

CONSTRAINTS ON THE STRUCTURE AND TECTONIC DEVELOPMENT OF THE EARLY MESOZOIC SOUTH GEORGIA RIFT, SOUTHEASTERN UNITED STATES; SEISMIC REFLECTION DATA PROCESSING AND INTERPRETATION

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Abstract. Seismic reflection data collected by the Consortium for Continental Reflection Profiling (COCORP) over the buried Triassic-Jurassic South Georgia rift, reprocessed in order to improve the upper 5 s of reflection time, provide a window into the regional deep structure of the rift and delineate variations in basin structure and depositional styles. Located at the southernmost extent of the North American east coast early Mesozoic rift system, the structure of the South Georgia rift basin has previously been known only from scattered drilling and potential field interpretation, leaving the internal and boundary, as well as the deep, structure unknown. The reflection data reveal that the South Georgia basin consists of a broad, complex terrane of isolated synrift grabens with intervening structural highs, in contrast with earlier concepts of a single narrow trough or an amorphous "sag" basin. Two main subbasin depocenters are observed in west and west central Georgia, the largest of which is more than 100 km in width, and the deepest at least 7 km at its inferred base. Analysis of the reflection data indicates that the distinct structural and seismic-stratigraphic character of the reflection packages is analogous to other, better studied extensional provinces (e.g., North American Basin and Range). The reprocessing of the reflection data provides a view of contrasting styles of faulting and subsidence within the rift. The structural style of the subbasins varies drastically along strike, changing from (1) a narrow asymmetric graben bordered by a planar and more deeply penetrating normal fault to (2) a broad and roughly symmetric graben bordered by a shallower-dipping, possibly listric fault, along which extension may have been accommodated at depth by a low-angle detachment or by a more complex system of high-angle faults. Only limited crustal extension is suggested by the narrower graben and planar fault (1), whereas much greater extension would be

expected from the wider graben bordered by a listric/low-angle fault (2). Such a dual style of basin formation is predicted by segmented plate models of variable extension along continental margins and intracratonic rifts, and may imply a significant change in crustal rheology along the developing rift. Integration of the interpretation of the regional structure of the South Georgia basin with that of the deeper crustal structure, as inferred from the 16-s (reflection time) COCORP data, indicates that the synrift basins developed mainly over the "upper plate" of the Alleghanian (late Paleozoic) suture between North America and west Africa. The major subbasin border faults dip northward in an antithetic relation to the predominantly northward vergence of the suture zone. The border faults thus do not appear to have reactivated antecedent structure. Although the development of the South Georgia rift appears to have approximately coincided with early Mesozoic thinning of the crust in the southeastern United States, no horizontally "layered" or "laminated" lower crust is observed as has been associated with other, more fully rifted terranes (e.g., North American Basin and Range; continental shelf around British Isles). However, the Moho discontinuity appears to have formed as a dynamic feature superimposed on late Paleozoic compressional structure probably associated with early Mesozoic rifting. These findings thus support the interpretation that the South Georgia rift developed as a major early Mesozoic depocenter and possible incipient spreading center associated with the initial formation of the central Atlantic Ocean.

INTRODUCTION

COCORP (Consortium for Continental Reflection Profiling) seismic reflection profiles across the Georgia (United States) Coastal Plain provide a view into the deep structure and seismic stratigraphy of the buried Triassic-Jurassic South Georgia rift. Originally collected at a correlated record length of 16 s (seconds, reflection travel time) [Nelson et al., 1985], the upper 5 s have been reprocessed in order to emphasize and better delineate fault structure and style, internal basin form, and regional basin geometry. Knowledge of the South Georgia basin has previously been restricted to drill hole penetrations through the overlying Cretaceous-Tertiary Coastal Plain sequence into the uppermost part of the lower Mesozoic section and to inferences from potential field data [Maher, 1971; Neathery and Thomas, 1975; Popenoe and Zietz, 1977; Gohn et al., 1978; Chowns and Williams, 1983; Daniels et al., 1983; Thomas et al., 1989]. Understanding of the interior and boundary structure as well as of the location and dimensions of the main depocenters remains limited.

This study presents the results of COCORP's reflection surveys over the South Georgia rift and addresses questions of early Mesozoic rift structure and development in the southeastern United States: (1) is the South Georgia basin an amorphous "sag"

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basin lacking any major structural control; (2) can we distinguish various early Mesozoic faulting episodes that have occurred within the rift; (3) if major faulting is present, what is its structural style (e.g., involving planar or listric faults; or subhorizontal detachments?); (4) what relation, if any, is there between early Mesozoic normal faults and antecedent structure; (5) what is the evidence for extension within the rift and how much along-strike variability exists; (6) what implications can be drawn from the reflection data for the rheological behavior of the crust during rifting (e.g., pure versus simple shear?); (7) how did the development of rifting in the upper crust relate to modification of lower crustal structure (e.g., the Moho discontinuity); (8) how does rift basin structure relate to the three-dimensional crustal structure of the dipping reflection zone within the Alleghanian suture and thus to late Paleozoic plate convergence.

REGIONAL STRATIGRAPHIC AND STRUCTURAL SETTING

The South Georgia rift [Daniels et al., 1983] lies near the southern end of the string of narrow, elongate, early Mesozoic rift basins that stretches from Nova Scotia southward along the east coast of North America (Figure 1). East coast basins occur in the exposed Appalachian Piedmont [e.g., Sanders, 1963; Cloos and Pettijohn, 1973; Fail, 1973; Faust, 1975; Lindholm et al., 1979; Manspeizer and Cousminer, 1988], buried beneath the Atlantic Coastal Plain [e.g., Marine and Siple, 1974; Stephenson and Chapman, 1988], and offshore [e.g., Hutchinson et al., 1986, 1988; Klitgord et al., 1988]. The South Georgia basin is unique among these in that it is centered between North American Grenville basement exposed in the Appalachian Piedmont (Pine Mountain belt) [Sears and Cook, 1984] and relict

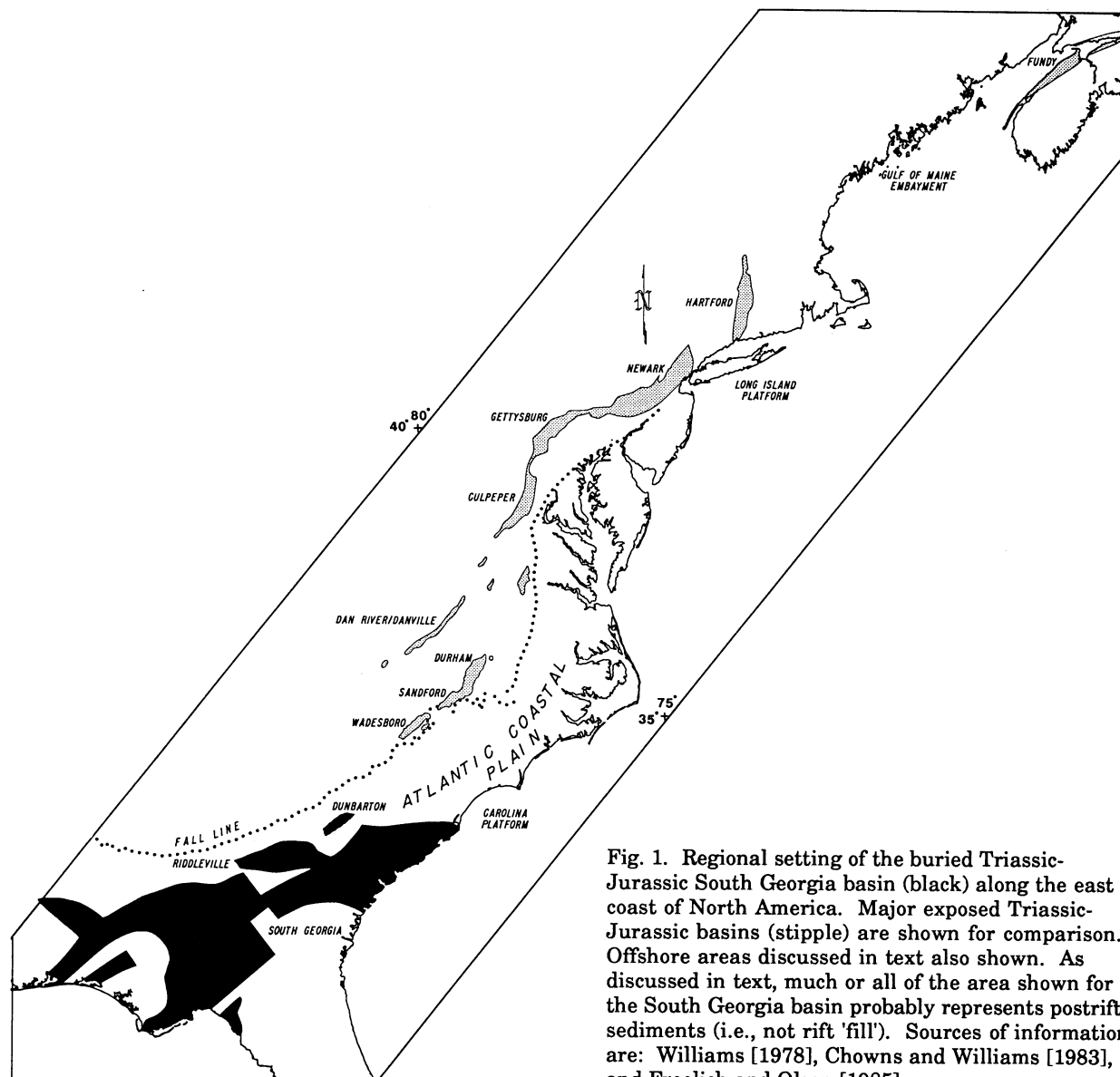


Fig. 1. Regional setting of the buried Triassic-Jurassic South Georgia basin (black) along the east coast of North America. Major exposed Triassic-Jurassic basins (stipple) are shown for comparison. Offshore areas discussed in text also shown. As discussed in text, much or all of the area shown for the South Georgia basin probably represents postrift sediments (i.e., not rift 'fill'). Sources of information are: Williams [1978], Chowns and Williams [1983], and Froelich and Olsen [1985].

west African crust (Paleozoic "Suwannee terrane") underlying northern Florida and southernmost Georgia [Cramer, 1971; Mueller and Porch, 1983; Smith, 1983; Dallmeyer et al., 1987] (Figure 2). From a regional paleogeographic perspective the basin appears to have aspects of both a rifted continental margin and an intracontinental rift or aulacogen [e.g., Burke, 1980]. Many workers have attempted to interpret the formation of the South Georgia rift as an aborted extension of the Gulf of Mexico and/or the central Atlantic Ocean [e.g., Woods and Addington, 1973; Barnett, 1975; Pilger, 1978; Smith, 1983; Manspeizer, 1985; Pindell, 1985; Salvador, 1987].

