COCORP seismic profiling of the Appalachian orogen beneath the Coastal Plain of Georgia

FREDERICK A. COOK
LARRY D. BROWN
SIDNEY KAUFMAN
JACK E. OLIVER
TODD A. PETERSEN
Department of Geological Sciences, Cornell University, Ithaca, New York 14853

ABSTRACT

A southeastward extension onto the Coastal Plain of an earlier COCORP traverse, which confirmed large-scale, thin-skinned thrusting of crystalline rocks of the southern Appalachians, has provided some of the most spectacular reflections yet seen in crustal seismic data. Most of the reflectors can be interpreted as either fault surfaces or as metamorphosed strata of late Precambrian–early Paleozoic age. They are consistent with the hypothesis that a major detachment extends eastward beneath this part of the orogen, although other interpretations with a more complex pattern of detachments or sutures are also possible. Large-scale overthrusting provides a mechanism for incorporating sedimentary rocks into the lower crust and may help to explain many of the layered features on crustal seismic data. Reflections from deep beneath the Coastal Plain indicate that the structural configuration of the rocks is complex and that the remains of a collision zone are being observed. Several east-dipping horizons, which bear strong similarities to thrust faults in Valley and Ridge sedimentary rocks, are seen in the basement at shallow and mid-crustal levels beneath the Coastal Plain. The Augusta fault, for example, displays a reflection which extends at a low angle some 80 km or more southeast of its surface position. In conjunction with surface geologic information, these new data demonstrate that late Paleozoic compressive deformation was pervasive and resulted in lateral movements in the upper crust extending from the Valley and Ridge to the crystalline rocks beneath the Coastal Plain — a distance of 400 km or more. A large antiform, cresting at about 2.3 sec, or about 6 km below the surface, and other structures beneath the Coastal Plain of Georgia deserve further consideration for petroleum exploration, although metamorphism may have eliminated petroleum from these rocks. Refracted arrivals and fault geometries indicate two Triassic rift basins beneath Coastal Plain sedimentary rocks, one of which has apparently not been recognized previously.

INTRODUCTION

With the recent addition of new data from the Eastern Piedmont and Coastal Plain, seismic-reflection profiles which cross much of the southern Appalachian orogen from the Valley and Ridge foreland belt to within a few miles of the Atlantic coastline have now been obtained by the Consortium for Continental Reflection Profiling (COCORP) (Figs. 1 and 2). These data are perhaps the first crustal-scale seismic-reflection data which transect a significant portion of an orogen and thus provide important information on the deep structure and formation of such a mountain system. The data demonstrate the great significance of westward-directed, horizontal compressive deformation and thin-skinned thrusting in the Paleozoic evolution of the southern Appalachians, and illustrate other complexities of the orogenic process.

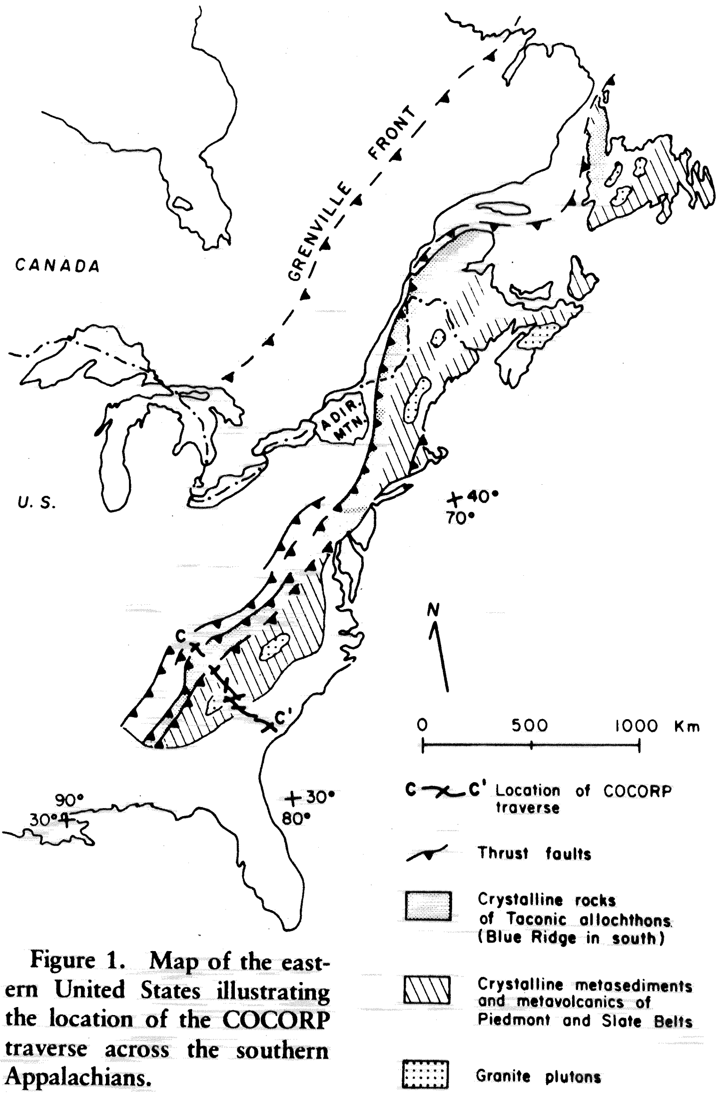

Figure 1. Map of the eastern United States illustrating the location of the COCORP traverse across the southern Appalachians.

Initial COCORP profiling revealed that reflections from layers

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Geological Society of America Bulletin, Part I, v. 92, p. 738–748, 8 figs., October 1981.

which are most easily interpreted as sedimentary strata can be traced eastward from the Valley and Ridge beneath the overthrust crystalline rocks of the Blue Ridge and Inner Piedmont (Cook and others, 1979). Thus, the Blue Ridge and Inner Piedmont have ridden westward above one or more major, subhorizontal detachments. However, as horizontal reflectors of unknown lithologies could be traced to the southeastern limit of the initial traverse (Fig. 3, H of Cook and others, 1979), it was uncertain how far detachments extend east of the Inner Piedmont, if at all. In one interpretation, for example, a décollement could extend in the crystalline rocks as far east as the present continental shelf (Cook and others, 1979; Harris and Bayer, 1979). The continuation of the COCORP traverse was in part intended to test such concepts by obtaining deep crustal information from beneath the Eastern Piedmont and Coastal Plain.

The new traverse extends from Lexington, Georgia, to within 30 km of Savannah, Georgia, thus crossing the Charlotte belt, Modoc Line, Kiokee belt, and Coastal Plain (Fig. 2). In this paper, the boundary between the Carolina slate belt and the Kiokee belt is referred to as the "Modoc Line" as suggested by Snoke and others (1980a). In some areas, it is demonstrably a fault, whereas in others, it is apparently a steep metamorphic gradient. The profile does not apparently cross exposed lithologies of the Carolina slate belt or the Belair belt (Pickering, 1976), although the Belair belt is probably present beneath the thin Coastal Plain cover on Line 5 (Fig. 2).

