

EARLY MESOZOIC BASIN STRUCTURE AND TECTONICS OF THE SOUTHEASTERN UNITED STATES AS REVEALED FROM COCORP REFLECTION DATA AND THE RELATION TO ATLANTIC RIFTING

J. H. McBRIDE², K. D. NELSON², AND L. D. BROWN¹

ABSTRACT

Recent seismic reflection profiling by COCORP (Consortium for Continental Reflection Profiling) provides the first detailed view of the internal structure of the Triassic-Jurassic South Georgia Basin beneath the coastal plain of the United States. This basin is the southernmost and largest of the onland Triassic-Jurassic rift basins of eastern North America. The reflection data indicate that the South Georgia Basin is a composite feature, which includes several large half-grabens separated by intervening regions where the Triassic-Jurassic section is much thinner. The largest of these individual half-grabens has an apparent width (along the north-south profile) of 110 km, and contains up to 6 km of basin fill sediment.

The COCORP profiling further indicates that the interior of the South Georgia Basin is vertically divisible into two distinct seismic stratigraphic intervals beneath the Cretaceous-Tertiary cover: a lower, thicker graben-filling ("syn-rift") sequence exhibiting structural truncation combined with stratal tilting, and an upper, thinner basin-overlapping ("post-rift") sequence characterized generally by less faulted, concordant reflectors. This two-part division, typical of continental rift basins, is akin to the Mesozoic development of the western North Atlantic margin and the North Sea. As seen on COCORP profiles in the South Georgia Basin, the two sequences are separated by a prominent Lower to Middle Jurassic basalt/diabase interval, which is traceable across most of the South Georgia Basin as far east as offshore South Carolina. The basalt interval is analogous to that observed in exposed Newark-style Triassic basins as far north as the Fundy Basin and is probably the extrusive equivalent of diabase dikes exposed in the Piedmont. This correlation, together with the separation by the basaltic interval of the syn-rift and post-rift phases of the basin, would support the hypothesis that the major diabase intrusive-extrusive event in eastern North America postdates the formation of onland Triassic basins and possibly marks the initiation of Atlantic seafloor spreading.

INTRODUCTION

Approximately 1180 km of new, deep, seismic reflection data were collected by COCORP (Consortium for Continental Reflection Profiling) over the coastal plain and adjacent Southern Appalachian Piedmont of the southeastern U.S. during the periods November, 1983 to May, 1984 (Nelson *et al.*, 1985a, 1985b) and December, 1984 to April, 1985. Together with previous Southern Appalachian survey programs (Cook *et al.*, 1979, 1983), these data make up two transects, each over 300 km long, across the Georgia Coastal Plain (Fig. 1). This region is underlain by a broad area of Triassic-Jurassic subcrop, as shown in Figure 1, defined previously on the basis of scattered well penetrations and potential field data. For the most part, wells have been drilled only into the upper part of the Triassic-Jurassic section, leaving the internal and boundary structure of the basin as well as total volume unknown.

The South Georgia Basin is the southernmost and largest of the series of narrow, elongate onland early Mesozoic rift basins of the eastern margin of North America. In areal extent, it is ten times the size of the Newark-Gettysburg-Culpeper system (Chowns and Williams, 1983). All along

the eastern edge of North America, the rift system is characterized by asymmetric basins each usually bounded by a single master normal fault. Where these fault boundaries have been studied in the Appalachian Piedmont, they appear to have reactivated the antecedent Paleozoic compressional structure (Lindholm, 1978; Swanson, 1986). In this report we describe the COCORP data over the South Georgia Basin, and analyze in greater detail the development of early Mesozoic rifting in the southeastern United States in the context of kindred development of Atlantic rifting along the eastern on- and offshore margin of North America.

Figure 2 shows summary cross-sections through the western and eastern Georgia-Florida transects, which serve to illustrate the main results of COCORP profiling in the South Georgia Basin and adjacent terranes. Drillhole and surface geological observations (e.g., Maher, 1971; Chowns and Williams, 1983; Williams and Hatcher, 1983) indicate that the basin separates Piedmont metamorphic strata and locally exposed Grenville basement rocks to the north, and the Paleozoic Suwannee Terrane of African affinity to the south. The South Georgia Basin thus lies above, and obscures the Alleghanian suture in the Southern Appalachian

¹Department of Geological Sciences, and Institute for the Study of the Continents (INSTOC), Snee Hall, Cornell University, Ithaca, New York 14853, U.S.A.

²Institute for the Study of the Continents (INSTOC), Snee Hall, Cornell University, Ithaca, New York 14853, U.S.A.

This research was supported by National Science Foundation Grants EAR83-13378 and EA R 84-18157. J.H. McBride received partial support from a Shell Foundation Doctoral Fellowship and a Society of Exploration Geophysicists Foundation Scholarship. Data acquisition was carried out by Crew no. 6834 of Petty-Ray Geophysical, a division of Geosource, Inc., and data were processed on the COCORP Megaseis (TM Seiscom Delta) computer system at Cornell University. Reviews by Messrs. J. C. Behrendt, D. E. Brown, G. Stockmal, and D. B. Snyder improved the paper. Ms. P. L. Bishop expertly drafted the figures and Ms. J. Lipka typed the manuscript. This is Institute for the Study of the Continents (INSTOC) Contribution to Geology no. 70.

Copyright ©1987, Canadian Society of Petroleum Geologists

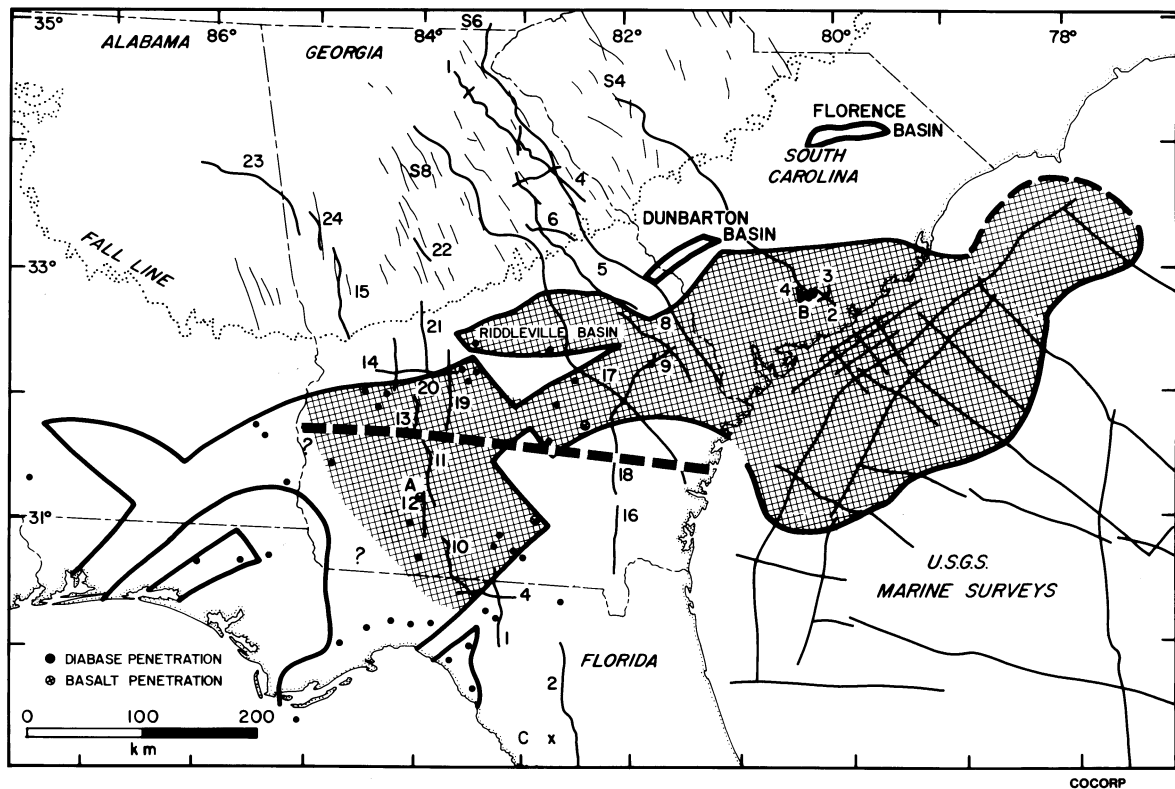


Fig. 1. Location map of study area. Hachured area indicates hypothetical areal extent of subsurface "J" reflector. Heavy line represents region of Triassic-Jurassic subcrop (including South Georgia Basin) (Chowns and Williams, 1983). Dots are drillholes penetrating basalt or diabase of Jurassic age. Thin lines show diabase dikes (from Dooley and Wampler, 1983). Heavy dashed line represents approximate southern limit of broad reflective zone inferred to be related to the Alleghanian suture. Numbered lines refer to COCORP surveys, lines S4, S6, and S8 to data acquired by the U.S.G.S. (Behrendt, 1986), and lines offshore to marine surveys (Behrendt *et al.*, 1983; Dillon *et al.*, 1983).