Extensive studies in exposed Newark-type basins have yielded a typical maximum basin-fill thickness of about 6.0 km [Van Houten, 1977; Marine and Siple, 1974], with dominant rock types being fluviolacustrine mudstone, sandstone, and coarse-grained arkosic sandstone and conglomerate [Randazzo et al., 1970; Thayer, 1971; Fail, 1973; Lindholm et al., 1979; Lorenz, 1988]. Evidence for a Triassic-Jurassic age of the buried South Georgia basin is largely inferential and is based mainly on the general lithologic similarity of arkosic sandstones and mafic igneous rocks encountered in drill holes below the Coastal Plain sequence as compared with equivalent rocks of the Newark Supergroup or Eagle Mills Formation [Barnett, 1975;

Gohn et al., 1978; Miller, 1982; Chowns and Williams, 1983; Gohn, 1983; Lanphere, 1983; Smith, 1983].

The structural style of early Mesozoic east coast basins typically consists of a single master normal fault with an asymmetric graben in the hanging wall [Marine and Siple, 1974; Swanson, 1986; Hatcher et al., 1988]. The master normal fault characteristically dips seaward [e.g., Swanson, 1986] although exceptions exist [Ratcliffe and Newell, 1986]. It has long been recognized that the trend of the basins follows general Appalachian structural trends (for a review see Swanson [1986]; and de Boer et al. [1988]). Mesozoic basin-border faults appear to follow older Paleozoic foliations and faults and in some cases reactivation of Paleozoic or older structure is well documented on the basis of surface geology [Ratcliffe, 1971; Lindholm, 1978; Ratcliffe and Burton, 1985; Ratcliffe et al., 1986] or inferred from seismic reflection data [e.g., Petersen et al., 1984; Ratcliffe et al., 1986; Grierson et al., 1987; Nelson et al., 1987a; Hutchinson et al., 1988]. Where mapped in the field, early Mesozoic basin normal faults dip 60°-90° and in some instances have been suggested to flatten with depth in a listric style [Odom and Hatcher, 1980; Hatcher et al., 1988]. From geophysical observations a broad range of fault structural styles and dip angles has been described;

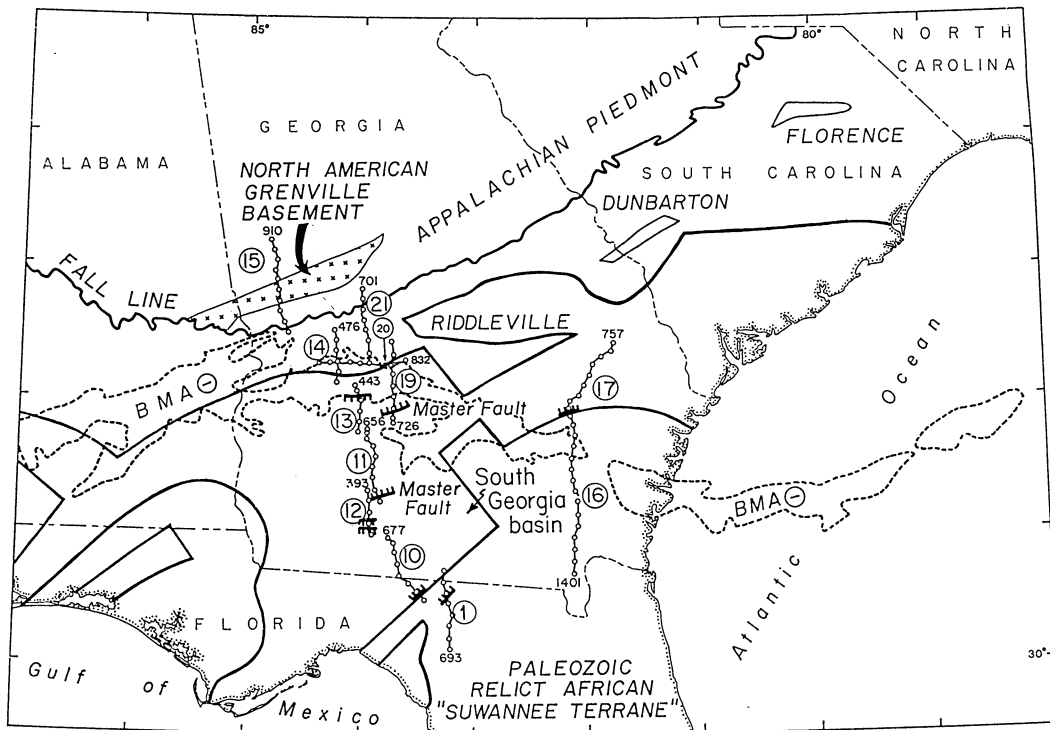


Fig. 2. Triassic-Jurassic subcrop map of the South Georgia basin (outline shown as heavy line), as based on drill hole data from Chowns and Williams [1983], showing location of COCORP seismic reflection surveys discussed in this report. Vibrator stations are marked by small open circles along the survey lines at every hundredth point. Vibrator station

numbers are posted at the end of each line. Also shown as toothed brackets are major faults inferred from the reflection data with the two principal interpreted master normal faults within the basin indicated. Selected total magnetic intensity contours (dashed) show trend of Brunswick magnetic anomaly minimum (BMA) [from Zietz, 1982].

both low-angle detachments and more deeply penetrating normal faults are proposed as dominant basin-forming structures [e.g., see Ratcliffe et al., 1986; Keen et al., 1987].

Although the interpretation of the South Georgia basin as an early Mesozoic feature is generally accepted, few drill holes have tested the deeper structure of the basin [e.g., Chowns and Williams, 1983]. Results from industry seismic reflection and drill hole data over the Florida panhandle suggest that at least the southernmost portion of the basin was block faulted and subsided along northeast striking normal faults [Arden, 1974; Barnett, 1975; Miller, 1982; Smith, 1983]. Earlier results derived from COCORP reflection data in the Riddleville portion of the South Georgia basin (Figure 2) delineated a relatively small (2-3 km maximum thickness; ~15 km apparent width) half-graben with a well-formed master normal fault [Petersen et al., 1984]. Line drawing interpretations of unmigrated regional reflection surveys presented by Behrendt [1986] across the basin in southeastern Georgia and

South Carolina show the occasional presence of small isolated rift basins below the base of the Coastal Plain sequence.

DATA ACQUISITION AND PROCESSING

The survey source, recording, and data processing parameters for the COCORP reflection data are given in Table 1 and Table 2. The Vibroseis™ seismic reflection surveys were carried out over local roads using four or five in-line vibrators with a station interval of ~100.6 m (330 ft). An upsweep of 8-32 Hz was used to generate the source in 8 or 16 sweeps per station sampled at 8 ms to produce a total correlated record length of 16 s. The data were recorded using off-end or asymmetric split (12/84) geophone spreads with a maximum far-offset of almost 10 km and a nearest group offset of three or four vibrator stations. Stacking fold is nominally 48.

The role of data processing and reprocessing has been critical in the interpretation of the reflection

TABLE 1. Seismic Data Acquisition Parameters

Acquisition Parameter	Specification
Date recorded	1983-1984 (line 19: 1985)
Recording system	MDS-10
Number of channels	96
Geophone group spacing	~100.6 m (330 feet)
Anti-alias filter	31.25 Hz
Sample rate	generally 8 ms/sample
Sweep frequencies	8-32 Hz (line 19: 10-32 Hz); upsweep
Sweeps/VP	16 (line 19: 8)
Correlated record length	16 s
Source	4 or 5 Vibrators, in line at ~15.2 m (50 feet) separation
Source spacing	~100.6 m (330 feet)
Source/nearest receiver offset	3 stations (~301.8 m) (990 feet)
Source/furthest receiver offset	~9858.8 m (32,350 feet); line 19: ~8349.8 m (27,400 feet)
Receiver spread configuration	off-end; line 19 asymmetric split (12/84 stations)

TABLE 2. Seismic Data Processing Parameters

Processing and Testing	Parameters
Demultiplex	
Vibroseis™ correlation	8-32 Hz sweep; correlated record length: 16 s
Elevation statics	Elevation datum = 100 m (~328 feet); static velocity = 2 km/s (~6563 feet/s)
CDP sort and gather	CDP spacing = ~50.3 m (165 feet)
Adjacent trace amplitude balance	1500 ms window; average amplitude of 1.0
Velocity analysis	Generally determined every ~50 CDPs on basis of semblance and velocity scans
Normal moveout correction	
Variable front mute	Maximum cut = 3500 ms at 10,000 m (~32,815 feet); every ~ 50 CDPs
CDP stack	Nominal fold = 48
Autocorrelation analysis	
Noise spike removal (depulsing)	
Deconvolution	4 s autocorrelation window; 250 ms operator length, 48 ms lag (gap)
Bandpass frequency filter	10-32 Hz
Noise spike removal (depulsing)	
Wave equation migration	Maximum allowed angle = 40°; variable velocity
Coherency filter	see Zheng and Brown [1986]
Display	Variable area, no wiggle, and zero trace bias = 40 %; V.E. = 2:1 at 3.0 km/s

data and would require a separate paper to discuss fully; only the most important aspects affecting the interpretation are outlined here. Data processing for this study was designed to enhance mainly the upper 5 or 6 s. Processing consisted of a routine sequence of steps (Table 2; see Zhu and Brown [1986] for a review of typical processing applied to similar data) but also included detailed time-space varying velocity analysis and variable muting, band-pass frequency filtering, deconvolution, wave equation migration, and coherency filtering. The complexly reflective upper 3 to 6 s of the data necessitated detailed and closely spaced stacking velocity analyses (e.g., every 50 common depth points (CDPs)—4 per spread length—on line 11) (Figure 3), and muting of direct waves, refractions, CDP stretch, and correlation noise. Depth conversion for individual reflections was carried out using interval velocities derived from stacking velocities by the Dix formula. The flat-lying sequence of continuous reflectors in the upper 1 s was problematic in generating local velocity inversions and short-path and low-velocity long-path multiples that propagate throughout the seismic section (Figures 4 and 5). Most long-path multiples (e.g., Figure 5) were attenuated by the normal move-out correction and deconvolution. In order to attack the problem of short-path multiples, several deconvolution parameter trials were designed from autocorrelations by varying the lag time (travel time to second zero-crossing in autocorrelation function) between 48 and 100 ms (Figure 4). Both prestack and poststack deconvolution applications were tested (Table 2). Due possibly to noise and the complexity of the multiples (Figure 5), deconvolution applied poststack produced superior results over prestack.