Due to the length of the traverse and the difficulty of reproducing seismic sections, the data are presented for this paper in line drawings, with certain portions of actual seismic sections shown to illustrate significant features. Except for hand migration of certain critical features, these data have not yet been migrated, although the presence of dipping events suggests that enhanced detail and somewhat improved interpretation may result from precise migration of reflections to their correct spatial positions. Otherwise, a normal sequence of processing has been applied (Schilt and others, 1979). In general, the data are discussed by referring to surface geological nomenclature. However, since a significant amount of lateral transport of the surface rocks may have taken place, there may be little or no relationship between a surface feature and the subsurface structures revealed by the seismic data directly below it. From northwest to southeast, the following is a description of the major observations.

Charlotte Belt–Modoc Line

The recently acquired data were recorded along a line (Line 5; see Fig. 2) which is parallel to the east end of the original traverse. The new line was tied to the original profile by extending a cross line (Line 4) southwestward (Fig. 2). In the area from the northwestern end of the profile to the Modoc Line, the surface geologic features consist of northeast-striking, polyphase deformed metasedimentary and metavolcanic rocks of the Charlotte belt. The Carolina slate belt is located southeast of the Charlotte belt throughout much of the Carolinas and east-central Georgia. However, surface exposures of Carolina slate belt lithologies may not extend as far southwest as the new profile (Pickering, 1976).

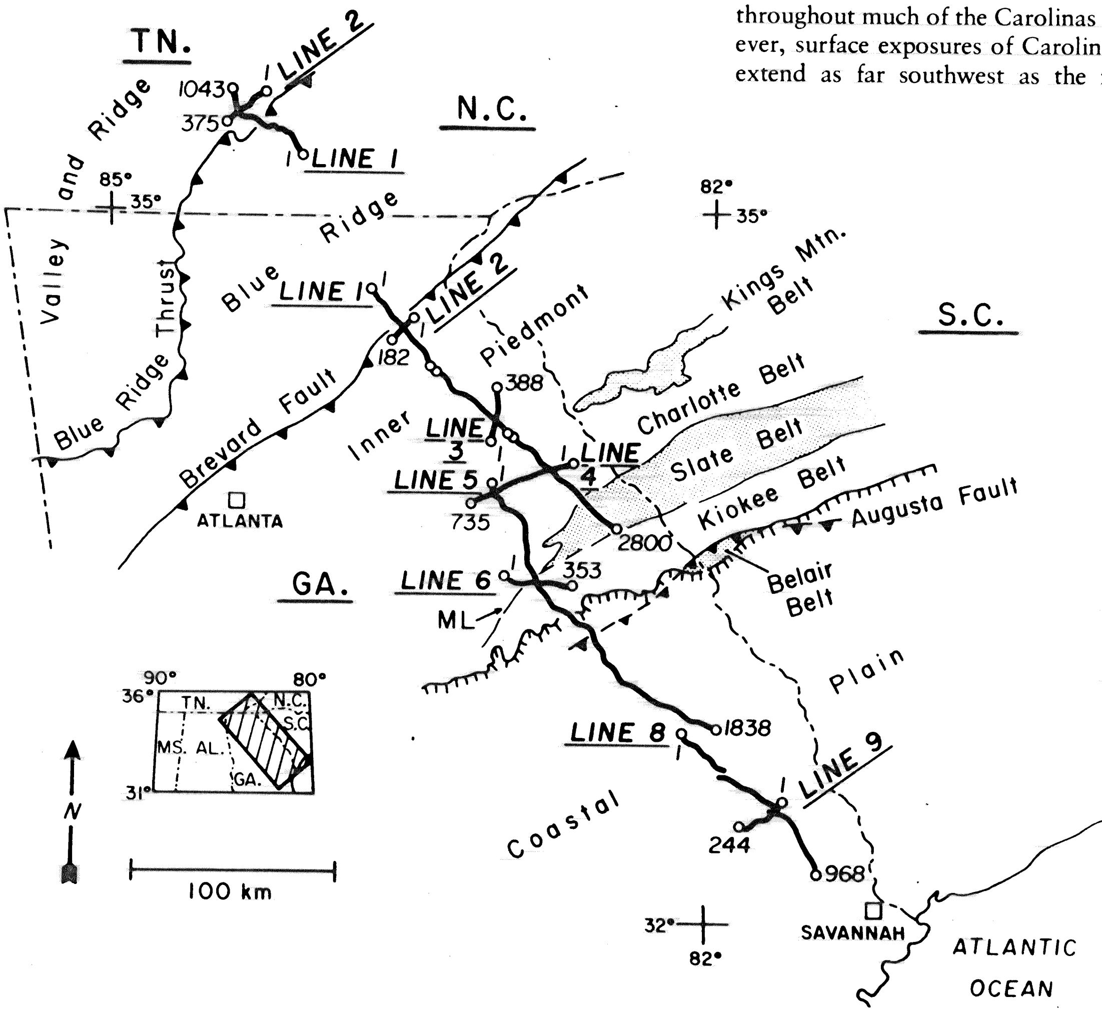

Figure 2. Location diagram for the COCORP profiles in the southern Appalachians. Geologic contacts and faults are from Pickering (1976) and Williams (1978). ML = Modoc Line.

Additionally, the projection of the Modoc Line based on magnetic anomalies (Hatcher and others, 1977) would place it between stations 450 and 500 on Line 5 (Fig. 3).

The reflection data show several southeast-dipping events near the northwest end of Line 5 at two-way travel times of 3.5 to 5.5 sec (about 10.5- to 16.5-km depth for an average velocity of 6.0 km/sec; Fig. 3, location A). Similar reflections were observed on the initial traverse 30 km to the northeast (Fig. 3, G of Cook and others, 1979). It thus appears that these events are correlative along strike and demonstrate the existence of east-dipping layers beneath the Charlotte belt over this distance. The exact lithologic and structural nature of these layers is unknown at this time. One model (Hatcher and Zietz, 1980) holds that they may be from thrust faults or layers that dip steeply into the crust. Another interpretation (Cook and Oliver, 1981) implies that these reflections are from late Precambrian and/or early Paleozoic strata that may have been deposited near an ancient shelf edge, or that may have been imbricately stacked against a shelf edge as lateral movement occurred during thrusting.

Southeast of these layers, there is a sequence of subhorizontal reflections which extends to at least station 400 (Fig. 3, B). As similar events were observed from beneath the Charlotte and Carolina slate belts on the original traverse (Cook and others, 1979, their Fig. 3, H), the presence of these reflections on the new data strongly implies that the zone of reflectors is continuous along strike. Furthermore, Black and others (1975) have observed reflections at 4.0 to 5.0 sec in the Carolina slate belt of North Carolina, nearly 400 km northeast of the COCORP traverses. It is thus possible that such layers are present at depth over an extensive area of the Eastern Piedmont.

The assignment of lithologies to the reflectors at depth is neither straightforward nor unambiguous. However, the continuity, layered character, and lateral position of the mid-crustal layers with respect to the (interpreted) shelf strata to the northwest suggest that they may be layered (meta-) sedimentary strata which were deposited basinward of the late Precambrian–early Paleozoic shelf of southeast proto–North America. In support of this idea, the seismic-refraction velocities in the middle crust of this area do not appear (on average) to exceed 6.0 km/sec (Long, 1979; Lee, 1980; Dainty and others, 1980). Other possible interpretations could include layered intrusions or layered metamorphic rocks which bear no direct relationship to the shelf strata to the west.

