DEEP SEISMIC REFLECTION CONSTRAINTS ON PALAEOZOIC CRUSTAL STRUCTURE AND DEFINITION OF THE MOHO IN THE BURIED SOUTHERN APPALACHIAN OROGEN

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Abstract. Experimental reprocessing of COCORP deep seismic reflection data collected over the buried Southern Appalachian orogen (southeastern USA) provides a more accurate characterisation of middle/lower crustal structure and Moho, thus allowing a quantitative basis for geologic interpretation. Reprocessing and migration of data over the late Palaeozoic suture (Alleghanian≈Hercynian) between North America and relict west Africa reveal varying north-vergent thrust geometries including ramp-and-flat, antiformal, and planar structures. Interpretation of a strike-parallel line over the suture zone implies that the suture is dominated by discrete bands of south-dipping thrusts which are expressed, in strike view, as a "layered" fabric of sub-horizontal reflections. The internal structure of the suture zone varies dramatically along strike becoming broader and less steep eastward across the Atlantic Coastal Plain as the amount of crustal "overlap" between relict west African and North American terranes progressively increases. Suture-zone reflections are abruptly truncated in the lower crust by a ubiquitous sub-horizontal reflection Moho which is anomalously shallow generally at 33-36 km (relative to a much deeper Moho beneath the Blue Ridge and Inner Piedmont to the west). The character of the reflection Moho varies throughout the area and, after deconvolution and frequency filtering, appears either as a simple doublet/triplet or more complex multicycle event. This multicyclic character may be suggestive of magmatic underplating by mafic igneous sills intruded during a regional thermal event brought on by early Mesozoic extension and crustal thinning related to the initial rifting and opening of the North Atlantic. The broad correspondence between a highly reflective Moho underlying thinned crust and the region of early Mesozoic rifting, together with its horizontal truncation of Palaeozoic suture-zone structure, suggests that the Moho is a dynamic boundary that is early Mesozoic in age and was produced by rifting processes.

Introduction and Regional Setting

In the southeastern United States, the Appalachian orogen disappears abruptly beneath the Atlantic Coastal Plain obscuring the suture between North American and relict west African crusts (Figure 1). The structure of the buried portion of the orogen has been the subject of intense interest and speculation for geologists. The purpose of this study is to utilise experimental processing and testing of deep seismic reflection data collected over the Georgia Coastal Plain by COCORP (Consortium for Continental Reflection Profiling) in order to provide a more quantitative basis for the geologic interpretation of Palaeozoic compressional structure and the reflection Mohorovicic discontinuity, and then to constrain crustal cross-sections through the orogen.

Information on the pre-Mesozoic basement of the Southern Appalachians is sharply divided across the Fall Line (inland limit of Cretaceous-Tertiary onlap) (Figure 1). Mapping of the diverse metamorphic and sedimentary rocks exposed north of the Fall Line indicates that this region is composed of two northeast-trending composite terranes (Inner Piedmont terrane; Carolina or Avalon terrane), that were juxtaposed in Devonian-Carboniferous time (now separated by the "Central Piedmont suture"—Taconic or Acadian(?)) [Hatcher, 1987; Horton et al., 1989] (see map, Plate 1). Subsequently, in Carboniferous-Early Permian time, these terranes were transported, en masse, westward over the North American continental margin during terminal continent/continent convergence between North America and west Africa

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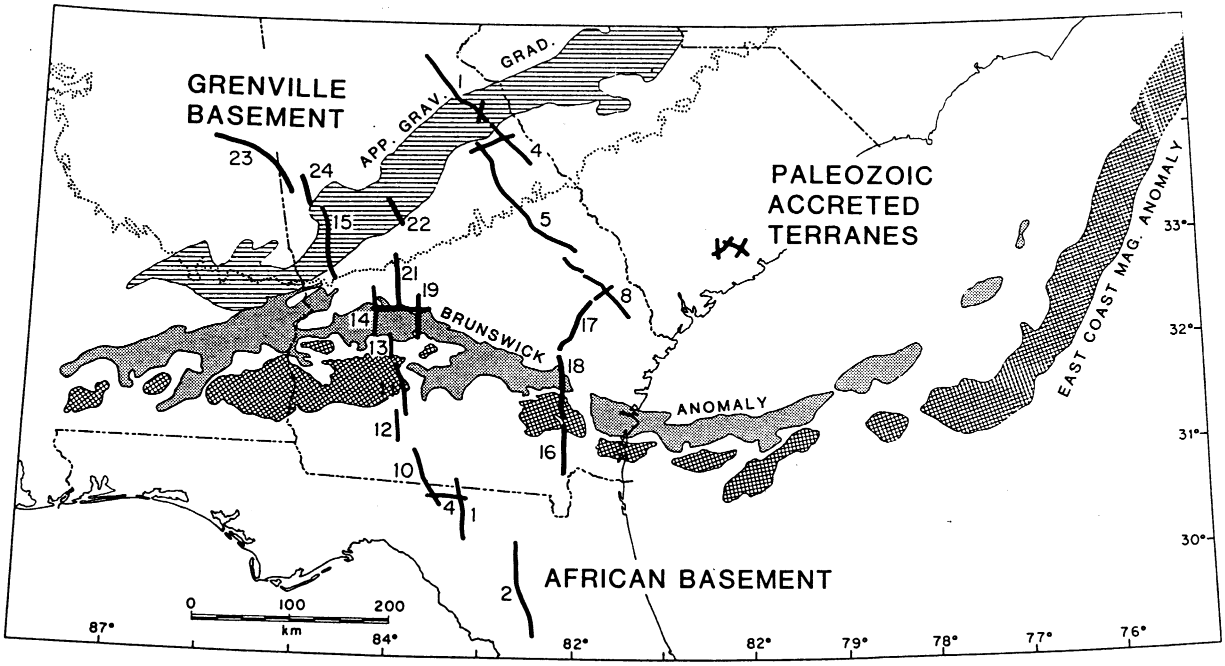

Fig. 1. Location map showing major crustal terranes and COCORP survey lines. Grid= magnetic intensity high; stipple= magnetic intensity low; hachured= Bouguer gravity gradient.

(Alleghanian orogeny). South of the Fall Line, the subsurface geology below the Coastal Plain is known only from scattered drilling but indicates that lower Palaeozoic platform sedimentary strata and Precambrian/lower Palaeozoic felsic volcanic rocks with west African affinities ("Suwannee terrane") underlie northern Florida and southernmost Georgia [Chowns and Williams, 1983; Dallmeyer et al., 1989] (Figures 1 and 2). Triassic-Jurassic continental clastic sediments ("South Georgia basin") [Behrendt, 1986; McBride et al., 1989] overlap the northern limit of the Suwannee terrane (map, Plate 1), and thus obscure the Alleghanian (Middle Carboniferous to Permian, ≈Hercynian) suture between North America and a fragment of west Africa accreted during the late Palaeozoic assembly of Pangea [Secor et al., 1986].

