SUBSURFACE STRUCTURE OF THE OUACHITA MOUNTAINS. RKANSAS, FROM COCORP DEEP SEISMIC REFLECTION PROFILES

R. J. Lillie, K. D. Nelson, B. de Voogd, J. E. Oliver, L. D. Brown and S. Kaufman
Department of Geological Sciences, Cornell University

In a continuing effort to better understand the subsurface nature and evolution of the North American continent, the Consortium for Continental Reflection Profiling (COCORP), recently recorded approximately 200km(124 mi)of deep seismic reflection profiles across the Ouachita Mountains in western Arkansas. The Late Paleozoic Ouachita orogenic belt forms a sinuous pattern across the south-central United States, stretching from central Mississippi to west Texas (Flawn, 1961). Paleozoic strata at the core of the belt are exposed only in the Ouachita Mountains of Arkansas and Oklahoma, and in the Marathon Mountains of West Texas (Figure 1). Borehole and geophysical data demonstrate that the remainder of the belt is buried beneath Mesozoic and Cenozoic strata of the Gulf Coastal Plain. Many recent workers (Briggs and Roeder, 1975; Viele, 1979; Walper, 1977) interpreted the Ouachita belt as the remnants of a collisional orogeny in which an exotic terrane ("Llanoria") was sutured to the North American continent in Late Paleozoic time.

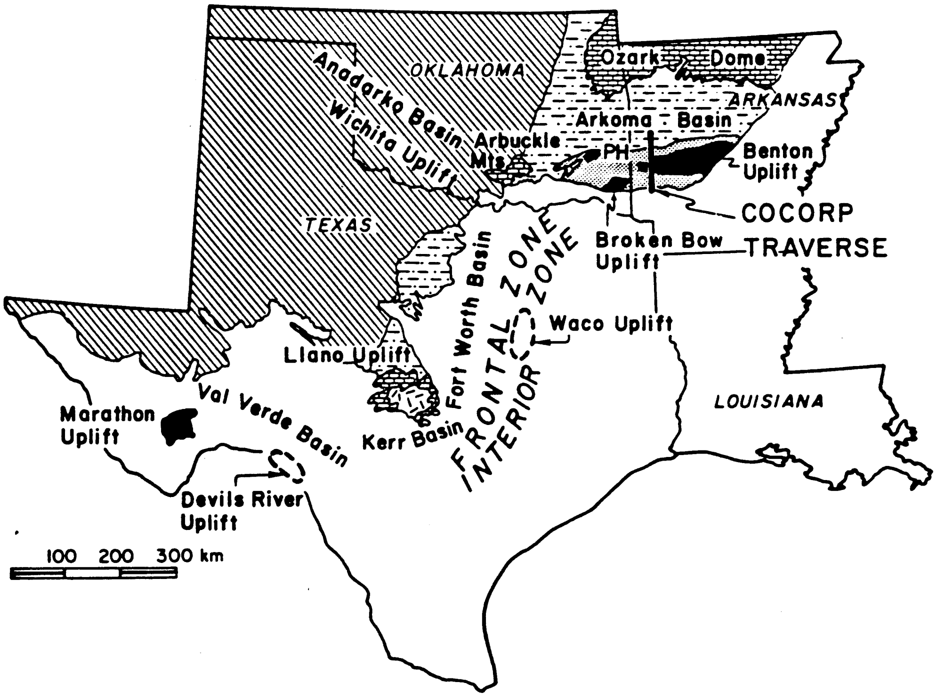


Figure 1: Generalized geologic map of south-central United States showing the approximate location of the COCORP traverse across the Ouachita Mountains in western Arkansas. The Late Paleozoic Ouachita orogenic belt extends in the subsurface around the Llano Uplift in central Texas, connecting the Marathon Uplift to the Devils River, Waco, Broken Bow, and Benton uplifts. Parts of the belt can also be traced beneath Mesozoic and Cenozoic cover into southeastern Arkansas and central Mississippi.

The data shown on the accompanying panels are unmigrated time sections for the upper 8.5 secs of the north-south dip lines (that is, a composite of lines 1 and 3 shown on Figure 2). Detailed interpretations of the data, emphasizing regional geological and geophysical constraints, are found in Nelson et al (in prep.) and Lillie et al (in prep.). A brief discussion of gross structural features interpreted from the data is presented here. The line drawing (Figure 3a) schematically portrays prominent events observed on the unmigrated time sections for lines 1 and 3. Figure 3b is a preferred interpretation of the data in which tectonically thickened Paleozoic sediments (and metasediments) overlie crust of North American affinity. Alternative interpretations, in which crust exotic to North America extends as far north as the Southern Ouachitas or the Benton Uplift, are discussed in the Nelson et al, and Lillie et al papers. Major structural boundaries are shown in their approximate migrated time positions in Figure 3b. The approximate depth scales assume that 1.0 sec of two-way traveltime represents 2.5 km (or 8,000 ft) of section. Note, however, that depth conversions given below utilize stacking velocity functions and may differ from these approximations.

The seismic lines on the north end of the survey (Figure 4a) cross the Frontal Thrust Zone, which is a foreland fold and thrust belt related to the Carboniferous Ouachita orogeny (Viele, 1979). Well data near the northern parts of the survey suggest that prominent reflections beneath the north end of line 1 represent the top of thin platform carbonates known to floor the Arkoma basin (events at 3.0 secs beneath VP 200). These Lower-to-Middle Paleozoic "Arbuckle Facies" rocks are shown by the reflection data to continue their southward dip to at least VP 300 on line 1, where they appear to be offset by one or more normal faults. Analogous offsets beneath the Arkoma basin to the north are documented by 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 shelf) of North America extends southward in the subsurface to at least the northernmost portion of line 3.

Above the carbonates a Carboniferous flysch sequence, cut by numerous north-verging thrusts, thickens dramatically southward within the Frontal Thrust Zone (Berry and Trumbly, 1968). The wedge-shaped zone of prominent reflections in the upper few seconds of the seismic sections demonstrates that the flysch is at least 12 km (40,000 ft) thick in the southern parts of the Frontal Zone (that is, the wedge thickens to about 4.5 secs beneath VP 100 on line 3). Geometry in this zone indicates broad folds and truncated interfaces within the flysch wedge which can be closely related to surface geology. Beneath VP 340 to 370 on line 1, a series of thrust faults are mapped at the surface (Haley et al, 1976). These correlate with a series of fairly steep, south-dipping reflections which flatten out with depth. Other prominent, but more gently, south-dipping events extend for several kilometers beneath the thrusts (see Figures 3b, 4a). Apparently, major north-verging thrusts within the more interior parts of the Frontal Thrust Zone are listric at depth, analogous to those in the subsurface to the north noted by Berry and Trumbly (1968).