Seismic time migrations were applied to CDP-stacked sections using a smoothed time-space varying velocity function based on interval velocities derived from stacking velocities (e.g., Figure 3). Migration was a particularly necessary step due to the possibility of artifacts produced on unmigrated

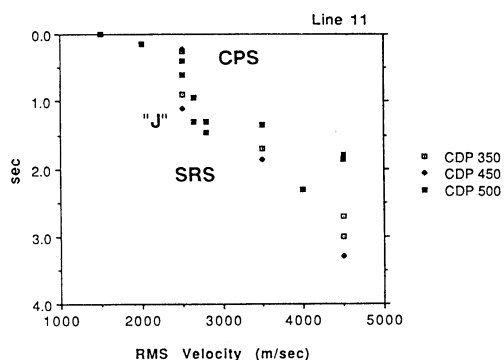


Fig. 3. Scatter diagram of P wave stacking velocities for the central portion of Georgia seismic line 11. Note the distinct lower velocity character of the Coastal Plain sequence (CPS; 0- ~ 0.9 s) overlying the synrift sequence (SRS), with the two being separated by the basalt/diabase J reflection (at ~1.3 s). This distribution indicates only the relative trend of velocity and not absolute rock velocity.

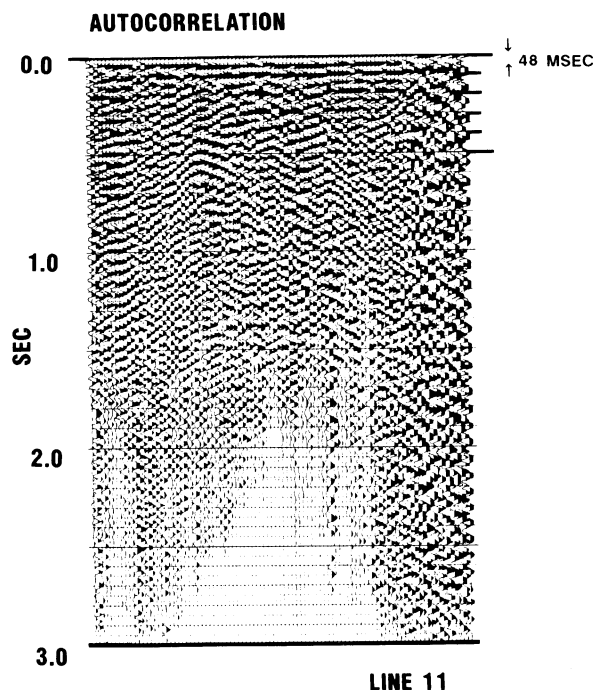


Fig. 4. Seismic autocorrelation (correlation of a wavelet with itself) from southern part of Georgia line 11 showing periodic presence of contamination by multiple reflections (e.g., propagating from ~50 ms to ~1500 ms) from the Coastal Plain sequence (0-~ 0.9 s). For this study, autocorrelation computations were used for identifying multiples and designing multiple-suppression deconvolution parameters. In this case, a lag time of 48 ms was used for a deconvolution.

data by steep vertical velocity gradients associated with faults [e.g., Withjack and Pollock, 1983; Unger, 1988; Allen and Brusca, 1989]. In cases of poorer data quality, migration was not feasible and the sections were analyzed unmigrated (lines FL-1, GA-16A, and GA-17). A coherency enhancement filter developed at Cornell University [Zheng and Brown, 1986] was applied to the migrated sections. This processor involves slant stacking within a sliding window and then, in order to reduce artifacts, modifying the processed stack according to the intertrace coherence with the original section. Finally, display parameters were chosen so as to lower the background gain while brightening higher relative amplitude events. The net result of the additional processing has been to improve the accuracy and interpretability of the original sections [cf. Nelson et al., 1985; 1987b].

RESULTS AND INTERPRETATION

Recognition of General Reflection Sequences

The reflection data comprise two main transects each over 300 km long across the western and eastern Georgia portions of mapped South Georgia

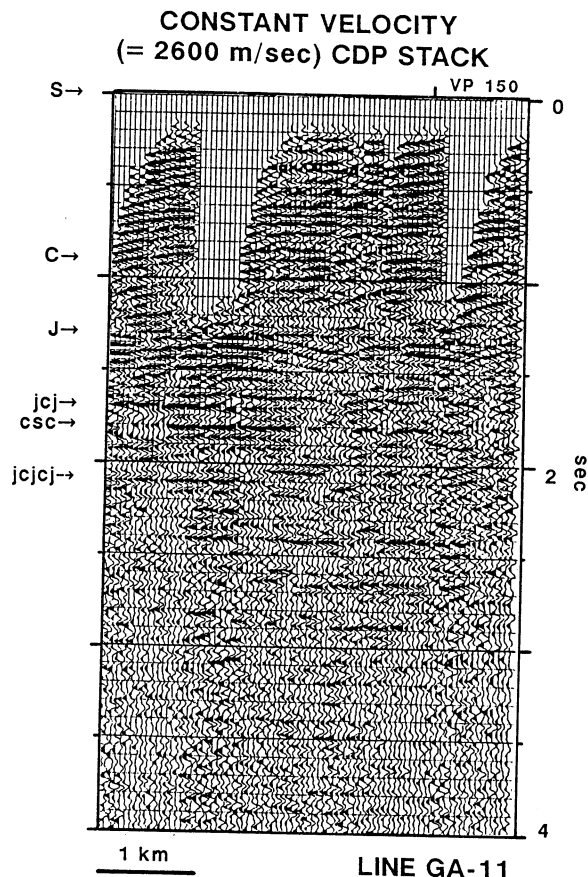


Fig. 5. Example of a constant-stacking-velocity section (nondeconvolved) from Georgia line 11 demonstrating severe problem of contamination from multiples generated mainly by the uniformly layered reflectors of the Coastal Plain sequence (0--0.9 s) and by the J reflector. Abbreviations are S, surface; C, base of Coastal Plain sequence primary; J, basalt/diabase primary; jcj, multiple from path between C and J; and so on.

basin subcrop (Figures 2, 6, and 7). Two additional lines are located about 50 km east of the western Georgia transect. Two gross seismic-stratigraphic sequences are easily recognized from the reflection data (e.g., Figures 6 and 8a). On all of the sections south of the Fall Line (landward extent of Cretaceous-Tertiary onlap) is a uniform and pervasive sequence of bright subhorizontal reflections in the upper ~1 s which, on the basis of drill hole data, can be associated with the Cretaceous-Tertiary (locally including Jurassic) Coastal Plain sequence (Figure 7) [Maher, 1971; Cramer, 1974; Popenoe and Zietz, 1977; Behrendt et al., 1983; Chowns and Williams, 1983; Cook et al., 1983; Gohn, 1988]. Below this sequence is a structurally and stratigraphically more complex and discontinuous reflection package that rests between ~1.2 and 4-5 s, maximum (Figures 6 and 7). This second, lower sequence is most dramatically developed on lines 11 (Figure 8a), 13 (Figure 8b), and 19 (Figure 9) and reaches a

maximum depth-converted thickness of 5-6 km (cf. Figures 10, 11, and 12).

Velocity analyses show that these two sequences each have a distinct velocity character (Figures 3 and 5), analogous to results from laboratory and seismic refraction studies for east coast Triassic basins in general [Bonini and Woollard, 1960; Antoine and Henry, 1965; Yantis et al., 1983; Petersen et al., 1984; Costain and Çoruh, 1988]. The two sequences are separated by a continuous and bright reflection (J) previously associated with Lower-Middle Jurassic basalt/diabase flows or sills in drill holes in South Carolina and Georgia [Schilt et al., 1983; McBride et al., 1989], which serves as a useful chronostratigraphic marker. As known for other parts of the South Georgia basin [e.g., Smith and Foley, 1988], some of the deeper bright reflections may also be related to mafic igneous bodies.

The well-developed reflectivity of the lower sequence below the J reflection contrasts sharply with the relatively non-reflective portions of the sections immediately to the south of the interpreted main basin depocenters (e.g., unreflective portions south of VP 40 on line 11 (Figure 8a); south of VP 670 on line 19, (Figure 9); and throughout line 12, (Figure 11)). Drillholes in western Georgia that penetrate the base of the Coastal Plain sequence in the vicinity of lines 11, 12, 13, 17, 19, and FL-1 encounter a sequence of basalt, diabase, and/or terrigenous clastic rocks of inferred Triassic-Jurassic age [Chowns and Williams, 1983] (Figure 2) which would probably be more reflective internally than older Paleozoic "basement" [Cook et al., 1983; Petersen et al., 1984; Behrendt, 1986]. The reflective seismic stratigraphic package beneath the J reflection is postulated to represent the South Georgia basin Triassic-Jurassic assemblage [McBride et al., 1989], although it is possible (and perhaps probable?) that lower portions may include prerift material [e.g., Arden, 1974; Smith, 1982].

Western Georgia Transect (Lines GA-12, 11, 13, and FL-1)

The lower seismic stratigraphic sequence below the J reflection appears abruptly, beginning on the southern ends of lines 11 (Figure 8a) and 19 (Figure 9), reaches 3.0 s or more in time-depth, and then continues northward as a distinct package (Figure 6). The J reflection forms a flat, generally undisturbed bevel surface (i.e., as an angular unconformity) below which deeper basinal reflections are truncated. The most notable truncation feature on line 11 is at its southern end (Figure 8a, VP 50) where gently south dipping reflections R₁ and R₂ are cut by a shallow north dipping reflection, F₁₁. F₁₁ is interpreted to be a gently dipping (< 20°, apparent) basin-bounding normal fault, although, since the regional strike is unknown, the dip of this and other interpreted faults is only apparent so that the actual dip may be much greater. R₁ appears to be folded into a large rollover next to the bounding fault with concentric rollovers appearing deeper in the section

