

COCORP profiling across the Southern Oklahoma aulacogen: Overthrusting of the Wichita Mountains and compression within the Anadarko Basin

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ABSTRACT

COCORP (Consortium for Continental Reflection Profiling) deep reflection profiles recorded across the Wichita Mountains and Anadarko Basin suggest that significant crustal shortening occurred in the final stages of the evolution of the Southern Oklahoma aulacogen. The crystalline rocks of the Wichita Mountains were thrust in Pennsylvanian time northeastward over sedimentary rocks of the Anadarko Basin along a series of faults with moderate (average 30° to 40°) and southwesterly dips. These faults can be traced possibly as deep as 20 to 24 km. Listric thrust faults and hanging-wall anticlines developed in the sedimentary rocks of the basin. These features contrast with conventional interpretations of Pennsylvanian structures as the result of predominantly vertical movements along high-angle faults, and they suggest that Pennsylvanian downwarping of the Anadarko Basin was at least partially due to thrust loading. Truncations of reflections from Cambrian-Ordovician rocks in the deepest part of the basin suggest normal faulting, which would support ideas of an early extensional stage in the aulacogen cycle. The distinctive Precambrian layering seen on earlier COCORP data recorded south of the Wichita Mountains cannot be recognized under the Anadarko Basin, and the Proterozoic basin containing that layering may have been bounded on its north side by a Precambrian fault. This inferred fault was probably twice reactivated during formation of the Southern Oklahoma aulacogen—once during late Precambrian(?)–Early Cambrian extension, and again during Pennsylvanian compression. The popular view that aulacogens originated from radial rifting of updomed, homogeneous continental crust is probably too simplified, and a more important constraint on their location and development may be the nature of pre-existing lines of weakness.

INTRODUCTION

The Southern Oklahoma aulacogen is a major tectonic element of the southern midcontinent of the United States (Fig. 1). Despite much detailed work on surface or shallow subsurface rocks (e.g., Ham et al., 1964; Powell et al., 1980) and thousands of wells drilled for oil and gas, there is very little published information on the fundamental structures and their evolution. COCORP (Consortium for Continental Reflection Profiling) surveys in southern Oklahoma started in 1979, and results from these surveys (Fig. 2, lines 1 through 5), recorded in the Wichita Mountains and Hardeman Basin, are discussed in Brewer et al. (1981). We present results from additional surveys in 1980 (Fig. 2, lines 2A, 5A, 6 through 10), which continue across the

northern flank of the mountains and traverse the Anadarko Basin, thus completing a north-south profile across the aulacogen. The new COCORP data reveal many previously unreported aspects of the Pennsylvanian deformation of the area, in particular that late-stage structures may reflect crustal shortening along moderately dipping thrust faults—in contrast to previous ideas of mainly vertical movements along high-angle normal or reverse faults (e.g., Ham et al., 1964; Harlton, 1963, 1972; Takken, 1967). In this respect, and because of the evidence of reactivation of much earlier features, this aulacogen appears to conform closely to cycles of development suggested for aulacogens in the Russian and Siberian platforms (Milanovsky, 1981).

There is some confusion over the exact definition of the Southern Oklahoma aulacogen. Shatski (1946) called the trend of basements and uplifts in southern Oklahoma a “transverse boundary structure,” later referring to these as aulacogens

(Shatski and Bogdanov, 1961), or furrow-like complicated structures lying between two platform areas similar to each other (E. E. Milanovsky, 1982, personal commun.). However, studies by Ham et al. (1964) showed that basement rocks previously considered to be the floor of the Southern Oklahoma aulacogen actually included a metagraywacke (Tillman metasediments) found in wells on the south side of the Wichita Mountains and under the Hardeman Basin, which, they thought, indicated a previously unrecognized late Precambrian or Early Cambrian trough. They suggested that igneous activity occurred in this trough in the Early to Middle Cambrian, with gabbros and granites intruding and consolidating what is now the Wichita Mountain block, while farther north only basalts and rhyolites were emplaced in the trough where it later became the site of extensive Paleozoic subsidence. This Paleozoic basin was intensely disrupted in the Pennsylvanian when the Wichita Mountains, Anadarko Basin, and

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other uplifts and basins of the Wichita trend (Fig. 1) were formed. More than 11.5 km of Cambrian-Permian sedimentary rocks were deposited in the region of what is now the Anadarko Basin, compared to about 3 km on the surrounding craton (Ham, 1969).

