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COCORP SEISMIC REFLECTION PROFILING IN THE OUACHITA MOUNTAINS OF WESTERN ARKANSAS: GEOMETRY AND GEOLOGIC INTERPRETATION

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Abstract. COCORP seismic reflection profiling in the Ouachita Mountains of western Arkansas indicates that (1) Carboniferous foreland basin deposits within the Arkoma Basin thicken dramatically toward the south, reaching an aggregate thickness in excess of 12 km (4.5 s two-way travel time) beneath the southern edge of the Frontal Thrust Zone, (2) evidence for northward directed low-angle thrusting within this clastic sequence is prominent, with a probable decollement surface lying at or near the contact with underlying Early Paleozoic shelf carbonates, (3) beneath the Benton Uplift a sequence of discontinuous events defines a broad antiform cresting at approximately 7 km (2.8 s); this structure appears to mimic the anticlinorial shape of the Benton Uplift indicated by the surface outcrop pattern, (4) beneath the Southern Ouachitas, south dipping stratified events are observed to depths in excess of 14 km (5.0 s), (5) deeper in the section a prominent, gently north dipping reflection occurs at approximately 22 km depth (7.6 s) beneath the northern Coastal Plain/Southern Ouachitas.

Extrapolation of data along strike in the Ouachita belt, and consideration of large-scale structure observed in other collisional orogenic belts, suggest that the reflection events observed beneath the Benton Uplift represent Early Paleozoic shelf carbonates correlative with those that floor the Arkoma Basin to the north. This interpretation requires that the Early Paleozoic deep-water sediments exposed in the core of the Ouachitas be allochthonous, and also implies significant basement uplift beneath the core zone. To the south, the prominent package of layered reflections occurring beneath the Southern Ouachitas and northern Coastal Plain indicates that a significant portion of the crust in that region is composed of imbricate sedimentary and/or metasedimentary strata. At relatively 'shallow' levels these strata are correlative with the Carboniferous flysch cropping out in the Southern Ouachitas, and at somewhat deeper levels, they are correlative with the Early to Middle Paleozoic deep-water sediments exposed on the Benton Uplift.

INTRODUCTION

Recently, the Consortium for Continental Reflection Profiling (COCORP) completed a seismic reflection survey across the Ouachita Mountains in western Arkansas (Figure 1). This area represents an

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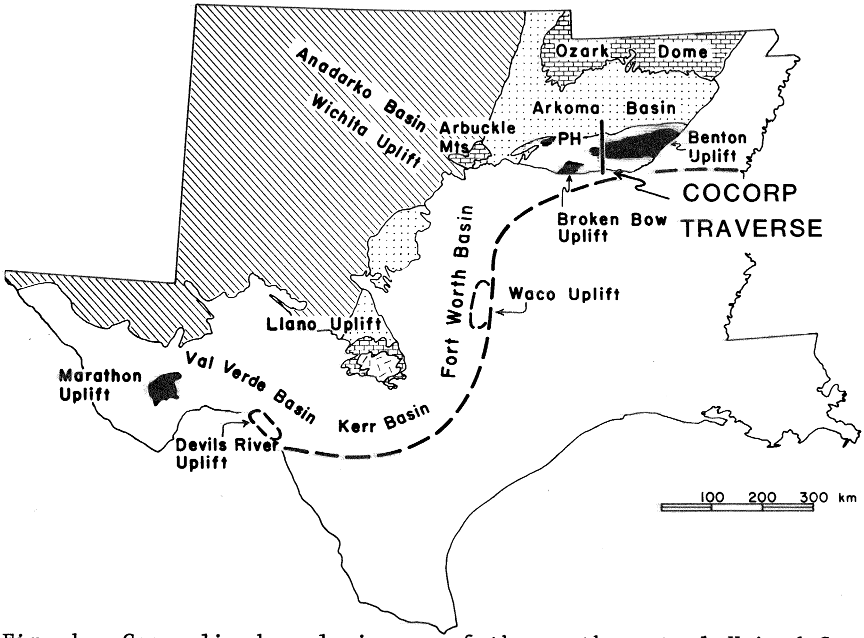

Fig. 1. Generalized geologic map of the south central United States. Heavy dashed line marks trend of Ouachita gravity high. Slash pattern--Precambrian basement; brick pattern--Early Paleozoic platform sediments ('Arbuckle facies'); solid black--Early Paleozoic deep-water sediments ('Ouachita facies,' includes Mississippian flysch in the Marathon area); grey--Mississippian flysch; stipple--Pennsylvanian flysch/molasse; diagonal rule--Late Paleozoic sediments of the continental interior; white--Mesozoic/Cenozoic Coastal Plain onlap.

exposed portion of the Late Paleozoic Ouachita orogenic belt, which along most of its length is buried beneath Mesozoic and Cenozoic sediments of the Gulf Coastal Plain. Borehole and geophysical data indicate that the Ouachita belt extends as a continuous feature southwest of the exposures in Arkansas and Oklahoma, cropping out again in the Marathon Uplift of southwest Texas [Flawn et al., 1961]. From there it turns southward into Mexico. Borehole data also indicate that Ouachita strata extend southeastward from the exposures in Arkansas into the region of the Mississippi Embayment [Thomas, 1973]. Further continuation of the belt to the southeast, and the nature of its intersection with the southwesterly trending Appalachian orogen, are subjects of speculation at present (see, for instance, Thomas [1973] and P. King in Flawn et al. [1961]). The 'known' extent of the belt within the United States is approximately 1500 km, and given its southern continuation in Mexico, it is probably considerably longer. Though details are in doubt, the evolution of the Ouachitas is commonly viewed in terms of a Carboniferous collisional event involving a south facing, Atlantic-type continental margin of North America and an oceanic island arc complex or active continental margin that impinged from the south ('Llanoria'; see, for example, Briggs and Roeder [1975], Walper [1977], Viele [1979]). The COCORP data collected in Arkansas are compatible with this hypothesis and furthermore, appear to yield considerable insight into the nature and geometry of subsurface structure associated with this collisional event. In this paper we describe the principle features observed on the COCORP seismic sections and discuss their interpretation in light of regional geologic constraints. Detailed description of the seismic data, including actual seismic lines, and a discussion of other geophysical