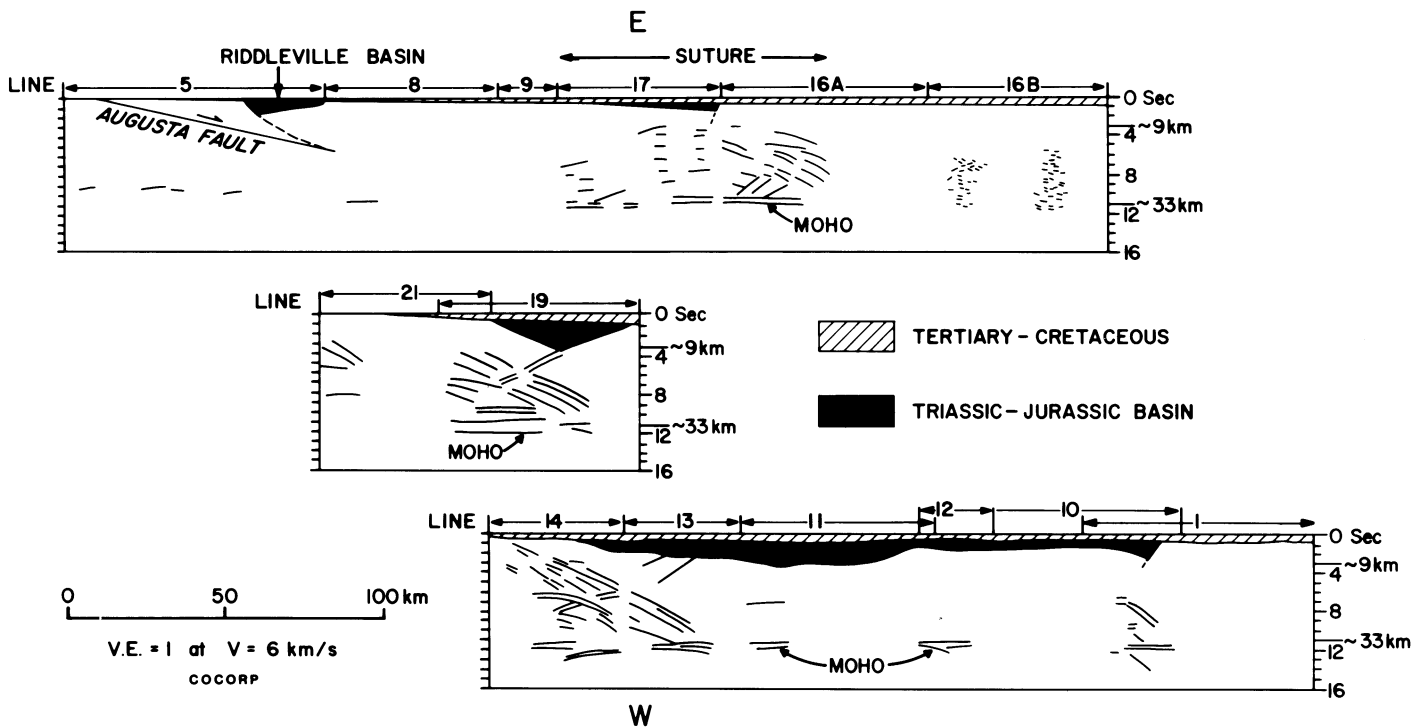


Fig. 2. Schematic cross-sections of the COCORP data showing generalized line drawings of prominent mid- and lower crustal reflections. Sections displayed with no vertical exaggeration using a conversion seismic velocity for "basement" rocks (6 km/s). Numbers refer to COCORP lines.

Orogen. The new COCORP profiling has revealed a broad, complex zone of generally south-dipping reflections, which penetrates the entire thickness of the crust beneath the coastal plain in western and eastern Georgia. This zone, which is approximately 70 km wide in western Georgia and widens to over 80 km in eastern Georgia, is interpreted as marking the Alleghanian suture between North America and Africa (Nelson *et al.*, 1985a, 1985b). The new reflection data also reveal that the main body of the South Georgia Basin rests over the southern, down-dip flank of the broad dipping zone (Figs. 1, 2 and 3).

RESULTS OF COCORP PROFILING

COASTAL PLAIN SEQUENCE

On all the seismic sections south of the fall line (landward edge of the Cretaceous-Holocene overlap), strong and highly continuous reflections occur in the upper 0 to 1 s (two-way time). This sequence of bright, subhorizontal reflections thickens gradually southward from the fall line (Fig. 3), reaches a maximum thickness at about the southern end of line 11 of 1400 m (0.90s) (Fig. 4), and then thins gradually southward into northern Florida. These and all other calculations of depth or thickness are based on interval velocities derived from stacking velocities. Well data from throughout the coastal plain area indicate that this sequence originates from repeating series of poorly to moderately consolidated beds of sand, clay, and limestone ranging from Early Cretaceous to Late Tertiary (Late Jurassic locally) in age (Cramer, 1969; Gohn *et al.*, 1978; Chowns and Williams, 1983). Known as the Coastal Plain Sequence (Chowns and Williams, 1983), this package has been similarly mapped by previous reflection programs in the southeast, onland (Cook *et al.*, 1979; Hamilton *et al.*, 1983; Schilt *et al.*, 1983; Behrendt, 1986) and continuing out onto the continental margin (Behrendt

et al., 1981, 1983). The well layered and uniform character of the coastal plain seismic stratigraphic sequence throughout the region distinguishes it from the underlying pre-Mesozoic basement or buried South Georgia Basin sediments. Laboratory and seismic refraction velocity studies (Bonini and Woollard, 1960) of rocks in the southeast indicate that Coastal Plain Sequence sediments fall into a distinct low-velocity category compared with the underlying Triassic basin strata or Piedmont rocks. This velocity contrast is manifest on the seismic sections as a smooth, prominent reflection marking the base of the Coastal Plain Sequence. The structural configuration of the base of the Coastal Plain Sequence, as indicated by reflection profiling, generally corroborates the structure of the fall line unconformity (Popenoe and Zietz, 1977), as determined from drilling.

SOUTH GEORGIA BASIN

Beneath the base of the Coastal Plain Sequence, the new COCORP data reveal a thickened and prominent series of layered reflections extending as deep as 4 or 5 s locally. The areal extent of this series generally coincides with the limits of the Triassic to Early Jurassic South Georgia Basin as defined by scattered drilling (Chowns and Williams, 1983) and potential field analysis (Daniels *et al.*, 1983). This sequence is generally highly reflective in contrast to the relatively unreflective Suwannee Basin Paleozoic strata in northern Florida and the Piedmont metamorphic and igneous rocks to the north. Shallow drilling within the South Georgia Basin indicates that this reflective package directly beneath the Coastal Plain Sequence represents continental clastic deposits (Maher, 1971; Gohn *et al.*, 1978; Chowns and Williams, 1983). Well indurated arkosic sandstone interbedded with red shale and siltstone as well as basaltic igneous rocks have been described from cuttings taken from drillholes in the basin (Chowns and Williams, 1983).

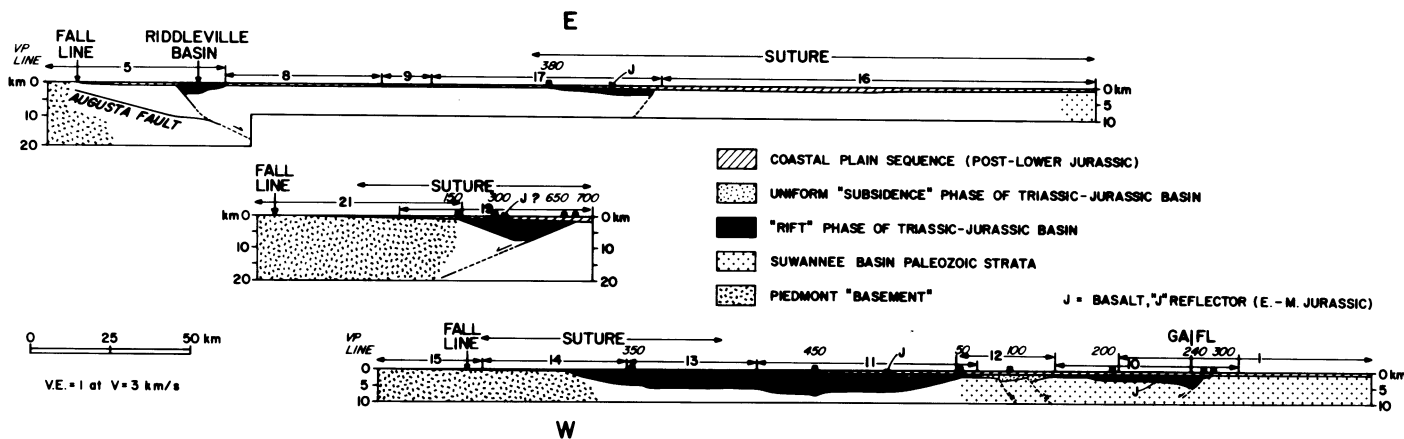


Fig. 3. Schematic cross-sections showing the main features of the COCORP data for the South Georgia Basin. Sections displayed with no vertical exaggeration using a typical conversion seismic velocity for clastic sedimentary rocks (3 km/s). Numbers refer to COCORP lines. Selected VP locations refer to points discussed in text.

