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Deep structure and evolution of the continental margin off the eastern United States

Continental margin
Structure
Evolution
Eastern United States

Marge continentale
Structure
Évolution
Est des États-Unis

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ABSTRACT

Continental rifting and crustal thinning took place between North America and Africa during the Triassic and Early Jurassic, and sea floor spreading began in the Early to Middle Jurassic. Very rapid and variable subsidence along the continental margin off the eastern United States during the Jurassic was controlled by transverse fracture zones, which segmented the margin into four major sedimentary basins — the Georges Bank Basin, the Baltimore Canyon Trough, the Carolina Trough, and the Blake Plateau Basin.

Upper Triassic to Lower Jurassic evaporite deposits (including salt) have been drilled in Georges Bank Basin, and linear chains of salt (?) diapirs have been found along the East Coast Magnetic Anomaly in the Carolina and Baltimore Canyon Troughs. The maximum thicknesses of undeformed postrift sedimentary units in these basins are 7, 13, 11, and 12 km respectively. The thickness of deformed synrift sedimentary units (sediments deposited during active rifting) within faulted Triassic grabens beneath these basins probably exceeds 5 km in some places. Gravity models across the three northern basins indicate that 8 to 15 km of transitional crust underlie the basins. The transitional crust probably was formed by extension and thinning of the pre-existing continental crust. Thicker transitional crust (15 to 25 km) that underlies the 350-km-wide Blake Plateau Basin may include mixed continental fragments and extensive volcanics. An eastward jump of the spreading center from beneath the western Blake Plateau to the Blake Escarpment 10 to 15 m.y. after initial continental separation appears to have caused this anomalously wide basin.

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RÉSUMÉ

Structure profonde et évolution de la marge continentale au large de l'est des États-Unis.

Le rifting continental et l'amincissement crustal sont advenus entre l'Amérique du Nord et l'Afrique durant le Triassique et au début du Jurassique, et l'expansion océanique a commencé entre le Jurassique Inférieur et le Jurassique Moyen. Une subsidence très rapide et très variable le long de la marge continentale au large de l'est des États-Unis, au Jurassique, a été contrôlée par des zones de fracture transverses qui ont séparé la marge en quatre principaux bassins sédimentaires : le bassin de Georges Bank, la dépression du canyon de Baltimore, la dépression de Caroline et le bassin du plateau de Blake.

Les dépôts évaporitiques (y compris le sel) du Triassique Supérieur et du Jurassique Inférieur ont été forés dans le bassin de Georges Bank, et on a trouvé des chaînes linéaires de diapirs de sel le long de l'Anomalie Magnétique de la côte est dans les dépressions de Caroline et du canyon de Baltimore. Les épaisseurs maximales des unités sédimentaires « post-rift », non déformées dans ces bassins, mesurent respectivement 7, 13, 11 et 12 km. L'épaisseur des unités sédimentaires « post-rift » déformées (sédiments déposés durant la phase active du rifting) dans les grabens faillés du Triassique sous ces bassins dépasse probablement 5 km. Les modèles de gravité à travers les trois bassins du Nord montrent que 8 à 15 km de croûte intermédiaire sont sous-jacents au bassin. Il est probable que la croûte intermédiaire a été formée par l'extension et l'amincissement de la croûte continentale pré-existante. Il se peut que la croûte intermédiaire plus épaisse (15 à 25 km) qui est sous-jacente au bassin du plateau de Blake, comprenne des fragments continentaux et volcaniques. Un saut vers l'est du centre d'expansion de la partie sous-jacente depuis le plateau de Blake occidental vers l'escarpement de Blake, 10 à 15 millions d'années après la séparation continentale initiale, semble avoir créé ce bassin anormalement large.

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INTRODUCTION

Geophysical surveys and oil-exploration drilling along the United States Atlantic continental margin during the last 5 years are beginning to answer many questions concerning its deep structure and how it evolved during the rifting and early sea floor-spreading stages of the separation of this region from Africa. Earlier geophysical studies of the United States continental margin used marine refraction (Ewing *et al.*, 1950 ; Drake *et al.*, 1959 ; Hersey *et al.*, 1959 ; Sheridan *et al.*, 1966) and submarine gravity measurements (Worzel, Shurbet, 1955). Single-channel seismic-reflection, marine magnetic, aeromagnetic, and continuous gravity measurements became available during the 1960's (Ewing *et al.*, 1966 ; Taylor *et al.*, 1968 ; Emery *et al.*, 1970). Interpretations of the margin based on proprietary oil company multichannel data began to appear in the early 1970's. These interpretations suggested that basins containing as much as 12 km of sedimentary rocks underlie the Continental Shelves (Emery, Uchupi, 1972 ; Mattick *et al.*, 1974 ; Sheridan, 1974). In 1973, the US Geological Survey contracted the first publicly available multichannel seismic profiles (Schlee *et al.*, 1976). The first exploration leases for the Outer Continental Shelf off New Jersey were granted in 1976, and drilling of the first exploration wells began in 1978.

