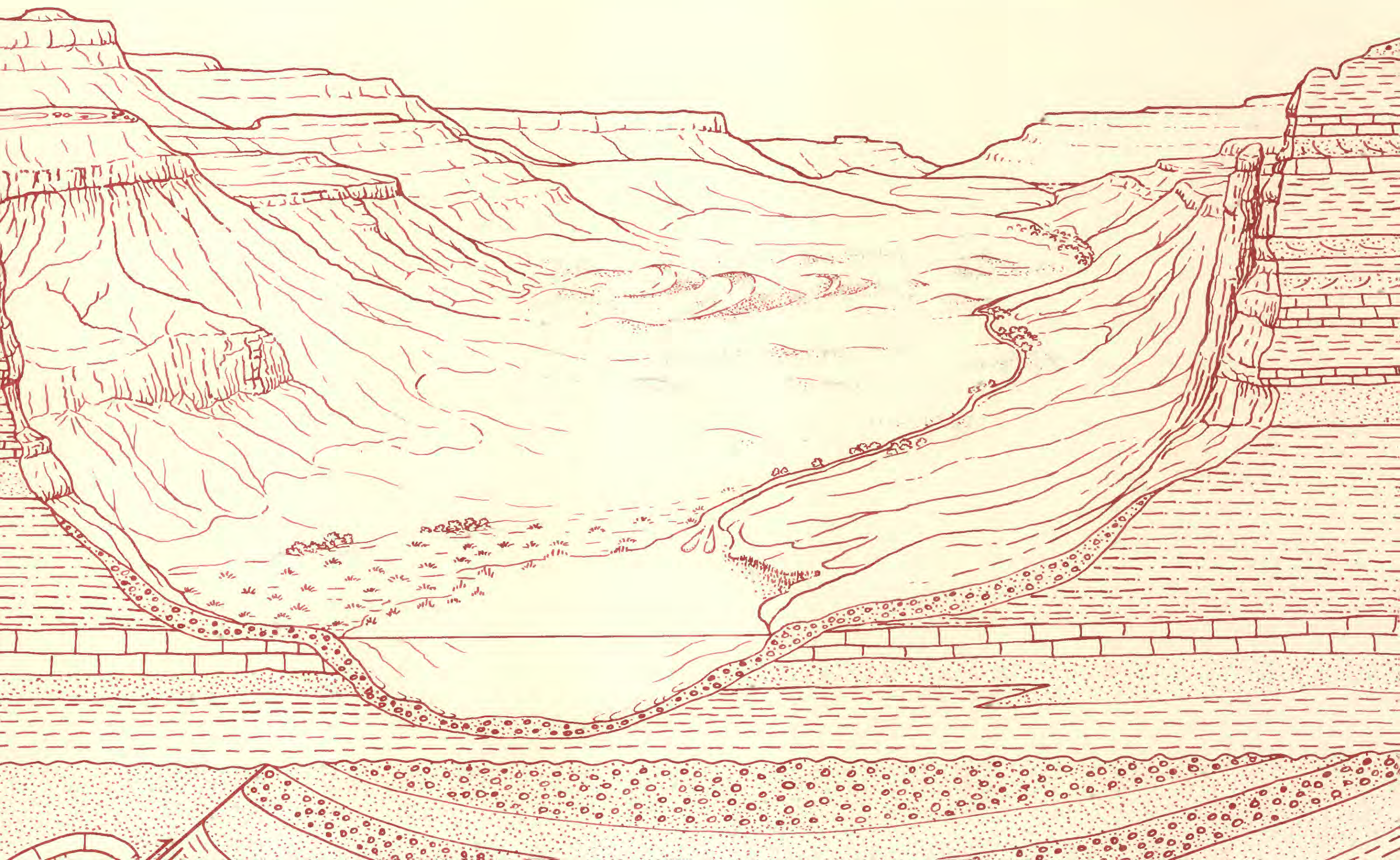
Tectonic Evolution of the Anadarko Basin Region, Oklahoma

U.S. GEOLOGICAL SURVEY BULLETIN 1866–A



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Chapter A

Tectonic Evolution of the Anadarko Basin Region, Oklahoma

By WILLIAM J. PERRY, JR.

A multidisciplinary approach to research studies of sedimentary rocks and their constituents and the evolution of sedimentary basins, both ancient and modern

U.S. GEOLOGICAL SURVEY BULLETIN 1866

EVOLUTION OF SEDIMENTARY BASINS—ANADARKO BASIN

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U. S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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FIGURES

CONVERSION FACTORS FOR SOME SI METRIC AND U.S. UNITS OF MEASURE

To convert from	To	Multiply by
Feet (ft)	Meters (m)	0.3048
Miles (mi)	Kilometers (km)	1.609
Pounds (lb)	Kilograms (kg)	0.4536
Degrees Fahrenheit (°F)	Degrees Celsius (°C)	Temp °C = (temp °F−32)/1.8

Tectonic Evolution of the Anadarko Basin Region, Oklahoma

By William J. Perry, Jr.

Abstract

The Anadarko basin occupies the northern flank of the late Proterozoic(?) to early Paleozoic southern Oklahoma aulacogen. The basin began to form as an independent structural feature in Late Mississippian time, when the Texas promontory of the southern continental margin of Paleozoic North America first reacted to early stages of plate collision with Gondwana or an intervening microplate. Late Mississippian to Early Pennsylvanian structural inversion of the core of the southern Oklahoma aulacogen into the Wichita thrust-bounded uplift involved thrust loading of the region to the north, which became the Anadarko basin. Late Pennsylvanian transpression, oblique to the preexisting structural grain, modified the basin and formed numerous thrust-cored, en echelon anticlines within the southeastern part of the Anadarko basin. Many of these structures are erosionally beheaded, flanked by synorogenic sedimentary rocks, and unconformably overlain by undeformed Permian rocks. Latest Pennsylvanian strike-slip faulting in the Arbuckle Mountains is enigmatic and apparently not of great magnitude. The basin continued to subside in Middle Permian time, probably in response to compaction of older rocks, and has been essentially dormant since late Paleozoic time.

INTRODUCTION

The Anadarko basin of the southern midcontinent (fig. 1) is the deepest Phanerozoic sedimentary basin within the North American craton. Locally it contains more than 12 km (40,000 ft) of Cambrian though Permian sediments (Ham and Wilson, 1967) that mostly were deposited in shallow-water environments. Subsidence rates rarely exceeded deposition rates, and the Anadarko basin was seldom a topographic basin. The Anadarko basin is structurally deepest along its southern margin and is fault separated to the south and southeast from Cambrian igneous rocks exposed in the Wichita Mountains (Ham and others, 1964). It is one of the principal oil- and gas-producing basins within the North American craton.

The Anadarko basin region has a long and complex structural history that can be divided into four periods: (1) Precambrian crustal consolidation, (2) late Precambrian (?) to Middle Cambrian aulacogen development, (3) Cambrian through Early Mississippian development of the southern Oklahoma trough, and (4) late Paleozoic tectonism associated with development of the Anadarko basin on the northwestern flank of the trough.

The present report focuses on structural events related to the late Paleozoic Anadarko basin. I attempt to develop a broad overview of these structural events, based both on numerous published detailed subsurface studies and my own field investigations along the southeastern margin of the Anadarko basin, and to develop a sequence of deformation based on these structural investigations. In these efforts, I have found myself continually in debt to the extraordinarily astute observations and findings of W.E. Ham, R.E. Denison, and Ham's student, R.J. Dunham. Although Bob Dunham went on to make his reputation in carbonate studies, his landmark report on the geology of the northern part of the southwestern Arbuckle Mountains (Dunham, 1955) remains a classic.

Helpful reviews by R.E. Denison, R.O. Fay, S.E. Frezon, T.W. Henry, and L.M. Wilson, as well as by designated U.S. Geological Survey reviewers, are appreciated. During the course of my studies of Oklahoma geology, helpful advice was given by T.W. Amsden, W.G. Brown, R.E. Denison, R.N. Donovan, R.O. Fay,

Manuscript approved for publication, November 22, 1988.

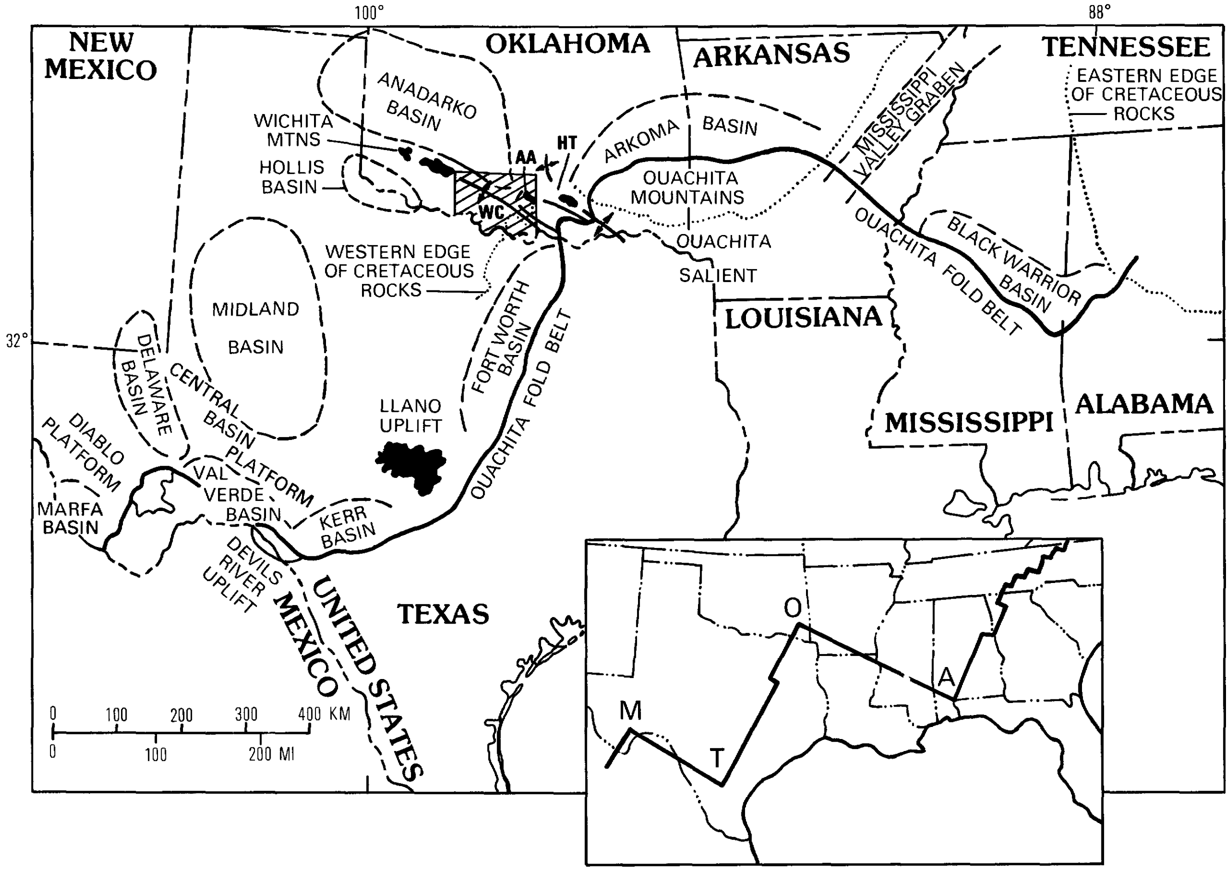


Figure 1. Location of foreland basins and uplifts associated with Ouachita fold belt and outcrops of crystalline basement rocks (in black) in the southern midcontinent of North America. Area of figure 8 shown by ruled pattern. AA, Arbuckle anticline; HT, Hunton–Tishomingo arch; WC, Wichita–Criner arch. Modified from Denison (in press, fig. 1). Inset: A, Alabama promontory; M, Marathon reentrant; O, Ouachita reentrant; T, Texas promontory of pre-Pennsylvanian continental margin. Modified from Thomas (1977).