Reflections returned from the lower crust (below 6.0 sec) in this area bear no obvious relationship to those observed on the initial

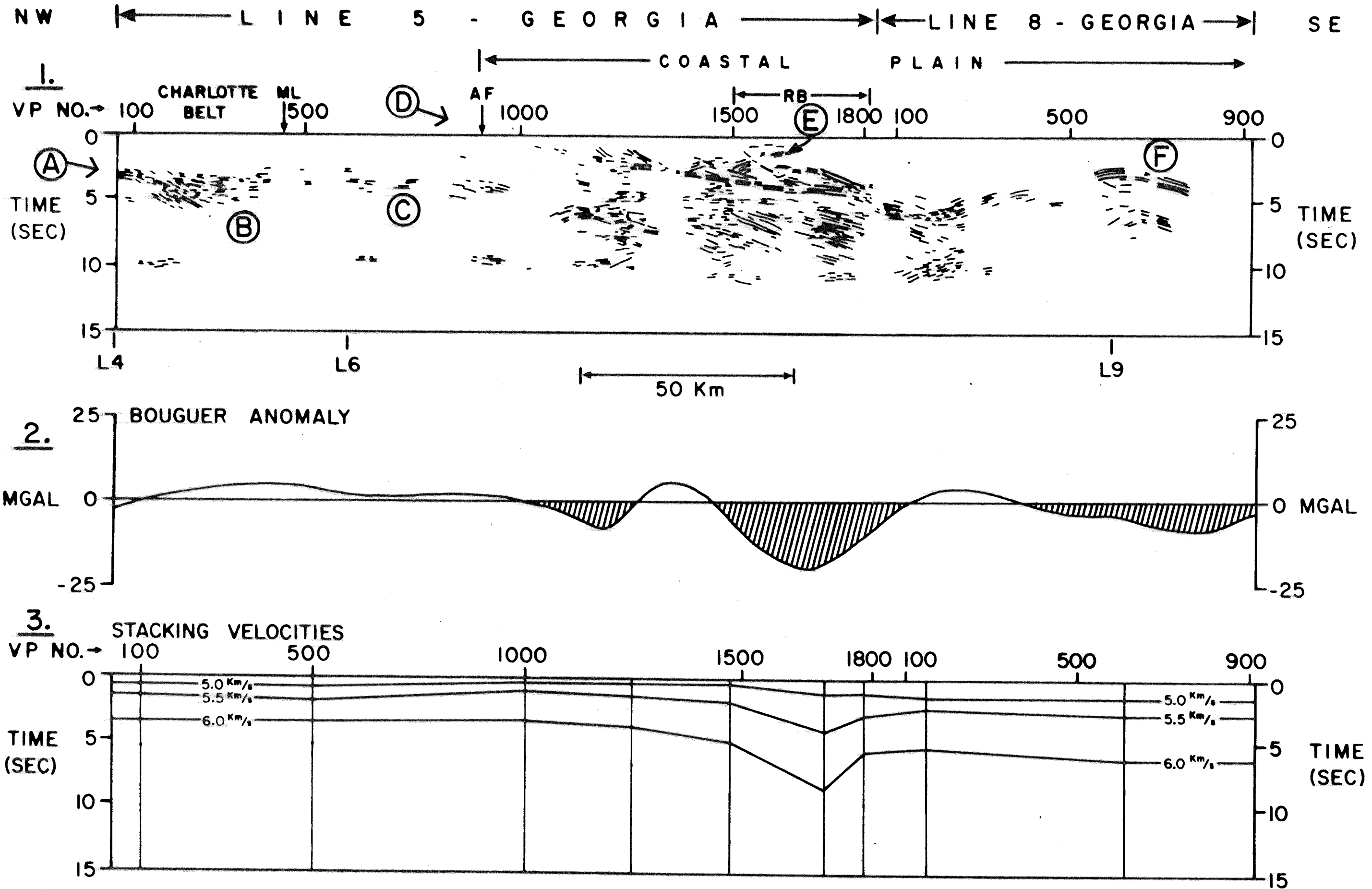

Figure 3. (1) Line drawing of seismic events seen on the COCORP profile from the Eastern Piedmont to near Savannah, (2) Bouguer gravity profile along the COCORP line (from Long and others, 1972), and (3) stacking (processing) iso-velocity contours calculated from the reflection data. The letters denote significant reflection features discussed in the text, and the shaded areas on the gravity profile show low values which correspond to the layering observed on the reflection data. Locations of the cross lines are indicated by L4, L6, and L9. Abbreviations used are: ML = Modoc Line, AF = Augusta fault, RB = Riddleville basin.

traverse. In particular, an apparently significant west-dipping feature which was present on the first profile (Cook and others, 1979, their Fig. 3, J) has no obvious counterpart on the new profile. The implication is that the event on the original data may be a local feature, or some kind of coherent seismic "noise" (for example, a reflected refraction).

As on the original traverse, laminated reflections are present on the new traverse at 10.0 to 11.0 sec. As pointed out by Cook and others (1979), these may be reflections from the vicinity of the crust-mantle transition (Moho).

Data near the Modoc Line or its southwestward extension show few reflection events. There are at least two possible reasons for the lack of returned energy in this area. First, the Kiokee belt and Modoc Line are characterized by a complex zone of multiply deformed, steeply dipping rocks which may extend to depth. As the technique of seismic-reflection profiling preferentially enhances reflections from low-angle boundaries, this zone may produce few identifiable events. Second, this area is characterized by excessive cultural noise (towns and interstate highways, for example) which can mask the returned signals. As these effects cannot be distinguished in this case, the significance of the loss of reflections cannot be evaluated. However, since there appear to be no clear reflection events from the lower crust or Moho in this area, whereas there are in adjoining areas, the interpretation that the signal to noise ratio is low is favored.

Kiokee Belt–Augusta Fault–Belair Belt

The Kiokee belt is an area of polyphase deformed, highly metamorphosed rocks which are probably high-grade equivalents to the Carolina slate belt lithologies (Secor and Snoke, 1978; Snoke and others, 1980a, 1980b). Many of the late Paleozoic (320-260 ma) intrusives in this area have been affected by post-intrusion folding episodes and brittle deformation. At least four stages of deformation have been recognized in the Eastern Piedmont, three of which are demonstrably Carboniferous or later (Secor and Snoke, 1978; Snoke and others, 1980a, 1980b). The Kiokee belt is flanked on the northwest by the Modoc Line, which is described as a steep metamorphic gradient in some areas and a brittle fault in others (Snoke and others, 1980b). Southeast of the Kiokee belt is the Augusta fault which displays an early history of deep-seated ductile deformation and a later stage of brittle faulting (Maher, 1978). The Augusta fault has been interpreted as an east-dipping, late Paleozoic thrust fault which juxtaposes the low-grade (greenschist) rocks of the Belair belt against the higher-grade Kiokee belt assemblages (Maher, 1978). Southeast of the Augusta fault, the Belair belt is a zone of low-grade metasedimentary and metavolcanic rocks which show lithologic similarities to rocks of the Carolina slate belt.

The seismic profiles do not cross exposures of either the Augusta fault or the Belair belt, for in this area they are covered by Coastal Plain sedimentary strata (Fig. 2). However, a southwestward extension of the Augusta fault based on magnetic data (Prowell, 1978) indicates that the COCORP traverse should cross it near stations 900 to 1,000 (Line 5).