Between 1973 and 1978, the Geological Survey (USGS) collected or contracted approximately 20,000 km of multichannel seismic reflection data (Fig. 1 ; from Folger *et al.*, 1979), 185,000 km of aeromagnetic data (Klitgord, Behrendt, 1979), 39,000 km of marine gravity profiles (Grow *et al.*, 1979 A), and three deep-refractions profiles (Sheridan *et al.*, 1979). Drill hole information from five Continental Offshore Stratigraphic Test (COST) wells has been released since 1978 (Fig. 1), and more than 25 commercial exploration wells have been drilled. Although many interpretations of individual basins and segments of the margin have been published (Schlee *et al.*, 1976 ; 1977 ; Grow, Markl, 1977 ; Dillon *et al.*, 1979 ; Grow *et al.*, 1979 B ; Grow, 1980 ; Schlee, Grow, 1980), preliminary syntheses of the entire margin's structure and evolution are just beginning to be possible (Klitgord, Behrendt, 1979 ; Folger *et al.*, 1979 ; Schlee *et al.*, 1979 ; Grow *et al.*, 1979 A).

A preliminary synthesis of these data has delineated four major troughs or basins (Klitgord, Behrendt, 1979). From North to South, these basins are the Georges Bank Basin, the Baltimore Canyon Trough, the Carolina Trough, and the Blake Plateau Basin (Fig. 2). This paper is a brief summary of information on each of these basins, incorporating some of the most recently available seismic and drill hole data. We have selected the most representative profiles through the center of each of the four major basins in order to demonstrate how the deep crustal and sedimentary structures across the ocean-continent transition zone evolved.

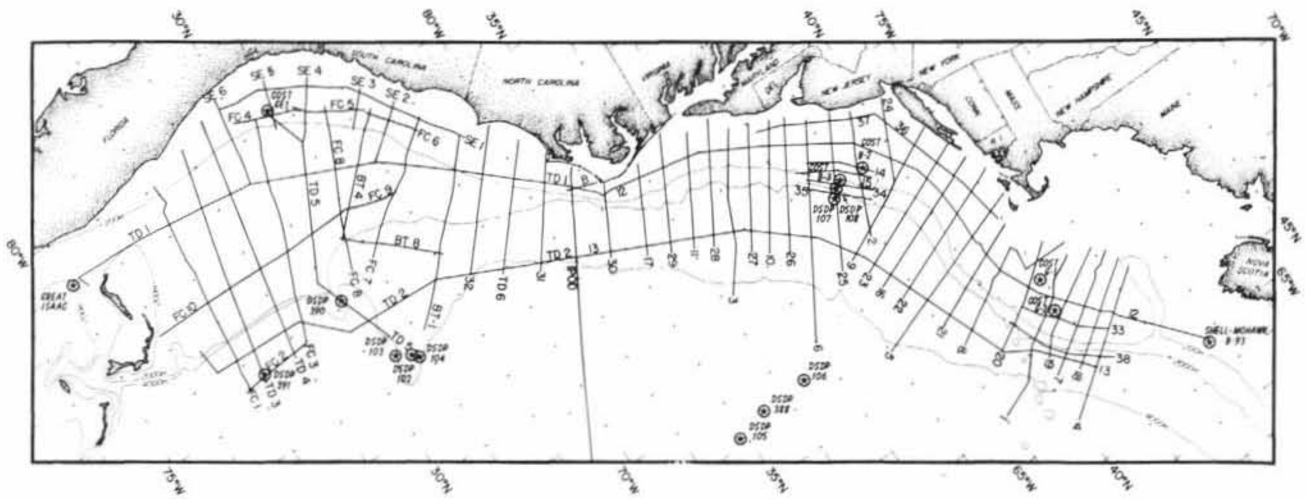


Figure 1

Multichannel seismic reflection profiles collected for the US Geological Survey between 1973 and 1978 (from Folger et al., *1979). Drill sites from DSDP and COST wells are also shown.*