M.C. Gilbert, K.C. Nielsen, F.A. Peterson, and J.S. Wickham, and by geoscientists involved in petroleum exploration, in particular, H.F. Gaines, T.J. Grealy, and M.I. Jacobson.

PRECAMBRIAN STRUCTURAL EVENTS

The oldest structural events recognized in the Anadarko basin region are associated with crustal consolidation and regional high-grade metamorphism of middle Proterozoic age (1.3 to 1.4 Ga) (Ham and others, 1964; Denison, 1973; Bickford and Lewis, 1979). Dikes in the eastern Arbuckle Mountains emplaced during or shortly after this event trend N. 60° W. (Denison, 1982) and are the first evidence of a profound crustal grain (direction of crustal weakness) that affects the entire subsequent tectonic history of Oklahoma.

The deep Proterozoic Hardeman basin (beneath the Paleozoic Hollis basin shown in fig. 1) along the Oklahoma-Texas border south of the Wichita Mountains is perhaps as old as 1.2 Ga and is known only by seismic data (Brewer and others, 1981). This basin, interpreted as containing 7 to 10 km of "clastic sedimentary and felsic volcanic rocks" (Brewer and others, 1981), may represent the first phase of crustal extension associated with formation of the southern Oklahoma aulacogen to the north.

CHARACTER OF THE SOUTHERN OKLAHOMA AULACOGEN

Early to Middle Cambrian rifting to the north of the Proterozoic Hardeman basin, in the region of the present Wichita and southwestern Arbuckle Mountains of southern Oklahoma, is represented by large volumes of Early Cambrian(?) basaltic and gabbroic rocks, the youngest suite of which has been dated at 552±7 Ma (Bowring and Hoppe, 1982). Erosion and subsequent emplacement of about 40,000 km^3 of Middle Cambrian silicic intrusive and volcanic rocks (Gilbert, 1983)

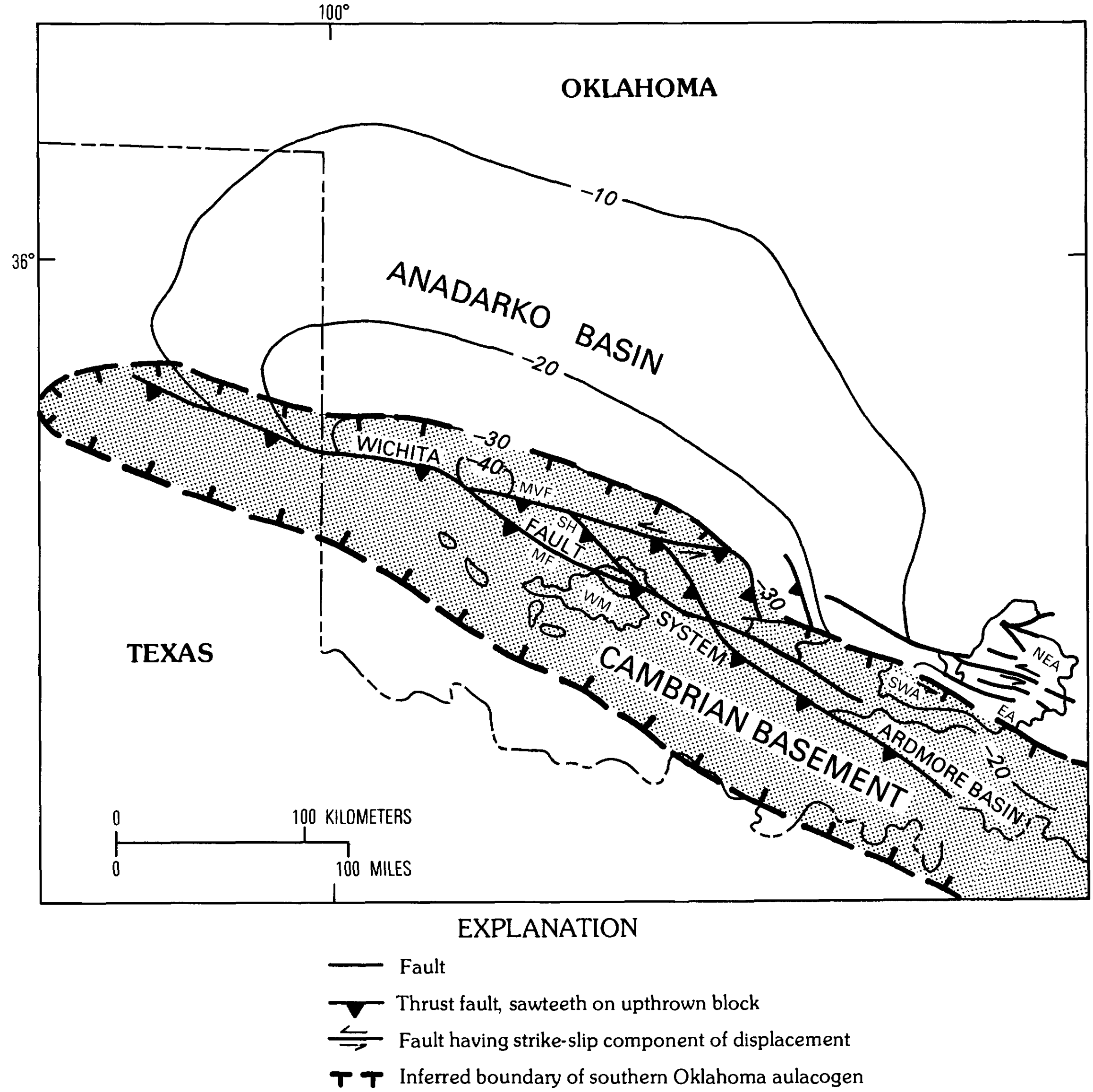


Figure 2. Inferred location and limits of southern Oklahoma aulacogen (patterned area) and generalized basement structure and fault pattern of Anadarko basin. Contours show generalized depth to basement in Anadarko basin, in thousands of feet below sea level. EA, eastern Arbuckle Mountains; MF, Meers fault; MVF, Mountain View fault; NEA, northeastern Arbuckle Mountains; SH, Slick Hills fault block; SWA, southwestern Arbuckle Mountains; WM, Wichita Mountains. Southwestern margin of aulacogen generalized from midline of steep Bouguer gravity gradient of Papesh (1983). Northeastern margin of aulacogen modified from Ham and others (1964) and Denison (1982).

followed intrusion and extrusion of mafic rocks. Bounding normal faults trending approximately N. 60° W. are inferred to have existed along the northern margin of the rift (Gilbert, 1982, 1987). The mafic rocks represent tholeiitic basaltic types similar in composition to those of the older Midcontinent rift (Gilbert, 1983). The Cambrian structural setting of southern Oklahoma is considered to be that of a failed arm (aulacogen or linear rift) of an inferred plate tectonic triple junction (Burke, 1977). This inferred rift is commonly termed the southern Oklahoma aulacogen (fig. 2). Although Ham and Wilson (1967, fig. 2) and Denison (1982) speculated that much of the Anadarko basin is underlain by intrusive and metamorphic rocks of Cambrian age, such rocks have not been penetrated by drilling within the basin, except in fault blocks associated with the southern and southeastern margin of the basin. The deep southernmost part of the basin may be underlain by continental crust that was somewhat thinned during the rifting phase, as indicated by geologic relations in the Wichita Mountains to the south. (See Mitchell and Landisman, 1970.) A thin veneer of Cambrian extrusive and shallow intrusive rocks may indeed be under this southernmost part of the basin.

The northern margin of the aulacogen probably is beneath the southern part of the Anadarko basin: the zone of abrupt southward thickening shown in an isopach map of the Cambrian through Lower Ordovician carbonate rocks (Gatewood, 1978) (fig. 3) may represent the paleo-hingeline along the northern margin of the aulacogen (fig. 3). This zone is about 32 km (20 mi) north-northeast of the northern margin of the Wichita uplift, the southern margin of the Anadarko basin (Gatewood, 1978, fig. 6). South-dipping reverse faults of the Wichita fault system (fig. 2) along the southern margin of the Anadarko basin may represent reactivated normal faults of late Proterozoic (?) to Cambrian age associated with development of the southern Oklahoma aulacogen. The Wichita fault zone currently exhibits more than 12 km (40,000 ft) up-to-south vertical separation that developed during Pennsylvanian and Permian growth of the Anadarko basin (figs. 4, 5). Seismic data (Brewer and others, 1983) and deep drilling indicate that these faults dip southwest and are major thrust faults having moderate dips (30°– 40°).

