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Crustal Structure of Ouachita Mountains, Arkansas: A Model Based on Integration of COCORP Reflection Profiles and Regional Geophysical Data[1]

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ABSTRACT

COCORP deep seismic reflection profiles across the Ouachita Mountains in western Arkansas suggest that a large fraction of the crust in this region is composed of tectonically thickened Paleozoic sediments (and metasediments). Reflections representing a southward-thickening wedge of layered rock on the northern portions of the survey are associated with approximately 12 km (39,000 ft) of Carboniferous flysch overlying thin, lower to middle Paleozoic shelf strata in the Frontal thrust zone. Toward the interior of the mountain belt, the Benton uplift is a broad antiform, apparently cored by crystalline basement at depths below 7 km (23,000 ft). Beneath the southern Ouachitas and the adjacent Gulf coastal plain, a zone of south-dipping reflections probably represents at least 14 km (46,000 ft) of tectonically thickened, lower to middle Paleozoic off-shelf strata and Carboniferous flysch.

Regional Bouguer gravity data show a minimum coincident with the thickest accumulation of flysch in the Frontal thrust zone. To the south, the Benton uplift lies on a steep gravity gradient which is continuous along most of the Ouachita trend and which may be analogous to a gradient observed along the Appalachian chain. The Ouachita gravity signature can be modeled as a southward shallowing of the Moho (from 40 km [131,000 ft] in northern Arkansas to about 30 km [98,000 ft] just south of the Ouachitas), coincident with the tectonic thickening of the Paleozoic strata interpreted from the COCORP data. The resulting crustal section can be interpreted as the remnants of an early Paleozoic passive margin which was subducted beneath a thick accretionary wedge in Carboniferous time. The Benton uplift is viewed as a late-stage involvement of crystalline basement in foreland thrusting as the margin entered the south-dipping subduction zone.

INTRODUCTION

In a continuing effort to understand the nature of orogenic belts at depth, the Consortium for Continental Reflection Profiling (COCORP) recently recorded deep seismic reflection profiles across the Ouachita Mountains in western Arkansas. Elsewhere (Nelson et al, 1982), three possible interpretations for the reflection profiles are presented, along with a comparison of the geology of the Ouachitas to that of other mountain belts. Key features interpreted from the sections include a southward-thickening wedge of Paleozoic strata, interrupted by a large antiformal structure at the core of the mountains. In this paper, further details of the interpretation of the reflection data, including interpreted and uninterpreted seismic sections, are presented. Additionally, other published geophysical data are analyzed to infer a total crustal structure which includes a southward shallowing of the Moho to accommodate the thick wedge of Paleozoic strata. The last part of this paper is a model for the tectonic evolution of the Ouachita Mountains involving south-dipping subduction of a Paleozoic passive margin in Carboniferous time.

The late Paleozoic Ouachita orogenic belt lies landward of the modern continental margin of the southern United States (Fig. 1). Lower to middle Paleozoic, deep-marine strata associated with the belt are exposed at the surface in the Ouachita Mountains of southeastern Oklahoma and western Arkansas and in the Marathon region of west Texas (McBride, 1975). Borehole data (Flawn et al, 1961) demonstrate that the orogenic belt continues beneath coastal-plain sediments along the Interior (metamorphic) zone and the Frontal (thrust) zone of Texas. These tec-

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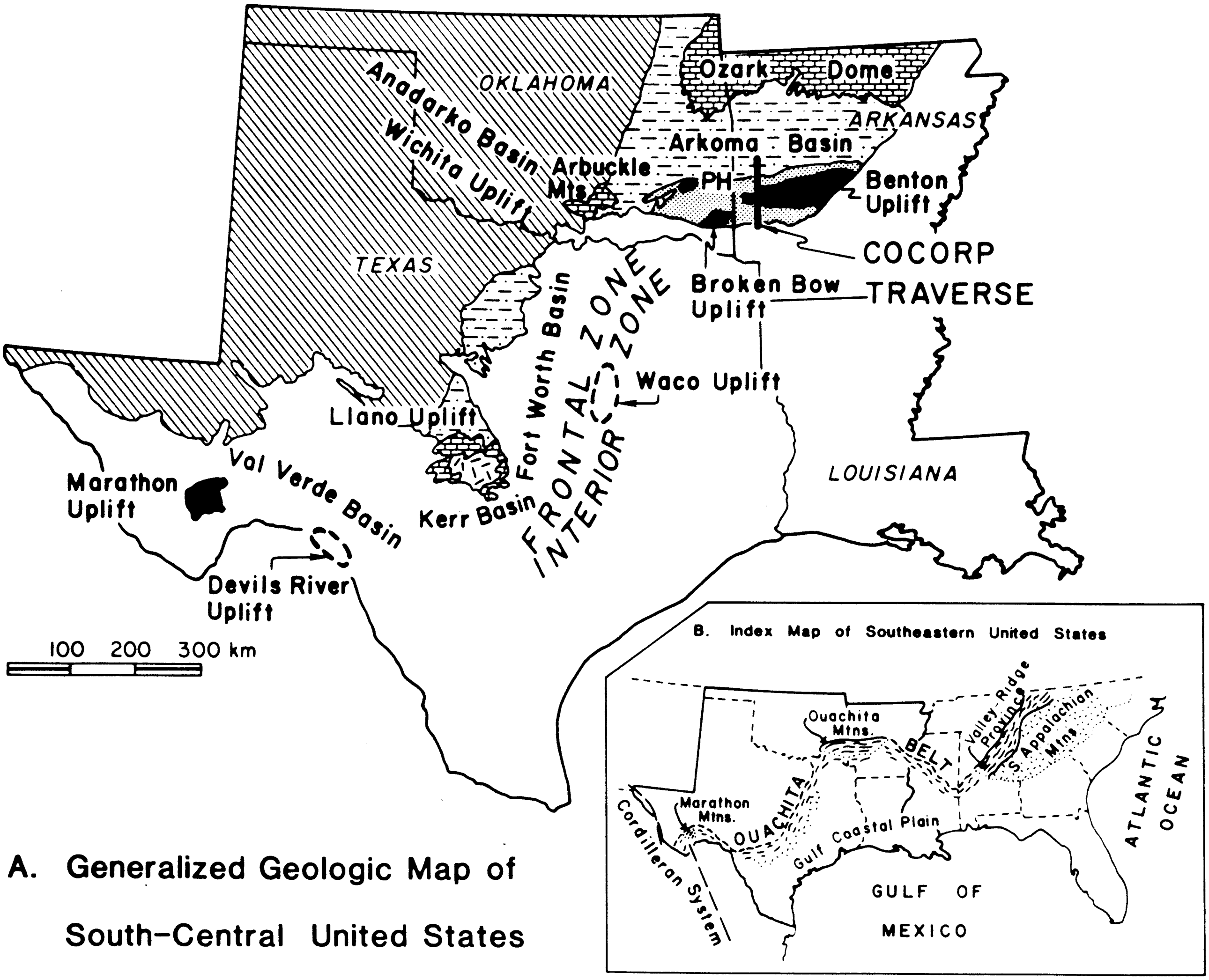

FIG. 1—A. Generalized geologic map of south-central United States showing approximate location of COCORP traverses across Ouachita Mountains in western Arkansas. Brick pattern = lower to middle Paleozoic platform sediments ("Arbuckle facies"); solid black = lower to middle Paleozoic deep-water sediments in Ouachita Mountain area, entire Paleozoic section in Marathon area; stipple = Mississippian flysch; dash-dot = Pennsylvanian flysch and molasse; diagonal rule = upper Paleozoic sediments of continental interior; dash pattern = Precambrian (Grenville) crystalline basement exposed in core of Llano uplift; white = Mesozoic and Cenozoic coastal plain onlap. PH = Potato Hills.

B. Index map of southeastern United States showing Southern Appalachian-Ouachita-Marathon trend (modified from Cebull and Shurbet, 1980).

tonic elements form a broad recess around late Precambrian (Grenville) crystalline rocks of the Llano uplift in central Texas (Flawn and Muehlberger, 1970). Southwest of the Marathon region, evidence of the Ouachita orogeny has been overprinted by later tectonic events associated with the Cordilleran system (Flawn et al, 1961).

East of the Ouachita Mountains, Paleozoic rocks of the Ouachita belt are also overlain unconformably by coastal-plain sediments (Fig. 1). Subsurface data indicate that the orogene continues in a southeastward trend from southeastern Arkansas to eastern Mississippi, where it approaches southwestward trends associated with the Appalachian Mountains (Flawn et al, 1961; Graham et al, 1975; Thomas, 1977 a, b). Many recent workers interpret the Ouachita trend as a suture along which an exotic terrane ("Llanoria") was accreted to the North American continent in late Paleozoic time (e.g., see Wood and Walper, 1974; Briggs and Roeder, 1975; Walper, 1977, 1980; Ross, 1979; Viele, 1979; Kluth and Coney, 1981; Viele and Zietz, 1981).

Several types of geophysical data are available to aid in the understanding of the deep subsurface configuration of the Ouachitas. Regional gravity data show a steep Bouguer gradient separating a series of gravity minima over foreland basins on the landward side of the Ouachita belt from subtle maxima on the seaward side (e.g., see Woollard and Joesting, 1964). These gravity data are typically used to establish the approximate size and trend of the major structural and stratigraphic elements of the belt (e.g., Nicholas and Rozendal, 1975; Viele, 1979). Previously available seismic reflection data provide valuable constraints on parts of the Ouachita belt, but typically deal

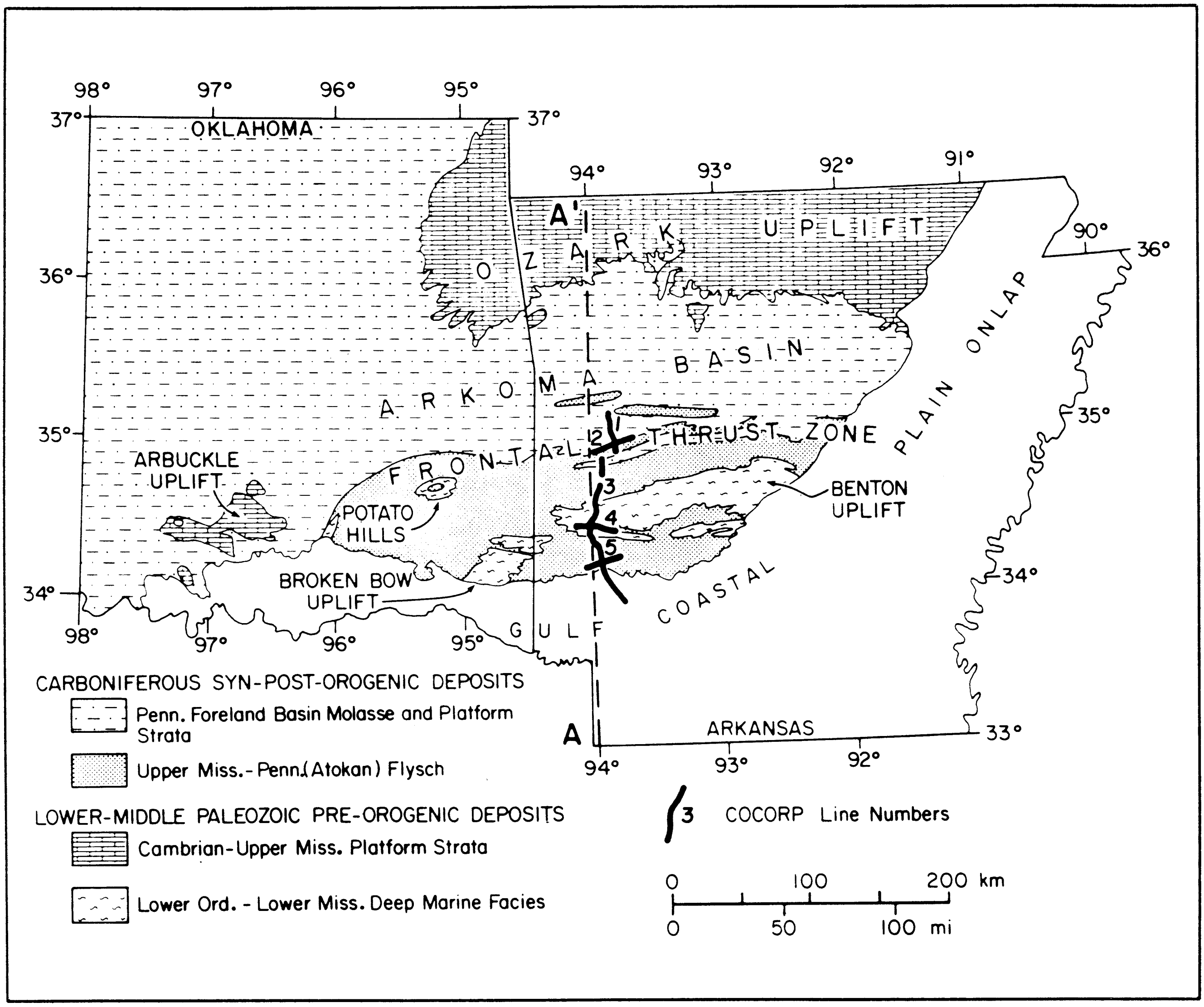

FIG. 2—Generalized geologic map of Arkansas and eastern Oklahoma showing positions of COCORP seismic reflection lines. AA′ is line of section for gravity models shown in Figure 8. Brick pattern: in Arkansas is Jefferson City Dolomite to Pitkin Limestone, in Oklahoma is Arbuckle Group to Caney Shale; wavy pattern: Collier Shale to Arkansas Novaculite; stipple pattern: Stanley Shale, Jackfork Sandstone, Johns Valley Shale, and lower Atoka Formation; dash dot pattern: middle Atoka and younger formations. Upper parts of lines 1 and 3 are displayed as unmigrated time sections in Figure 4(A, B) and as line drawing in Figure 5(A).

with only the upper 10 km (33,000 ft), more or less, of the crust. Published seismic sections by Rozendahl and Erskine (1971) and Nicholas and Rozendahl (1975) show that basement-cored anticlines lie within the area of steep gravity gradient in Texas. A single north-south refraction line across southern Mississippi (interpreted by Warren et al, 1966, to show a shallow Moho near the juncture of the Ouachita and Appalachian trends) represents the only published data of that type which may directly relate to the Ouachita belt (e.g., see Warren and Healy, 1973). Interpretation of a recently released aeromagnetic map by Viele and Zietz (1981) suggests that basement rocks on opposite sides of the Ouachita belt are fundamentally different in magnetic character. COCORP data provide detailed subsurface constraints which can be integrated with these regional studies to enhance understanding of the total crustal structure associated with the Ouachita belt.

INTERPRETATION OF COCORP TRAVERSE

Five deep seismic reflection profiles, totaling approximately 200 km (125 mi) of surface coverage, were recorded in western Arkansas in the early part of 1981. The bulk of the survey is a 130 km (80 mi) north-south traverse (lines 1 and 3) extending across the Ouachita Mountains from the southern part of the Arkoma basin, near Booneville, to the Cretaceous portion of the Gulf coastal plain overlap, near Nashville, Arkansas (Fig. 2). Lines 2, 4, and 5 are short, east-west strike lines within the Frontal thrust zone, Benton uplift, and southern Ouachitas, respectively. Parameters used in the acquisition and processing of the 24-fold Vibroseis (Conoco, Inc., trademark) data are listed in Appendix A. Information regarding release of the entire data set can be found in Kaufman (1982).

