Normal-fault boundary of an Appalachian basement massif?: Results of COCORP profiling across the Pine Mountain belt in western Georgia

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ABSTRACT

Recent seismic reflection profiling in western Georgia and adjacent eastern Alabama, conducted by the Consortium for Continental Reflection Profiling (COCORP), shows that reflections commonly associated with the Appalachian detachment do not continue southeastward beneath the Pine Mountain belt. Rather, these reflections terminate abruptly on the north side of the belt, along the downdip projection of the Towaliga fault. This observation is difficult to reconcile with the basement duplex interpretation traditionally applied to the Pine Mountain belt and to all other Appalachian interior basement massifs. An alternative interpretation, consistent with the reflection data and with local surface geologic relations, is that the Towaliga fault is, at least in its later evolution, a large northwest-dipping normal fault that cuts the Piedmont allochthon, Appalachian detachment, and Grenville basement. Where crossed by the COCORP profile, this fault has an inferred average dip of about 54° and offsets Grenville basement about 9 km. This interpretation is consistent with the view that the Pine Mountain belt is a structural window through the Piedmont allochthon. However, it implies that much of the structural relief on the basement exposed in the window is due to late normal faulting rather than to thrust imbrication alone. If correct, this has several important implications for Appalachian geology: (1) It implies that normal faulting of late Paleozoic and/or Mesozoic age has played a much more important role in the development of the exposed southern Appalachians than has generally been considered to date. (2) Grenville basement exposed in the Pine Mountain belt has been attached to North America since Precambrian time; it does not represent a Paleozoic accreted terrane. (3) The Appalachian detachment may be exposed around the periphery of the Pine Mountain belt and hence may be available for direct observation at this locality.

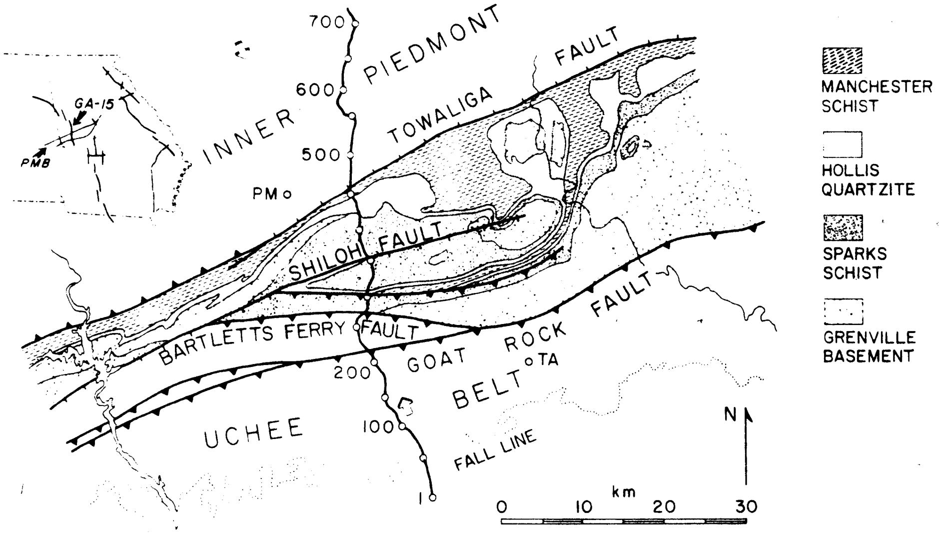

Figure 1. Geologic map of Pine Mountain belt (PMB) (after Schamel et al., 1980). PM = town of Pine Mountain; TA = town of Talbotton. Numbers refer to station locations along COCORP's Georgia line 15. Arrows indicate line of section shown in Figure 4. Inset map shows location of existing COCORP lines in Georgia.