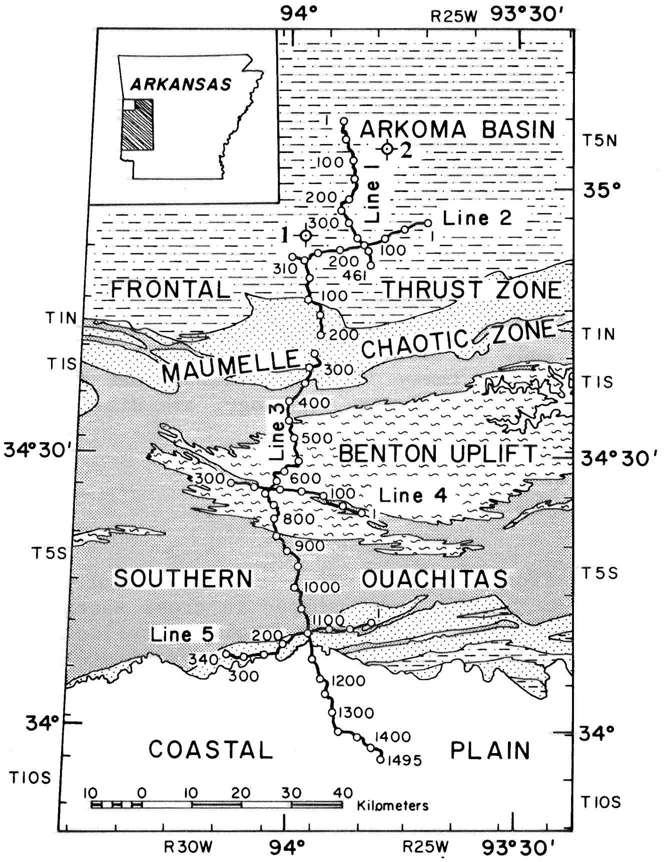

Fig. 2. Geologic map of western Arkansas showing location of the COCORP seismic reflection lines. Wavy horizontal rule--Early to Middle Paleozoic deep water sediments exposed in the Ouachita core zone (Ouachita facies); fine stipple--Mississippian Stanley Shale; coarse stipple--Jackfork and Johns Valley Formations (Morrow); dash-dot pattern--Pennsylvanian Atoka and younger formations; white--Coastal Plain onlap (generalized from Haley et al. [1976]).

data pertaining to the area are presented in a companion paper [Lillie et al., 1982].

The COCORP seismic traverse of the Ouachita orogen begins within the Arkoma Basin near Booneville, Arkansas, and extends 130 km southward, crossing the Frontal Thrust Zone, Benton Uplift, and southern Ouachitas (lines 1 and 3, Figure 2). The line ends 20 km south of the present northern edge of the Coastal Plain onlap, near Nashville, Arkansas. Three east-west cross lines were also completed: one within the southern portion of the Arkoma Basin (line 2), one near the center of the Benton Uplift (line 4), and one adjacent to the northern edge of the Coastal Plain (line 5). The primary results of the survey are schematically illustrated in Figure 3a, which is a composite line drawing of the upper 10 s of the unmigrated north-south seismic sections. These are nominal, 24-fold Vibroseis (trademark Conoco, Inc.) seismic reflection lines recorded by a commercial contractor and processed at Cornell University. The acquisition and processing parameters used in the survey are given by Lillie et al. [1982]. Depth estimates indicated in the following discussion were calculated by using the stacking velocity function at the point in question.

These in turn were derived from analysis of constant velocity stacked sections. As a general rule, 1 s of two-way travel time corresponds to 2-2.5 km depth within the upper 3 s of data at the north end of the survey, and 2.5-3 km depth within the upper 8 s at the south end (i.e., rock velocities between 4 and 6 km/s). As displayed, the line drawing is roughly 1:1.

Although the COCORP data provide important new information on the geometry of crustal structure in the Ouachitas, the local geological/geophysical constraints do not, at present, allow for a unique interpretation of the seismic profiles. For this reason, we present the COCORP results along with several (though by no means all) possible geologic interpretations (Figures 3b-3d). Each of these interpretations is consistent with the overall geometry indicated by the seismic reflection data and, we believe, with the local surface geologic data. The rationale for these interpretations, and their relative plausibility in light of the regional geology, are discussed in the succeeding section.

RESULTS

Frontal Thrust Zone

COCORP data within the Frontal Thrust zone indicate that the foreland basin in this area is broadly wedge-shaped in cross section, thickening to the south. Relatively bright, continuous reflection events occur as far down as 3.0 s two-way travel time (approximately 6 km depth) at the north end of line 1 and down to at least 5.0 s (approximately 14 km depth) near the beginning of line 3. Projection of surface and well geologic data indicate that essentially the entire reflection sequence in this area originates from within the Carboniferous foreland basin sequence. Borehole and commercial seismic reflection data collected just north of the survey area indicate that the Arkoma Basin is floored by Early Paleozoic shelf carbonates that dip gently to the south ('Arbuckle facies'; Buchanan and Johnson [1968]). Extrapolation of these data to the south indicates that the top of the carbonates should occur at a depth of approximately 7.3 km in the vicinity of VP 200, corresponding to a two-way travel time of about 3.0 s. The prominent reflections marked A1 on Figure 3a intersect this time beneath VP 200, and we therefore interpret these as originating from the top of the carbonate sequence. The prominent reflection segments marked A2, A3, and A4 on Figure 3a represent their probable continuation to the south. Beneath the anticlinal structure centered at VP 300, these events appear to be stepped down to the south, possibly along one or more south facing normal faults similar to those known to affect the carbonates farther north [Buchanan and Johnson, 1968]. By using the depth estimates indicated above, the reflection data show that the floor of the Carboniferous basin has a regional dip southward of approximately 15° beneath the Frontal Thrust Zone.