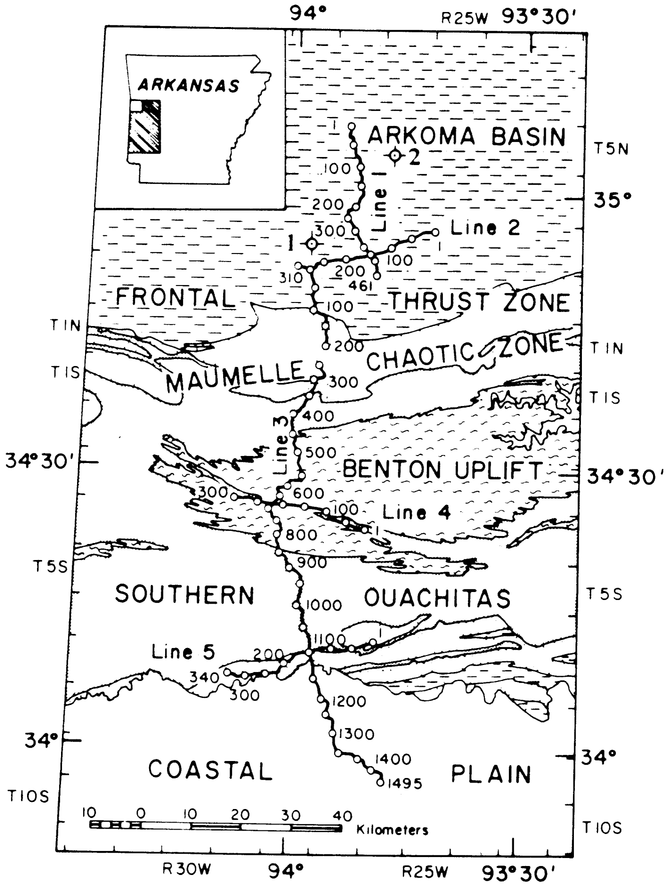

FIG. 3—Geologic map of west-central Arkansas showing Vibrator Point (VP) locations along COCORP seismic reflection lines. Wavy pattern = lower to middle Paleozoic (Collier Shale through Arkansas Novaculite) deep-water sediments; fine stipple = Mississippian Stanley Shale; coarse stipple = Lower Pennsylvanian (Morrow) Jackfork and Johns Valley Formations; dash-dot pattern = lower to middle Pennsylvanian (Atokan and younger) formations; white = Cretaceous and Cenozoic Gulf coastal plain onlap. Exploratory boreholes: (1) El Paso 1 Cheesman, Sec. 22, T3N, R28W; (2) Pacific 1 Garner, Sec. 29, T5N, R26W.

Figure 3 shows Vibrator Point (VP) locations for the COCORP survey and surface geology generalized from the map of Haley et al (1976). Unmigrated time sections of the upper 8 sec of the north-south traverse (lines 1 and 3) are shown in Figure 4A and B. Surface geologic data shown on the sections are from the map of Arkansas (Haley et al, 1976). Depths to formation tops reported for two petroleum exploration wells have been projected onto the sections (Boyd Haley, personal commun.). Figure 4B shows an interpretation of the data (Fig. 5B) superimposed on the section. As a general rule, 1 sec of two-way travel time corresponds to approximately 2.0 to 2.5 km (6,600 to 8,200 ft) in depth for the upper 5 sec in the northern parts of the survey and 2.5 to 3.0 km (8,200 to 9,800 ft) depth for the upper 8 sec in the southern part (i.e., rock velocities between 4.0 and 6.0 km/sec [13,000 and 20,000 ft/sec]). Note, however, that depths quoted in this paper were approximated using the stacking velocity at the point in question and, thus, may differ from depths calculated using these more general conversions. All seismic sections, lines drawings, and interpretations illustrated in this paper have an approximate vertical exaggeration of one-to-one.

Figure 5A is a composite line drawing which schematically shows events observed in the upper 10 seconds of the north-south sections. Migrated time sections (not shown in this paper) were analyzed to aid in the presentation of three possible interpretations which are illustrated in Figure 5 (B, C, D). These models are similar in part, but differ in the interpreted northward extent of "exotic" crystalline basement. In Nelson et al (1982) we conclude, based on a detailed look at local and regional geological constraints, that models 5B and 5C are the most likely. In this paper, further details of the interpretation of the seismic reflection data are put into the context of a north-south traverse across western Arkansas.

Arkoma Basin–Frontal Thrust Zone

Figure 2 shows the location of the COCORP traverses relative to major structural and stratigraphic features of Arkansas and eastern Oklahoma. In the northern part of Arkansas, a thin (about 1 km [3,300 ft] thick) section of lower to middle Paleozoic, shallow-marine carbonate rocks is exposed in the Ozark uplift. These strata (here collectively termed the "Arbuckle facies") can be associated with the stable North American craton in early to middle Paleozoic time (Viele, 1979). Several authors have inferred the southward transition of the carbonates into south-facing shelf and slope facies in the subsurface (e.g., Briggs and Roeder, 1975; Walper, 1977).

Borehole data indicate that the lower to middle Paleozoic carbonate strata dip gently to the south beneath Carboniferous foreland basin clastic sediments filling the Arkoma basin (Berry and Trumbly, 1968; Buchanan and Johnson, 1968). These clastics range from Early Pennsylvanian (Morrowan) to Middle Pennsylvanian (Desmoinesian) in age and show both upward and cratonward (northward) gradation from deep-marine flysch to a shallow-marine to continental molasse facies (Viele, 1979). Steep, dominantly down-to-the-south normal faults cut the carbonates flooring the deeper part of the Arkoma basin and probably offset the underlying Precambrian basement (Buchanan and Johnson, 1968). In the southern half of the Arkoma basin, Carboniferous clastics are deformed into a series of east-northeast–trending open folds cored by north-verging thrust faults (Berry and Trumbly, 1968). Commercial seismic reflection work has shown that these thrusts commonly ramp up along the preexisting normal fault offsets in the underlying carbonate sequence (Buchanan and Johnson, 1968).

COCORP line 1 begins in the southern fringes of the Arkoma basin where thrust faults first break through to the surface (Frontal thrust zone). There, the Carboniferous clastics exposed at the surface change from a molasse to a deep-water flysch facies and thicken rapidly to the south. North-verging thrusts within the northern part of this zone are steep at the surface but flatten considerably above crystalline basement rocks (Berry and Trumbly, 1968). Cumulative northward transport of at least 80 km (50 mi) has been estimated for the Oklahoma portion of the Frontal thrust zone (see review of published estimates in Berry and Trumbly, 1968).

On the north end of line 1, high-amplitude events occurring at about 3.0 sec (7.3 km, 24,000 ft) beneath VP 200 project to approximately 2.45 sec (5.0 km, 16,400 ft) beneath the Pacific Garner well in Sec. 29, T5N, R26E. This well penetrated the top of Morrowan shale at a depth of 3,478 m (11,411 ft subsea) and was drilled to a total depth of 4,249 m (13,941 ft subsea) without reaching pre-Pennsylvanian rocks. These data, coupled with stratigraphic thicknesses for the pre-Pennsylvanian section observed in other wells in the vicinity of the survey (e.g., see Buchanan and Johnson, 1968), suggest that the high-amplitude events represent reflections from sedimentary layering at or near the top of the lower to middle Paleozoic carbonate sequence that floors the Arkoma basin. The base of layered reflections is observed at 3.4 sec beneath VP 200 and presumably marks the top of the underlying Precambrian basement. Thus, at VP 200 on line 1 approximately 7.3 km (24,000 ft, 3.0 sec) of Pennsylvanian clastic sediments and 1.2 km (3.900 ft; i.e., the interval 3.0 to 3.4 sec) of pre-Pennsylvanian platform carbonates overlie the Precambrian crystalline basement. The total sedimentary assemblage thickens substantially to the south, reaching about 14 km (46,000 ft, 5.0 sec) beneath VP 100 on line 3.

The north end of line 3 is offset from the south end of line 1 by about 12 km (7.5 mi). Coincidently, the last basement point of line 1 (approximately at VP 460) lies along surface geologic strike with the first basement point of line 3 (approximately at VP 45). Cross line 2 (not illustrated) follows geologic strike on the upper plate of a major zone of thrusting which begins at VP 345 on line 1. A paucity of coherent reflection events is observed in the upper 2 sec (4.8 km, 14,700 ft) of line 2, probably indicating intense thrust imbrication within lower Atokan rocks on the upper plate. Lower in the section, a band of high-amplitude, horizontal reflections occurs from 2.0 to 4.2 sec (4.8 to 11.6 km, 15,700 to 38,100 ft), probably indicating less intense deformation within the Carboniferous flysch sequence on the lower plate. The prominent events in this lower sequence on line 2 can be correlated with high-amplitude events at the tie point (VP 380) on line 1, and with nearly flat events on the north end of line 3. Accordingly, the ends of lines 1 and 3 tie along strike as displayed in Figure 4.

The prominent reflections representing the lower to middle Paleozoic carbonate sequence can be traced with confidence to VP 300 on line 1 where they appear to be offset, possibly along one or more south-facing normal faults (e.g., see Buchanan and Johnson, 1968). Farther south, less prominent events are interpreted to represent the subsurface continuation of the carbonates to the end of line 1 and the beginning of line 3. As the carbonates were deposited on North American crust, the reflection data indicate that the mid-Paleozoic craton (or south-facing margin) of North America extends southward in the subsurface to at least the northernmost portion of line 3 (Fig. 5).

The reflection geometry in the Carboniferous flysch overlying the older carbonate sequence indicates broad folds and truncated interfaces which can be closely related to surface geology. Between VP 340 and 370 on line 1, a series of thrust faults is mapped at the surface (Fig. 4A). These correlate with the northern edge of a package of fairly steep, south-dipping reflections which flatten with depth (see migrated positions of these events superimposed on the unmigrated section of Fig. 4B). Other prominent but more gently south-dipping events extend for several kilometers beneath, and are truncated by, the thrusts. These relationships demonstrate that major, north-verging thrusts mapped at the surface in this part of the survey also flatten with depth, indicating that listric fault geometries extend well into the southern part of the Frontal thrust zone.

Inasmuch as reverse offsets on the lower to middle Paleozoic carbonate sequence are not observed within the northern and central portions of the Frontal thrust zone, a major detachment is inferred to lie above these rocks. Above the detachment, the Carboniferous flysch was transported and deformed as a series of north-verging folds and thrusts. A thrust apparently ramps up along the normal fault beneath VP 300, forming a thrust-cored "snakehead" anticline within the overlying flysch sequence. Because north-verging thrusts are exposed north of the survey, detachments at some level must continue beyond the northern extent of this structure.

In summary, the seismic reflection data in the Frontal thrust zone indicate that (Fig. 5B, C, D): (1) the thin lower to middle Paleozoic (Arbuckle facies) carbonate sequence can be traced to at least the southern part of the Frontal zone; (2) the overlying Carboniferous flysch sequence is wedge shaped, thickening to at least 12 km (39,000 ft) in the southern part of the Frontal zone; and (3) north-verging thrust faults are listric within the flysch sequence, probably flattening on detachments above the carbonates.

Maumelle Chaotic Zone–Benton Uplift

South of VP 100 on line 3, an older, highly deformed Mississippian and Lower Pennsylvanian flysch sequence is exposed at the surface (Stanley Shale, Jackfork Sandstone, Johns Valley Shale). This area (which lies along geologic strike with the Maumelle chaotic zone of Viele, 1974) lies between thrust-imbricated Carboniferous flysch of the Frontal thrust zone to the north, and lower to middle Paleozoic, deep-water sediments ("Ouachita facies") exposed in the Benton uplift to the south. The latter consist primarily of deformed graptolite-bearing shales, radiolarian cherts, turbidite sandstones, and submarine debris-flow deposits. These strata are cut by numerous east-west–trending thrust faults and show evidence of polyphase deformation. South of the Benton uplift, Carboniferous flysch is again exposed. Walthall (1967) has shown that these strata are correlative with the flysch deposits of the Frontal thrust zone to the north. The Benton uplift is, therefore, a broad, surface anticlinorial feature consisting of a core of Ordovician through Lower Mississippian (Collier Shale to Arkansas Novaculite) deep-water sediments surrounded by Upper Mississippian to Pennsylvanian (Stanley Shale and younger) flysch deposits (Figs. 2, 3).

On the basis of their bulk lithology and slight (stratigraphic) thickness, the Ouachita facies rocks are generally thought to have been deposited in a sediment-starved, deep-marine basin (e.g., Briggs and Roeder, 1975). Viele (1979) interprets these strata as slope-rise to abyssal sediments deposited upon and to the south of a south-facing North American continental margin in early to middle Paleozoic time. He also interprets two phases of deformation within these rocks. The first involves initial northward translations of nappes, as evidenced by stratigraphic facing and the rotation sense of small folds. Later, the nappes were backfolded toward the south in a second phase of deformation. Thus, within the northern half of the Benton uplift early north-verging recumbent structures are overprinted by south-verging chevron folds and associated thrusts. Though locally backfolded, the strata exposed within the Benton uplift are considered by most workers to have been transported a considerable, though indeterminate, distance from the south.

VP 100 to VP 400 of line 3 (Fig. 4A, B) represent the unmigrated seismic expression of the on-strike continuation of the Maumelle chaotic zone. Note that between VP 216 and VP 237 a gap exists in the data owing to the inability to operate vibrator trucks across the north slope of Buck Knob. The main feature within the northern part of the inferred Maumelle zone is a prominent set of crossing events which projects to the surface at a major thrust mapped near VP 100 on line 3. There, the Lower Pennsylvanian (Morrowan) Johns Valley Shale is thrust over younger rocks of the middle Atoka. North-dipping events between 1.0 and 3.0 sec at VP 150 to VP 200 on the unmigrated section suggest a north-dipping sedimentary section on the upper thrust sheet. If this shallow structure flattens to the south, as suggested by subhorizontal events between 1.2 and 2.3 sec at VP 250 to VP 300, then the structure immediately beneath the northern part of the Maumelle zone is a large hanging-wall anticline (Fig. 5B, C, D).

South of VP 300 on line 3, the seismic character in the upper few seconds of the section changes drastically. Unlike the seismic sections within the Frontal thrust zone to the north (Fig. 4A), strong, continuous reflection events are lacking within the upper 3 sec in the southern part of the Maumelle zone and the Benton uplift. Although this may in part be due to rough terrain and rapid changes in near-surface geology, the paucity of prominent events is probably also indicative of intense deformation of the upper few kilometers of Paleozoic sedimentary sequences in these areas. Short wavelength folding and faulting are therefore schematically portrayed within the Maumelle zone in Figure 5 (B, C, D).

Below the zone lacking coherent reflections, a lineup of low-amplitude, north-dipping reflection segments is observed. These events rise from about 4.0 sec (11 km, 36,000 ft) beneath VP 380 on line 3 to about 2.8 sec (7 km, 23,000 ft) beneath VP 500. Beginning at about VP 620, flatter events at the same level are observed beneath the mapped center of the Benton uplift. Farther south, events at this level gradually curve into south-dipping reflections (i.e., south dips at 2.8 sec begin at about VP 750). The Benton uplift is therefore a surface anticlinorium which apparently overlies a broad antiformal structure at depth.

Nicholas and Rozendal (1975) presented interpretations of drilling results of two subsurface structures in Texas that lie along the Ouachita trend in positions analogous to the Benton uplift. These structures have deep antiformal seismic expressions that are grossly similar in geometry to that observed across the Benton uplift in this study, although consisting of events with higher signal-to-noise ratios. Wells drilled on the Waco uplift (Shell 1 Barrett in Sec. A-337, Stephen Greenwell Survey, Hill County, Texas) and the Devils River uplift (Shell 1 Stewart in Val Verde County, Texas) penetrated approximately 1.84 and 0.46 km (6,040 and 1,500 ft) of metasediments, respectively, which have been interpreted as uplifted lower Paleozoic foreland carbonate rocks. These are underlain by metaquartzite in both wells. In the Devils River (Stewart) well, Denison et al (1977) determined approximate 700 m.y.B.P. Rb/Sr age dates for metarhyolites beneath the lower sequence. The well was also drilled an additional kilometer into the "basement" and penetrated a mixed metasedimentary-metabasaltic interval that yielded late Precambrian (1,121 to 1,270 m.y.B.P.) Rb/Sr age dates (Nicholas and Rozendal, 1975). We note the similarity of these older dates to those determined by Flawn and Muehlberger (1970) for Grenville-age rocks exposed in the nearby Llano uplift (Fig. 1) which are of definite (pre-Carboniferous) North American affinity.

The Waco uplift well penetrated a sequence of phyllite and quartzite (Interior metamorphic belt) overlying the intensely deformed carbonate rocks. In contrast, the Devils River well went directly from Cretaceous cover into a relatively undisturbed sequence of Lower Ordovician Ellenburger Dolomite, which is part of the foreland facies encountered in wells to the north. Nicholas and Rozendal (1975) interpreted both the Devils River and Waco uplifts as basement-involved uplifts affecting crust of North American affinity. The Waco uplift is interpreted to have been overridden by the north-moving, allochthonous sheet of phyllite and quartzite. The allochthonous sheet is inferred by Rozendahl and Erskine (1971) to be correlative with the lower to middle Paleozoic (Ouachita facies) deep-marine strata, which the COCORP survey crosses at the core of the Benton uplift. Nicholas and Rozendahl (1975) further concluded that the early Paleozoic continental shelf of North America extended southward and eastward to at least the position of both uplifts and was tectonically overridden by Ouachita facies rocks. For the Waco uplift, this model requires that the deformed carbonates are also correlative with the Ellenburger (i.e., that they represent strata deposited on North American crust).