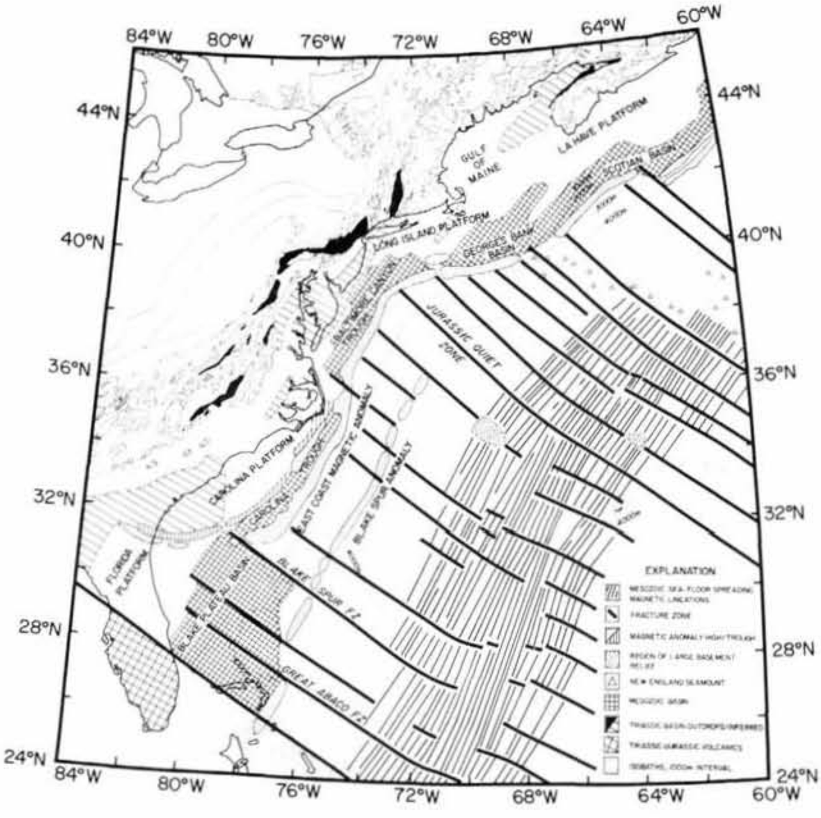


Figure 2

Location of Georges Bank Basin, Baltimore Canyon Trough, Carolina Trough, and the Blake Plateau Basin along the continental margin off the Eastern United States. Information based on multichannel seismic and aeromagnetic results (from Klitgord, Behrendt, 1979). Note correlation of basin boundaries with fracture zones. Major fracture zones also show abrupt changes in the Free-air gravity anomalies along the length of the margin (Grow et al., *1979 A).*

THE CAROLINA TROUGH

The Carolina Trough is approximately 80 km wide and 400 km long and contains as much as 11 km of Jurassic to recent sediment. It lies north of the Blake Spur fracture zone between the East Coast Magnetic Anomaly (ECMA) on the southeast and the Brunswick Magnetic Anomaly (BMA) on the northwest (Klitgord, Behrendt, 1979 ; Dillon *et al.*, 1979). We will start our discussion of the US Atlantic margin with the Carolina Trough because 1) it has the narrowest and simplest transition zone from continental to oceanic crust ; 2) the separation of North American and Africa here appears to have been a simple pulling apart of the continents without oblique or translational complications ; 3) the Mesozoic lineations here are parallel to the pre-existing Paleozoic tectonic lineations ; and 4) there is no evidence of any secondary volcanism or tectonism that has affected the trough itself.

The first publicly available multichannel profile across the trough was the IPOD (International Phase of Ocean Drilling) line which crossed the northern part of the trough (Grow, Markl, 1977). The IPOD line showed three diapiric structures near the ECMA ; approximately 20 other diapirs have since been found along the ECMA in the Carolina Trough (Grow *et al.*, 1977 ; unpublished USGS seismic lines obtained during 1979). The diapirs are inferred be salt on the basis of a small salinity anomaly detected over one diapir and the presence of salt along the margin from the Grand Banks to Nova Scotia (Jansa, Wade, 1975) and to Georges Bank (Amato, Simonis, 1980). Three additional diapiric structures have been found along the ECMA in the Baltimore Canyon Trough, and salt has been drilled in one exploration well near these structures (Grow, 1980). A gravity model along the IPOD line (Fig. 3) shows the position of the Carolina Trough in relation to the ECMA, the diapirs, and the inferred ocean-continental crustal structure (D. R. Hutchinson, J. A. Grow, unpublished data). The gravity modeling procedure and assumptions are similar to those of previously published models of Baltimore Canyon Trough and Georges Bank Basin (Grow *et al.*, 1979 A). Note that the crust between the ECMA and the Blake Spur Anomaly (Fig. 2) appears to be thin and is inferred to be oceanic whereas the Carolina Trough is underlain by transitional thickness crust (8 to 15 km thick). The diapirs and ECMA are present at the boundary between the transitional crust and the oceanic crust. The western flank of the Carolina Trough is marked by a hinge zone just east of the BMA that appears to be underlain by crust that shows an abrupt change in thickness.