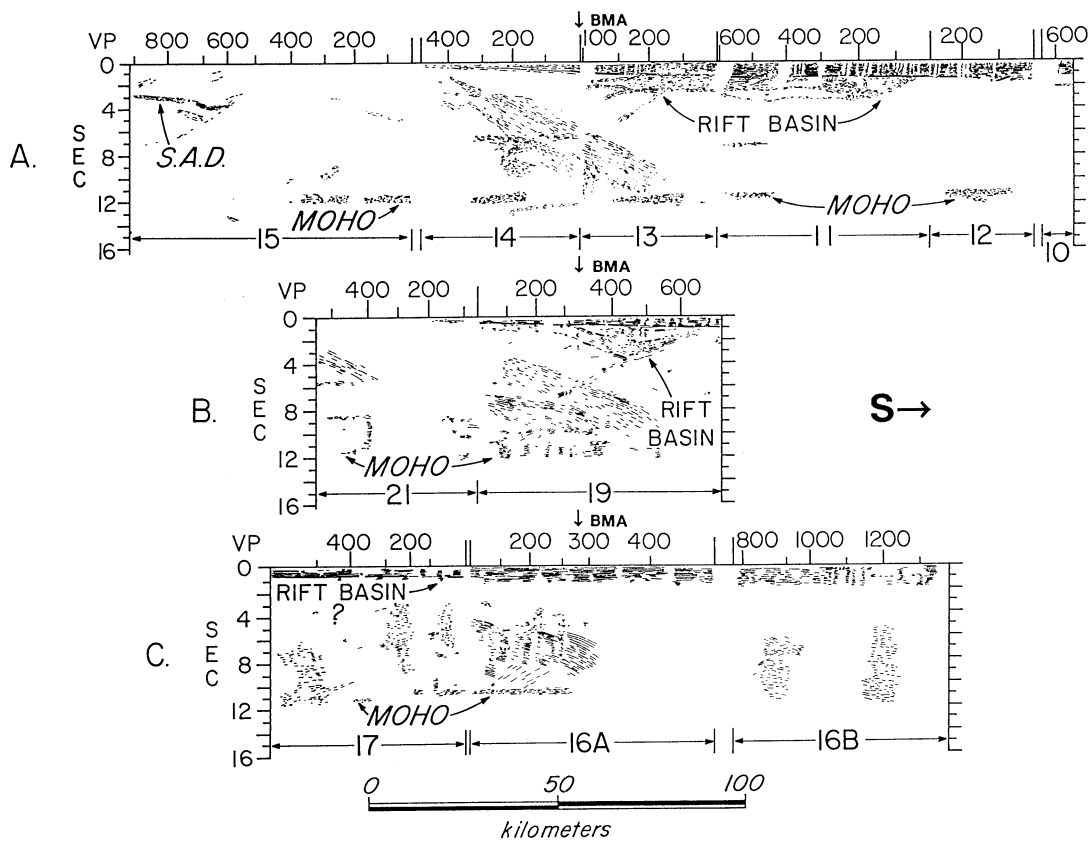


Fig. 6. Summary interpretive line drawings for the three COCORP deep seismic reflection (unmigrated) transects across the Georgia Coastal Plain (see Figure 2 for location): (a) lines 11-15, (b) lines 19 and 21, (c) lines 16A, 16B, and 17. Data are displayed from 0 to the full 16 s (two-way travel time) correlated record length. The broad, mainly south dipping reflection zone that extends from near the surface to the interpreted Moho discontinuity can be inferred to mark the deep crustal "root zone" of the Alleghanian (late Paleozoic) suture between North America and relict west Africa [e.g., Nelson et al., 1985]. S.A.D. is: Southern Appalachian detachment [Nelson et al., 1987a]. No vertical exaggeration using conversion velocity = 6.0 km/s.

along the fault (Figure 8a). Reflection R₂ is similar to R₁ but continues subhorizontally across the basin interior at 2.0 to 2.3 s. F₁₁ dips down to, and appears to merge with, reflection R₃, which can then be traced continuously along lines 11 and 13 as a subhorizontal, gently undulating surface for a total distance of about 100 km. R₃ occurs as deep as 3.3 s (~7.1 km) on line 11 (below VP 450) (Figure 8a) and as shallow as 1.9 s (~4.0 km) on the north end of line 13 (below VP 300) (Figure 8b) and forms the base of the reflective and/or coherent section (Figure 6). The F₁₁ border fault may become listric as it merges with the basal reflection R₃. An alternate interpretation for the border fault would be that F₁₁ continues deeper beneath the basin as a perfectly planar fault (dashed line in Figure 8a).

The basin sequence observed on line 11 can be traced northward onto line 13 (Figures 6, 8a, and 8b). As defined from the reflection data, the northern boundary of the basin on line 13 appears to be more complex than that on the southern end of line 11.

The multiple displacement and tilting of R₃ at the northern end of line 13 (Figure 8b) suggest that the northern boundary of the basin may have extended along more than one master fault. Below VP 270, R₃ intersects, and appears to continue downward as, a high-amplitude and coherent north dipping reflection, R₄ (Figure 8b).

Along the western Georgia transect the prominent basin sequence is restricted to lines 11 and 13. South of line 12, on Georgia line 10 and Florida line 1, no large, well-developed reflection packages are resolved below J. However, on the northern end of Florida line 1 (Figure 10) a south dipping reflection sequence appears below J and is abruptly truncated below VP 250 (Figure 2). This point approximately coincides with the southern boundary of the South Georgia basin as mapped from drilling (Figure 2). Although no fault plane reflection is imaged, a north dipping normal fault may be inferred from the southward fanning and downward truncation of basin reflections (Figure 10) and suggests that the

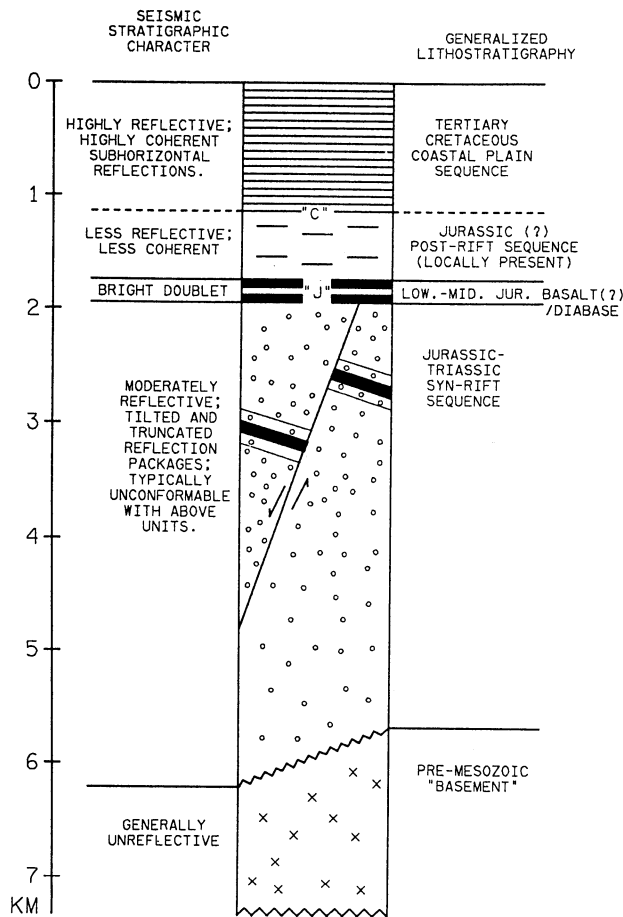


Fig. 7. Schematic representation of Mesozoic and Cenozoic sedimentary and igneous rocks of the South Georgia basin area as known from drill holes [Maher, 1971; Gohn et al., 1978; Chowns and Williams, 1983] and their observed seismic stratigraphic character. C is base of Coastal Plain Sequence; J is basalt/diabase reflector.

southern boundary of the basin in northern Florida is fairly simple and perhaps similar to the F₁₁ fault on line 11.

In addition to basin-bounding faults, smaller, late-stage faults affecting the rift sequence also occur. The entire rift basin sequence below the J reflection is offset by relatively minor faulting in a few places, most notably below VP 200 on line 11 (Figure 8a) and below VP 170 on line 13 (Figure 8b). The nature of these offsets appears to be steeper, postdating the formation of the main rift basin; these offsets do not cut the J reflection. Although the J reflection itself is generally not faulted, offsets do occur, most notably on line 12 below VP 50 and VP 100 (Figure 11). Here, faulting of the J reflector defines two small half-grabens (Figure 11), and reflections immediately above J appear flat and thus not related to synfaulting deposition of basin fill. The tilting of the J reflection on line 12 implies either rotation along a listric fault surface dipping

northward or a northward tilted series of planar domino-style faults; however, the deeper portions of the inferred faults are not imaged. On line 11, a small depression (depositional channel?) or half-graben involving J appears to be superimposed over the main basin sequence (Figure 8a). Dipping, high-amplitude reflections within this zone may be related to fault-contemporaneous sedimentation or perhaps ponding of a local lava flow [e.g., see Lindholm, 1977; Lindholm et al., 1979] as suggested by high seismic velocities in the interval. Therefore at least three episodes of early Mesozoic age faulting have occurred within the South Georgia rift beginning with the master normal fault phase (e.g., along fault plane reflector F₁₁) (i, Figure 13), followed late in the sequence by minor, steeper offsets of reflectors R₂ and R₃ (ii, Figure 13), and finally faulting and tilting of the J reflector which, from dating of the J basalt/diabase, must be post-Early-Middle Jurassic (iii, Figure 13).

West Central and Eastern Georgia Transects (Lines GA-19, 21/17, 16A)

A second set of north-south surveys, Georgia lines 19 and 21, extends over the northern edge of the South Georgia basin roughly paralleling lines 11 and 13 about 50 km east of the main transect (Figure 2). Line 19 (Figure 9) reveals a reflection package below the base of the Coastal Plain sequence with an apparent width of ~35 km and a travel time to the interpreted base of ~4.0 s (~7.0 km). The line 19 assemblage is defined by a south dipping set of reflections, B, which terminates sharply updip against the base of the Coastal Plain sequence and extends downdip towards a steeper, north dipping line of reflections, F. Reflections B are interpreted as strata deposited in an actively subsiding asymmetric basin bordered by a single master normal fault located just updip of reflections F. The definition of the boundary fault is complex and not as clear-cut as on line 11 with no single reflection standing out as the principal fault plane. The segmentation of F may be due to subsequent antithetic faulting, although complexities not accounted for in the migration could have produced poor imaging. In contrast to line 11, the interpreted fault plane on line 19 extends well below the level of the main basin to at least 4.5 s, possibly penetrating deeper to 6.5 s (~20 km) [McBride et al., 1987; Nelson et al., 1987b] (Figure 6), and no flattening of the fault with depth is inferred. On the eastern Georgia transect (lines 17, 16A; Figure 6), little or no synrift development is implied by the reflection data. Line 17 (Figure 2) delineates a possible thin, half-graben sequence bordered by an inferred north dipping normal fault below the base of the Coastal Plain sequence as defined by the southward fanning of events (Figure 12). This sequence occurs below the region of mapped Triassic-Jurassic sediments (Figure 2) and does not continue southward onto line 16A (Figure 12) where drill holes pass directly from the Coastal Plain sequence into a Pre-Cambrian/early Paleozoic felsic volcanic "basement" [Chowns and Williams, 1983].

