basement highs were created. Regional subsidence, coupled with a rejuvenation of source areas during the Early Cretaceous, combined to produce widespread regression and the progradation of large clastic wedges, most notably in the Sable Island region (McIver, 1972). Widespread volcanism began to create the New England Seamounts and the J-anomaly Ridge. Associated with uplift of parts of the Scotian Shelf and Georges Bank, an influx of terrigenous material occurred which inundated reef structures still growing along the southern part of Georges Bank (Ryan et al., 1978; Fig. 2, Line 21). Presumably, this regressive phase and the major transgression which followed it during the Late Cretaceous caused the extinction of all reefs in the region. In the Baltimore Canyon Trough, this tectonic episode may be marked by an unconformity just below the Lower Cretaceous—Upper Cretaceous boundary which Mattick (1977) believes is due to the reactivation of a mid-shelf intrusive plug known as the Great Stone Dome. Even farther to the south, the sedimentary sequence composing the Blake—Bahama Outer Ridge is disrupted by a hiatus of mid-Aptian age (Vail et al., in press).

As a result of the formation of a number of seamounts and volcanic ridges in the North Atlantic during the Lower Cretaceous, bottom circulation became restricted and a thick black shale sequence was deposited (Tucholke and Vogt, in press). The basin did not become oxygenated again until the Cenomanian—Turonian. On the shelf, Middle Cretaceous clastic sequences were disrupted by a Cenomanian—Maestrichtian transgressive cycle, during which limestones of the Dawson Canyon and Wyandot formations were deposited (Jansa and Wade, 1975).

Tertiary

World-wide regressions mark the transition from the Cretaceous to the Tertiary. In contrast to the Lower Cretaceous, these regressive episodes occurred in response to continental glaciation. Paleoclimatic reconstructions from temporal distribution of calcareous nannoplankton (Haq et al., 1977) and from isotopic compositions of planktonic foraminifera (Savin et al., 1975) indicate that temperatures began to decrease toward the end of the Cretaceous. The temperature drop near the Cretaceous—Tertiary boundary, however, was small and short-lived, as temperatures remained warm and relatively constant through the Paleocene and Early and Middle Eocene. Associated with this initial cooling was a regression during which the Scotian Shelf and central Grand Banks were eroded (King et al., 1974; King and MacLean, 1975, 1976; King and Young, 1977). A more drastic cooling episode occurred in the Late Eocene, where there was a sharp temperature drop culminating in a temperature minimum in the Late Oligocene (Savin et al., 1975; Ingle, 1977). Other cooling episodes occurred in latest Miocene (Messinian) and Late Pliocene. The temperature decrease in the Pliocene probably signaled a major increase in polar glaciation and sea-ice formation (Savin et al., 1975).

During the Late Eocene—Oligocene regression, the Laurentian Channel, Scotian Shelf and Georges Bank underwent considerable erosion (King et al., 1974; Austin, 1978). Large canyons were cut on the continental slope from the Grand Banks to as far south as the Blake Outer Ridge (Fig. 2, Line 42, Reflector *1*; Vail et al., in press). Many of these slope canyons have deep-sea channels associated with them. On the Laurentian Cone, these connections extend for hundreds of kilometers offshore (Parsons, 1975; Uchupi et al., in preparation), indicating that Horizon A (Tucholke and Mountain, 1977) in this region may be the product of turbidity current erosion. Some of the canyons carved into the slope and rise have since been buried by prograding wedges of clastic sediments (Fig. 2, Line 42). According to some writers (Tucholke and Vogt, in press), the continental rise sequence (including the outer ridge systems) developed primarily as a result of bottom-current activity. Others ascribe its origin to turbidity currents and even gravitational tectonics (Emery et al., 1970; Vail et al., in press). Our detailed study of the Laurentian Cone indicates that the depositional history of the rise is more complicated than either of these hypotheses. In the vicinity of the Laurentian Cone, the rise consists of three, to as many as five, sequences superimposed on one another (Fig. 6). This sedimentary fabric would appear to favor a turbidity current origin for at least this portion of the rise. An already complex stratigraphy is made even more chaotic by the eustatic changes in sea level during the Pleistocene. These changes resulted in numerous episodes of cut-and-fill topography, which are evident from an examination of Fig. 5.