Structures visible within the Carboniferous section are indicative of north directed thrusting. For example, the prominent 'bow tie' structure on the beginning of line 3 (B in Figure 3a) marks an angular discordance between steeply north dipping beds on the left and moderately south dipping beds on the right. Where this discordance projects to the surface, Early Pennsylvanian Johns Valley Formation is found thrust northward over younger Middle Atoka strata [Haley et al., 1976]. Angular discordances at C and just above the prominent reflections at A1 probably also mark the locations of north directed thrusts; though the latter may alternatively represent northward depositional onlap of Carboniferous clastics over Early Paleozoic carbonates. The antiformal structure centered beneath VP 300 on line 1 is interpreted to be a hanging wall anticline ('snake head'). The prominent reflections marked A2, A3, which step down beneath this structure, do not appear to be folded, whereas the overlying Carboniferous strata clearly are. This structure is probably cored by a blind thrust that ramped up along a preexisting offset in the underlying carbonates [Buchanan and Johnson, 1968]. This thrust, and those cropping out farther south, are all likely to be splays off a low-angle detachment (decollement) occurring at or near the interface between Early Paleozoic carbonates and overlying Carboniferous flysch (i.e., just above A1). This thrust, or possibly one at a higher stratigraphic level, must propagate in the subsurface beyond the northern limit of our survey, since thrusts are mapped at the surface farther north.

Maumelle Zone and Benton Uplift

Between VP's 213 and 239 on line 3 there is a data gap of approximately 3 km caused by the crew's inability to operate vibrator trucks across Buck Knob. Beyond this gap the line crosses the broad zone of deformed Mississippian flysch (mostly Stanley Shale), which along strike to the east has been termed the Maumelle Chaotic Zone [Viele, 1974], and then continues to the south, crossing the Early Paleozoic deep water sediments exposed on the Benton Uplift (Arkansas Novaculite and older units). Within this region relatively few coherent reflections are observed in the upper several seconds of the seismic section. This change in data character toward the south is probably due, at least in part, to an increase in structural complexity in the upper few kilometers of the crust. In general, the strata cropping out within the Maumelle Zone and Benton Uplift are relatively thin bedded sediments that are tightly folded and disrupted by thrust faults on a much finer scale than occurs to the north. Presumably, the relatively short-wavelength discontinuous nature of the structure in these rocks is too fine to be resolved by the survey technique, which was designed primarily to enhance deeper reflection events. Where previous COCORP surveys have crossed terranes exhibiting similar structural style, near surface results have generally been minimal. Examples include line 1 of the Georgia survey crossing the Inner Piedmont [Cook et al., 1979] and New York line 1 crossing the Taconic Allochthon [Ando et al., 1982].

Despite the apparent paucity of shallow reflections in the region of the Benton Uplift, a notable sequence of discontinuous events is observed at depth. These events describe a broad antiformal structure centered beneath the core of the Benton Uplift, apparently mimicking the anticlinorial structure of this region, indicated by the surface outcrop pattern (D1, D2, D3 in Figure 3a; see Figure 2). These events are first observed at VP 350 on line 3 at approximately 4.3 s two-way travel time. Toward the south they rise gently, reaching 2.8 s beneath the core of the Uplift (approximately 7 km). From there they continue to the south, dipping moderately southward beneath the southern half of the Benton Uplift and Southern Ouachitas.

At present, we are unable to trace this antiformal sequence directly on the seismic section into any of the geologically 'identified' reflections occurring to the north. For this reason the interpretation of this sequence is equivocal. One possibility is that North American basement and overlying Arbuckle facies carbonates continue to the south beneath the Benton Uplift, where they are deformed into an antiformal basement arch. This possibility is illustrated in Figures 3b and 3c, where it is suggested that the antiformal sequence of reflections observed in the region of the Benton Uplift originates within, or at the top of, Arbuckle facies carbonates, analogous to the better defined reflections that mark this sequence farther north (A1-A4). Alternatively, the Benton Uplift may be cored by Precambrian or Paleozoic basement, which is exotic to cratonic North America. This possibility, illustrated in Figure 3d, would imply that the Maumelle Chaotic Zone marks a crustal penetrating suture. A third possibility (not shown) is that the antiformal reflections beneath the Benton Uplift originate entirely from within thrust-imbricated sedimentary strata, perhaps similar to the thrust-imbricated Ouachita facies cropping out at the surface in this area.

Although local geologic constraints do not allow distinction between these possibilities, consideration of geologic data along strike in the Ouachita belt suggests that the first possibility is most likely (i.e., where Precambrian North American basement continues southward beneath the Ouachita core zone, Figures 3b and 3c). Regional gravity data indicate that the Benton Uplift lies along a steep, positive seaward, Bouguer gravity gradient, which can be traced continuously along strike through Oklahoma and Texas (Woollard and Joesting [1964]; see Lillie et al. [1982]). Commercial seismic reflection work has demonstrated the existence of other large antiformal structures in the subsurface, coinciding with this regional trend (Broken Bow area in Oklahoma [C. Arbenz, personal communication, 1982], and Waco and Devils River areas in Texas [Nicholas and Rozendal, 1975]). In the Waco and Devils River areas, drilling has demonstrated that the reflection events delineating these antiforms originate within carbonates [Rozendal and Erskin, 1971; Nicholas and Rozendal, 1975]. In the Devils River area, these carbonates are clearly correlative with Early Paleozoic platform carbonates exposed to the north (Ordovician Ellenburger Limestone). Although the carbonates drilled in the Waco area are deformed and lack diagnostic fossils, a similar correlation is commonly assumed [Nicholas and Rosendal, 1975; Dennison et al., 1977]. In both areas the carbonate sequences are underlain by metaquartzite, which, in the case of the Devils River Uplift, in turn is underlain by a mixed metasedimentary-volcanic assemblage overlying igneous basement. The latter has yielded late Precambrian (Grenville) Rb/Sr ages [Nicholas and Rozendal, 1975]. On the basis of these results, Nicholas and Rozendal [1975] have argued that the Early Paleozoic continental shelf of North America extends beneath the Ouachita gravity gradient in Texas. Furthermore, the shelf strata in that area have apparently been uplifted relative to those lying immediately to the north beneath Carboniferous foreland basin deposits. The antiformal structure centered beneath the Benton Uplift has a similar seismic expression to, and occurs along geologic strike with, the antiformal structures described by Nicholas and Rozendal [1975]. Lacking data to the contrary, we presume it has a similar origin.