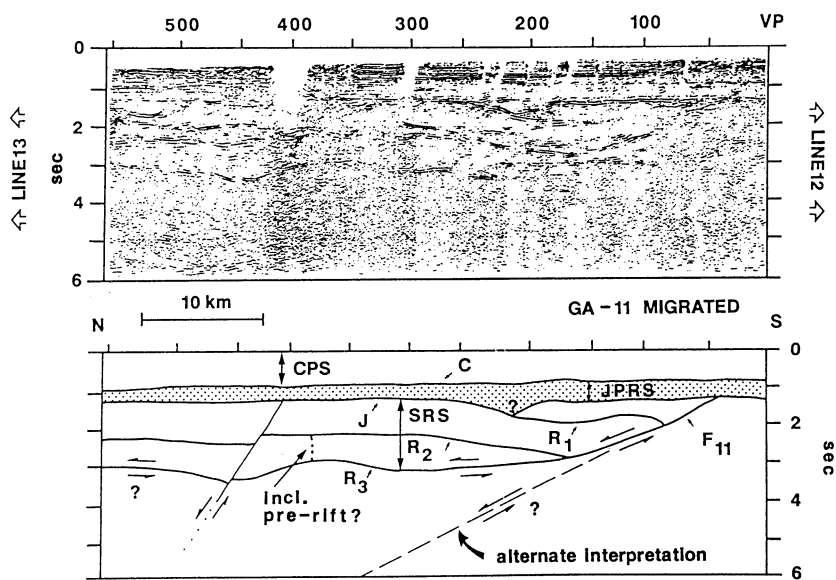


Fig. 8a. Migrated CDP section and interpretation of COCORP Georgia line 11 (see Figure 2 for location). Note the contrasting reflection character between the Coastal Plain sequence (CPS) and the interpreted synrift sequence (SRS). F₁₁ is interpreted master normal fault on southern portion of line 11 (see Figure 2). F₁₁ may continue deeper below the basin (dashed lines) or sole into a possible subhorizontal detachment (R₃). Reflections R₂ and R₃ continue northward onto line 13 (Figure 8b). JPRS: Jurassic postrift sequence (dots). J is: interpreted Jurassic age basalt/diabase reflection, locally the postrift unconformity. C is: interpreted base of the highly reflective Cretaceous-Tertiary Coastal Plain sequence. Vertical exaggeration = 2:1 at 3.0 km/s (average for sedimentary rocks). See Tables 1 and 2 for details of data acquisition and processing parameters, respectively.

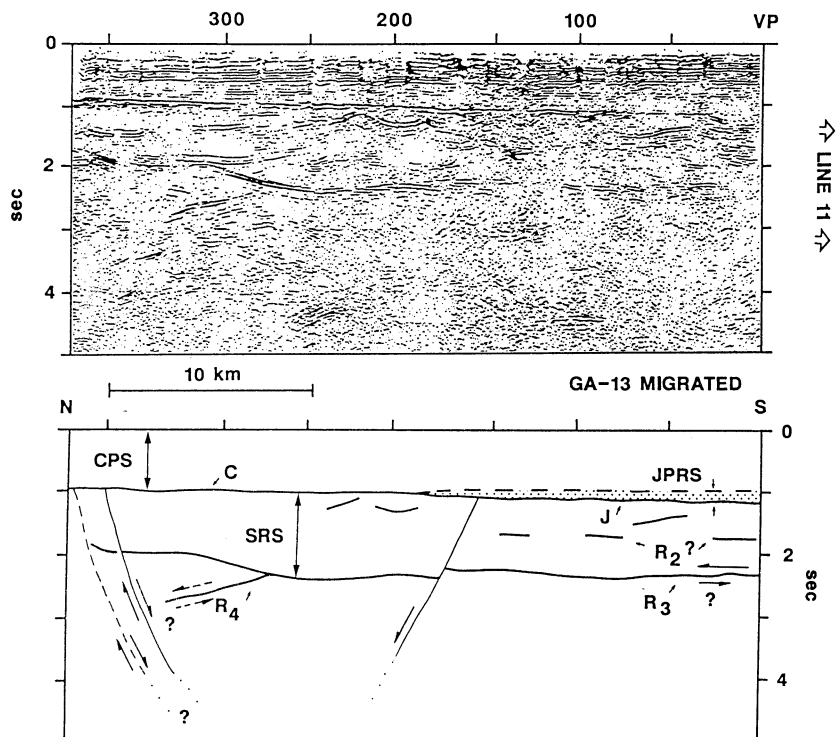


Fig. 8b. Migrated CDP section and interpretation of COCORP Georgia line 13 (see Figure 2 for location). Abbreviations, vertical exaggeration, and data processing as in Figure 8a.

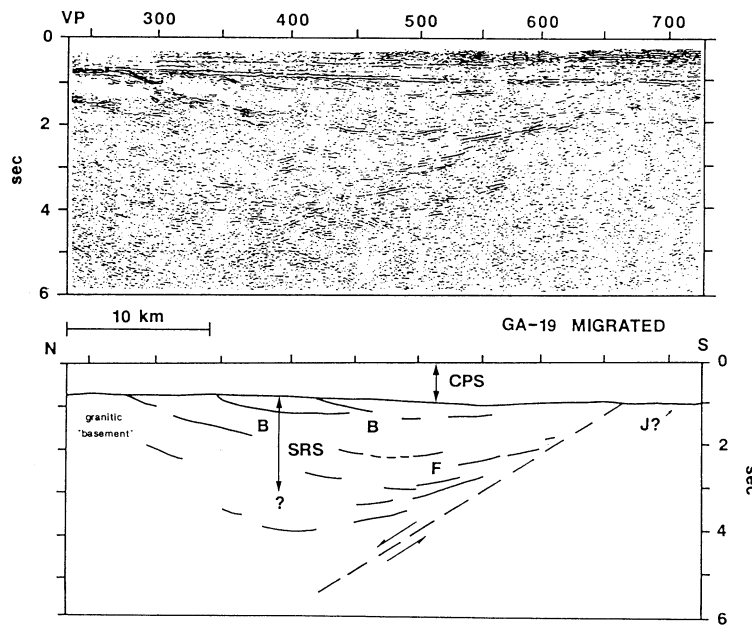


Fig. 9. Migrated CDP section and interpretation of COCORP Georgia line 19 (see Figure 2 for location). Rift basin interpretation based in part on the asymmetric southward tilting of reflections B towards, and truncated by, reflections F (cf. Figure 14). Normal fault (dashed) interpretation based on southward termination of all subCoastal Plain sequence reflections. Note that the base of the interpreted synrift sequence is not well defined as on lines 11 and 13. Indication of a granitic "basement" north of VP 300 is from nearby drill hole data [McBride and Nelson, 1988]. Abbreviations, vertical exaggeration, and data processing as in Figure 8a.

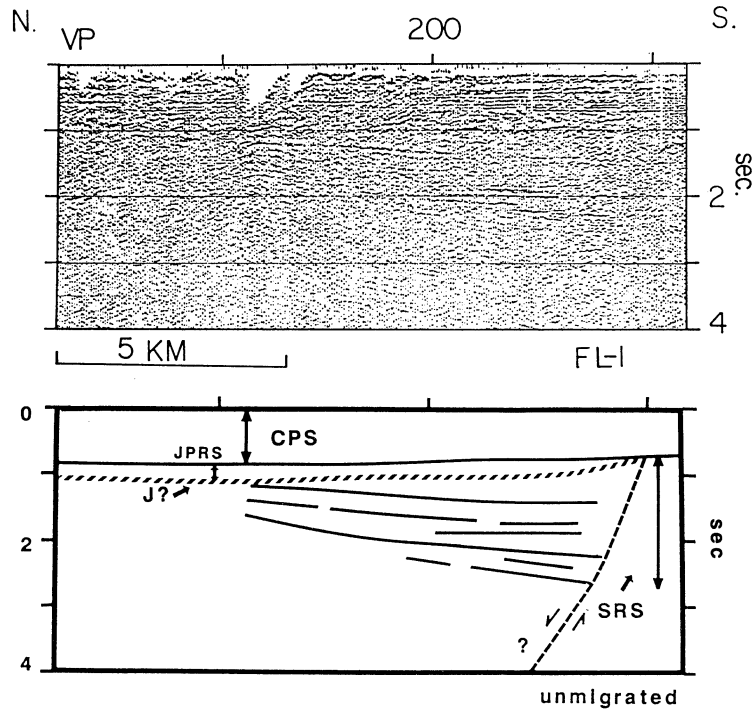


Fig. 10. Unmigrated CDP section and interpretation of COCORP Florida line 10 (see Figure 2 for location). No coherency enhancement filter has been applied to this section. Abbreviations as in Figure 8a. Vertical exaggeration = 1:1 at 3.0 km/s (average for sedimentary rocks).

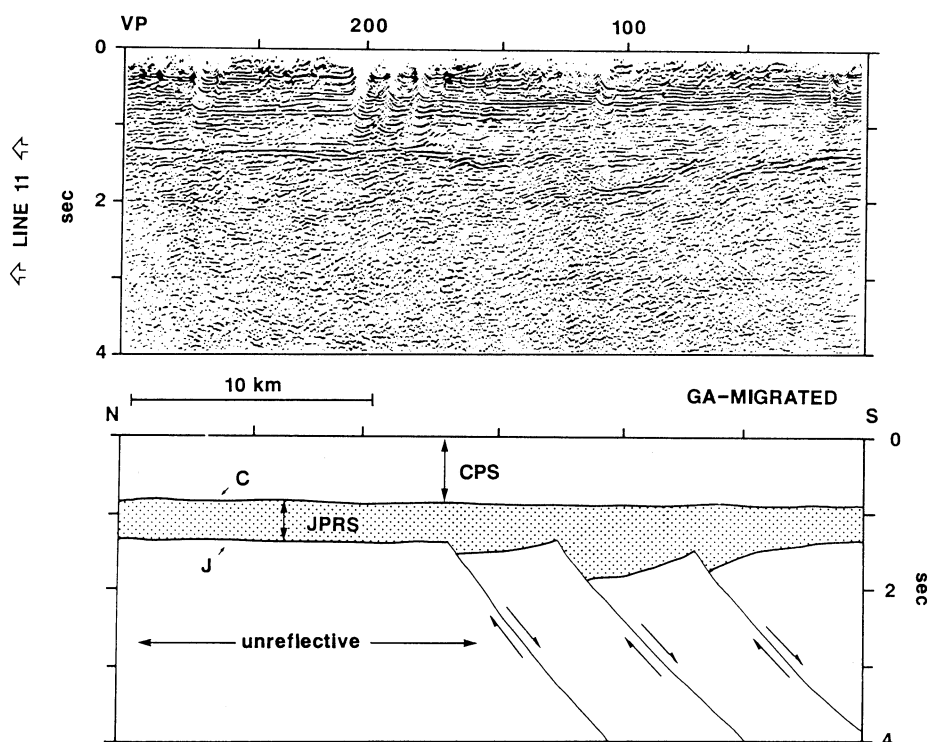


Fig. 11. Migrated CDP section and interpretation of COCORP Georgia line 12 (see Figure 2 for location). On this line, only the postrift (i.e., above J basalt/diabase reflector) portion of the basin assemblage is observed. Normal fault interpretation based on disruption and tilting of the J reflection. Abbreviations, vertical exaggeration, and data processing as in Figure 8a.