DISCUSSION

Our reconstruction of the geology of this segment of the passive margin off eastern North America differs to some extent from previous attempts. For example, we identify Falvey's (1974) "breakup unconformity" with the major angular unconformity underlying Georges Bank which separates Late Triassic—Early Jurassic graben-fill from the overlying sediments, not with the unconformity separating the Early Jurassic Mohican Formation from the Middle Jurassic Scatarie limestone, as proposed by Given (1977). We assume that the sedimentary ridge off Nova Scotia has a salt core, and that this salt is equivalent to the Early Jurassic Argo Formation. We concur with Keen and Keen (1974) who have suggested that the sedimentary ridge is underlain by a transitional crust. We further believe that the oceanic basement hinge and outer slope magnetic anomaly mark the contact of the transitional—oceanic crusts. The continental basement hinge and inner slope magnetic anomaly define the continental—transitional crusts contact. We further postulate that the separation of Africa and North America must have been completed by the Early Jurassic. We also believe that the J-anomaly Ridge is an oceanic basement structure formed during the separation of North America and Eurasia, and not a collapsed section of the Grand Banks, as stated by Grant (1977) and Gradstein et al. (1977).

Although we have provided possible solutions as to the nature and exact geographic position of the transition from oceanic to continental crust, the relationship of this transition to the physiography of the margin is not fully determined. Available data do indicate that the continental slope does not always record this transition, as was previously believed. In addition, the connection between the transition and pronounced sedimentological features, like the Mesozoic reef complex—carbonate platform situated beneath the southern Georges Bank, is as yet unclear. It is possible to imagine reef growth on either continental or oceanic crust, given the proper environmental conditions. At this point, neither alternative can be ruled out. A more complete characterization of the crust beneath these carbonates awaits more detailed geophysical surveying and drilling.

ACKNOWLEDGEMENTS

Financial support for this study came from the Office of the International Decade of Ocean Exploration under Grant IDO74-04094, National Science Foundation Grants 20/82146, and 20/9421, Sea Grant contracts 23/3500.17 and 22/4000.13, U.S. Department of State contract 1722-620214, and the Ocean Industry Program of the Woods Hole Oceanographic Institution. We wish to thank Imperial Oil, Ltd. for providing multi-channel seismic reflection profiles from the Laurentian Cone and the Scotia Rise. Finally, our appreciation goes to K.O. Emery and J.D. Milliman for their suggestions during the preparation of this report. Contribution No. 4225 of the Woods Hole Oceanographic Institution.

REFERENCES

Austin, J.A., Jr., 1978. The geologic history of the passive margin off New England. Ph.D. dissertation. Woods Hole Oceanographic Institution-Massachusetts Institute of Technology, 201 pp.

Ballard, R.D. and Uchupi, E., 1975. Triassic rift structures in the Gulf of Maine. Bull. Am. Assoc. Pet. Geol. 59: 1041—1072.

Bott, M.H.P., 1971. Evolution of young continental margins and formation of shelf basins. Tectonophysics, 11: 319—327.

Dietz, R.S., 1963. Wave-base, marine profiles of equilibrium and wave-built terraces: a critical appraisal. Geol. Soc. Am. Bull., 74: 971—990.

Emery, K.O., Uchupi, E., Phillips, J.D., Bowin, C.O., Bunce, E.T. and Knott, S.T., 1970. Continental rise off eastern North America. Bull. Am. Assoc. Pet. Geol., 54: 44—108.

Falvey, D.A., 1974. The development of continental margins in plate tectonic theory. Aust. Petrol. Explor. Assoc. J., 14: 95—106.