Assuming shelf strata do continue southward beneath the Ouachita core zone, then the Early to Middle Paleozoic 'Ouachita facies' exposed at the surface in this area must be allochthonous, since they overlie, structurally, coeval shelf carbonates. Northward transport of these strata has been suggested by several previous workers, based on regional stratigraphic and structural arguments (for example, Flawn et al. [1961] and Viele [1966, 1974]). In each of the interpretations depicted in Figure 3, Ouachita facies are shown as part of an imbricate allochthonous 'sheet' transported toward the north. Arching of the basement beneath the Benton Uplift presumably occurred synchronously with, or after, emplacement of the allochthon. Unfortunately, the reflection data within the Maumelle Zone and Benton Uplift are such that the subsurface geometry of faults in this region, related to northward transport, cannot be determined. In Figures 3b and 3c we schematically illustrate two alternate geometries; others are possible. The reflection data do indicate, however, that the structural thickness of transported Early Paleozoics may be as much as 7 km at the center of the Benton Uplift (i.e., the entire sequence down to 2.8 s). We note that the Viersen and Cochran No. 1 Weyerhaeuser well, drilled immediately along strike on the Broken Bow uplift, penetrated

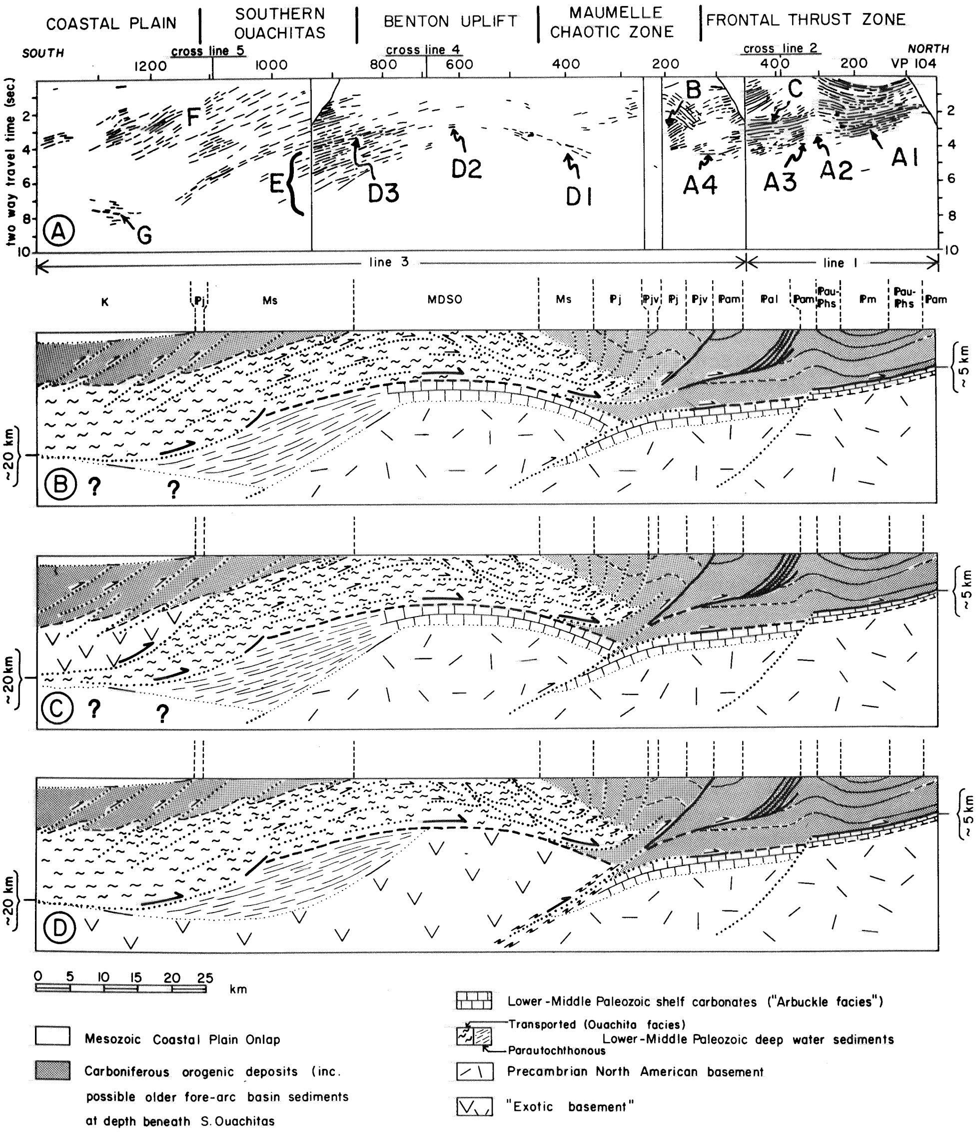

Fig. 3. 3a is a composite line drawing of the upper 10 s of the COCORP unmigrated north-south seismic lines. The diagram represents roughly the upper 25 kilometers of the crust and is approximately 1:1 assuming an average upper crustal velocity of 5 km/s. Panels 3b, 3c, and 3d illustrate three possible geologic interpretations of the seismic reflection data. These interpretations incorporate geometric information gained from analysis of migrated time sections. Each of the interpretations shown is consistent with 'local' geologic constraints. However, based on regional considerations, the authors prefer the interpretations shown in panels 3b and 3c.

more than 3 km of similar strata without reaching 'basement' of any sort [Dennison et al., 1977].

In the alternate (less favored) interpretation shown in Figure 3d, northward transport of Ouachita facies strata is not required by the basement configuration. By assuming northward transport, this interpretation becomes essentially a three-plate model with one suture occurring beneath the Maumelle Zone, represented by the contact between North American and exotic basement, and a second, low-angle suture occurring beneath the Southern Ouachitas and Benton Uplift, represented by the basal thrust of the Ouachita facies allochthon. The seismic data in Arkansas do not preclude the possibility that Ouachita facies strata were transported southward over the Benton Uplift from the area of the Maumelle Zone. Indeed, south vergent structures that might be attributed to such transport are observed in Ouachita facies strata both in Arkansas and Oklahoma. However, at present we prefer to interpret these structures as a local effect superimposed on what is essentially a northward transported assemblage. The numerous thrust faults within the Frontal Zone, north of the Benton Uplift, are clearly north vergent, as are the thrusts in the Southern Ouachitas, immediately to the south [Haley et al., 1976; Walthall, 1967]. Greater than 80 km of cumulative northward transport has been determined for strata within the Frontal Zone, clearly demonstrating northward transport of Ouachita facies in that region (i.e., Black Knob Ridge, Potato Hills [Arbenz, 1968]). Significant southward transport of Ouachita facies has not been demonstrated anywhere in the Ouachita orogenic belt.