INTRODUCTION

The Pine Mountain belt of western Georgia and adjacent eastern Alabama is the southernmost of a series of internal Grenville basement massifs cropping out in the Appalachian Piedmont (Fig. 1). Other massifs within this group include the Tallulah Falls dome (Hatcher, 1974, 1976), Sauratown Mountains anticlinorium (Hatcher, 1984), State Farm Gneiss (Farrar, 1984), and Baltimore gneiss domes (Muller and Chapin, 1984). Clark (1952) first recognized that the metamorphic rocks composing the Pine Mountain belt closely resemble metamorphosed North American basement and cover rocks exposed in the Blue Ridge province to the northwest, and that these rocks are separated from surrounding Piedmont metamorphic rocks by major fault zones. To explain these relations, Clark suggested that the Piedmont rocks compose a large allochthon that was thrust northwestward during the Paleozoic over North American basement and its miogeoclinal cover. He further suggested that the Pine Mountain belt is a structural window exposing the basement, and its parautochthonous cover, beneath the Piedmont allochthon (Clark, 1952).

Subsequent field and geochronological studies have confirmed the main aspects of Clark's interpretation (Bentley and Neathery, 1970; Schamel and Bauer, 1980; Odom et al., 1973, 1985; Schamel et al., 1980; Hatcher et al., 1981; Kish et al., 1982; Sears et al., 1982; Sears and Cook, 1984). The rocks composing the Pine Mountain belt include an older, Grenville-age, basement gneiss complex ("Wacoochee Complex" of Bentley and Neathery, 1970) and an unconformably overlying metasedimentary sequence (Pine Mountain group). U/Pb zircon and Rb/Sr whole-rock ages demonstrate that the basement gneisses were metamorphosed to granulite facies at about 1.1 Ga (Odom et al., 1973, 1985; Kish et al., 1982). Later, during the Paleozoic, both the basement and the unconformably overlying cover sequence were deformed into a series of northwest-vergent recumbent thrust nappes and were metamorphosed to amphibolite facies (Schamel and Bauer, 1980; Schamel et al., 1980; Sears et al., 1982). The nappes are arched about a gently northeast plunging axis, resulting in the map-scale antiformal outcrop pattern of the belt.

The rocks composing the Pine Mountain belt are everywhere separated from surrounding eugeoclinal Piedmont metamorphic rocks by major fault zones. On the south, the boundary is formed by the Goat Rock and Bartletts Ferry faults. These are prominent, synmetamorphic, southeast-dipping mylonite zones, greater than 1 km thick. Rb/Sr whole-rock ages from phyllonites within the Bartletts Ferry fault suggest that this fault was active during Devonian time (~375 Ma), at or near the time of peak metamorphism affecting both the Piedmont allochthon and the structurally underlying Pine Mountain belt (Russell, 1985). To the northeast, where the Pine Mountain belt plunges beneath the Inner Piedmont, the boundary between the two is an annealed mylonite zone, the Box Ankle fault (Hatcher et al., 1981). To the north, the Pine Mountain belt is separated from the Inner Piedmont by the Towaliga fault. In Alabama this is a moderately steep, northwest-dipping mylonite zone, similar in character to the Goat Rock and Bartletts Ferry faults, but apparently younger because stable mineral assemblages within the mylonite zone indicate that its formation postdates the peak of regional metamorphism (Hooper, 1982). Along strike to the northeast, the mylonite is replaced by a broad zone of cataclasite that crosscuts metamorphic foliation in the rocks on both sides of the fault (Schamel and Bauer, 1980; Schamel et al., 1980). Schamel et al. (1980) have suggested that this is a late-stage brittle normal fault that overprinted an earlier ductile (mylonitic) thrust. An apparently similar brittle normal fault also occurs within the Pine Mountain belt (Shiloh fault). There is no direct information on the age of these brittle faults or on the magnitude of the displacements across them. However, they have been presumed to be relatively minor features that did not play a significant role in the overall development of the Pine Mountain belt (e.g., see cross sections in Schamel et al., 1980, and Sears and Cook, 1984).