Given, M.M., 1977. Mesozoic and Cenozoic geology of offshore Nova Scotia. Bull. Can. Pet. Geol., 25: 63—91.

Gradstein, F.M., Grant, A.C. and Jansa, L.F., 1977. Grand Banks and J-anomaly Ridge: a geological comparison. Science, 197: 1074—1077.

Grant, A.C., 1977. Multichannel seismic reflection profiles of the continental crust beneath the Newfoundland Ridge. Nature, 270: 22—25.

Haq, B.U., Premoli-Silva, I. and Lohmann, G.P., 1977. Calcareous plankton paleobiogeographic evidence for major climatic fluctuations in the early Cenozoic Atlantic Ocean. J. Geophys. Res., 82: 3861—3876.

Hathaway, J.C., Schlee, J.S., Poag, C.W., Valentine, P.C., Weed, E.G.A., Bothner, M.H., Kohout, F.A., Manheim, F.T., Schoen, R., Miller, R.E. and Schultz, D.M., 1976. Atlantic margin coring project of the U.S. Geological Survey, U.S. Geol. Surv. Open File Rep., 76—844: 217 pp.

Hubert, J.F., Reed, A.A. and Carey, P.J., 1976. Paleogeography of the East Berlin Formation, Newark Group, Connecticut Valley. Am. J. Sci., 276: 1183—1207.

Ingle, J.C., Jr., 1977. Evidence of global late Paleogene climatic and eustatic events and the Oligocene hiatus. In: The New Unformitarism: Events on a Cenozoic Scale, or "What's so unusual about a Catastrophe?"; a symposium sponsored by Woods Hole Oceanographic Institution, June 6—10, 1977 and organized by W.A. Berggren, 3 pp.

Jansa, L.F. and Wade, J.A., 1975. Geology of the continental margin off Nova Scotia and Newfoundland. In: W.J.M. van der Linden and J.A. Wade (Editors), Offshore Geology of Eastern Canada. Geol. Surv. Can., Pap., 74—30, 2: 51—105.

Jansa, L.F., Gradstein, F.M., Williams, G.L. and Jenkins, W.A.M., 1977. Geology of the Amoco Imp Skelly A-1 Osprey H-84 well, Grand Banks Newfoundland. Geol. Surv. Can. Pap., 77—21: 17 pp,

Kay, M., 1951. North American geosynclines. Geol. Soc. Am. Mem., 48: 143 pp.

Keen, C.E. and Keen, M.J., 1974. The continental margin of eastern Canada and Baffin Bay. In: C.A. Burk and C.L. Drake (Editors), The Geology of Continental Margins. Springer, New York, N.Y., pp. 381—389.

Keen, C.E., Keen, M.J., Barrett, D.L. and Heffler, D.E., 1975. Some aspects of the ocean-continental transition at the continental margin of eastern North America. In: W.J.M. van den Linden and J.A. Wade (Editors), Offshore Geology of Eastern Canada. 2. Regional Geology. Geol. Surv. Can. Pap., 74—30: 189—197.

King, L.H. and MacLean, B., 1975. Stratigraphic interpretation of the Central Grand Banks from high resolution seismic reflection profiles. In: W.J.M. van der Linden and J.A. Wade (Editors), Offshore Geology of Eastern Canada. 2. Regional Geology. Geol. Surv. Can. Pap., 74—30: 175—185.

King, L.H. and MacLean, B., 1976. Geology of the Scotian Shelf. Geol. Surv. Can. Pap., 74—31: 31 pp.

King, L.H. and Young, I.F., 1977. Paleocontinental slopes of East Coast Geosyncline (Canadian Atlantic Margin). Can. J. Earth Sci., 14: 2553—2564.

King, L.H., MacLean, B. and Fader, G.B., 1974. Unconformities on the Scotian Shelf. Can. J. Earth Sci., 11: 89—100.

