12

Thin-skinned tectonics in the crystalline southern Appalachians; COCORP seismic-reflection profiling of the Blue Ridge and Piedmont

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ABSTRACT

COCORP seismic-reflection profiling in Georgia, North Carolina, and Tennessee and related geological data indicate that the crystalline Precambrian and Paleozoic rocks of the Blue Ridge, Inner Piedmont, Charlotte belt, and Carolina slate belt constitute an allochthonous sheet, generally 6 to 15 km thick, which overlies relatively flat-lying autochthonous lower Paleozoic sedimentary rocks, 1 to 5 km thick, of the proto-Atlantic continental margin. Thus, the crystalline rocks of the southern Appalachians appear to have been thrust at least 260 km to the west, and they overlie sedimentary rocks that cover an extensive area of the central and southern Appalachians. The hydrocarbon potential of these sedimentary rocks is unknown and untested. The data show that the Brevard fault is the surface expression of an eastward-dipping splay off the main sole thrust, and they show, or imply, that other major faults of this region have similar origins. The data support the view that large-scale, thin crystalline thrust sheets may be significant features of orogenic zones.

INTRODUCTION

During the course of a COCORP (Consortium for Continental Reflection Profiling) seismic survey across the Brevard zone in northeastern Georgia, it became apparent that the major reflection feature in this area is a relatively horizontal, layered sequence of rocks, here interpreted as sedimentary rocks, underlying near-surface crystalline rocks between 6 and 15 km thick. These results confirm the suggestion of Hatcher (1971, 1978) and Clark and others (1978) that Valley and Ridge sedimentary strata extend beneath the Brevard zone and thus that the major tectonic feature in the southern Appalachians is an overthrust that transported crystalline rocks over sediments and which crops out as the Great Smoky (Blue Ridge) thrust in Georgia and Tennessee. In an effort to gain definitive information on the extent and nature of the overthrusting and on the interrelation of regional structures, COCORP extended the lines to include 348 km of profile (including cross spreads). The lines traverse from Madisonville, in the Valley and Ridge of Tennessee, to the Modoc fault, near the Coastal Plain overlap in Georgia, with a gap of about 60 km between Murphy, North Carolina, and Helen, Georgia (Fig. 1).

Overthrusting may have been as great as 260 km horizontally, and perhaps considerably more. The similarity of outcrop patterns along strike in the Appalachian system (Fig. 2) and the new seismic data imply that much of the crystalline Appalachians is allochthonous and overlies an extensive area of relatively undeformed lower Paleozoic sediments.

Some of the major seismic-reflection events and their implications for the structure of the southern Appalachians are described here. Forthcoming publications will develop more detailed structural and tectonic models that incorporate the constraints imposed by these data. A comprehensive list of references pertaining to the geology of the area may be found in Hatcher (1971, 1978). Because of the length of the profiles and the difficulty of reproducing seismic sections faithfully on a small scale, line drawings abstracted from the seismic sections are used to illustrate the observed events. Acquisition and processing of the seismic data are essentially the same as for other sets of COCORP data (Schilt and others, 1979). The following is a province-by-province discussion of the data and their interpretation, from west to east.

VALLEY AND RIDGE–BLUE RIDGE

The traverse begins within the Valley and Ridge sedimentary province. As shown by Harris and Milici (1977), and supported by these data, the surface structures of the Valley and Ridge do not involve crystalline basement rocks below the Paleozoic sedimentary sequence.

The contact between the Valley and Ridge and Blue Ridge provinces is marked by a major thrust fault (Fig. 1), the Great Smoky thrust. The seismic section demonstrates that this thrust (Fig. 3, loc. A) dips relatively steeply near the surface, then flattens very rapidly and merges at depth with a near-horizontal, layered sequence of reflections at about 1.7 to 2.0 s (5 to 6.5 km). These horizontal events correlate with similar events identified as Cambrian-Ordovician sedimentary reflections in the Valley and Ridge (Harris and Milici, 1977), and they are thus almost certainly reflections from the Cambrian and/or Ordovician sedimentary rocks. These rocks extend to the southeast end of this part of the traverse (Fig. 3, B) and have a thickness of about 1 km throughout this area. Near station 300 (in Tennessee), a small structure is visible that may have controlled the location of a minor subsidiary thrust and produced repetition of part of the sedimentary section.