Reflection data from the Kiokee belt and Belair belt exhibit several events. Between stations 600 and 900, subhorizontal reflections are visible at 4.0 to 5.5 sec (Fig. 3, C). In this area, our traverse crosses the Sparta granite (between stations 650 and 900) which has been shown to have a complex intrusive history (Fullagar and Butler, 1976). The reflections at 4.0 to 5.5 sec may represent a subhorizontal detachment which correlates with a decollement to the west at about the same depth, or may indicate the base of the granite or some other unrelated feature. However, the fact that these reflections occur at about the same travel time as those from beneath the Charlotte belt is an important, although not conclusive, indication that they are correlative with the mid-crustal Charlotte belt layers, and thus that a detachment extends eastward. Few reflections are present at times less than 4.0 sec, suggesting that the near-surface rocks may be structurally complex, or homogeneous with respect to the input signal.

Farther to the east, numerous reflections are seen throughout the crust as the profile encroaches upon Coastal Plain sedimentary rocks. The data quality improves considerably where the profile traverses the thin surface sediment layers of the Coastal Plain. A major east-dipping reflecting boundary is evident (Fig. 3, D and Fig. 4), and it projects to the surface location of the Augusta fault. This event is almost certainly a reflection from the fault zone; its extent (about 80 km southeast from the surface position) and its character imply that it is an important lithologic and tectonic boundary in the crystalline crust of this area.

Coastal Plain

The sedimentary cover of the Coastal Plain consists primarily of Cretaceous and Tertiary rocks which were deposited from subaerial erosion of the Appalachians following the opening of the Atlantic Ocean. In some areas, there are extensional basins (such as the Dunbarton basin described by Marine and Siple, 1974) which contain rocks as old as Triassic. The Coastal Plain cover thickens southeastward to as much as 1.5 km near the coast (Milton and Hurst, 1965).

The shallow data reflect the presence of Triassic basins beneath the Coastal Plain; the most effective indicators of Triassic material are the first refracted waves. The Triassic rocks typically have seismic velocities of 4.5 to 5.0 km/sec (Siple, 1967) and are intermediate between the velocities of Coastal Plain sediments (about 2.0 to 3.0 km/sec) and sub–Coastal Plain crystalline rock velocities (about 6.0 to 6.2 km/sec). Examination of the field data for appropriate refracted arrivals indicates that there is at least one, and perhaps a second, "peripheral" Triassic basin located beneath our profile (a peripheral basin being one which is not part of the main Atlantic rift; Daniels and Zietz, 1981). The larger of these is located between stations 1500 and 1800 on Line 5 and has a depth to basement of about 2.1 to 2.5 km based on refracted arrivals. The existence of this basin was first proposed by Daniels and Zietz (1978), on the basis of magnetic anomalies; they later labeled it the "Riddleville basin" (Daniels and Zietz, 1981) and calculated a depth to the crystalline basement of 1.7 to 2.2 km. A recent well confirmed the presence of Triassic rocks in this basin (Daniels and Zietz, 1981). Northwest of this basin, short segments of refracted arrivals with velocities of 4.5 to 5.0 km/sec indicate that there may be a small Triassic basin between stations 1100 and 1250 on Line 5. Although this latter area (about 33.2°N lat. and 82.3°W long.) corresponds to a small gravity low (Long and others, 1972) and magnetic low (Daniels and Zietz, 1981), there apparently has not been a previous suggestion of Triassic material this far northwest.

The Triassic basins may produce slight velocity "pulldown" anomalies since they effectively replace crystalline material with lower velocity Triassic sediments. However, for a basin that is 2.0 km deep, the maximum anomaly expected is about .10 sec, and

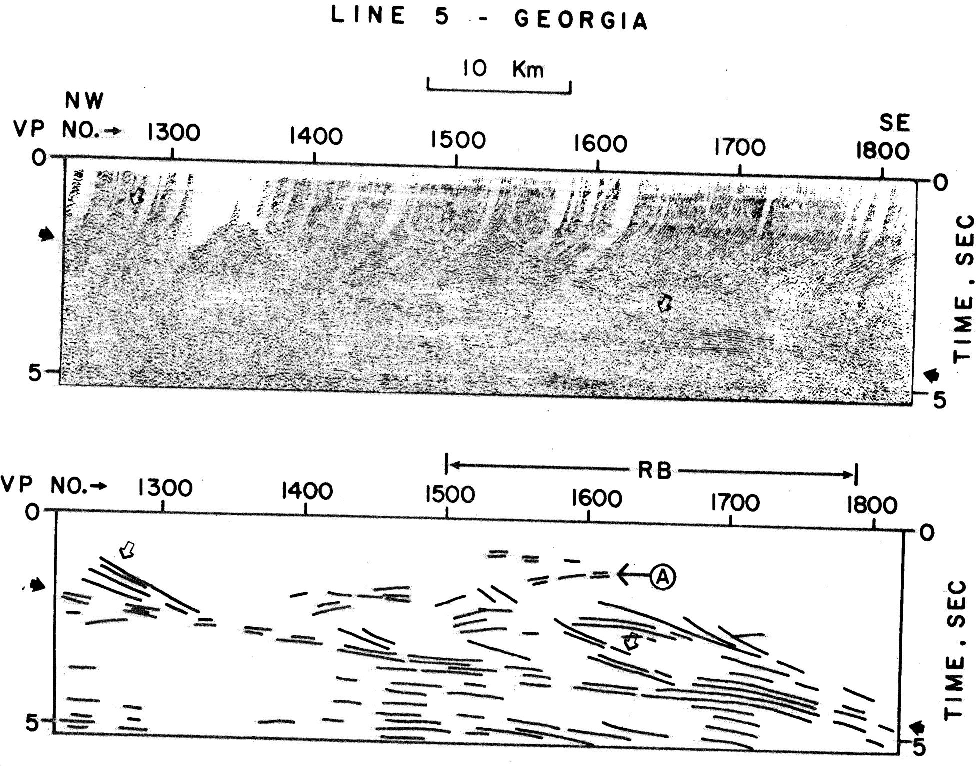

Figure 4. Part of the seismic data and companion line drawing display a major east-dipping reflection (arrows at edges). This event projects to the surface location of the Augusta fault and is thus interpreted as a reflection from it. Note the events which seem to splay upward and are interpreted as listric faults (open arrows). "A" indicates a west-dipping reflection which may be rotated due to normal faulting at the west edge of the Riddleville basin (RB). This is the same event as in Figure 3, E.

hence the pulldown is too small to alter the interpretation of the deep structure presented here.

The significant southeastward-dipping event which correlates with the Augusta fault projects far beneath the Coastal Plain to the east. Near the end of Line 5, this band of reflected energy appears to merge with underlying reflections at about 4.3 sec, implying that the Augusta fault originated at 12 km or more.

Several reflection events which are concave upward are observed on Line 5. These features seem to "splay" off of the Augusta fault reflection in a manner similar to ramping of thrust surfaces in Valley and Ridge sedimentary strata (Harris and Milici, 1977) and splay faults in the crystalline thrust sheet to the northwest. Although it is unknown if these reflections project to faults below the Coastal Plain sedimentary layer, because faults there would not normally be mapped, their listric appearance and association with the Augusta fault reflection strongly suggest they are reflections from faulted rocks or fold limbs which are genetically related to the Augusta fault. The similarity of these features to Valley and Ridge faulted sediment reflections suggests that the simplest interpretation is that they represent sedimentary strata which were telescoped in a manner similar to Valley and Ridge foreland rocks, with the implication that one or more detachments must underlie these faults.