Because no apparent reverse offsets of the Lower-to-Middle Paleozoic carbonate sequence are

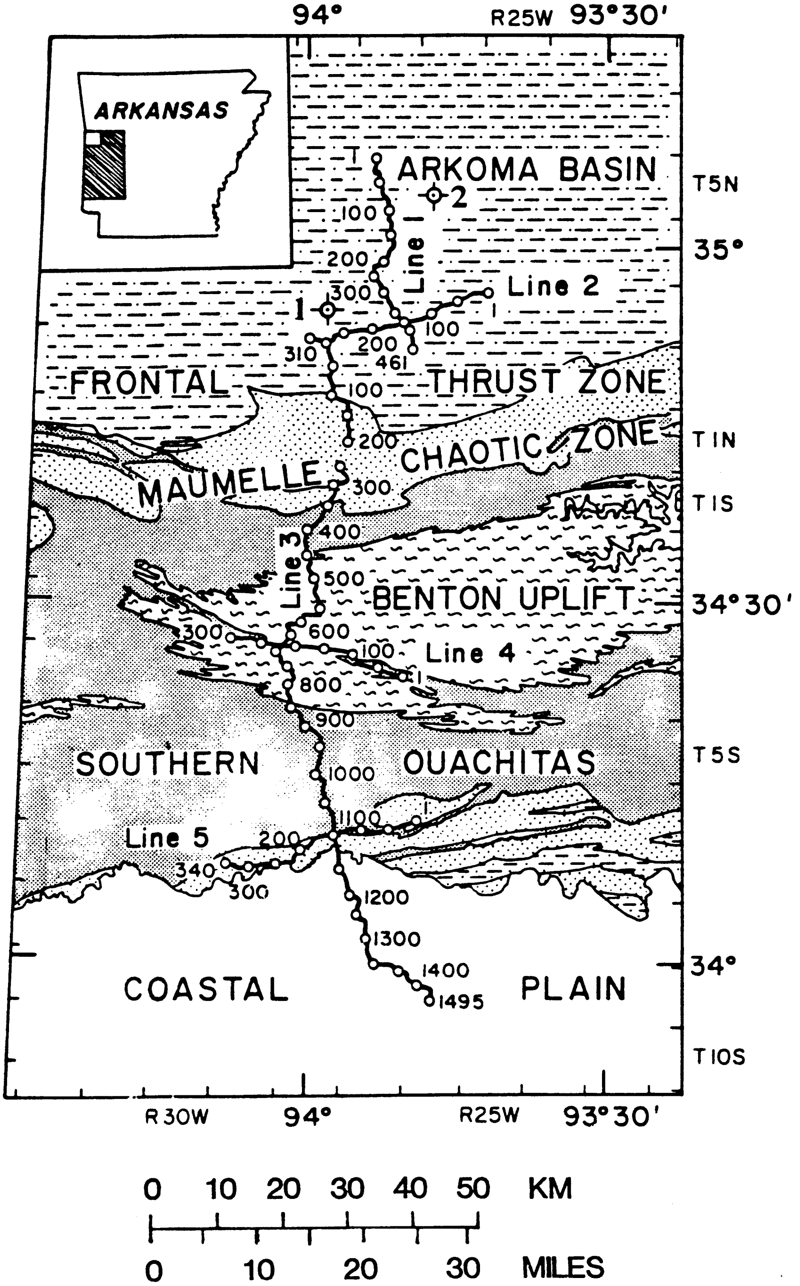


Figure 2: Geologic map of west-central Arkansas (generalized from Haley et al, 1976) showing Vibrator Point (VP) locations along the COCORP seismic reflection lines. *Wavey Pattern*: Lower-to-Middle Paleozoic (Collier Shale through Arkansas Novaculite) deep marine sediments; *Fine Stipple*: Mississippian 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 No. 1 Cheesman, Sec. 2, T3N, R28W; (2) Pacific, No. 1 Garner, Sec. 29, T5N, R26W.

observed within the northern and central parts of the Frontal Thrust Zone, a major detachment is inferred to lie above these rocks. Above the detachment the Carboniferous flysch is deformed into a series of folds cut by north-vergent thrusts. A thrust fault apparently ramped up along the normal fault offset occurring beneath VP 300 on line 1, forming a hanging-wall anticline within the overlying flysch sequence. Because north-verging thrusts are exposed north of the survey, detachments at some level must continue beyond this structure.

South of the Frontal Thrust Zone reflection quality deteriorates, due at least in part to rugged terrain and rapid changes in near-surface velocity (south end Figure 4a; north end Figure 4b). The paucity of prominent reflections in the upper few seconds of the sections, however, may also be related to intense deformation of the Paleozoic sedimentary sequences in the subsurface beneath the Maumelle Chaotic Zone and the north flank of the Benton Uplift. Structures indicative of polyphase deformation have been observed at the surface in these areas (Viele, 1974). Though these features are beyond the resolution of the reflection data, structural complexity within the upper few kilometers of Carboniferous flysch and Lower-to-Middle Paleozoic deep-marine strata exposed in these areas is schematically shown on the cross section (Nelson et al, in prep.).

Below this deformed zone, a lineup of low amplitude, north-dipping reflection segments is observed (south side Figure 4a). These rise from about 4.0 secs (11 km; 36,000 ft) beneath VP 380 to about 2.8 secs (7 km; 23,000 ft) beneath VP 550, where they appear to flatten out across the mapped center of the Benton Uplift (north end Figure 4b). Further to the south (2.8 secs at VP 750), events at this level gradually curve into south-dipping reflections. The Benton Uplift is therefore a surface anticlinorial feature (Figure 2) which displays a broad antiformal structure at depth on the unmigrated (and migrated) seismic section.

Without subcrop data from the Benton Uplift, it is not possible to make an unequivocal interpretation of the subsurface antiform. However, analogy with similar structures that were drilled along the Ouachita trend in Texas suggests the interpretation shown in Figure 3b. Like the Benton Uplift, the Waco and Devils River uplifts (Figure 1) have similar deep antiformal seismic expressions and lie on the same steep Bouguer gravity gradient. Nicholas and Rozendal (1975) suggested that crystalline basement rocks encountered beneath thin (metamorphosed) carbonate sequences in wells on the uplifts are of (Late Precambrian) North American affinity. Most workers correlate the carbonates with strata which floor foreland basins to the northwest (for example, Lower Ordovician Ellenburger Dolomite). Hence, the mid-Paleozoic continental margin of North America is inferred to extend in the subsurface at least as far southeastward as the basement uplifts and coincident Ouachita gravity gradient.