Gohn *et al.* (1978) and Schamel *et al.* (1986) among others, have inferred that the sedimentary rocks of this package are equivalents of the Middle Triassic to Middle Jurassic Newark Supergroup (Van Houten, 1969; Froelich and Olsen, 1985). Fluvio-lacustrine mudstone, sandstone, and coarse-grained arkosic sandstone and conglomerate are the three principal sedimentary rock types composing this group all along the east coast (Marine and Siple, 1974). Newark Supergroup sediments are in general often interlayered with basalt flows and diabase sills, although these tend to be concentrated near the upper part of the section (Faust, 1975; Lanphere, 1983). Isotopic age-dating of basalts beneath the Coastal Plain Sequence in South Carolina (Lanphere, 1983) and Georgia (Gohn *et al.*, 1978) gives an age of 184 ± 3.3 Ma implying that the deeper, basinal sediments are pre-Middle Jurassic. Palynological age-dating indicates that some Newark equivalent sediments are as old as Middle Triassic (Cornet *et al.*, 1973; Schamel *et al.*, 1986).

The well developed reflectivity below the coastal plain seismic sequence in the sections over the basin contrasts markedly with the relatively non-reflective Suwannee Basin Paleozoic sequence crossed by Florida lines 1, 2, and 4 and also with the Piedmont basement strata to the north crossed by Georgia lines 14, 15, 20, 21, 22 and 24. This important distinction has also been observed in previous reflection studies in the Riddleville Basin in eastern Georgia (Cook *et al.*, 1983; Petersen *et al.*, 1984) and in northern Florida (Arden, 1974). Sharp acoustic impedance contrasts in the interior of the basins would be expected, for example, from lacustrine mudstone interlayered with coarser sediment or from basalt flows or diabase sills. Petersen *et al.* (1984) interpreted high-amplitude reflections within and at the base of the Riddleville portion of the South Georgia Basin as coming from lacustrine mudstone or basalt. High-amplitude reflections from the interior of terrestrial basins of the Basin and Range province have been likewise attributed to fluvio-lacustrine deposits (Effimoff and Pinezich, 1981; Anderson *et al.*, 1983).

Along the western Georgia transect, the reflection package beneath the Coastal Plain Sequence reaches its maximum thickness of about 6 km near the northern end of Georgia line 11 (VP 450, Worth Co.) (Fig. 4) from where it thins gradually to the north and south. On the southern end of line 11, subhorizontal reflections in the lower part of this package are truncated against a north-dipping set of reflections, which separates the package from a non-reflective basement to the south (VP 50, Colquitt Co.). Toward the northern end of line 13, the reflective package thins to about 2.8 km (below VP 350, Sumter Co.). Altogether, between the southern end of line 11 and the northern end of line 13, the base of this reflective interval is marked by a more or less continuous line of subhorizontal reflections ("D", Fig. 4), which varies in depth below the surface from a maximum of 7.3 km (VP 450, line 11) to as shallow as 4.0 km (VP 350, line 13). We infer this boundary between reflective and unreflective material to be the base of the South Geor-

gia Basin lower Mesozoic section, although locally it is possible that some Paleozoic rocks may also be represented.

South of line 11 on the western transect, the reflective section beneath the Coastal Plain Sequence becomes more restricted. On Georgia line 12, reflections occur at a maximum travel time of 2 s (2.9 km) below VP 100 (Figs. 3 and 6). Below this level, most of the seismic sections south of line 11 are relatively transparent. Southward from line 12, both the coastal plain seismic sequence and the underlying basin sequence thin nearer the Florida — Georgia border. On the southern half of line 10 (Fig. 3), beginning below VP 280 (Brooks Co.), the basin section begins to thicken southward to a maximum depth of 6.4 km on the northern end of Florida line 1 (below VP 240, Hamilton Co.). At this point, the south-dipping reflections of the lower part of the basin seismic sequence are abruptly truncated. This southern limit of the basin sequence approximately coincides with the limit of the South Georgia Basin as inferred from drilling (Barnett, 1975; Chowns and Williams, 1983). As in the case of the southern and northern ends of Georgia lines 11 and 13 (Fig. 3), respectively, the truncation of the lower basin sequence on Florida line 1 strongly suggests a north-dipping master normal fault.

Georgia lines 19 (Fig. 5) and 21 comprise a 115-km transect (Fig. 3) across the northern boundary of the South Georgia Basin located about 40 km east of the main western COCORP transect (Fig. 3). On Georgia line 19 (Fig. 5), between VPs 150 and 700, is a prominent reflective zone beneath the base of the coastal plain seismic sequence. This package is similar to that described on lines 11 and 13 and extends as deep as about 5 s (about 8 km). The interior of the sequence is characterized by south-dipping reflections which terminate up-dip against the base of the Coastal Plain Sequence at VP 300 (Dooly Co.) and down-dip against a set of steeper, north-dipping reflections. The steeper set terminates up-dip against the base of the Coastal Plain Sequence (VP 650, Crisp Co.). This entire reflective package, the northern boundary of which approximately coincides with the northern limit of the South Georgia Basin in this area, is thus interpreted as an asymmetric basin bounded on the south by a master normal fault. Drilling results north of VP 150 indicate that the unreflective material immediately below the Coastal Plain Sequence is Piedmont metamorphic rock.

Along the eastern transect, shallow drilling indicates that the South Georgia Basin is areally more restricted, as shown in Figure 1. Analyses of drilling results for the southeast coastal plain (Maher, 1971; Chowns and Williams, 1983) indicate that the eastern portion of the basin is bordered on the south by a large basement terrane of Eocambrian (?) felsic volcanic rocks, which extends southward approximately to the Florida-Georgia border. North of the basin, Piedmont metamorphic rocks are penetrated in wells drilled through the Coastal Plain Sequence. Georgia line 16 begins on the south in southeastern Georgia over buried Suwannee Basin Paleozoic rocks and then transects the

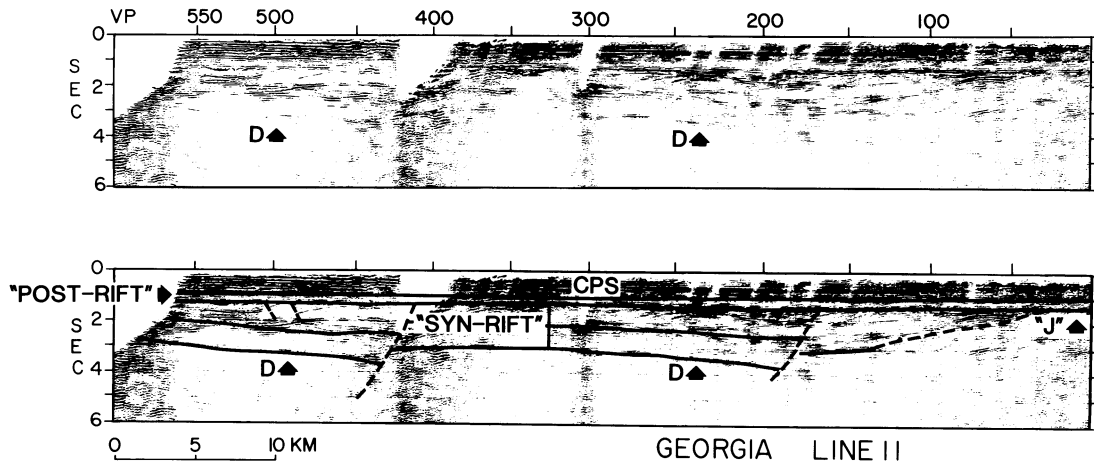


Fig. 4. Upper portion of Georgia line 11 unmigrated stacked section. Annotation shows Tertiary-Cretaceous Coastal Plain Sequence (CPS), inferred post-rift and syn-rift seismic stratigraphic sequences, and "J" reflector. Dashed lines indicate interpreted normal faults. No vertical exaggeration at 3 km/s.