An alternative interpretation is that they are listric normal faults of Mesozoic age which sole into the older Augusta fault. At least one of them appears to project to the west side of the Riddleville basin with the crystalline basement rotated in a listric fashion (Fig. 3, E; Fig. 4, A). A third possible interpretation involves a combination of these two in that perhaps late Paleozoic thrust faults were reactivated during Mesozoic extension as listric normal faults to produce the Triassic basins. In any event, there is no evidence for high-angle normal faults which extend through the crust (that is, the low-angle Augusta fault reflection is not offset).

Beneath the Augusta fault reflection and between 3.0 and 9.0 seconds, there are numerous layered reflections which commonly display an eastward dip. As Figure 3 shows, the areas in which these layered reflectors are most common are also areas of significant Bouguer gravity lows. Furthermore, an apparent lateral decrease in the stacking (processing) velocities occurs between stations 1500 and 1800 (Fig. 3). These velocities, which are determined from the reflection data, may indicate gross variations in the average crustal velocity structure. At a travel time of 6.0 sec, for example, there is a lateral decrease of about 2000 ft/sec (610 m/sec). Although some of the velocity variation may be caused by near-surface Triassic material in the Riddleville basin, if the indicated velocity decrease is representative of the crustal rocks, it could correspond to a lateral density change of about −.10 gm/cc according to Nafe and Drake (1957) and Gardner and others (1974). If a lateral density decrease of this magnitude is characteristic of this part of the crust, the associated 25 mgal gravity low can be easily explained by Triassic material near the surface and low density rocks at depth. Thus, more drastic rift models (Long, 1979) would not be required to explain the low gravity. Although the effects of multiply reflected waves are yet to be determined, the layered character of the reflection events and these other properties suggest that these layers are metasedimentary strata.

Southeast of Line 5, the adjoining segment (Line 8) displays a change in reflection orientation and character. Beginning near station 200, the dip of the 4.0- to 9.0-sec reflections changes to a westward orientation. It is not clear whether this change marks a major crustal boundary.

Between stations 600 and 800 on Line 8 (Fig. 3, F) an unusually distinct antiformal reflection is observed (Fig. 5). Relevant to its interpretation are the following observations: (1) The antiformal reflection has an east-dipping limb of considerable extent (Fig. 5). (2) An east-dipping event located in the time section somewhat beneath the apex of the antiform (arrow on Fig. 5) is present on some processed data. As a synthetic seismogram of a faulted anticlinal structure shows (Fig. 20 of May and Hron, 1978), the reflection indicated by the arrow on Figure 5 could migrate westward to a position which would be appropriate for a fault plane. Thus, a reasonable interpretation of this structure is that it is a faulted anticline with a significant westward vergence of thrusting. Migration of this antiformal reflection at various velocities indicates that it is

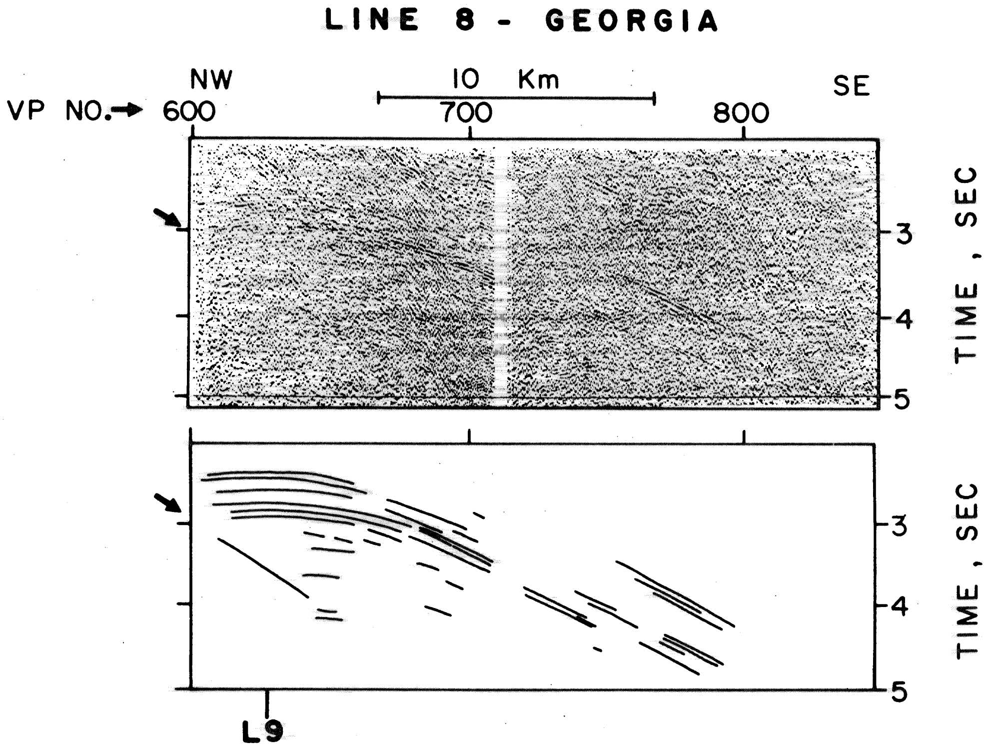

Figure 5. Seismic data and companion line drawing of part of Line 8 from the eastern Coastal Plain which display a major anticlinal reflection. The event shown by the arrow is present on some of the processed data and may be interpreted as a fault-plane reflection. L9 is the location of the intersection of Line 9. Processing of this line was accomplished on the Cornell computer.

not likely a diffraction phenomenon. However, other interpretations for this feature, such as a domal intrusion, cannot be ruled out at this time.

Figure 6 shows a cross line (Line 9) and a line drawing interpretation of it located over this antiform. Significantly, this line indicates that the structure strikes northeast and has perhaps .30 sec (about 0.9 km) of closure.

If the interpretation presented here is correct, west-directed compressive deformation significantly affected rocks this far east. As the ages of the rocks involved are not known, although they are likely Paleozoic, a lower limit time constraint on the formation of this feature is difficult to discern. However, there is little evidence for large-scale compressive deformation after the end of the Paleozoic, indicating this anticline formed prior to the Mesozoic.

While false hopes should not be raised, it must be noted that the petroleum potential of this and other such structures in the area may deserve some attention. Although these Appalachian rocks may turn out to be too highly metamorphosed to retain petroleum, the possibility that they are not should be kept open and perhaps investigated further until demonstrated otherwise.

Interpretation

Crustal structure beneath the Eastern Piedmont and Coastal Plain is obviously complex. Crustal models which assume flat layers (Amick, 1979; Lee, 1980) must be reconsidered in the light of the complexity observed in the reflection data. Whereas certain events on the new profile from beneath the Eastern Piedmont and western Coastal Plain may be easily correlated with events observed on the original traverse, the increased complexity of reflections on the east half of Line 5 and on Line 8 calls for caution with regard to any simple unambiguous interpretation.