As pointed out by Hoffman and others (1974) and Burke (1977), the Soviet geologist Nicholas Shatski was the first to characterize the long linear troughs that extend into continental cratons from marginal-fold and thrust belts as aulacogens. Although Shatski's (1946) type examples were in the U.S.S.R., he suggested the existence of an aulacogen in southern Oklahoma. Hoffman and others (1974, figs. 1, 2) were the first to document the aulacogen nature of the southern Oklahoma geosyncline of earlier workers (see Ham and others, 1964). As summarized by Burke (1977, p. 371–372):

> Aulacogens were clearly distinct from other areas with thick sediments on cratons, and their properties generally included (a) extension from an orogen far into a craton with gradual diminution in size, (b) a thick unfolded or gently folded sedimentary sequence, (c) location of the junction between the aulacogen and the orogen at a re-entrant, or deflection in the fold belt, (d) long duration of the aulacogen as an active structure normally corresponding to the active period of the related orogen, (e) an early history of the aulacogen as a narrow fault-bounded graben and a later history as a broader superimposed basin itself sometimes involved in later faulting, (f) the occurrence of horst-like features within the aulacogen that influenced sedimentation, especially in the early history, (g) the occurrence of evaporites, (h) occurrences of igneous rocks often in a bimodal rhyolitic and basaltic association, the igneous rocks being commonly, but not exclusively formed at the beginning of the aulacogen's history, (i) a tendency to reactivation

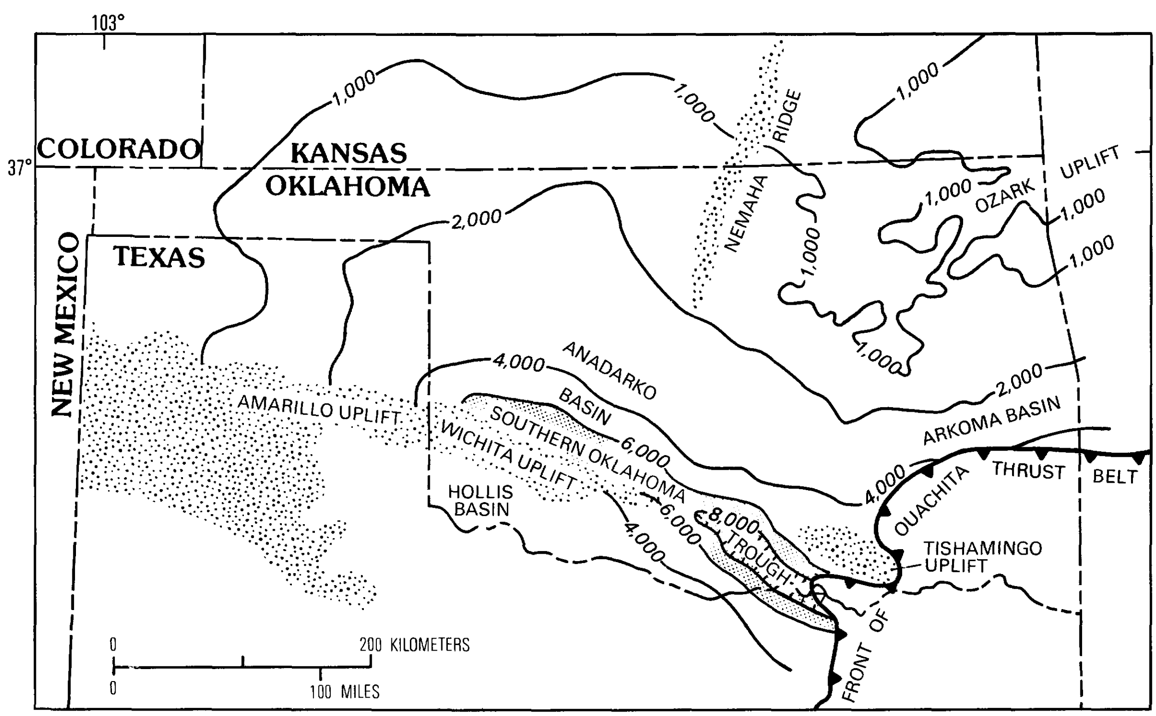


Figure 3. Isopach map of Cambrian Timbered Hills and Upper Cambrian through Lower Ordovician Arbuckle Groups, Oklahoma and western Texas. Contour interval, 1,000 and 2,000 ft; contour hachured to indicate closed low. Stippling represents areas in which Cambrian and Lower Ordovician rocks are deeply eroded or removed to basement. Screen pattern represents depocentral area of southern Oklahoma trough. Modified from Gatewood (1978, fig. 6).

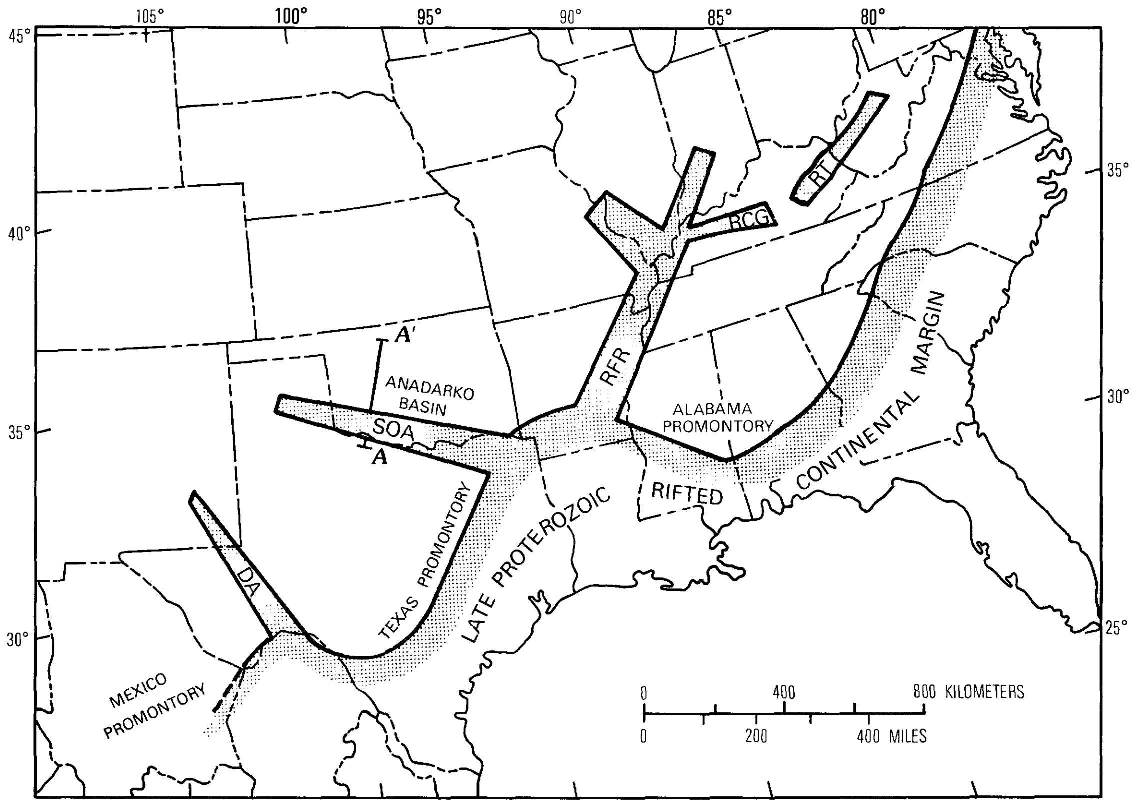


Figure 4. Generalized Late Proterozoic and early Paleozoic paleotectonic map showing rifts and paleocontinental margin, southeastern United States. Margin dashed where extent uncertain. DA, Delaware aulacogen; RCG, Rough Creek graben; RFR, Reelfoot rift; RT, Rome trough; SOA, southern Oklahoma aulacogen. Line of section *A-A'* (fig. 5) also shown. Modified from Keller and others (1983).

marked by renewed faulting and thick sedimentation long after the associated orogen completed its cyclical development.

Virtually all these features are present in the southern Oklahoma aulacogen; this region, however, has been so structurally modified since aulacogen development in Early to Middle Cambrian time that the position of the older extension faults can only be inferred (Gilbert, 1983, 1987). To consider the present Anadarko basin as synonymous with the southern Oklahoma aulacogen leads to a variety of problems that are outlined here and will become evident as the complex structural history of southern Oklahoma is summarized in this report: (1) The keel of the southern Oklahoma aulacogen, as characterized by its thick bimodal igneous suite of Cambrian age, is now exposed in the Wichita and southwestern Arbuckle Mountains, south and southeast of the Anadarko basin, respectively. (2) The Anadarko basin is a successor basin that formed during late Paleozoic plate collision (Kluth, 1986); only its southern and deepest part is possibly coincident with the southern Oklahoma aulacogen (figs. 2, 3). (3) The southern Oklahoma geosyncline of Ham and others (1964), represented by more than 3.35 km (11,000 ft) of Cambrian through Early Devonian (primarily Ordovician) carbonate rocks in the southwestern Arbuckle Mountains and northern flank of the Wichita Mountains (Ham, 1973), overlies the thick igneous extrusive and intrusive complex of the older aulacogen. The Anadarko basin represents only the northern flank of this older trough, the southern Oklahoma trough of this report.

The aulacogen phase began during earliest Cambrian (or late Proterozoic) time when inferred rifts or failed arms of triple junctions extended into the North American craton (fig. 4) during rifting associated with the opening of the proto-Atlantic Ocean (Burke and Dewey, 1973). Vast amounts of bimodal igneous rocks were intruded (gabbros and granites) and extruded (basalts and rhyolites) along the axis of the southern Oklahoma aulacogen (Ham and others, 1964; Gilbert, 1982, 1983). In the Wichita Mountains these include, from oldest to youngest, the Glen Mountains Layered Complex (more than 525 Ma and possibly as old as 730 Ma), the Roosevelt gabbros (552±7 Ma), the undated Navajoe Mountain Basalt-Spilite Group, and the Carlton Rhyolite Group (525±25 Ma), which forms the volcanic cover of the Wichita Granite Group of the same age (usage and dates from Gilbert (1982) and Bowring and Hoppe (1982)). Gilbert (1987, p. 152) summarized the

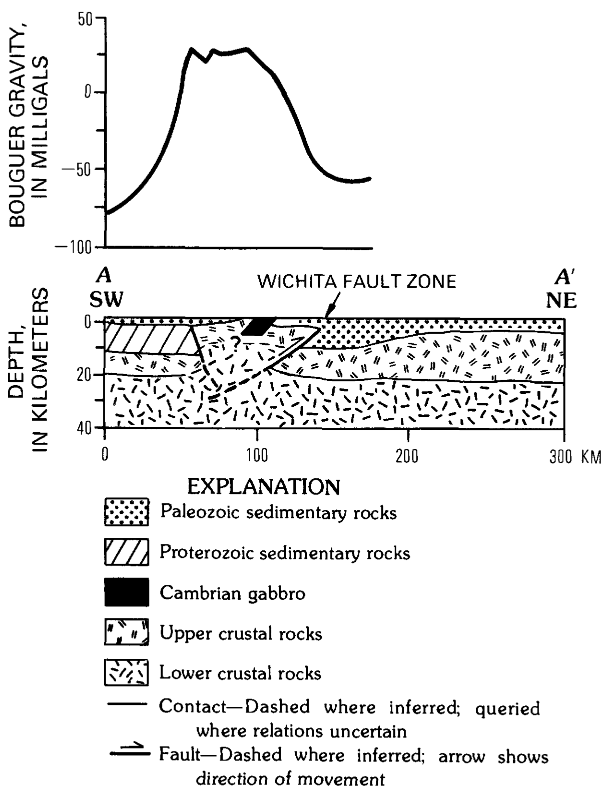


Figure 5. Generalized cross section showing geology and Bouguer gravity of southern Oklahoma aulacogen (region of gravity high) and adjacent Anadarko basin to the north. Line of section shown in figure 4. Modified from Keller and others (1983, fig. 7).

structural and petrologic evidence that suggested the "bimodal igneous suite making up the Wichita Mountains was emplaced in a rift environment at surface to shallow crustal levels, accompanied by seismicity" and probably by normal faulting.