In Figure 5 (B, C), the large antiformal structure observed on line 3 is interpreted in an analogous manner. The north-dipping events rising from deep (approximately 4 sec, 11 km, 36,000 ft) beneath the projected Maumelle zone to a shallower position (approximately 2.8 sec, 7 km, 23,000 ft) beneath the Benton uplift are depicted to represent the general form of lower to middle Paleozoic carbonate strata (Arbuckle facies) which, to the north, floor the Frontal thrust zone and Arkoma basin. This interpretation requires that the lower to middle Paleozoic, deep-marine sediments exposed at the surface (Ouachita facies) are allochthonous, because now they structurally overlie coeval shelf carbonates. In Figure 5B, the decollement separating these two units is schematically shown to continue

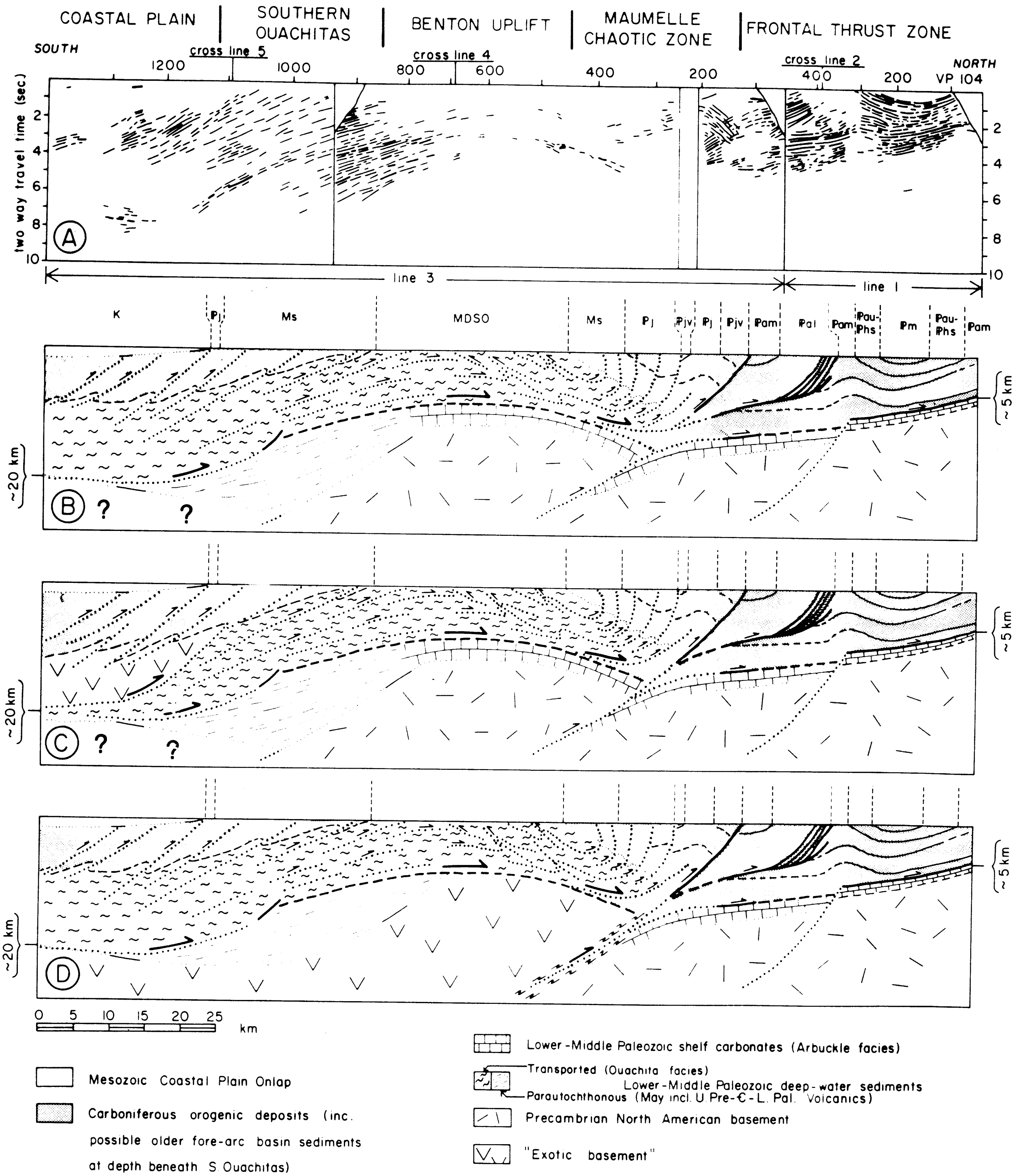

FIG. 5—A. Line drawing schematically showing major reflection events from seismic sections (Fig. 4A). Section has one-to-one vertical exaggeration for seismic velocity of 5.0 km/sec (16,400 ft/sec).

B. Suggested interpretation of A. Cross section uses same time scale depicted in A but incorporates geometric information from migrated time sections. Heavy lines = faults; thin lines = stratigraphic contacts. (Solid lines: interpretation consistent with surface and/or well data; dashed lines: geometry consistent with seismic reflection data; dotted lines: generalized structure consistent with regional geology). Depths represent approximate conversions using stacking velocities. Formation symbols same as in Figure 4.

C. Alternative interpretation showing crystalline basement, exotic to (mid-Paleozoic) North America, at shallow levels beneath the northernmost Gulf coastal plain.

D. Alternative in which the Benton uplift is cored by exotic crystalline basement.

northward in the subsurface as a major detachment within the Carboniferous flysch. Arching of the basement and cover beneath the Benton uplift is suggested to be due to later movement along one or more deeper thrusts that actually cut into basement in this region. The deeper thrust zone is inferred to continue north as the lowest decollement surface within the Frontal thrust zone. Alternatively, the deep-seated reverse offset may cut across earlier, higher thrusts and actually crop out within the Maumelle zone (Fig. 5C). At least one reverse fault with a significant amount of stratigraphic throw is mapped in this region (Fig. 4A) (Haley et al, 1976). In both of these interpretations, arching of the (North American) basement would have occurred after (or during the late stages of) emplacement of the Ouachita deep-water facies over the coeval platform (or shelf) sequence, inasmuch as arching of both sequences is inferred. An alternative interpretation (Fig. 5D) in which the deep core of the Benton uplift consists of crystalline rocks exotic to pre-Carboniferous North America is considered less likely, because of the drilling data from the other uplifts on the Ouachita trend in Texas (see also Nelson et al, 1982).

A constraint for the minimum (structural) thickness of the allochthonous sediments is found in the Vierson and Cochran 1 Weyerhauser well (Sec. 25, T5S, R23E, McCurtain County, Oklahoma), which was drilled on the core of the Broken Bow uplift in Oklahoma (Fig. 2). This structure is probably continuous with the Benton uplift in the subsurface. The well penetrated 3,054 m (10,019 ft) of highly deformed schists and phylites without encountering basement. Denison et al (1977) interpreted the entire sequence as lower to middle Paleozoic "Ouachita facies" equivalents. The continuity of the two uplifts suggests that the 3 km (10,000 ft) minimum (structural) thickness for the stack of lower to middle Paleozoic deep-water sediments is also appropriate for the rocks exposed in the core of the Benton uplift. Possibly, the entire sequence down to the horizontal reflections at 2.8 sec (7 km, 23,000 ft) is composed of these rocks (Fig. 5B, C, D).

On cross line 4 (not shown), a paucity of strong reflection events is observed above about 2.7 sec. As on line 3, this seismically transparent zone may indicate approximately 7 km (23,000 ft) of highly deformed, allochthonous lower to middle Paleozoic deep-water sediments. From 2.7 to 4.3 sec (7.0 to 12.0 km, 23,000 to 39,000 ft) on line 4, sequences of fairly prominent reflections are observed. These events are horizontal from the east end of the line to VP 180 and dip gently westward on the western part of the line, indicating an apparent westward plunge of the Benton uplift at depth. This subsurface geometry is consistent with the outcrop pattern shown in Figure 3. Accordingly, the structural saddle observed at the surface to the west of the COCORP survey (Fig. 2) is interpreted as the result of differential basement uplift between the Benton and Broken Bow uplifts.

From about 5.5 to 8.0 sec (15.9 to 23.2 km, 52,000 to 75,000 ft) on the east side of line 4, another set of reflections dipping gently westward is observed. These events, if not multiples or side reflections, may represent complexities within the crystalline basement. Because similar events are not associated with the crystalline basement on cross line 2, the possibility exists that the basement beneath line 4 is of different character than the basement of the Paleozoic North American craton (or shelf) to the north. Possibly, the basement beneath the Benton uplift is transitional crust associated with the passive Paleozoic continental margin. A less likely alternative (Fig. 5D) is that the crystalline basement is associated with an exotic terrane emplaced from the south (e.g., see Nelson et al, 1982).

In Figure 4B we interpret the band of high-amplitude reflections, extending from 2.8 sec beneath VP 700 to about 4.0 sec beneath VP 940 on line 3, to indicate the approximate position of the south-dipping detachment beneath the transported lower to middle Paleozoic deep-marine strata. Below this "surface," a series of south-dipping reflections exhibits a wedge-shaped geometry, thickening toward the south. These events probably correlate with the nearly horizontal reflections from 2.7 to 4.3 sec on line 4 described above. The high-amplitude events at 5.2 sec beneath VP 850 on line 3 migrate to about 5.0 sec beneath VP 800. The corresponding depth to reflectors within this sequence is calculated to be at least 14 km (46,000 ft). Somewhat weaker, south-dipping events between 5 and 6 sec at VP 900 to VP 950 suggest that this sequence may continue to depths in excess of 16 km (52,000 ft). Though interpretation of these deep reflections is not constrained by surface or drilling data, their stratified appearance and wedge-shaped geometry might suggest that they are of sedimentary (or metasedimentary) origin. If so, they could represent the transition of the North American shelf carbonates into an off-shelf clastic sequence (Fig. 5B, C), or they could be sedimentary strata related to the exotic crystalline terrane (Fig. 5D). Another possibility is that the deep events represent reflectors within upper oceanic crust (adjacent to the mid-Paleozoic North American continental margin) that are now buried beneath the thick cover of tectonically emplaced Paleozoic strata. Analogous, seaward-dipping events have recently been associated with layered volcanic sequences adjacent to the modern Norwegian continental margin (Hinz, 1981; Mutter et al, 1982). The interpretation of these events is complicated by the fact that the seismic expression may be partly or entirely due to thrust imbrication or metamorphism.

In summary, the seismic reflection data across the Maumelle chaotic zone and the Benton uplift, when analyzed in conjunction with local and regional geologic data, suggest the following (Fig. 5B, C).

1. A paucity of "shallow" reflections within the southern Maumelle zone and the Benton uplift is due, in part, to intense deformation of Paleozoic strata beneath those areas.

2. The Benton uplift, a surface anticlinorial feature, apparently has a broad antiformal seismic expression at depths below 7 km (23,000 ft). This seismic signature is similar (though deeper on the time section and lower in signal-to-noise ratio) to that of other uplifts on the Ouachita trend which are known to be cored by Precambrian crystalline rocks.

3. Low-amplitude, north-dipping reflections on the north flank and crest of the antiform may represent the form of the subsurface continuation of lower to middle

Paleozoic carbonate strata that floor the Arkoma basin and Frontal thrust zone to the north. Metamorphosed carbonate sequences have been drilled at the crest of basement-cored uplifts on the Ouachita trend in Texas.

4. A south-dipping wedge of layered reflections originating at depths below 7 km (23,000 ft) on the south flank of the antiform may indicate deeply buried sediments (metasediments?) and/or layered volcanic sequences. These could be related to a buried, south-facing (mid-Paleozoic) continental margin in one of two ways: (a) transition of the shelf strata into a thicker off-shelf clastic sequence, or (b) a seaward-dipping, layered volcanic sequence within upper oceanic crust adjacent to the margin. A lack of near-surface constraints as well as unknown degrees of thrust imbrication and metamorphism prohibit unequivocal interpretation of these events.

Southern Ouachitas–Gulf Coastal Plain

The southern half of line 3 is recorded across the southern Ouachitas and the northern edge of the Gulf coastal plain. Within the southern Ouachitas, Carboniferous flysch is exposed at the surface. These strata are disposed in a series of east-west–trending folds cut by north-verging thrusts. Walthall (1967) interpreted the Carboniferous flysch sequence (Stanley Group through lower Atoka Formation) as correlative with similarly named formations exposed in the Frontal thrust zone to the north.

The present Mesozoic coastal-plain sediments are believed to overlie a continuation of the Carboniferous stratigraphy and structure for a considerable distance to the south. Woods and Addington (1973) presented borehole and seismic reflection data which show that in southwestern Arkansas, highly deformed Carboniferous clastic rocks are overlain by a Middle Pennsylvanian (Desmoinesian), shallow-shelf facies. The younger rocks are in places overlain by a Permian (Wolfcampian) nonmarine clastic sequence. During the Triassic, block-fault topography was developed within these sequences, with locally thick accumulations of deltaic red beds filling fault-bounded basins. Jurassic evaporites overlain by Upper Jurassic through Cretaceous transgressive marine deposits and, finally, a thick regressive and prograding Cenozoic clastic wedge form the remainder of the Gulf coastal plain sediments. An interpretation of the coastal plain stratigraphy in the context of a passive (or "trailing") North American continental margin in Mesozoic and Cenozoic time is given by Walper et al (1979). Note that the southern end of line 3 extends over only the Cretaceous portion of the coastal plain sequence. Outcrops of Tertiary sediments begin several kilometers south of the end of the COCORP survey.

Vibrator Points 850 to 1376 on Figure 4 (A, B) are the unmigrated seismic sections for the southern Ouachitas and the northermost Gulf coastal plain. Within this area, reflections have a pervasive south dip. These events project to the surface in the zone of south-dipping thrusts and bedding planes within the lower to middle Paleozoic allochthonous sediments north of VP 850 and the Carboniferous flysch sequence exposed between VP 850 and VP 1100. The coincidence of pervasive south dips in outcrop and on the seismic sections suggests that the reflections represent a southward continuation of the Paleozoic strata to considerable depths in the subsurface. These events are continuous to about 5 sec beneath VP 1120, suggesting a structural thickness of at least 14 km (46,000 ft) for the Paleozoic strata beneath the southernmost Ouachita Mountains.

Though the contact between the Carboniferous clastics and the older (Ouachita facies) rocks beneath the southern Ouachitas is not clearly defined, a suggested position is schematically shown within the south-dipping reflection package on Figure 4B. The actual nature of this contact is probably more complex, as illustrated schematically in Figure 5. The bottom of the Carboniferous flysch sequence (i.e., Stanley Shale) is interpreted to be in both depositional and thrust contact with the Mississippian portion of the underlying lower to middle Paleozoic deep-water sediments (i.e., uppermost Arkansas Novaculite).

Southward from VP 1120, the COCORP survey crosses the Cretaceous portion of the Gulf coastal plain sequence. Woods and Addington (1973) show that wells just southeast of the end of the line penetrate a maximum of about 3 km (10,000 ft) of Cretaceous to Desmoinesian strata before encountering Carboniferous clastic rocks. The Exxon Royston well (Sec. 31, T10S, R24W, Hempstead County, Arkansas) encountered over 2 km (6,500 ft) of red beds within the Eagle Mills Formation, interpreted to represent Triassic graben fill. In contrast, the Exxon Harris well (just to the northwest) penetrated very thin Cretaceous and Desmoinesian sections before entering Carboniferous clastic rocks at a depth of less than 1 km (3,300 ft). Because the Harris well is very near the south end of the COCORP survey, relatively flat reflection segments at 0.45 sec beneath VP 1270 and VP 1370 (Fig. 4A, B) may represent the shallow Paleozoic-Cretaceous unconformity which line 3 crosses near VP 1120. Thus, the seismic lines apparently have not reached the Triassic grabens that Woods and Addington (1973) have documented to the south. We note, however, that steeply south-dipping processing artifacts on the stacked sections tend to mask structure in the upper 2 sec beneath the Cretaceous exposures.

Deeper on the coastal plain seismic section, south-dipping reflections, like those beneath the southern Ouachitas, are again observed. These events presumably represent an even more southward continuation of the Paleozoic strata and structures exposed in the southern Ouachitas, and possibly in the Benton uplift. The layered reflections are continuous to times of 4 to 5 sec beneath the northern portion of the coastal plain, again suggesting that the Paleozoic strata revealed in outcrop (and subcrop) are continuous southward in the subsurface to depths in excess of 11 to 14 km (36,000 to 46,000 ft).