DISCUSSION

Analysis of the COCORP seismic reflection data across the South Georgia rift demonstrates that the basin is a complex composite of large, isolated rift grabens with little or no along-strike continuity. This view is also supported by dip-oriented regional reflection data discussed by Behrendt [1986] which also show isolated synrift grabens. The boundaries of the basins, where crossed by the COCORP lines, vary between simple onlap to major normal faults. Interpretation of the reflection data further suggests a picture of the basin as having a buried Basin and Range-like "rift topography" consisting of broad highlands and intervening valleys. The reflection data thus add a partial third dimension to pre-Cretaceous subcrop maps [e.g., Chowns and Williams, 1983; Daniels et al., 1983; Horton et al., 1989] which generally only represent a higher, postrift stratigraphic level. Although the three dip-oriented transects are not sufficient to provide a final understanding of along-strike variation within the rift, the data do permit testing of hypotheses regarding its regional structure and tectonic development. The broadness of the rift terrane in Georgia contrasts with the concept of a narrow, linear basin such as the Newark-Gettysburg-

Culpeper system (Figure 1), and may be more like the extensive synrift terrane situated between the Atlantic coastline and the offshore hingeline [e.g., Klitgord and Behrendt, 1979] or within the Gulf of Maine [Hutchinson et al., 1986] (Figure 1). The overall shape and the internal patterns of the individual grabens are typical of better studied extensional provinces in general [e.g., Effimoff and Pinezich, 1986]. The reflection data show that the South Georgia basin is neither a simple subsided trough nor, as proposed by Higgins and Zietz [1983], Klitgord et al. [1988], and others, a single narrow linear graben following the Brunswick magnetic anomaly minimum (Figure 2) (see also McBride and Nelson [1988]).

Analysis of Structural Styles of Extension

Formation of narrower, asymmetric basins. Two distinct styles of basin geometry occur in the South Georgia rift. These two styles are best distinguished on the line 19-21 transect and the line 12-11-13 transect (Figure 13). A "structural" approach to interpretation of reflection data from any area of the basin should be pursued with caution in that intrusion of mafic dikes and sills within the synrift or prerift section could be misleading [Smith and

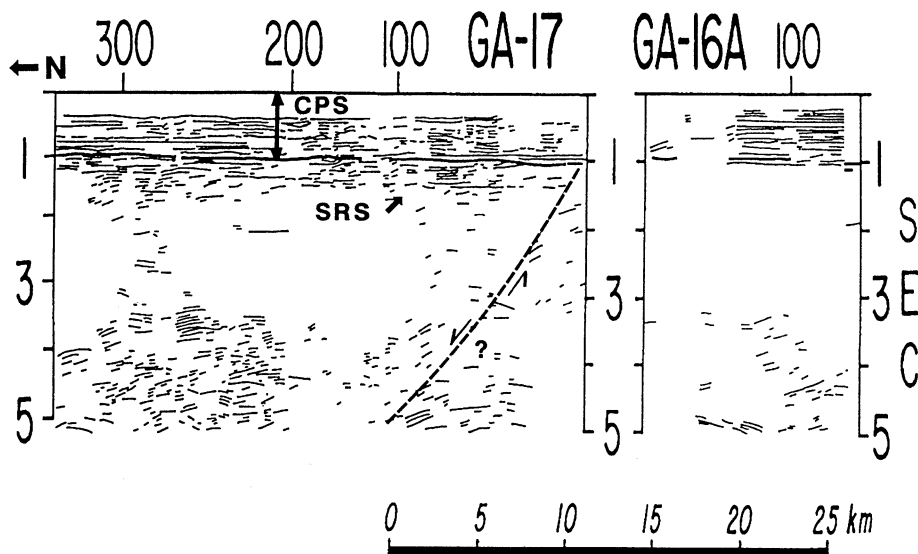


Fig. 12. Detailed line drawing of unmigrated CDP section of COCORP Georgia lines 17 (southern part) and 16A (northern part) (see Figure 2 for location). Abbreviations as in Figure 8a. Vertical exaggeration = 2:1 at 3.0 km/s (average for sedimentary rocks).

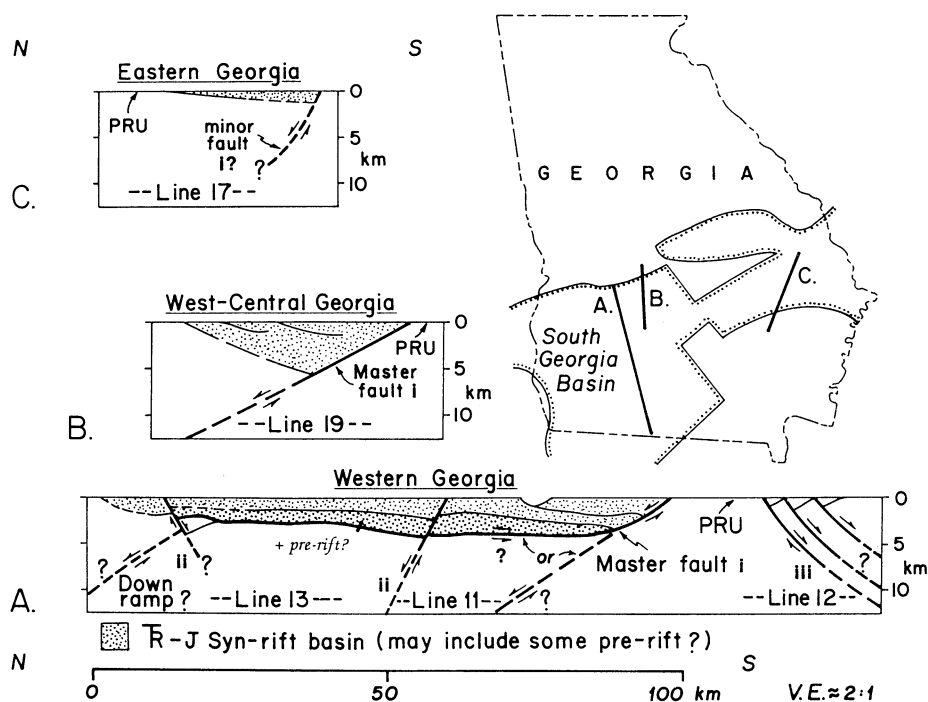


Fig. 13. Simplified composite cross-section interpretations of the rift basin portion (stippled) of the seismic reflection data leveled on the postrift unconformity (PRU), with the Coastal Plain sequence removed, for the three transects over the buried South Georgia basin (dotted outline; modified from Chowns and Williams, 1983]. Note the extreme change in basin shape proceeding along strike. (a) Composite of COCORP Georgia lines 13, 11, and 12; (b) Composite of lines 21 and 19; (c) Composite of lines 17 and 16. See Figure 2 for location of survey lines making up composites.

Foley, 1988; F. D. Foley, written communication 1990]. More than one interpretation is probably possible for the disparity in style, although the reflection data unequivocally imply a significant change in basin structure and tectonics. The line 19-21 transect depicts a narrower and better defined graben. This graben is strongly asymmetric with a relatively steep and deeply penetrating master normal fault. Interpretation of the entire 16-s record suggests that the fault penetrates to ~20 km with no change in dip, and antithetically offsets deep suture zone structure (Figure 6). The asymmetric shape and interior geometry of the basin are particularly analogous to that of Tertiary continental grabens of the Basin and Range province [e.g., Stewart, 1980; Effimoff and Pinezich, 1986; Wernicke and Burchfiel, 1982]; the typical form of these basins is illustrated in Figure 14. The upward flattening of reflector dip within the northern half of the line 19 basin (reflections B, Figure 9), together with the reversal in reflector dip (reflections F, Figure 9) next to the interpreted master normal fault, implies that this basin subsided asymmetrically more or less as a single "unit". As in the case of typical asymmetric rift grabens (e.g., Figure 14), stratal reflectors dipping away from the fault formed in the basin moat, and those dipping toward the fault formed over the basin ramp [Effimoff and Pinezich, 1986; Anderson et al., 1983].

Formation of broader, roughly symmetric basin.
In contrast to the line 19-21 transect, lines 11 and 13 together depict a much broader basin with a more complex interior, and with an overall roughly symmetric cross section. The relatively small offsets of R₃ and J clearly postdate the main phase of basin formation and cannot account for the observed substantial subsidence of the basin. This observation, combined with the possible interpretation that the master normal fault F₁₁ on the southern end of line 11 soles into R₃, suggests that the R₃ surface may represent in a general way a level of detachment that accommodated extension (Figure 13). It is unclear whether R₃ could have

formed progressively as a bedding plane fault (in analogy to growth faults; see Crans et al. [1980]), or as a normal slip detachment. The position of the detached hanging wall block within the basin is also not clear and could either be at the end of the line 13 basin (Figure 8b) or within the lower part of the reflective sequence on line 11 (i.e., within the possible prerift section; see Figure 13). Regional low-angle detachments have been proposed as fundamental structures for other east coast rift basins both on- and offshore [Ratcliffe et al., 1986; Keen et al., 1987]. For example, Ratcliffe et al. [1986] use reflection, drill hole, and surface geologic data to argue that the Newark basin in eastern Pennsylvania formed by extension on a low-angle (25° to 35°) border normal fault flattening into a regional subhorizontal detachment at depth similar to that on the southern end of line 11. As noted above, an alternate interpretation for the F₁₁ border fault is that it extends deeper as a more or less planar surface (Figure 8a). It is also possible that R₃ may have been produced, or at least enhanced, by intrusion of mafic sills similar to the J reflector.