The ideas of Ham et al. (1964) were adopted by Burke and Dewey (1973) and Hoffman et al. (1974) to explain aulacogens as "failed" rift arms at re-entrants in passive plate margins later reactivated during continental collision. In southern Oklahoma, the extent of the failed arm should be defined by the distribution of Tillman metagraywackes, but several problems then arise: (1) the known area of metagraywackes is restricted to the south side of the Wichita Mountains (Plate I of Ham et al., 1964), (2) their thickness and extent under the Anadarko Basin, as inferred from the COCORP data, are much less than suggested by Ham et al. (1964), and (3) scattered age data suggest that they are more than 1,000 m.y. old (Muehlberger et al., 1967; Denison et al., 1981). Thus, the exact configuration of the failed arm, and

hence the boundaries of the aulacogen, is questionable. The COCORP data suggest that the Tillman metasediments may instead belong to a much earlier Proterozoic basin inferred to lie south of the Wichita Mountains (Brewer et al., 1981), in which case the aulacogen is restricted to the site of Paleozoic subsidence, probably concentrated in the area of what is now the Anadarko Basin and Wichita Mountains.

SUMMARY OF RESULTS FROM COCORP DATA COLLECTED IN 1979

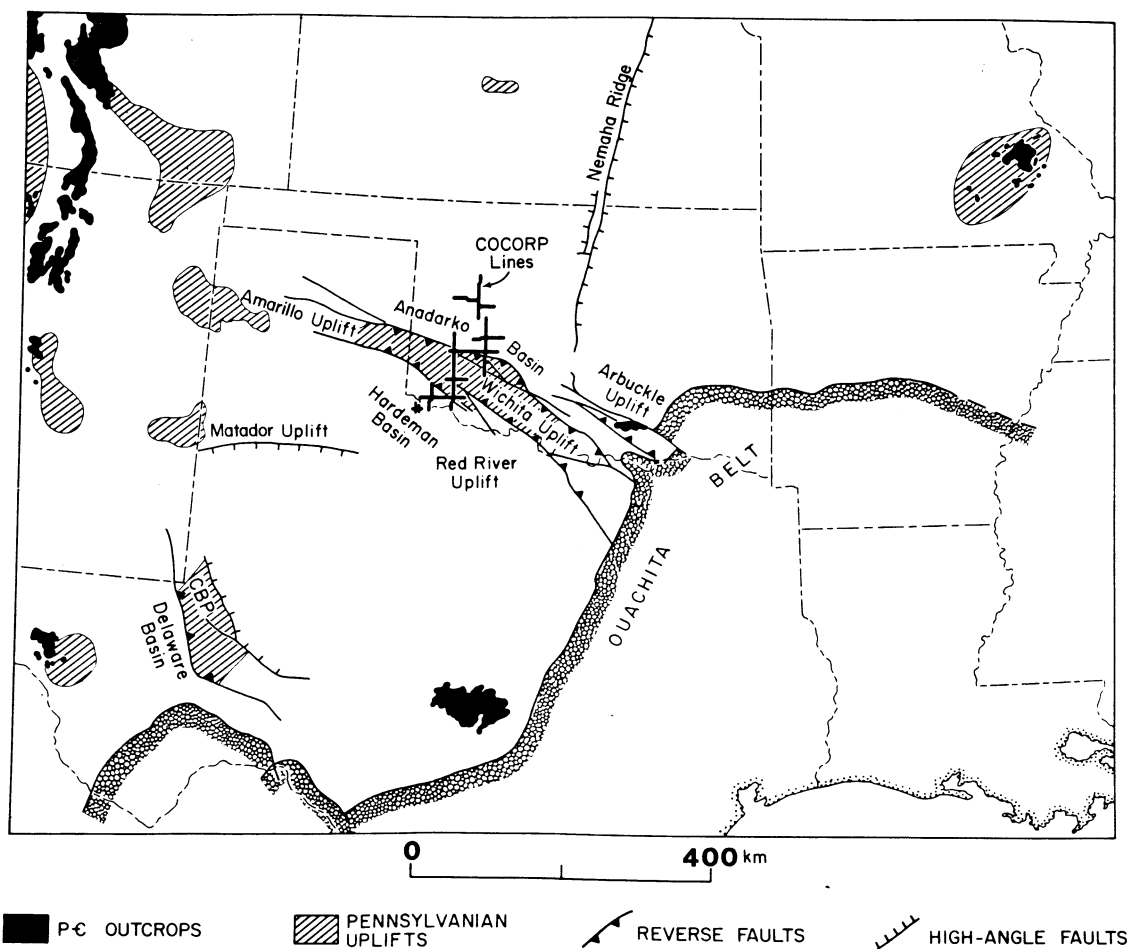
These data show that Precambrian trends were probably important for the configuration and development of the aulacogen. The Precambrian crust south of the Wichita Mountains is clearly layered to depths of about 13 km, probably the expression of a Proterozoic basin 1,400 to 1,200 m.y. old there (Brewer et al., 1981), although layered igneous bodies have also been proposed (Lynn, 1980). The distinctive layered sequence is truncated on the south side of the Wichita Mountains, but discontinuous events suggest that remnants