In the interpretation shown in Figure 3b, the Benton Uplift is also cored by North American crystalline basement. The faint north-dipping events beneath the north flank of the feature (south end, Figure 4a) are interpreted to represent the form of the Lower-to-Middle Paleozoic shelf carbonates (Arbuckle facies) as they continue southward in the subsurface. This interpretation requires that the Lower-to-Middle Paleozoic, deep marine strata (Ouachita facies) exposed at the center of the Benton Uplift are allochthonous, since they now structurally overlie the coeval shelf strata. The decollement separating these two units is schematically shown to continue 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 movement along one or more deeper thrusts that actually cut into basement in this region. The deeper thrust zone is inferred to continue to the 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 (Nelson et al, in prep.). At least one reverse fault with considerable stratigraphic throw is mapped in this region (Haley et al, 1976).

Reflections have pervasive south dips on the south side of the Benton Uplift (Figure 4b). These project to the surface in zones of south-dipping Lower-to-Middle Paleozoic deep-marine sediments cropping out on the Benton Uplift (Ouachita facies) and thrust imbricated Carboniferous flysch within the Southern Ouachitas (e.g., Walthall, 1967). The continuation of these events to at least 5 secs two-way traveltime on the section suggests that at least 14 km (45,000 ft) of tectonically thickened, Lower-to-Middle Paleozoic deep-marine strata and Carboniferous flysch underlies the Southern Ouachitas and northernmost Gulf Coastal Plain (Figures 3a, 3b). Possibly, gently north-dipping events occurring at about 7.6 secs beneath VP 1250-1300, represent reflections from crystalline basement at the bottom of this sequence. If so, then the total structural thickness of the Paleozoic strata (or metamorphosed equivalents) may be about 22 km (72,000 ft).

Below 3 secs beneath the south flank of the Benton Uplift, another prominent, south-dipping wedge of layered reflections is observed (Figure 4b). The top of the wedge extends from about 3.0 secs at VP 800 to about 4.0 secs at VP 950. While interpretation of these events is not constrained by surface or well log information, their layered nature and position relative to that of the inferred Lower-to-Middle Paleozoic shelf sequence might suggest an off-shelf clastic sequence. Similar events, which lie near the palinspastically restored shelf edge of the (Early Paleozoic) East Coast of the United States, are observed on the Southern Appalachian COCORP profiles. These in turn lie on steep Bouguer and magnetic gradients, which are interpreted by Cook and Oliver (1981) to mark the buried passive margin of the (Early Paleozoic) North American continent. The analogous sequences observed on the Ouachita profiles lie on similar potential field gradients (see maps of Woollard and Joesting, 1964; and Zietz, 1981) and may mark a southwestward continuation of this ancient margin in the subsurface (Lillie et al, in prep.).

Thus, the COCORP traverse across the Ouachitas reveals a southward-thickening wedge of Paleozoic strata interrupted by the (basement cored) Benton Uplift (Figure 3b). Because these strata probably represent a negative density contrast within the upper crust, the observed gravity data require high densities at lower crustal levels south of the Benton Uplift (Lillie et al, in prep.). These high densities are reasonably interpreted in terms of a southward shallowing of the Moho by about 10 km (30,000 ft) across the Ouachita Mountains. The resulting crustal section can be interpreted as the remnants of the Early Paleozoic (Atlantic style) passive margin which was subducted beneath the thick (accretionary) wedge of Paleozoic strata in Carboniferous time (see Briggs and Roeder, 1975; Walper, 1977). The Frontal Thrust Zone represents the evolution of the accretionary wedge into a foreland thrust belt as the margin entered the (south-dipping) subduction zone. The Benton Uplift is interpreted as a late-stage uplift along the margin as reverse faults cut deeply into the underlying crystalline basement.

REFERENCES

Berry, R. M., and W. D. Trumbly, 1968, Wilburton gas field, Arkoma basin, Oklahoma, *in* L. M. Cline, ed., Guidebook, geology of the western Arkoma basin and Ouachita Mountains: Okla. City Geol. Soc., p. 86-102.

Briggs, G., and D. H. Roeder, 1975, Sedimentation and plate tectonics, Ouachita Mountains and Arkoma basin, *in* G. Briggs, E. F. McBride, and R. J. Miola, eds., Sedimentology of Paleozoic flysch and associated deposits, Ouachita Mountains - Arkoma basin, Oklahoma: Dallas Geol. Soc., p. 1-22.

Buchanan, R. S., and F. K. Johnson, 1968, Bonanza gas field — a model for Arkoma basin growth faulting, *in* L. M. Cline, ed., Guidebook, geology of the western Arkoma basin and Ouachita Mountains: Okla. City Geol. Soc., p. 75-85.

Cook, F. A., and J. E. Oliver, 1981, The late Precambrian — early Paleozoic continental edge in the Appalachian orogen: Am. Jour. Sci., v. 281, p. 993-1008.

Flawn, P. T., et al, 1961, The Ouachita system: Austin, Univ. Texas Pub. No. 6120, 401 p. + maps.

Haley, B. R., et al, 1976, Geologic map of Arkansas: U. S. Geol. Survey and Arkansas Geol. Comm., scale 1:500,000.

Lillie, R. J., et al, (in prep.), Crustal structure of the Ouachita Mountains, Arkansas; a model based on the integration of COCORP reflection profiles and regional geophysical data.

Nelson, K. D., et al, (in prep.), COCORP seismic reflection profiling in the Ouachita Mountains of western Arkansas; geometry and geologic interpretation.

Nicholas, R. L., and R. A. Rozendal, 1975, Subsurface positive elements within Ouachita foldbelt in Texas and their relationship to Paleozoic cratonic margin: AAPG Bull., v. 59, p. 193-216.

Viele, G. W., 1974, Structure and tectonic history of the Ouachita Mountains, Arkansas, *in* K. A. De Jong and R. Scholten, eds., Gravity and tectonics: New York, John Wiley and Sons, p. 361-377.

———, 1979, Geologic map and cross section, eastern Ouachita Mountains, Arkansas: Geol. Soc. America, Map and Chart Series MC-28F, scale 1:250,000, 1 sheet, 8 p. text.

Walper, J. L., 1977, Paleozoic tectonics of the southern margin of North America: Gulf Coast Assoc. Geol. Socs. Trans., v. 26, p. 230-241.