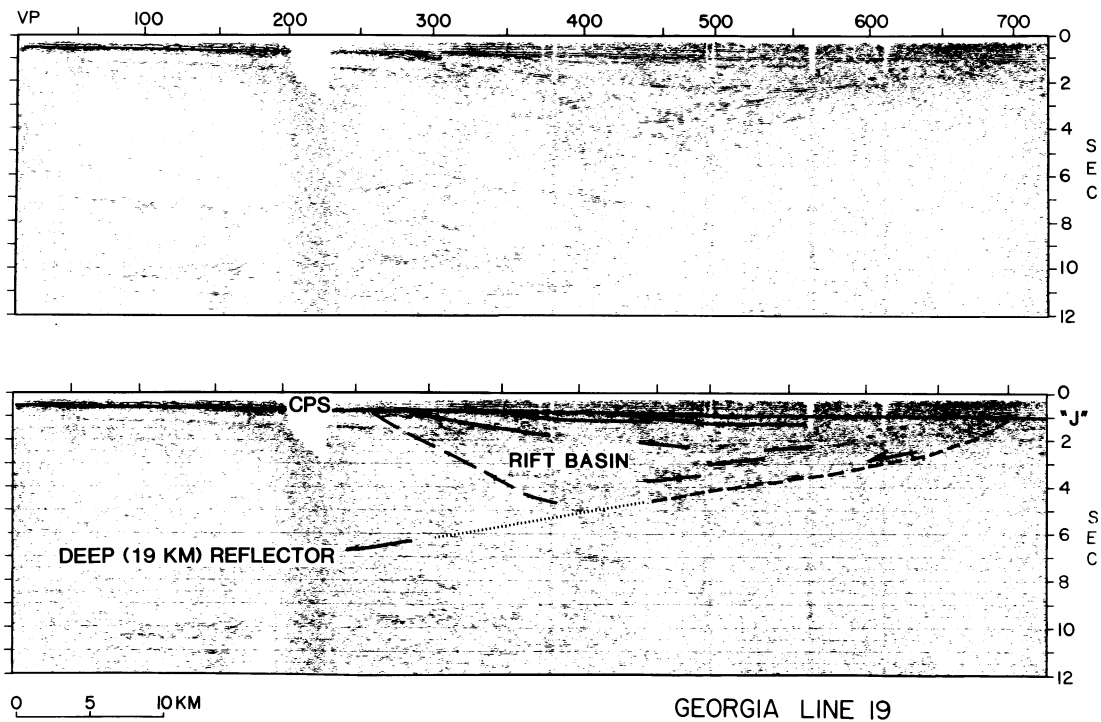


Fig. 5. Georgia line 19 unmigrated stacked section. Annotation shows Tertiary-Cretaceous Coastal Plain Sequence (CPS), syn-rift seismic stratigraphic sequence, inferred master normal fault, and the possible deep projection of the master fault. No vertical exaggeration at 3 km/s.

subsurface felsic volcanic terrane (Fig. 3). On this line, no sub-Coastal Plain Sequence reflections attributable to sedimentary strata are visible, and analysis of shot record refractions indicates that Coastal Plain Sequence sediments rest directly over a high-velocity (≥ 6 km/s) basement.

In contrast, on Georgia line 17 (Fig. 3), the Coastal Plain Sequence begins to thin northeastward and is underlain by a weakly resolved package of slightly southwestward-dipping reflections attributed to the South Georgia Basin sequence. This reflection package reaches a maximum thickness of 1

km at the southern end of line 17 where it appears to be abruptly terminated. To the northwest, this package thins and disappears at about VP 380 below the base of the Coastal Plain Sequence.

The new reflection data for the South Georgia Basin therefore indicate that the maximum thickness of the reflective pre-Middle Jurassic basin section is about 6 km in the north-central area where crossed by Georgia lines 11 and 19 (Fig. 3). This figure is close to that given for the maximum possible thickness of the Newark Supergroup in

the Newark Basin of 6100 m (Van Houten, 1969; Marine and Siple, 1974). In the South Georgia Basin, only one known drillhole (near Riddleville, Georgia) has penetrated an entire section of the basin, revealing 2200 m of redbeds and diabase (Chowns and Williams, 1983). Previous COCORP profiling in this portion of the South Georgia Basin suggests a maximum thickness of about 3 km (Petersen *et al.*, 1984). In eastern Georgia, northwest of line 17, magnetic field modelling has been used to infer a total thickness of 3500 m (Daniels *et al.*, 1983) and in the northern Florida panhandle over 1800 m of basin fill can be estimated from industry reflection data (Arden, 1974).

"J" BASALT REFLECTOR

The overall seismic stratigraphic sequence of the South Georgia Basin in western Georgia is divisible into two distinct reflection sequences separated by a very prominent high-amplitude, two-cycle reflection (e.g., Fig. 4). On Georgia lines 11 and 12 this prominent reflection correlates with Lower to Middle Jurassic (Gohn *et al.*, 1978; Lanphere, 1983) basaltic flows or diabase sills in nearby wells. The reflection can also be recognized on part of the eastern transect. Shot records indicate that this reflection is associated with a high-velocity refractor yielding velocities at or above 5.5 km/s. This is distinctly higher than average velocities associated with sedimentary rocks of the basin sequence. A similarly strong, smooth reflector is mapped over the basin sequence on Georgia line 19 and on line 17 of the eastern COCORP transect, which also shows a high-velocity refraction beneath the Coastal Plain Sequence.

A similar reflector, termed the "J" reflector, was previously mapped on COCORP and U.S.G.S. reflection profiles (Schilt *et al.*, 1983; Yantis *et al.*, 1983; Hamilton *et al.*, 1983) in southeastern South Carolina. The "J" reflector was also found to extend offshore onto the continental shelf (Dillon *et al.*, 1983; Behrendt *et al.*, 1983). This reflector correlates with Lower to Middle Jurassic tholeiitic basalt flows encountered in the Clubhouse Crossroads wells (Gottfried *et al.*, 1983). The new COCORP data suggest that essentially the same basaltic sequence may extend throughout the South Georgia Basin in Georgia and as far away as offshore South Carolina (McBride *et al.*, *in press*) (Fig. 1). This reflector is a prominent structural marker within the basin and separates the thinner, upper interval of the basin below the Coastal Plain Sequence from the thicker and more complex lower interval. This relationship is well expressed, for example, on Georgia line 11, as shown in Figure 3. On lines 19 and 17, however, the uppermost part of the basin sequence between the base of the Coastal Plain Sequence and the "J" reflector is missing due perhaps to erosion, reduced subsidence, or nondeposition. As discussed in the previous section, drilling indicates that basalt or diabase is absent beneath the coastal plain south of line 17.

In the rift basins of the east coast, a similar concentration of basalt flows or diabase sills stratigraphically above the

majority of the basin fill is well documented (e.g., Faust, 1975; Lindholm, 1978; Manspeizer *et al.*, 1978; Swanson, 1982). Faust (1975) has noted that most (80-90%) of the Newark Supergroup sediments in the Newark Basin were deposited before the first major basalt flow. Farther north in the Fundy Basin, marine seismic reflection profiling has revealed an interval of Lower Jurassic tholeiitic basalt flows (North Mountain Basalt) stratigraphically above as much as 9 km of lower Mesozoic fill (Brown, 1986; Grierson, 1986). In these surveys, the basalt horizon produces a bright reflection, similar to the "J" reflector, and has been similarly interpreted to rest atop or above the post-rift unconformity. Manspeizer *et al.* (1978) report that basaltic volcanism in general along the east coast of North America and the northwestern margin of Africa followed the accumulation of 3-5 km of basin fill, about 75 My after initial crustal thinning. This interval of basaltic volcanism also probably produced most of the diabase dikes exposed in the Appalachian Piedmont (Dooley and Wampler, 1983). The new COCORP data therefore confirm the occurrence of volcanism late in the rift sequence in the South Georgia Basin at or just before the onset of uniform subsidence.

LOWER "RIFT" INTERVAL

Along the western Georgia transect over the South Georgia Basin, the "J" reflector rests over a thick, lower basin interval of layered reflections. This lower interval is best developed on lines 11 (Fig. 4), 13, and 19 (Fig. 5). On the southern end of Georgia line 11 this lower basin interval begins at about 1.3 s (1200 m) just below the "J" reflector. The lower interval is characterized by structural truncations and displacements of interior basin reflectors, which are interpreted as representing normal faulting associated with early-stage rifting (Fig. 4). In this area, the lower basin interval is limited on the south by a prominent north-dipping reflection, which truncates and separates prominent dipping reflectors from the non-reflective basement to the south. We therefore interpret this dipping reflector as a basin-bounding normal fault. A similar interpretation is applicable to Georgia line 19 (Fig. 5) on which a set of north-dipping basin-bounding reflections beneath the base of the Coastal Plain Sequence (i.e., at 2.5 s beneath VP 533) appears to truncate subparallel, south-tilted reflections. The interpretation that the lower reflective interval corresponds to initial basin formation ("syn-rift") and not to older structure or stratification ("pre-rift") is supported by the progressive upward-shallowing of the reflector dip on the southern portions of the reflective interval on lines 19 and 11. This consistent upward-shallowing of dip implies that the strata formed in a single subsiding basin and are not relict. Basin reflectors located immediately next to the inferred faults on each line dip basinward, not into the fault, but away from it. Farther to the north in the basin, the dip reverses and reflectors dip toward the fault. This pattern is not uncommon for rifted terranes and indicates that subsi-

dence proceeded asymmetrically — reflectors dipping away from the fault forming in the basin moat, and those dipping toward the fault forming over the basin ramp (Anderson *et al.*, 1983).