The best publicly available multichannel profile across the Carolina Trough obtained to date is line 32 southeast of Cape Fear (Fig. 4, see Fig. 1 for location). Line 32 is quite similar to the IPOD line, but continental basement and a Triassic graben are clearly cut by a "breakup unconformity" (Falvey, 1974) or "postrift unconformity" (Dillon *et al.*, 1979) ; the postrift Jurassic and younger sedimentary units lie above the unconformity. Prerift or synrift sedimentary units (sediments deposited before or during active rifting respectively) appear to be present beneath the unconformity in a Triassic (and Early Jurassic ?) graben. A diapir also is present at the ECMA on line 32 and the Jurassic shelf edge is about 15 km landward of the axis of the ECMA (Fig. 4). A composite crustal section along line 32 (Fig. 5 ; D. R. Hutchinson, J. A. Grow, unpublished data based on a gravity model) reveals a crustal structure very similar to that of the IPOD model (Fig. 3). In both line 32 and the IPOD profiles, the Carolina Trough is underlain by transitional thickness crust bounded by abrupt

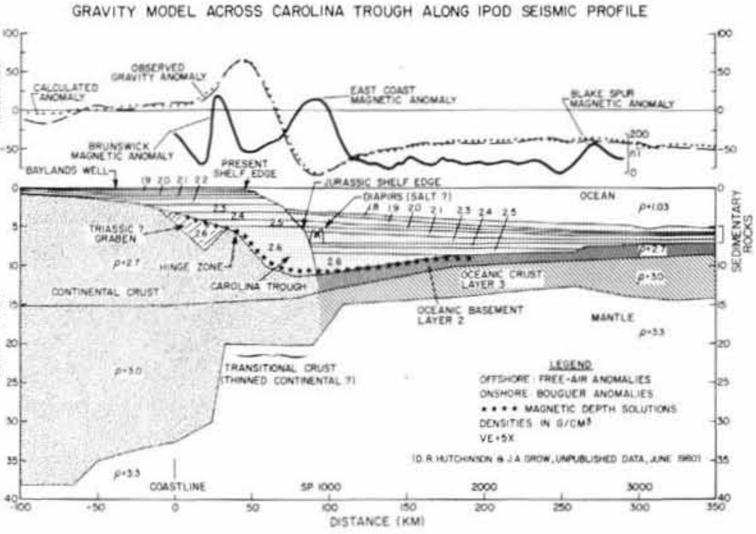


Figure 3

Gravity model across Carolina Trough along IPOD multichannel seismic profile (from D. R. Hutchinson, J. A. Grow, unpublished data, 1980). Note that the 11-km-deep Carolina Trough lies between the Brunswick Magnetic Anomaly and the East Coast Magnetic Anomaly (ECMA) and is underlain by transitional crust 8-15 km thick. Also note thin oceanic crust underlying Continental Rise sediments between the ECMA and the Blake Spur Anomaly. Three diapirs (salt ?) were observed near the ECMA on the IPOD profile (Grow, Markl, 1977), and 20 other diapirs have now been found along the ECMA.

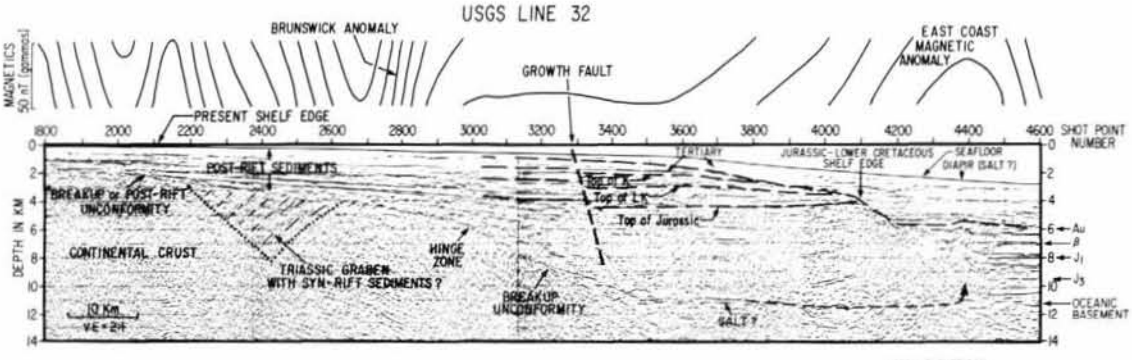
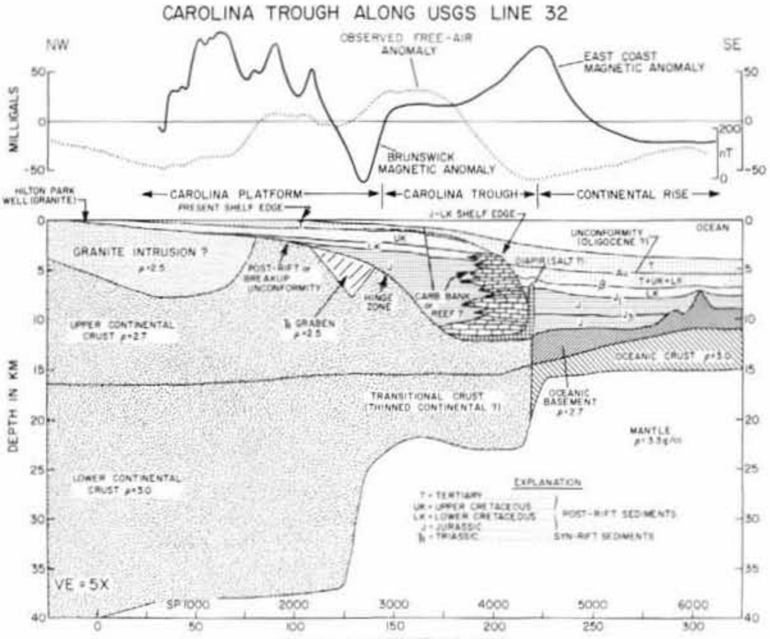


Figure 4

Multichannel seismic depth section across Carolina Trough along part of line 32.

