

STUDY OF SOUTHERN OKLAHOMA AULACOGEN, USING COCORP DEEP SEISMIC-REFLECTION PROFILES

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INTRODUCTION

The Southern Oklahoma Aulacogen, the type aulacogen in the United States, is a major structural feature in the southern Midcontinent region. For the purposes of this paper, I define the aulacogen in the region of the COCORP¹ traverse as including the Hardeman Basin, Wichita Mountains, and Anadarko Basin, although there is some confusion in the literature over the exact use of the term and the age of onset of the aulacogen. The Anadarko Basin is the deepest basin in the North American craton (Ham and Wilson, 1967) and the site of intensive oil and gas exploration since the turn of the century. However, relatively little is known of the deepest parts of the basin, especially in the complexly deformed area close to the Wichita Uplift; knowledge of the uplift itself is based on relatively shallow well data and studies of exposed igneous rocks.

From such data, Ham and others (1964) proposed that the first major event in the evolution of southern Oklahoma (apart from the formation of the crystalline basement) was Early Cambrian subsidence of a trough, centered beneath the present Anadarko Basin and Wichita Uplift, and thought to be filled largely with clastic metasediments (Tillman Metasedimentary Group). This trough was intruded by gabbros and overlain by basalts, subjected to uplift and erosion, and further overlain by rhyolites and intruded by granites. These intrusive rocks consolidated into what is now the Wichita block. Subsequent (Late Cambrian–Permian) subsidence was concentrated north of the Wichita block, and deformation culminated in the Pennsylvanian with uplift of the Wichita block and subsidence to the north, forming what are now the Wichita Mountains and Anadarko Basin. Thus, the present mountains and basins all lie within Ham and others' (1964) inferred Early Cambrian trough. Subsequent radiometric dating (Muehlberger and others, 1967) suggests that the Tillman Group is at least 1,000 m.y. old, or twice as old as the granites in the Wichita Mountains (500–525 m.y.; Ham and others, 1967), thus raising questions about the significance of the Tillman Group in the Paleozoic structural evolution of southern Oklahoma.

Hoffman and others (1974) interpreted Ham and others' (1964) evolutionary scheme in a plate-tectonic framework, suggesting that the inferred Early Cambrian trough formed during an ex-

tensional episode in which continental crust to the east and southeast rifted completely away from the North American craton. Although the southern Oklahoma trough failed to extend very far (a "failed rift arm"), the region continued subsiding through most of Paleozoic time. The culmination of deformation in the Pennsylvanian was related to closure of the arms that rifted successfully, and formation of the Ouachita belt. This final deformation of the Southern Oklahoma Aulacogen has been considered by most workers (for example, Harlton, 1963, 1972; Wickham, 1978) to be due to vertical or strike-slip movements along predominantly high-angle faults.

COCORP deep seismic-reflection profiling was carried out in southwestern Oklahoma to study the deep structures of the aulacogen and to determine its structural development. Three new aspects of the aulacogen are inferred from the data: (1) it is aligned along the northern margin of a hitherto unknown Proterozoic basin; (2) crustal extension occurred in late Precambrian–Early Cambrian time, with normal faulting in what is now the deepest part of the Anadarko Basin; (3) major crustal shortening occurred in Pennsylvanian time, causing the Wichita Uplift to overthrust the Anadarko Basin along moderately dipping faults. Listric thrust faulting and hanging-wall anticlines formed in the sedimentary rocks of the Anadarko Basin, which at this time was probably subsiding from thrust-loading of its southern margin. These interpretations thus suggest significant revision of ideas of the basement structural framework and style of deformation of the aulacogen.

LOCATION OF COCORP LINES

The COCORP data were recorded in three phases (figs. 24, 25): (1) the first COCORP surveys ever conducted, in 1975, in the Hardeman Basin, Hardeman County, Texas (Oliver and others, 1976); (2) in 1979, continuing the 1975 work farther north, in the Hardeman Basin and through the Wichita Mountains (Brewer and others, 1981); (3) in 1980, extending the surveys still farther north across the Frontal Fault system of the Wichita Mountains and through the Anadarko Basin, ending in Northern Dewey County, Oklahoma (Brewer and others, 1982). The surveys thus extend across the width of the Southern Oklahoma Aulacogen. The data were collected by the Vibroseis² technique, and field configurations and recording parameters were similar to those described by Oliver and others (1976).

¹ COCORP is an acronym denoting Consortium for Continental Reflection Profiling.

² Trademark of Continental Oil Co.