The above interpretations imply that Georgia lines 11 and 19 each define a large asymmetric graben within the lower basin interval having a depocentre on the south bounded by a north-dipping master normal fault, and shallowing northward. The migrated dips of the master faults of these two grabens are between 10° and 15° ; however, because the survey lines may trend oblique to the basin strike, these values are only apparent and the actual dips may be higher. In general, east coast basin border faults dip from 60° to 90° , although many are thought to flatten with depth (Odom and Hatcher, 1980). Where these border faults have been studied in detail (e.g., Marine and Siple, 1974; Gohn, 1983; Kaye, 1983) the fault appears to be defined by a zone of cataclasis or microbrecciation, which could possibly produce a significant acoustic impedance contrast. Low-angle faults in the Basin and Range also have intensely brecciated contacts capable of producing impedance contrasts, as observed by (Armstrong, 1972). The northern border fault of the early Mesozoic Fundy Basin in Nova Scotia is the thrust-component of the Minas Geofracture (Brown, 1986), a highly deformed deep crustal shear zone with transverse motion recorded from the Middle Devonian to Early Jurassic (Keppie, 1982). Where this zone forms the master normal fault of the basin half-graben, it is expressed as a prominent reflector on marine seismic profiles (Brown, 1986).

The portion of the lower basin interval as mapped on Georgia lines 11 and 13 has a width of 110 km and a maximum thickness of 5800 m (or maximum depth of 7000 m below sea level) and on Georgia line 19 a width of 38 km and a maximum thickness of 6000 m (or maximum depth of 7500 m below sea level) (Fig. 3). The approximate cross-sectional area of each is 480 km² and 120 km², respectively. The cross-sectional area of the basin on line 19 is shown schematically in Figure 7 and is compared with selected other early Mesozoic basins of the east coast. Note the relatively large size of this basin in the context of other syn-rift basins.

South of line 11 (Fig. 3), the lower seismic sequence is less well expressed. As noted previously, an individual seismic stratigraphic sequence of south-tilted reflections was mapped below the “J” reflector on the southern half of Georgia line 10 continuing onto Florida line 1. On the basis of the position of this lower sequence below the “J” reflector, together with its unconformable relationship with overlying basin reflectors, it is interpreted as equivalent to the lower basin “syn-rift” interval as described above for lines 11, 13, and 19 (Figs. 3, 4, and 5). Reflections within this sequence on Florida line 1 terminate down-dip at a position approximately coincident with the southern limit of the South Georgia Basin and are interpreted as defining an asymmetric graben bounded on the south by a north-dipping

master fault. The position and orientation of the fault, as shown in Figure 3, are based on the geometry of truncated reflections. On the southern end of line 17, the reflective interval beneath the “J” reflector is also made up of south-dipping reflections, which are truncated up-dip. This seismic stratigraphic sequence can, in a like manner, be related to the lower “syn-rift” interval of the basin.

UPPER “UNIFORM SUBSIDENCE” INTERVAL

An upper, thinner reflection interval can be recognized between the “J” reflector and the base of the Coastal Plain Sequence (i.e., between 1.3 and about 1.0 s, respectively, in Fig. 4). Because this upper interval, where mapped by COCORP surveys, lies above the “J” horizon of Early to Middle Jurassic age, and below the Lower Cretaceous fall line unconformity, it is inferred to be Middle to Late Jurassic in age. This persistent saucer-shaped interval extends from the northern part of Florida line 1 to about the middle of Georgia line 13 and is distinctive in being characterized by weaker, but internally concordant, reflections. Including the “J” reflector, the upper interval generally rests with angular unconformity on dipping reflectors defining the lower basin interval (e.g., Fig. 4). We interpret this angular unconformity or bevel surface, therefore, as the post-rift unconformity. This feature has been recognized previously on the offshore continental margin as a surface separating “syn-rift” grabens from “drift phase” (or “post-rift”) Jurassic sediments above (Dillon *et al.*, 1983). Where studied offshore from seismic data (Hamilton *et al.*, 1983; Behrendt *et al.*, 1983), the post-rift unconformity appears as a smooth surface dipping regionally seaward with little vertical displacement. Where the “J” reflector extends offshore, it rests just above, but not exactly on, the post-rift unconformity (Behrendt *et al.*, 1983).

Because the “J” reflector represents a structural (i.e., chronostratigraphic) marker just above the post-rift unconformity, it can be used to observe the amount of displacement, if any, in the overlying upper sequence (e.g., Behrendt *et al.*, 1983; Hamilton *et al.*, 1983; Schilt *et al.*, 1983). In the South Georgia Basin, the upper basin interval shows evidence of only minor and restricted deformation. This deformation occurs in two places, first on the southern half of Georgia line 11 (near VP 200) in the form of a small half-graben about 6.5 km wide with a minimum displacement of 1000 m (Fig. 4). Second, on the southern half of line 12 two half-grabens have developed with widths and minimum displacements of 5 km and 500 m, respectively (Fig. 6). In each case, deformation is defined on the basis of disruption of the “J” reflector. The small sub-basin on line 11 shows rather dramatic evidence for ponding of possible basaltic lava. In addition to the strong suggestion based on geometry, detailed velocity inversion for this portion of the data (Xianhuai Zhu, *pers. comm.*) indicates that the interior of the sub-basin is composed of high-velocity (>6.5 km/s) layers. In the Culpeper Basin of Virginia, Lindholm (1977)

reported field evidence for possibly similar ponding of lava against a fault scarp. The implication of this relationship is that later, Early to Middle Jurassic normal faulting of lesser magnitude may have been in some places coincident with volcanism. Over most of the basin, however (e.g., line 12, Fig. 6), reflectors immediately above the faulted "J" horizon appear horizontal and concordant.

North of these two smaller, localized grabens, the upper basin interval thins gradually and pinches out beneath the Coastal Plain Sequence near the middle of line 13 (Fig. 3). On all the COCORP profiles north of this point, including line 17 and line 19 to the east and possibly line 5 over the Riddleville Basin, the upper basin interval is likewise absent. The portion of the South Georgia Basin south of the main depocentre, on Georgia lines 12 and 10 and the northernmost portion of Florida line 1, shows a much thinner lower reflection interval below the "J" reflector. The broad, upper interval does, however, persist across the western survey as depicted in Figure 3. The upper basin interval continues southward into Florida on Florida line 1 for a few kilometres beyond the limit of the lower interval, where it finally pinches out beneath the Coastal Plain Sequence (VP 300, Hamilton Co.).

In summary, the contrasting character of the upper and lower basin intervals suggests that the lower interval represents the early, *rift* stage of basin formation accompanied by significant normal faulting and possibly crustal extension, whereas the upper interval represents the later *uniform subsidence* stage (see, e.g., Keen *et al.*, 1986). This subdivision is, however, not evenly distributed throughout the South Georgia Basin. In particular, the syn-rift phase is more fully developed in the northern and western portions of the basin and the post-rift phase is best developed in the southwest. Along the eastern COCORP transect (Fig. 3) the South Georgia Basin is areally more restricted and less developed with only the syn-rift phase present. The sequence in the South Georgia Basin is analogous to the development of the offshore Atlantic margin, which involved an initial phase of block faulting followed by an Early Jurassic phase of uniform subsidence (Klitgord *et al.*, 1983). This analogous development suggests that the evolution in time and space of the South Georgia Basin may have been linked to that of the early Atlantic Ocean.

CONCLUSIONS AND DISCUSSION

RELATIONSHIP OF SOUTH GEORGIA BASIN TO ATLANTIC MARGIN

The South Georgia Basin is the southernmost of a series of inland rift basins, which formed early in the Mesozoic rift sequence that ultimately led to the opening of the Atlantic Ocean. These basins have been well studied where exposed in the Piedmont; however, the largest area of Triassic-Jurassic subcrop, centred in southern Georgia, has remained generally unexplored. The new COCORP profiling sug-

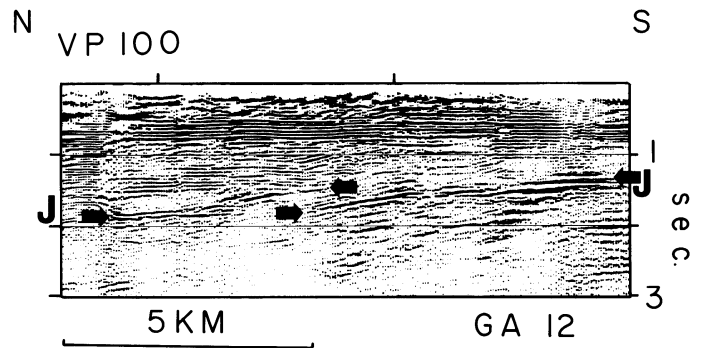


Fig. 6. Small portion of Georgia line 12 stacked section showing disrupted "J" reflector. No vertical exaggeration at 6 km/s.

gests that an unusually complete record of early inland rifting and subsidence is preserved in the South Georgia Basin. Because of this more complete record, the structure of the basin can illustrate a link between the early inland Triassic rifting and the ultimate Jurassic Atlantic opening.