Figure 5

Composite geologic section across Carolina Trough along multichannel line 32 (Fig. 4); deeper crustal structure is based on gravity modeling (D. R. Hutchinson, J. A. Grow, unpublished data, 1980). Note that the "hinge zone" near the Brunswick Magnetic Anomaly is underlain by an abrupt change in depth to the Moho. Another abrupt change in depth to the Moho occurs near the ECMA, which has a single diapir at its axis (Fig. 4). The Jurassic shelf edge system is about 15 km northwest of the ECMA, whereas the present shelf edge (200-m depth contour) is 100 km farther landward. Assuming that the ECMA marks the initial ocean-continent boundary, the shelf edge remained near the initial boundary during the Jurassic and Cretaceous and then retreated during the Tertiary.



transitions — seaward into thin oceanic crust at the ECMA and landward into thick continental crust near the BMA. A prominent hinge zone occurs near shot point 3,000 in line 32 (Fig. 4), just east of a low-density Triassic (?) graben and directly above the very abrupt change in depth to the Moho (160 km distance as shown on fig. 5).

The Carolina Trough and the transitional thickness crust underlying it are unique in that the transition zones at the ECMA and BMA are very narrow, but broader zones of transitional thickness crust have been observed beneath the Baltimore Canyon Trough and Georges Bank Basin (Grow *et al.*, 1979 A). Furthermore, although the hinge zones seen on lines 32 and IPOD are clearer and more abrupt than on most other profiles, similar hinge zones can be seen along the inner edge of the other three basins.

BALTIMORE CANYON TROUGH

The Baltimore Canyon Trough lies beneath the Outer Continental Shelf between Virginia and New Jersey. It varies in width from 50 km off Virginia to 150 km wide off New Jersey, and in depth from 10 km off Virginia to more than 13 km deep off New Jersey with an abrupt increase in width and depth north of Delaware Bay (Klitgord, Behrendt, 1979). The southern Baltimore Canyon Trough is similar to the Carolina Trough in that the separation from Africa was a direct pulling apart, but the similarities decrease northward where the trough and zone of transitional crust are wider.

Multichannel seismic-profile 25 (Fig. 6) crosses the Baltimore Canyon Trough at its widest and simplest region. In this area, a 40-km progradation of the shelf edge took place during the Jurassic and was followed by a 20 km retreat of the shelf edge during the Tertiary. The 4,823 m deep COST B-3 well was drilled 10 km north of line 25 and penetrated Middle Jurassic horizons near the bottom (Amato, Simonis, 1979 ; Scholle, 1980). Subhorizontal reflectors, presumed to represent undeformed postrift deposits are present down to 13 km depth (Fig. 6), and synrift (Triassic and Jurassic ?) deformed sedimentary rocks are interpreted between 13 and 18 km depth (Grow, 1980).

A geologic section (Fig. 7) across Baltimore Canyon Trough summarizes the line 25 and COST B-3 data. Some salt

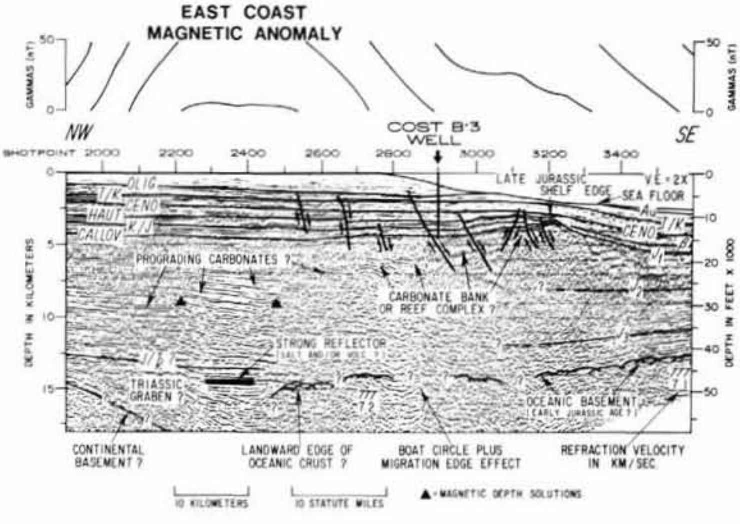


Figure 6

Multichannel seismic depth section across widest and deepest part of Baltimore Canyon Trough along part of line 25 near the COST B-3 well (from Grow, 1980). Note refraction values of 7.1-7.2 km/sec. which imply that the oceanic crust continues up to the ECMA. Assuming that the ECMA marks the initial ocean-continent boundary, the Jurassic shelf edge appears to have prograded 40 km out over the Lower Jurassic oceanic crust in this area. Carbonate bank or reef structures are interpreted to lie along the Jurassic and Lower Cretaceous shelf edge.