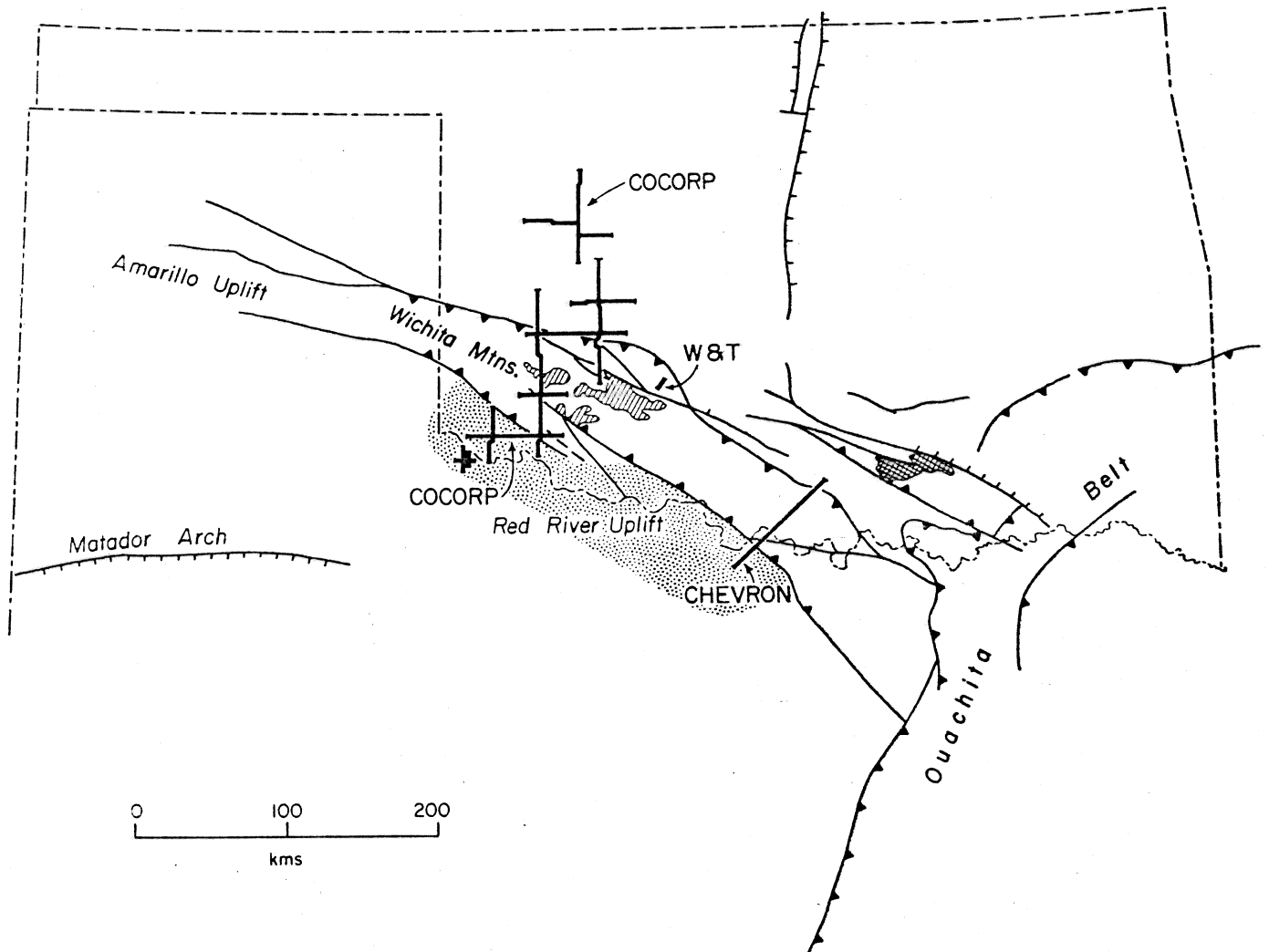


Figure 24. Major fault trends of Southern Oklahoma Aulacogen and surrounding areas of southern Midcontinent, with locations of COCORP traverse and Chevron regional seismic line. Shading patterns: diagonal stripes, granite and gabbro outcrops in Wichita Mountains; crosshatched, 1,370–1,400–m.y. old granites and granite gneisses of Arbuckle Mountains (Bickford and Lewis, 1979); dots, inferred minimum extent of relatively undisturbed Precambrian layering south of Wichita Mountains. *W & T*, location of Widess and Taylor (1959) seismic data recorded in Frontal Fault system of Wichita Mountains. These data were interpreted (Ham and others, 1964) to indicate extensive pre-Reagan Sandstone layered rocks under Anadarko Basin. These data might, however, represent thrusting along Wichita Mountain front, along moderately dipping faults.

RESULTS OF COCORP STUDIES

1. A Proterozoic basin inferred south of the Wichita Mountains.

This basin is inferred from pronounced, high-amplitude, laterally continuous and relatively undeformed layering in the Precambrian crust (fig. 26), seen on all COCORP data recorded south of the Wichita Mountains (Brewer and others, 1981). The layering extends over an area of at least 2,500 km² (based on the extent of COCORP data) and probably much more, and in places lies as deep as 13 km. The character of the layering suggests depositional processes, because there are suggestions of angular unconformities and onlapping and downlapping rela-

tionships, although other possibilities, such as layered igneous bodies (for example, Lynn, 1980), cannot be ruled out. If the depositional hypothesis is correct, the layering is most likely due to clastic sediments and felsic volcanics (probably metamorphosed to an unknown degree), since these rocks are widespread in the southern Midcontinent and in many areas are relatively undeformed (for example, Denison and others, 1981). Other rock types, such as basalts or carbonates, also could be present. A well drilled just south of the most southerly COCORP lines penetrated a micrographic microgranite porphyry, dated at $1,265 \pm 40$ m.y. (R. E. Denison, unpublished data), and farther north (for example, VP's 1–400 of line 1, fig. 26), Tillman metasediments lie at the top of the basement (inferred from pl. 1, Ham and