may still be present under the mountains. This truncation is probably due to Precambrian or Early Cambrian normal faulting, perhaps in conjunction with granitic intrusions, although reverse faulting is also possible (Brewer et al., 1981). The faults were reactivated in a reverse dip-slip sense in Pennsylvanian time.

RESULTS OF SECOND PHASE OF COCORP PROFILING IN 1980 Absence of Thick Precambrian Layering under Anadarko Basin

Line 2-2A (Fig. 3), running from the Wichita Mountains into the Anadarko Basin, shows that the distinctive Precambrian layering south of the Wichita Mountains is not seen under the Anadarko Basin. Sedimentary rocks in the basin were identified using the section in the Lone Star Rogers 1 well (LS, Fig. 2), which bottomed at -8.9 km in Upper Arbuckle Group Limestone of Ordovician age. Data from this well suggest that the Phanerozoic section in the Anadarko Basin is about 11.2 km thick (Rowland, 1974). Correlations of the deepest layered reflections on

Figure 1. Southern mid-continent of U. S. with location of COCORP lines. Wichita trend (consisting of, among other uplifts and basins, Wichita and Amarillo Uplifts and Anadarko Basin) strikes at high angle from Ouachita overthrust belt (formed about same time; Tomlinson and McBee, 1959) and can be traced into Colorado. Delaware Basin is also thought to be a Paleozoic aulacogen (Shatski, 1946).