On the basis of surface geology and by analogy with other orogenic belts, it has generally been presumed that uplift of the basement in the Pine Mountain belt resulted from west-directed thrust imbrication and associated ductile folding of basement that occurred during Paleozoic collisional orogeny (e.g., Schamel et al., 1980; Sears and Cook, 1984). An essentially similar interpretation has been applied to virtually all Appalachian interior basement massifs (e.g., Hatcher, 1984, and references therein; Stanley and Ratcliffe, 1985). By implication, the Appalachian detachment (basal decollement) should continue eastward beneath these basement massifs, and the exposed faults framing the massifs should be transported higher level thrusts.

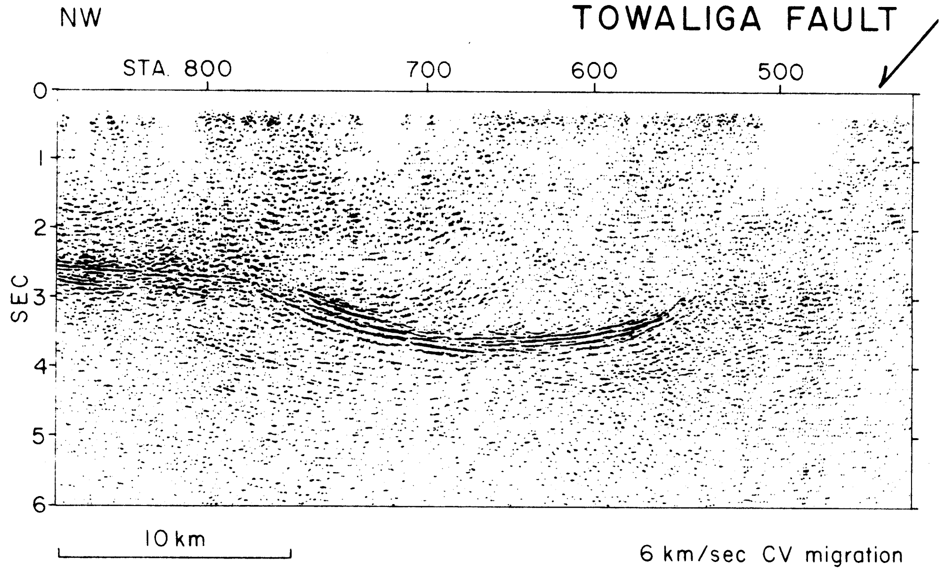

Figure 2. Part of COCORP's Georgia line 15 crossing southeastern part of Inner Piedmont and adjacent northwest edge of Pine Mountain belt (migrated, CMP-stacked section). Note that prominent reflection horizon associated with Appalachian detachment does not continue southeastward beneath Pine Mountain belt. Profile is approximately 20° oblique to regional dip, and 1:1 assuming an average crustal velocity of 6 km/s.

COCORP DATA

COCORP recently completed a series of deep seismic reflection profiles, which together compose a traverse from the Valley and Ridge province in northeastern Alabama to the buried African terrane in northern Florida (Nelson et al., 1985, 1987). The most prominent feature visible on the northern half of this traverse is a gently southeast dipping band of reflectors in the upper crust, which extends from the level of the basal decollement in the Valley and Ridge province (Rome Shale) 130 km southeastward beneath the Talladega belt, Ashland Wedowee belt, and Inner Piedmont. This band of reflectors is virtually identical, in terms of its reflection character, level in the crust, and position in the orogenic belt, to the reflectors associated with the Alleghanian age Appalachian detachment on earlier COCORP lines in Tennessee and northeastern Georgia (Cook et al., 1979, 1981) and on Virginia Polytechnic Institute and U.S. Geological Survey lines collected farther to the north in the Appalachians (Clark et al., 1978; Milici et al., 1979; Harris et al., 1981, 1982). This basal decollement is distinct from and presumably younger than the shallower Blue Ridge–Piedmont thrust, recently identified on seismic reflection profiles in South Carolina (Hatcher et al., 1987). The prominent reflections marking the Appalachian detachment are commonly thought to originate from autochthonous metasedimentary strata immediately beneath the detachment, and overlying Grenville basement (Rome Shale or its eastward equivalents; Cook et al., 1979), though it has been argued that the more interior part of these reflections might originate from the detachment itself (i.e., a mylonite zone; Iverson and Smithson, 1982).