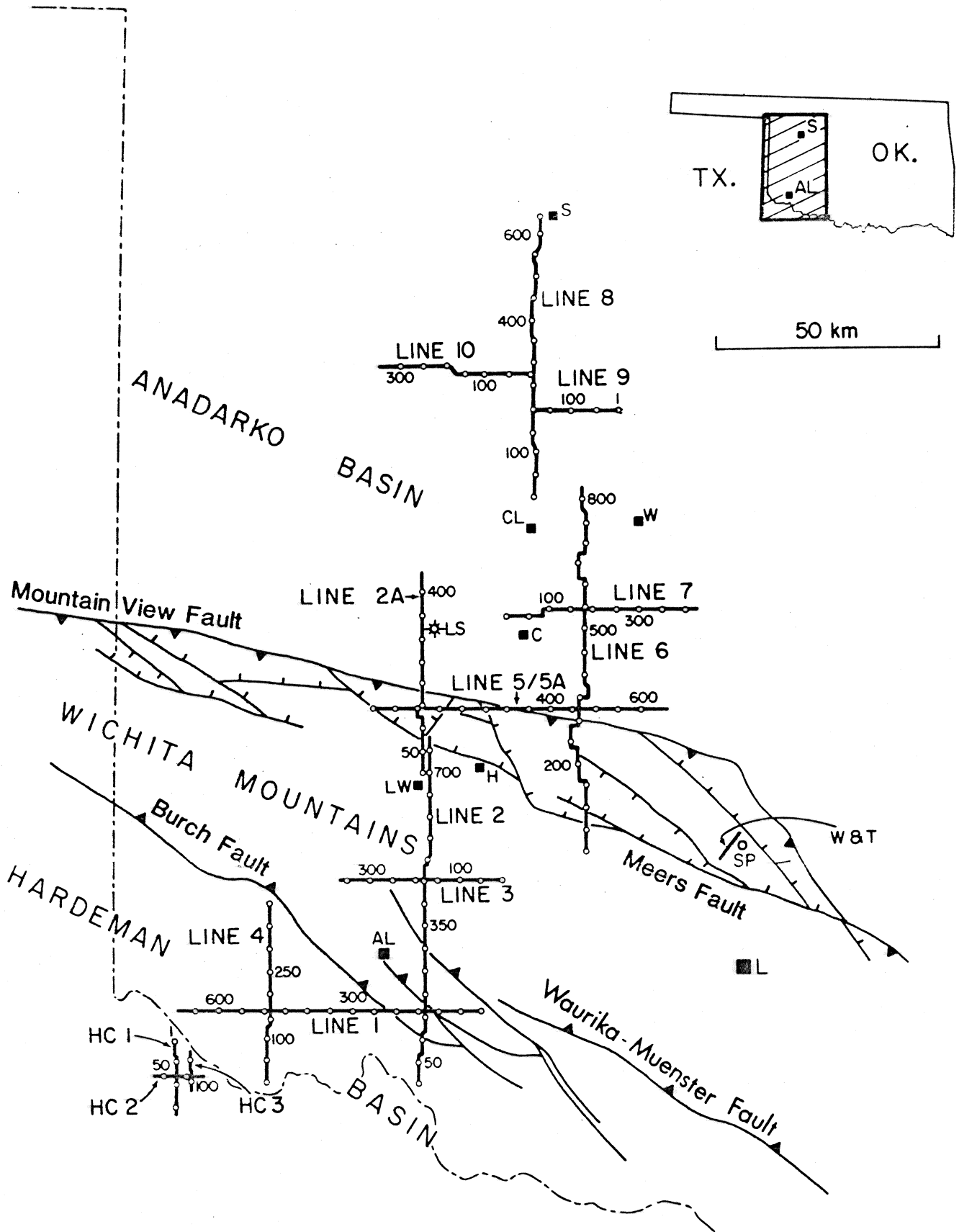


Figure 25. Location of COCORP deep seismic-reflection profiles in southwestern Oklahoma. Lines HC1–HC3 are original Hardeman County, Texas, data (Oliver and others, 1976). Numbers along profiles are ground stations or vibrator points (VP's). Towns are L, Lawton; LW, Lone Wolf; AL, Altus; H, Hobart; C, Cordell; CL, Clinton; W, Weatherford; S, Seiling. Wells are LS, Lone Star 1 Rogers; SP, Standing 1 Perdasofy. W & T, Widess and Taylor (1959) seismic data.