On cross line 5 (not shown), faint horizontal reflections in the upper 4.0 sec are masked by steeply dipping artifacts similar to those mentioned above. From 4.0 to 8.0 sec (11.0 to 22.4 km, 36,000 to 73,000 ft), numerous discontinuous horizontal reflections are observed. These events correlate with the south-dipping reflections observed on line 3 and may, likewise, represent deeply buried Paleozoic strata. Reflection quality (as well as the lack of other subsurface constraints) in this part of the survey, however, does not allow identification of gross stratigraphic units or structural detail. The interpretation in Figure 5B merely infers, based on the pervasive south dips and previously presented structural and stratigraphic arguments, that thrust imbricated sections of Carboniferous flysch and allochthonous lower to middle Paleozoic deep-marine sediments overlie a less imbricated, authochthonous (or parauthochthonous) lower to middle Paleozoic off-shelf clastic (or volcanic) wedge.

A prominent reflection occurs at about 7.6 sec (approximately 21 km, 69,000 ft) beneath VP 1250 to VP 1300 on line 3. The anomalous nature of this deep event is shown in Figure 6, which is a true-amplitude display of the Vibroseis correlated field record for VP 1263. The very strong hyperbolic event at about 7.6 sec is observed on several field records recorded on the coastal plain. On field records in other parts of the survey prominent, high-amplitude events at these delay times are not observed. The event dips gently to the north and migrated sections suggest that it is correlative with a similar, horizontal event that occurs at 8.1 sec (about 23 km, 79,000 ft) on the east side of line 5. A tentative interpretation is that these events are primary reflections from near the interface between Paleozoic sediments (or metasediments) and an underlying crystalline basement. This basement may represent North American continental crust, greatly thinned during late Precambrian to early Paleozoic rifting (Walper, 1977); or perhaps it represents a preserved segment of Paleozoic oceanic crust upon which the lower to middle Paleozoic deep-marine sediments were deposited. A similarly interpreted "remnant" of Paleozoic oceanic crust has recently been suggested to lie at depth beneath the Atlantic coastal plain, seaward of the Appalachian Mountains in Georgia (Cook and Oliver, 1981). Deeper, horizontal reflections at 9.5 to 9.7 sec (about 28 km, 92,000 ft) on line 5 may represent the bottom of this preserved oceanic crust.

The alternative interpretations shown in Figure 5C and 5D differ from that of Figure 5B in that they show exotic crystalline basement and associated sedimentary rocks thrust over the North American margin to positions on or near the Ouachita trend. In Figure 5C, the exotic terrane is shown beneath the northern edge of the coastal plain where it partially overrides the allochthonous deep-marine sediments and the off-shelf clastic (or volcanic) sequence. A zone lacking coherent reflections between 4 and 7 sec on the south end of line 3 could be interpreted to represent this crystalline basement in the subsurface (e.g., see VP 1150 to VP 1400 on the seismic section, Fig. 4A, and the line drawing, Fig. 5A). In this interpretation, the Carboniferous flysch south of the Benton uplift would have been deposited, in part, above the more southerly basement and might be in the position of a fore-arc basin associated with the overriding plate (e.g., see Viele, 1979).

The model of Figure 5D shows an interpretation in which exotic basement is thrust even farther northward over the North American shelf (or craton?). South of the Maumelle zone the Arbuckle facies carbonate strata (or their seaward equivalents), if they exist, are no longer at upper crustal levels. On the south flank of the Benton uplift, the wedge-shaped series of events at depth might then be interpreted as strata deposited on the exotic terrane before emplacement of the allochthonous sheet of lower to middle Paleozoic deep-marine strata from the south. The model requires first thrusting the North American margin beneath the exotic terrane, and then emplacing the lower to middle Paleozoic strata by closing a basin even farther south (see Nelson et al, 1982). As mentioned, regional drilling data make this model unlikely, as they suggest that North American basement forms the core of other large anticlinoria on the Ouachita trend in Texas.

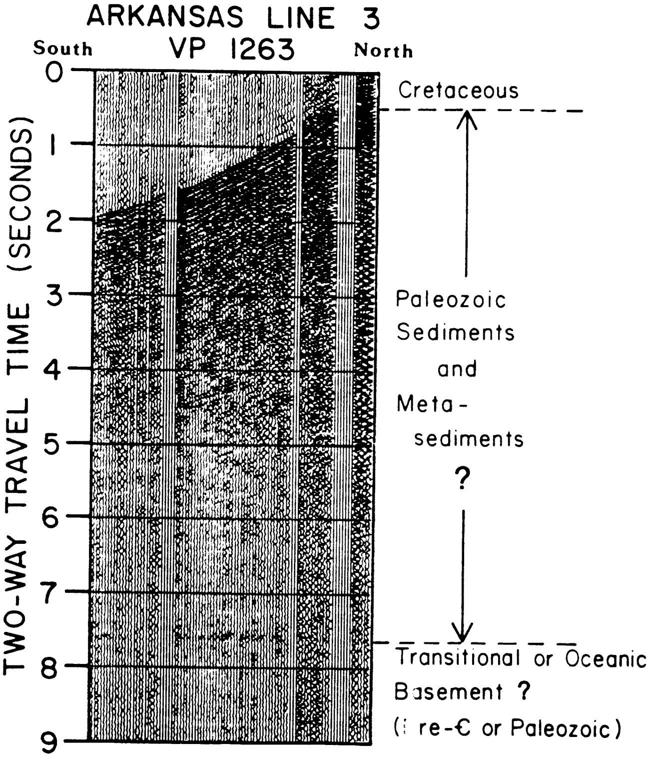

FIG. 6—Vibroseis-correlated field record for VP 1263 on COCORP line 3. Noisy traces have been zeroed. No AGC has been applied to record. Strong event at 7.6 sec may be a reflection from bottom of Paleozoic sedimentary (metasedimentary) column beneath Gulf coastal plain south of Ouachita mountains in western Arkansas, as suggested in Figures 4B and 5(B, D). See Figure 3 for location. Nominal trace spacing 100.6 m (330 ft). Actual near offset 395 m (1,295 ft), far offset 8,048 m (26,403 ft).

Observations and favored interpretations of the southern Ouachita–Gulf coastal plain portions of the COCORP survey are summarized as follows (Fig. 5B, C).

1. Pervasive south-dipping reflections project to the surface within exposures of Paleozoic sediments in the Benton uplift and the southern Ouachitas. The continuation of these events to deeper levels on the seismic section indicates that the imbricated Paleozoic sediments (or metasediments) extend to depths in excess of 14 km (46,000 ft) beneath the southern Ouachitas and the Gulf coastal plain. Below this level, the events "fade" into a zone lacking prominent reflections, leaving the total thickness of the sediment package (and hence the maximum depth to crystalline basement) unconstrained.
2. High-amplitude, slightly north-dipping reflections

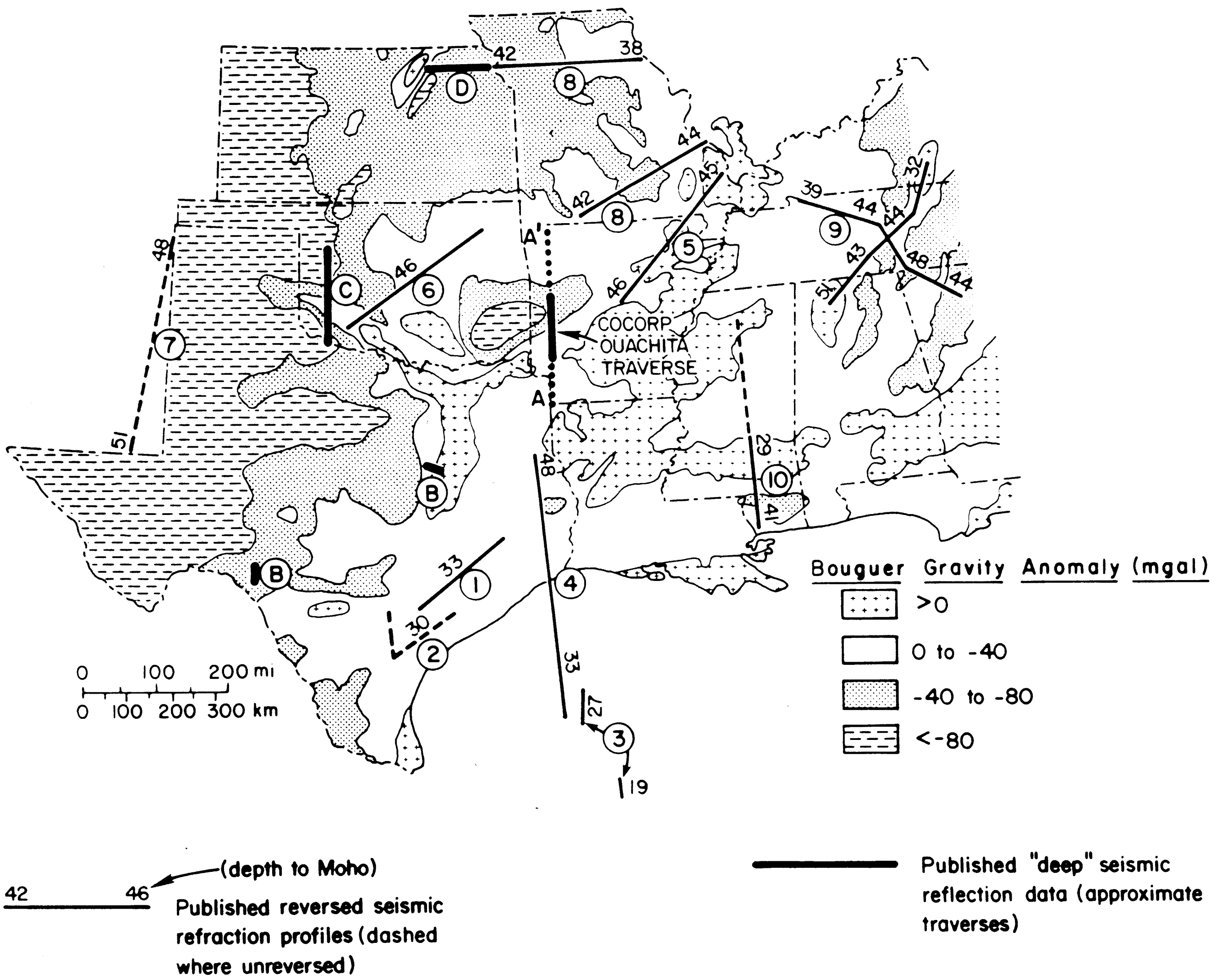

FIG. 7—Bouguer gravity anomaly map of south-central United States, generalized from Woollard and Joesting (1964). Approximate location of COCORP Ouachita traverse shown by heavy line in western Arkansas. AA′ is gravity profile modeled in Figure 8. Other published "deep" seismic reflection data shown schematically on map include: B, Shell Oil Company lines across Waco and Devils River uplifts (Nicholas and Rozendal, 1975); C, COCORP lines across Hardeman basin, Wichita Mountains, and Anadarko basin (Brewer et al, 1981); D, COCORP lines across northeastern Kansas (Brown et al, 1983). Interpretations of depth (in kilometers) to Moho along seismic refraction lines from: 1, Cram (1961); 2, Dorman (1972); 3, Ewing et al (1955); 4, Hales et al (1970); 5, McCamey and Meyer (1966); 6, Mitchell and Landisman (1970); 7, Stewart and Pakiser (1962); 8, Stewart (1968); 9, Warren (1968); 10, Warren et al (1966).

recognized at 7.6 to 8.1 sec beneath the Gulf coastal plain may indicate the bottom of the Paleozoic sedimentary (metasedimentary) section (Fig. 5B). The basement upon which these sediments were deposited would, therefore, now be buried at a depth of about 22 km (72,000 ft). Alternatively, these prominent events may be related to the suture zone between North America and an "exotic" terrane, though in this case a more precise interpretation for the events is not clear (Fig. 5C).

3. The inferred (autochthonous or parautochthonous) lower to middle Paleozoic off-shelf clastic (or volcanic?) sequence, interpreted to lie at depth beneath the south flank of the Benton uplift, may also extend to depths in excess of 14 km (46,000 ft) beneath the southern Ouachitas.

DEEP CRUSTAL STRUCTURE OF OUACHITAS

Thus far, the Ouachita COCORP data have been presented in the light of upper crustal structural and stratigraphic constraints. A broader perspective of the configuration of the entire crust requires an examination of other regional geophysical data pertaining to the south-central United States. These data are helpful in understanding the nature and evolution of the southern continental margin of North America.

Figure 7 is a regional Bouguer gravity anomaly map of the south-central United States (Woollard and Joesting, 1964) with the approximate locations of published seismic refraction and deep seismic reflection data superimposed.

Interpretations of total crustal thickness (depth to Moho, as reported in the references listed in Fig. 7 caption) are plotted along each of the refraction lines. Section AA′ represents the observed gravity profile (taken from the map of Woollard and Joesting, 1964) used for the two-dimensional gravity models shown in Figure 8.

Gravity Data

The Ouachita belt (Fig. 1) can be traced from Arkansas to central Texas through trends in the gravity anomalies (Fig. 7). A very pronounced gravity minimum, coincident with the Frontal thrust zone in western Arkansas and southeastern Oklahoma, is the largest of a series of lows which also follows the buried Frontal zone in Texas (Flawn et al, 1961). To the south (in Arkansas) and east (in Texas) a sharp gradient separates the lows from a series of subtle highs. The seismic lines across the Waco and Devils River uplifts ("B" on Fig. 7), as well as the Benton uplift portion of the Ouachita COCORP survey, lie on this very steep (up to 2.5 mgal/km in southeastern Oklahoma) Bouguer anomaly gradient.

In eastern Arkansas and Mississippi, trends in the gravity data related to the Ouachita belt are obscured by effects of the Mississippi embayment. Positive anomalies in this area may be indicative of high-density materials at lower crustal levels beneath the embayment (Ervin and McGinnis, 1975). Thus, the very pronounced Bouguer low/high couple observed in a seaward direction across the Ouachita trend in Texas, Oklahoma, and Arkansas does not occur over the northwest-southeast-trending Ouachita subcrops in Mississippi. Still farther east, Bouguer anomalies trend northeast-southwest, reflecting the trend of the southern Appalachian Mountains. Cook and Oliver (1981) interpreted a strong gravity gradient along the length of the southern Appalachian orogene to mark the buried Paleozoic continental edge of North America. The Ouachita gravity gradient may represent a continuation of the Appalachian gradient to the west and south.

Refraction Data

North and west of the Ouachita trend, all interpretations of depth to Moho along the refraction profiles are 38 km (15,000 ft) or greater (Fig. 7). These are perhaps indicative of a "normal" thickness of continental crust. Note, however, that on profiles 5, 6, and the more southerly profile 8, an "anomalous" lower continental crust has been interpreted. In northeastern Arkansas, McCamy and Meyer (1966) reported a lower crustal velocity of 7.4 km/sec (24,300 ft/sec). This corresponds to the high-density layer which Ervin and McGinnis (1975) attributed to incipient continental rifting associated with the late Precambrian Reelfoot rift, and the more recent Mississippi embayment. In southern Missouri, Stewart (1968) reported a lower crustal velocity of about 7.0 km/sec (23,000 ft/sec), although the evidence for this high-velocity zone is based on information from secondary phases. Mitchell and Landisman (1970) interpreted velocities greater than 7.0 km/sec (23,000 ft/sec) for the lower crust in central Oklahoma. What may be described as a "normal" continental crust has been reported for the refraction survey across northern Missouri (Stewart, 1968). On Stewart's interpreted cross section, an upper crust 22 km (72,000 ft) thick with a velocity of 6.1 to 6.2 km/sec (20,000 to 20,300 ft/sec) overlies a lower crust that is 19 km (62,000 ft) thick with velocity of 6.6 km/sec (21,700 ft/sec).

Though it is obvious from the foregoing statements that the nature of the crust landward of the Ouachita trend is neither simple nor well understood, first-arrival interpretations of depth to Moho and first-order approximations of velocity within the crust provide some information that is useful in understanding the evolution of the southern continental margin. Apparently the crust north and west of the Ouachita trend is about 38 to 46 km (125,000 to 151,000 ft) thick and consists of an upper "half" with velocity of about 6.1 to 6.4 km/sec (20,000 to 21,000 ft/sec) above a 6.6 to 7.4 km/sec (21,700 to 24,300 ft/sec) lower crust, although intracrustal complexities undoubtedly exist (e.g., Brown et al, 1983). The crust outside the Mississippi embayment likely represents the North American craton upon which the shelf carbonate sequence (Arbuckle facies) was deposited in early to middle Paleozoic time.