The observation of a significant number of reflectors below the Augusta fault reflection can be construed as supporting evidence for the notion of an extensive detachment at depth beneath the eastern part of the southern Appalachian orogen (Cook and others,

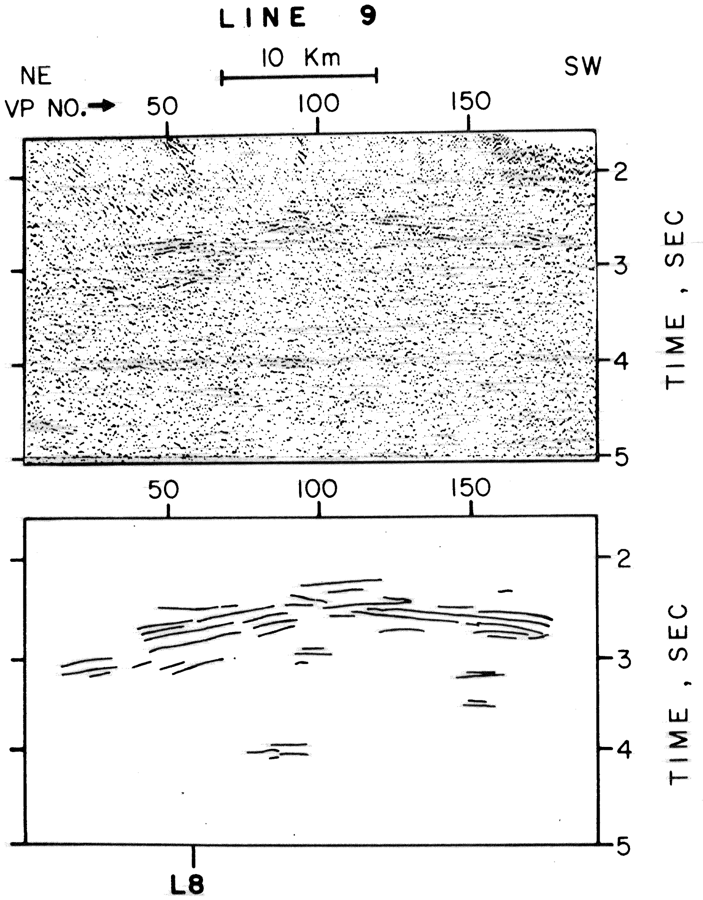

Figure 6. Seismic data and companion line drawing from Line 9, which is perpendicular to Line 8. The significant reflection at 2.3 to 3.5 sec correlates with the anticlinal reflection in Figure 5. L8 is the location of the intersection with Line 8. Processing of this line was accomplished on the Cornell computer.

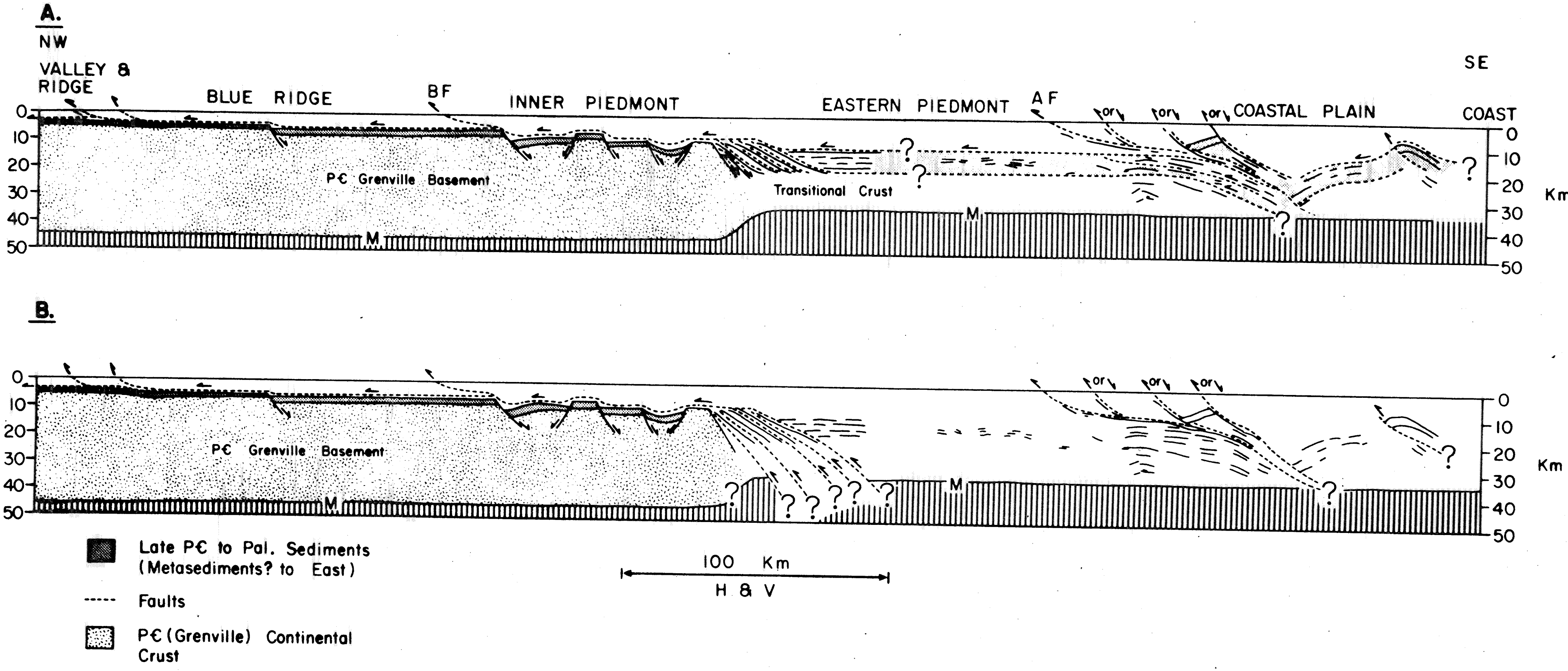

Figure 7. (A) Schematic cross section from the Valley and Ridge to the coast based on the COCORP data in which a subhorizontal detachment is interpreted to extend beneath the Coastal Plain. (B) An alternate interpretation in which the thrust surfaces of the Inner Piedmont–Blue Ridge allochthon are interpreted to "root" near the Charlotte belt (after Hatcher and Zietz, 1980). The shaded areas are interpreted as late Precambrian/early Paleozoic strata of the continental shelf and associated ocean basin; the lined pattern represents the mantle, and the hachured pattern represents continental crust. Thrust faults are indicated by dashed lines; listric faults east of the Augusta fault are shown as either thrust faults or normal faults. BF = Brevard fault; AF = Augusta fault.

1979; Harris and Bayer, 1979), and, in fact, this interpretation seems most reasonable and most likely. However, until there is more definitive information on the lithologies of these deep reflectors, such an interpretation must be considered one of several working hypotheses. Other possible interpretations of these reflectors include: (1) layered intrusions; (2) intrabasement reflections and/or multiple reflections which bear no direct relation to the sedimentary reflectors beneath the Blue Ridge and Inner Piedmont; and (3) layered mylonitic rocks.