Walthall, B. H., 1967, Stratigraphy and structure, part of Athens Plateau, southern Ouachitas, Arkansas: AAPG Bull., v. 51, p. 504-528.

Woollard, G., and H. Joesting, 1964, Bouguer gravity anomaly map of the United States: U. S. Geol. Surv., scale 1:2,500,000.

Zietz, I., 1981, Preliminary composite magnetic anomaly map of the conterminous United States: U. S. Geol. Survey, Open File Rept. No. 81-1132.

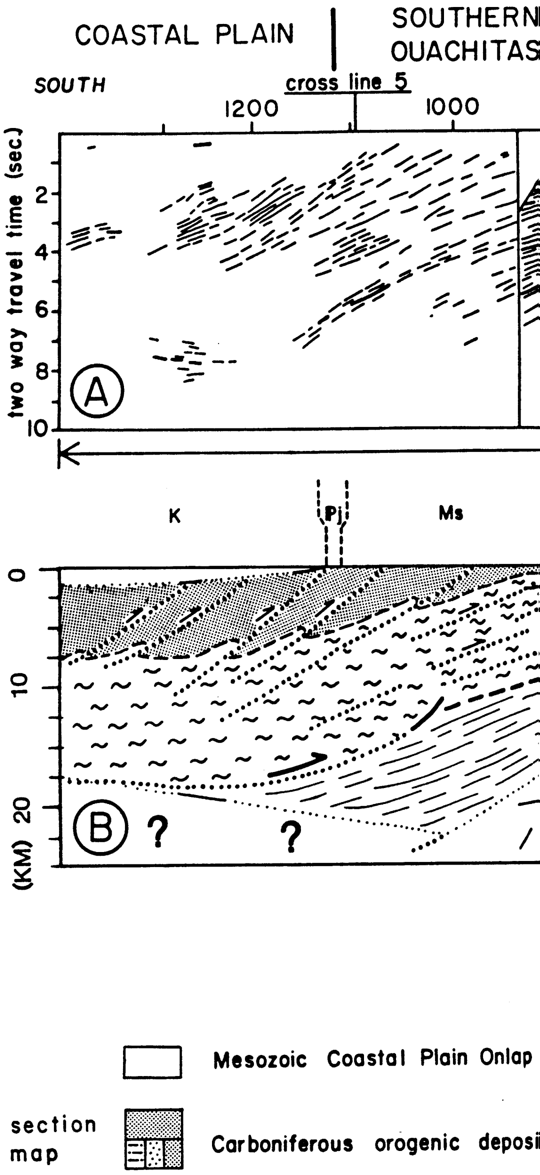
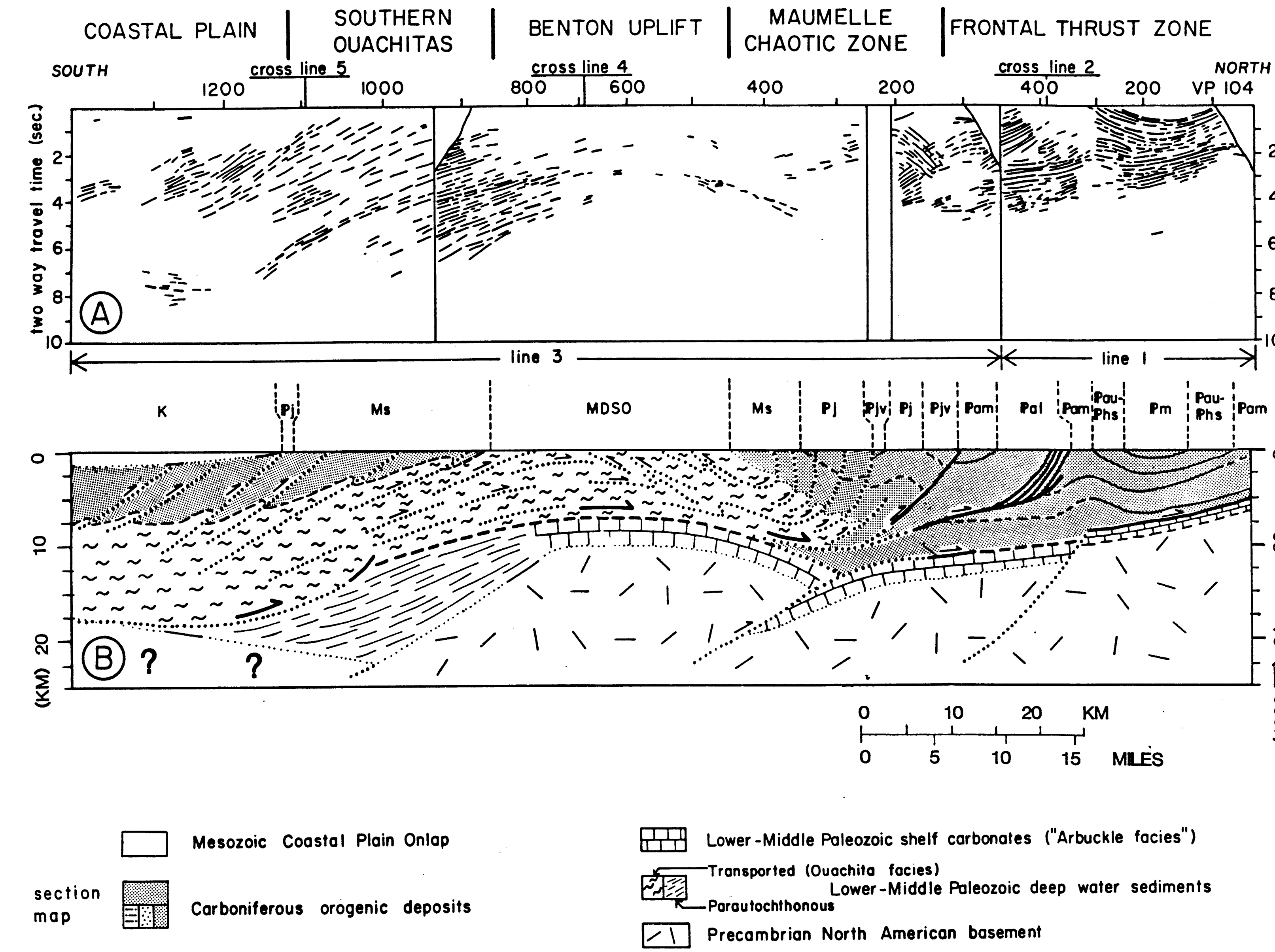


Figure 3: **(a)** Line drawing schematically showing major reflection events from the upper 10 secs of lines 1 and 3. **(b)** Preferred interpretation of (a). The cross section uses the same time scale depicted in (a) but incorporates geometric information from migrated time sections. Generalized surface geology and formation symbols from the state geologic map of the Haley et al, 1976. Section one-to-one vertical exaggeration for a seismic velocity of 5.0 km/sec (about 16,000 ft/sec).