The reflection data reveal that the South Georgia Basin is vertically divisible into distinct lower and upper intervals, which represent initial Newark rifting and later regional uniform subsidence episodes, respectively, in the formation of the entire basin. This two-part division is typical of many rift basins (e.g., the Michigan Basin, McKenzie, 1978, Hinze and Wold, 1982; Central North Sea Basin, Pegrum and Mountney, 1978, Selater and Christie, 1980) and suggests that development of the South Georgia Basin followed a cycle connected to that along the Atlantic passive continental margin. All along the North Atlantic margin, as in the North Sea, this division between rifting and uniform subsidence corresponds in time to the beginning of active seafloor spreading offshore (Pegrum and Mountney, 1978) and the drastic subsidence and marine flooding of the entire continental margin. Seaward of the hinge zone of the Carolina Trough, Baltimore Canyon Trough, and Georges Bank Basin, the post-rift section thickens dramatically. Landward of these hinge zones, however, the offshore section is extensive but relatively thin (Hutchinson *et al.*, 1986).

In the South Georgia Basin, the rift and subsidence intervals are separated by a widespread basalt-diorite reflector at the post-rift unconformity. The implied areal extent of this horizon as shown in Figure 1 is over 100,000 km², placing it on the same scale as the Deccan Traps of India and the Columbia Plateau basalts (Williams and McBirney, 1979). As mentioned earlier, an apparently similar basalt flow has been described from the Fundy Basin and covers an area of about 13,000 km² (Brown, *pers. comm.*). The basaltic interval in the South Georgia Basin is probably correlative with the phase of tholeiitic volcanism recognized along the east coast and occurring at about 200 Ma (Sutter, 1985). Diorite dikes in the Southern Appalachian Piedmont are thought to be no older than 195 Ma on the basis of isotopic age dating (Dooley and Wampler, 1983) and are probably equivalent to diorite dikes elsewhere in the Appalachian Orogen and in West Africa (Manspeizer *et*

al., 1978). As pointed out above, it is well known that this magmatic phase postdates the majority of rift-basin filling as evidenced by cross-cutting of dikes through basins (Faust, 1975). The basalt horizon in the South Georgia Basin is also probably equivalent to Piedmont diabase dikes. The position of basalt flows or sills atop rift-basin fill in the South Georgia and other exposed early Mesozoic basins supports the hypothesis that the major diabase intrusive-extrusive event around the North Atlantic margin postdates the formation of onland basins and probably marks the initiation of seafloor spreading offshore together with the cessation of crustal extension onshore.

MODE OF BASIN FORMATION

The lower rift basin intervals on line 19 and on lines 11 and 13 (Fig. 3) appear to be defined by two styles of reflection geometry. The basin mapped on line 19 is more restricted and displays a more pronounced asymmetry than that on lines 11 and 13. The asymmetry of the basin on line 19 is accentuated by the colinearity of the inferred position of the border fault on the south and a deep planar reflection at about 6.5s (19 km) (Fig. 5). The inclined reflector on the down-dip trend of the inferred border fault may represent a steep and more deeply penetrating master fault. This deep reflector appears to disrupt southward-dipping reflectors of the inferred Alleghanian suture in an antithetic sense. A smaller, but similar, asymmetric rift basin, also bounded by a steep border fault, was previously mapped by COCORP (Cook *et al.*, 1983) to the east near Riddleville (Fig. 1) and occupies an equivalent on-strike position with respect to the line 19 basin (Fig. 3). Analysis of reflection data over the Riddleville Basin suggests that it subsided along a border fault that merges at depth, in a synthetic sense, with the down-dip extension of the Augusta Fault, a major, south-dipping, low-angle, Paleozoic thrust (Petersen *et al.*, 1984). The available reflection data therefore demonstrate that in two places along the northern margin of the South Georgia Basin, asymmetric and relatively narrow and confined sub-basin depocentres each subsided along a single master normal fault, which appears to extend to mid- or lower crustal depths.

In contrast to line 19, the overall shape and asymmetry of the lower basin interval on lines 11 and 13 are not as sharply defined. On the southern end of line 11 it is not clear whether the inferred master normal fault penetrates deeper below the base of the reflective zone or merges with it. The bottom of the entire reflective package here appears to be marked by a generally sub-horizontal reflector ("D", Fig. 4), which can be traced northward onto line 13 for approximately 90 km. Below this level, the sections are remarkably unreflective. The fact that the reflector does not show significant offsets, in spite of evidence for major structural displacements in the section above, raises the possibility that this persistent basal reflector may represent a major subhorizontal detachment, similar to those described in the

Basin and Range province (Anderson *et al.*, 1983). Some workers (e.g., Odom and Hatcher, 1980; Behrendt *et al.*, 1983) have hypothesized that high-angle Mesozoic faults bounding east coast rift basins may in general flatten with depth and merge with a subhorizontal "ductile" fault at depth.

A somewhat similar dual style of basin geometry has also been recognized from deep reflection data over the Mesozoic Grand Banks Basin, offshore Newfoundland (Keen *et al.*, 1986), in which relatively narrow and confined basins appear to be bounded by steeply dipping and possibly crustal-penetrating normal faults, whereas broader areas of subsidence are underlain by subhorizontal detachments. The detachment underlying some of the basins is interpreted as representing a brittle/ductile transition. Analogous interpretations of subhorizontal detachments as brittle/ductile transitions have been made for other extensional areas (e.g., by de Charpal *et al.* (1978) for the Bay of Biscay and by Gans *et al.* (1985) for the northern Snake Range Detachment in eastern Nevada). In the case of the subhorizontal reflector beneath lines 11 and 13, it is not clear whether this surface would represent a relict brittle/ductile transition or a normal-slip detachment. What does seem clear from the above models is that the two styles of basin reflection geometry in the South Georgia Basin may be related to two different modes of extension.

ON-STRIKE DISPARITY WITHIN BASIN

As noted, the South Georgia Basin is composed of several partially isolated rift basins each representing a separate depocentre. These individual rift depocentres occupy a complex composite structure characterized by disparate basin geometry along strike. This disparity is evident from the cross-sections in Figure 3. If other, better studied, on-shore east coast basins were used as a model (Fig. 7), the South Georgia Basin might be expected to be internally complex (Cloos and Pettijohn, 1973; Marine and Siple, 1974; Ackermann *et al.*, 1976; Wise and Robinson, 1982; Chowns and Williams, 1983; Smith *et al.*, 1986). A number of workers have attempted to explain the on-strike discontinuity observed in general within rifts. Observations from seismic reflection profiling over lakes of the East African Rift valleys by Project PROBE (e.g., Rosendahl *et al.*, 1986) indicate that as border normal faults die out along strike on one side of the rift, equivalent faults gradually develop on the opposite side. Asymmetric grabens formed in this way are often observed to be separated by a large intrabasinal upwarp. Lister *et al.* (1986) have formulated a model to postulate that passive margins extend by either low-angle "lower plate" (broad shelf) or high-angle "upper plate" (narrow shelf) detachments. These two extension regimes can form in alternating blocks, which divide the extending terrane into segments. It is certainly intriguing that the new COCORP data for the South Georgia Basin indicate that broad basin areas are possibly underlain by a low-angle

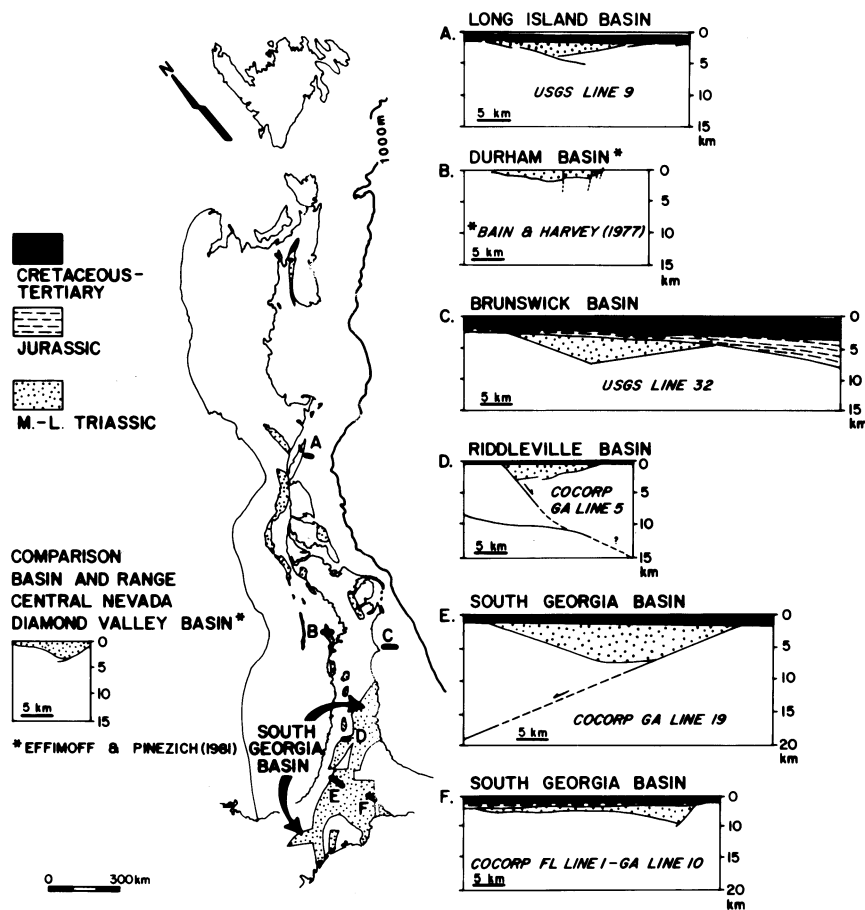


Fig. 7. Summary diagram showing distribution of onland early Mesozoic basins. Shown also are cross-sections through selected early Mesozoic basins (with no vertical exaggeration). Sources: Hutchinson *et al.* (1986), Bain and Harvey (1977), Hutchinson *et al.* (1982), Petersen *et al.* (1984), Effimoff and Pinezich (1981), and Chowns and Williams (1983).

detachment (lines 11 and 13) and narrower basins are bounded by a steeper, crustal-penetrating normal fault (Riddleville Basin and line 19). Although data from the South Georgia Basin support the observation of on-strike disparity in rift structure, a more complete picture of this structure awaits more detailed and three-dimensional studies of reflection data from east coast early Mesozoic basins.