Previous interpretation of COCORP data in eastern Georgia postulates that the Blue Ridge and Inner Piedmont, and probably the Eastern Piedmont, were transported along a low-angle décollement ("Southern Appalachian décollement") over autochthonous Precambrian Grenville basement which itself extends at least as far to the southeast as the seaward edge of the Inner Piedmont [Cook and Oliver, 1981; Cook et al., 1983]. It is thus implied that all the terranes of the Piedmont provinces have been displaced northwestward by the last major episode of thrusting during the Alleghanian orogeny [Secor et al., 1986]. However, the relationship between this deformation and where (and how) the Alleghanian sole décollement roots into the lower crust and upper mantle beneath the Coastal Plain has remained unclear. Also unclear have been the nature and extent of the early Mesozoic "overprint" of rifting and magmatism associated with the early opening of the North Atlantic Ocean [Nelson et al., 1986; de Boer et al., 1988].

Results and Interpretation

Dipping Reflection Structure Within the Late Palaeozoic Suture Zone

On all three crossings of the Brunswick magnetic anomaly (BMA) (Figure 1), the middle and lower crust is marked by a complex, steeply dipping zone of reflections and diffractions which, together with the coincident BMA, separates North American Appalachian terranes from relict west African crust, and thus has been interpreted as marking the late Palaeozoic "whole-crustal" suture [Nelson et al., 1985; Nelson et al., 1987; Tauvers and Muehlberger, 1987; McBride and Nelson, 1988]. However, the character of the reflective zone varies along strike, changing from a narrow, steeply dipping zone in western Georgia to a shallow dipping, more broadly distributed zone in eastern Georgia (Figure 2). This study examines the internal fine-structure of this zone and poses a possible tectonic explanation for its variation.

The western Georgia transect over the BMA (lines 13 & 14) shows the greatest amount of, and variation in, internal structural detail, and thus is useful for finer-scale processing

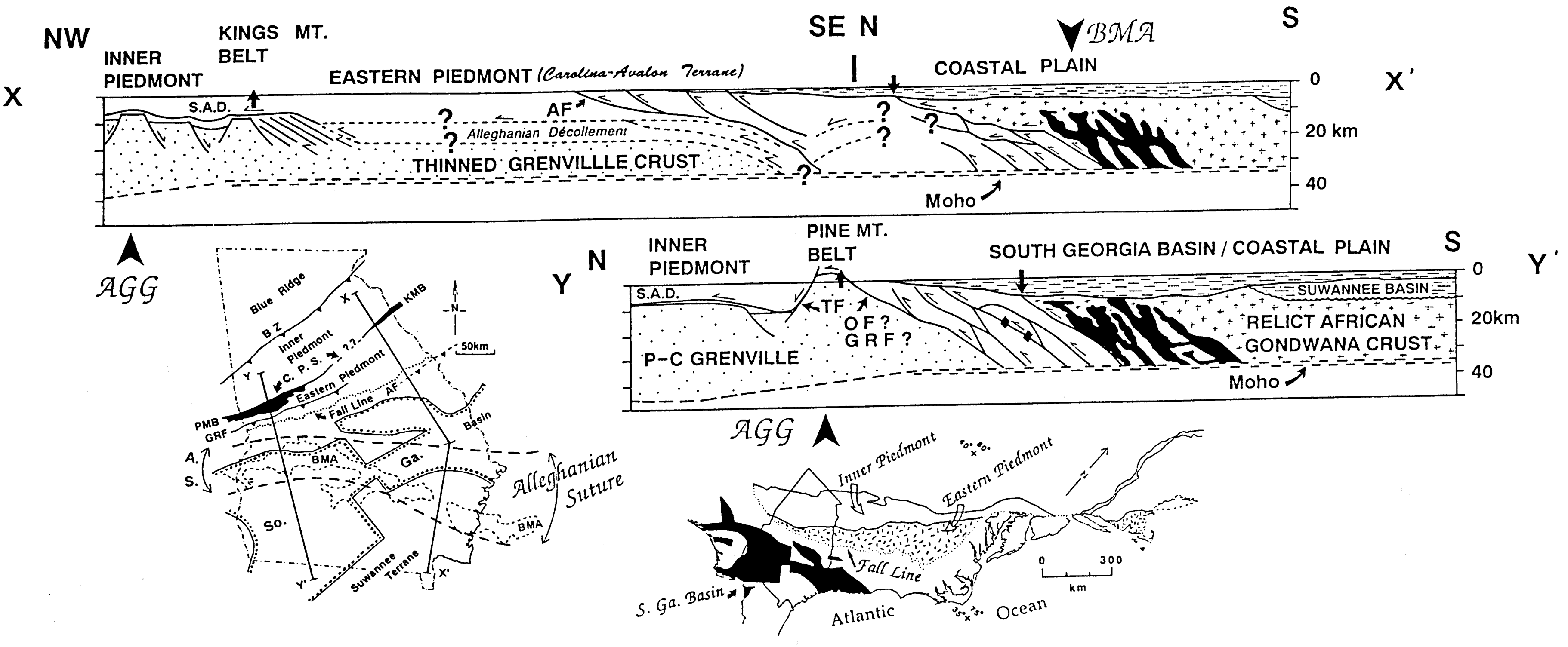

Plate 1. Map and summary schematic geologic interpretation of the Southern Appalachians for the crust, Moho, and upper mantle based on regional geophysical and geologic data as outlined in text. Cross pattern: Relict west African crust; Black: interpreted zone of highly magnetised (see Figure 2) rift-stage crust as deduced from magnetic modeling by McBride and Nelson [1988]; Blank: allochthonous Palaeozoic Appalachian Piedmont terranes shortened between North American Grenville basement and west African plate including Eastern Piedmont (Carolina-Avalon) terrane southeast of the CPS (and AGG), and Inner Piedmont to the northeast of the CPS; dotted: Precambrian Grenville crust; Black diamonds: major diffractors. Structure of crustal thickness transition below the AGG based reflection data [Çoruh et al., 1987] and gravity modeling [McBride et al., 1988]. Index map [modified from Hatcher, 1987; Horton et al., 1989] shows major terranes, cross-section locations, BMA, and widening of the Alleghanian suture across the Coastal Plain. AF: Augusta fault; AGG: Appalachian gravity gradient; AS: Alleghanian suture; BMA: Brunswick magnetic anomaly low; BZ: Brevard zone; CPS: Central Piedmont suture; GRF: Goat Rock fault; KMB: Kings Mountain belt; OF: Ocmulgee fault; PMB: Pine Mountain belt; SAD: Southern Appalachian décollement; TF: Towaliga fault. Northwest portion of X-X' modified in part from Cook et al. [1983].