Although the present-day depth of R₃ of 6 to 7 km reflects both the effects of postrift uplift and subsidence, it nevertheless falls near the shallow limit of the general range of depth to extensional detachments based on observations and palinspastic reconstructions [Allmendinger et al., 1983; Gibbs, 1983; Wernicke, 1985; Keen et al., 1987]. At the northern end of line 13 the relatively steep dip (~8°) and anomalous character of R₄ plus its apparent role as a downward continuation of R₃ make it a speculative candidate for a deep basement ramp associated with normal slip along R₃. Such a scenario of a low-angle detachment ramping into deeper levels has been envisaged for the Central Graben of the North Sea and other rifts [Gibbs, 1984, 1987; Bosworth, 1985], and clearly observed for the Tertiary Sevier Desert detachment, eastern Basin and Range in west central Utah [Allmendinger et al., 1983] (Figure 15). Evidence from surface geology and seismic reflection profiling [McDonald, 1976;

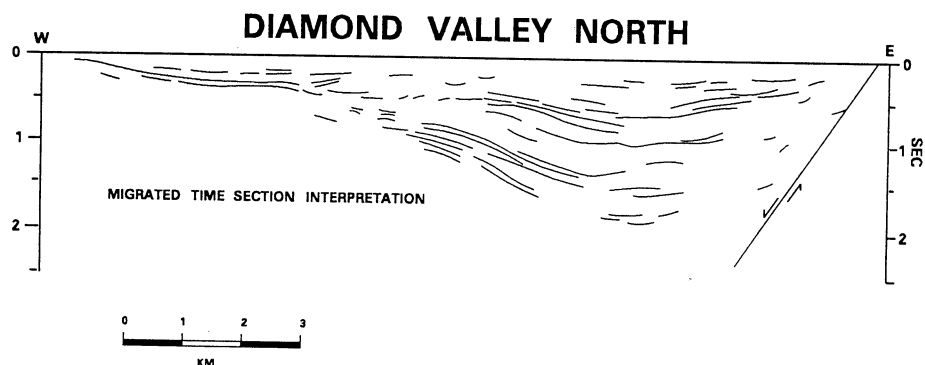


Fig. 14. Line drawing interpretation of seismic line across the Diamond Valley, northeastern Nevada Basin and Range illustrating a typical reflection sequence associated with an asymmetric graben bordered by a steeply dipping master normal fault. Compare with Georgia line 19 (Figures 6b, 9, and 13b). Modified from Effimoff and Pinezich [1986] and Anderson et al. [1983].

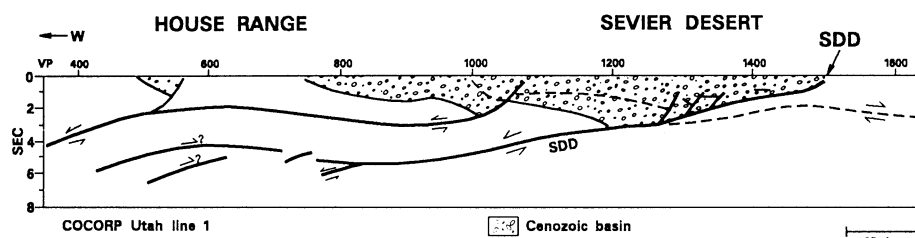


Fig. 15. Interpretation of COCORP Utah line 1 from the eastern Basin and Range over the Sevier Desert basin and House Range showing the Cenozoic basin portion of the data and major low-angle normal faults (e.g., Sevier Desert detachment, SDD). Compare with Georgia line 13-11-12 transect (Figures 6a and 13a). Modified from Allmendinger et al. [1983].

Allmendinger et al., 1983] indicate that formation of the Sevier Desert basin was controlled by extensional displacement along one or more low-angle detachments and that steeper normal faults cutting basin strata do not cut the detachment (Figure 15). The scale of basin formation and lateral extent of the Sevier Desert detachment is comparable to that of the line 12-11-13 transect of the South Georgia basin (cf. Figures 13 and 15).

Along-Strike Disparity in Basin Architecture: Change in Crustal Rheology During Rifting?

One of the most striking results of this study is that the main basin depocenters located on the transects show markedly disparate structural styles along the rift (Figure 13). The along-strike variability in basin structure contrasts with the more consistent picture presented by the deep reflection structure (Figure 6). Various models have been proposed to explain the general along-strike disparity in rift basin structure [e.g., Bally, 1982; Gibbs, 1984; Bosworth, 1985; Lister et al., 1986; Rosendahl, 1987; Ebinger, 1989; Morley, 1988; 1989]. Most of these models predict an along-strike offset or polarity reversal of the master normal fault commonly accompanied by a change in the amount and structural style of extension. The adjacent basin segments are typically separated by a transfer zone inferred to have strike-slip displacement (Figure 16). As shown by Rosendahl [1987] and Scott and Rosendahl [1989] for the North Sea and Lake Tanganyika rifts, many configurations for the polarity of the master fault, with respect to the intervening transfer zones, are possible (e.g., Figure 16). In the genetic models of Bally [1982], Gibbs [1984], and Lister et al. [1986], as the initial rift develops into two opposing passive continental margins, the two margins asymmetrically segment into adjacent blocks each having differing deformation mechanisms involving either low-angle detachments (possibly a "brittle-ductile" transitions [e.g., Miller et al., 1983; Gans et al., 1985]) or steeper faults accompanied by lesser extension.

For the case of the South Georgia basin, certain elements of segmented plate extension models apply,

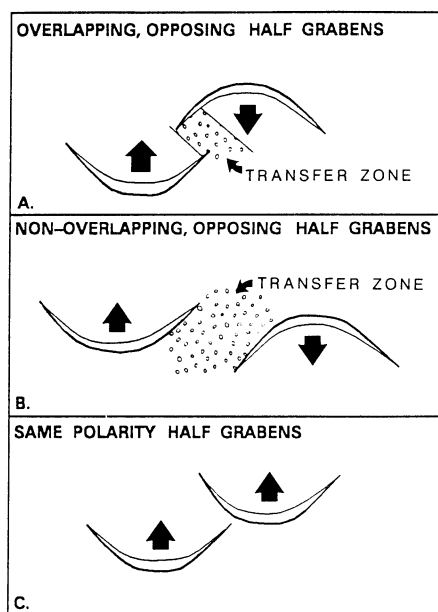


Fig. 16. Idealized representation of (a) overlapping, opposing, (b) nonoverlapping, opposing, and (c) same-polarity modes of along-strike disruption (transfer or accommodation zone is stippled area) between discontinuous half-graben basins based on observations from the East African and other rifts [Rosendahl, 1987; Scott and Rosendahl, 1989]. From the reflection data in this report, the same-polarity mode (Figure 16c) appears to be the most applicable in characterizing the along-strike disparity observed for the South Georgia rift. Figure modified from Rosendahl [1987] and Scott and Rosendahl [1989].

while others do not. The reflection data suggest a picture of limited crustal extension for the eastern two transects, consistent with the observed smaller graben width, whereas the structural style of the westernmost Georgia transect implies much greater extension with an expected greater graben width (Figure 13). A deep, through-going planar normal fault along the line 19-21 transect is at least suggestive of deformation of the crust (and

lithosphere?) by uniform-sense symmetric simple shear (e.g., Figure 17a). On the other hand, the apparent confinement of deformation to the upper 6 or 7 km of the crust along the line 11-13 transect, together with the fact that no major faults cut R3, would be consistent with an extension regime involving rotated tilt blocks deforming in a brittle upper crust over a more uniformly stretched (by pure shear) middle/lower crust (e.g., Figure 17b). By analogy with Basin and Range studies [Rehrig and Reynolds, 1980; Eaton, 1979], pure shear deformation below a detachment may have taken place by ductile flow and igneous intrusion [Royden and Keen, 1980] and would account for the almost total lack of reflectivity below the basin on line 11 (Figure 3b). As discussed by Morley [1989], rift basins that formed by extension along a low-angle fault are typically accompanied by significant amounts of volcanism as compared to narrower, less-extended basins. Other important predictions of a variable extension, segmented plate model are not observed. No dominant reversal in fault polarity (e.g., as in Figures 16a, 16b) is observed between the three transects across the basin (Figures 2, 13, and 16c); and no direct evidence of intervening northwest trending transfer or strike-slip faults exists as proposed by Salvador [1987] or Tauvers and Muehlberger [1987] although the along-strike disparity in basin architecture supports their hypothesis (Figure 2). Clearly, more reflection profiling is needed to complete, and test the interpretation of, along-strike variation in the rift.

Relationship of Deep Crustal Structure to the South Georgia Rift

Deep seismic reflection structure below the observed subbasins is dominated by a complex zone of mainly south dipping events that penetrates the middle and lower crust and follows the trace of the Brunswick magnetic low (Figure 6). This zone is imaged on all three COCORP transects across the South Georgia basin. It has been previously argued that this zone is associated with the Alleghanian (late Paleozoic) suture between North America and relict west Africa, possibly as a root zone for north

verging Inner Piedmont nappes [Nelson et al., 1985; McBride et al., 1987; Tauvers and Muehlberger, 1987; McBride and Nelson, 1988]. The entire region below the South Georgia basin is underlain by a relatively flat reflection Moho discontinuity at ~11-12 s (~33-36 km). Reprocessing of the lower crustal reflection data has been undertaken for line 13 in order to better understand the relationship between the dipping late Paleozoic compressional structure and the reflection Moho (Figure 18). The primary result of the reprocessing is that the reflection Moho clearly truncates dipping reflection structure associated with the suture suggesting that the Moho is a younger, superimposed feature in this region. This truncation relationship, as shown for line 13, is a fundamental feature of the entire survey (Figure 6). The derived depth to the Moho below the basin is anomalously shallow relative to that below the interior of the Appalachians further to the northwest (as much as ~55 km) [Allenby and Schnetzler, 1983; Costain et al., 1989]. The presence of a thinned crust below the Coastal Plain and Inner Piedmont [Costain et al., 1989] may be genetically related to the episode of early Mesozoic graben formation and tholeiitic magmatism in the Appalachians [de Boer et al., 1988]. In the Basin and Range province of North America and the continental shelf around the British Isles, crustal thinning due to regional extension has been associated with the production of a well-developed lower crustal reflection "layering" or "lamination" and has often been explained as magmatic underplating and/or intrusion of basaltic sills accompanying extension [Cheadle et al., 1987; Nelson, 1991; Warner, 1990]. That no such pattern of lower crustal reflectivity is observed anywhere below the South Georgia rift on the three COCORP transects is difficult to interpret but may imply that rifting was arrested prior to the stage of pervasive lower crustal intrusion.