A striking feature of this prominent reflecting horizon, on the new COCORP profiles, is that it does not continue southeastward beneath the Pine Mountain belt. Rather, it terminates abruptly beneath the Inner Piedmont, just to the northwest. Figure 2 shows part of COCORP's Georgia line 15 crossing the southwest part of the Inner Piedmont and adjacent northeast flank of the Pine Mountain belt (migrated, common midpoint, stacked section). The reflections associated with the Appalachian detachment are clearly visible as an approximately 0.4-s-thick band, the top of which intersects the northwest end of the profile at 2.6 s (about 7.8 km depth). From there the band of reflectors dips gently southward, describes a gentle synform, and then terminates abruptly at 3.0 s beneath vibration point 540. This termination is approximately 6.5 km northwest of the Pine Mountain belt (measured perpendicular to regional strike) at a depth of about 9 km, and it appears to be along the downdip projection of the Towaliga fault (Figs. 1, 2). No similar band of reflectors is visible on Georgia line 15 at any level, beneath or southeast of the Pine Mountain belt.

Whatever produces the reflections associated with the Appalachian detachment, it apparently does not continue southeastward beneath the Pine Mountain belt. This observation is difficult to reconcile with the conventional basement duplex interpretation of the Pine Mountain belt. That interpretation implies that Grenville basement, and its autochthonous metasedimentary cover, must extend at least some distance beneath the Pine Mountain belt in that transported basement with cover is exposed in the belt (Fig. 3A). Assuming the reflections associated with the Appalachian detachment originate from metasedimentary strata attached to Grenville basement (the conventional view), then these reflections would likewise be expected to extend southeastward beneath the belt. This interpretation does not appear to be in accord with the seismic data.

No doubt some unconventional thrust geometries can reconcile the surface geologic relations with the seismic data. For example, it is conceivable that the detachment, along which the Piedmont allochthon was first emplaced, cut downsection in the vicinity of the Pine Mountain belt, locally stripping the cover from Grenville basement. Subsequent imbrication of basement across this region might then have produced a situation where high-level basement slices with metasedimentary cover locally overlie a basal detachment lacking cover in the footwall and hence lacking associated reflections (Fig. 3B). In general, however, this class of interpretations appears to require fortuitous circumstance and/or nonstandard thrust geometries (i.e., thrusts cutting downsection in the direction of transport).

Figure 4 illustrates a simple alternative interpretation of the Pine Mountain belt consistent with both the seismic data and the local geologic relations. The main feature of the interpretation is the Towaliga fault, which we suggest is a large, northwest-dipping normal fault. This fault offsets Grenville basement and its overlying metasedimentary cover, the Appalachian detachment, and the Piedmont allochthon by about 9 km. The fault has an average dip of about 54°, measured between the surface and the cutoff of the Appalachian detachment reflections beneath VP 540. The Towaliga fault is slightly steeper than this in outcrop, implying that it curves somewhat with depth. We infer that the reflections that mark the Appalachian detachment north of the Pine Mountain belt originate from metasedimentary strata beneath the detachment. The Pine Mountain group, which crops out in the footwall of the Towaliga fault, is in an analogous position and thus is interpreted to be the southern continuation of the strata that produce the reflections associated with the detachment to the north. Similarly, the Goat Rock–Bartletts Ferry fault system, which carries the Piedmont allochthon over the southeast side of the Pine Mountain belt, is interpreted to be the exposed southern continuation of the Appalachian detachment.