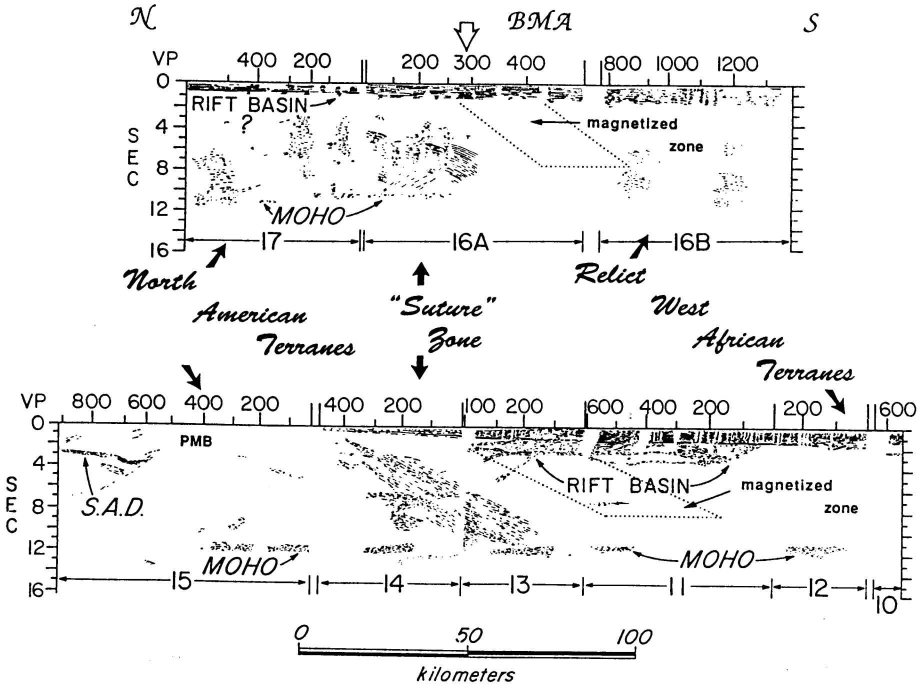

Fig. 2. Summary interpretive line drawings for the main COCORP deep reflection (unmigrated) transects across the Georgia Coastal Plain. Data are displayed from 0 to the full 16 s (two-way time) correlated record length. Dotted outline shows highly magnetised zone deduced from magnetic modeling constrained by the reflection data [McBride and Nelson, 1988]. S.A.D.: Southern Appalachian décollement; PMB: Pine Mountain belt [Nelson et al., 1987a]; BMA: Brunswick magnetic anomaly minimum. Vertical exaggeration = 1:1 @ 6.0 km/s.

and testing. Seismic time migrations were applied to merged CDP-stacked sections together with a coherency enhancement filter developed at Cornell University [Zheng and Brown, 1986]. This processor involves slant stacking within a sliding window and then, in order to reduce artefacts, modifying the processed stack according to the intertrace coherence with the original section. The coherency-filtered unmigrated stack clearly shows a dominant pattern of south-dipping reflections (arrows, Figure 3), with three north-dipping reflections on line 13 between 2 and 5 s (~6 & 15 km, @ 6 km/s). Individual reflector segments are typically no longer than 6-8 km, and dips typically range from ~30° in the upper crust to ~20° in the lower crust, apparent unmigrated dip (@ 6 km/s). An unusual concentration of diffractions occurs on line 14 between 6 and 9 s (~18 and 27 km, @ 6 km/s) indicating the presence of several "sharp-edged" point sources (small intrusions or steep structure?). Such a diffraction pattern is not a characteristic feature of the suture zone on the three transects (e.g., Figure 2). South of the dipping reflective zone, the crust is unreflective excepting three north-dipping events. This change in reflectivity, which appears to be distributed across a south-dipping line, probably not a single, planar fault (Figure 3), is interpreted to mark a terrane boundary between a relatively unreflective west African "upper plate" and a more reflective thrust root zone "lower plate" [see also Nelson et al., 1985].

Migration was used primarily to focus on specific problems involving steep dips. A reduced velocity of 3.5 km/s is used to partially migrate a portion of the section in Figure 4 while minimising distortion (with increasing travel time) and over-migration [Warner, 1987]. The principal effect of the migration is to concentrate the dipping reflective zone into a more compact and well-defined package of events consisting of several separated and distinct dipping reflectors. An explanation for this pattern is that the reflector segments represent thrusted pods or lozenges bound by shear zones that may "ramp" upward in the direction of vergence (Figure 4). Because of the smaller Fresnel zone diameter in the upper crust, imaging the finer structure of such thrust complexes may be easier at shallower levels. One possible thrust complex is imaged below about VP 200 between 2 and 5 s, line 14 (Figures 4 and 5). Figure 5 shows a small portion of this zone migrated with a velocity of 6 km/s, which is probably closer to the true interval velocity and can produce a more stable migration due to the shorter travel times (≤ 5 s) and seismic wavelengths involved. The migrated reflector structure is reminiscent of a partial thrust duplex or a single

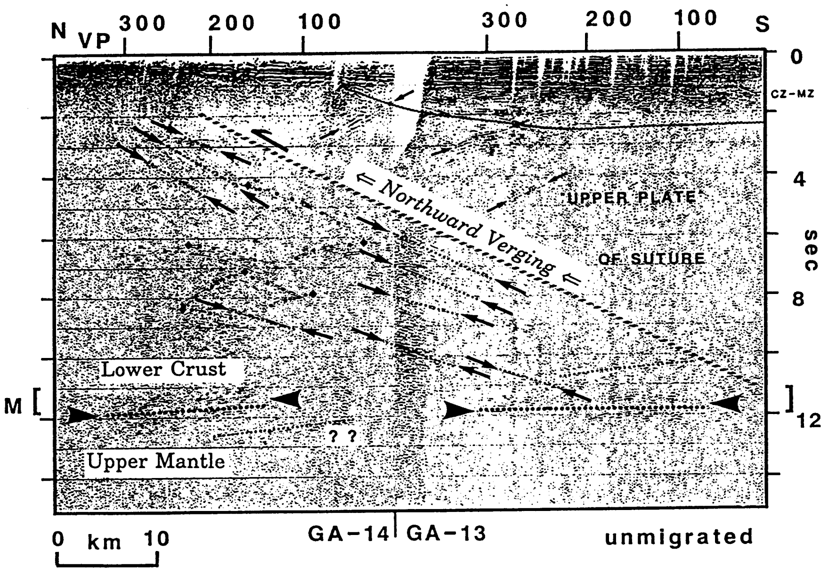

Fig. 3. Merged unmigrated section of deconvolved lines 13 and 14 with coherency enhancement filter. Major dipping reflections (small dots), interpreted diffractors (dots, diamonds), and the reflection Moho (large dots, M) are noted. Diffractors are located only roughly; source may lie out of the plane. Dashed line marks interpreted terrane boundary (not necessarily as a fault) separating lower and upper plates in the suture zone. Vertical exaggeration = 1:1 @ 6.0 km/s.

thrusted anticline verging northward [e.g., Suppe, 1985]. Such structures would be typical of other major thrust root zones in the Appalachian fold belt [Ando et al., 1983; Secor et al., 1986; Çoruh et al., 1987; Hatcher, 1987; Pratt et al., 1988]. The interpretation of the prominent north-dipping reflectors is more problematic, but they may represent back thrusts in the upper plate of the suture.