King, L.H., Hyndman, R.D. and C.E. Keen, 1975. Geological development of the continental margin of Atlantic Canada. Geosci. Can., 2: 26—35.

Mattick, R.E., 1977. Geologic setting. In: P.A. Scholle (Editor), Geological Studies of the COST B-2 Well, U.S. Mid-Atlantic Outer Continental Shelf Area. Geol. Surv. Circ., 750: 4—7.

McIver, N.L., 1972. Cenozoic and Mesozoic stratigraphy of the Nova Scotia Shelf. Can. J. Earth Sci., 9: 54—70.

Parsons, M.G., 1975. The geology of the Laurentian Fan and the Scotia Rise. In: C.J. Yorath, E.R. Parker and D.J. Glass (Editors), Canada's Continental Margins and Offshore Petroleum Exploration. Can. Soc. Pet. Geol. Mem., 4: 155—167.

Ryan, W.B.F., Cita, M.B., Miller, E.L., Hanselman, D., Nesteroff, W.D., Heckler, B. and Nibbelink, M., 1978. Bedrock geology of New England submarine canyons. Oceanologica Acta, 1: 233—254.

Savin, S.M., Douglas, R.G. and Stehli, F.G., 1975. Tertiary marine paleotemperatures. Geol. Soc. Am. Bull., 86: 1499—1510.

Schlee, J., Behrendt, J.C., Grow, J.A., Robb, J.M., Mattick, R.E., Taylor, P.T. and Lawson, B.J., 1976. Regional framework off northeastern United States. Bull. Am. Assoc. Petr. Geol., 60: 926—951.

Scientific staff, 1975. "Glomar Challenger" drills in the North Atlantic. Geotimes, 20: 18—21.

Sleep, N.H., 1971. Thermal effects of the formation of Atlantic continental margins by continental breakup. Geophys. J. R. Astron. Soc., 24: 325—350.

Tucholke, B.E. and Mountain, G., 1977. The Horizon-A complex: lithostratigraphic correlation and paleo-oceanographic significance of reflectors in the western North Atlantic. EOS, Trans. Am. Geophys. Union, 58: 406.

Tucholke, B.E. and Vogt, P.R., in press. Synthesis of western North Atlantic depositional and tectonic history. In: Initial reports of the Deep Sea Drilling Project. U.S. Government Printing Office, Washington, D.C., XLIII.

Uchupi, E., Ballard, R.D. and Ellis, J.P., 1977. Continental slope and upper rise off western Nova Scotia and Georges Bank. Bull. Am. Assoc. Pet. Geol., 61: 1483—1492.

Uchupi, E. and Austin, J.A., Jr. in press. The stratigraphy and structure of the Laurentian Cone region. Can. J. Earth Sci.

Vail, P.R., Mitchum, R.M., Jr., Shipley, T.H. and Buffler, R.T., in press. Unconformities of the North Atlantic. Philos. Trans. R. Soc. London.

Vogt, P.R., 1973. Early events in the opening of the North Atlantic. In: D.H. Tarling and S.K. Runcorn (Editors), Implications of Continental Drift to the Earth Sciences. Academic Press, London, pp. 693—712.

Wade, J.A., 1977. Stratigraphy of Georges Bank Basin: Interpreted from seismic correlation to the western Scotian Shelf. Can. J. Earth Sci., 14: 2274—2283.

Wade, J.A., 1978. The Mesozoic—Cenozoic history of the northeastern margin of North America. Proc. 10th Annu. Meet. Offshore Technol. Conf., 3: 1849—1858.

Weed, E.G.A., Minard, J.P., Perry, W.J., Jr., Rhodehamel, E.C. and Robbins, E.I., 1974. Generalized pre-Pleistocene geologic map of the northern United States Atlantic continental margin. U.S. Geol. Sur. Misc. Invest. Ser. Map. I-861, 1:1 000 000, plus text, 8 pp.