Southern Ouachitas

Beginning at approximately VP 700 on line 3, a prominent series of south dipping, apparently planar reflection events are observed beneath the south flank of the Benton Uplift (E in Figure 3a). This sequence of events appears to thicken and deepen in a wedge-shaped fashion toward the south, with individual events being traceable to at least 5.0 s two-way travel time beneath the Southern Ouachitas (approximately 14 km). Although interpretaton of these events is not constrained by surface or borehole data, their stratified nature and apparent wedge-shaped geometry suggest that they may be reflections from sedimentary or metasedimentary strata, perhaps interstratified with volcanics (see Lillie, et al., 1982). If so these strata have probably been structurally modified by tilting or perhaps thrust imbrication, since the observed dips appear too steep to be depositional. Alternatively, these reflection events may represent interfaces within crystalline basement, though we note that further north on the survey, Precambrian basement does not exhibit a similar layered character on the north-south seismic sections. In Figures 3b and 3c, these events are interpreted as sedimentary and are suggested to represent the transition to deeper, thicker, off-shelf facies in the buried Early Paleozoic continental margin. In Figure 3d they are also suggested to be of sedimentary origin, though in this case the sediments would have been deposited on, or to the south of, the exotic basement shown coring the Benton Uplift.

Beneath the Southern Ouachitas and northern Coastal Plain, a zone of south dipping reflections is also observed at somewhat shallower depths (F on Figure 3a). These reflections are visible in the range 1 to approximately 4 s two-way travel time (approximately 2-11 km depth). Extrapolation of these events to the surface indicates that they are correlative with thrust-imbricated Mississippian flysch (mostly Stanley Shale), exposed in the Southern Ouachitas, and at somewhat deeper levels with the Early Paleozoic strata exposed on the Benton Uplift. This correlation indicates that the structural thickness of sedimentary strata beneath the Southern Ouachitas and northern Coastal Plain is at least comparable to that occurring within the Frontal Thrust Zone and may be considerably greater. Surface mapping has shown that the strata cropping out in the Southern Ouachitas are cut by numerous south dipping (north vergent) thrust faults, similar to those occurring within the Frontal Thrust Zone

[Walthall, 1967]. Apparent low-angle crosscutting relations observed within the reflection sequence may mark the locations of such thrusts in the subsurface.

Beneath the northern Coastal Plain a very prominent deep reflection horizon is also observed (G on Figure 3a). This event occurs at 7.6 s two-way travel time beneath VP 1300 (approximately 22 km depth) and is clearly distinguishable on single VP records [see Lillie et at., 1982]. It appears to dip gently northward, and on migrated sections is tracable at least as far north as VP 1100, where it can be identified on cross line 5. Interpretation of this reflection horizon is problematic. On the basis of its relatively high amplitude, we suggest that it may represent the top of crystalline basement (Figures 3b and 3d). This interpretation would imply that approximately the upper 20 km of the crust beneath the Southern Ouachitas and northern Coastal Plain is composed of thrust imbricated sedimentary and/or metasedimentary strata. Assuming Precambrian North American basement extends beneath the Benton Uplift (Figure 3b), then the basement below this assemblage is likely to be 'transitional' or oceanic crust formed adjacent to the Early Paleozoic continental margin (see discussion of gravity data by Lillie et al., [1982]).

In Figure 3c we note the possibility that exotic basement might exist at depth beneath the northern Coastal Plain/Southern Ouachitas but not extend as far north as the Benton Uplift. This possibility is not constrained by the seismic data, except in the sense that the top of such basement would have to lie at a depth greater than about 11 km, since the reflections above this level are correlated with reasonable confidence with sedimentary strata exposed at the surface. In Figure 3c the exotic basement is drawn, somewhat arbitrarily, in the 'reflection-free' zone occurring from about 4 to 8 s beneath the northern Coastal Plain/Southern Ouachitas. As such, it lies immediately to the south, and in part overrides, transported Ouachita facies from behind. Basement in this general position may reasonably be regarded as relict 'forearc basin basement' in the sense used by Dickinson [1974]. In this scenario the Carboniferous sediments cropping out south of the Benton Uplift lie in depositional contact, in part on exotic basement and in part (just to the north) on imbricate Ouachita facies. As noted by Viele [1979], clastic sediments in this geologic setting would lie 'in the position of' a forearc basin. The nature of the 7.6 s reflection occurring beneath the Coastal Plain is not specified in model 3c, as it may lie above, within, or, conceivably, below the exotic basement.

COMPARISON WITH OTHER OROGENIC BELTS

The antiformal sequence observed beneath the Benton Uplift and the relatively deep, south dipping events occurring beneath the Southern Ouachitas and Coastal Plain represent newly discovered, large-scale features of the Ouachita orogen. As is clear from the previous discussion, intepretation of these features is of necessity based on regional correlation and inference rather than direct geologic data gained from drilling. For this reason, it seems appropriate to compare the geometry of these features, indicated by the seismic data, with that of structures observed at the surface in other, more deeply eroded, orogenic belts for which a grossly similar evolution has been inferred.