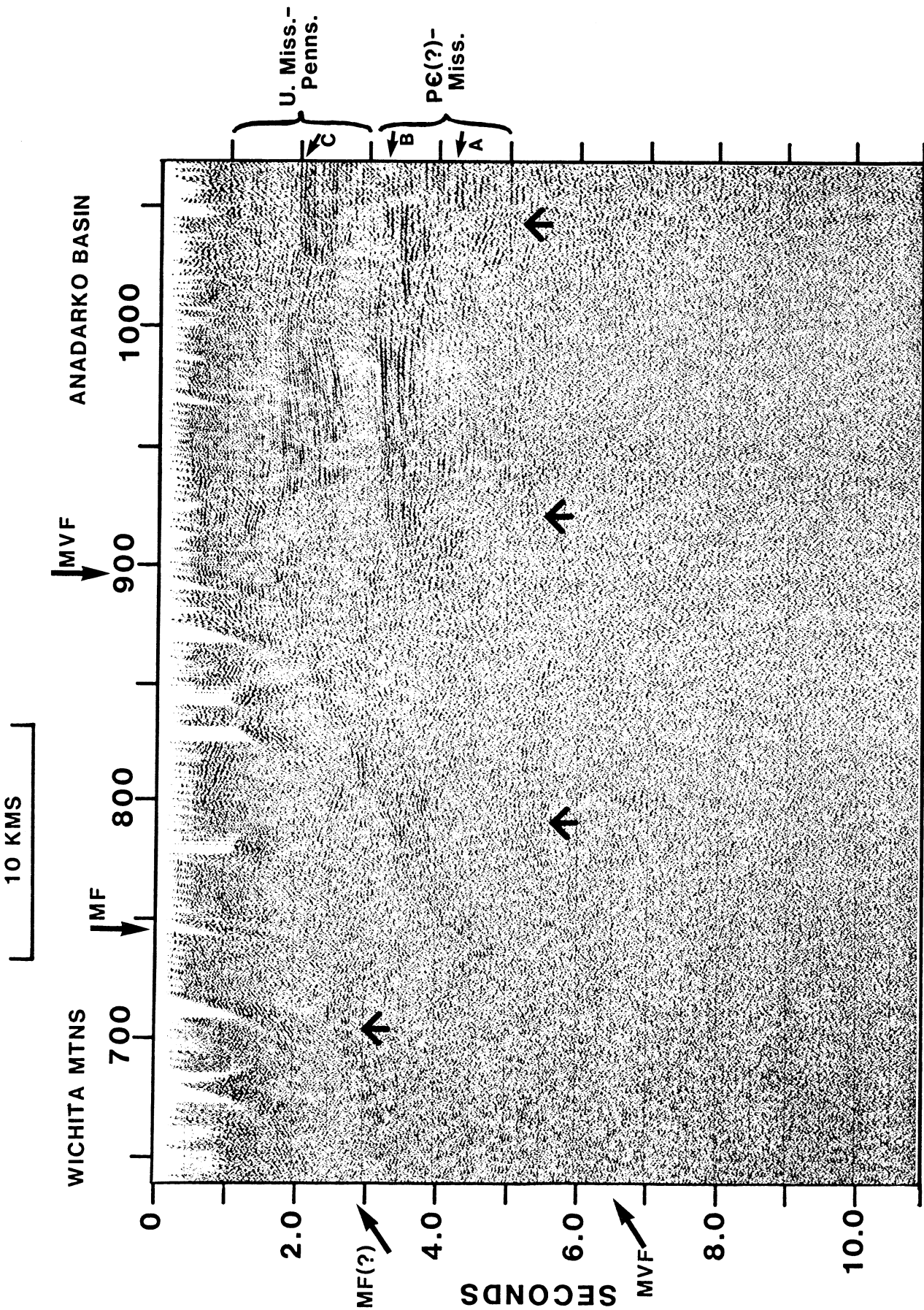


Figure 3. Details of COCORP line 2-2A. Lower arrows indicate deepest reflections from Anadarko Basin that can be traced under footwall of Mountain View fault (MVF). They are interpreted as lowermost sedimentary rocks of basin, probably highly disrupted under mountains. Arrow under VP 700 indicates possibly similar rocks in footwall of Meers fault (MF). Cordell anticline lies between 2 and 3 s under VP 1000. Sedimentary horizons: A = Cambrian-Ordovician Arbuckle, B = Mississippian Chester, C = Pennsylvanian Atoka. Figure is composite of lines 2 and 2A; VPs (ground stations) 700 through 1100 are equivalent to line 2A VPs 1 through 400 in Figure 2. Vertical scale is two-way travel-time in seconds; to convert to approximate depth in kilometres, multiply by 2.5 to 3. Vertical and horizontal scale approximately equal.

on the basis of possible reflections of similar dip to those from the Mountain View fault. Well data close to the mountain front show that sedimentary beds are in many places overturned and faulted (Harlton, 1963, 1972; Takken, 1967), and it is likely that structures in the Frontal Wichita Fault System are too complex to be clearly imaged with COCORP techniques.

Thrusting along the Wichita Mountain Front is also suggested by data from line 6 (Fig. 2) that crosses the subcrop of the Mountain View fault at about station 300 and of the Meers fault at about station 60. Although no clear fault-plane reflections are seen, discontinuous, subhorizontal reflecting horizons occur between stations 100 and 200, from 3.0 to 4.5 s, with a character somewhat similar to the lower Paleozoic sedimentary section in the undeformed part of the Anadarko Basin. A magnetotelluric survey recorded close to lines 6 and 8 shows a high conductivity zone, probably due to sedimentary rocks, at depth south of the Mountain View fault (Vozoff, 1972). These two surveys suggest that extensive overthrusting (10 to 20 km, on the basis of the southerly extent of the subhorizontal reflections) occurred in the region of line 6.