An event which can be correlated with known surface features is the Augusta fault reflection (Fig. 3, D; Fig. 4). The extent of the Augusta fault on the seismic section, coupled with surface geologic information on its deformational history, indicates that it is a major structural boundary in the crystalline rocks beneath the Coastal Plain. The eastward limit of the Augusta fault reflection is nearly 400 km from the western edge of the Blue Ridge. Thus, if the Augusta fault is a late Paleozoic thrust fault as suggested by Snoke and others (1980b), then the late Paleozoic deformation which resulted in thrusting in the Valley and Ridge, Blue Ridge, and Brevard zone produced significant concomitant compressive deformation as far east as the eastern limit of the Augusta fault. This particular figure (400 km) is not the amount of transport, but rather the lateral distance over which deformation affected the rocks. The apparent paucity of late Paleozoic metamorhpism and deformation in the Inner Piedmont (Griffin, 1974) may thus indicate stress relief along major thrust planes as compression was applied from the east.

The interpretation of a faulted anticline in the crystalline rocks below the Coastal Plain implies that a significant compressional deformation also affected rocks even farther to the east than the Augusta fault. Although the age of such deformation is unknown, it may have been the same deformation which last affected the rocks of the Kiokee belt and Belair belt (Carboniferous-Permian).

Figure 7 illustrates two postulated cross sections from the Valley and Ridge to the coast based on the COCORP data. Offshore data, such as those described by Behrendt and others (1981) and Harris and Bayer (1979) show reflections at similar travel times as on the COCORP data, though correlations are tenuous at this time. Furthermore, subhorizontal reflections seen at 9.0 to 11.0 sec on the offshore profiles may correlate with the deep layered reflections on the COCORP data, although they may also be interpreted as Moho reflections.

Nevertheless, one likely interpretation of the COCORP results (Fig. 7, A) is that the layered reflections beneath the Coastal Plain represent late Precambrian/Paleozoic ocean or marginal basin sedimentary strata which underthrust (or were overridden by) highly deformed and metamorphosed crystalline rocks beginning in the Paleozoic (Taconic?). The apparent increase in complexity seen as the profile extends eastward may reflect late Paleozoic deformation which folded and faulted the layered strata at depth. Such a severe compressive orogeny was probably due to the continent-continent collision of the southeastern United States with Africa or with South America. Alternatively, Figure 7, B shows a cross section on which the thrust boundaries of the Inner Piedmont–Blue Ridge allochthon "root" or dip steeply into the crust near the Charlotte belt (after Hatcher and Zietz, 1980).

Implications for Evolutionary Models

Tectonic evolutionary models have been constructed for the Appalachians ever since Dana (1873) and Hall (1883) first suggested the geosynclinal concept. Most early models stressed the importance of vertical movements in the development of this orogen. As newer data have accumulated, however, the evidence tends to enhance the significance of horizontal forces and movements in tectonic evolution. During the 1960s, the concept of plate tectonism evolved rapidly and became widely accepted. This theory, which establishes the interaction of laterally moving lithospheric plates as controlling many surface geologic features, has been applied to the Appalachian-Caledonian system in several proposed models (for example, Dewey, 1969; Bird and Dewey, 1970; Dewey and Kidd, 1974; Hatcher, 1978).

In general, these models are based on surface geologic data with minimal geophysical constraints. Occasionally, however, geophysical data which measure large-scale subsurface variations are included (Watkins and Hugget, 1970; Haworth and others, 1978). Until recently, these models have included no significant constraints based on detailed subsurface geologic structures of the continents. The application of deep seismic profiling by COCORP has provided such data. However, as the identification of lithologic and structural boundaries corresponding to seismic reflectors is occasionally ambiguous, various interpretations, and thus various models based on these interpretations, should be considered. In this light, some of the significant constraints which should be used to delimit the possible models are: (1) sedimentation patterns in the Valley and Ridge (for example, time of clastic influx, source direction, unconformities); (2) patterns of plutonic and metamorphic events with respect to lithologic and structural variations; (3) limitations on minimum amounts of lateral transport (palinspastic restorations); (4) comparisons with modern plate interactions; (5) correlation with the known geology of Africa and South America; and (6) interpretation of subsurface seismic-reflection data (for example, structural and lithologic interpretations of reflections at depth).

Several models have been proposed to explain known parameters for 1 through 5 (for example, Hatcher, 1978). More recently, models which incorporate the initial COCORP traverse have been presented (Cook and others, 1979; Cook and others, 1980). Modifications of these models based on the new data likely fall between two end member interpretations: (1) those which incorporate an eastward extension of a detachment surface at depth beneath the Coastal Plain (Fig. 7, A), and (2) those which do not extend such a detachment east of the Charlotte belt (Fig. 7, B). Intermediate interpretations could include terminating a detachment near the Modoc Line or beneath the Coastal Plain.

Figure 8 illustrates two essential elements of an evolutionary model sequence for this part of the Appalachian orogen. In it the late Precambrian rifting resulted in a distribution of various plates which probably resembled the complexity observed in the southwest or western Pacific today with continental fragments and island arcs separated from the major continental masses. Then, as Paleozoic ocean basins closed, these fragments and arcs were accreted to the cratonic areas during the various orogenic episodes (Taconian-Caledonian, Acadian, Alleghanian-Hercynian). Although Figure 8A illustrates these fragments as composed of continental crust, the only ones for which there is good evidence of such basement material are North America, Africa/South America, and perhaps the Carolina slate belt (Glover and others, 1978).

The essential elements of such an evolutionary sequence are discussed in Hatcher (1978) and Cook and others (1980). As new data become available, models such as these are modified to accommodate them. For example, perhaps the collision of the slate belt [Armorica of Van der Voo's (1980) model?] was responsible for the Ordovician orogeny in the southern Appalachians (1 in Fig. 8), as data are now available which indicate it was part of North America since that time (Brown and Barton, 1980). A fragment or arc which was located east of the slate belt and which is now beneath the