REFERENCES

- Ackermann, H. D., Bain, G. L. and Zohdy, A. A. R. 1976. Deep exploration of an east-coast Triassic basin using electrical resistivity. *Geology*, v. 4, p. 137-140.
- Anderson, R. E., Zoback, M. L. and Thompson, G. A. 1983. Implications of selected subsurface data on the structural form and evolution of some basins in the northern Basin and Range province, Nevada and Utah. *Geological Society of America, Bulletin*, v. 94, p. 1055-1072.
- Arden, D. D., Jr. 1974. Geology of the Suwannee Basin interpreted from geophysical profiles. *Gulf Coast Association of Geological Societies, Transactions*, v. 24, p. 223-230.
- Armstrong, R. L. 1972. Low-angle (denudation) faults, hinterland of the Sevier orogenic belt, eastern Nevada and western Utah. *Geological Society of America, Bulletin*, v. 83, p. 1729-1754.
- Bain, G. L. and Harvey, B. W. (Eds.), 1977. Field guide to the geology of the Durham Triassic basin. *Carolina Geological Society Annual Meeting*, 83p.
- Barnett, R. S. 1975. Basement structure of Florida and its tectonic implications. *Gulf Coast Association of Geological Societies, Transactions*, v. 25, p. 122-142.
- Behrendt, J. C. 1986. Structural interpretation of multichannel seismic reflection profiles crossing the southeastern United States and the adjacent continental margin — decollements, faults, Triassic (?) basins and Moho reflections. *In: Barazangi, M. and Brown, L. D. (Eds.), Reflection Seismology: The Continental Crust*. Washington, D.C.: American Geophysical Union Geodynamic Series, v. 14, p. 201-214.
- _____, Hamilton, R. M., Ackermann, H. D. and Henry, V. J. 1981. Cenozoic faulting in the vicinity of the Charleston, South Carolina, 1886 earthquake. *Geology*, v. 9, p. 117-122.
- _____, _____, and Bayer, K. C. 1983. Marine multichannel seismic-reflection evidence for Cenozoic faulting and deep crustal structure near Charleston, South Carolina. *In: Gohn, G.S. (Ed.), Studies Related to the Charleston, South Carolina, Earthquake of 1886 — Tectonics and Seismicity*. United States Geological Survey Professional Paper 1313, p. J1-J29.
- Bonini, W. E. and Woollard, G. P. 1960. Subsurface geology of North Carolina — South Carolina Coastal Plain from seismic data. *American Association of Petroleum Geologists, Bulletin*, v. 44, p. 298-315.
- Brown, D. E. 1986. The Bay of Fundy: thin-skinned tectonics and resultant early Mesozoic sedimentation (*abstract*). *Halifax: The Atlantic Geoscience Society Symposium, Basins of Eastern Canada and Worldwide Analogues*, p. 28.
- Chowns, T.M. and Williams, C.T. 1983. Pre-Cretaceous rocks beneath the Georgia Coastal Plain — regional implications. *In: Gohn, G.S. (Ed.), Studies Related to the Charleston, South Carolina, Earthquake of 1886 — Tectonics and Seismicity*. United States Geological Survey Professional Paper 1313, p. L1-L42.

- Cloos, E. and Pettijohn, F. J. 1973. Southern border of the Triassic basin, west of York, Pennsylvania: Fault or overlap? *Geological Society of America, Bulletin*, v. 84, p. 523-536.
- Cook, F. A., Albaugh, D. S., Brown, L. D., Kaufman, S., Oliver, J. E. and Hatcher, R. D., Jr. 1979. Thin-skinned tectonics in the crystalline southern Appalachians: COCORP seismic-reflection profiling of the Blue Ridge and Piedmont. *Geology*, v. 7, p. 563-567.
- _____, Brown, L. D., Kaufman, S. and Oliver, J. E. 1983. The COCORP seismic reflection traverse across the southern Appalachians. *Tulsa: American Association of Petroleum Geologists, Studies in Geology* no. 14, 61p.
- Cornet, B., Traverse, A. and McDonald, N. G. 1973. Fossil spores, pollen, and fishes from Connecticut indicate Early Jurassic age for part of the Newark Group. *Science*, v. 182, p. 1243-1247.
- Cramer, H. R. 1969. Structural features of the coastal plain of Georgia. *Southeastern Geology*, v. 10, p. 111-123.
- Daniels, D. L., Zietz, I. and Popenoe, P. 1983. Distribution of subsurface lower Mesozoic rocks in the Southeastern United States as interpreted from regional aeromagnetic and gravity maps. *In: Gohn, G.S. (Ed.), Studies Related to the Charleston, South Carolina, Earthquake of 1886 — Tectonics and Seismicity. United States Geological Survey Professional Paper 1313*, p. K1-K24.
- de Charpal, O., Montadert, L., Guennoc, P. and Roberts, D.G. 1978. Rifting, crustal attenuation and subsidence in the Bay of Biscay. *Nature*, v. 275, p. 706-711.
- Dillon, W. P., Klitgord, K. D. and Paull, C. K. 1983. Mesozoic development and structure of the continental margin off South Carolina. *In: Gohn, G.S. (Ed.), Studies Related to the Charleston, South Carolina, Earthquake of 1886 — Tectonics and Seismicity. United States Geological Survey Professional Paper 1313*, p. N1-N16.
- Dooley, R. E. and Wampler, J. M. 1983. Potassium-argon relations in diabase dikes of Georgia: the influence of excess ^{40}Ar on the geochronology of early Mesozoic igneous and tectonic events. *In: Gohn, G. S. (Ed.), Studies Related to the Charleston, South Carolina, Earthquake of 1886 — Tectonics and Seismicity. United States Geological Survey Professional Paper 1313*, p. M1-M24.
- Effimoff, I. and Pinezich, A. R. 1981. Tertiary structural development of selected valleys based on seismic data: Basin and Range province, northeastern Nevada. *Philosophical Transactions of the Royal Society of London, Series A*, v. 300, p. 435-442.
- Faust, G. T. 1975. A review and interpretation of the geologic setting of the Watchung Basalt flows, New Jersey. *United States Geological Survey Professional Paper 864-A*, 42 p.
- Froelich, A. J. and Olsen, P. E. 1985. Newark Supergroup, a revision of the Newark Group in eastern North America. *In: Robinson, G.R. and Froelich, A.J. (Eds.), Proceedings of the Second United States Geological Survey Workshop of the Early Mesozoic Basins of the Eastern United States, United States Geological Survey Circular 946*, p. 1-3.
- Gans, P. B., Miller, E. L., McCarthy, J. and Ouldcott, M.L. 1985. Tertiary extensional faulting and evolving ductile-brittle transition zones in the northern Snake Range and vicinity: new insights from seismic data. *Geology*, v. 13, p. 189-193.
- Gohn, G. S. 1983. Geology of the basement rocks near Charleston, South Carolina — data from detrital rock fragments in lower Mesozoic (?) rocks in Clubhouse Crossroads test hole #3. *In: Gohn, G. S. (Ed.), Studies Related to the Charleston, South Carolina, Earthquake of 1886 — Tectonics and Seismicity. United States Geological Survey Professional Paper 1313*, p. E1-E22.
- _____, Gottfried, D., Lanphere, M. A. and Higgins, B. B. 1978. Regional implications of Triassic or Jurassic age for basalt and sedimentary red beds in the South Carolina Coastal Plain. *Science*, v. 202, p. 887-890.
- Gottfried, D., Ansell, C. S. and Byerly, G. R. 1983. Geochemistry and tectonic significance of subsurface basalts near Charleston, South Carolina: Clubhouse Crossroads test holes #2 and #3. *In: Gohn, G.S. (Ed.), Studies Related to the Charleston, South Carolina, Earthquake of 1886 — Tectonics and Seismicity. United States Geological Survey Professional Paper 1313*, p. A1-A19.
- Grierson, G.C. 1986. The structural and stratigraphic evolution of the Fundy basin half-graben (*abstract*). *Halifax: The Atlantic Geoscience Society Symposium, Basins of Eastern Canada and Worldwide Analogues*, p. 52.
- Hamilton, R. M., Behrendt, J. C. and Ackermann, H. D. 1983. Land multichannel seismic reflection evidence for tectonic features near Charleston, South Carolina. *In: Gohn, G.S. (Ed.), Studies Related to the Charleston, South Carolina, Earthquake of 1886 — Tectonics and Seismicity. United States Geological Survey Professional Paper 1313*, p. I1-I18.
- Hinze, W. J. and Wold, R. J. 1982. Lake Superior geology and tectonics - overview and major unsolved problems. *In: Wold, R. J. and Hinze, W. J. (Eds.), Geology and Tectonics of the Lake Superior Basin. Geological Society of America, Memoir 156*, p. 273-280.
- Hutchinson, D. R., Grow, J. A., Klitgord, K. D. and Swift, B. A. 1982. Deep structure and evolution of the Carolina trough. *In: Watkins, J. S. and Drake, C.L. (Eds.), Studies in Continental Margin Geology. American Association of Petroleum Geologists, Memoir 34*, p. 129-154.
- _____, Klitgord, K. D. and Detrick, R. S. 1986. Rift basins of the Long Island platform. *Geological Society of America, Bulletin*, v. 97, p. 688-702.
- Kaye, C. A. 1983. Discovery of a Late Triassic basin north of Boston and some implications as to post-Paleozoic tectonics in northeastern Massachusetts. *American Journal of Science*, v. 283, p. 1060-1079.
- Keen, C. E., Mudford, B. and Stockmal, G. S. 1986. Extensional models for the Grand Banks basin: new insights based on deep seismic reflection results (*abstract*). *Halifax: The Atlantic Geoscience Society Symposium, Basins of Eastern Canada and Worldwide Analogues*, p. 60.
- Keppie, J.D. 1982. The Minas Geofracture. *In: St-Julien, P. and Bland, J. (Eds.), Major Structural Zones and Faults of the Northern Appalachians. Geological Association of Canada, Special Paper 24*, p. 263-280.
- Klitgord, K. D., Dillon, W. P. and Popenoe, P. 1983. Mesozoic tectonics of the Southeastern United States Coastal Plain and continental margin. *In: Gohn, G.S. (Ed.), Studies Related to the Charleston, South Carolina, Earthquake of 1886 — Tectonics and Seismicity. United States Geological Survey Professional Paper 1313*, p. P1-P15.
- Lanphere, M. A. 1983. $^{40}\text{Sr}/^{39}\text{Ar}$ ages of basalt from Clubhouse Crossroads test hole #2, near Charleston, South Carolina. *In: Gohn, G.S. (Ed.), Studies Related to the Charleston, South Carolina, Earthquake of 1886 — Tectonics and Seismicity. United States Geological Survey Professional Paper 1313*, p. B1-B8.
- Lindholm, R. C. 1977. The Culpeper basin, Virginia: a case study in which Triassic tectonic patterns were inherited from preexisting structural fabrics (*abstract*). *Geological Society of America, Abstracts with Programs*, v. 9, p. 1070.
- _____. 1978. Triassic-Jurassic in eastern North America — a model based on pre-Triassic structures. *Geology*, v. 6, p. 365-368.
- Lister, G. S., Etheridge, M. A. and Symonds, P. A. 1986. Detachment faulting and the evolution of passive continental margins. *Geology*, v. 14, p. 246-250.
- Maher, J. C. 1971. Geologic framework and petroleum potential of the Atlantic Coastal Plain and continental shelf. *United States Geological Survey Professional Paper 659*, 98p.
- Manspeizer, W., Puffer, J. H. and Cunsminer, H. L. 1978. Separation of Morocco and eastern North America: a Triassic-Liassic stratigraphic record. *Geological Society of America, Bulletin*, v. 89, p. 901-920.
- Marine, I. W. and Siple, G. E. 1974. Buried Triassic basin in the central Savannah River area, South Carolina and Georgia. *Geological Society of America, Bulletin*, v. 85, p. 311-320.
- McBride, J. H., Nelson, K. D. and Brown, L. D. (*in press*). Evidence for an extensive basalt/diabase horizon beneath the Southeast Coastal Plain: implications for Mesozoic rifting. *Geological Society of America, Bulletin*.
- McKenzie, D. 1978. Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters*, v. 40, p. 25-32.
- Nelson, K. D., Arnow, J. A., McBride, J. H., Willemin, J. H., Huang, J., Zheng, L., Oliver, J. E., Brown, L. D. and Kaufman, S. 1985a. New COCORP profiling in the southeastern United States. Part I: Late Paleozoic suture and Mesozoic rift basin. *Geology*, v. 13, p. 714-718.
- _____, McBride, J. H., Arnow, J. A., Oliver, J. E., Brown, L. D. and Kaufman, S. 1985b. New COCORP profiling in the southeastern United States. Part II: Brunswick and east coast magnetic anomalies, opening of the north-central Atlantic Ocean. *Geology*, v. 13, p. 718-721.
- Odom, A. L. and Hatcher, R. D., Jr. 1980. A characterization of faults in the Appalachian foldbelt. *United States Nuclear Regulatory Commission Report CR-1621*, 314p.