BREVARD ZONE

Results of the COCORP survey (Fig. 3, C; Fig. 4) support the concept of the Brevard zone as a thrust fault rooted in the sole thrust of the Blue Ridge and Piedmont (Hatcher, 1971). Figure 4 shows the seismic section in the vicinity of the Brevard fault on the main traverse. The Brevard fault does not extend beneath the horizontal layer of reflections at 2.0 to

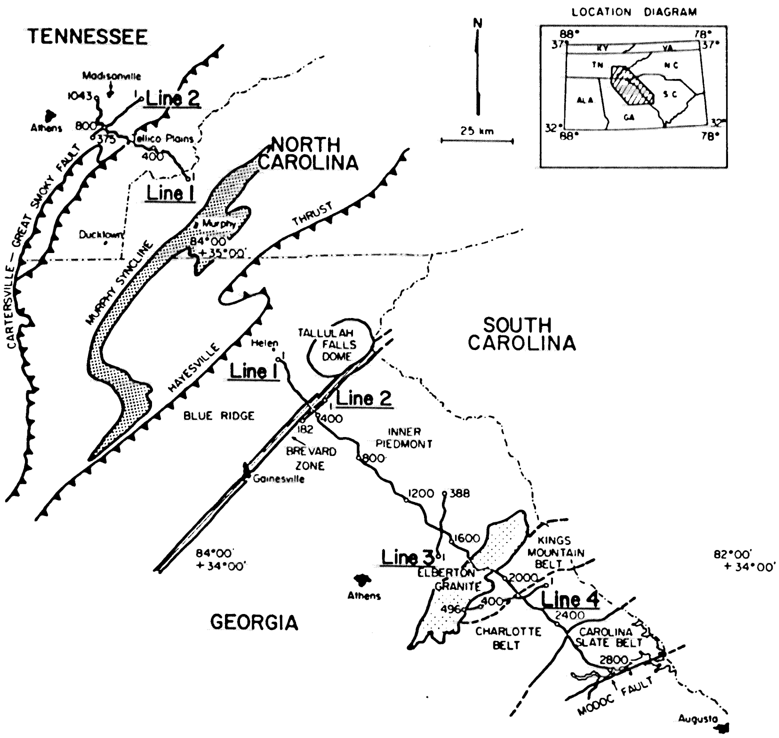

Figure 1. Generalized map of geologic provinces and line locations for COCORP southern Appalachian traverse. Geologic contacts and faults are from Pickering (1976) and Williams (1978).