South of the Ouachita trend, refraction lines in general show crustal thinning toward the center of the Gulf of Mexico (Martin and Case, 1975). The crust thins from 48 km (157,000 ft) in northeast Texas to around 33 km (108,000 ft) near the coast (Hales et al, 1970). Farther out to sea, depths to Moho as shallow as 17 km (56,000 ft) have been reported from refraction profiles within the Gulf abyssal plain (Ewing et al, 1955). Thus, from the Texas coast seaward, the refraction data indicate the modern-day transition to true oceanic crust (Worzel and Watkins, 1973). The transition may not be smooth, however, as suggested by alternating gravity highs and lows in places within this zone (e.g., see Dehlinger and Jones, 1965).

The only published refraction line which crosses the Ouachita trend is a north-south line recorded across Mississippi (Warren and Healy, 1973). This line (profile 10 in Fig. 7) was reversed on its southern half, which extends approximately to the subsurface continuation of the Ouachita trend in central Mississippi, but unreversed on the north. Warren et al (1966) considered calculated depths to Moho accurate on the southern (reversed) portion of the survey but unreliable on the unreversed portion in northern Mississippi. On the reversed portion, they reported a crustal thickness of 41 km (135,000 ft) near the Mississippi coast, thinning to 29 km (95,000 ft) at lat. 32°N. The thick crust is coincident with a broad Bouguer gravity low; a Bouguer gravity high occurs near the crustal thin (Worzel and Watkins, 1973). Warren et al (1966) pointed out that this apparent abrupt change in crustal thickness occurs near the juncture of the Ouachita and Appalachian trends.

Magnetic Data

Aeromagnetic data for the central United States have been compiled by Zietz (1981). Viele and Zietz (1981) noted that linear magnetic highs and lows (most of which are coincident with linear gravity anomalies) over the cra-

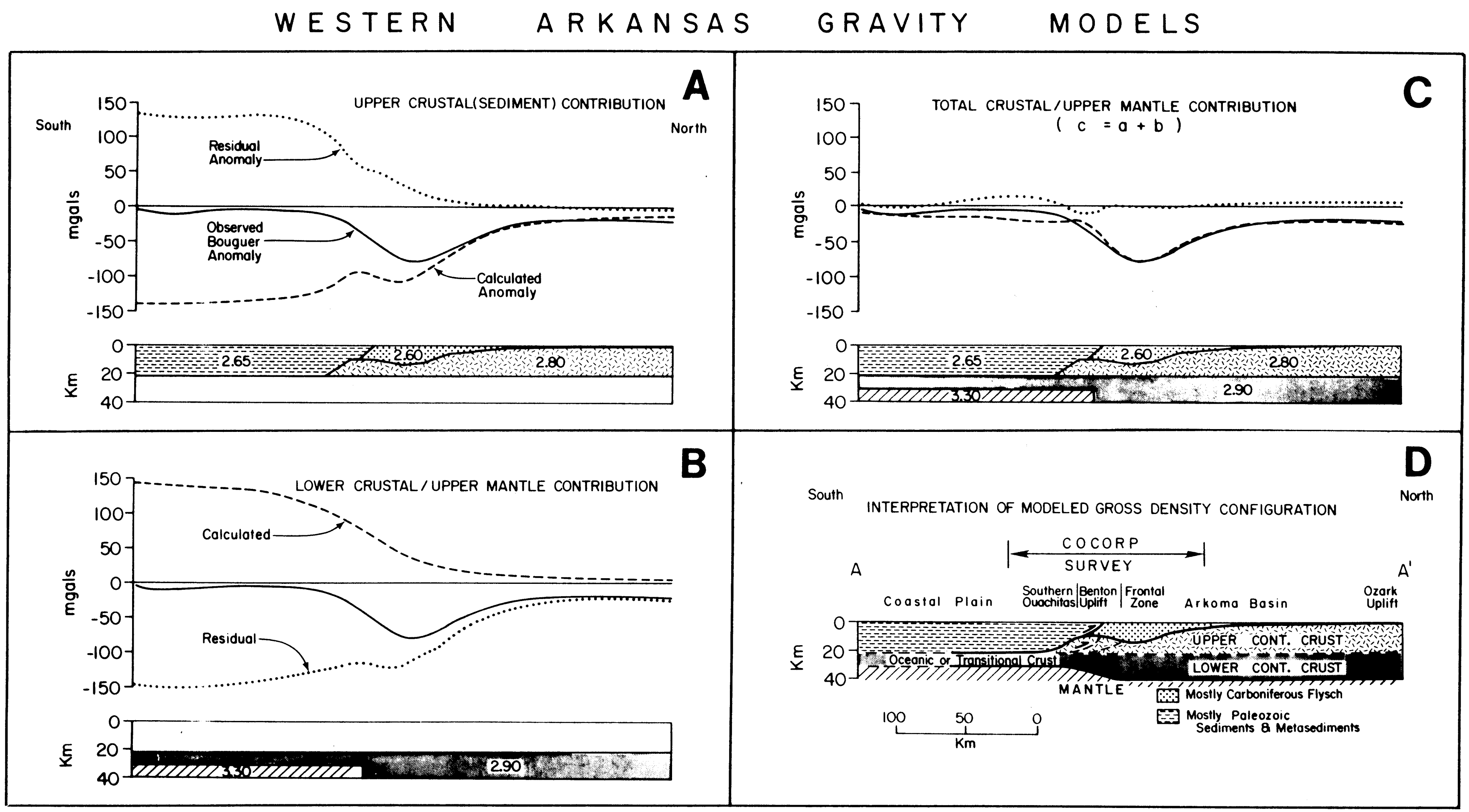

FIG. 8—Two-dimensional gravity models for south-north line across western Arkansas along 94°W long. (AA′ in Figs. 2, 7). Observed Bouguer anomaly values (solid lines) from map of Woollard and Joesting (1964). Densities in g/cm^3. Figures have no vertical exaggeration.

A. Upper crustal anomaly (dashed line) due to sediment thicknesses interpreted from COCORP traverse along central part of line of section (Figs. 4B, 5B). Thicknesses unconstrained on extreme southern part of model. Layers with densities of 2.60 and 2.65 g/cm^3 represent gross sediment (metasediment?) thicknesses relative to a 2.80 g/cm^3 (granitic) upper continental crust. Residual anomaly (dotted line) is observed minus calculated.

B. Residual anomaly of model A is closely mimicked with a simple model in which lower crust (2.90 g/cm^3) thins by about 10 km (33,000 ft) from northern to southern Arkansas. Result is a shallower upper mantle (3.30 g/cm^3) beneath southern Arkansas.

C. Composite model incorporating density contrasts illustrated in models A and B.

D. Interpretation of gross crustal structure of western Arkansas. Compare to model C and Figures 5B and 9D. Shallowing of crystalline basement depicted south of southern Ouachitas in Figure 5C is also consistent with observed gravity if the Moho also deepens (relative to depth shown in model C) in that area. Approximate location of COCORP traverses is shown above figure.

ton are truncated abruptly on their seaward ends by the Ouachita trend. South of the Ouachita trend, there is little variation in magnetic intensity (magnetic "quiet" zone), whereas much variation exists on the craton side. Additionally, we note that, in general, anomalies show a gradual increase in wavelength, approaching the Ouachita trend from the craton, which suggests that a southward deepening of magnetic basement may be at least partially responsible for the "quieting" of the anomalies across the trend. Viele and Zietz (1981) have suggested that the pronounced differences in magnetic intensity may indicate that a (continental) basement seaward of the Ouachita trend is fundamentally different from that of the North American craton. Accordingly, they interpreted a truncation of the North American craton in the vicinity of the Ouachita trend, the truncation possibly marking the position of the (now buried) Paleozoic continental margin.

Gravity Model

Figure 8 shows a series of two-dimensional models which suggest (A) upper, (B) lower, and (C) total crustal density distributions. Estimates of crustal and upper mantle densities north of the Ouachita Mountains are determined by applying the empirical (Nafe and Drake) relationship between compressional wave velocity and density (Garland, 1971, p. 181) to refraction velocities interpreted by Stewart (1968) for the northern Missouri refraction profile. The relationships for this "normal" continental crust are as follows: upper 22 km (72,000 ft) of crust, 6.1 to 6.2 km/sec (20,000 to 20,300 ft/sec), 2.8 g/cm^3; lower 19 km (62,000 ft) of crust, 6.6 km/sec (21,700 ft/sec), 2.9 g/cm^3; upper mantle, 8.0 km/sec (26,000 ft/sec), 3.3 g/cm^3. Stacking velocities, which are in general between 5.0 and 6.0 km/sec (16,400 and 19,700 ft/sec) near the interpreted bottom of the thick sedimentary sections on the COCORP lines (Fig. 4B), suggest a negative density contrast for the Phanerozoic sediments relative to the underlying crystalline basement. The individual component models (Fig. 8A, B) illustrate the geometry of gross density features which, when taken together (Fig. 8C), are consistent with the observed simple Bouguer gravity anomalies.

From the north, the observed Bouguer anomaly follows a gentle gradient in which anomaly values decrease from about -20 mgal near the Missouri state line to -79 mgal within the Frontal thrust zone of the Ouachitas. The steep Ouachita gravity gradient (here about 1.2 mgal/km) is observed farther south, rising over the Benton uplift and southern Ouachitas. Within the Gulf coastal plain the anomaly is nearly flat, with a very subtle high of -5 mgal about 75 km (45 mi) north of the Louisiana state line. This maximum follows the trend of gravity highs on the southeastern fringe of the buried Ouachita trend in Texas (Figs. 1, 7).

In Figure 8A, the upper 22 km (72,000 ft) of the crust is modeled. An average upper crustal density of 2.8 g/cm^3 is assumed as the norm for crystalline (granitic) upper continental crust. The lower densities represent total sediment (metasediment?) thicknesses from one of the favored interpretations of the COCORP lines (Figs. 4B, 5B) and from published information on basement depths to the north (e.g., Bush et al, 1977). South of the COCORP lines, total sediment thickness is not constrained and it is plausible that a shallowing of crystalline basement (as illustrated in Fig. 5C) occurs somewhere north of the Louisiana state line. The boundary between the 2.60 and 2.65 g/cm^3 material schematically represents the transition from unmetamorphosed Carboniferous flysch to well-indurated, slightly metamorphosed Paleozoic rocks occurring to the south. Both stacking velocities and "first-break" refraction velocities calculated from the COCORP field records show a general increase across this transition.

The -0.20 g/cm^3 contrast between the Paleozoic sediments filling the Arkoma basin (2.60 g/cm^3) and the "normal" upper continental crust (2.80 g/cm^3) appears to account for the observed anomaly on the northern part of the profile (Fig. 8A). Approaching the Frontal thrust zone of the Ouachitas, however, calculated values (Fig. 8A, dashed line) from the sediment-fill model are much lower than the observed values (solid line). Even farther south, the 22 km (72,000 ft) of sediments and metasediments (2.65 g/cm^3), interpreted from the COCORP data to underlie the southern Ouachitas and northernmost Gulf coastal plain (Fig. 5B), produce anomaly values which are more than 100 mgal lower than the observed. Accordingly, the residual anomaly for this model (Fig. 8A, dotted line) shows a steep gradient separating values near zero in the Arkoma basin to the north from values of about 130 mgal on the Gulf coastal plain to the south. This gradient represents additional density contrasts which, if accounted for in the model, would bring the calculated anomaly (dashed line) into agreement with the observed anomaly (solid line).

A simple density distribution which will closely account for the residual anomaly of Figure 8A is presented in Figure 8B. The presence of a density contrast of $+0.40$ g/cm^3 at lower crustal levels (i.e., between 31.5 and 41 km; 103,000 and 135,000 ft) beneath the Benton uplift, southern Ouachitas, and Gulf coastal plain produces the calculated anomaly shown by the dashed line. This anomaly closely resembles, in both amplitude and gradient, the residual anomaly of the sediment-fill model in Figure 8A. We suggest that the 3.30 g/cm^3 layer represents a southward shallowing of the mantle across the Ouachita trend in Arkansas. The calculated anomaly in Figure 8B resembles Bouguer anomalies observed across modern (Atlantic style) passive margins, which are largely attributable to a similar (though more pronounced) shallowing of the Moho.

Figure 8C represents a composite of models 8A and 8B. Note that agreement between observed and calculated anomalies is now ± 11 mgal at the worst, with most of the model within ± 4 mgal. In Figure 8D, a geologic interpretation of this total crustal configuration is presented, although the southernmost portion of the model is poorly constrained. In general, the model suggests that the crust beneath the thick Phanerozoic sedimentary (and metasedimentary) cover thins southward from about 40 km (131,000 ft) beneath the Ozark uplift to about 10 km (33,000 ft) under the northernmost Gulf coastal plain. These numbers could represent the approximate thickness of the crystalline crust associated with a passive North

American continental margin in early to middle Paleozoic time. The margin is inferred to have been thrust beneath the tectonically thickened Paleozoic sediments during the Carboniferous Ouachita orogeny. This wedge of relatively low-density sediments and metasediments (interpreted from the COCORP seismic reflection data to underlie the southern Ouachitas and possibly the northernmost Gulf coastal plain in southern Arkansas) is nearly compensated by a southward shallowing of the Moho. The net effect is a pronounced Bouguer low over the Frontal thrust zone, a steep Bouguer anomaly gradient within the Ouachita Mountains and a relatively flat Bouguer anomaly in the remainder of southern Arkansas (Fig. 8C). The thick package of Paleozoic sediments was probably continuous across the area of the Benton uplift, but subsequent uplift of the crystalline basement (Fig. 5B) resulted in erosion of part of the sediments. A 20 mgal Bouguer anomaly calculated to be associated with the Benton uplift (e.g., see calculated anomaly in Fig. 8A) is not readily perceptible because it is masked by the steep gradient associated with the southward shallowing of the mantle (Fig. 8B).

The preceding interpretation of the gravity profile is consistent with the limited available refraction data (Fig. 7). North of the Ouachitas, the crust is at least 38 km (125,000 ft) thick, constraining the northern part of the model. The only refraction line which may be pertinent within the Ouachita trend shows an interpreted Moho depth of 29 km (95,000 ft) in central Mississippi (Warren et al, 1966). Though this shallow depth may be due to overprinting by Mesozoic rifting events associated with the Mississippi embayment and/or the Gulf coastal plain, it is tantalizing to speculate that it could represent the remnants of crustal thinning associated with the early Paleozoic continental margin. Obviously, additional refraction work across other parts of the Ouachita trend would be invaluable in more accurately determining crustal thicknesses associated with the belt.

Two previously published gravity models imply a southeastward thinning of Paleozoic crust across the Ouachita trend in Texas. Keller and Cebull (1973) interpreted the crust, without the Phanerozoic sediments, to be less than 20 km (66,000 ft) thick. They further suggested that oceanic crust underlies a 20 km (66,000 ft) thick section of Paleozoic and younger sediments just southeast of the Ouachita trend (e.g., see Keller and Shurbet, 1975, Fig. 4). Nicholas and Rozendal (1975) show a (pre-Paleozoic sediment) crustal thickness of about 25 km (82,000 ft) east of the Waco uplift in Texas (their line of section includes the more northerly seismic line labeled "B" in Fig. 7). They call on the thickening of a lower crustal, high-density (gabbroic) layer to model the steep isostatic gravity gradient in that area. A similar effect, however, could be achieved by an eastward shallowing of high-density mantle material together with a thickening Phanerozoic sediment wedge (as in Keller and Shurbet, 1975, Fig. 4). Because of the interpreted thick sedimentary section beneath the southern Ouachitas and northernmost Gulf coastal plain, a southward shallowing of the Moho is likewise inferred to accommodate the Bouguer gravity anomaly of the Ouachitas in western Arkansas (Fig. 8).

The preceding interpretation is also consistent with the inferred position of the early Paleozoic North American continental margin (or transition from continental to oceanic crust) presented by Nicholas and Rozendal (1975). They inferred that the transition is now buried in the subsurface just seaward of the Devils River uplift, Waco uplift, Benton–Broken Bow uplift, and the Central Mississippi ridge (Vernon, 1971). The 2.90 g/cm^3 layer beneath the southern Ouachitas and the Gulf coastal plain in southern Arkansas (Fig. 8C) may therefore represent buried oceanic or transitional crust which was roughly 10 km (33,000 ft) thick. In a general sense, the steep Bouguer gravity gradient which follows the Ouachita trend (Fig. 7) can be interpreted to mark the buried (partially subducted?) edge of the Paleozoic continental margin of North America. As previously suggested, this gradient may be a fundamental geophysical signature which delineates the buried Paleozoic margin along the entire Appalachian-Ouachita orogenic belt (Nicholas and Rozendal, 1975; Cook and Oliver, 1981; Ando et al, in press).

