UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

STRUCTURAL STYLE OF THE WICHITA AND ARBUCKLE OROGENIES, SOUTHERN OKLAHOMA

A Dissertation

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

Doctor of Philosophy

By

Christopher Paul Saxon
Norman, Oklahoma
1998

UMI Number: 9839792

STRUCTURAL STYLE OF THE WICHITA AND ARBUCKLE OROGENIES, SOUTHERN OKLAHOMA

A DISSERTATION

APPROVED FOR THE SCHOOL OF GEOLOGY AND GEOPHYSICS

BY

ACKNOWLEDGMENTS

There is no way to adequately thank all of those who have given me support and encouragement through the course of this study. I can only hope that those not listed in this section will not think that their help and encouragement was not appreciated. There are simply too many people to thank!

Dr. James Forgotson served as Chair of this study. Dr. Forgotson encouraged me to be self-directing, yet went considerably out of his way to see that I had all the support I needed. I owe him an enormous debt of gratitude. Dr. Raymon Brown of the Oklahoma Geological Survey provided support, advice, and encouragement as only a true friend can. Ray was always available to talk and flattered me with his interest in my work. Dr. John Castagna came to the committee with little notice, yet provided strong encouragement and enthusiasm. Dr. Charles Gilbert and Dr. Mark Morrisey took time from their busy schedules to serve on m committee and I deeply thank them both.

It is not an exaggeration to say that this dissertation, my geologic education, and professional career would not have been possible without the guidance of my outside reader, Dr. William G. Brown of Baylor University. There are no words to tell the world how glad I am that this patient teacher, and brilliant geologist, took the time and interest to take me as his student. It is to him that I dedicate this work.

Brian Sralla and Bob Allen of Kabodi Inc. in Ardmore have spent many hours sharing insights, providing me with data, and taking me to the field. Wendy Sumner, Rob Beuhring, Wayne Narr, Chuck Kluth, and Bill Higgs of Chevron all provided me with valuable insights and discussions. Pat O'Connell of Conoco has been extremely helpful and a great friend. Discussions (and sometimes debates) with John Price, Doug Johnston, Dr. Noel Donovan, Jerry McCaskill, Jerry Kendall, John Taylor, Dr. Roger Young, Glenn Bixler, Dr. Steven Naruk, David Pulling, Dr. Steve Hook, Dr. James

Willis, and the so many others I simply have failed to mention, have been greatly appreciated.

Funding came from a grant from Phillips Petroleum, distributed through Dr. Dan O'Meara; a true friend of students with a petroleum interest! Additional funding was graciously provided by Vastar and Mobil. I would like to specifically thank Dr. Kris Meisling at Mobil for his input and efforts. Additional funding was provided by the Robert C. Lang III Scholarship, a fund donated by Dr. Roger "Tim" Denison, and various loans from my parents, friends, and family. Seismic was provided by SEI, Vestige Petroleum, the Ardmore Geological Society, and PGI (through Texaco). Well logs were obtained through the generosity of the Oklahoma City Geological Society Log Library and Bob Allen's log library in Ardmore. Dip meters were provided by Ed and Mark Rawls.

I would like to than Tom and June Larrow and Stan and Penny Babb for helping me through tough times at the end. My best friends, Lawrence Jones and Bruce Unruh, also deserve thanks for being there whenever I needed them. My sister, Mary Beth, and brother, Michael, always encouraged me to keep plowing on, and their phone bills prove it.

Lastly, I thank my parents, Paul and Carol Saxon, who took so much time to read to me as child, and encourage me to be interested in the world. Whether it was a fossil or a snake, they encouraged me to learn more about it. Without their devotion as parents, I never would have accomplished this. In a sense, this is their study!

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ABSTRACT

Pennsylvanian deformation in the Southern Oklahoma Foreland occurred as a basement-involved fold belt which resulted in intra-plate crustal shortening foreland of the Ouachita System. Deformation of the Southern Oklahoma Foreland is characterized by northwest trending faults which dip at low- to moderate-angles to the southwest and northeast. The Pennsylvanian deformation is superimposed across an older (Precambrian-Cambrian) grain of extension. Pennsylvanian deformation of the Southern Oklahoma Foreland was part of the greater Pennsylvanian Foreland which encompasses regional Mississippian-Permian intra-plate crustal shortening of the central and western interior of North America, and may be related to low-angle subduction in Mexico. Deformation occurred in two pulses which overlapped spatially and temporally: 1) the Wichita Orogeny, which occurred from Mississippian through Atokan, resulting in uplift of Amarillo-Wichita Mountains, and 2) the Arbuckle Orogeny, which occurred from Virgilian to early Wolfcampian and resulted in the uplift of the Arbuckle Anticline. The general trend of deformation was to move southwest to northeast, with thrusts breaking forward.

Overall structural style is of horizontal compression along low-angle basement-involved thrusts. Locally, structural style is determined by amount of basement folding during early-stages of deformation. Shortening was accomplished along primarily southwest-dipping basement-involved thrusts, although significant northeast dipping thrusts and back-thrusts are also present. The major basement-cored uplifts (Wichita Uplift, Arbuckle Uplift, Tishomingo Uplift) form an *en echelon* arraignment which

trends northwest-southeast, with primary structural vergence to the northeast. The major basement thrusts loses slip laterally, terminating as either fault-fold interchanges or against high-angle, regional, basement compartmental faults. Two end members of basement deformation exist, though in most areas deformation is a hybrid between end-members. Mode I is similar to fold-thrust model of Berg (1962) in which the mountain-flank undergoes a significant amount of folding prior to development of the main mountain-flank fault. In mode II, initial folding is relatively minor. Deformation occurs primarily by faulting along a low-angle thrust whose shape may be modified by fault-bend folding. After leaving the basement, the fault typically travels in the Arbuckle Group as a flat or low-angle ramp.