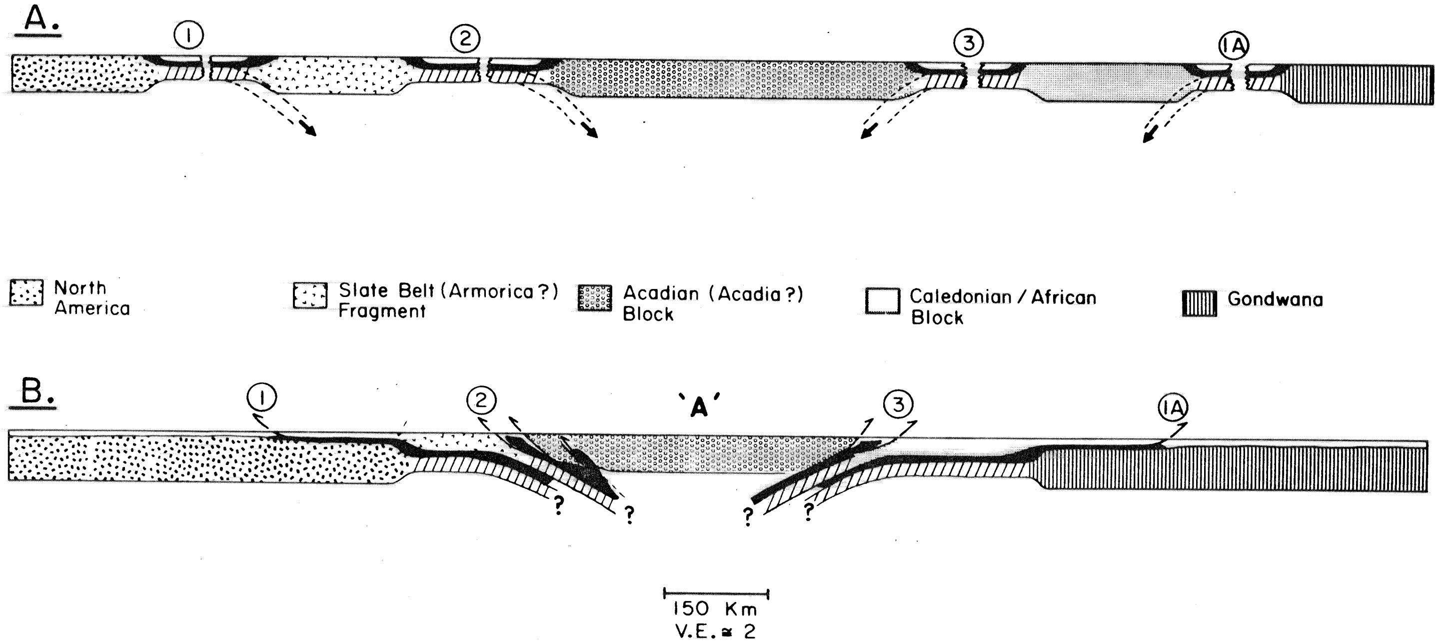

Figure 8. (A) Schematic illlustration of pre-thrusting configuration of various ocean basins and fragments which were later accreted to the cratons of North America and Africa/South America. The numbers refer to the order in which the basins closed: (1) and (1A) were Ordovician (Taconic/Caledonian) orogenies, (2) was the Devonian (Acadian) orogeny, and (3) was the Carboniferous (Alleghanian/ Hercynian) orogeny. (B) illustrates a possible configuration prior to the opening of the Atlantic rift (approximately at "A") with the leading edges of the accreted material indicated by the numbers. East-directed thrusting is indicated at 3 in Gondwana in a manner similar to the Augusta fault in the eastern United States. If such a structure exists, it would be located beneath the Mesozoic cover in West Africa and apparently has not been observed. The diagonally lined areas represent oceanic crust, and the darkened areas represent basinal sediments.

Coastal Plain may have been responsible for the Devonian deformation in the southern Appalachians (Acadia of Kent and Opdyke (1978)?) (2 in Fig. 8). An Ordovician orogeny was also significant in west Africa (Lecorché and Sougy, 1978) which implies an ocean basin closed at that time (1A in Fig. 8). Final collision of Gondwana with southern North America resulted from the closure of the basin which separated Africa and the Acadian fragment (3 in Fig. 8). Clearly, if an analogy with the present-day South Pacific is to be made, seamounts and other ocean floor irregularities could also be included.

The numbers in Figure 8, B correspond to the leading edges of sedimentary rocks which were thrust (accreted) continentward as a result of these ocean-basin closings. In this model, it is assumed that the seismic reflectors observed beneath the Coastal Plain are sedimentary (or metasedimentary) strata of Paleozoic age. If a model is assumed in which a different interpretation is made (such as rooting the thrust zones, see Fig. 7, B), it will contain different features.

A significant result of this exercise is that the interpreted (meta?) sediments below and east of the Augusta fault are of unknown age, but they may be as young as Early Devonian (pre-Acadian) if the slate belt had been accreted to North America in the Ordovician. Strata east of the slate belt may then have been deposited in the basin which separated Acadia. This is a testable hypothesis; the antiformal structure (Fig. 5) beneath the Coastal Plain may contain Devonian strata. Perhaps if it is drilled (its crest is at about 6.0 km on the COCORP line, but it may be shallower along strike), the information obtained will provide significant constraints on these ideas.

CONCLUSIONS

An extension of the COCORP seismic-reflection profile from the Eastern Piedmont to near Savannah has revealed significant reflecting boundaries within the crystalline crust. The following major points are important to the interpretation of crustal structure in this area.

1. Confirmation of the east-dipping layers beneath the Charlotte belt and subhorizontal layers east of these. Such mid-crustal layers are apparently extensive beneath the Eastern Piedmont and are most easily interpreted as late Precambrian/early Paleozoic metasediments and metavolcanics. The lateral correlation of these reflectors implies that a major detachment extends eastward beneath the crystalline rocks of the Eastern Piedmont and Coastal Plain.

2. Recognition of a major southeast-dipping reflector in the crystalline basement which projects to the surface location of the August fault and is thus interpreted as its subsurface extension. This feature extends 80 km or more southeast of the surface trace of the Augusta fault and is apparently a major lithologic and tectonic boundary in this area.

3. Recognition of upwardly concave reflectors which are listric into the Augusta fault. These may be late Paleozoic thrust faults, Mesozoic listric normal faults, or both.

4. Observation of a significant thickness (up to 6.0 sec) of layered reflections beneath the Augusta fault. One interpretation of these events is that they are late Precambrian/early Paleozoic basinal strata which have been thickened by repeated thrusting. If these were originally sedimentary strata which are now at mid-crustal

and lower crustal depths, they could have added a significant proportion of volatile compounds, such as water, to the lower crust. Furthermore, layering which is seen on many crustal seismic-reflection sections (Schilt and others, 1979) may have originated as sedimentary layering. Large-scale thrusting of crystalline rocks over sediments may thus provide a mechanism for incorporating such components and compositional layering at substantial depths.

5. Discovery of an important anticlinal feature in the crystalline rocks beneath the eastern Coastal Plain.

Tectonic evolutionary models must now incorporate compressional deformation in North America at least as far east as the eastern limit of the Augusta fault (about 80 km east of its surface trace) and perhaps as far east as the interpreted anticline. Eastward-directed compression in Africa may add considerably to the extent of this deformation. At the same time that compression was affecting the Eastern Piedmont and sub–Coastal Plain crystalline rocks, thrusting was taking place in the Valley and Ridge. Compressive stresses of late Paleozoic age were likely taken up along subhorizontal detachments as final emplacement of the Piedmont–Blue Ridge allochthon took place to the west.

The further acquisition of subsurface data from beneath the southeastern United States may provide more definitive information regarding the interpretation and correlation of mid-crustal and deep crustal layering. Nevertheless, the data presented here demonstrate the significant role of late Paleozoic compressive deformation in the evolution of the southern Appalachian orogen and illustrate the presence of large-scale subsurface features which are structurally and perhaps economically significant.

ACKNOWLEDGMENTS

The field data for the second phase of COCORP operations in the southern Appalachians were collected by crew 6834 of Petty-Ray Geophysical division of Geosource, Inc. The data were processed in part by Geosource and in part on the Megaseis computer system at Cornell University. We would like to thank A. Dainty, P. Talwani, and A. Snoke for preprints, R. Hatcher, Jr. for many helpful discussions, and the various personnel on the COCORP committees and at Cornell who have offered significant assistance.

The COCORP data are available to the public for the coast of reproduction. Details of procedures for obtaining the data are described in Kaufman (1979). This research was supported by the National Science Foundation under Grants EAR-78-23672 and EAR-78-23673.

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Manuscript Received by the Society December 1, 1980
Revised Manuscript Received March 27, 1981
Manuscript Accepted April 20, 1981
Cornell Contribution No. 686