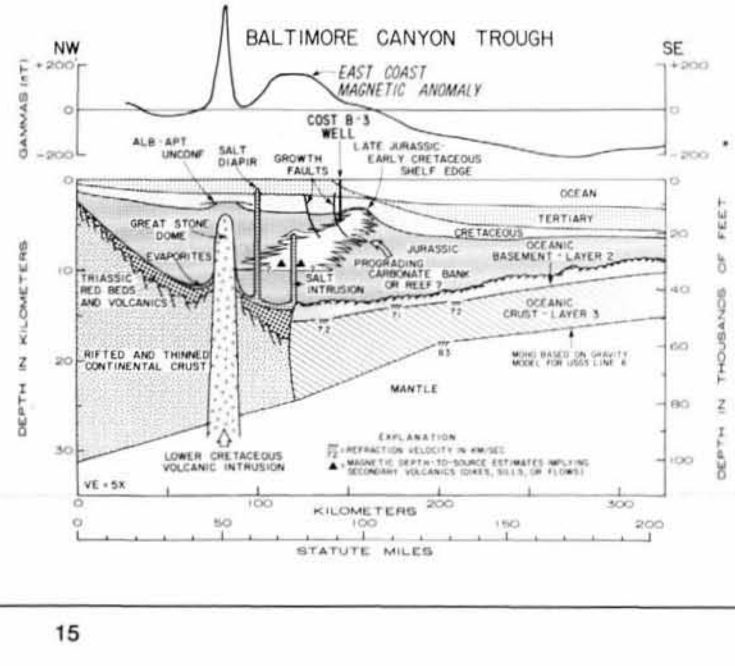


Figure 7

Composite geologic section across Baltimore Canyon Trough along line 25 (Fig. 5 and 6) ; mafic and salt intrusions are projected from north of line 25 (from Grow, 1980).

structures and a mafic intrusion slightly northeast of line 25 have been projected to illustrate the types of structures in the trough (Grow, 1980). The hinge zone seen clearly in the Carolina Trough (Fig. 3, 4, 5) is just landward of the northwest end of line 25 (Fig. 7), near the coastline. Refraction profiles have established that a 7.1-7.2 km/s. refractor lies at 13 to 15 km depth beneath the upper rise and slope ; this reflector is interpreted to indicate the top of oceanic-crust (layer 3) (Sheridan *et al.*, 1979). Note that the 7.1-7.2 km/s. refractor continues north-westward to the ECMA (Fig. 6), which marks the landward edge of oceanic crust (Keen, 1969 ; Klitgord, Behrendt, 1979 ; Sheridan *et al.*, 1979 ; Grow *et al.*, 1979 A).

The Baltimore Canyon Trough off New Jersey is the only area along the US Atlantic margin where the Jurassic or younger shelf edge appears to have prograded seaward of the ECMA onto the Lower Jurassic oceanic crust.

GEORGES BANK BASIN

Georges Bank Basin formed as a result of an oblique separation from Africa ; the ocean-continent boundary marked by the ECMA is at a 30 to 40 degree angle with respect to Paleozoic and Triassic tectonic lineations (Fig. 2). The basin is elongate along its southern border, but its width ranges from 60 km to 140 km because of several Triassic synrift grabens that splay off the main trough at various angles. Although the postrift sedimentary units reach a maximum thickness of about 7 km, synrift troughs at least 11 km deep underlie parts of the basin (Schlee *et al.*, 1976 ; 1977 ; Klitgord, Behrendt, 1979 ; Uchupi, Austin, 1979). The COST G-1 well penetrated to 4,900 m, passed through Middle and probably Lower Jurassic dolomitic sandstones and entered lower Paleozoic metamorphic basement rocks (Amato, Bebout, 1980). The COST G-2 well penetrated to 6,669 m, passed through Upper and Middle Jurassic carbonate deposits and ended up in Upper Triassic or Lower Jurassic dolomites and evaporites including salt (Amato, Simonis, 1980). Georges Bank Basin is also complicated by the New England Seamounts that disturbed the adjacent oceanic crust and nearby parts of the continental margin because of local secondary volcanism and secondary tectonic movements in Jurassic through Late Cretaceous time.

A composite geologic cross section along multichannel line 5 off Cape Cod that is based on a gravity model by Grow *et al.* (1979 A) crosses the southwest end of the Georges Bank Basin and shows the general crustal structure observed in Georges Bank (Fig. 8). Austin *et al.* (1980) have pointed out that a hinge zone along the northwestern margin of Georges Bank Basin is similar to hinge zone reported beneath the Nova Scotian Shelf by Jansa and Wade (1975). Here, as in the Carolina Trough, our Georges Bank profiles (Fig. 8) shows a noticeable hinge zone at the 100-km mark on the distance scale. Note also the transitional thickness crust between 100 and 180 km on the same scale.