SUBSIDENCE OF THE SOUTHERN OKLAHOMA TROUGH

At the close of the rifting phase, the aulacogen began to cool and subside, as elegantly modeled by Feinstein (1981), and form the southern Oklahoma trough (fig. 3) (southern Oklahoma geosyncline of earlier workers; Ham, 1973). The axis of this trough extended northwestward from the paleocontinental margin (fig. 4) southeast of the present Ardmore basin, through the Ardmore basin and southwestern Arbuckle Mountains, to the vicinity of the present-day Wichita Mountains of southwestern Oklahoma and into the northern Panhandle of Texas (figs. 2, 3), coaxial with the southern Oklahoma aulacogen. More than 3.3 km (11,000 ft) of Cambrian through Lower Devonian primarily carbonate rocks were deposited over the axis of the aulacogen in the region of the Wichita and southwestern Arbuckle Mountains (Ham, 1973).

Sedimentary rocks of the Upper Cambrian Timbered Hills Group (Honey Creek Formation and underlying Reagan Sandstone) unconformably overlie rift volcanic rocks within the southern Oklahoma trough, represented by the Carlton Rhyolite in the Wichita Mountains and equivalent Colbert Porphyry in the southwestern Arbuckle Mountains. Buried hills of rhyolite are surrounded by thicker aprons of Reagan Sandstone, which is locally absent over the crests of these features (Ham, 1973; Donovan, 1982), and more than 137 m (450 ft) of depositional relief is in the southwestern Arbuckle Mountains (Ham, 1973). In the northeastern Wichita Mountains, the Carlton Rhyolite is unconformably overlain by the Honey Creek Formation to the south and the Reagan Sandstone to the north, which represent depositional onlap of about 60 m (200 ft) of strata (Donovan, 1982). The lower part of the Reagan is locally conglomeratic and the upper part glauconitic. These and other features indicate a nonmarine to marine transition within the Reagan (Gilbert and Donovan, 1984, p. 45–54). A transition upward from marine glauconitic quartz arenite to sandy limestone marks the Reagan-Honey Creek contact in the Wichita Mountains (Gilbert and Donovan, 1984). An incomplete section of Cambrian and Ordovician carbonate rocks (Honey Creek Formation and overlying Upper Cambrian and Lower Ordovician Arbuckle Group) is about 1,600 m (5,200 ft) thick in this area (Donovan, 1984, fig. 1). More than 2,000 m (6,700 ft) of Arbuckle Group alone is in the southwestern Arbuckle Mountains, all of which was deposited in a shallow-water marine environment (Ham, 1973). In contrast, less than 650 m (2,100 ft) of Arbuckle Group is on the adjacent Texas shelf and less than 915 m (3,000 ft) is on the craton in central Oklahoma (Ham, 1973, fig. 3). The configuration of the basal unconformity in the area studied by Donovan and his students (Gilbert and Donovan, 1984) and the relative thickness of the various formations of the Arbuckle Group in the northeastern Wichita Mountains as compared to the southwestern Arbuckle Mountains suggest that the former area was slightly south of the axis of the southern Oklahoma trough. This position is consistent with a generalized isopach map of the combined Arbuckle and Timbered Hills Groups (Gatewood, 1978) (fig. 3). The isopach map suggests that the southern Oklahoma trough has been overridden in part by fault blocks of the south-dipping Wichita fault system. Donovan's (1984) observations were made within the Slick Hills fault block (fig. 2), between the Meers and Mountain View faults of this system.

The Arbuckle is unconformably overlain by the Middle Ordovician Simpson Group, which also achieves its maximum thickness (more than 700 m, 2,300 ft) on the southern flank of the southwestern Arbuckle Mountains (Ham, 1973). Amsden (1975, panel 6) showed a variable thickness of Silurian and Lower Devonian Hunton Group across the Anadarko basin; the Hunton is generally 75–170 m (250–560 ft) thick in the Anadarko basin but thickens dramatically southwestward toward the Wichita fault zone to as much as 400 m (1,300 ft). The hingeline of Hunton thickening in the western Anadarko basin is about 32 km (20 mi) north-northeast of the Wichita fault zone, in about the same position shown by Gatewood (1978) for the Cambrian and Ordovician carbonate rocks. R.E. Denison (written commun., 1988) pointed out, however, that no wells in this area penetrate the Cambrian and Ordovician isopached interval and that Gatewood's isopach contours for the deep Anadarko basin are mostly inferred. In the southeastern Anadarko basin, the depocenter is between the southwestern Arbuckle Mountains and the Wichita fault system (Amsden, 1975). The occurrence of almost 610 m (2,000 ft) of Hunton Group in frontal hanging-wall fault blocks of the Wichita fault system suggests that the depocenter of the southern Oklahoma trough in Hunton time was coincident in part with the Wichita uplift (fig. 3).

The overlying Upper Devonian to Lower Mississippian Woodford Shale, a black shale considered to be an important hydrocarbon source rock in the region (Webster, 1980), is from less than 15 to about 45 m (50–150 ft) thick throughout most of the Anadarko basin (Cardott and Lambert, 1985). It thickens dramatically, however, to more than 215 m (700 ft) in hanging-wall fault blocks of the frontal Wichita fault system at the southern margin of the Anadarko basin (Cardott and Lambert, 1985, fig. 2, modified from Amsden, 1975). Southward thinning of the Woodford within these fault blocks indicates that the depocenter during Woodford time was later obscured (overridden) by thrusting of the Wichita fault system. Vitrinite reflectance values of 0.47–0.48 (Cardott and Lambert, 1985) for samples from these hanging-wall fault blocks strongly suggest that these rocks were never buried more than 2 km (1.2 mi) for as long as 1 m.y. (Cardott and Lambert, 1985, fig. 6). (See burial history discussion in Perry and others, 1983.) This depth provides a probable constraint on the maximum thickness of Mississippian rocks deposited above the Woodford prior to structural inversion of the core of the southern Oklahoma aulacogen into the Wichita uplift in Morrowan (Early Pennsylvanian) time.

A decreasing rate of subsidence with time, from the Cambrian into the Early Mississippian, is ably shown by Feinstein (1981, figs. 2, 3, 5–8) for the southern Oklahoma trough. He concluded that this subsidence history in general supports the concept that thermally controlled isostatic subsidence was the chief mechanism in the developing geometry of the southern Oklahoma trough.

Throughout Cambrian to Mississippian time, a passive continental margin existed outward from the trough (Nicholas and Rozendal, 1975; Keller and others, 1983). Throughout Mississippian time, both the proto-Atlantic Ocean and the ocean to the south were closing (Thomas, 1977, 1985). By Late Mississippian time, the effects of this closing began to be felt in southern Oklahoma (Denison, in press). The era of a relatively simple southern Oklahoma trough ended as the Wichita-Criner and Hunton-Tishomingo arches (fig. 1) became positive features (Tomlinson and McBee, 1959; Ham and others, 1964; Ham and Wilson, 1967), synchronous with the initial phase of the Ouachita orogeny. A schematic diagram showing the evolution of the southern Oklahoma aulacogen into trough and the subsequent structural inversion of trough into Wichita uplift clarifies inferred structural relations (fig. 6).

LATE PALEOZOIC TECTONISM

In Late Mississippian (probably Chesterian) time, a fourth phase of tectonism began: growth of the asymmetric Anadarko basin in central and western Oklahoma on the northern flank of the Cambrian rift during structural inversion of the rift. Structural events during this phase are a subject of extraordinary controversy. Basically two schools of thought are represented: (1) this phase consists primarily of wrench-fault tectonics (Tanner, 1967; Wickham, 1978; Harding, 1985), or (2) the phase consists primarily of compressional tectonics (Dott, 1934; Denison, 1982; Brewer and others, 1983; Petersen, 1983; Brown, 1984). Recent advocates of both schools relate late Paleozoic tectonism in Oklahoma to a major plate collision between the North American plate and either Gondwana or an intervening microplate that resulted in the Ouachita orogeny and the development of the ancestral Rocky Mountains (Kluth, 1986). Mild tectonism occurred again during the Quaternary, with displacements on the Meers fault (fig. 2) along the southern margin of the basin (Donovan and others, 1983; Crone and Luza, 1986).

Although the exact position of the pre-Ouachita continental margin is still in question (Kruger and Keller, 1986), its approximate configuration has been known for some time (Nicholas and Rozendal, 1975; Thomas, 1977). Three major promontories of North America, the Mexico, Texas, and Alabama promontories, extended to the south and were separated by the Marathon and Ouachita embayments (figs. 1, 4). Thomas (1985, fig. 5C) indicated an arc-continent collision orogen in Late Mississippian time concurrent with early Alleghanian orogenic activity in the central Appalachians. Early Pennsylvanian compressional events in southern Oklahoma (Harlton, 1956; Hicks, 1956; Mullen, 1956; Neustadt, 1956; Parker, 1956; Rutledge, 1956;

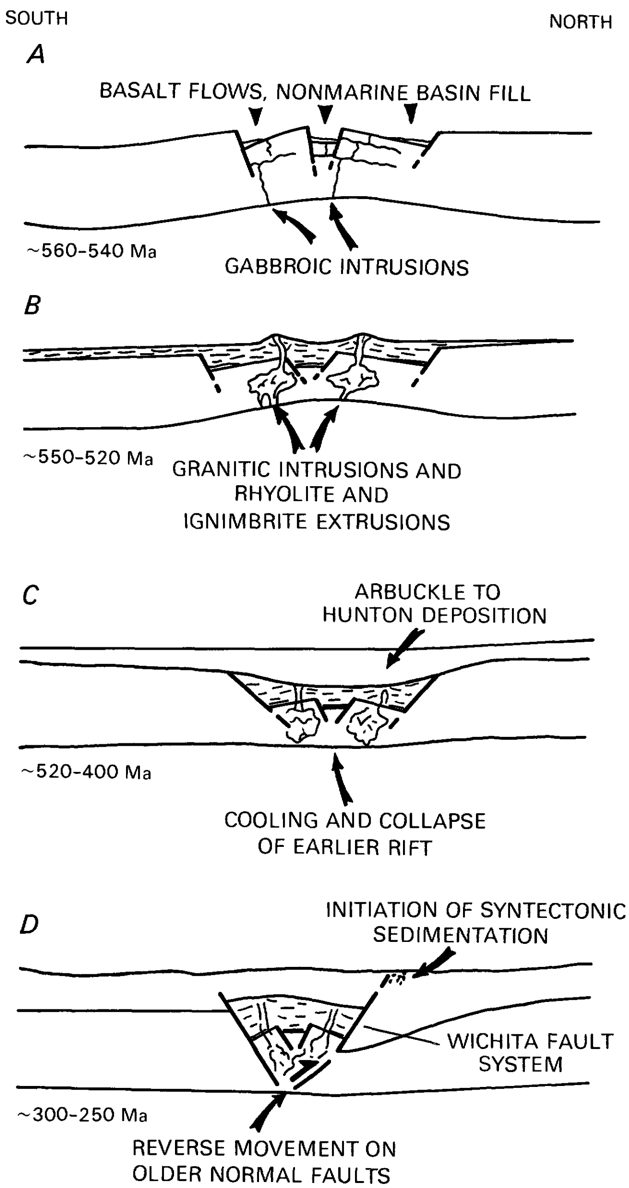


Figure 6. Sequence of development of southern Oklahoma aulacogen (*A*, *B*) (modified from Gilbert, 1983), southern Oklahoma trough (*C*), and Anadarko basin north of Wichita fault system (*D*). Same area occupies each view.