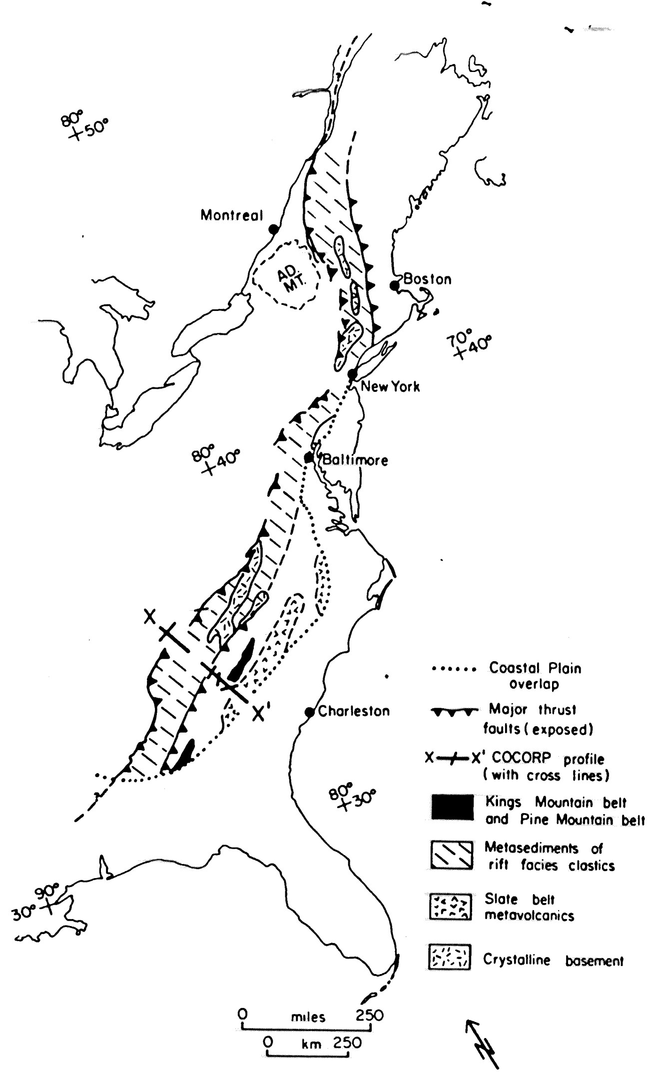

Figure 2. Map of eastern United States showing Precambrian and metamorphic belts (after Williams, 1978). Western boundary of these outcrops is generally a thrust fault, such as Great Smoky thrust.