We note that the reflections associated with the Appalachian detachment north of the Pine Mountain belt might, alternatively, originate from the detachment itself (mylonite zone) rather than from metasedimentary rocks beneath the detachment. Although some mylonite zones do produce reflections (e.g., Smithson et al., 1978; Fountain et al., 1984; Hurich et al., 1985), this interpretation appears to be less likely in the present situation because reflections comparable to those north of the Pine Mountain belt apparently are not produced by the Bartletts Ferry fault (mylonite zone) in the region crossed by the COCORP profile. The local map pattern indicates that the Bartletts Ferry fault rides directly on Grenville basement at this location (and along strike to the northeast, Figs. 1, 4). Thus, one would expect strong reflections from the Bartletts Ferry fault if the reflections north of the Pine Mountain belt are produced by a mylonite zone at the base of the Piedmont allochthon, whereas one would not expect reflections in this position if the reflections north of the belt are produced by metasedimentary rocks below such a mylonite zone. The latter situation appears to be more in accord with the seismic data. In either case, however, the two likely candidates for producing the detachment reflections are exposed around the periphery of the Pine Mountain belt and are offset some 9 km in a normal sense from the correlative reflectors occurring beneath the Inner Piedmont to the north.

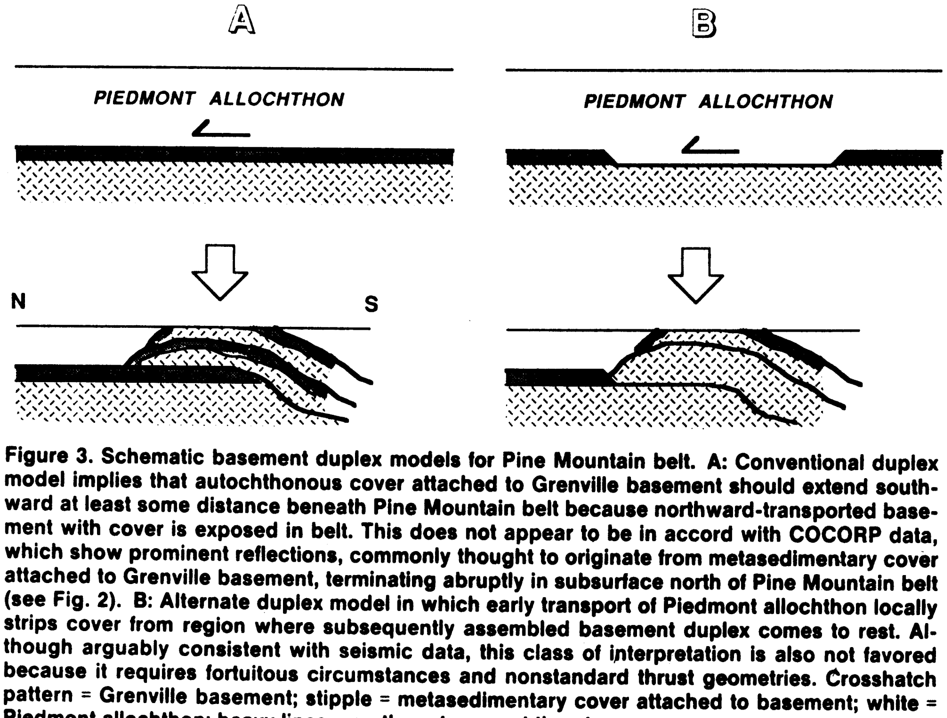

Figure 3. Schematic basement duplex models for Pine Mountain belt. A: Conventional duplex model implies that autochthonous cover attached to Grenville basement should extend southward at least some distance beneath Pine Mountain belt because northward-transported basement with cover is exposed in belt. This does not appear to be in accord with COCORP data, which show prominent reflections, commonly thought to originate from metasedimentary cover attached to Grenville basement, terminating abruptly in subsurface north of Pine Mountain belt (see Fig. 2). B: Alternate duplex model in which early transport of Piedmont allochthon locally strips cover from region where subsequently assembled basement duplex comes to rest. Although arguably consistent with seismic data, this class of interpretation is also not favored because it requires fortuitous circumstances and nonstandard thrust geometries. Crosshatch pattern = Grenville basement; stipple = metasedimentary cover attached to basement; white = Piedmont allochthon; heavy lines = northwest-vergent thrusts.