These interpretations of the COCORP data may be very significant for hydrocarbon exploration, for they suggest that sedimentary rocks lie deeper (6 to 7 km) in the Frontal Wichita Fault System than usually drilled and that sedimentary rocks are overthrust by crystalline rocks along the Meers fault, possibly by as much as 8 to 9 km. Although there is considerable structural variation along the front, a Chevron

regional seismic line 150 km to the southeast suggests similar thrusting, although with a much smaller offset. (J. Fairborn, 1981, personal commun.).

Normal and Reverse Faults in Anadarko Basin Close to Mountain Front

Truncation of Cambrian-Ordovician reflectors in the deepest part of the Anadarko Basin suggests down-to-the-basin normal faulting (Figs. 3, 4), although there is no evidence in outcrop for contemporaneous faulting of Ordovician strata (R. E. Denison, 1981, personal commun.) and other possibilities, such as near-surface effects on wave propagation, cannot be ruled out. Such faulting is consistent with models for an early rifting stage in the evolution of the Southern Oklahoma aulacogen (Hoffman et al., 1974).

The COCORP lines also cross the Cordell anticline (Fig. 3, VP1000), one of a series of anticlines of Pennsylvanian age in the Anadarko Basin. Thickening and arching of strata suggest that this is a hanging-wall anticline associated with blind listric thrust faults. Two levels of thrusting are inferred in this anticline: (1) in the Mississippian-Pennsylvanian Springer-Morrow sand-shale section above the Chester Limestone, where a hanging-wall anticline is associated with either erosional truncation or "toplap" (Mitchum et al., 1977), and (2) less clearly, at the base of the Cambrian-Ordovician Arbuckle limestone, where ramping over early normal faults may have occurred.

These listric thrusts accommodated shortening of the sedimentary section in response to overthrusting of the Wichita Mountains from the south. Offset of sedi-

mentary horizons suggests that these thrusts were active mainly in Morrow-Atoka time, during early stages of uplift of the Wichita Mountains (Tomlinson and McBee, 1959), although slight deformation of post-Atoka horizons suggests some movement in Late Pennsylvanian time.

DISCUSSION AND CONCLUSIONS

Deep seismic profiles indicate that structures in the Southern Oklahoma aulacogen are dominated by the effects of major Pennsylvanian crustal shortening (possibly 15 ± 5 km in the region of the COCORP lines). This crustal shortening, and possible late Precambrian-Early Cambrian extension, reactivated a much earlier zone of weakness. The shortening also caused inversion of the early Paleozoic basin, because the depocenter of this basin is now found in the hanging walls or foot walls of the Frontal Wichita Fault System (Harlton, 1963; Amsden, 1976; Figs. 3, 4 here). Perhaps processes were similar to those occurring today in the Zagros collisional belt, where thrust reactivation of normal faults is taking place during collapse of an attenuated continental margin (Jackson, 1980).

Although these stages in the cycle of development of aulacogens are well known (e.g., Burke, 1977; Milanovsky, 1981), the extent of lateral shortening in southern Oklahoma along thrust faults of moderate or subhorizontal dip has not generally been appreciated (see, however, Tomlinson, 1952). The original zone of weakness was the northern margin of a large Proterozoic basin thought to lie south of the Wichita Mountains. Best available evidence suggests that rocks in that basin are 1,200 to