Figure 4 shows schematic one-to-one cross sections of the Ouachitas and three other 'collisional' orogenic belts in which one side of the system is generally thought to have been an Atlantic-type continental margin. The latter include (1) the western New England Appalachians, interpreted in terms of Medial Ordovician continent-arc collision [Chapple, 1973; Rowley and Kidd, 1981], (2) the Tibetan Himalaya,

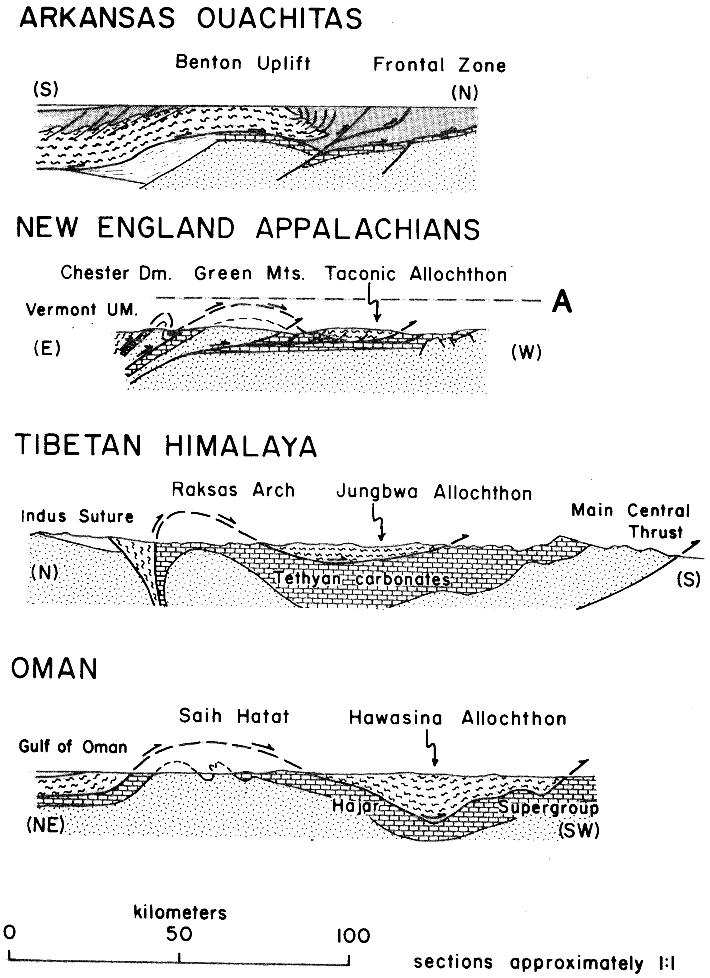

Fig. 4. Schematic geologic sections across the Ouachitas and several other mountain belts in which one side of the orogen is commonly thought to have been an Atlantic-type margin. In each of the cases depicted, deep-water sediments (wavey pattern) have been transported for a considerable distance over a coeval shelf sequence (brick pattern). Furthermore, in each of these areas the structurally underlying shelf sequence has been arched into an anticlinorial structure cored by continental basement. The COCORP seismic reflection data suggest that a similar structural configuration occurs within the Ouachita orogen in western Arkansas. (New England Appalachians--Ando et al., [1982]; central Tibetan Himalaya--revised after Gansser, [1964]; Oman Mountains--Bailey et al. [1981]).

representing Tertiary continent-continent collision [Le Fort, 1975; Gansser, 1980], and (3) the Oman Mountains, representing Late Cretaceous continent-arc (?) collision [Gealey, 1977; Coleman, 1981]. Each of the sections is oriented so that the inferred Atlantic-type margin is on the right side of the diagram and 'faces' left. Admittedly, the magnitude of crustal shortening observed in each of these orogenic belts is quite different, and no doubt the details of their evolutionary histories are also. Nonetheless, the cross sections depicted in Figure 4 have several large-scale features in common. Each shows a relatively 'thin' allochthonous sheet composed of deformed deep water sediment and, in the case of the Himalaya and Oman, ophiolite complex. These deep water assemblages have been transported tens of kilometers to locally greater than 100 km out over coeval miogeoclinal assemblages (i.e., Taconic klippen--Northern Appalachians; Jungbwa and Spontang klippen--Tibetan Himalaya; and Hawasina nappe complex--Oman). A second common feature is that in each case, these allochthonous sheets are now preserved as isolated klippen within regional synclinoria that lie immediately on the foreland side of broad anticlinorial structures cored by continental basement (i.e., Green Mountains--Northern Appalachians; Raksas Arch--Himalaya; Saih Hatat anticlinorium--Oman). Miogeoclinal sediments are clearly continuous across these basement arches, and, since in each case the structurally overlying allochthon must 'root' somewhere beyond the interior exposure limit of the miogeocline, they too must have originally been continuous across these anticlinoria. Recently acquired COCORP data in the Northern Appalachians suggest that the crystalline basement exposed in the Green Mountains has itself been transported along a second, deeper seated detachment (hence the decollement depicted beneath the Green Mountains in Figure 4; Ando et al. [1982]). In effect, it appears that the Green Mountain anticlinorium is a large hanging-wall anticline. COCORP seismic reflection data in the southern Appalachians, and U.S. Geological Survey reflection data in the central Appalachians indicate that virtually all the 'interior' basement massifs in those portions of the Appalachian orogen are also transported [Cook et al., 1979; Harris et al., 1981, 1982]. The Raksas Arch and Saih Hatat anticlinorium may be related to similar basement detachments, though, as yet, seismic reflection data are not available with which to test this hypothesis [Gealey, 1981].

Analysis of the sections in Figure 4 suggests a direct analogy between the structures observed at the surface in these relatively well exposed mountain belts and the large-scale geometry observed on the Ouachita seismic profiles. This analogy may best be illustrated by imagining a geologic section across the Northern Appalachians if the erosion surface were raised to the level indicated by the dashed line marked A in Figure 4. In this situation, the presently exposed Taconics might lie entirely buried beneath younger foreland basin deposits. However, their eastern extension, lying above the present Green Mountains, would be exposed in an erosional window similar to the Benton Uplift. Flysch-type sediments deposited on, and in front of, the allochthon would frame the erosional window, dipping away from it toward the east and west (analogous to the Stanley Shale). Similar sediments would also occur as thrust-bounded slices within the exposed allochthon, having been tectonically incorporated during transport. Beneath the area of the present-day Taconics, shelf sediments would dip gently eastward in the subsurface toward the position of the present-day Green Mountains. Indeed, shelf strata with this general geometry are observed beneath that area on COCORP's New England survey [Ando et al., 1982] and on the SOQUIP seismic reflection lines in Quebec [Ministere des Richesses Naturelles, 1979a,b]. Farther east, the present outcrop pattern indicates that correlative shelf sediments would rise in an antiformal structure cresting beneath the erosional window just described. On the east flank of this structure, these strata would again dip to the east (though in this case probably rising again over the Chester Dome). An equivalent statement could be made for each of the areas depicted in Figure 4. In each case, the outcrop pattern and geometry of the inferred geologic section would be essentially similar to the observed situation in the Ouachitas.