Westheimer and Schweers, 1956; Latham, 1970) suggest that similar events may have taken place at this time along the southern tip of the Texas promontory, events that jammed Texas northeastward into probably preweakened crust beneath the southern Oklahoma aulacogen and successor trough.

The relative ages of upper Paleozoic rocks in southern Oklahoma have been known for some time (Tomlinson, 1929; Elias, 1956; Harlton, 1956; Westheimer, 1956). Numerous subsurface oil field studies edited by Hicks and others (1956) benefited from this carefully developed biostratigraphic framework, such that the relative timing of deformation in southern and central Oklahoma and many of the subsurface structural patterns have been known for more than 40 years. Recently, the age of Upper Mississippian and Lower Pennsylvanian rocks in southern Oklahoma and the position of the Mississippian-Pennsylvanian boundary has been better defined (Lane and Straka, 1974; Lane, 1977; Sutherland, 1979; Morris and Sutherland, 1984) (fig. 7).

Age of the Wichita–Criner Uplift

Perhaps the first evidence of late Paleozoic tectonism in southern Oklahoma is the abrupt pinching out of upper Chesterian (uppermost Mississippian) and lower Morrowan (lowest Pennsylvanian) Springer sandstones southwestward in the western Ardmore basin near the northeast flank of the Criner Hills (fig. 8) (Tomlinson and McBee, 1959) (age of Springer Formation from Morris and Sutherland, 1984). By early late Morrowan time (fig. 7), the Jolliff Limestone Member of the Golf Course Formation of the Dornick Hills Group was deposited in the Ardmore basin and southwestern Arbuckle Mountains. This member, commonly termed the "Jolliff conglomerate" south of Ardmore, there contains cobbles and pebbles derived chiefly from the Meramecian and older Mississippian Sycamore Limestone and Upper Devonian to Lower Mississippian Woodford Shale, both of which are stratigraphically more than 1,370 m (4,500 ft) below the Jolliff farther north in the Ardmore basin (Tomlinson and McBee, 1959, p. 14–15). The composition and size of Jolliff clasts and clasts in the conglomerate of the younger Morrowan Otterville Limestone Member of the Golf Course Formation are evidence of a source area in the vicinity of the Criner Hills (fig. 8). A broad positive area extending from the Criner Hills southward into Texas was envisioned by Tomlinson and McBee (1959, p. 14). Harlton (1956) recognized that this uplift extended northwestward toward and included the Wichita Mountains, and he defined the Harrisburg trough as a narrow syncline developed during Morrowan to Desmoinesian time in front of (immediately northeast of) this uplift. Tomlinson and McBee (1959) later termed this uplift the Wichita-Criner arch.

Harrisburg Trough and Related Features

The Harrisburg trough of Harlton (1956) is west, south, and southeast of the Velma and associated oil fields (fig. 8). Subsequent work summarized by Jacobson (1984) indicates that Harlton (1956) misplaced the northeast-bounding fault of the Wichita-Criner uplift in

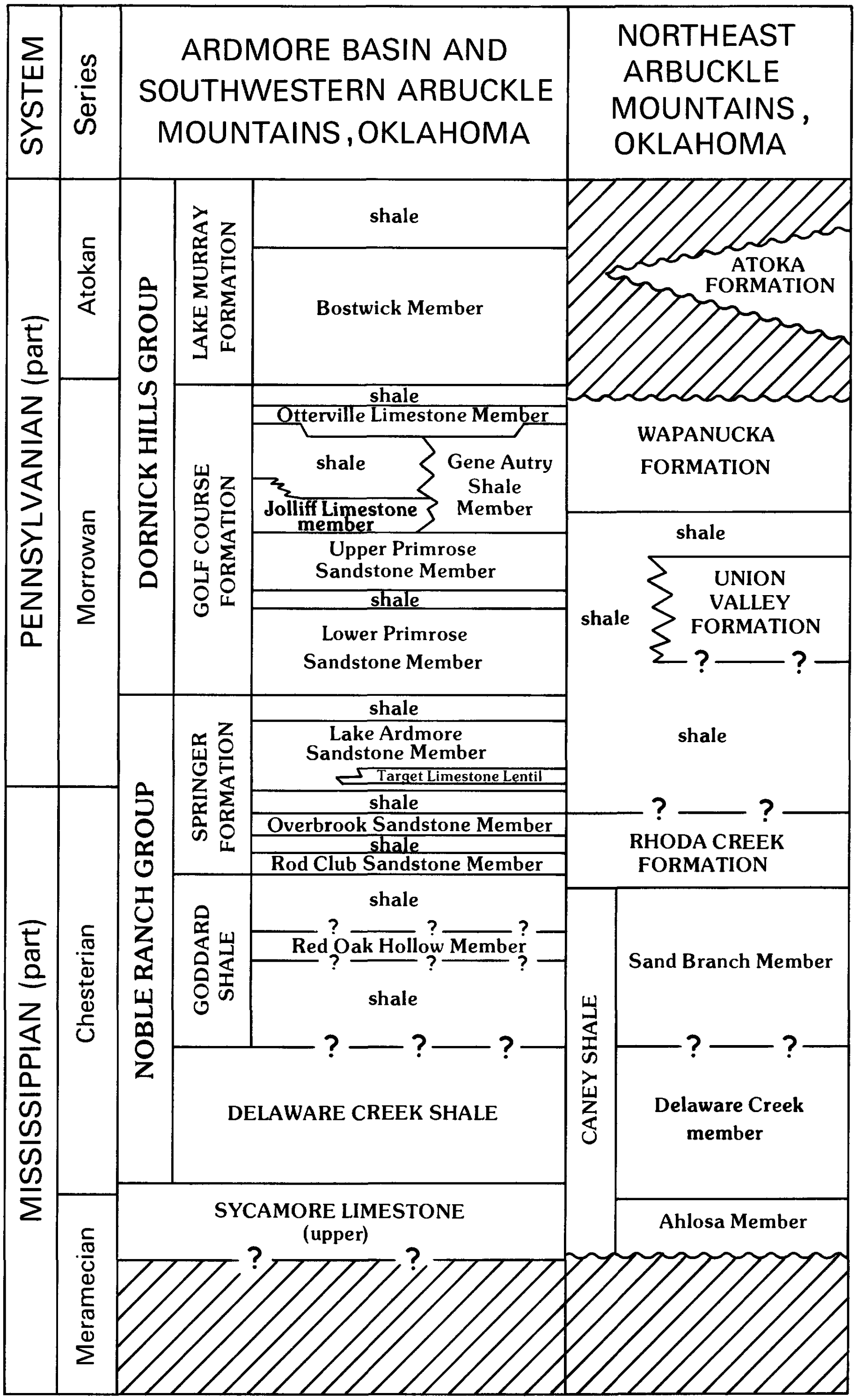


Figure 7. Correlation chart for Upper Mississippian and Lower Pennsylvanian rocks of Oklahoma. Modified from Morris and Sutherland (1984).

the Velma area. As redefined by Jacobson (1984, p. 127), that part of Harlton's Harrisburg trough west of, south of, and including the West Velma field (fig. 8) is "a syncline composed of Pennsylvanian-aged sediments located on *both* the Wichita uplift and within the Ardmore Basin." In that area, a sequence of deformation can be readily established (fig. 9). This West Velma block was uplifted by thrusting and deeply incised by erosion