The three-dimensional relationship between rift basin structure and the dipping reflection structure of the Alleghanian suture zone can be best analyzed where the line 12-11-13 transect and line 19-21 transects are tied by the cross line 20 (Figure 19). The deep structure below line 20 is characterized by bands of subhorizontal reflections between 2.5 and 11.5 s

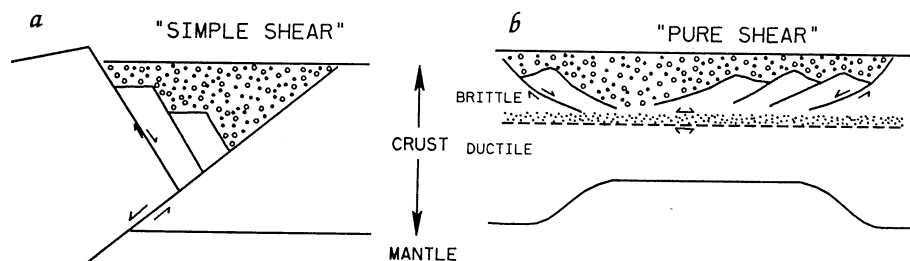


Fig. 17. Conceptual cartoon illustrating (a) "simple shear" and (b) "pure shear" models of crust and lithosphere extension showing dependence of basin shape on extension mode. Stippled area represents sediment rift fill. Both basin styles have been observed together for early Mesozoic rift basins of the offshore Atlantic of North America, and, as discussed in this report, for the Triassic-Jurassic South Georgia basin (cf. Figure 13). No scale implied. Modified from Keen [1985] and Wernicke [1985].

that are separated by relatively reflection-free zones. This "layered" fabric almost certainly represents a strike view of the corresponding set of south dipping surfaces as seen on the intersecting dip profiles. Furthermore, the separation of reflections into

distinct horizontal zones may be related to north-vergent thrust sheets within the suture in strike view. The layered character is not interpreted as relating to an "extensional" fabric associated with rifting. For the line 12-11-13 transect in westernmost

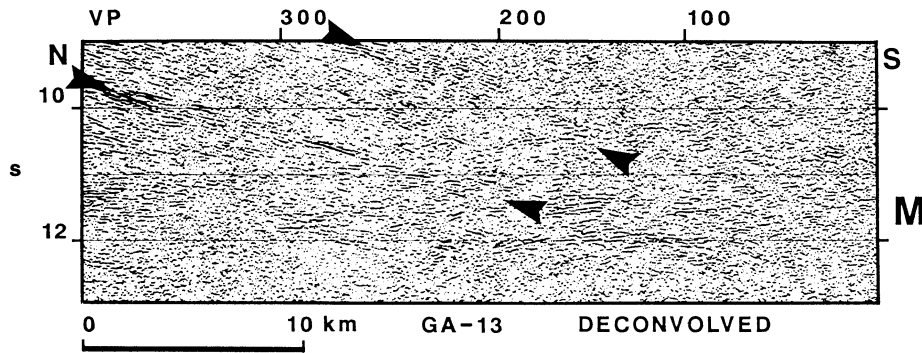


Fig. 18. Deconvolved CDP section for lower crust of a portion of Georgia line 13 (unmigrated) showing well-developed Moho (M) and intersecting dipping reflections from the Alleghanian suture zone. Vertical exaggeration = 1:1 at 6.0 km/s.

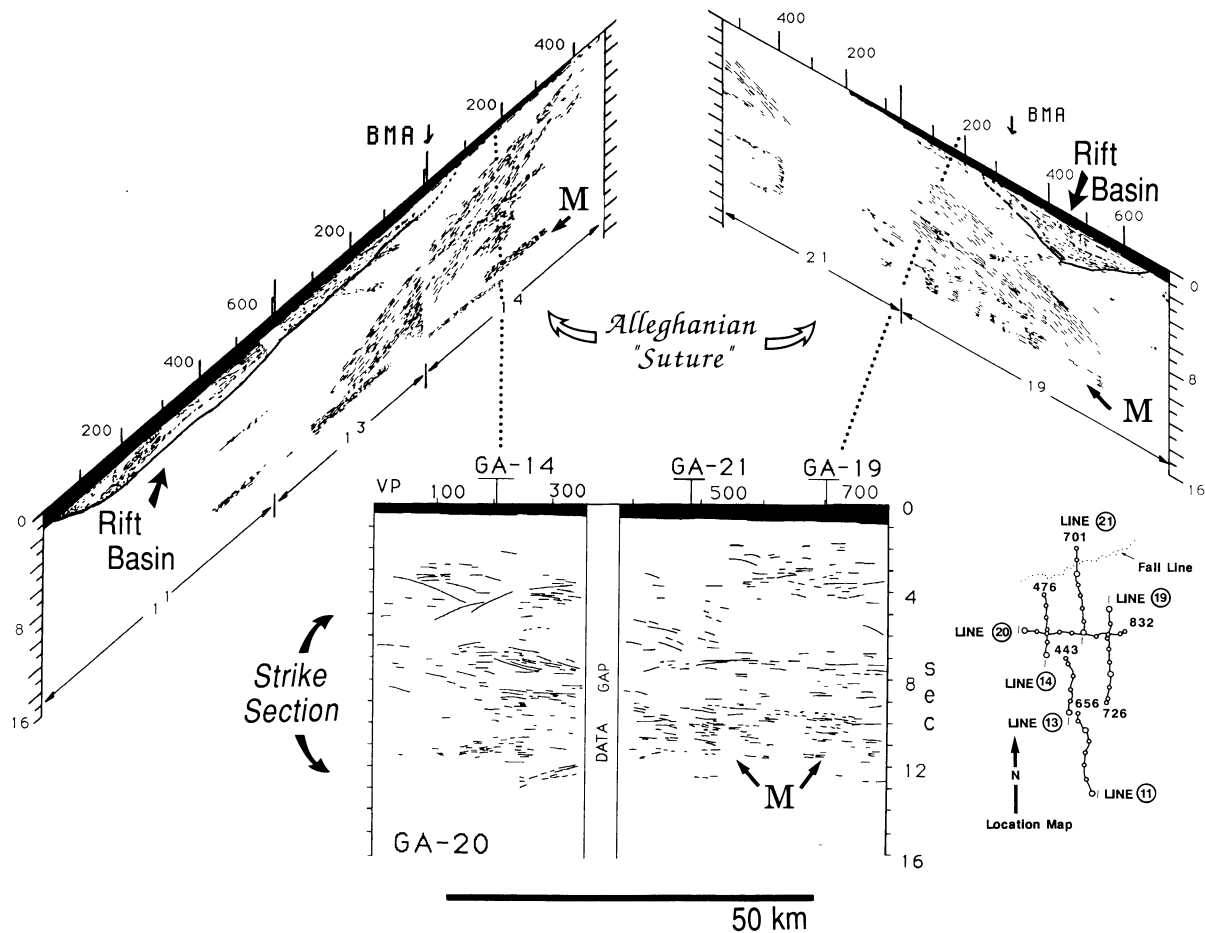


Fig. 19. Three-dimensional perspective diagram of reflection line drawings (unmigrated) showing two dip sections through the Alleghanian suture and the overlying rift basins, and one intersecting strike section (line GA-20) showing the subhorizontal fabric associated with the crustal dipping reflection zones. M is: reflection Moho discontinuity. Vertical exaggeration for line GA-20 = 1:1 at 6.0 km/s.

Georgia the basin assemblage is situated mainly to the south of the dipping reflection zone in what would be interpreted as the "upper plate" of the suture. The principal interpreted faults along this transect (e.g., F₁₁) (Figure 13) dip northward in an antithetic sense with respect to the interpreted northward "vergence" of the suture zone. On the seismic sections the region below the base of the basin on this transect (i.e., below R₃) is almost totally unreflective. The presence of strong Moho reflections implies that this unreflective zone is not a signal penetration problem so that the crust is truly transparent below the line 12-11-13 basin transect.

In marked contrast to the line 12-11-13 transect, the basin assemblage imaged on the line 19-21 transect in west central Georgia is localized directly over the downdip flank of the dipping reflection zone (Figure 6). As pointed out above, the interpreted north dipping master normal fault on the southern end of the graben is colinear with a midcrustal, north dipping reflection. This deep reflection disrupts the dipping reflection zone and is interpreted to be a planar extension of the master fault. It is unclear how much deeper this fault penetrates, but it may extend down to the reflection Moho at the northern end of line 19 (Figure 6). As is the case for the line 12-11-13 transect, the line 19 border fault does not appear to have reactivated structure of the suture zone. On the eastern Georgia transect (line 17/16A) the area traversed by the half-graben lies well to the north of the dipping reflection zone associated with the suture (Figure 6). Thus, on the basis of two- and three-dimensional perspectives, the locations of the observed basin reflection depocenters are inconsistent with respect to the position of the broad dipping reflection zones that define the Alleghanian suture.

In summary, there appears to be a "migration", with respect to the Alleghanian suture zone, of the South Georgia basin depocenter from far to the south of the suture zone in westernmost Georgia (Figure 6a), to directly over its south flank (Figure 6b), to a very limited development north of the suture in eastern Georgia (Figure 6c). The South Georgia rift thus appears to have developed principally over the upper plate of the late Paleozoic suture zone with only limited or no development to the north. Although reactivation of Paleozoic structure by Mesozoic normal faults has been suggested elsewhere in the southern Appalachians from reflection data [e.g., Nelson et al., 1987a; Petersen et al., 1984], the consistently northward dip of the subbasin border faults is antithetic to the implied northward vergence in the suture zone.

CONCLUSIONS

The South Georgia basin is a complex composite consisting of isolated rift grabens of varying widths and depths. It is not a simple subsided "sag" basin nor can it be characterized by a single linear graben as previously proposed. The structure of individual subbasins varies dramatically along strike, changing

from a broad symmetric graben possibly underlain by an interpreted low-angle detachment to a narrow asymmetric basin bordered by a steeper, crust-penetrating fault. Both structural styles are also observed in close association on the North American Atlantic margin and may suggest the dual operation of simple and pure shear extension in the formation of the South Georgia rift. At least three main episodes of faulting relating to main graben formation, and to postrift subsidence can be documented from the reflection data. The formation of the major early Mesozoic depocenters, as imaged on the COCORP data, was superimposed over the late Paleozoic suture with no apparent reactivation of older faults. These depocenters trend obliquely over the broad dipping reflection zone that marks the suture. The along-strike variation in basin architecture is, in a general way, predicted by segmented plate models of extension along continental margins and intracontinental rifts; however, more work is needed to fully document the mechanics of this segmentation and to detect any transfer zones. The interpreted 6 km of rift basin fill, together with the observed advanced development of rift basin subsidence and extension, are consistent with the hypothesis that the Southeast Coastal Plain was a region of early Mesozoic incipient seafloor spreading. The absence of a horizontally "layered" lower crust, as has been associated with other rifted terranes, may suggest that rifting was of a lesser magnitude compared to the Basin and Range or around the British Isles. The pervasive formation of the Moho discontinuity as a dynamic feature superimposed on late Paleozoic compressional structure is the principal manifestation of an early Mesozoic rifting event affecting the lower crust.

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