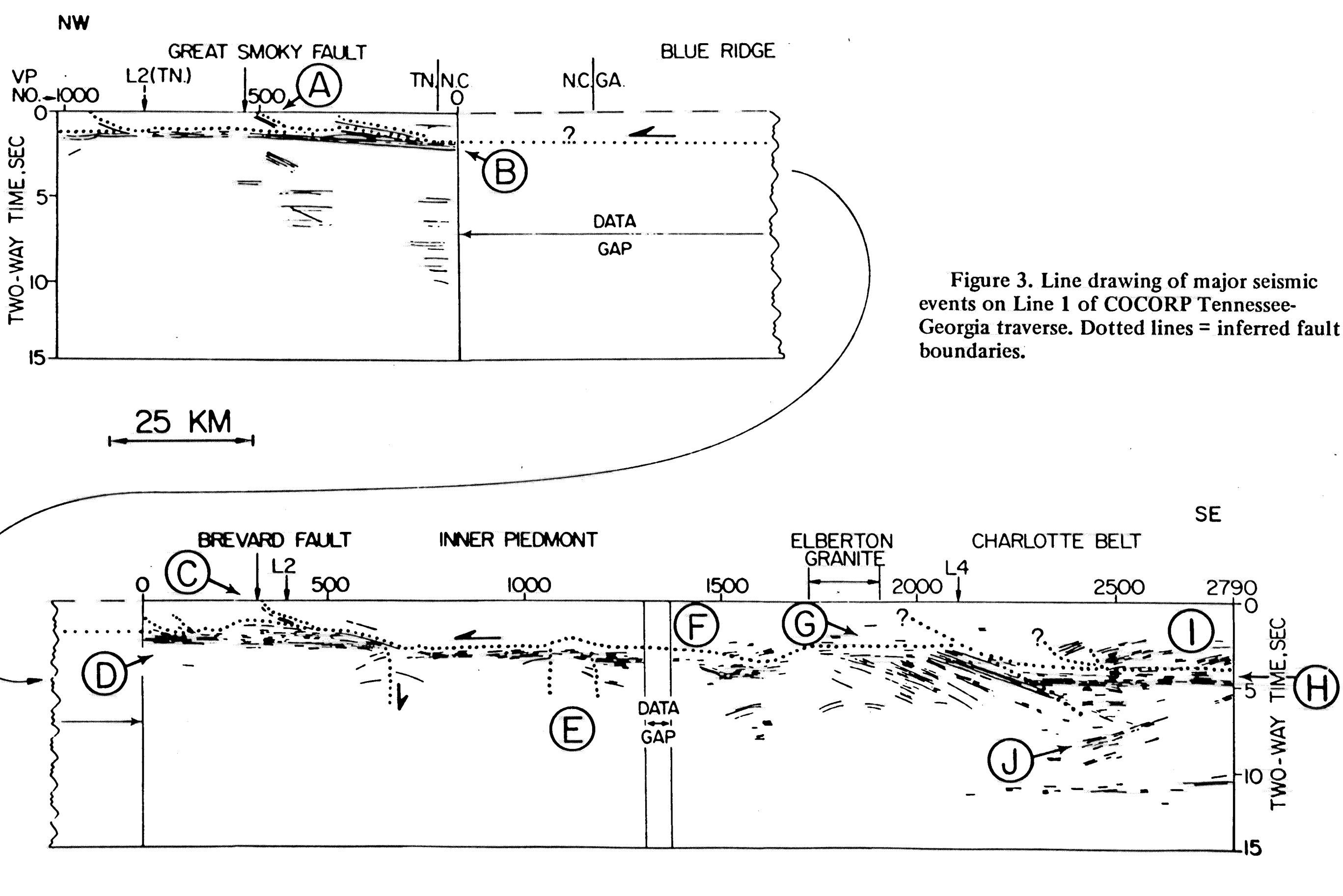

Figure 3. Line drawing of major seismic events on Line 1 of COCORP Tennessee-Georgia traverse. Dotted lines = inferred fault boundaries.

3.0 s (6 to 9 km). In the subsurface it dips about 16° east and is rooted in the sole thrust near an offset in the underlying layered rocks. This configuration suggests that the offset is a normal fault that acted as a tectonic ramp to initiate thrust motion along the west flank of the synformal Chauga belt during westward motion in the overlying sheet (Hatcher, 1971). Although this offset may represent a post-thrusting normal fault, it would seem unlikely that such a feature would occur at the location of the Brevard fault, except fortuitously.

Exotic carbonates within the Brevard zone were derived from the Cambrian-Ordovician Knox Group (Hatcher, 1978) and may have been transported to the surface during thrust motion along the Brevard fault. This evidence, the laminated character of the underlying horizontal seismic reflections (Fig. 3, D), and the correlation of these events with similar events in the Valley and Ridge, as discussed above, indicate that the horizontal reflections along this line are from a relatively unmetamorphosed Cambrian-Ordovician sedimentary sequence underlying the thrust sheet. Furthermore, Bryant and Reed (1970) have shown that relatively unmetamorphosed platform sedimentary rocks in the Grandfather Mountain window of North Carolina demonstrate the allochthonous nature of the Blue Ridge there. Thus, the events shown at D in Figure 3 are here postulated to be an eastward extension of the sedimentary strata (Fig. 3, B) beneath the Blue Ridge. A similar conclusion has been suggested by Clark and others (1978) on the basis of reflection data near Rosman, North Carolina. From the COCORP reflection data, the calculated minimum offsets on the Brevard fault are 8 km throw and 30 km heave.

Below 2.5 s (7.5 km), this section of the profile has very little reflected energy. Several explanations, such as a relatively homogeneous crust or low signal strength due to near-surface attenuation, are possible. The lack of deep reflections contrasts with the abundance of such events near the southeast end of the traverse (Fig. 3, J) and does not appear to be typical of the crustal heterogeneity observed elsewhere (Schilt and others, 1979).

With the exception of some faults, such as the Brevard fault, few seismic features are seen within the thrust sheet. Although the experiments are designed to obtain deep crustal information, the paucity of shallow events may also result from extreme structural complexity.