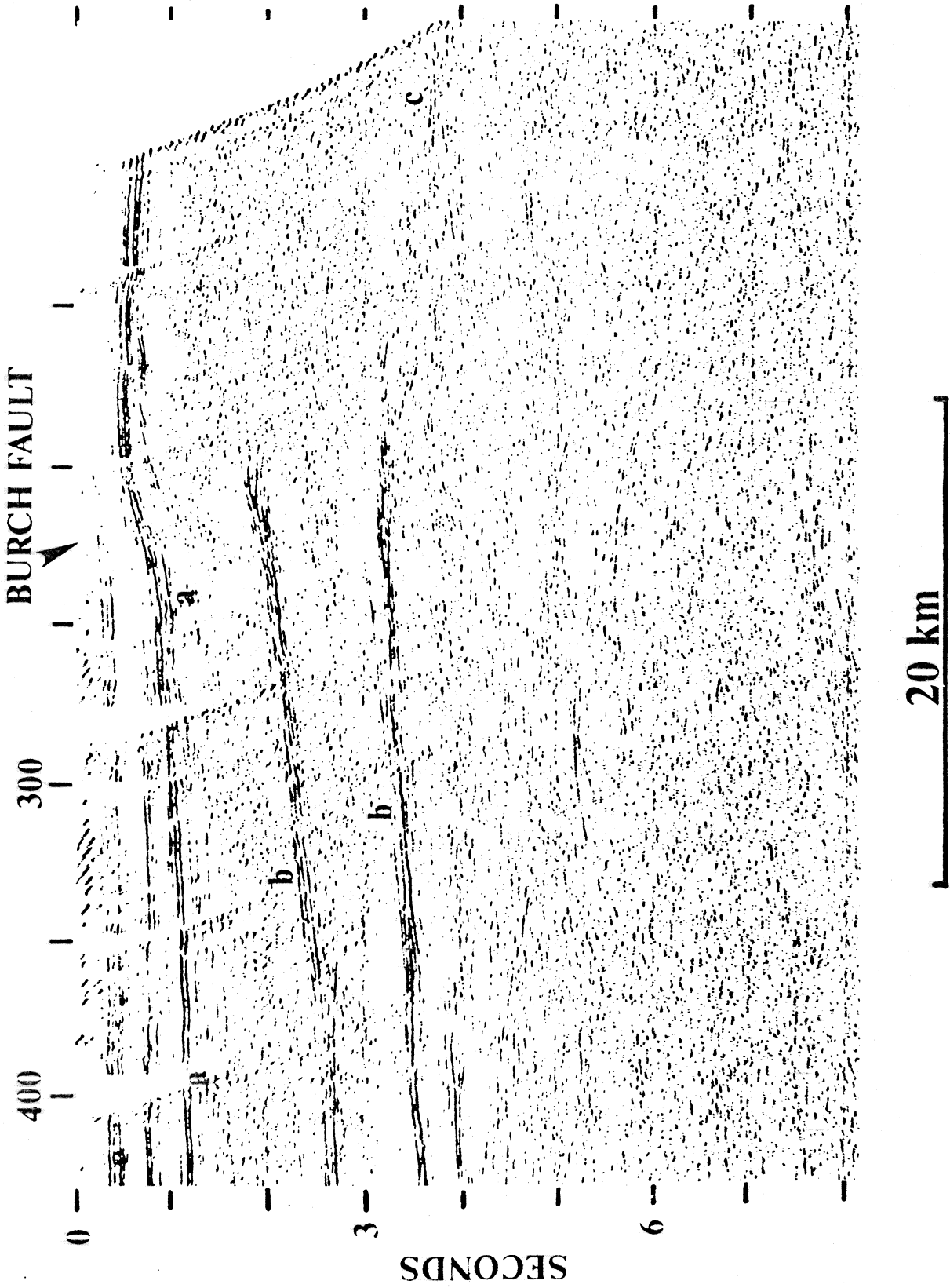


Figure 26. Detail of COCORP seismic data from Oklahoma line 1. Section is unmigrated and approximately 1:1 scale. Numbers along top are ground stations. Base of Paleozoic sedimentary section of Hardeman Basin marked by a; distinctive Precambrian layering south of Wichita Mountains marked by b. Note truncation at southern margin of Wichita Mountain block, which has been reactivated by Pennsylvanian Burch Fault in a reverse dip-slip sense. Original truncation thought to be due to late Precambrian-Early Cambrian normal faulting, because discontinuous events (for example, c), which also occur on south end of line 2, may represent remnants of Precambrian layering disrupted by faulting and by granitic rocks exposed in Wichita Mountains. If events such as c are not continuations of Precambrian layering, then distinctive truncation is most likely due to reverse faulting. To convert travel-time in seconds to approximate depth in kilometers, multiply by 3.

others, 1964). Together with other scattered well data, the most likely age of the basement layering is 1,200–1,400 m.y., although this is not a very well-constrained estimate (Brewer and others, 1981).

This Precambrian layering is seen also on a Chevron U.S.A., Inc., regional seismic line recorded 150 km to the southwest (fig. 24) (J. Fairborn, personal communication, 1981), which suggests that the inferred Proterozoic basin extends along the south side of the Wichita Mountains. North of the mountains, under the Anadarko Basin, there is no seismically distinguishable layering, in the Precambrian crust, of the thickness and character of that south of the mountains. Although this is conceivably due to total attenuation of seismic energy in the thick Paleozoic sedimentary succession, I feel it is more likely that the northern boundary of the Proterozoic basin underlies the Wichita Mountains. This northern boundary is probably fault-bounded, since basins of similar age elsewhere in the world are commonly bounded in this way (Salop, 1977).