The Early Cretaceous and Jurassic shelf edge on line 5 (Fig. 8) is directly over the boundary between thin continental and oceanic crust and about 20 km seaward of the present shelf edge. This position suggests that the shelf edge did not migrate significantly either landward or seaward of the initial ocean-continent boundary during the Jurassic and Cretaceous but that it did retreat during the Tertiary.

BLAKE PLATEAU BASIN

The Blake Plateau, a 350-km-wide marginal plateau between water depths of 500 and 1,500 m, is underlain by postrift sedimentary units that are as much as 12 km thick (Dillon *et al.*, 1979). The plateau is south of the Blake Spur fracture zone and the southern termination of the East Coast Magnetic Anomaly (Fig. 2). The thickest part of the basin is beneath the western plateau, and the sedimentary horizons beneath the middle and outer part of the plateau dip gently toward the west (Fig. 9).

Gravity modeling across the plateau indicates that a transitional crust 15-20 km thick underlies the western Blake Plateau Basin and that a transitional crust nearly 25 km thick underlies the eastern Blake Plateau Basin (Fig. 9, modified from Kent, 1979). A very abrupt transition takes place beneath the Blake Escarpment and a thin oceanic crust underlies the Blake Basin.

The configuration of the sedimentary and crustal units, combined with the absence of the ECMA south of the Blake

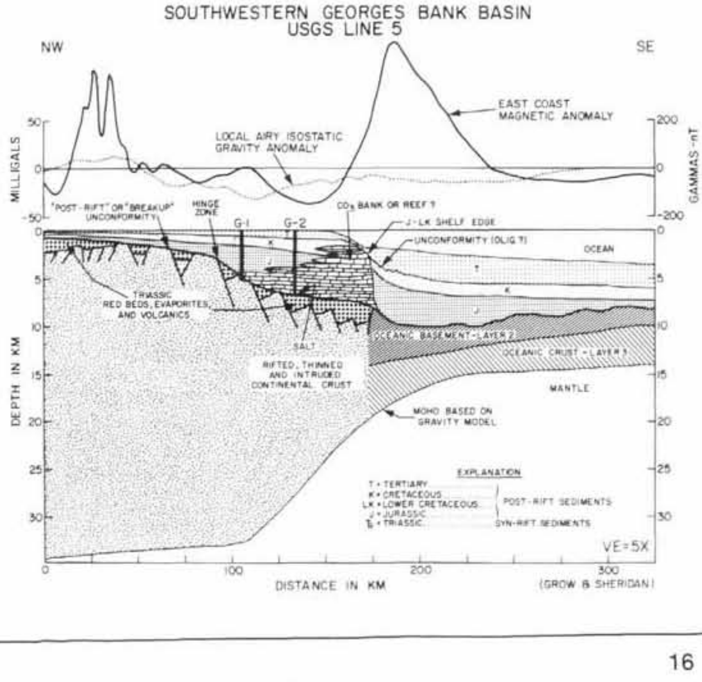


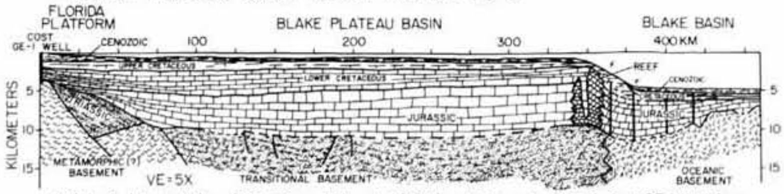
Figure 8

Composite geologic section across southwest end of Georges Bank Basin along multichannel seismic line 5 with recently available drill hole data projected from the COST G-1 and G-2 wells (Amato, Bebout, 1980 ; Amato, Simonis, 1980). Moho structure based on gravity model along line 5 (Grow et al., *1979 B). Note hinge zone and underlying change in depth to the Moho ; the structure is similar to the gravity models across the Carolina Trough (Fig. 3 and 5).*