- Pegrum, R. M. and Mounteney, N. 1978. Rift basins flanking North Atlantic Ocean and their relation to North Sea area. *American Association of Petroleum Geologists, Bulletin*, v. 62, p. 419-441.
- Petersen, T. A., Brown, L. D., Cook, F. A., Kaufman, S. and Oliver, J. E. 1984. Structure of the Riddleville basin from COCORP seismic data and implications for reactivation tectonics. *Journal of Geology*, v. 92, p. 261-271.
- Popenoe, P. and Zietz, I. 1977. The nature of the geophysical basement beneath the Coastal Plain of South Carolina and northeastern Georgia. *In: Rankin, D.W. (Ed.), Studies Related to the Charleston, South Carolina, Earthquake of 1886 — A Preliminary Report*. United States Geological Survey Professional Paper 1028, p. 119-137.
- Rosendahl, B. R., Burgess, C. F., Sander, S. and Lambiase, J. 1986. Structural symptoms of continental rifting (*abstract*). *American Association of Petroleum Geologists, Bulletin*, v. 70, p. 641.
- Schamel, S., Ressetar, R., Gawarecki, S., Taylor, G. K., Traverse, A., Houghton, H. F. and Letourneau, P. 1986. Early Mesozoic rift basins of eastern United States (*abstract*). *American Association of Petroleum Geologists, Bulletin*, v. 70, p. 644.
- Schilt, F. S., Brown, L. D., Oliver, J. E. and Kaufman, S. 1983. Subsurface structure near Charleston, South Carolina — results of COCORP reflection profiling in the Atlantic Coastal Plain. *In: Gohn, G.S. (Ed.), Studies Related to the Charleston, South Carolina, Earthquake of 1886 — Tectonics and Seismicity*. United States Geological Survey Professional Paper 1313, p. H1-H19.
- Sclater, J. G. and Christie, P. A. F. 1980. Continental stretching: an explanation of the post-mid-Cretaceous subsidence of the Central North Sea basin. *Journal of Geophysical Research*, v. 85, p. 3711-3739.
- Smith, W. A., Talwani, P. and Colquhoun, D. J. 1986. Geophysical and geological investigation of buried Triassic (?) rift basin in Coastal Plain of South Carolina (*abstract*). *American Association of Petroleum Geologists, Bulletin*, v. 70, p. 650.
- Sutter, J. F. 1985. Progress on geochronology of Mesozoic diabases and basalts. *In: Robinson, G. R. and Froelich, A. J. (Eds.), Proceedings of the Second United States Geological Survey Workshop of the Early Mesozoic Basins of the Eastern United States*. United States Geological Survey Circular 946, p. 110-114.
- Swanson, M. T. 1982. A possible complex decoupling history for Mesozoic rifting (*abstract*). *Geological Society of America, Abstracts with Programs*, v. 14, p. 88.
- 1986. Preexisting fault control for Mesozoic basin formation in eastern North America. *Geology*, v. 14, p. 419-422.
- Van Houten, F. B. 1969. Late Triassic Newark Group, north-central New Jersey and adjacent Pennsylvania and New York. *In: Subitzky, S. (Ed.), Geology of Selected Areas in New Jersey and Eastern Pennsylvania*. New Brunswick: Rutgers University Press, p. 314-347.
- Williams, H. and Hatcher, R. D., Jr. 1983. Appalachian suspect terranes. *In: Hatcher, R. D., Jr., Williams, H. and Zietz, I. (Eds.), Contributions to the Tectonics and Geophysics of Mountain Chains*. Geological Society of America, Memoir 158, p. 33-54.
- and McBirney, A. R. 1979. *Volcanology*. San Francisco: Freeman, Cooper and Co., p. 266-272.
- Wise, D. U. and Robinson, P. 1982. Tectonics of the Mesozoic Connecticut Valley graben (*abstract*). *Geological Society of America, Abstracts with Programs*, v. 14, p. 96.
- Yantis, B. R., Costain, J. K. and Ackermann, H.D. 1983. A reflection seismic study near Charleston, South Carolina. *In: Gohn, G. S. (Ed.), Studies Related to the Charleston, South Carolina, Earthquake of 1886 — Tectonics and Seismicity*. United States Geological Survey Professional Paper 1313, p. G1-G20.