DISCUSSION

Traditionally, mylonite zones in the Appalachian Piedmont have been interpreted as thrusts, or in the case of the Eastern Piedmont fault system, transcurrent faults (Bobyarchick, 1981). The COCORP data, however, indicate that at least one prominent example, the Towaliga fault, is likely to be a major normal fault, though it may have overprinted a preexisting thrust along part of its length. Recent studies of the Modoc zone in South Carolina imply that this prominent mylonite zone is also a late normal fault (Sacks and Secor, 1986), as is the Lake Char–Honey Hill fault system in eastern Connecticut (Goldstein, 1982; Goldstein and Owens, 1985). One wonders whether other mylonite zones in the interior of the Appalachians might also have a *significant* component of late normal slip, particularly in places where structurally lower (higher metamorphic grade) rocks occur in the footwall. The Augusta, Nutbush Creek, and Hylas faults of the southern and central Appalachian Piedmont would all seem to be reasonable candidates (Maher, 1978; Farrar, 1985; Bobyarchick and Glover, 1979).

Although there are no data constraining the time of normal slip on the Towaliga fault, the interpretation presented here implies that it postdated Alleghanian thrust movement on the Appalachian detachment. One possibility is that normal slip was "late Alleghanian" (Late Pennsylvanian–Permian?) in age, like that associated with the Modoc zone (Sacks and Secor, 1986), and resulted from gravitational collapse of the Alleghanian orogenic belt. Alternatively, part or all of the displacement could have occurred during early Mesozoic time. Normal-fault–bounded Triassic–Early Jurassic basins are a well-known

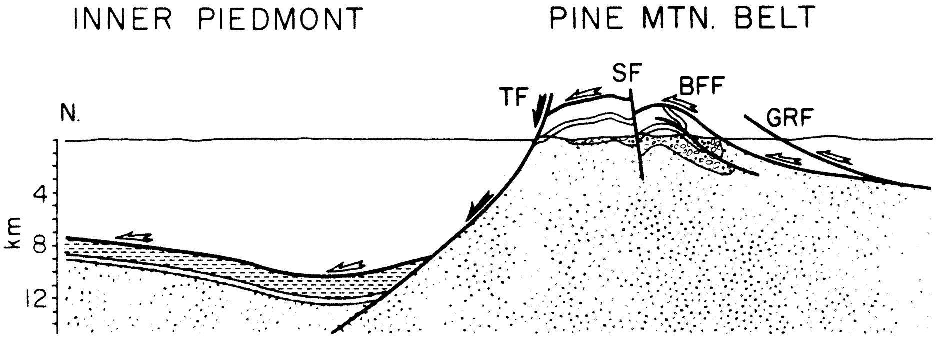

Figure 4. Interpretive geologic cross section of Pine Mountain belt based on integration of surface geology (essentially cross section B-B′ of Schamel et al., 1980) with COCORP seismic reflection data (Fig. 2). Line of section indicated by arrows in Figure 1. Pine Mountain belt is suggested to be large asymmetric horst that resulted largely from late normal displacement on Towaliga fault. By implication, Appalachian detachment is exposed around periphery of Pine Mountain belt. Open arrows = synmetamorphic northwest-directed thrusts (Appalachian detachment); solid arrows = postmetamorphic normal fault. TF = Towaliga fault; SF = Shiloh fault; BFF = Bartletts Ferry fault; GRF = Goat Rock fault. Patterns same as in Figure 1.

feature of the Appalachian Piedmont northeast of the Pine Mountain belt (Wadesboro basin, Deep River basin, etc.) and are also known to occur beneath the Georgia Coastal Plain immediately to the south (composite South Georgia basin). In the latter case, COCORP profiling has shown that displacements on the larger basin-bounding faults are comparable to the displacement suggested here for the Towaliga fault (Nelson et al., 1985; McBride et al., 1985). Mesozoic normal faults in the Appalachians are commonly thought to reactivate older Paleozoic faults (Peterson et al., 1984; Ratcliffe and Burton, 1985), and this could well be the case for the Towaliga fault. We note that other west-dipping Mesozoic normal faults occur in the Appalachians (e.g., Jonesboro fault—Durham basin, Eastern Border fault—Hartford basin), and both east- and west-facing Mesozoic rift basins exist beneath the U.S. Atlantic margin (Bally, 1981).