This comparison lends plausibility to the inference that the antiformal sequence beneath the Benton Uplift represents the southern continuation of the Early Paleozoic continental margin of North

America rather than some exotic basement or cover. It also leads to the suggestion that the Early Paleozoic deep-water sediments exposed on the Benton Uplift are, in fact, part of a 'Taconic-type' allochthon exposed over a basement arch. In this regard, we note that the range of lithologies cropping out on the Benton Uplift and their overall structural style are quite similar to the Taconics, suggesting a similar origin (compare, for example, descriptions by Morris [1974] and Clardy et al. [1980] with those of Zen [1967] and Rowley et al. [1979]). The bulk of the sedimentary assemblage comprising the Taconic allochthon (and other similar examples) is generally thought to represent transported slope and rise facies, originally deposited adjacent to the shelf assemblage they now structurally overlie [Bird and Dewey, 1970; Williams, 1975]. This conclusion is based (1) on the range of sedimentary lithologies represented in the allochthons and (2) on the occurrence within allochthonous sediments of detrital material derived from the shelf and/or underlying craton (for example, conglomerates in the Nassau, West Castleton, Hatch Hill Formations of the Taconic allochthon; Cow Head Breccia in the Humber Arm Allochthon, Newfoundland). Granitic clasts in the Crystal Mountain Formation, yielding 1200 m.y. zircon ages, demonstrate a cratonic source for at least some of the Ouachita facies assemblage (P. Bickford, personal communication, 1982). Shallow water carbonate clasts, occurring in a number of Ouachita facies units, may well be shelf derived, though as yet diagnostic fossils have not been identified within them (for example, Ordovician oolitic limestone clasts in the Collier Shale [Clardy et al., 1980]).

In Arkansas, it is doubtful that transported Early Paleozoic sediments actually extend in the subsurface much beyond their present northern outcrop limit. The seismic data in the Frontal Thrust Zone suggest that the basin in that area is entirely filled with Carboniferous deposits, leaving little room for a 'tongue' of transported material immediately above shelf carbonates. However, along strike in Oklahoma, equivalent strata clearly do extend in the subsurface well north of the core zone. This is demonstrated by the occurrence of Ouachita facies strata cropping out in the Potato Hills area some 60 km north of the Broken Bow Uplift. As noted, it is not clear from the seismic data how far transported Early Paleozoic strata extend in the subsurface south of the Ouachita core area. Comparison with the across-strike widths of Taconic-type allochthons exposed elsewhere suggests that these strata may well extend tens of kilometers beyond the southern limit of the COCORP survey.

EVOLUTION

On the basis of the preceding discussion, it appears that a crustal configuration like that illustrated in either Figures 3b or 3c represents the most likely situation in the Arkansas Ouachitas. Regional considerations suggest that the basement configuration shown in Figure 3d is unlikely, as would be the case where 'no basement' exists beneath the Benton Uplift. Figure 5 illustrates a simplified evolutionary scheme for the Ouachita orogen drawn specifically to address the crustal configuration illustrated in Figure 3b, though with minor modification it is also compatable with that of Figure 3c. The model involves Carboniferous arc-continent collision, followed by Permo-Triassic rifting to the south (opening of the Gulf). Although this general scenario has been suggested previously (for example, Briggs and Roeder, [1975]), the scheme depicted here represents a somewhat modified version, which we feel gives plausible explanation for (1) northward transport of Early Paleozoic slope and rise sediments over the coeval shelf assemblage, (2) the development of a basement uplift beneath the core of the Ouachitas, and (3) the occurrence of a large thickness of imbricate Paleozoic sedimentary strata beneath the

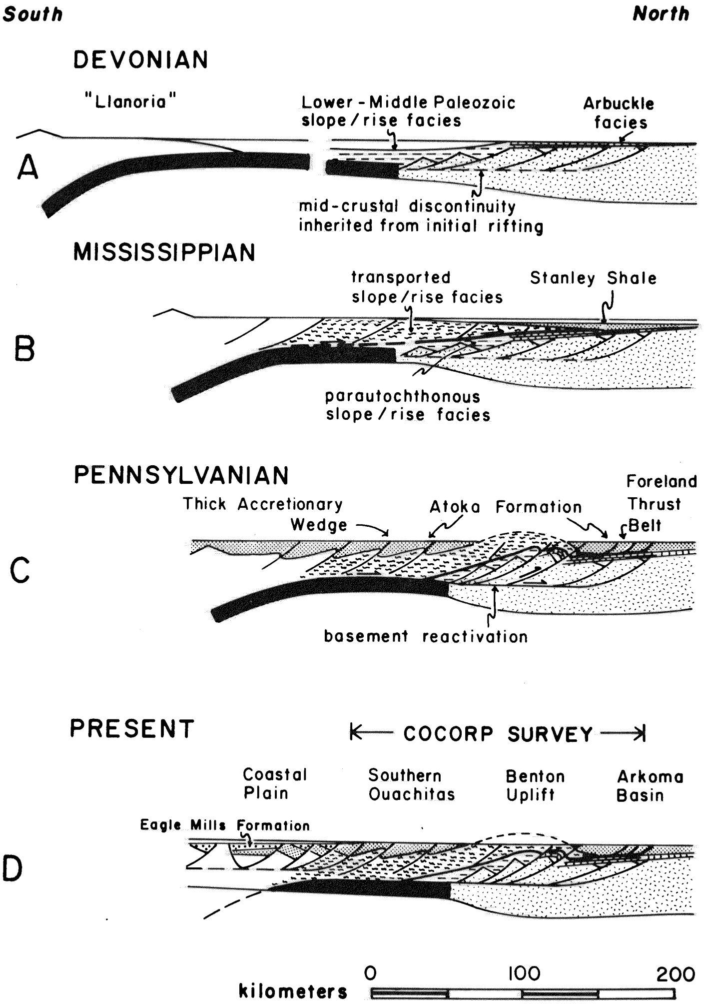

Fig. 5. A simple plate tectonic model for the evolution of the Ouachita orogen, involving Late Paleozoic arc-continent collision followed by Permo-Triassic opening of the Gulf of Mexico. This scenario provides a reasonable explanation for (1) northward transport of Ouachita facies deep water strata over coeval shelf rocks, (2) development of a basement cored uplift beneath the Ouachita core zone, and (3) the occurrence of a thick assemblage of thrust-imbricated Paleozoic sediments beneath the Southern Ouachitas and northern Coastal Plain.