The interpretation by Viele and Zietz (1981) of aeromagnetic data is also consistent with the model shown in Figure 8C. As these authors suggested, the North American craton is truncated at the Ouachita trend, and crystalline (magnetic) basement rocks on opposite sides of the trend are fundamentally different. In Figure 8C, the basement north of the Ouachita trend is associated with continental crust of the (Paleozoic) North American craton (and passive margin), whereas oceanic crust (and/or "exotic" continental crust; Fig. 5C, D) lies south of the trend. Possibly, the magnetic "quiet" zone just seaward of the Ouachita trend in Arkansas is preserved from the (now buried) Paleozoic passive margin, and is analogous to the magnetic "quiet" zone observed off the modern East Coast of the United States (e.g., see Rabinowitz, 1974). Alternatively, the Gulf coastal plain "quiet" zone may be mostly attributable to buried continental basement with magnetic properties differing from those of the continental basement north of the Ouachita trend (Viele and Zietz, 1981). Before accepting any of these models, however, we must keep in mind the possibility that a magnetic basement of any sort may be buried very deeply beneath (zero magnetic susceptibility) coastal plain sediments, the net result being a very flat magnetic signature.

As a final observation regarding geophysical data in the south-central United States (Fig. 7), note the geometry of the Ouachita trend (which essentially follows the inferred early Paleozoic continental margin) in relation to the position of the modern continental margin (which essentially parallels the present coastline; e.g., Martin and Case, 1975, Fig. 10). These two features are interpreted to mark zones of transition from crust of continental thickness to oceanic thickness in Paleozoic and Cenozoic time, respectively. Through southern Arkansas and Louisiana, the distance between the two features is about 600 km (370 mi) but it is only about 300 km (185 mi) in southeast Texas. Refraction surveys in southernmost Mississippi and northeast Texas (Fig. 7, profiles 10 and 4) indicate that the intervening area is underlain by crust of "normal" continental thickness (i.e., 41 and 48 km, 135,000 and 157,000 ft, respectively). In contrast, refraction lines just southeast of the Ouachita trend in southeast Texas (profiles 1 and 2 in Fig. 7) show Moho depths of 33 km (108,000 ft) and less (i.e., somewhat less than "normal" continental thickness). Thus, a fragment of crust of continental thickness apparently underlies a portion of the Gulf coastal plain, roughly in the position occupied by Louisiana between the inferred Paleozoic and present continental margins. This crust could be associated with the "Llanorian" (or upper plate) terrane postulated by several authors to have collided with the North American margin in the Ouachita orogeny (e.g., see Viele, 1979). In southern Mississippi, Louisiana, and northeast Texas, a portion of this exotic crust may have been left behind during Mesozoic rifting which opened the Gulf of Mexico. In southeast Texas, however, this break may have occurred much closer to the Ouachita trend, resulting in thinning or rafting away of most (or all) of the Llanorian terrane.

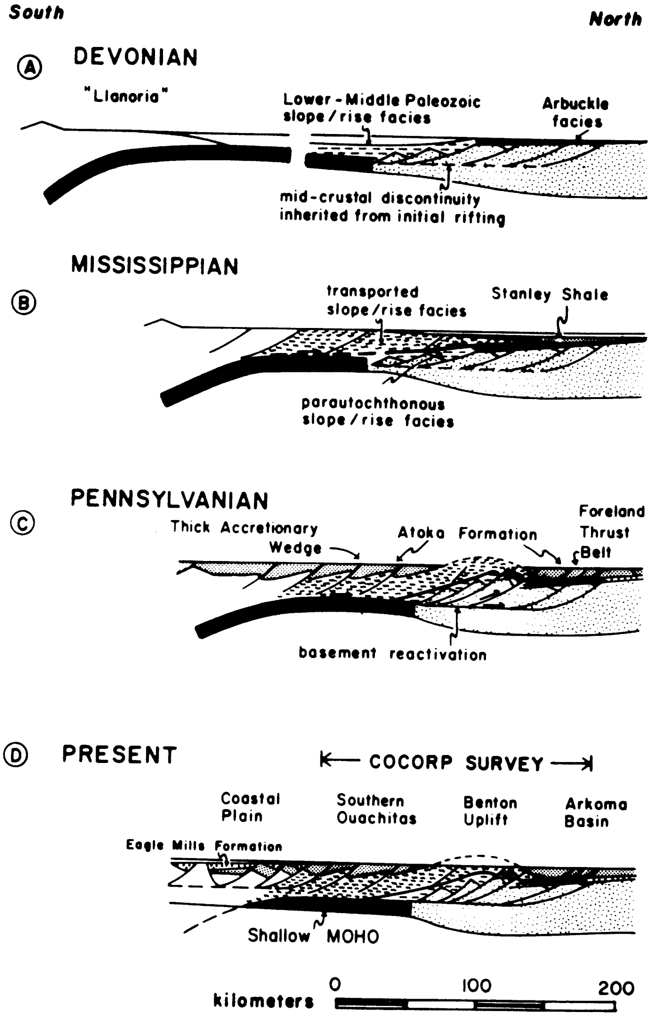

FIG. 9— Suggested plate-tectonic evolution of Ouachita Mountains along approximate line of COCORP traverses in western Arkansas. This model is consistent with interpretation shown in Figure 5B and gravity model shown in Figure 8C.

A. Early Paleozoic ("Atlantic-style") passive continental margin inherited from late Precambrian rifting. South-dipping subduction of oceanic portion of North American plate may have begun by Devonian time.

B. Subduction of continental margin, beginning in Mississippian time, resulted in deep-water (slope-rise) sediments (Ouachita facies) structurally overlying coeval shelf carbonates (Arbuckle facies).

C. Involvement of Precambrian crystalline basement in foreland thrusting resulted in formation of Benton uplift during late stages of Ouachita orogeny.

D. Present configuration after Mesozoic opening of Gulf of Mexico. Shallow Moho, possibly inherited from earlier passive margin, is inferred to underlie southern Ouachitas and northernmost Gulf coastal plain. Note approximate north-south extent of COCORP traverses.

SUMMARY

The details of the interpretation of the COCORP seismic reflection survey have been presented in the context of local surface geologic and borehole data in the Ouachita Mountain area and published seismic reflection and deep borehole data along the Ouachita trend. Additionally, regional gravity, seismic refraction, and magnetic results have been reviewed in order to evaluate the total crustal configuration of the Ouachita orogenic belt. Any model for the tectonic evolution of the Ouachita Mountains must take into account observations and interpretations based on the integration of these data. The new COCORP data, when integrated with stratigraphic and structural control along the profiles, demonstrate the following.

1. The thin, lower to middle Paleozoic (Arbuckle facies) carbonate sequence that floors the Arkoma basin can be traced southward to at least the southern portions of the Frontal thrust zone of the Ouachitas.

2. The overlying Carboniferous flysch sequence is wedge shaped, thickening to at least 12 km (39,000 ft) in the southern part of the Frontal zone, where a large Bouguer gravity minimum is observed. North-verging thrust faults within the flysch are steep at the surface but flatten out with depth. They probably sole into a detachment zone above the underlying carbonate sequence.

3. At depth, the Benton uplift shows a broad antiformal seismic expression, with an apparent westward plunge in the area of the COCORP survey.

4. Pervasive south-dipping reflections project to the surface within exposures of Paleozoic sediments on the south flank of the Benton uplift and in the southern Ouachitas. The continuation of these events to deeper levels on the seismic section suggests that the Paleozoic sediments (or metasediments) extend to depths in excess of 14 km (46,000 ft) beneath the southern Ouachitas and possibly beneath the Gulf coastal plain.

Integration of regional geological and geophysical data with the COCORP data lead to the following additional, although perhaps more speculative, suggestions.

5. Weak, north-dipping reflections just north of the Benton uplift reveal the form of an uplifted continuation of the lower to middle Paleozoic carbonate sequence. Accordingly, the Benton uplift is interpreted as a basement-involved uplift of the Paleozoic continental margin of North America, analogous to other basement uplifts along the Ouachita trend in Texas.

6. The lower to middle Paleozoic deep-marine facies exposed at the core of the Benton uplift are allochthonous,

inasmuch as they are interpreted to overlie structurally the coeval shallow-water carbonate sequence.

7. A south-dipping wedge of layered reflections, originating from depths in excess of 7 km (23,000 ft) beneath the Benton uplift and southern Ouachitas, represents an off-shelf clastic sequence or layered volcanics occurring along the (now buried) early Paleozoic continent-ocean transition.

8. Very strong, slightly north-dipping reflection events recognized at 7.6 to 8.1 sec (21 to 23 km; 68,900 to 75,500 ft) beneath the Gulf coastal plain indicate the bottom of the Paleozoic sedimentary (or metasedimentary) section.

Other important observations and interpretations, based primarily on regional geophysical data, which are important in understanding the tectonic evolution of the Ouachitas are the following.

9. Crust of "normal" continental thickness occurs both landward (north) and seaward (south) of the Ouachita orogenic belt. Along the belt, however, the thickness of the crust is poorly constrained.

10. The presently observed transition of crust of "normal" continental thickness to near "normal" oceanic thickness on the southern continental margin of the United States occurs seaward from the approximate position of the present coast of the Gulf of Mexico.

11. Magnetic anomalies have been interpreted to indicate the truncation of the North American craton along the Ouachita trend. Apparently, the magnetic basement of the craton landward of the Ouachitas is fundamentally different from that which underlies the Gulf coastal plain to the south.

12. Regional gravity data, when viewed in terms of the southward-thickening wedge of low-density Paleozoic sediments and metasediments interpreted from the COCORP data, suggest a southward shallowing of the Moho across the Ouachita trend in Arkansas.

SUGGESTED TECTONIC MODEL

Most recent interpretations of the evolution of the Ouachita orogenic belt have emphasized plate-tectonic models involving continent-continent collision (Wood and Walper, 1974; Briggs and Roeder, 1975; Wickham et al, 1976; Walper, 1977, 1980; Ross, 1979; Viele, 1979; Kluth and Coney, 1981) or island arc–continent collision (Graham et al, 1975, 1976). In these models, the culmination of the Ouachita orogeny occurs when a passive North American continental margin enters a south-dipping subduction zone in Late Carboniferous time. Alternative models involving north-dipping subduction, well south of the Ouachita trend, have also been proposed (e.g., see Keller and Cebull, 1973; Morris, 1974; Garrison and Goldstein, 1981; Goldstein, in prep.). A companion paper (Nelson et al, 1982) suggests that subsurface geometries recognized through the COCORP survey, in the context of local and regional geological constraints, are most consistent with a collisional model involving south-dipping subduction in late Paleozoic time. Though the COCORP data do not preclude the possibility of north-dipping subduction in a position far south of the Ouachita trend in early to middle Paleozoic time, the great thickness of Paleozoic deep-marine sediments (Carboniferous flysch and lower to middle Paleozoic Ouachita facies) above the interpreted shelf and off-shelf strata implies at least a partial southward underthrusting (subduction?) of the continental margin in Carboniferous time. The tectonic model (Fig. 9) incorporates interpretations of the COCORP data (Fig. 5), as well as the ideas of numerous other authors. A detailed review of this model, in the context of the reflection profiles and other regional geophysical data, is presented below.

Early Paleozoic Passive Margin (Fig. 9A)

In Figure 9A, a south-facing, passive (Atlantic style) continental margin is inherited from the late Precambrian breakup of a larger landmass (Keller and Cebull, 1973). Possible remnants of this breakup include the Delaware (south Texas), Wichita (southern Oklahoma), and Reelfoot (Mississippi embayment precursor) aulacogens, each of which have been tentatively interpreted as failed arms of systems of triple junctions involved in the initial stages of rifting (e.g., see Walper, 1977). Stretching of continental crust is inferred to have occurred along south-facing, listric normal faults (for a modern analog, see recently published results of seismic reflection work in the Bay of Biscay by Montadert et al, 1979). The thin 2.90 g/cm^3 layer, inferred to underlie the area just south of the Ouachitas in Figure 8C, may represent the subducted remnants of this stretched continental crust or it may be the oceanic crust adjacent to the Paleozoic continental margin.

Subsidence along the margin (and/or eustatic sea-level rise) resulted in the deposition of the lower to middle Paleozoic shallow-water carbonate sequence (Arbuckle facies) now exposed on the Ozark uplift and inferred to continue in the subsurface beneath the Arkoma basin, Frontal thrust zone, and possibly the Benton uplift. On the COCORP sections, reflections correlative with these strata can be traced as far south as the southern portion of the Frontal thrust zone, where they now occur at a depth of about 12 km (39,000 ft). Faint, north-dipping reflections beneath the north flank of the Benton uplift may represent the form of a continuation of these rocks to a position beneath the core of the uplift. The similarity of the COCORP section across the Benton uplift to seismic sections across other uplifts on the Ouachita trend in Texas, in which carbonate rocks have been drilled (Nicholas and Rozendal, 1975), provide tentative on-strike constraints for this interpretation.

At the core of the Benton uplift, a lower to middle Paleozoic deep-water (i.e., black shale and chert) sequence is exposed. These rocks, which contain exotic blocks of granite, chert, sandstone, and limestone in lower formations, are regarded as a continental slope-rise to abyssal facies deposited downslope from the rifted North American margin (Morris, 1974; Viele, 1979). Inasmuch as these rocks now occur above the inferred position of the coeval shelf carbonates, they are interpreted to be allochthonous. They are, therefore, depicted to have been deposited in a much more southerly position relative to the North American margin in early and middle Paleozoic time. Between the shallow (shelf) and the deep (slope-rise-abyssal) sequence, a wedge-shaped sequence of seaward-dipping reflections (Fig. 4) is interpreted to represent either a shelf-slope clastic assemblage or a layered volcanic sequence within upper oceanic crust (e.g., see Hinz, 1981; Mutter et al, 1982).

Carboniferous Collisional Orogeny (Fig. 9B, C)

By Mississippian time, south-dipping subduction is inferred south of the North American margin (i.e., North America was attached to the down-going plate). The magmatic arc depicted for the upper plate has been postulated to have been an island arc (Graham et al, 1975) or it could have been on another continent (or microcontinent). The crust now underlying the Gulf coastal plain farther to the south has been shown by refraction data to be of continental thickness (Fig. 7), but the composition or thickness of crust in this position in Paleozoic time is not known. Two of the possibilities which others have proposed for the preserved remnants of the colliding crustal block include the northern South America portion of an Afro-South American landmass (e.g., see Walper, 1980) or a Yucatan microcontinental block (e.g., see White, 1980).

As the two plates converged, the thick Carboniferous flysch (Stanley Shale through lower Atoka Formation) was simultaneously deposited and involved in foreland deformation. From the foreland basin (Arkoma basin) to the foreland thrust belt (Frontal zone) the seismic reflection data reveal that the flysch thickens (structurally and stratigraphically) to at least 12 km (39,000 ft). Movement of the flysch within these areas was along north-verging folds and thrusts which are listric above the shelf-carbonate sequence. As subduction continued, the North American continental margin was transported farther southward beneath the cumulative package of accreted sediments, resulting in the tectonic emplacement of the (now allochthonous) lower to middle Paleozoic deep-marine sediments onto the coeval shelf carbonates. Thick Paleozoic sediment packages, interpreted from the seismic reflection data to underlie the southern Ouachitas and northermost Gulf coastal plain, were therefore first "accreted" to the more southerly terrane and then "obducted" onto the North American plate. The series of strong reflections near 8 sec beneath the coastal plain on the COCORP survey may represent the boundary between these sediments (or metasediments) and crystalline basement (previously transitional or oceanic crust) below.

At some time late in the subduction episode, reverse faults are interpreted to have propagated deep into the crystalline basement south of the Frontal thrust zone, resulting in the northward and vertical movement of a portion of the continental margin as the Benton uplift. This fault movement could have been accomplished through the reactivation of listric normal faults related to the late Precambrian rifting (for a possible modern analog, see recent interpretation of basement fault reactivation in the Zagros collision zone by Jackson, 1980). Alternatively, the crystalline basement beneath the Benton uplift may not have (mid-Paleozoic) North American affinity. In this case, which is considered less likely, models in which the North American shelf (or craton) abruptly descends to great depths just south of the Frontal zone might be appropriate (Fig. 5D).