The second important feature of our interpretation is the idea that the ductile faults framing the Pine Mountain belt represent an exposed segment of the Appalachian detachment. If so, then the latest thrust motion on these faults should be Alleghanian in age, having occurred concurrently with shortening in the Valley and Ridge province. Subsequent postmetamorphic uplift and cooling of the region should have occurred, at least in part, concurrently with late normal slip on the Towaliga fault. As yet we do not know how to rationalize the Devonian Rb/Sr whole-rock age reported for phyllonites from the Bartletts Ferry fault zone (Russell, 1985). However, we question whether this date actually constrains the latest movement on the fault. In any case, appropriate geochronological studies should provide a ready means for testing our interpretation.

If our interpretation is correct, then the Pine Mountain belt provides a natural laboratory in which to examine structures associated with the Appalachian detachment, within the interior of the orogen. For example, surface geology indicates that the detachment carrying the Piedmont allochthon rides on metasedimentary cover on the northwest side of the Pine Mountain belt (Pine Mountain group below the Towaliga fault), whereas to the southeast it apparently cuts downsection into Grenville basement (Wacoochee Complex in footwall of the Goat Rock fault) (Fig. 1). Projection along regional strike indicates that the Pine Mountain belt is in a position approximately parallel to that where, on COCORP lines in northeastern Georgia, Appalachian detachment reflections merge into a zone of steep east-dipping reflections beneath the Kings Mountain belt. That zone of dipping reflections has been interpreted to mark a major thrust ramp where the Appalachian detachment cuts downward from metasedimentary cover into basement (Cook et al., 1981, Fig. 7B; Iverson and Smithson, 1982). The ramp exposed in the Pine Mountain belt might simply be the along-strike extension of this feature, exposed as a consequence of late normal slip on the Towaliga fault. A corollary of this interpretation is that of Grenville basement exposed in the Pine Mountain belt is North American basement, sensu stricto. It does not represent a Grenville age continental block accreted to North America during the Paleozoic (as Thomas, 1977, suggested *might* be the case).

Perhaps of more general significance is the question of what actually produces the reflections associated with the Appalachian detachment, particularly beneath the more interior parts of the orogen. Indeed, answering this question conclusively is one of the primary reasons cited for drilling a deep borehole in the southern Appalachians—potentially the most expensive United States earth science research project in history (Williams and Hatcher, 1985; Smithson and Pujol, 1985). The COCORP data, together with surface geology in the Pine Mountain belt, appear to support the view that these reflections originate from metasedimentary rocks below the detachment rather than from the detachment itself. In either case, however, our interpretation implies that both the detachment and the underlying strata are exposed in the Pine Mountain belt and hence are available for direct observation. Appropriate field and laboratory studies (particularly velocity/density measurements) of these rocks might therefore contribute greatly to answering this fundamental question.

Finally, we suggest that the Pine Mountain belt is, in a general sense, analogous to the Cordilleran metamorphic core complexes that have received so much attention in recent years (e.g., Coney, 1980; Armstrong, 1982). Like the Cordilleran core complexes, the Pine Mountain belt is an antiformal basement culmination that occurs within the interior of an orogenic belt, in a region last affected by crustal extension. Furthermore, like those features, it lies in the footwall of a major ductile high-strain zone overprinted by later brittle deformation. Although the Towaliga fault is not a *low-angle* extensional detachment, with increasing displacement it might well have become one. We question whether other interior basement massifs in the Appalachians might similarly be the product of late Paleozoic and/or Mesozoic extension, rather than thrust imbrication alone. Such a finding would profoundly alter the prevailing view of the evolution of the Appalachian interior.

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