Figure 3, p. 1 of 2


COASTAL PLAIN
SOUTHERN OUACHITAS
BENTON UPLIFT
MAUMELLE CHAOTIC ZONE
FRONTAL THRUST ZONE
SOUTH
NORTH
cross line 5
cross line 4
cross line 2
1200
1000
800
600
400
200
400
200
VP 104
two way travel time (sec)
2
4
6
8
10
A
line 3
line 1
K
Pj
Ms
MDSO
Ms
Pj
Pjv
Pj
Pjv
Pam
Pal
Pam
Pau-Phs
Pm
Pau-Phs
Pam
0
10
20
(KM)
B
?
?
0
10
20
KM
0
5
10
15
MILES
Mesozoic Coastal Plain Onlap
section
map
Carboniferous orogenic deposits
Lower-Middle Paleozoic shelf carbonates ("Arbuckle facies")
Transported (Ouachita facies)
Lower-Middle Paleozoic deep water sediments
Parautochthonous
Precambrian North American basement

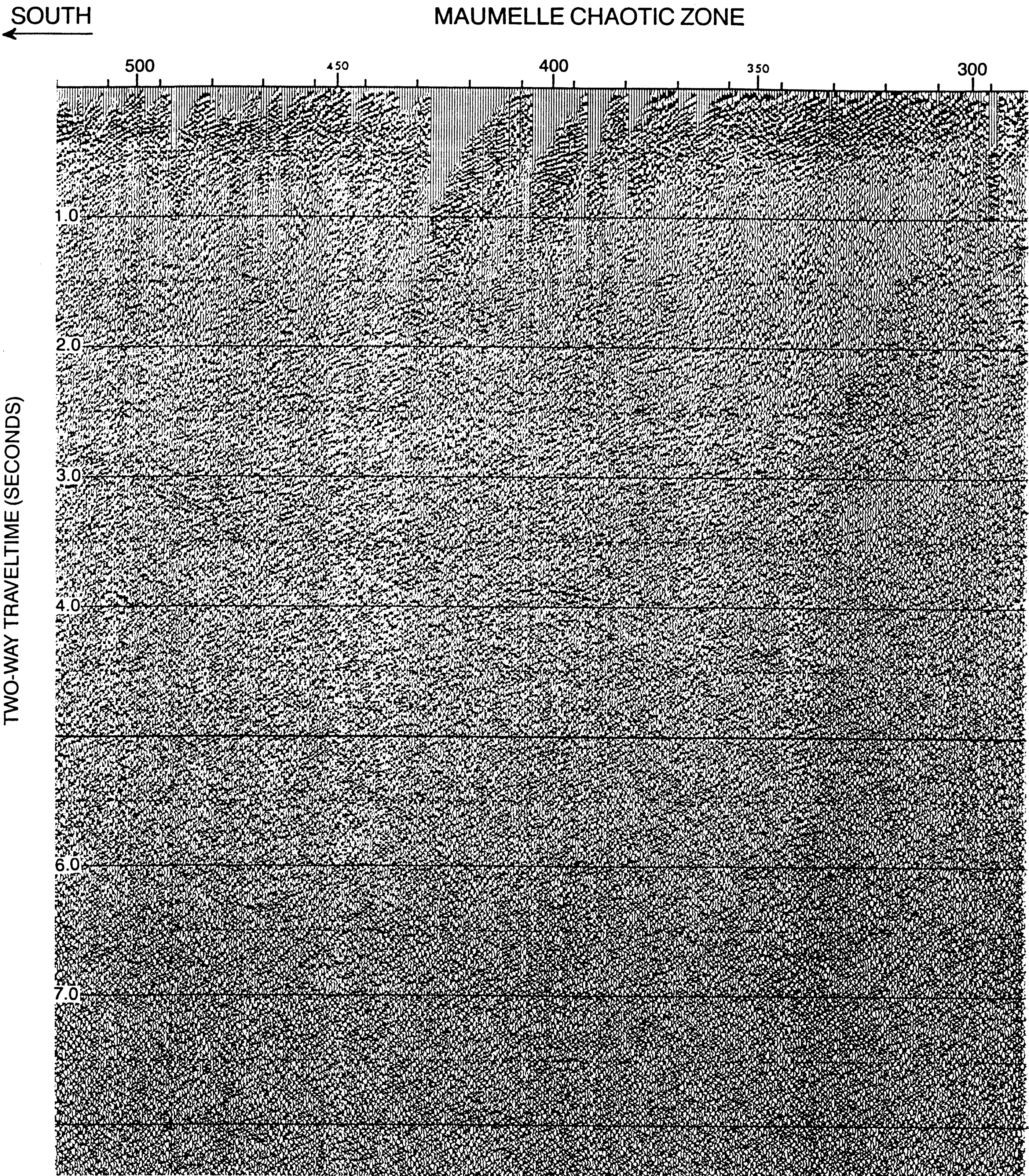
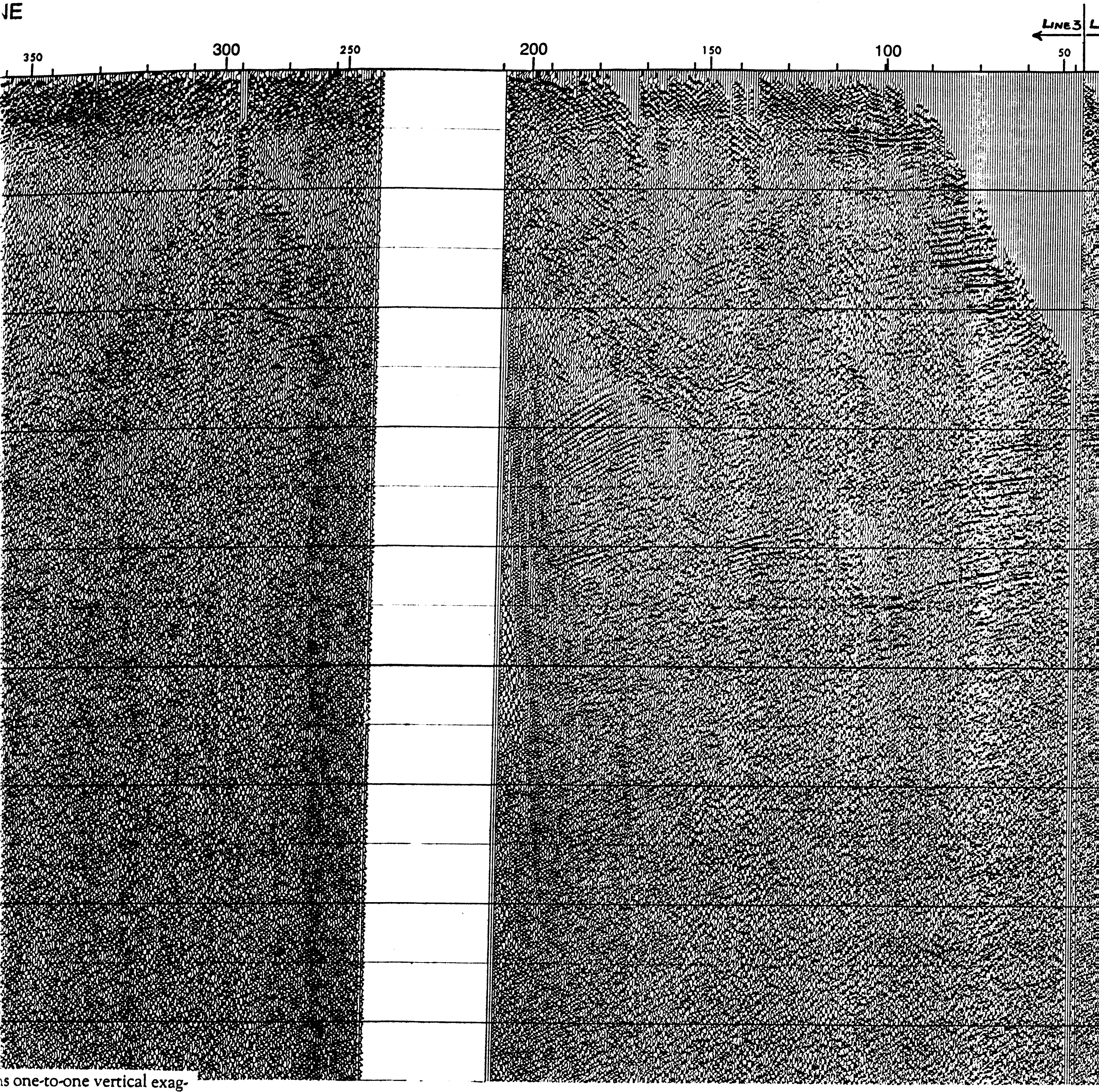
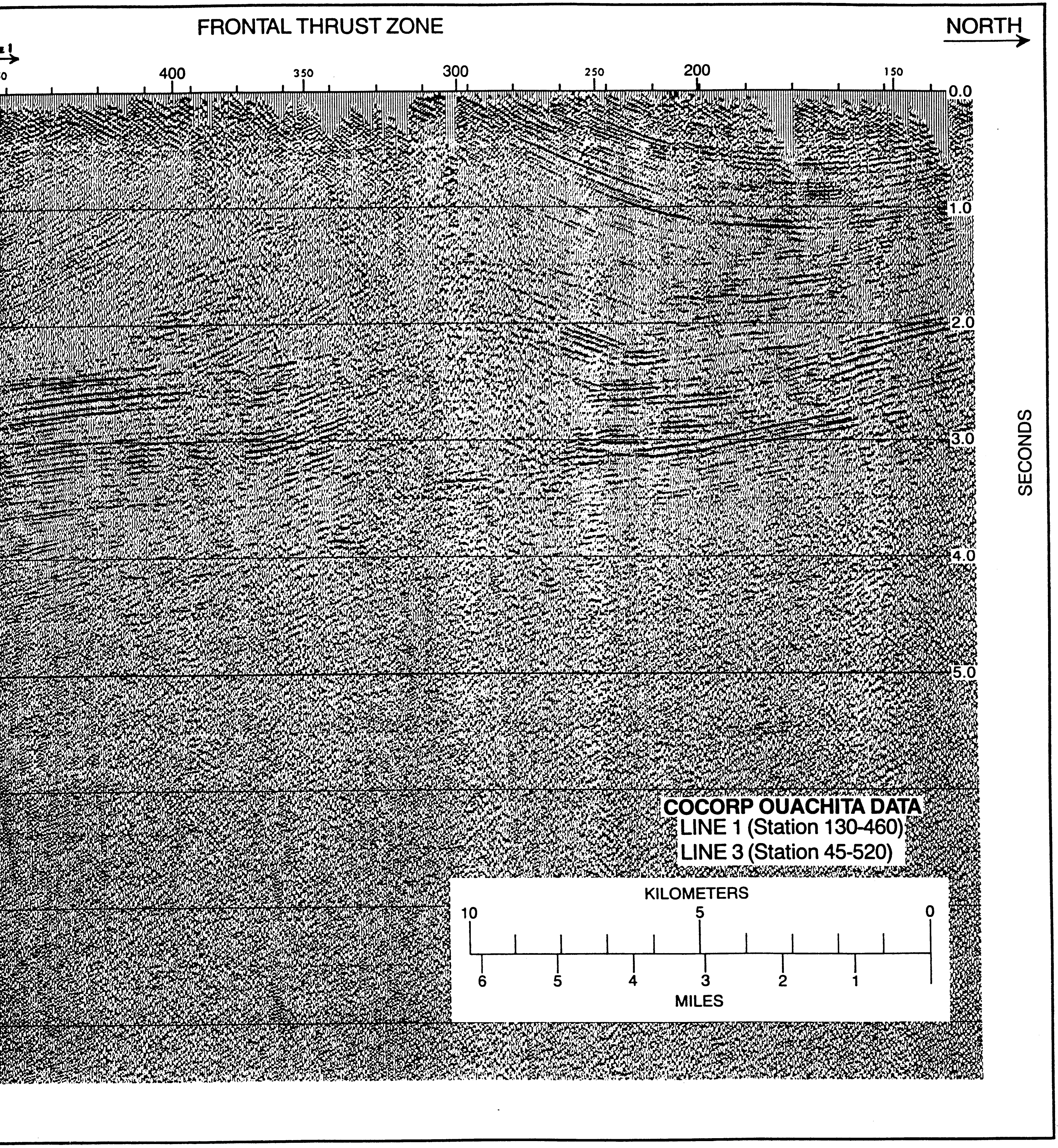
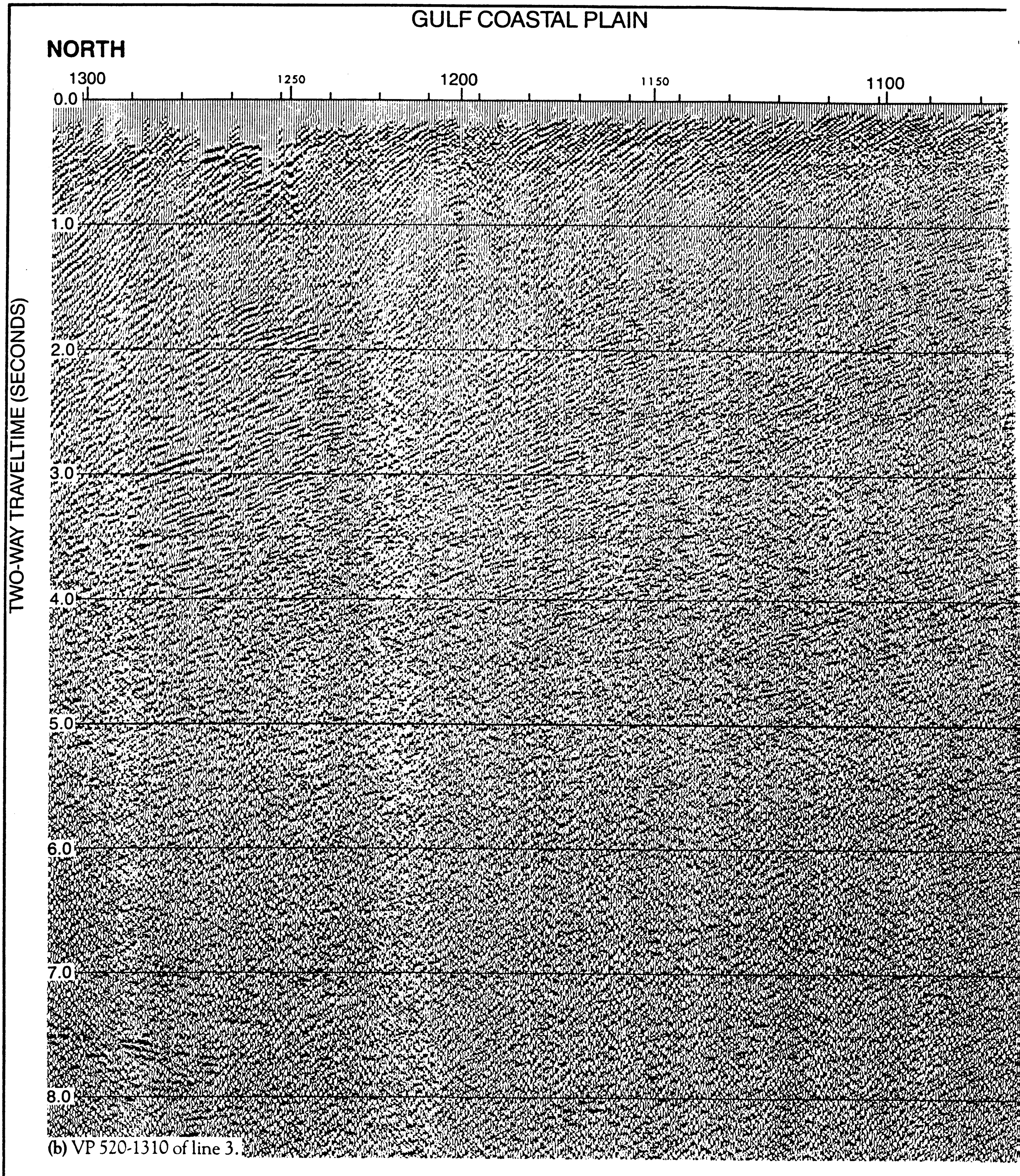