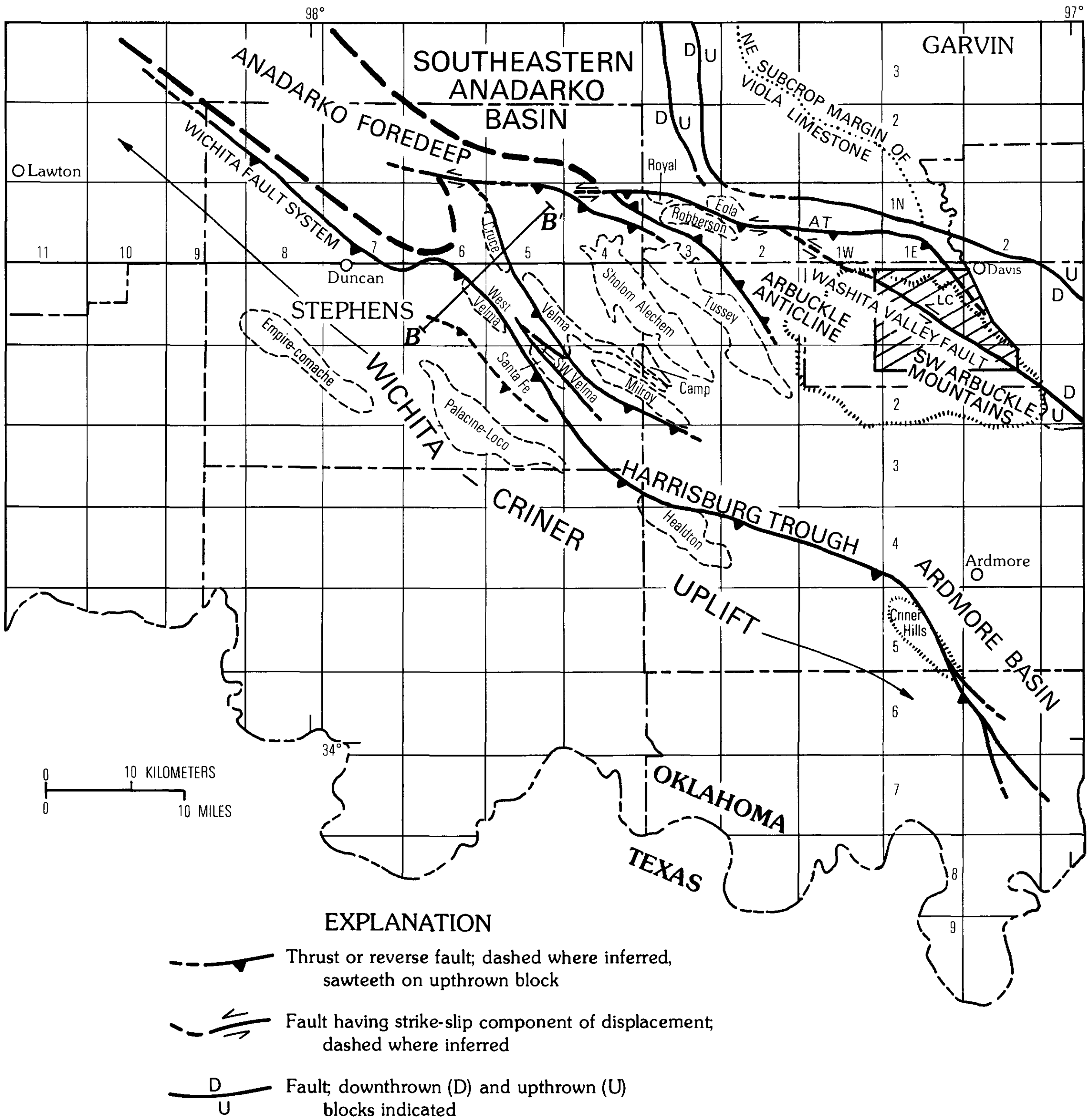


Figure 8. Oil and gas fields (dashed outlines) and selected structural features in southeastern Anadarko basin region and adjacent areas to the south. AT, Arbuckle thrust; LC, Lake Classen area, southwest of Davis. Oil and gas field outlines from Hicks (1956, fig. 1). Subcrop trace of Arbuckle thrust (AT) from Brown (1984, fig. 5); Harrisburg trough region modified from Harlton (1956, fig. 1); selected structural features from Hicks (1971), Brown (1984), and Jacobson (1984, figs. 1, 4); northeast subcrop margin of Viola Limestone and associated faults northwest of Davis from Hicks (1971, fig. 40). Northeast of subcrop margin, Ordovician Bromide Formation and older rocks lie unconformably beneath Upper Pennsylvanian and younger rocks. Line of section *B–B'* (fig. 9) and area of figures 10 and 12 (diagonal ruled pattern) also shown. Hachures mark boundaries of southwest Arbuckle Mountains and Criner Hills.

during Atokan or early Desmoinesian time. The Velma fault, a listric thrust of very Late Pennsylvanian to Early Permian age (post-Cisco Group) has dip-slip displacement of more than 2.9 km (1.8 mi). If the Deese/Hoxbar contact is assumed originally to have been horizontal, then backstripping indicates the pre-Hoxbar Formation (pre-Missourian) structural configuration of the area (fig. 9*B*). According to Jacobson (1984), Morrowan sediments have been completely stripped from this area. As much as 850 m (2,800 ft) of Atokan sediments occupies a paleovalley on the hanging wall of the West Velma fault along the margin of the uplift (Jacobson, 1984, fig. 6). The restored structural configuration at the close of Desmoinesian time (top of Deese Formation) shows approximately 1,500 m (5,000 ft) of structural relief on the West Velma fault (fig. 9*B*). Unconformable relations and hanging-wall versus footwall thicknesses indicate that most of the displacement on this fault occurred during Atokan or very early Desmoinesian time and that only about 450 m (1,500 ft) of structural relief developed during the later part of early Desmoinesian time. Northeast of the West Velma fault, the Velma anticline developed prior to or during Atokan or very early Desmoinesian time and apparently controlled the position of the younger Velma thrust fault.

In the Velma area, chert conglomerates first occur in the basal Bostwick Conglomerate Member of the Atokan Lake Murray Formation; pebbles of the conglomerate are composed of Upper Devonian and Lower Mississippian Woodford chert (Harlton, 1956). In the western Anadarko basin, upper Morrowan chert conglomerates are abundant near the Wichita–Amarillo mountain front, where they form deep elusive traps for natural gas (Shelby, 1980). Near the mountain front in this area, more than 3 km (10,000 ft) of Atokan or very early Desmoinesian through Permian granite wash, arkose derived from erosion of igneous rocks in the Wichita Mountains, overlies these chert conglomerates. Such arkose is absent southeast of the Anadarko basin (Tomlinson and McBee, 1959, fig. 7). The Morrowan to lower Desmoinesian rocks of the Harrisburg trough and its western extension adjacent to and beneath the Wichita mountain front represent sedimentary debris from the unroofing of the Wichita–Criner arch (fig. 1) and date the inception and possibly the main period of structural growth of this uplift.

Subsurface studies of oil and gas fields southwest and west of Ardmore on the uplift (Westheimer and Schweers, 1956; Mullen, 1956; Neustadt, 1956; Latham, 1970) clearly indicate that folding and reverse faulting along the Wichita-Criner uplift in this region had essentially ended by Desmoinesian (early Middle Pennsylvanian) time. Basement crystalline rocks were exposed in the higher parts of the Wichitas by late Morrowan or earliest Desmoinesian time (or perhaps earlier, Evans, 1979). These subsurface studies, as well as the later COCORP (Consortium for Continental Reflection Profiling) seismic lines across the Wichitas (Brewer and others, 1983) and recent structural investigations (McConnell, 1986, 1987), also show that this deformation resulted primarily from northeast-directed basement-involved thrusting. Concurrent left-reverse slip is inferred for east-west-trending fault segments (fig. 2).

A series of well-constrained subsurface studies of the major anticlinal oil fields along the southeastern margin of the Anadarko basin and adjoining areas of the Ardmore basin (Harlton, 1956; Hicks, 1956; Hoard, 1956; Parker, 1956; Rutledge, 1956; Walker, 1956) indicates that deformation proceeded from southwest to northeast: the footwall rocks of the Wichita thrust system in this region were first folded in Atokan or very early Desmoinesian time. These early anticlines were erosionally beheaded and overlain or flanked by later Desmoinesian sediments. The main episode of deformation north of the Harrisburg trough occurred during Late Pennsylvanian to Permian time. These anticlines trend mostly N. 45°–55° W.; they generally are asymmetric, have steep northeastern limbs, and are bounded on the northeast by reverse faults that dip southwest. Seismic data (Jacobson, 1984) indicate that these reverse faults are listric and flatten southwestward with depth. The trend and style of these faults indicate that the direction of maximum compression was northeast-southwest in the southeastern part of the Anadarko basin during Pennsylvanian time. North of the Sholom Alechem and Tussy fields (fig. 8), the south-dipping Arbuckle thrust of Brown (1984) trends east-west and probably is a compartmental fault having left-reverse slip. It bounds a region to the south that exhibits significant northeast-southwest shortening on thrusts that appear to merge northward into but do not cross the Arbuckle fault. Thus, the Arbuckle fault forms the northern structural domain boundary of a region of Late Pennsylvanian to Permian transpressional tectonism.

Arbuckle Anticline and Associated Structures

Northeast of the Harrisburg trough and Anadarko foredeep, both of which developed during the main phase of Wichita-Criner thrusting, a forebulge developed in the region of the Hunton-Tishomingo uplift and northern flank of the Arbuckle anticline (fig. 1). Subdued uplift began in this region in late Morrowan time and extended through early Desmoinesian time with little, if any, evidence of compressive tectonism (Ham, 1954; Dunham, 1955; Sutherland, 1984; R.O. Fay, written commun., 1987). In the Tussy field (fig. 8), immediately west of the southwestern Arbuckle Mountains, the Desmoinesian Deese Formation rests unconformably on Morrowan (?) lower part of the Dornick Hills Group (Hoard, 1956). In the Lake Classen area (fig. 8), on the northern flank of the Arbuckle anticline, the Deese rests unconformably on Mississippian Delaware Creek Shale and the entire Goddard and Springer Formations and Dornick Hills Group are absent (Dunham, 1955, Hart, 1974). Farther to the northeast, the Deese has been removed by subsequent erosion and the middle Virgilian Ada Formation rests directly on Ordovician rocks (Hart, 1974).

The main period of deformation in the Tussy field is post-Ada and pre-Vanoss (Hoard, 1956); that is, late

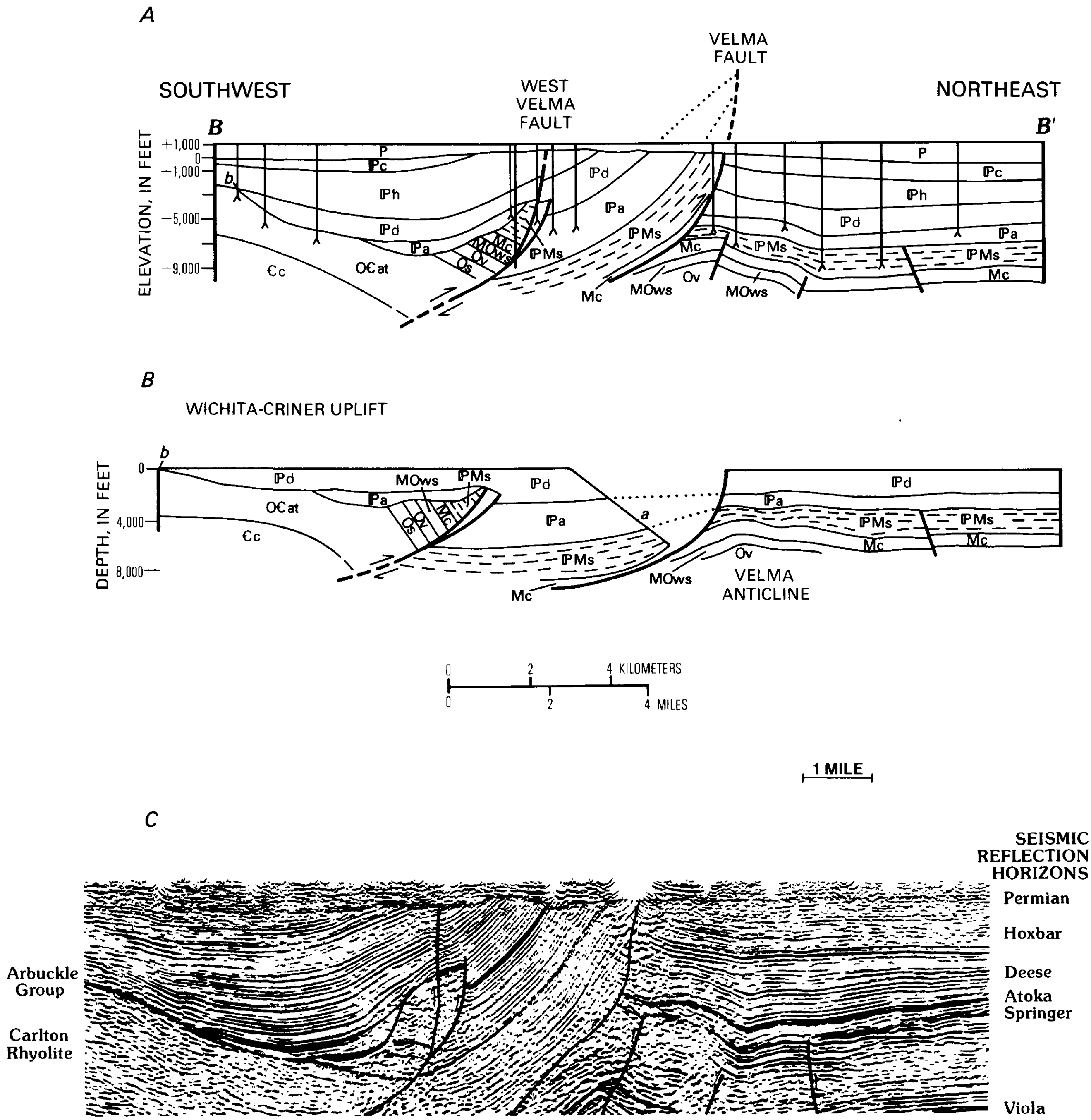


Figure 9 (above and facing page). Cross sections showing Paleozoic structural features in area of Velma fault and Wichita-Criner uplift. *a*, post-Cisco (late Virgilian to Early Permian) erosion surface. Initial phase of deformation was pre-Desmoinesian, probably Atokan, and present-day structural relief developed during late Virgilian to Early Permian time. *b*, equivalent point on sections *A* and *B*. *A*, Present-day section; modified from Jacobson (1984, fig. 5). Location of drill holes (vertical lines) also shown. *B*, Section restored (backstripped) to structural configuration at close of Deese (Desmoinesian) time. *C*, Seismic reflection profile (Jacobson, 1984, fig. 5a). Line of section shown in figure 8.