The three-dimensional relationship of the dipping reflection structure of the suture zone can be best analysed where the line 11-13-14 and line 19-21 transects are tied by cross-line 20

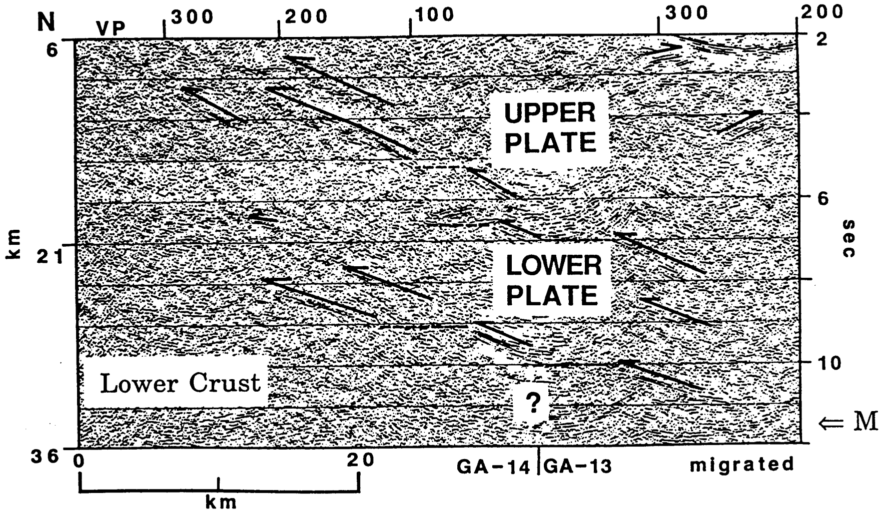

Fig. 4. Partially migrated (@ 3.5 km/s) CDP section and interpretation of merged lines 13 and 14. Vertical exaggeration = 1:1 @ 6.0 km/s. Solid lines mark interpreted thrusts and dashed lines indicate possible "flat" thrust surfaces. Distortion is caused in the middle of the section due to partially zeroed CDP traces at the juncture of lines.

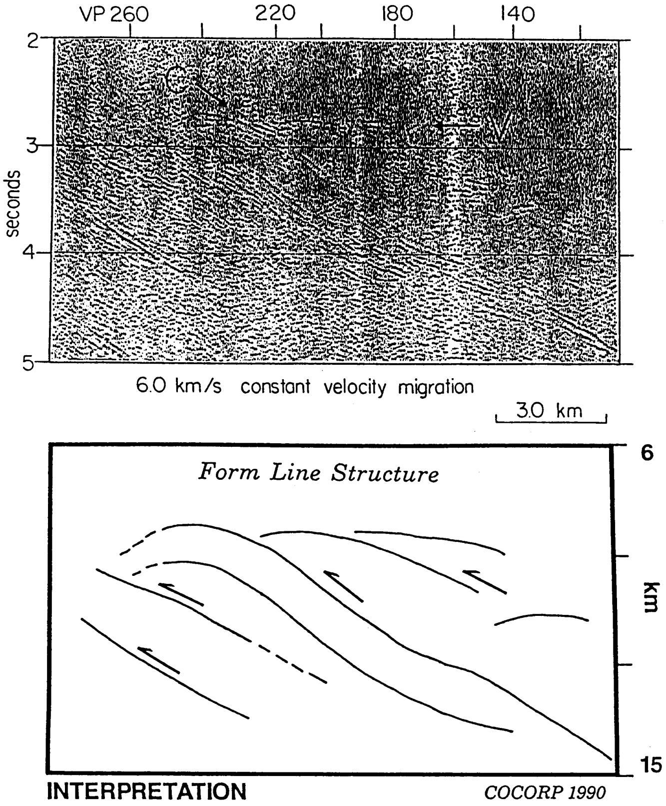

Fig. 5. Detail of migrated (@ 6 km/s) line 14 [modified from unpublished COCORP work].

(Figure 6). The deep structure below line 20 is characterised by bands of sub-horizontal reflections between 2 and 12 s that are separated by relatively reflection-free zones. This "layered" fabric is interpreted to represent 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 zones may be related to north-vergent thrusted sheets within the suture exposed in strike view. Although this area has been widely affected by early Mesozoic rifting and magmatism [McBride et al., 1989], the observed layered character is not interpreted as an "extensional fabric" associated with rifting as has been postulated for major extensional provinces in general [cf. Matthews and Cheadle, 1986; Warner, 1990].

The line 16-17 transect, at about 200 km east of lines 13 and 14, exhibits a relatively simple pattern of gently south-dipping events below the BMA (Figures 2 and 7). The most coherent reflections on the record are a line of 1 to 3-km long events between 4 and 6 s that rises in the section to the north below a relatively blank record. Before migration, these events show an arcuate, upward concave character and may include multiples [Wille, 1987] (Figure 2). After applying a ~5.5 km/s migration [Wille, 1987] (Figure 7), the events collapse into a pattern of bent and flattened segments with an antiformal shape somewhat similar to that imaged on line 14 (Figure 5). Taken as a whole, this reflector pattern appears to represent the upper surface (i.e., separating upper and lower plates) of a broad thrust complex that climbs and verges northward. Although detailed interpretation here is not unambiguous, the alternation between dipping and flat events may result from a ramp-and-flat surface typical of thrust belts in general [e.g., Suppe, 1985, p. 343]. The increased broadness of the dipping reflective zone on the line 16-17 transect indicates an eastward widening of the Alleghanian suture zone, as well as an overall change in structural style.

The Reflection Moho in the Buried Southern Appalachians

Sub-horizontal reflections appear in discontinuous strands at between 11.0 and 12.0 or 12.5 s (33-36 or 37.5 km @ 6 km/s) on the three COCORP transects across the Georgia Coastal Plain. The reflection strands, which are typically 5-10 km long and are equally well-developed beneath the early Mesozoic basins and the suture zone (Figure 2), approximately match the depth of the Moho as determined from regional refraction data and thus have been interpreted as the "reflection Moho" [Nelson et al., 1985; Behrendt, 1986; Costain et al., 1989]. Seismic amplitude studies [Arnow, 1987] indicate that the characteristically blank section below the Moho represents an actual transparent zone in the upper mantle and not an artefact of lost signal penetration.

Raw, unprocessed shot records (Figure 8) typically show the Moho as a relatively strong, simple, 2-3 cycle event clearly visible in the near-source offsets. Because this event may contain reverberations, possibly generated in the flat-lying Atlantic Coastal Plain sequence (Cretaceous-Tertiary) in the upper ~1 s, deconvolution testing was necessary to derive a more accurate image of the reflector and to address the significance of its apparent layered character. This study considers two areas where the Moho is particularly well-expressed, beneath one of the main Triassic-Jurassic basins and beneath the dipping reflection zone along the BMA. Beneath the main basin depocentre at the northern end of line 11, the Moho appears as isolated packages of multicyclic events (e.g., Figure 9). 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. Both pre- and post-stack deconvolution applications were tested, although due possibly to noise and the complexity of the multiples, deconvolution applied post-stack often produced superior results over pre-stack. Deconvolutions having longer time lags (100 ms) produced a better defined image. The main effect of the deconvolution has been to transform a reverberative multicyclic section into one with 2 or 3 events dominated by a single prominent reflection (Figure 9). Although the events appear laterally discontinuous, because the Fresnel zone width