Southern Ouachitas and northern Coastal Plain. The diagram is patterned in part after one recently presented by Rowley and Kidd [1981] for the New England Appalachians and, in general sense, would be appropriate for each of the mountain belts illustrated in Figure 4.

Precollisional elements in the diagram are an Early Paleozoic Atlantic-type continental margin and somewhere to the south, an active island arc formed over a south-dipping subduction zone (Figure 5a). The choice of an oceanic island arc rather than an active continental margin is arbitrary, and indeed, at this time available geologic data do not allow one to differentiate between these possibilities. The Atlantic-type margin depicted in the figure is generalized from the work of Montadert et al. [1979] on the Bay of Biscay. Their study probably represents the best constrained view of 'transitional' crust beneath an Atlantic-type margin currently available.

Figure 5b illustrates a syn-collisional configuration in which the Atlantic-type margin has been partially subducted beneath the forearc region of the opposing island arc. Somewhat earlier in the collision a thick assemblage of continental rise and slope sediments would have been added to the arc accretionary prism, significantly expanding its across-strike width. With continued subduction, the continental shelf is transported beneath these accreted sediments, resulting in relatively far traveled slope and rise facies structurally overlying coeval shelf carbonates. Clastic material derived primarily from exposed accretionary complex will be deposited, synchronously with movement, across the front of the accretionary wedge and depressed continental shelf immediately in front (Stanley Shale). These clastics are likely to contain intercalated water-laid tuff horizons derived from the active volcanic arc immediately to the south (Hatton and Beaver Bend Tuffs [Niem 1971). Downward flexure of the continental shelf in front of the advancing subduction zone results in formation of seaward facing normal faults cutting shelf carbonates and overlying prograding clastics (normal faults described by Buchanan and Johnson [1968]). The present-day collision of the north Australian continental margin with the Banda arc system represents a modern example of this configuration [Hamilton, 1979].

In Figure 5b the primary detachment zone beneath the forearc region is shown at or near the top of the downgoing shelf carbonates, analogous to the present situation beneath the Banda forearc. However, at some later time in the convergence history the primary slip surface probably migrated to a deeper level in the subducting continental margin--perhaps to a preexisting midcrustal discontinuity similar to that observed on seismic profiles recorded in the Bay of Biscay (Figure 5c; Montadert et al. [1979]). Conceivably, dewatering and/or strain hardening of sediments within the subduction zone causes an increase in their shear strength to a point where slip along a deeper zone of weakness is preferred. Alternatively, the leading edge of subducted continental crust may have reached the bend in the subduction zone beneath the volcanic arc, at which point the entire thickness of attenuated continental crust was forced to shorten, rather than continue smoothly down the subduction zone. In any case, movement along a deeper slip surface, and consequent reactivation of basement normal faults as thrusts (see, for example, Jackson [1980]), would have shortened the upper part of the continental crust and imbricated the continental shelf and overlying thrust emplaced rise/slope assemblage. Where one or more basement slices ramped upward relative to their neighbors, a basement uplift would have resulted. Though cut by thrusts, the sediments overlying these uplifted blocks would be disposed in a regional anticlinorium. This scenario provides a reasonable explanation for each of the anticlinoria depicted in Figure 4 and similarly we feel, for the Benton Uplift.

After collisional shortening ceased in Late Pennsylvanian time, the arc terrane lying south of the present Ouachitas apparently subsided below sea level, resulting in deposition of the Late Pennsylvanian/Permian platform sediments known from wells drilled through the Coastal Plain [Woods and Addington, 1973]. Subsequent crustal stretching associated with Triassic opening of the Gulf resulted in renewed subsidence in this area and the development of normal faults in the Paleozoic basement [Vernon, 1971; Woods and Addington, 1973]. Fault bounded basins filled with locally derived clastic material (Eagle Mills Formation) and were then covered by northward onlapping Jurassic/Cretaceous carbonates. The resulting configuration is illustrated in Figure 5d.

CONCLUSIONS

The COCORP seismic reflection data, when coupled with regional geological and geophysical information, yield significant new insight into the subsurface structure of the Ouachita orogen. Major aspects of our interpretation of these data are as follows:

1. The structural thickness of Carboniferous clastics within the Frontal Thrust Zone in Arkansas increases dramatically toward the south, reaching an aggregate thickness of 12-15 km beneath the southern edge of the Frontal Thrust Zone.
2. The Benton Uplift coincides with a broad antiformal structure occurring in the subsurface. This antiform is probably cored by uplifted North American Precambrian basement.
3. Early to Middle Paleozoic 'Ouachita facies' strata exposed at the surface on the Benton Uplift are allochthonous, having been transported an indeterminate distance from the south. The structural thickness of this transported assemblage may be as great as 7 km at the center of the Benton Uplift.
4. A significant portion of the crust beneath the Southern Ouachitas and northern Coastal Plain is composed of thrust-imbricated Paleozoic sedimentary and/or metasedimentary strata. This assemblage has a structural thickness of at least 11 and possibly as much as 22 km. It is not known whether exotic ('Lanorian') crystalline basement exists at depth beneath these strata.
5. The major structural features observed on the COCORP seismic sections can reasonably be interpreted as having formed during a 'simple' arc/continent collision, in which the subduction zone dipped south. Although more complex scenarios can be imagined, they are not warranted by the available data.

In closing, we note that this study leaves unanswered the question of whether or not any 'Llanorian' crust actually exists at depth beneath the Southern Ouachitas or Coastal Plain. Given the widths of modern forearc regions, one need not expect crystalline Llanorian basement for a considerable distance to the south. Pre-Desmoinesian volcanics, penetrated in wells drilled on the Sabine Uplift, could represent the northernmost extent of Llanorian basement (D. Nicholas, personal communication, 1982). Alternatively, this basement may have been entirely removed during subsequent opening of the Gulf [White, 1980; Pindell and Dewey, 1982]. An obvious way to address this question, and others relating to Gulf Coast evolution, would be to extend the COCORP Ouachita survey to the south.

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