middle Virgilian. The dominant structural trends (structure contours and anticlinal axes) within the Tussy field range from north-south to N. 30° W. (Hoard, 1956, fig. 3), and two sets of crosscutting faults exist, right-separation faults that trend from about N. 40° E. to east-west, and apparent dip-slip faults that trend north-northwest. The folds and faults within the area of the Tussy field are quite similar to the second-order faulted folds and faults to the east that are exposed on the northern flank of the Arbuckle anticline. Of these

EXPLANATION

P	Permian rocks, undivided
IPc	Cisco Group (Upper Pennsylvanian)
IPh	Hoxbar Formation (Upper Pennsylvanian)
IPd	Deese Formation (Middle Pennsylvanian)
IPa	Atoka Formation (Middle Pennsylvanian)
IPMs	Springer Formation (Lower Pennsylvanian and Upper Mississippian)
Mc	Caney Shale (Upper Mississippian) of subsurface usage (probably equivalent to Goddard and Delaware Creek Shales of Hart (1974)
MOws	Woodford Shale (Lower Mississippian and Upper Devonian), Hunton Group (Devonian and Silurian), and Sylvan Shale (Upper Ordovician), undivided
Ov	Viola Limestone (Upper and Middle Ordovician)
Os	Simpson Group (Middle Ordovician)
OЄat	Arbuckle (Lower Ordovician and Upper Cambrian) and Timbered Hills (Upper Cambrian) Groups, undivided
Єc	Carlton Rhyolite (Middle Cambrian)

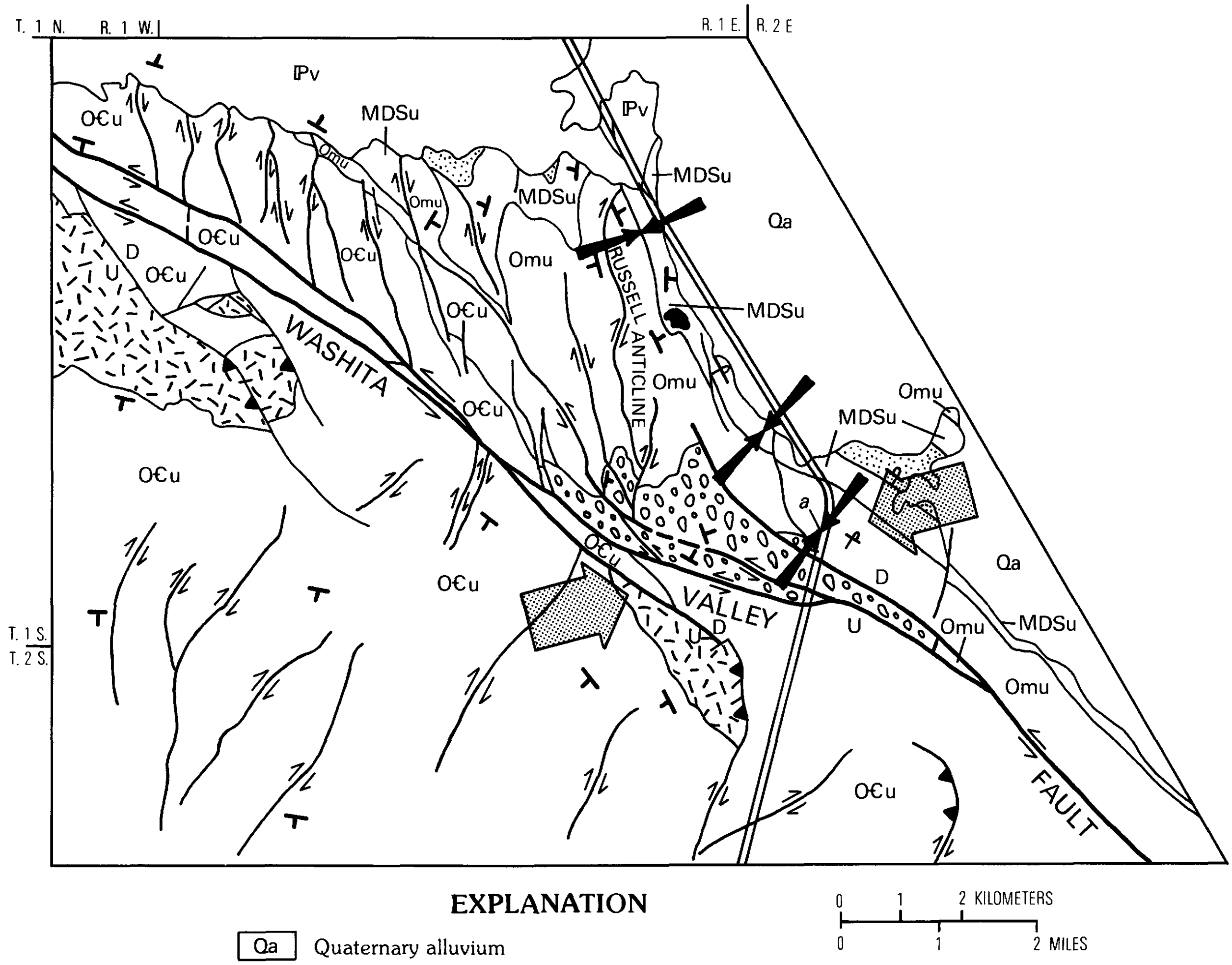
structures mapped by Dunham (1955) in the Lake Classen area, I examined the Russell anticline (fig. 10) in some detail.

Deformation of the western Arbuckles is tightly constrained as late Pennsylvanian in age, and subsequent subdued uplift occurred in Permian or post-Permian time (Dunham, 1955). This timing requires a complex sequence of deformation (Perry, 1987) to have occurred in a short period of time: (1) Compression trending N. 35°–60° E., associated with the Arbuckle thrust of Brown (1984), produced mesoscopic folds and contraction faults on the northeast limb of the Arbuckle anticline in the Lake Classen area (figs. 10, 11). (2) These mesoscopic structures were then rotated to or past the vertical within enveloping Ordovician to Mississippian strata. (3) Several kilometers of erosion occurred such that the inferred Ada-equivalent (middle Virgilian) Collings Ranch Conglomerate rests on steeply dipping Ordovician rocks. Phases 1, 2, and 3 may have closely overlapped in time. Left-reverse slip on the Arbuckle thrust north of the Arbuckle anticline (fig. 8) is indicated by en echelon anticlines and synclines on the hanging wall (upper plate) of this thrust west of Lake Classen (fig. 12). Complementary structures on the adjacent footwall are unknown. (4) About 4.3 km (2.7 mi) of left slip developed on the Washita Valley fault, synchronous in part with deposition of the Collings Ranch Conglomerate (fig. 12). The array of very Late Pennsylvanian strike-slip faults in this area indicates that the compression direction had rotated to about N. 70°–75° E. during final phases of deformation (fig. 10). Deformation of the Arbuckle anticline was essentially completed by latest Pennsylvanian (late Virgilian Vanoss) time (Dunham, 1955).

Less than 1.5 km (5,000 ft) and generally less than 0.9 km (3,000 ft) of post-Virgilian cover exists in the Anadarko basin as shown by many authors (for example, Hill and Clark, 1980, figs. 2–5). This amount of basin fill can be explained by post-tectonic subsidence during compaction of the thick Pennsylvanian sequence. The Anadarko basin has been essentially dormant since Early Permian time. Subdued modest reactivation of older basin faults may have occurred during the Jurassic and Cretaceous, and minor Holocene movement has occurred on the Meers fault (Crone and Luza, 1986) and possibly other faults within the basin.

Wrench-Fault(?) Tectonism

Southern Oklahoma has been considered a major wrench-fault province by many workers (for example, Tanner, 1967; Walper, 1977; Carter, 1979; Booth, 1981; Haas, 1981; Axtmann, 1983). A left-lateral offset of more than 64 km (40 mi) along the Washita Valley fault was proposed by Tanner (1967), based on his isopach map of the basal sand of the Oil Creek Formation (Middle Ordovician Simpson Group). Using dipmeter-corrected thicknesses, Brown (1984) showed, however, that no significant lateral offset of this sand is required. Carter (1979) drew an isopach map for the Hunton Group on both sides of the Washita Valley fault and concluded from this map that 32 km (20 mi) of left slip occurred along the Washita Valley fault. Based on his career-long study of the Hunton Group, Amsden (1975; oral commun., 1985) vigorously disagreed with Carter's conclusion and saw no evidence of large-scale lateral slip. My independent analysis of offset along the Washita



EXPLANATION

- Qa — Quaternary alluvium
- IPv — Vanoss Formation (Upper Pennsylvanian)
- Collings Ranch Conglomerate (Upper Pennsylvanian)
- Deese Formation (Middle Pennsylvanian)
- MDSu — Mississippian-Devonian-Silurian rocks, undivided
- Omu — Ordovician rocks, Upper and Middle, undivided
- O€u — Arbuckle (Lower Ordovician and Upper Cambrian) and Timbered Hills (Upper Cambrian) Groups, undivided
- Colbert Porphyry (Cambrian)
- D U — Strike-slip fault, dashed where inferred; arrows indicate apparent relative movement. D, downthrown side; U, upthrown side
- Thrust fault, sawteeth on upthrown block
- Generalized strike and dip of beds
- Overturned beds
- Lake Classen
- Interstate Highway I–35

Figure 10. Geologic map of northeastern Arbuckle anticline. Narrow black arrows indicate Late Pennsylvanian maximum compression directions obtained from slip lines on mesoscopic contraction faults; slip lines rotated to bedding flat about the strike of bedding. Broad stippled arrows indicate inferred maximum compression directions during later strike-slip deformation. Location of area shown in figure 8. *a*, location of area of figure 11. Modified from Ham and McKinley (1954).