INNER PIEDMONT

The seismic section across the Inner Piedmont from the Brevard zone to the Elberton granite shows a relatively horizontal sequence of reflections between 3.0 and 4.0 s (9 to 12 km), as shown in Figure 3, E and F. These reflections are interpreted as a continuation of the Paleozoic sedimentary rocks beneath the thrust sheet. In general, these events show little complexity. Notable exceptions occur near stations 1000 to 1200 (Fig. 3, E) and near stations 1400 to 1600 (Fig. 3, F). From 1000 to 1200 there appears to be an uplift in the sedimentary strata, and the reflections on top of the uplift are less continuous than those on either side. One interpretation of this feature (as shown at E in Fig. 3) is that it represents a prethrusting horst block on the Paleozoic continental margin of North America from which sediments were tectonically removed during thrusting. On the basis of our calculated stacking velocities, this uplift is not likely entirely a velocity anomaly. From stations 1400 to 1600, the zone of reflections appears to be more complex, forming a synformal trough (graben?) centered beneath station 1550 (Fig. 3, F).

The Elberton granite, a major intrusive body in the Piedmont, is located at the surface between stations 1700 and 1900. East of the granite the layered reflections have an eastward dip and increase in thickness to about 2.0 s (6 km). The continuity of events beneath the granite (Fig. 3, G) suggests that the granite was transported. Hatcher and Zietz (1978) proposed that the Kings Mountain belt is the root zone for the main sole thrust; thus, the eastward-dipping features beneath the granite and Charlotte belt could reflect the downturn of the sediments and thrust plane. This model does not, however, explain the layered sequence still farther east (Fig. 3, H).

A more plausible interpretation is that the eastward-dipping features southeast of the Elberton granite and layered reflections that continue to the southeastern limit of the traverse are a continuation of the sedimentary sequence. This interpretation is consistent with low velocities in the layers determined from the COCORP data and a possible low-velocity layer below 10 km, as suggested by Long (1979) on the basis of refraction data. The change of the seismic facies from the relatively thin, flat-lying sequence west of the granite to a dipping, multilayered, thicker sequence east of the granite suggests that this location marked a change in thickness of deposition prior to thrusting and prior to granite emplacement. The lateral thickening of the layers (Fig. 3, G) may also represent the imbrication of eastward-dipping thrust sheets within the sediments.

KINGS MOUNTAIN BELT–CHARLOTTE BELT–CAROLINA SLATE BELT

The zone of layered reflections dipping eastward below and east of the Elberton granite (Fig. 3, G) becomes horizontal

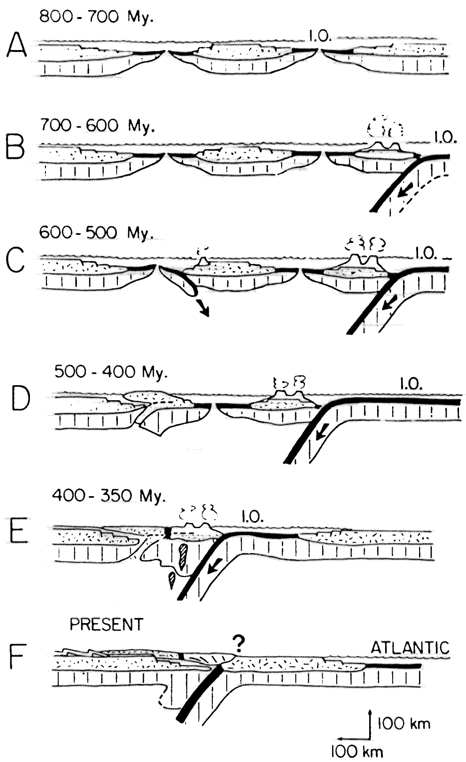

Figure 5. Schematic illustration of plate-tectonics model for evolution of southern Appalachians (after Hatcher, 1978). Black areas = oceanic crust; lined areas = lower lithosphere. VR = Valley and Ridge; KMB = Kings Mountain belt; I.O. = Iapetus Ocean; ? = proto-African (or South American)-North American suture (unknown location). Mechanism of initiation of thrusting in transition from C to D is not well constrained.