The Precambrian layering is abruptly truncated along the south side of the Wichita Mountains (fig. 26). This truncation, seen in both the COCORP and Chevron data, occurs coincidentally with the trend of Pennsylvanian faults along the south side of the mountains (Burch and Waurika–Muenster Faults). The magnitude and sense of offset of the Precambrian layering cannot be explained just by Pennsylvanian fault movements (about 1 km, in a reverse dip-slip sense), suggesting that Precambrian or Cambrian (that is, pre-basal Upper Cambrian Reagan Sandstone) faulting, perhaps in conjunction with intrusions of granitic composition, caused the truncation. The COCORP data suggest that this faulting was normal, with downthrow to the north, because discontinuous seismic events occur within the Wichita block (north of the Burch Fault), which could then be explained as remnants of the Precambrian layering. However, equivalent events are not seen in the Chevron data, which might therefore be more consistent with major reverse faulting, with upthrow to the north. The normal-faulting interpretation is tentatively favored. Note that this prominent truncation does not correspond to the northern margin of the Proterozoic basin (assumed to be fault-bounded, but downthrown to the south), which is inferred to be farther north, under the main part of the Wichita Uplift.

The Meers Quartzite, found as inclusions in the granites and rocks of the Glen Mountains Layered Complex of the Wichita Mountains (Ham and others, 1964), is interpreted to be remnants of the Proterozoic basin. Ham and others (1964) suggested that the Meers Quartzite is part of the Tillman Group. The Tillman Group may comprise part of the Precambrian layering south of the Wichita Mountains, and my interpretation of the pre-Late Cambrian structural framework differs from Ham and others in that I believe that a large, pre-Late Cambrian basin existed south of and under the Wichita Mountains, but not farther north, under the Anadarko Basin.

2. Thrusting along the northern flank of the Wichita Uplift.

Major thrusting of the Wichita Mountains over the southern margin of the Anadarko Basin is suggested from dipping seismic events that can be traced from the subcrop of faults of the Frontal Fault system. The Mountain View Fault, the northern boundary of the Frontal Fault system with the relatively undeformed sedimentary rocks of the Anadarko Basin, is imaged best and can be traced to approximately 20–24 km in depth, with an approximate average south-southwesterly dip of 30°–40° (figs. 27, 28). The southern boundary of the Frontal Fault system with the massive crystalline rocks of the Wichita Mountains (the Meers Fault) is less well imaged, but it may have a similar dip. Farther south, in the middle of the Wichita Mountains, other events occur in the upper few kilometers with a dip subparallel to the Mountain View Fault. Possibly these are other thrusts, although there is little evidence for them in the exposed igneous rocks (Gilbert, 1982). Few coherent reflections are recorded from sedimentary rocks within the Frontal Fault system, which are known to be intensely folded and faulted in the upper 2–3 km (Harlton, 1963, 1972; Takken, 1968). The COCORP data are the first reported indications of the attitude and depth extent of the faults, which most workers have assumed to be nearly vertical at depth.

The dip of the faults suggests significant crustal shortening during Pennsylvanian uplift of the Wichita Mountains. Palinspastic reconstruction, based on the attitudes (poorly imaged) of the sedimentary rocks under the hanging walls of faults of the Frontal Fault system, suggests as much as 10–15 km, and perhaps more, of crustal shortening in the region of the COCORP profiles. This crustal shortening implies that subsidence of the Anadarko Basin during Pennsylvanian time was due largely to thrust-loading by the overthrust Wichita Mountains.

3. Normal faults and hanging-wall anticlines within the Anadarko Basin.

Sedimentary rocks are correlated from published well data, in particular the Lone Star 1 Rogers, which bottomed in carbonates of the Upper Cambrian–Lower Ordovician Arbuckle Group (Rowland, 1974). From extrapolations of the depth of the Upper Cambrian Reagan Sandstone (about 11.2 km; Rowland, 1974), there is apparently 1.5–2.5 km of seismically definable pre-Reagan Sandstone layering beneath the Anadarko Basin. Ham and others (1964) assumed that any such layering would be composed largely of Tillman metasediments and basalts; however, the thickness of this layering in the region of the COCORP profiles is much less than they suggested. The age of this layering is unknown, but it is probably either Middle Cambrian [as suggested by Ham and others (1964) from data from the Stanolind Perdasofpy well (fig. 25) in the Frontal Fault system] or perhaps similar to the inferred age of the Proterozoic