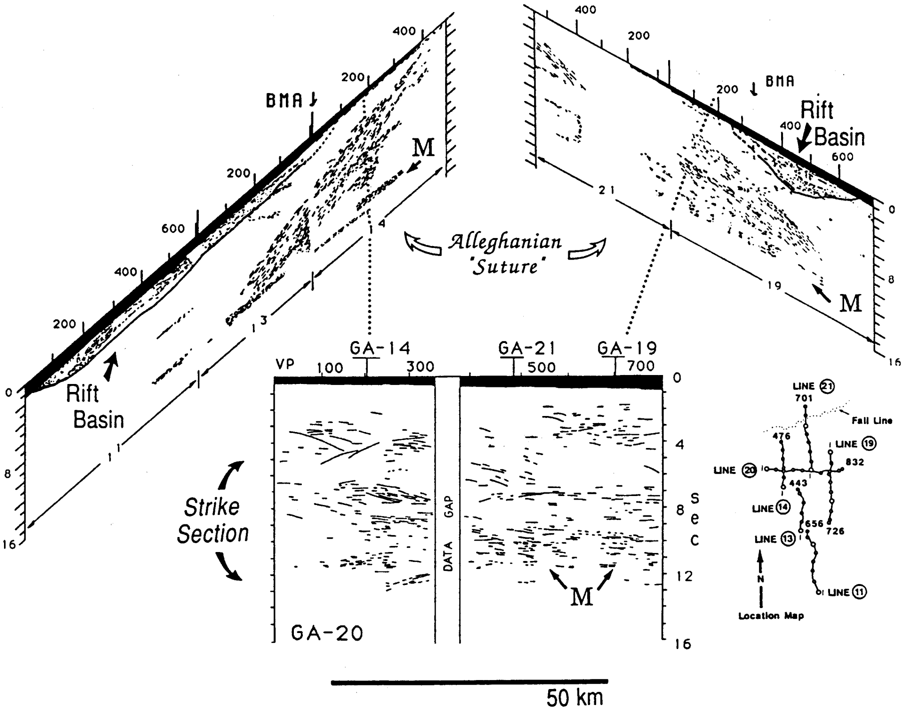

Fig. 6. Three-dimensional perspective diagram of reflection line drawings (unmigrated) of two dip sections through the Alleghanian suture and overlying rift basins, with intersecting strike section (line GA-20, vertical exaggeration = 1:1 @ 6.0 km/s). Note sub-horizontal fabric associated with the dipping reflection zones.

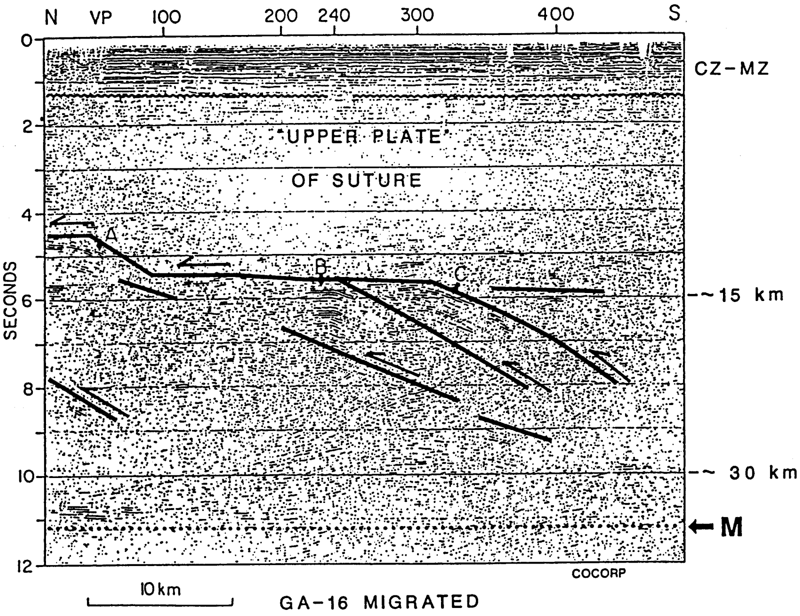

Fig. 7. Migrated (@ ~5.5 km/s) CDP section and interpretation of line 16. Note the gradual northward rise of dipping and flat reflection segments (A, B, C). M: Moho. Data processing from Wille [1987]. Vertical exaggeration = 1:1 @ 6.0 km/s.

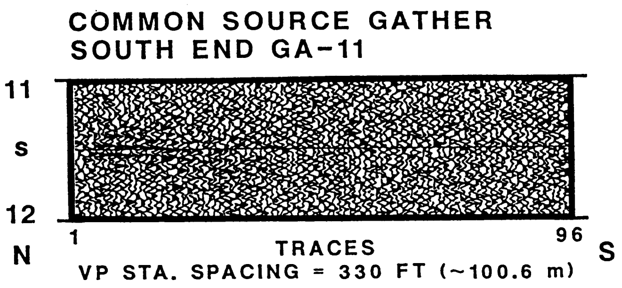

Fig. 8. Small portion of unprocessed vibrator point record from the southern end of line 11 showing well-developed Moho reflection.

at Moho traveltimes is probably at least 4.0 km (for a spherical wave; frequency ≤ 25 Hz; velocity ≥ 6.0 km/s; Sheriff and Geldart, 1982), most apparent fine-scale lateral variation is probably artificial. On the other hand, an idealised vertical resolution of 60-133 m is possible for average velocities between 6 and 8 km/s and for frequencies between 15 and 25 Hz using the "quarter wavelength" (or Rayleigh) criterion (and wavelength = velocity/frequency) [Sheriff and Geldart, 1982]. These values correspond to a reflection time "resolution" of ~30 ms which, however idealised, is well below the observed vertical separation between Moho reflections (Figure 9). Thus, the vertical "structure" of the reflection Moho on the COCORP transects may represent actual layering and not necessarily reverberation or interference.

Reprocessing of a portion of the lower crustal reflection data has been undertaken for line 13 in order to better understand the relationship between dipping Palaeozoic compressional structure and the reflection Moho. The Moho beneath the BMA dipping reflection sequence, after applying deconvolution, appears as a simple, two-cycle reflection at the base of a discontinuous band of subhorizontal reflections (Figure 10). A similar relationship is seen along lines 13, 14, 15, 19, 20, and 21 below the BMA dipping sequence (Figures 2 and 6). As argued above, this band may represent an actual thin "layered" sequence at the base of the crust just above the seismic Moho. On lines 16 and 17, where the South Georgia basin is much less developed or absent, the Moho appears as a sharp, flat reflection following pre-stack deconvolution [Wille, 1987] (northern end of line 16, Figure 7). A striking feature of the Moho is its truncation of planar dipping reflections that project downward into the lower crust. Also notable is that no dipping reflections have been observed to cross-cut or continue below the reflection Moho anywhere along the transects (Figures 2 and 6). This behaviour is suggested in Figure 10 where planar dipping events continue down to, but do not cut, the reflective band at the base of the crust. Dipping events just above the Moho remain planar and show no listric or asymptotic character as they deepen as has been interpreted from deep reflection data sets elsewhere in the Appalachians [e.g., Phinney, 1986; Hall et al., 1990].