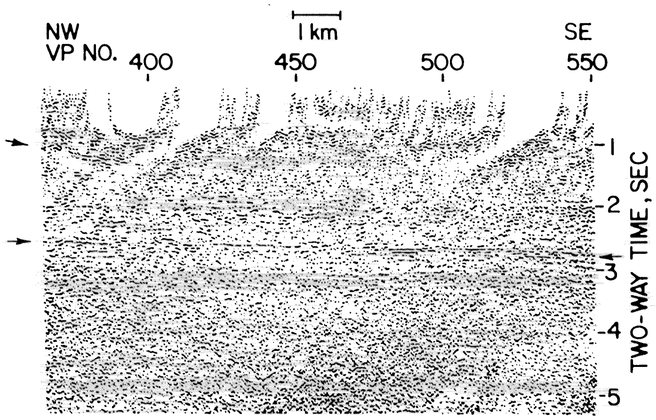

Figure 4. Detail of Line 1 in vicinity of Brevard zone. Upper arrow indicates reflection from Brevard fault; lower arrows indicate zone of sedimentary reflections.

near station 2300 (Fig. 3, H). Although the surface features in this area are strongly deformed (Whitney and others, 1978), this sequence of reflections appears relatively undisturbed. If these reflections correspond to sediments (or relatively undisturbed metasediments), the surface rocks are then part of the thrust sheet, which must be rooted east of the present limit of the profile, if at all. Thus, the Elberton granite, Kings Mountain belt, Charlotte belt, and Carolina slate belt would all be allochthonous. This interpretation implies that most, if not all, of the southern Appalachians is allochthonous and overlies relatively undeformed and unmetamorphosed sedimentary strata. As the distance from the Blue Ridge thrust to the eastern end of the COCORP line is about 260 km, an extensive area of the central and southern Appalachians may be underlain by these sedimentary rocks.

Several features on the southeast end of the traverse are difficult to interpret without cross lines but may be important structures. For example, Figure 3, locality I shows events with an apparent westward dip that are above the horizontal reflections (Fig. 3, H). As the character of these events is similar to that of the underlying layered reflections, one interpretation is that overthrusting from the east produced the observed configuration.

Another, much deeper feature is visible between stations 2300 and 2700 at 6.0 to 9.0 s (18 to 27 km) with an apparent west dip of about 18° (Fig. 3, J). Several geologic interpretations are suggested. The dipping reflections may indicate thrust faults induced during collisional episodes, or reflections from a paleo–subduction zone complex, or older features of the Grenville basement unrelated to Appalachian geology. The flat-lying deep reflections at 11.0 to 12.0 s are near reported Moho depths (Long, 1979) and may indicate the top of the mantle.

HYDROCARBON POTENTIAL

The sedimentary rocks beneath the crystalline thrust sheet have unknown hydrocarbon potential. Stearns (1971) noted that future targets for hydrocarbon exploration in the southern Appalachians are the Cambrian-Ordovician Knox Group and various Cambrian formations. It is this sequence of rocks, or a part thereof, that most likely extends beneath the southern Appalachian thrust sheet. The depths and implied degree of metamorphism of the Paleozoic sedimentary rocks suggest that if hydrocarbons are present in producible quantities, they would be in the form of natural gas.

Many questions remain regarding the nature of these sedimentary rocks and their degree of metamorphism, but it is clear that the discovery of these strata calls for reconsideration of the resource possibilities of the crystalline southern Appalachians.

EVOLUTION OF CONTINENTAL MARGIN OF SOUTHEASTERN NORTH AMERICA

Although many models are possible to explain the tectonic history of the southern Appalachians and the mechanical details remain to be worked out, we feel it is important to relate the COCORP findings to the tectonics of this area. Therefore, a plate-tectonics model for the evolution of the southern Appalachians, modified from Hatcher (1972) and compatible with the COCORP data, follows. The directions used are referred to present-day coordinates rather than to paleocoordinates.