In the preferred models (Fig. 5B, C), the collisional processes are inferred to have ceased after only limited underthrusting (subduction) of the North American continental margin in the Pennsylvanian time, resulting in the preservation of a large portion on the accretionary wedge between the subducted North American continental margin and a more southerly "Llanorian" terrane. The present gravity anomaly across the area (Fig. 8C) is interpreted as the (subdued) positive Bouguer anomaly due to the buried passive margin (Fig. 8B), superimposed on a negative anomaly due to the thick wedge of low-density sediments (Fig. 8A).

The interpretation in Figure 5B suggests that the current COCORP survey did not extend far enough south to define conclusively the crystalline basement of the southern terrane. Alternatives (Fig. 5C, D) suggest that crystalline basement exotic to North America extends as far north as the northern edge of the coastal plain, or possibly to the Benton uplift. The later interpretation (Fig. 5D) would require a more complicated tectonic scenario (Nelson et al, 1982), involving first the emplacement of the Benton uplift basement over the North American plate and then the closing of an ocean basin farther south (i.e., to accommodate northward movement of the allochthon of deep-marine sediments to the position of the Benton uplift). Figure 5C is considered much more plausible and would require only a slight modification of the northward extent of the exotic terrane shown in the tectonic model.

Mesozoic-Cenozoic Rifted Margin (Fig. 9D)

Although the current COCORP data end after only a short traverse onto the Cretaceous onlap sequence, Figure 9D is extended southward to include a greater portion of the Gulf coastal plain. The configuration to the north is a preferred interpretation of the exposed portion of the Ouachita orogenic belt in western Arkansas. It represents the combined products of rifting, subduction, collision, and erosion depicted in Figure 9 (A, B, C), along with a Mesozoic rifting episode. Note that the present configuration incorporates a north-south shallowing of the Moho inherited from the earlier passive margin, and now roughly coincident with a thickening of the accretionary wedge. Gross crustal densities which might be expected from this buried margin are shown by the models of Figure 8 to be consistent with observed Bouguer anomalies. Interpretations of aeromagnetic anomaly patterns by Viele and Zietz (1981) are also consistent with this model, inasmuch as the North American craton is attenuated beneath the Ouachita trend and fundamentally different basement now exists on either side of the belt.

South of the COCORP survey, evidence from commercial seismic reflection and drilling data (e.g., Woods and Addington, 1973; Walper et al, 1979) suggest that the opening of the Gulf of Mexico began in Triassic time. Prior to this, subsidence of the North American (and possibly the more southerly) terrane is revealed by Middle Pennsylvanian (Desmoinesian) and Permian platform strata beneath southern Arkansas (Woods and

Addington, 1973). During the rifting stage, additional subsidence and normal faulting offset the Paleozoic basement (Vernon, 1971). On the northern edge of the Gulf basin, Triassic grabens were filled with clastic red beds (Eagle Mills Formation) which were in turn overlain by Jurassic evaporites and Upper Jurassic through Cretaceous transgressive marine deposits (Woods and Addington, 1973). A thick Cenozoic prograding clastic wedge covers earlier strata from the Louisiana state line southward to the Gulf of Mexico (Walper et al, 1979). Thus, more conclusive evidence for the southern (or "Llanorian") terrane may be buried beneath these deposits, between the position of the early Paleozoic continental margin (interpreted to be coincident with the Ouachita belt) and the present margin (which roughly parallels the coastline.)

APPENDIX A. ACQUISITION AND PROCESSING PARAMETERS FOR COCORP OUACHITA LINES

Acquisition Parameters for All Lines

Source:
  Vibroseis (trademark Conoco, Inc.)
  5 vibrator array
  16 sweeps/VP
  8 to 40 Hz upsweep
  26 sec duration
  201.2-m (660-ft) spacing

Receiver:
  100.6-m (330-ft) station spacing
  96 channels
  Near 402.3 m (1,320 ft) nominal offset
  Far 9,957.8 m (32,670 ft) nominal offset

Recording:
  42 sec recording time
  16 sec correlated record length
  0.004 sec sample rate
  24 (nominal) fold
  62.5 Hz anti-alias filter
  60 Hz notch filter

Direction:
  (a) *Line 1 and VP 98-213 of Line 3*
    pull to south
  (b) *VP 239-1376 of Line 3*
    push to south
  (c) *Lines 2, 4 and 5*
    pull to west

General Processing for All Lines

1. *Demultiplex*
2. *Vibroseis Correlation*
3. *Edit*
4. *Geometry*
   Crooked line processing
   50.3 m (165 ft) CDP spacing
5. *Gather*
   Resample at 0.008 sec
   Zero noisy traces
   Tailmute single VP records with late vibrator effects
   Generate gather tapes
6. *Elevation Statics*
   Datum 304.8 m (1,000 ft)
   Elevation static velocity
     (a) *Lines 1, 2 and station 98-213 of line 3*
       3,810 m/sec (12,500 ft/sec)
     (b) *Lines 4, 5 and station 238-1475 of line 3*
       4,572 m/sec (15,000 ft/sec)
7. *Velocity Analysis*
   Velocities picked from CONSTANT VELOCITY STACK SECTIONS at 304.8 m/sec (1,000 ft/sec) increments
   Some velocities refined with single CDP velocity scans and velocity contour plots
8. *Normal Moveout*
9. *Mute*
   Linear frontmute as follows:
     0.0 to 548.6 m (1,800 ft) = 0.0 sec
     9,144 m (30,000 ft) = 3.0 sec
     9,144 m (30,000 ft) to 9,957.8 m (32,670 ft) = 3.0 sec
10. *Trace Amplitude Balance*
11. *Stack*
    Generate stack tape
12. *Automatic Gain Control*
    Window 1.5 sec
13. *Display* (Sections shown in this paper processed to this point)
    Unmigrated time section
14. *Constant Velocity Migrations*
15. *Display* (Used to aid in interpretations shown in this paper)

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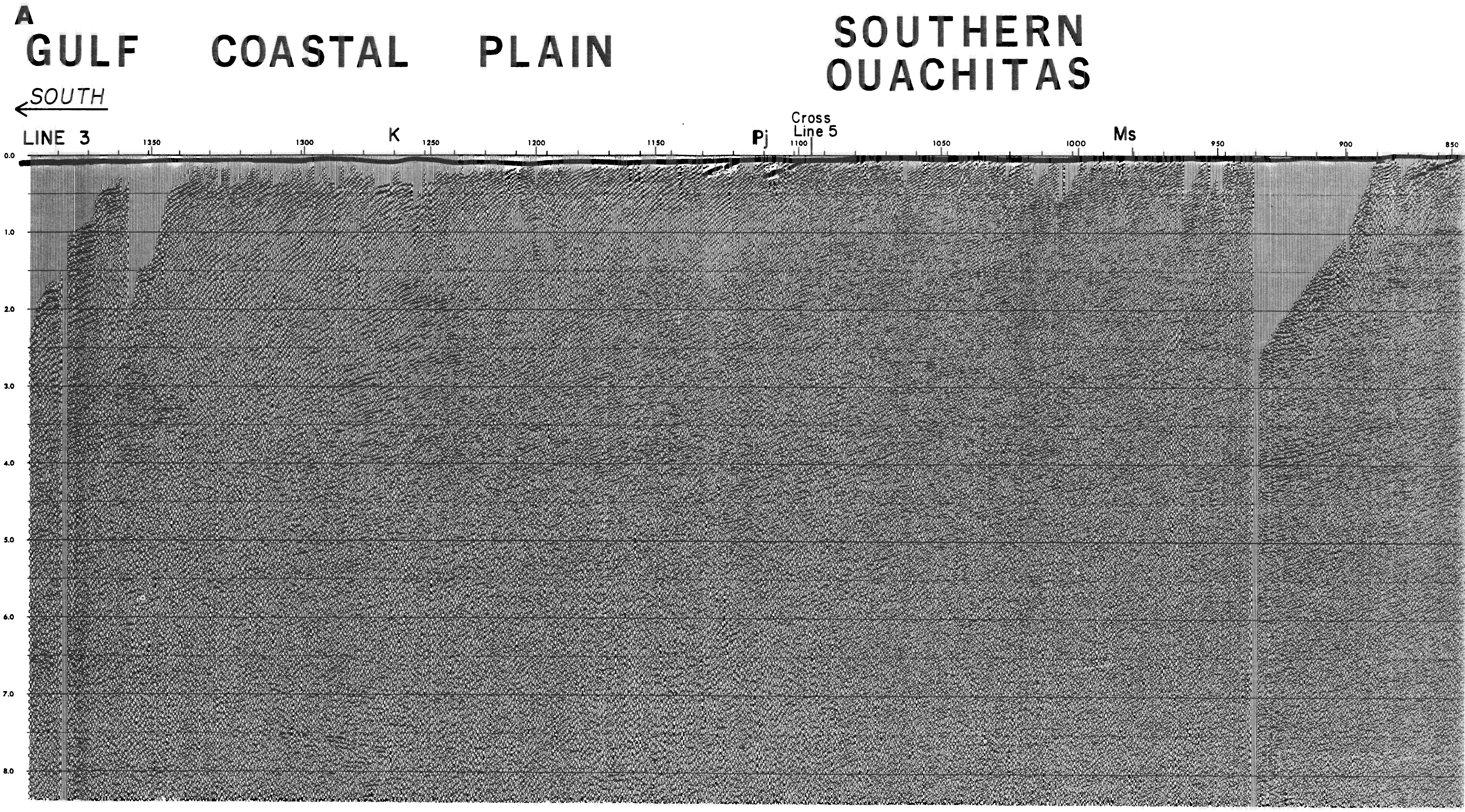


FIG. 4—A. Time section. Upper 8 sec of unmigrated time sections for COCORP lines 1 and 3 (see Appendix A for general processing sequence). Cross line 2 was used to tie ends of two lines together as shown. Generalized surface geology from quadrangle maps used by Haley et al (1976) to construct state geologic map of Arkansas. Well constraints from Boyd Haley (personal commun.). Section is one-to-one vertical exaggeration for seismic velocity of 5.0 km/sec (16,400 ft/sec). K, Cretaceous (undifferentiated); ₽m = McAlester Formation; ₽hs = Hartshorne Sandstone; ₽au = Upper Atoka Formation; ₽jv = Johns Valley Shale; ₽j = Jackfork Sandstone; Ms = Stanley Shale; MDSO = lower to middle Paleozoic deep-water sediments (Collier Shale to Arkansas Novaculite).

B. Possible geologic interpretation of time section A, which is also shown in cross-sectional form in Figure 5B.

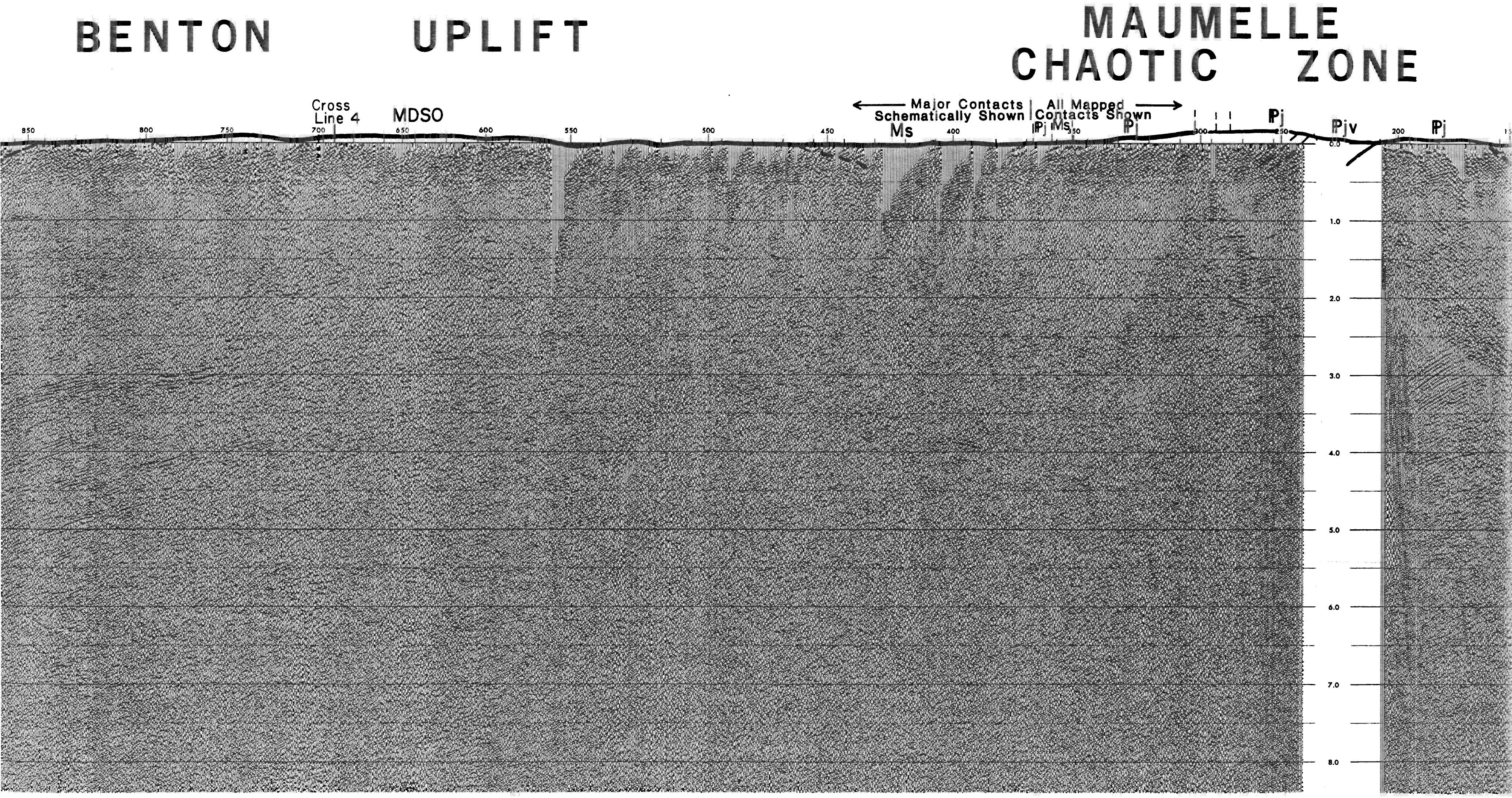

BENTON UPLIFT
MAUMELLE CHAOTIC ZONE
Cross Line 4
MDSO
← Major Contacts Schematically Shown
All Mapped Contacts Shown →
Ms
IPj
Ms
IPj
IPj
IPjv
IPj
850
800
750
700
650
600
550
500
450
400
350
300
250
200
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0