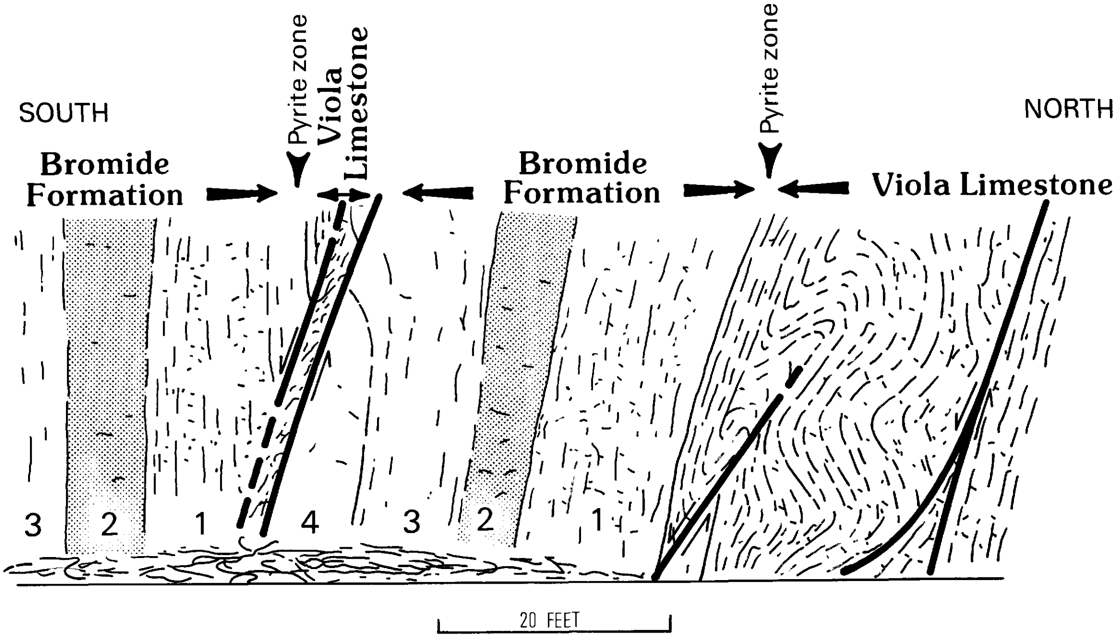


Figure 11. Sketch showing contraction faults and kink folds in imbricate zone on northeast limb of Arbuckle anticline; stratigraphic top of bed to right. Contraction faults are inferred to have formed as uplimb thrusts in beds dipping gently to northeast before limb rotated to vertical. West side of Interstate Highway 35, Murray County, Oklahoma. Location of area shown in figure 10. Pyrite zone provides excellent marker at base of Viola Limestone. Units 1, 2, 3, and 4 are distinctive informal units in upper Bromide Formation that allow extent of offset along fault at left to be determined.

Valley fault (fig. 12) (4.3 km (2.7 mi) of left separation), based on offset of anticlinal and synclinal axes as interpreted from mapping by Ham and McKinley (1954), agrees closely with that of Ham (1951; approximately 4.8 km or 3 mi) and removes this fault from the megashear category. Based on Ham and McKinley, dip-slip down-to-northeast separation is 0.8–0.9 km (2,500–3,000 ft) in the map area (fig. 10).

Strike-slip faults having a few to tens of meters displacement are common on the western Arbuckle anticline. My observations indicate that these faults dip more than 60°; many are almost vertical. Several strands of the Washita Valley fault exposed along Interstate Highway I–35 also are almost vertical. Crosscutting relationships indicate that these faults postdate the second-order anticlines and synclines of Late Pennsylvanian age in the Lake Classen area mapped by Dunham (1955) and that they offset and dismember both map- and outcrop-scale folds. The character of gouge associated with these faults indicates that little erosion occurred subsequent to their development. The gouge commonly is poorly consolidated, contains abundant breccia, and is iron oxide stained; the staining indicates the fault gouge was in communication with vadose ground water. Contraction faults in the same area commonly exhibit calcite-fiber growth on slickenside steps and fault surfaces. Calcite-filled extension fractures (calcite veins) indicative of natural hydraulic fracturing are geometrically and spatially associated with these contraction faults. Both fiber growth and calcite veins suggest strongly that these faults formed at depth. If the strike-slip faults had not been observed to die out upward into the Upper Pennsylvanian Collings Ranch Conglomerate and northward into the upper Virgilian (uppermost Pennsylvanian) Vanoss Formation, it would be easy to suspect that these faults were post-Paleozoic in age.

Wiltse's (1978) wrench-fault analysis of the Southwest Davis oil field on the Russell anticline (fig. 10) suffers from the underlying assumption that the Washita Valley fault and Russell anticline formed at the same time. My analysis (Perry, 1987, unpub. data) indicates that this is not the case. The growth of the Russell anticline and other en echelon folds is related to left-reverse motion on the older Arbuckle thrust (phase 1, above). The Washita Valley fault (phase 4) cut diagonally across the Arbuckle anticline and second-order Russell anticline subsequent to compressional deformation (leading to thrust uplift and erosion) associated with movement on the Arbuckle thrust.

SUMMARY OF CONCLUSIONS

The tectonic history of the Anadarko basin is complex and cannot be considered independently from

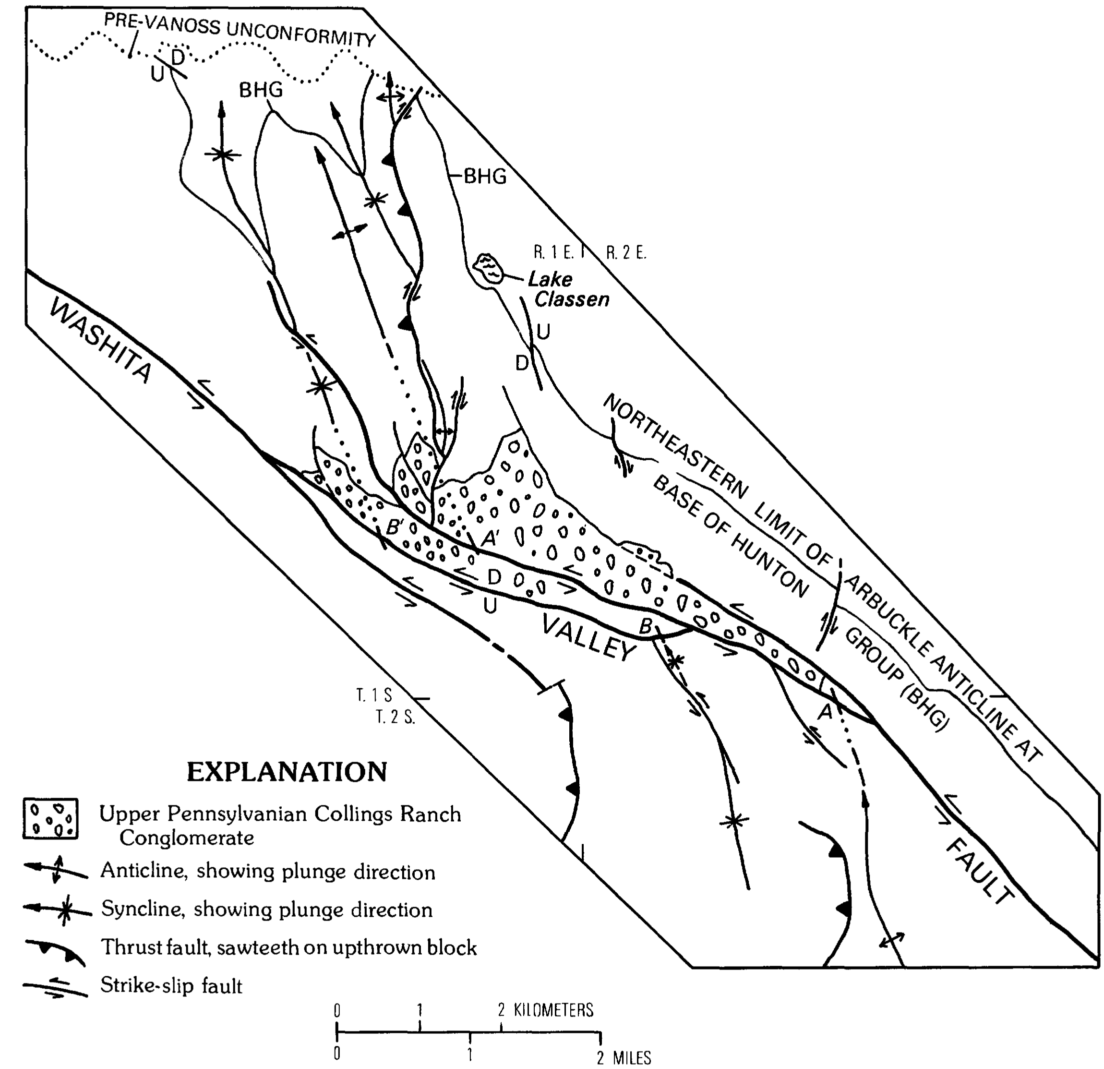


Figure 12. Generalized tectonic map of northeastern Arbuckle anticline showing anticline-syncline pair offset by left-stepping Washita Valley fault. Apparent offset of anticline (*A–A'*) is 4.8 km (3 mi); apparent offset of syncline (*B–B'*) 3.7 km (2.3 mi). Difference in offset is attributed to straight-line projections (dotted) of anticline and syncline to fault southward beneath Collings Ranch Conglomerate to Washita Valley fault and northward through complexly deformed rocks along the southern margin of the Washita Valley fault from known positions as indicated by strike and dip symbols and formation contacts on geologic map of Ham and McKinley (1954). Left-slip separation on Washita Valley fault is therefore estimated as 4.26±0.56 km (2.65±0.35 mi). Location of area shown in figure 8; geology of area shown in figure 10. Adapted from geologic map of Ham and McKinley (1954).

that of adjoining parts of the southern North American midcontinent. The dominant structural grain in the basin is inherited from Precambrian events. Both the adjacent Wichita-Criner arch to the south and Arbuckle anticline to the southeast are cored by Cambrian igneous rocks of a major seaward-opening rift, the southern Oklahoma aulacogen. The aulacogen narrowed westward into the craton and probably terminated in the central part of the northern Panhandle of Texas. Cambrian igneous rocks may underlie the deepest part of the Anadarko basin. The Anadarko basin developed in latest Mississippian through Pennsylvanian time, primarily north of the aulacogen, during structural inversion of the core of the central and western part of the aulacogen. The structural development of the basin is yoked to left-reverse transpressional tectonism in the Wichita thrust system and subsequent Arbuckle thrust system. Strike-slip faulting in the southwestern Arbuckle Mountains post-dated oblique compression and the major phases of basin development.

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