The above analysis suggests that the multicyclic nature of the reflection Moho may represent a thin "layered" sequence at the base of the crust. The thickness of this zone ranges from 1.3 ± 0.2 km below the South Georgia basin on line 11 to 3.2 ± 0.5 km below the BMA dipping reflection zone on line 13 (@ 6-8 km/s). Based only on observed wavelet "thicknesses" and separations, individual layers 100 to 300 m thick might be expected. This observation is consistent with models of wide-angle seismic data for the lower crust and Moho in general that suggest a laminated zone involving individual layers of about 100 m thickness [Wenzel et al., 1987; Paul and Nicollin, 1989].

Synthesis

The analysis of the reflection data provides for more detailed and accurate "images" of the reflection Moho and Palaeozoic crustal structure. Constrained crustal cross-sections (Plate 1) through the Southern Appalachian orogen demonstrate both the along-strike correlation of Palaeozoic compressional structure as well as significant along-strike variability, and the relation of this structure to the Moho.

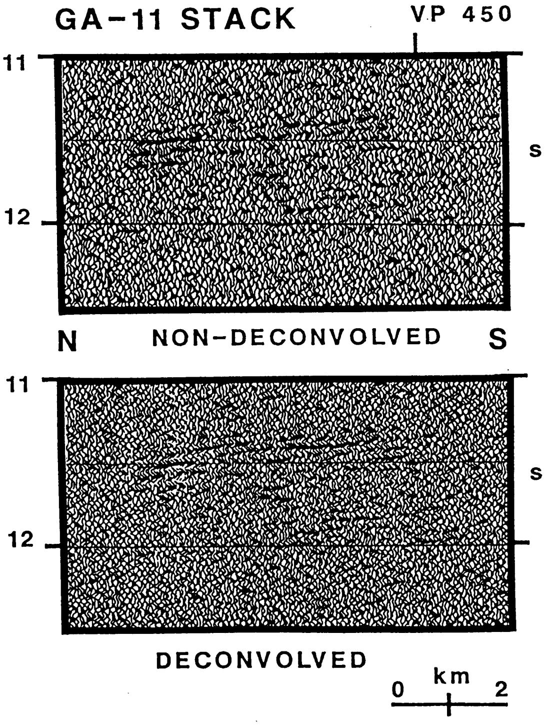

Fig. 9. Portion of CDP stack (unmigrated) of Moho on line 11 below the South Georgia basin. Note effects of pulse deconvolution (gap= 100 ms). Vertical exaggeration = 1:1 @ 6.0 km/s.

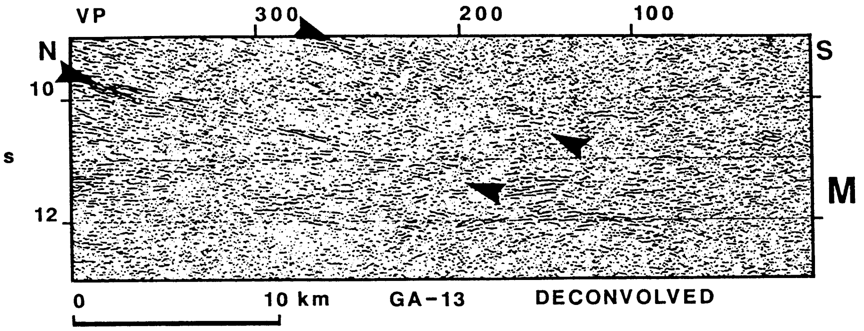

Fig. 10. Portion of line 13 below the Brunswick magnetic anomaly dipping reflection sequence showing the more complex character of the Moho (M). Vertical exaggeration = 1:1 @ 6.0 km/s.

Palaeozoic Compressional Structure

In western Georgia, regional geology [Hooper and Hatcher, 1988] indicates that the Inner Piedmont—Eastern Piedmont (Carolina-Avalon) terrane boundary ("Central Piedmont suture") projects to immediately south of the Pine Mountain Belt and forms the lower plate of the BMA dipping reflection zone on lines 13 and 14 (section Y-Y', Plate 1). The timing of this suturing is uncertain but may be associated with the mid-Palaeozoic closure of the Iapetus Ocean between the Avalonian arc and the Inner Piedmont during the Acadian or Taconic(?) orogeny [Hatcher, 1987]. Thus, at least in westernmost Georgia, both the Inner and Eastern Piedmont have been transported over autochthonous Grenville basement out of a relatively narrow root zone below lines 13 and 14 (Figure 3). This implies that the composite Inner and Eastern Piedmont with its embedded Central Piedmont suture was transported northwestward during the Alleghanian orogeny, and that at depth the Central Piedmont suture merges with (and is overprinted by) the Alleghanian suture represented by the zone of dipping reflections on lines 13 and 14. The North American-west African suture cannot be located as accurately but would be very near to the upper plate of the BMA dipping reflection zone (section Y-Y', Plate 1). Constrained magnetic intensity modeling of the BMA [McBride and Nelson, 1988] suggests that the outboard portion of the suture was intruded (reactivated?) by early Mesozoic-age, highly magnetised (Figure 2) mafic/ultramafic material (gabbroic composition?) as part of a zone of rift-stage crust [cf. Hutchinson et al., 1983] that extended onland from the present-day offshore along the East Coast magnetic anomaly. The implication of all the above is that in western Georgia, mid- and late Palaeozoic sutures have occupied the same, or nearly the same, thrust root zone which was reactivated yet again by a concentration of early Mesozoic intrusion (Plate 1, section Y-Y').

On the eastern Georgia transect (section X-X', Plate 1), the BMA dipping reflection zone is shallower-dipping and broader—here regional geology [Chowns and Williams, 1983; Secor et al., 1986] suggests that the northern limit of west African crust extends further northward and produces a broadened zone of "crustal overlap" of west African and North American Piedmont terranes [Tauvers and Muehlberger, 1987] as shown in Plate 1. This crustal overlap appears to have been accommodated by a more distributed deformation within the suture. Likewise, the Eastern Piedmont terrane, between the west African and Central Piedmont sutures, is even more expanded as an allochthonous sheet transported over thinned Grenville or "transitional" crust [Cook et al., 1983; Phinney and Roy-Chowdhury, 1989]. Along the eastern Georgia section, the crust is marked by a wider distribution of deformation including a possible additional root zone below the Augusta fault. Phinney and Roy-Chowdhury [1989] interpret this feature as a root zone for the Taconic thrusts further north. The location of the southernmost edge of Grenville basement here is unknown but analysis of the reflectivity of the dipping reflection zone down-dip of the Augusta fault (Plate 1) suggests a limit as shown in section X-X' [cf. Phinney and Roy-Chowdhury, 1989] although a root zone much further outboard (e.g., offshore) is also conceivable [Seeber and Armbruster, 1981].

In summary, Alleghanian convergence has transported the entire Inner and Eastern Piedmont northwestward over an eastward-widening autochthon between western and eastern Georgia. The widening of the Alleghanian allochthon is shown diagrammatically in Plate 1 as the eastward opening of the zone defined by arrows (between ↓ and ↑). Thrusting associated with Alleghanian convergence roots into the lower crust and upper mantle at the North American/west African suture (↓, Plate 1) and rises into the upper crust or surface at the Central Piedmont suture (↑, Plate 1) and beyond in the Valley and Ridge thrust belt.

An Early Mesozoic Age for the Moho?