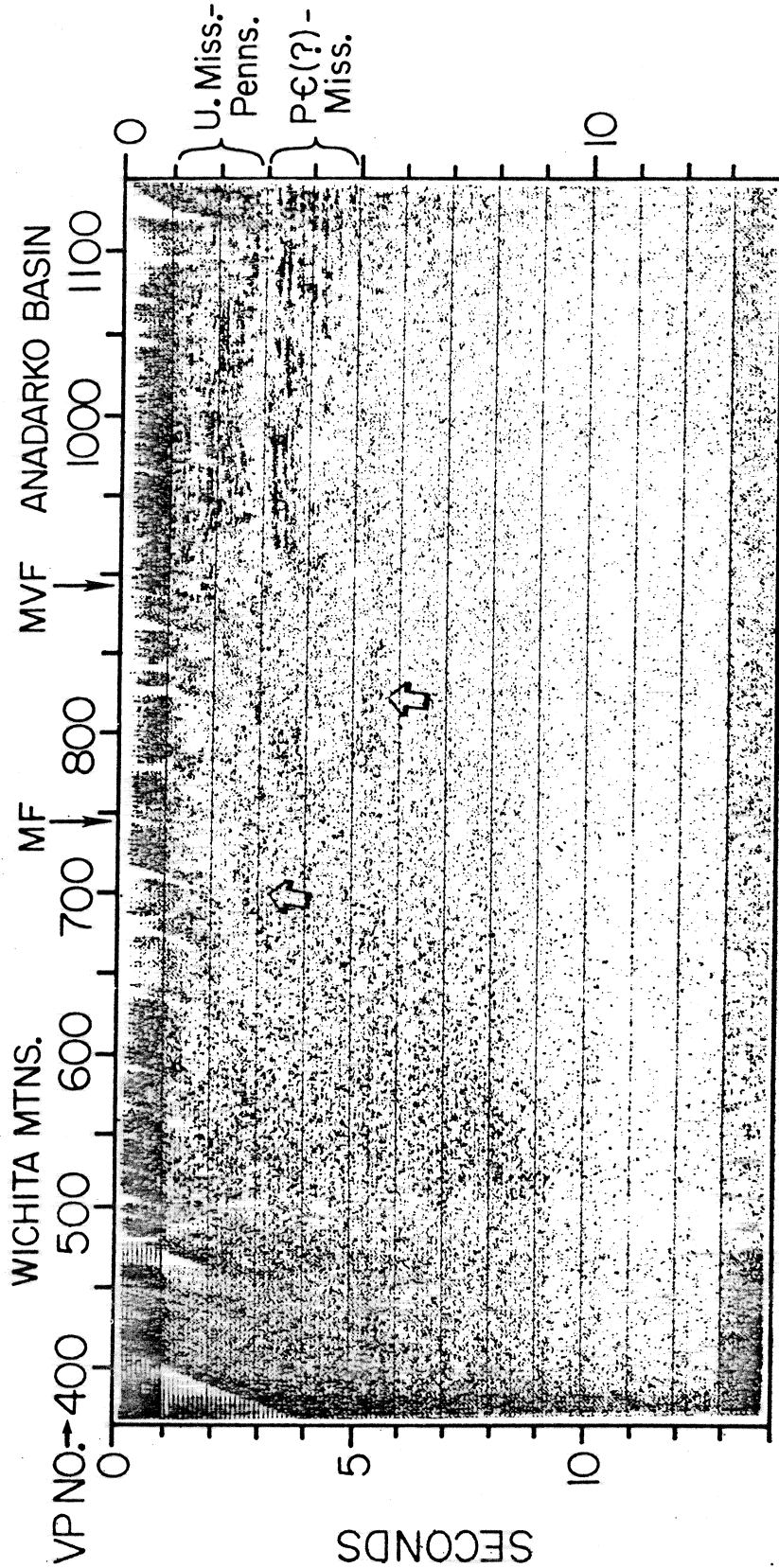


Figure 27. COCORP seismic data, Oklahoma line 2 (northern half) and 2A. Section is unmigrated and approximately 1:1 scale [100 VP's (stations) = 10 km]. Note that VP's 700-1100 are equivalent to stations 1-400 of line 2A (fig. 25). MF and MVF mark subcrop of Meers and Mountain View Faults. Band of events dipping to about 8 seconds under VP-500 is interpreted to be trace of Mountain View Fault. Note that layered sedimentary rocks of Anadarko Basin are well imaged away from mountain front, but their character rapidly deteriorates farther south. Discontinuous events marked by open arrows are interpreted as continuations of these sedimentary rocks in footwalls of Mountain View and Meers Faults. Disruption of their reflection character is probably due to faulting and perhaps to complex, near-surface structure, causing distortion of seismic energy. Cordell Anticline underlies VP-1000.