During late Precambrian time, rifting of a supercontinent resulted in the development of the proto–Atlantic Ocean (Iapetus) and a continental fragment (Piedmont microcontinent) (Fig. 5, A). This fragment was separated from the larger proto-American continent by an accreting plate margin, thus forming a marginal basin. Growth in the Iapetus Ocean basin about a central accreting plate margin led to the development of a passive Atlantic-type margin along the eastern edge of the Piedmont microcontinent.

In Early Cambrian time, a consuming plate margin formed east of the Piedmont continental fragment. Subduction of oceanic lithosphere resulted in the creation of the ensialic Carolina slate belt island arc (Fig. 5, B).

During Middle to Late Cambrian time (550 to 500 m.y. B.P.), an eastward-dipping subduction zone formed along the westward flank of the Piedmont microcontinent (Fig. 5, C). The closing of the marginal basin resulted in the juxtaposition of the Piedmont microcontinent and the proto–North American continent (Fig. 5, D). This event resulted in a collisional orogeny in Middle Ordovician to Early Silurian time (about 480 to 450 m.y. B.P.) and correlates with the Taconian orogeny. Thrusting of the Blue Ridge and part of the Piedmont over the North American shelf sedimentary strata probably began at this time.

A second converging plate margin developed west of the island arc soon after the Piedmont collision occurred. The collapse of this marginal basin culminated in a continent–island arc collision in Devon-