The enhanced reflectivity and relative shallowness of the reflection Moho below the Piedmont and the Atlantic Coastal Plain lead to a suggestion of an early Mesozoic age for the

Moho below the Appalachian orogen [see also Nelson et al., 1986; Nelson et al., 1987b; McBride et al., 1988]. The seismic expression of the reflection Moho on the COCORP data consists of a relatively thin package of discontinuous events. Much thicker and well-developed "layered" sequences in the lower crust occur elsewhere and have been associated with regional extension [e.g., U.S. Basin and Range, Klemperer et al., 1986; North Sea, Matthews and Cheadle, 1986; western Europe, Bois et al., 1988] or a crust-mantle décollement [Matte and Hirn, 1988]. No clear explanation for these sequences has emerged, but possible interpretations have included high-strain shear zones [Reston, 1988], or basaltic sills [Nelson, 1991; Warner, 1990]. The presence of a layered reflection sequence at the Moho may be suggestive of material added to the base of the crust [e.g., Latham et al., 1988]. The mechanism of magmatic "underplating" of the lower continental crust [Furlong and Fountain, 1986] by, for example, ponding of basaltic magma from the mantle [Meissner et al., 1983] could explain the observed highly reflective and layered expression of the Moho. For the Southern Appalachians, an interpretation of basaltic sill intrusion at the base of the crust is consistent with a regional geologic history of extension and graben formation (e.g., in the South Georgia basin) together with the widespread occurrence of early Mesozoic tholeiitic basalt/diabase dikes, sills, and/or flows in the upper crust [Nelson et al., 1986; de Boer et al., 1988; McBride et al., 1989]. Furthermore, the truncation of planar thrust surfaces within the suture zone by the reflection Moho carries a strong implication that the Moho is a younger feature that cross-cuts, and thus is unrelated to, older compressional structure. Because the youngest tectonic event in the Appalachians is manifested as faulting and magmatism associated with early Mesozoic crustal thinning and heating, and the initial opening of the North Atlantic Ocean, a probable candidate age for the Moho is Triassic-Jurassic.

Cook and Oliver [1981] have previously interpreted the presence of thinned crust in the Appalachians as a relict late Precambrian/early Palaeozoic rifted margin (i.e., seaward limit of Precambrian Grenville basement) delineated by the Appalachian gravity gradient (Figure 1), although as pointed out by Hutchinson et al. [1983], the observed crustal thickness differential seems too small to represent a true continent-ocean crust transition (i.e., only ~10 instead of 30 km). The relict margin hypothesis can be rephrased by asking, where is the easternmost extent of Precambrian Grenville basement? In the New England Appalachians, the restored position of exposed Grenville basement is far east of the gravity gradient and presumed edge of crustal thinning [Stanley and Ratcliffe, 1985]. As stressed above, the southern limit of Grenville basement in the Southern Appalachians is unknown but probably extends beyond the gravity gradient (Figure 1 and Plate 1) [Phinney and Roy-Chowdhury, 1989] and thus would be unrelated to crustal thinning, whatever the cause. As argued in the present study, an explanation for crustal thinning and Moho development involving early Mesozoic rifting magmatic processes is more attractive in being consistent with the post-Palaeozoic geologic history of the Appalachians.

Acknowledgments. Data processing and reprocessing were performed at the Institute for the Study of the Continents at Cornell University. This research was supported largely by United States National Science Foundation grants to the COCORP project, most recently EAR-89161129. E. I. Prussen suggested some of the steps used in data processing. AGU reviews by P. Matte and an anonymous referee improved the paper. Institute for the Study of the Continents Contribution No. 166.

References

Ando, C. J., B. L. Czuchra, S. L. Klemperer, L. D. Brown, M. J. Cheadle, F. A. Cook, J. E. Oliver, S. Kaufman, T. Walsh, J. B. Thompson, Jr., J. B. Lyons, and J. L. Rosenfeld, Crustal profile of mountain belt: COCORP deep seismic reflection profiling in New England Appalachians and implication for architecture of convergent mountain chains, *Am. Assoc. Petrol. Geol. Bull., 68*, 819-837, 1984.

Arnow, J. A., Deep structure from continental collision: COCORP deep seismic reflection profiles across the southern Appalachians [M.S. thesis]: Cornell University, Ithaca, New York, 82 pp., 1987.

Behrendt, J. C., 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 *Reflection seismology: The Continental Crust, Geodyn. Ser., vol. 14*, edited by M. Barazangi and L. D. Brown, pp. 201-214, AGU, Washington, D. C., 1986.

Bois, C., M. Cazes, A. Hirn, A. Mascle, P. Matte, L. Montadert, and B. Pinet, Contribution of deep seismic reflection profiling to the knowledge of the lower crust in France and neighbouring areas, *Tectonophys. 145*, 253-275, 1988.

Chowns, T. M., and C. T. Williams, Pre-Cretaceous rocks beneath the Georgia Coastal Plain - regional implications, in Studies Related to the Charleston, South Carolina, Earthquake of 1886—Tectonics and Seismicity, edited by G. S. Gohn, *U.S. Geol. Surv. Prof. Pap. 1313*, L1-L42, 1983.

Cook, F. A., L. D. Brown, S. Kaufman, and J. E. Oliver, The COCORP seismic reflection traverse across the southern Appalachians, *AAPG Stud. Geol., 14*, 61 pp., 1983.

Cook, F. A., and J. E. Oliver, The late Precambrian–early Paleozoic continental edge in the Appalachian orogen, *Am. J. Sci., 281*, 993-1008, 1981.

Çoruh, C., J. K. Costain, R. D. Hatcher, Jr., T. L. Pratt, R. T. Williams, and R. A. Phinney, Results from regional vibroseis profiling: Appalachian ultra-deep core hole site study, *Geophys. J. R. astr. Soc., 89*, 147-156, 1987.

Costain, J. K., R. D. Hatcher, Jr., C. Çoruh, T. L. Pratt, S. R. Taylor, J. J. Litehiser, and I. Zietz, Geophysical characteristics of the Appalachian crust, *The Geology of North America, Volume F-2*, in *The Appalachian-Ouachita Orogen in the United States*, edited by R. D. Hatcher, Jr., W. A. Thomas, and G. W. Viele, pp. 385-416, Geological Society of America, Boulder, Colo., 1989.

Dallmeyer, R. D., M. Caen-Vachette, and M. Villeneuve, Emplacement age of the post-tectonic granites in southern Guinea (West Africa) and the peninsular Florida subsurface: Implications for origins of southern Appalachian exotic terranes, *Geol. Soc. Am. Bull., 99*, 87-93, 1987.

de Boer, J. Z., J. G. McHone, J. H. Puffer, P. C. Ragland, and D. Whittington, Mesozoic and Cenozoic magmatism, in *The Geology of North America, Volume I-2, The Atlantic Continental Margin, U.S.*, edited by R. E. Sheridan and J. A. Grow, pp. 217-241, Geological Society of America, Boulder, Colo., 1988.

Furlong, K. P., and D. M. Fountain, Continental crustal underplating: Thermal considerations and seismic-petrologic consequences, *J. Geophys. Res., 91*, 8285-8294, 1986.