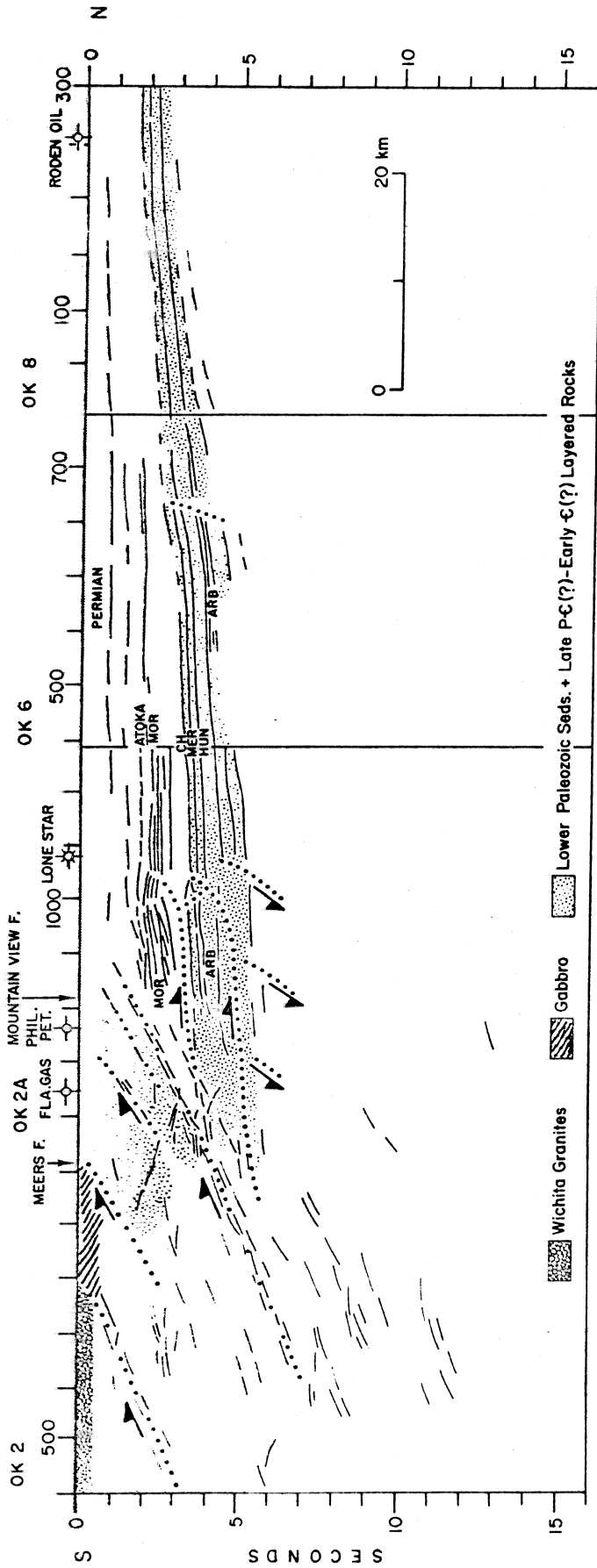


Figure 28. Interpretive line-drawing of (unmigrated) COCORP lines 2 (northern half), 2A, 6, and 8. Solid lines, seismic events (mostly reflections); dotted lines, interpreted faults with arrows indicating sense of motion. Sedimentary horizons are: ARB, Cambrian-Ordovician Arbuckle; HUN, Silurian-Devonian Hunton; MER, Mississippian Meramecian; CH, Mississippian Chesterian; MOR, Pennsylvanian Morrowan. Note interpreted normal faults at base of Anadarko Basin, and two levels of listric thrusting inferred to underlie Cordell Anticline (VP-1000). Evidence for lower level of thrusting is not as strong as for upper level.

basin south of the Wichita Mountains (1,200–1,400 m.y.).

The seismic character of the sedimentary rocks of the Anadarko Basin deteriorates close to the Wichita Mountain front, owing probably to wave propagation through Pennsylvanian-age granite wash, known to be a poor transmitter of seismic energy. The sedimentary rocks are inferred to extend deeply beneath the hanging wall of the Mountain View Fault (figs. 27, 28, 29), on the basis of reflections under the Lone Star well, which appear to step down to the south. These step-downs are interpreted as due to normal faults, which, on the basis of offsets in sedimentary reflectors, may have been active into Arbuckle Group time. There is little evidence for such faulting in the Arbuckle Group in places where it is exposed or has been drilled (R. E. Denison, personal communication, 1981). However, in the COCORP data, these inferred normal faults appear to be restricted to the deepest part of the Anadarko Basin, and possibly rocks from these regions have not been adequately sampled.

Anticlines occur higher in the sedimentary section (for example, Cordell Anticline). From seismic relationships, these are interpreted to be hanging-wall anticlines cored by listric thrust faults (figs. 28, 29; Brewer and others, 1982). These thrusts probably root in the Frontal Fault system and represent the response of the sedimentary layered rocks of the Anadarko Basin to crustal shortening and uplift of the crystalline rocks of the Wichita Uplift. This interpretation of these anticlines contrasts with earlier ideas of vertical or strike-slip movements along high-angle faults.

DISCUSSION: TIMING AND ORIENTATION OF PENNSYLVANIAN DEFORMATION

Structures of Pennsylvanian age along the Wichita trend are highly complex and are frequently cited as examples of left-lateral wrenching (for example, Groshong and Rodgers, 1978).