Figure 4: Upper 8.5 secs of unmigrated time sections for the north-south (dip) lines. Sections one-to-one vertical exaggeration for a seismic velocity of 5.0 km/sec (about 16,000 ft/sec). **(a)** VP 130-460 of line 1 and VP 45-520 of line 3. Cross line 2 was used to tie the ends of the two lines together as shown.



s one-to-one vertical exag-
d VP 45-520 of line 3.

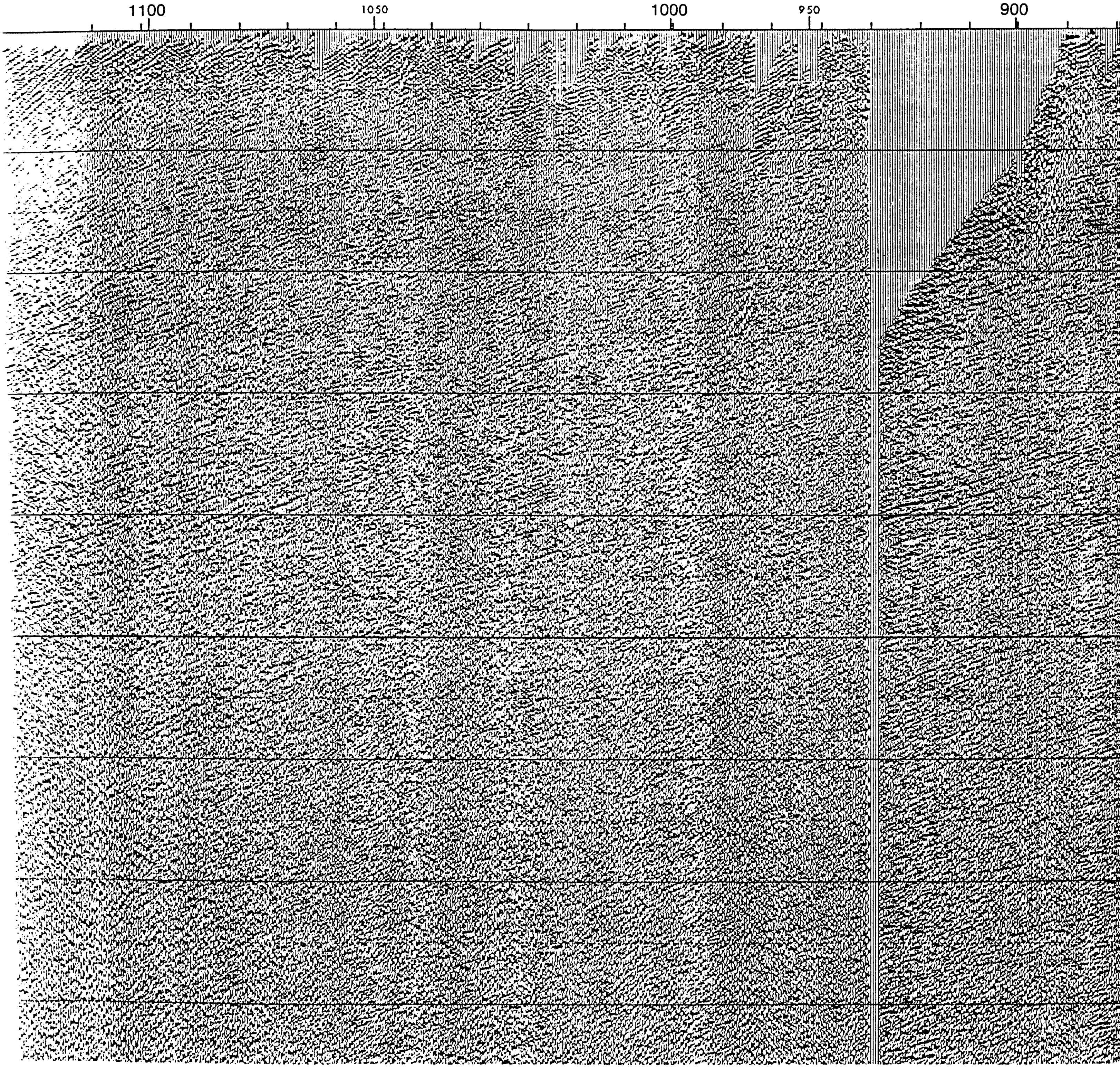

FRONTAL THRUST ZONE
NORTH
400
350
300
250
200
150
0.0
1.0
2.0
3.0
4.0
5.0
SECONDS
COCORP OUACHITA DATA
LINE 1 (Station 130-460)
LINE 3 (Station 45-520)
KILOMETERS
10
5
0
6
5
4
3
2
1
MILES



(b) VP 520-1310 of line 3.

Lillie, Nelson, de Voogd, Oliver, Brown and Kaufman

SOUTHERN OUACHITAS



Detached Sediments / Decollement Tectonics (A-Subduction)

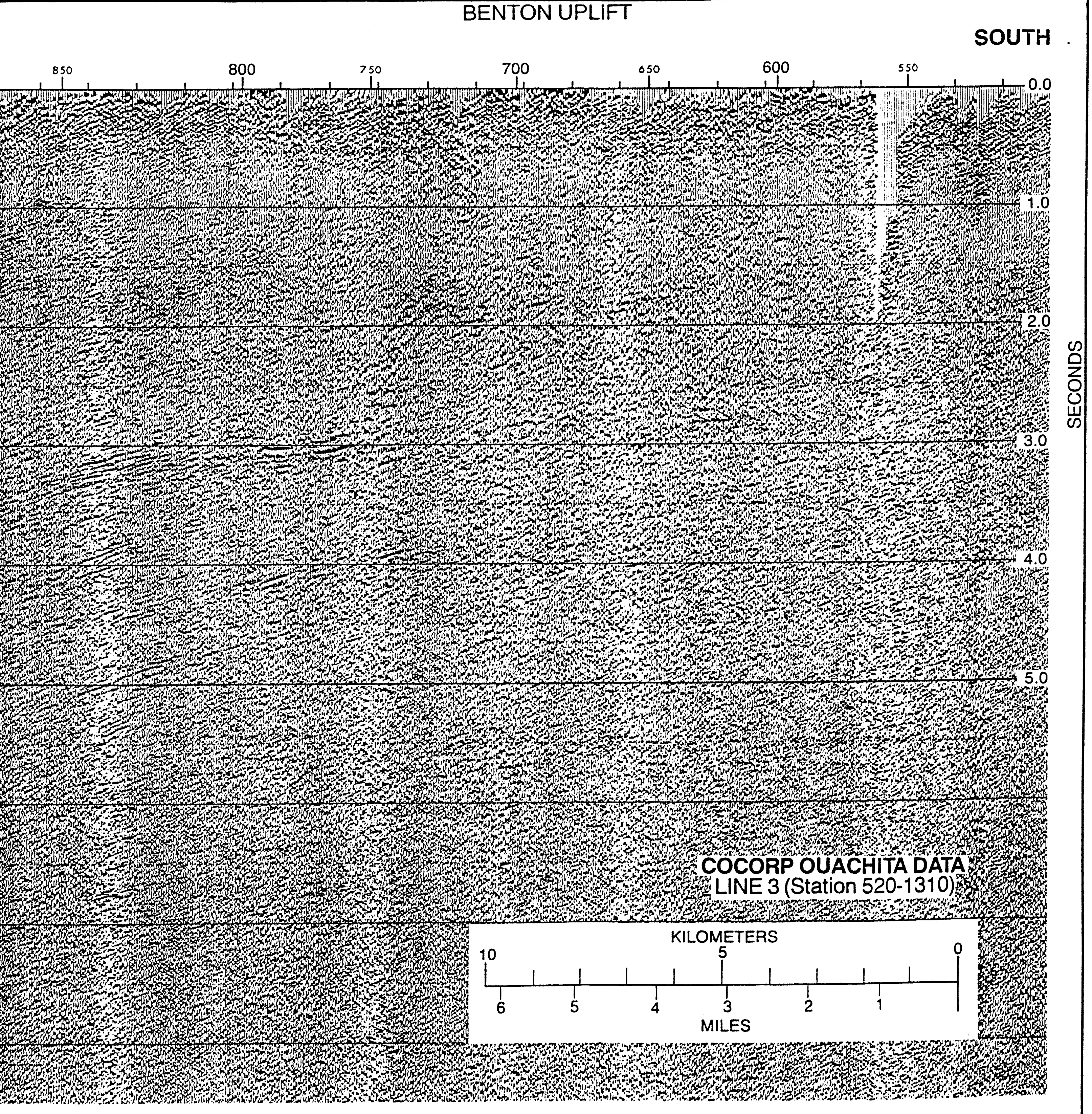

BENTON UPLIFT
SOUTH
850
800
750
700
650
600
550
0.0
1.0
2.0
3.0
4.0
5.0
SECONDS
COCORP OUACHITA DATA
LINE 3 (Station 520-1310)
KILOMETERS
10
5
0
6
5
4
3
2
1
MILES

Fig 4, p. 6 of 6