Hall, J., G. Quinlan, F. Marillier, and C. Keen, Dipping shear zones and the base of the crust in the Appalachians, offshore Canada, *Tectonophys., 173*, 581-593, 1990.

Hatcher, Jr., R. D., Tectonics of the southern and central Appalachian internides, *Ann. Rev. Earth Planet. Sci., 15*, 337-362, 1987.

Hooper, R. J., and R. D. Hatcher, Jr., Pine Mountain terrane, a complex window in the Georgia and Alabama Piedmont; evidence from the eastern termination, *Geology, 16*, 307-310, 1988.

Horton, J. W., Jr., A. A. Drake, Jr., and D. W. Rankin, Tectonostratigraphic terranes and their Paleozoic boundaries in the central and southern Appalachians, in Terranes in the Circum-Atlantic Paleozoic Orogens, edited by R. D. Dallmeyer, *Spec. Pap. Geol. Soc. Am. 230*, 213-246, 1989.

Hutchinson, D. R., J. A. Grow, K. D. Klitgord, and B. A. Swift, Deep structure and evolution of the Carolina trough, in Studies in Continental Margin Geology, edited by J. S. Watkins and C. L Drake, *Am. Assoc. Petrol. Geol. Mem., 34*, pp. 129-154, 1983.

Hutchinson, D. R., J. A. Grow, and K. D. Klitgord, Crustal structure beneath the southern Appalachians: Nonuniqueness of gravity modeling, *Geology, 11*, 611-615, 1983.

Klemperer, S. L., T. A. Hauge, E. C. Hauser, J. E. Oliver, and C. J. Potter, The Moho in the northern Basin and Range province, Nevada, along the COCORP 40°N seismic reflection transect, *Geol. Soc. Am. Bull., 97*, 603-618, 1986.

Matte, P., and A. Hirn, Seismic signature and tectonic cross section of the Variscan crust in western France, *Tectonics, 7*, 141-155, 1988.

Matthews, D. H., and M. J. Cheadle, Deep reflections from the Caledonides and Variscides west of Britain and comparison with the Himalayas, in *Reflection seismology: The Continental Crust, Geodyn. Ser., vol. 14*, edited by M. Barazangi and L. D. Brown, pp. 5-19, AGU, Washington, D. C., 1986.

McBride, J. H., and K. D. Nelson, Integration of COCORP deep reflection and magnetic anomaly analysis in the southeastern United States: Implications for the origin of the Brunswick and East Coast magnetic anomalies, *Geol. Soc. Am. Bull., 100*, 436-445, 1988.

McBride, J. H., K. D. Nelson, and L. D. Brown, Regional Bouguer gravity and deep seismic reflection patterns in the Appalachian-Ouachita orogen [abstract], *EOS Trans.* AGU, 1988.

McBride, J. H., K. D. Nelson, and L. D. Brown, Evidence and implications of an extensive early Mesozoic rift basin and basalt/diabase sequence beneath the Southeast Coastal Plain, *Geol. Soc. Am. Bull., 101*, 512-520, 1989.

Nelson, K. D., A unified view of craton evolution motivated by recent deep seismic reflection and refraction results, *Geophys. J. Int.*, 1991.

Nelson, K. D., J. A. Arnow, J. H. McBride, J. H. Willemin, J. Huang, L. Zheng, J. E. Oliver, L. D. Brown, and S. Kaufman, New COCORP profiling in the southeastern United States. Part I: Late Paleozoic suture and Mesozoic rift basin, *Geology, 13*, 714-718, 1985.

Nelson, K. D., J. A. Arnow, M. Giguere, and S. Schamel, Normal-fault boundary of an Appalachian basement massif?: Results of COCORP profiling across the Pine Mountain belt in western Georgia, *Geology, 15*, 832-836, 1987a.

Nelson, K. D., J. H. McBride, and J. A. Arnow, Deep reflection character, gravity gradient, and crustal thickness variation in the Appalachian orogen: relation to Mesozoic extension and igneous activity [abstract], *Geol. Soc. Am. Abstr. Prog., 18*, 704-705, 1986.

Nelson, K. D., J. H. McBride, J. A. Arnow, D. M. Wille, L. D. Brown, J. E. Oliver, and S. Kaufman, Results of recent COCORP profiling in the southeastern United States, *Geophys. J. R. astr. Soc., 89*, 141-146, 1987b.

Paul, A., and F. Nicollin, Thin crustal layering in Northern France: observations and modelling of the P_MP spectral content, *Geophys. J. Int., 99*, 229-246, 1989.

Phinney, R. A., A seismic cross section of the Appalachians; The orogen exposed, in *Reflection seismology: The Continental Crust, Geodyn. Ser., vol. 14*, edited by M. Barazangi and L. D. Brown, pp. 157-172, AGU, Washington, D. C., 1986.

Phinney, R. A., and K. Roy-Chowdhury, Reflection seismic studies of crustal structure in the eastern United States, in *Geophysical framework of the continental United States*, edited by L. C. Pakiser, and W. D. Mooney, *Geol. Soc. Am. Mem., 172*, 613-653, 1989.

Pratt, T. L., Ç. Coruh, J. K. Costain, and L. Glover, III, A geophysical study of the Earth's crust in central Virginia: Implications for Appalachian crustal structure, *J. Geophys. Res., 93*, 6649-6667, 1988.

Reston, T. J., Evidence for shear zones in the lower crust offshore Britain, *Tectonics, 7*, 929-945, 1988.

Secor, Jr., D. T., A. W. Snoke, and R. D. Dallmeyer, Character of the Alleghanian orogeny in the southern Appalachians: Part III. Regional tectonic relations, *Geol. Soc. Am. Bull., 97,* 1345-1353, 1986.

Seeber, L., and J. G. Armbruster, The 1886 Charleston, South Carolina earthquake and the Appalachian Detachment, *J. Geophys. Res., 86*, 7874-7894, 1981.

Sheriff, R. E., and L. P. Geldart, *Exploration Seismology Volume I*, 253 pp., Cambridge University Press, 1982.

Stanley, R. S., and N. M. Ratcliffe, Tectonic synthesis of the Taconian orogeny in western New England, *Geol. Soc. Am. Bull., 96*, 1227-1250, 1985.

Suppe, J., *Principles of structural geology*, 537 pp., Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1985.

Tauvers, P. R., and W. R. Muehlberger, Is the Brunswick magnetic anomaly really the Alleghanian suture?, *Tectonics, 6,* 331-342, 1987.

Warner, M., Migration-why doesn't it work for deep continental data?, *Geophys. J. R. astr. Soc., 89*, 21-26, 1987.

Warner, M., Basalts, water, or shear zones in the lower continental crust?, *Tectonophys., 173*, 163-174, 1990.

Wenzel, F., K. Sandmeier, and W. Wälde, Properties of the lower crust from modeling refraction and reflection data, *J. Geophys. Res., 92*, 11575-11583, 1987.

Wille, D. M., The COCORP Surrency bright spot: possible evidence for fluid in the deep crust [M. S. thesis]: Cornell University, Ithaca, New York, 46pp., 1987.

Zheng, L., and L. D. Brown, Application of coherency enhancement to deep reflection data, *EOS Trans., 67*, AGU, 303, 1986.