Uplift of the Arbuckle Mountains, which climaxed in early Virgilian time (Tomlinson and McBee, 1962), is usually interpreted as due to wrenching (Wickham, 1978; see Booth, 1981, for references), although Brown (1982) has shown that some structures might be equally consistent with folds and reverse faults that were formed possibly under lateral compression. The COCORP data suggest that movements on the Mountain View Fault and the listric thrust underlying the Cordell Anticline occurred mainly by the end of Atoka time, and the moderate dip and extent to depth of this fault are consistent with lateral compression normal to the Wichita trend at these times (R. E. Denison, personal communication, 1981). In this case, any later wrenching along the Wichita trend was probably along the fault

trends established by earlier thrusting. A test of this hypothesis is the timing of faults along the south side of the Wichita Mountains (Burch, Waurika–Muenster trend); these faults have a sense of slip and *en-echelon* pattern consistent with left-lateral wrenching. They should be mainly Virgilian in age, and paleogeographic maps (Tomlinson and McBee, 1962) indicate that whereas some deformation along this trend occurred in Atoka time, it was most pronounced in Virgilian–Missourian time. Although this timing is reasonably consistent with earlier overthrusting followed by later wrenching, the COCORP data might be equally consistent with oblique slip (combined wrenching and thrusting) in both pre-end of Atokan and Virgilian times.

CONCLUSIONS

These interpretations of the COCORP data imply that present structures in southern Oklahoma reflect severe crustal shortening during the final stages of evolution of the aulacogen. The aulacogen has passed through a cycle of deformation in which an ancient fault trend was reactivated, first owing to crustal extension and then to crustal shortening; thus it evolved in a manner similar to aulacogens described from the Russian and Siberian Platforms (Milanovskiy, 1981). These results, while not disproving the crustal updoming and radial-rifting origin of aulacogens proposed by Burke and Dewey (1973), raise the possibility that the aulacogen might have started by reactivation of the ancient fault trend under some alternative tectonic scheme.

These seismic data have started to reveal some of the fascinating details of the complex structural evolution of southern Oklahoma, yet they give little information on the equally fascinating igneous rocks that are exposed in the Wichita Mountains. Only by integrating surface and well studies with seismic and other geophysical evidence will the evolution of the basement rocks and their sedimentary cover be fully understood.

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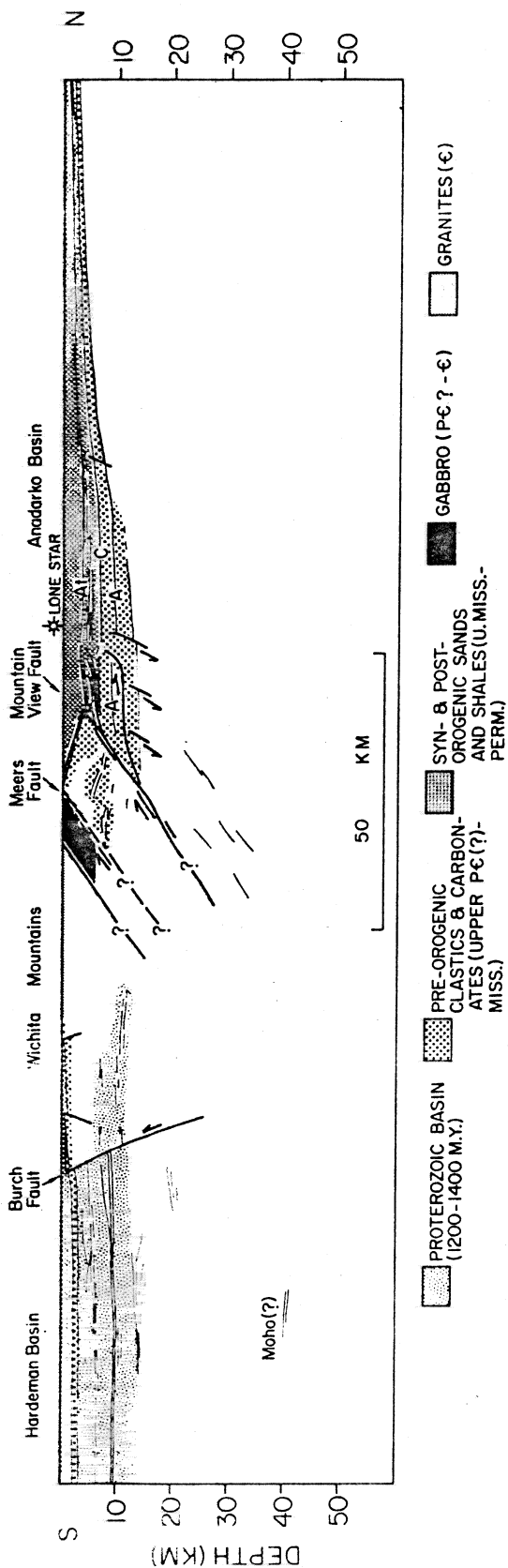


Figure 29. Section across Southern Oklahoma Aulacogen, based on COCORP data. Note (1) Proterozoic basin inferred to lie south of, and partially beneath, Wichita Mountains; (2) interpreted normal faulting near base of Anadarko Basin; (3) thrust nature of Mountain View and Meers Faults; (4) listric thrust faults in Anadarko Basin. Lone Star, position of Lone Star 1 Rogers. Sedimentary horizons are: A, Cambrian-Ordovician Arbuckle; C, Mississippian Chesterian; At, Pennsylvanian Atokan.

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