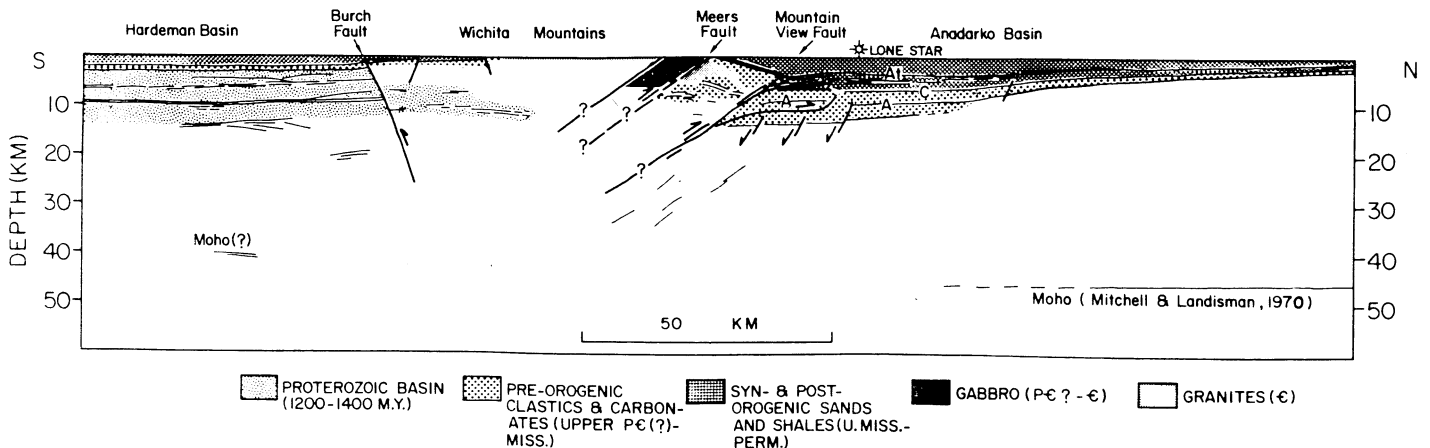


Figure 4. Section across Southern Oklahoma aulacogen based on COCORP lines. Lone Star = position of Lone Star Rogers 1 unit. At = Pennsylvanian Atoka; C = Mississippian Chester Limestone; A = Cambrian-Ordovician Arbuckle. "Orogenic" in legend refers to Pennsylvanian deformation. Note inferred Proterozoic basin south of Wichita Mountain, overthrust nature of Wichita Mountain Front, and normal and listric thrust faults in Anadarko Basin. Two levels of listric thrust faulting are shown: (1) above Chester horizon and (2) (more interpretive) below Chester horizon. Anadarko Basin thus evolved from rift-controlled feature to foreland, partially thrust-loaded basin.

1,400 m.y. old (Brewer et al., 1981). Granitic and basic igneous bodies now exposed in the Wichita Uplift are thought to have been emplaced into the northern margin of the basin. This emplacement may have occurred during the late Precambrian–Early Cambrian extensional phase, although there are uncertainties about time of emplacement of some of the basic rocks (Powell et al., 1980). Pennsylvanian shortening probably coincided with a change in mechanism of subsidence of the Anadarko Basin from thermally related in the early Paleozoic (Feinstein, 1981) to possibly thrust-loading related.

Stress orientation during uplift of the Wichita Mountains is not clear; it could have been north-northeast–south-southwest, perpendicular to the Wichita trend (R. E. Denison, 1980, 1981, personal commun.). However, left-lateral strike-slip movements are thought to be important in the Late Pennsylvanian formation of the Arbuckle Mountains to the east (Tanner, 1967), and the COCORP data could be consistent with oblique slip along the Wichita trend. Some degree of left-lateral oblique slip is suggested by an echelon faults flanking the south side of the Wichita Mountains (Burch fault, Waurika-Muenster faults), and in the Frontal Wichita Fault System (Plate 2 of Ham et al., 1964), which have a reverse dip-slip offset where crossed by the COCORP surveys. Possibly, Late Pennsylvanian strike-slip movements occurred on trends established by Early Pennsylvanian thrusting.

The absence of a seismically definable, thick, Precambrian layered sequence under the Anadarko Basin casts doubts on previous definitions of the location and age of the early phases of the aulacogen in which it was assumed that a late Precambrian–Early Cambrian trough underlay the whole area. While there may have been a relatively shallow trough of that age in southern Oklahoma, it appears that major subsidence actually started in Late Cambrian time.

Although the aulacogen may somehow have been connected with stages of formation of the Ouachita Belt (Hoffman et al., 1974), the evidence for the reactivation of an earlier trend suggests that models of aulacogens originating as failed arms of a radial rift system in continental crust (Burke and Dewey, 1973) may be too simplified. Early lines of weakness could well have been reactivated under some alternative stress field.

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