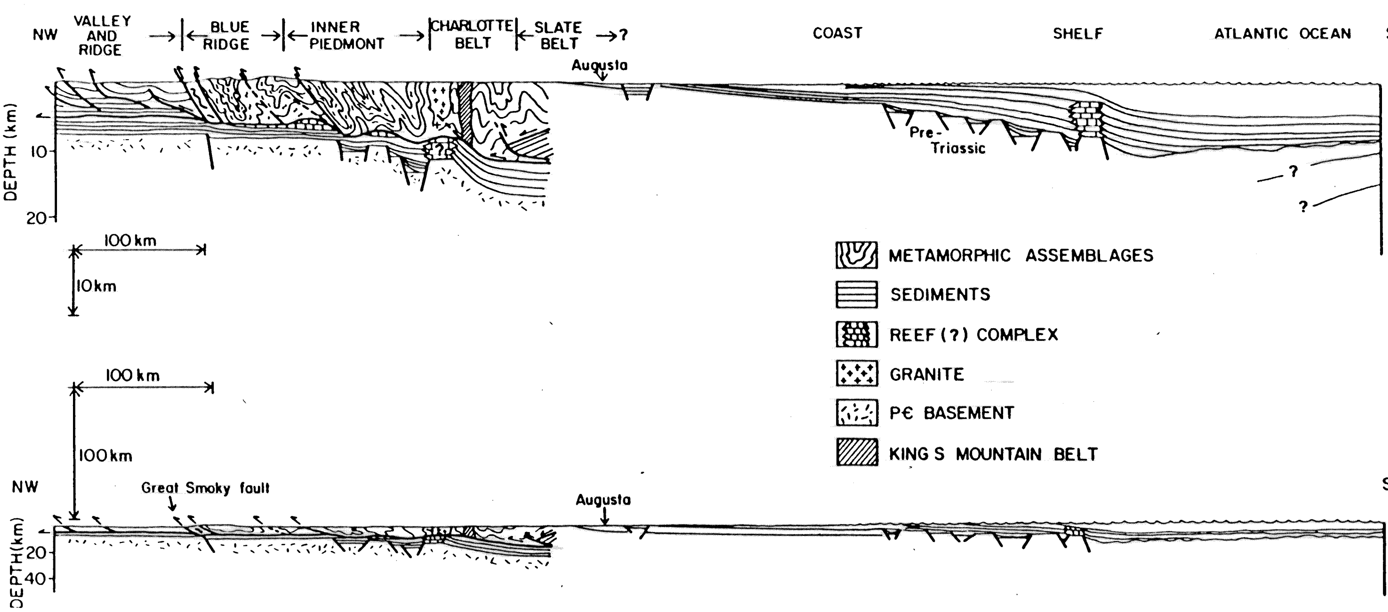

Figure 6. Generalized cross section of southeastern United States and present offshore Atlantic shelf, based on proposed interpretation of COCORP traverse and offshore cross sections of Grow and others (1979).

ian time, about 380 m.y. ago, (Fig. 5, E) and was responsible for a second episode of deformation and regional metamorphism—the Acadian orogeny. The postulated closed back-arc basin is manifested at the surface as the Kings Mountain belt (Glover and others, 1978), although it was probably transported westward during later deformational episodes.

Complete closure of Iapetus in Carboniferous and Permian time resulted in a diachronous continent-continent collision involving the proto-North American and African or South American plates, about 250 to 300 m.y. ago. This closure resulted in deformation and folding associated with pervasive thrusting in the southern Appalachians and is tentatively correlated with the Alleghanian orogeny (Hatcher, 1978). Thus, the suture of proto-Africa and North America may lie east of the Carolina slate belt (Fig. 5, F).

The similarity of the features observed on the COCORP traverse to seismic profiles across the present Atlantic margin is striking. Figure 6 is a generalized cross section of the southern Appalachians and the Atlantic coast. The onshore part is drawn from an interpretation of the COCORP traverse, and the offshore part is modified after Grow and others (1979). The normal faults, the continental rise, and the oceanward thickening on the offshore section appear much like the interpretation of the sediment layers on the COCORP traverse. By analogy with the offshore interpretation, a carbonate bank is shown to extend to the location of the eastward-dipping sedimentary layer beneath the Charlotte belt. This may mark the eastern limit of the early Paleozoic carbonate bank (Rodgers, 1968). The configuration of the Paleozoic sediment reflections on the COCORP data thus suggest that this area marks the location of the Paleozoic continental margin.

In the Paleozoic of southern North America, growth by creation of new continental crust appears to be of minimal significance. Rather, detachment of part of the continent, followed by reattachment and stacking by overthrusting were dominant mechanisms. It thus seems likely that overthrusting of thin, crystalline sheets is a key element in similar orogenic belts such as the Himalayas, the Alps, the western Cordillera, and the northern Appalachians.

SUMMARY AND CONCLUSIONS

The first phase of the COCORP seismic-reflection traverse across the southern Appalachians has revealed that the crystalline rocks of the Blue Ridge and Piedmont are part of a single allochthonous thrust sheet that varies in thickness from 6 to 15 km and overlies layered rocks that are most easily interpreted as Paleozoic sedimentary rocks. Layered reflections east of the Elberton granite could be interpreted as a continuation of the sedimentary strata, suggesting that the thrust may extend to the Modoc fault or even farther. These sedimentary rocks of the former continental margin probably underlie an extensive area in the central and southern Appalachians; their hydrocarbon potential is unknown.

The Brevard fault is an eastward-dipping thrust that is rooted in the main sole thrust of the Blue Ridge and Inner Piedmont. The relatively unmetamorphosed exotic carbonate rocks within the Brevard zone are important evidence that sedimentary strata underlie the thrust sheet beneath the Inner Piedmont.

The seismic data demonstrate the existence of a 260-km (or more)-wide sheet of highly deformed metamorphic rocks overlying relatively unmetamorphosed and undeformed sediments; thus, mechanical models of thrust faulting must account for such a configuration.

The data are consistent with the notion of westward thrusting resulting from as many as three stages of plate collision, during which a continental fragment, an island arc, and the proto-African continent were accreted to the North American continent.

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