Fig. 4A, p. 2 of 3

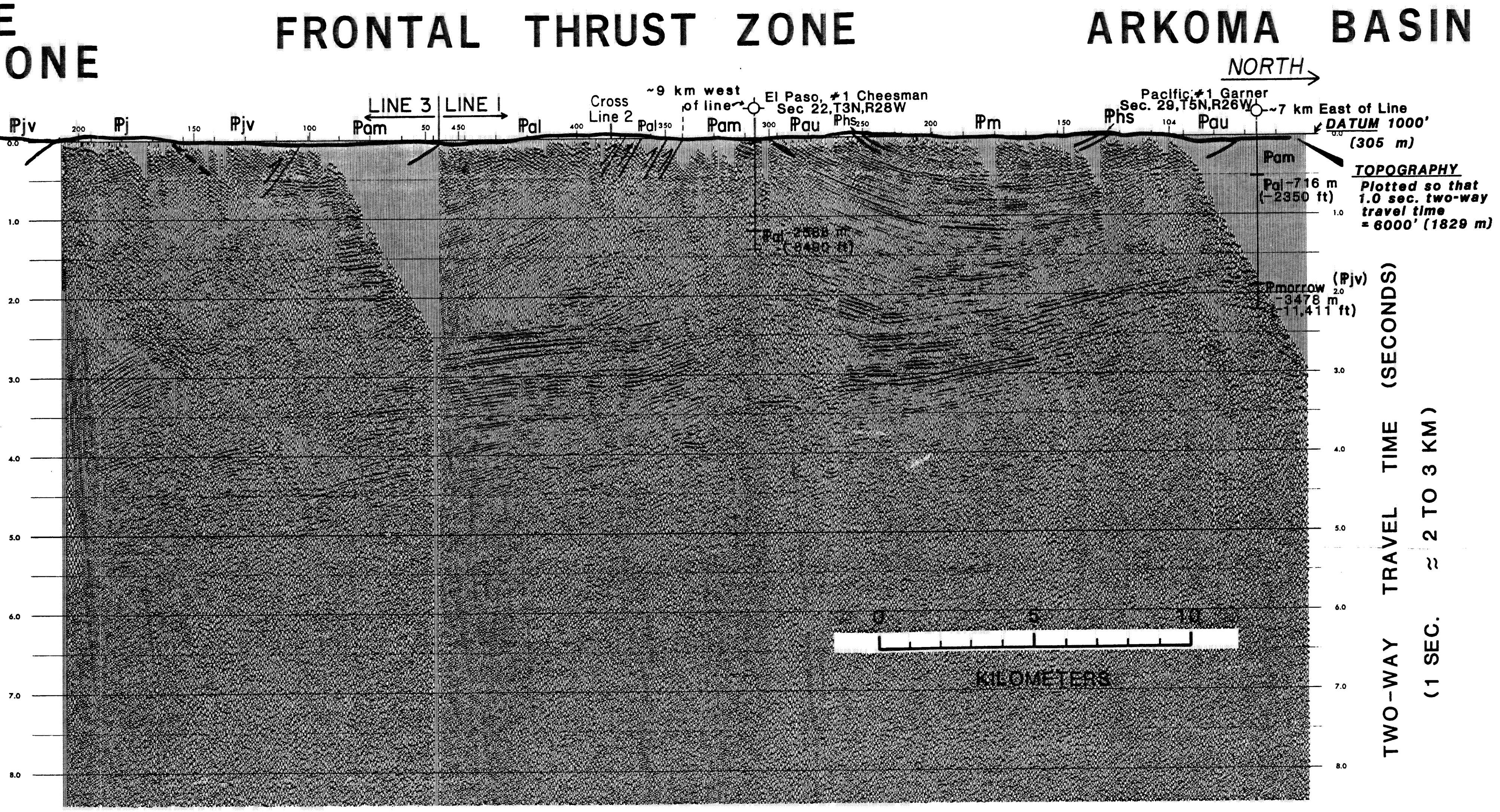

E
ONE
FRONTAL THRUST ZONE
ARKOMA BASIN
NORTH
LINE 3
LINE 1
Cross Line 2
~9 km west of line
El Paso, #1 Cheesman
Sec 22,T3N,R28W
Pacific #1 Garner
Sec. 29,T5N,R26W
~7 km East of Line
DATUM 1000' (305 m)
TOPOGRAPHY
Plotted so that 1.0 sec. two-way travel time = 6000' (1829 m)
ℙjv
ℙj
ℙjv
ℙam
ℙal
ℙal
ℙam
ℙau
ℙhs
ℙm
ℙhs
ℙau
ℙam
ℙal -716 m (-2350 ft)
ℙal -2588 m (-8490 ft)
ℙmorrow -3478 m (-11,411 ft)
(ℙjv)
200
150
100
50
450
400
350
300
250
200
150
104
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
0
5
10
KILOMETERS
TWO-WAY TRAVEL TIME (SECONDS)
(1 SEC. ≈ 2 TO 3 KM)

Fig. 4A, p. 3 of 3

Fig 4B,
p. 1 of 3

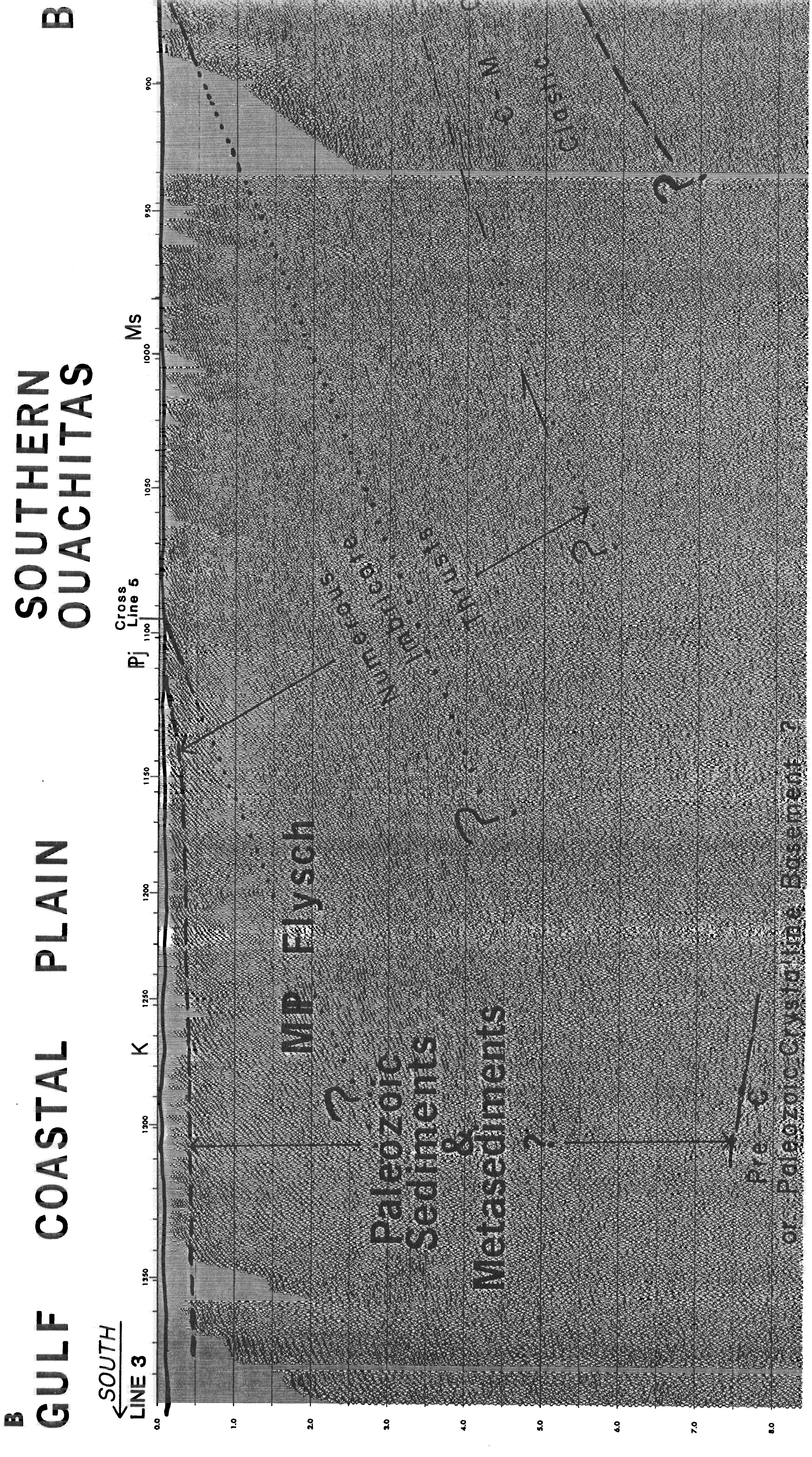
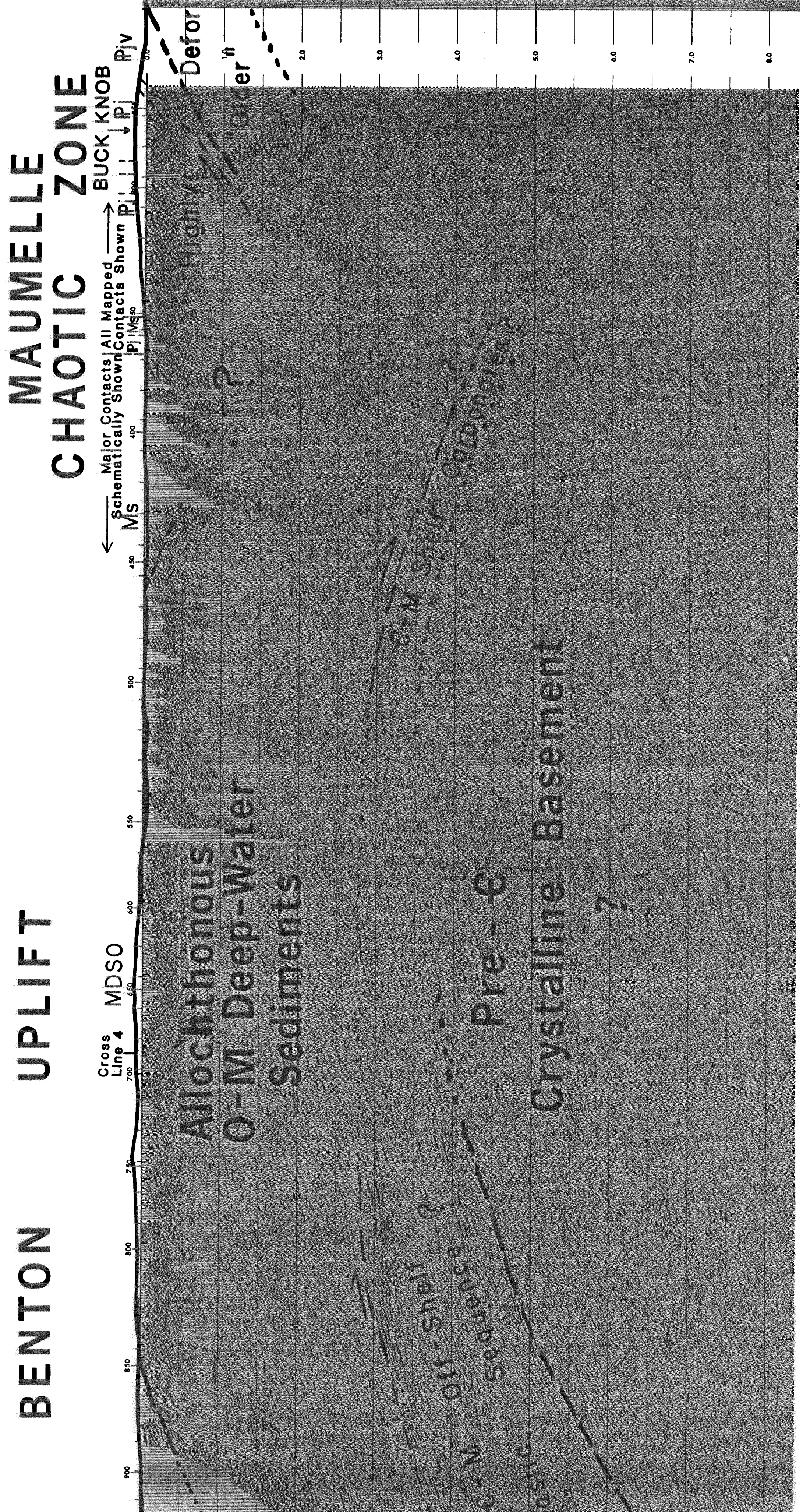

B
GULF COASTAL PLAIN
SOUTHERN OUACHITAS
B
SOUTH
LINE 3
K
Pj
Cross Line 5
Ms
900
950
1000
1050
1100
1150
1200
1250
1300
1350
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
MP Flysch
Paleozoic Sediments & Metasediments
?
Numerous Imbricate Thrusts
Є-M
Clastic
Pre-Є
or Paleozoic Crystalline Basement ?

Fig 4B,
p. 2 of 3


MAUMELLE CHAOTIC ZONE
BUCK KNOB
Pjv
Pj
Pj
Major Contacts Schematically Shown
All Mapped Contacts Shown
Pj Ms
Ms
UPLIFT
MDSO
Cross Line 4
BENTON
Highly Defor
"older"
?
C-M Shelf Carbonates ?
C-M Shelf
Allochthonous O-M Deep-Water Sediments
Pre-C Crystalline Basement
?
Off-Shelf C-M Sequence
Shelf ?
C-M
astic
0.0
1.0
2.0
3.0
4.0
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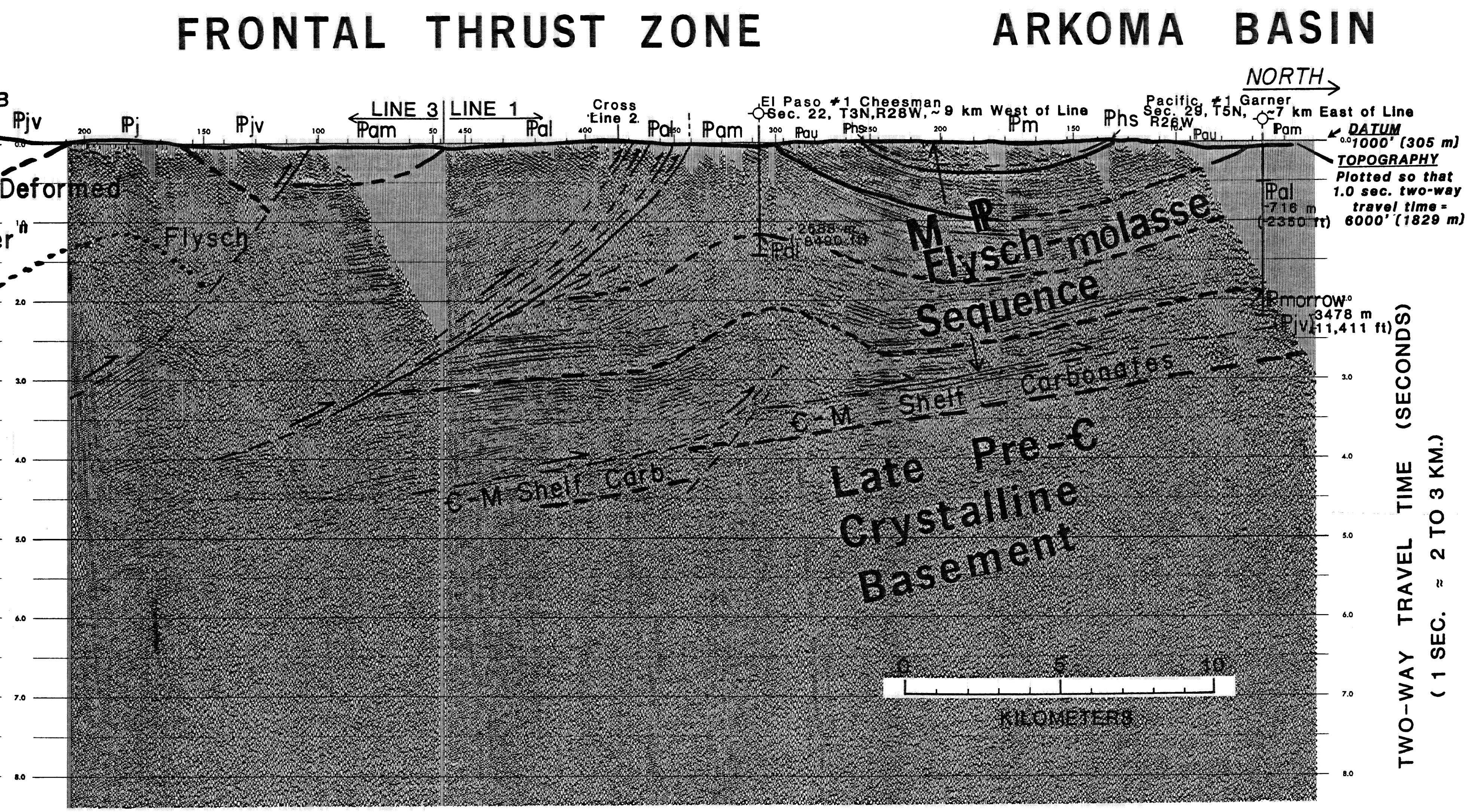
FRONTAL THRUST ZONE
ARKOMA BASIN
NORTH
LINE 3
LINE 1
Cross Line 2
El Paso #1 Cheesman
Sec. 22, T3N,R28W, ~9 km West of Line
Pacific #1 Garner
Sec. 29, T5N, R26W, ~7 km East of Line
Pjv
Pj
Pjv
Pam
Pal
Pal
Pam
Pau
Phs
Pm
Phs
Pau
Pam
DATUM
1000' (305 m)
TOPOGRAPHY
Plotted so that 1.0 sec. two-way travel time = 6000' (1829 m)
Deformed
Flysch
Pal
-2588 m
8490 ft
Pal
-716 m
(-2350 ft)
Pmorrow
Pjv
-3478 m
(-11,411 ft)
M P
Flysch-molasse
Sequence
€-M Shelf Carbonates
€-M Shelf Carb.
Late Pre-€
Crystalline
Basement
0
5
10
KILOMETERS
TWO-WAY TRAVEL TIME (SECONDS)
(1 SEC. ≈ 2 TO 3 KM.)
200
150
100
50
450
400
350
300
250
200
150
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0

Fig 4B, p. 3 of 3