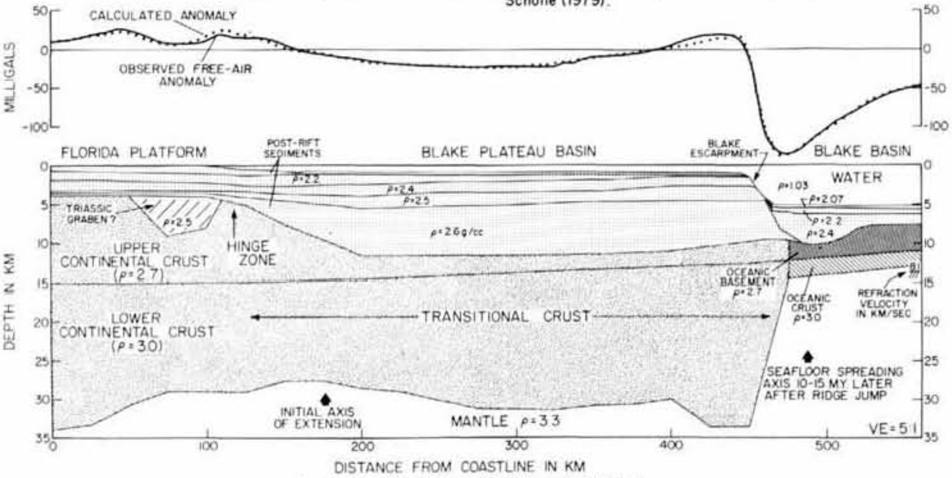
Figure 9

Composite geologic section across the Blake Plateau Basin along multichannel seismic line FC-3, modified from Dillon et al. *(1979) and Folger* et al. *(1979) ; Moho configuration is based on gravity model of Kent (1979). The COST GE-1 well data are from Scholle (1979). Thicker sediments and thinner transitional crust are present beneath the western Blake Plateau, where initial rifting probably began. A seaward jump in the extension axis from the western plateau to the Blake Escarpment probably took place 10 to 15 m.y. after initial continental separation.*

BLAKE PLATEAU BASIN ALONG PROFILE FC-3



A. Seismic Interpretation of FC-3 from Dillon et al (1979) and Folger et al (1979); Cost GE-1 Well from Scholle (1979).



B. Gravity Model Along FC-3 from Kent (1979)

Spur fracture zone, indicates a broad zone of extensional rifting and volcanism between Africa and North America in this area (Kent, 1979). Although the processes of Triassic rifting and crustal thinning beneath the western plateau probably were similar to those beneath the Carolina Trough and other basins to the north, the Early Jurassic history of the Blake Plateau Basin was different. Normal sea floor spreading between the ECMA and the Blake Spur Magnetic Anomaly began in the earliest Jurassic north of the Blake Spur fracture zone, but volcanic intrusions appear to have penetrated the thinned continental crust over a broad zone beneath the middle and western Blake Plateau for the first 10 to 15 million years. After an eastward jump of the extension and volcanic axis from the western plateau to the Blake Escarpment, normal sea floor spreading began in the Blake Basin with the formation of typical thin oceanic crust (Fig. 9). The above mentioned conclusions of Kent (1979) are consistent with earlier interpretations for sea floor spreading or extension-center jumps beneath the Blake Plateau (Sheridan, 1978 ; Dillon *et al.*, 1979 ; Klitgord, Behrendt, 1979).

CONCLUSIONS

1) Four major sedimentary basins formed along the US Atlantic continental margin in response to Triassic-Early Jurassic continental rifting and Early to Middle Jurassic sea floor spreading between Africa and North America : Georges Bank Basin, Baltimore Canyon Trough, Carolina Trough, and the Blake Plateau Basin.

2) Postrift sedimentary units in the four basins are as much as 7, 13, 11, and 12 km in thickness from north to south, respectively. The postrift units are typically separated from basement or synrift sedimentary rocks by a breakup or postrift unconformity underlain by synrift grabens, which may contain as much as 5 km of sedimentary rocks.

3) Upper Triassic and/or Lower Jurassic salt has been drilled at 6.7 km in the COST G-2 well within Georges Bank Basin in what appears to be late synrift or earliest postrift sedimentary units (Plate 4, Amato, Simonis, 1980). Three diapirs along the ECMA is the Baltimore Canyon Trough and 23 diapirs along the ECMA in the Carolina Trough also appear to rise from near the base of the postrift sedimentary units. Therefore, conditions favorable for evaporite deposits appear to have existed during the late rift stage and/or into the earliest postrift stage (i.e. after sea floor spreading between North American and Africa began).

4) The Jurassic sedimentary units that have been drilled to date in the Baltimore Canyon Trough (COST B-2 and B-3 wells : Scholle, 1977, 1980, respectively) and Georges Bank Basin (COST G-1 : Amato, Bebout, 1980 ; COST G-2 : Amato, Simonis, 1980) were of shallow-marine and nonmarine origin. This fact supports an inference that these basins subsided during the postrift stage in response to sediment loading and lithospheric cooling, as suggested by Watts and Steckler (1979).

5) Gravity models across the three northern basins indicate that the deepest parts of these basins are underlain by transitional crust 8 to 15 km thick, which appears to have formed primarily by extension and thinning of the pre-existing continental crust. The initial subsidence probably was controlled by this extensional mechanism (Le Pichon, Sibuet, 1980).

6) Beneath the Blake Plateau Basin, the 15 to 25 km thick transitional crust probably formed via a complicated mixing of continental fragments and volcanic intrusion over a zone 350 km wide zone during the first 10 to 15 m.y. of continental drift. Formation of this crust was followed by an abrupt eastward jump of the spreading center to the Blake Escarpment and the beginning of normal sea floor spreading, which formed thin oceanic crust beneath the blake Bahama Basin.

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