Foreland detachment structures are large intra-basinal folds generated by volumetric crowding of the mountain-flank syncline during early-stages of fold-thrust deformation. At the same time, detachments along the steep-limb formed rabbit-ear folds. Foreland detachment structures are cross-crestal folds consisting of a deep fault-propagation fold, generally cored by an Arbuckle-level detachment, and a shallow-fold, offset from the deep fold, carried along a detachment in Springer shales. Foreland detachment structures are strong geometric evidence for a fold-thrust style of deformation.

Structural style shows significant variation along the mountain front. Two types of variation in style occur. The first is an *abrupt* variation. This occurs where a compartmental fault offsets the mountain front and style shows an significant variation across the compartmental fault or across a steep lateral ramp. The second type is a *gradational* variation. This occurs as the result of change in fold shape, plunge, gradual variation in elevation of lateral ramps, fault-to-fold interchanges, and progressive loss of slip along strike.

Chapter 1

INTRODUCTION

Statement of Problem

The structural geometry of uplifts and basins in the Southern Oklahoma Foreland remain poorly understood. Although studies exist for individual structures, no comprehensive study exists which attempts to document and analyze structural style(s) and their causal mechanisms across the entire foreland. A wide variety of structural and tectonic regimes have been postulated to explain Wichita and Arbuckle deformation including; right-lateral slip (Walper, 1977), left-lateral slip (Tanner, 1967; Budnik, 1986; McConnell, 1989), differential vertical uplift (Harlton, 1951, 1963, 1970; Riggs, 1958; McLean, 1983), and reverse dip-slip faulting (Brown, 1984; McConnell, 1987). However, all-too often these explanations have been offered without proper documentation of structural geometry. Correctly oriented and properly constructed structural cross sections, seismic lines, and integrated surface-subsurface studies are severely lacking.

The Wichita and Arbuckle Orogenies are local manifestations of regional Mississippian-Pennsylvanian intra-plate deformation which resulted in crustal shortening of the Pennsylvanian Foreland. Deformation occurred foreland of, and contemporaneous with, the emplacement of the Ouachita-Marathon foldbelt. Collectively, the area encompassing basement-involved deformation of southern Oklahoma is referred to as the Southern Oklahoma Foreland, and should be regarded as a sub-province of the larger Pennsylvanian Foreland. The Wichita and Arbuckle Orogenies were superimposed across a pre-existing basement fabric created by late Precambrian-and Cambrian-aged rifting oriented northwest-southeast. The Wichita and Arbuckle Orogenies resulted in northeast-directed crustal shortening and the creation of several asymmetric basement-cored uplifts and associated basins. This deformation has produced some of the most complicated and economically significant structures in North America. Limited surface exposures exist as the vast majority of the uplifts have been deeply eroded and buried by onlapping syn- and post-orogenic sediments. However, due to the presence of significant economic oil and gas reserves, this area contains a wealth of subsurface geologic data.

This study combines surface and subsurface observations to document the style of deformation during the Wichita and Arbuckle Orogenies to:

1) establish a basic geometry of various basins and uplifts,

2) document the style and significance of important features subsidiary to these basins and uplifts.

3) establish the geometry, lateral extent, and slip of some of the major faults.

Objectives

The above-listed studies will contribute to attaining the following objectives:

1) document and define the major style(s) of deformation associated with the Wichita and Arbuckle uplifts and their associated sedimentary basins;

2) document the 3-dimensional geometry of the major uplift bounding faults;

3) document the geometry of the Wichita and Arbuckle uplifts and their associated basins;

4) identify the geometry and structural significance of subsidiary structures within the major basins and uplifts;

5) determine minimum estimates for slip direction, timing, and shortening using integrated and well documented structural analysis.

Outline of Dissertation

The initial phase of this study included a detailed review of literature regarding the structural evolution, interpretations, and structural and tectonic modeling of the study area. A brief summary of the review is presented in chronological order in order to present the evolution of the conceptual understanding of southern Oklahoma. This provides the framework for the current debate over structural styles and tectonic arguments. Chapter 2 provides a proper regional and tectonic frame of reference by discussing the Pennsylvanian and Southern Oklahoma Forelands and the likely plate tectonic during the Wichita and Arbuckle Orogenies in order to A review of the stratigraphy is presented in chapter 3. In chapter 4, the major fault systems and their locations and relationships are outlined. This serves as an introduction to more detailed discussion of these systems later in the dissertation and to define and clarify the sometimes ambiguous definitions and linkages of historical interpretations of subsurface fault systems in southern Oklahoma. Chapter 5 follows with a discussion of models of foreland deformation. Special attention is given to the geometric implications of these models, both in terms of the model specifically, and in application of the models to southern Oklahoma. A detailed examination of the fold-thrust model of deformation (Berg, 1962) and it's application to southern Oklahoma is presented in chapter 6. Chapter 7 examines foreland detachment structures and relates deformation of detached intra-basin structures to the deformation processes of the mountain-flank. Chapter 8 investigates variations in style with successive lateral position along the mountain front. Both gradational and abrupt changes in style are documented. Chapter 9 presents the closing tectonic arguments and addresses the debate over strike-slip versus horizontal compression as the dominant tectonic style for southern Oklahoma.

Location

The study area is located in south-central and southwestern Oklahoma (Fig. 1.1) concentrates on the central Wichita Uplift, Anadarko Basin, Tishomingo-Arbuckle Uplifts, and Ardmore Basin. Surface exposures are limited, with only small portions of the Wichita Uplift exposed in the Slick Hills (approximately T. 4 N., R. 12 W. northwest to T. 8 N., R. 14 W.) on the Blue Creek Canyon Block, the Wichita Mountains, and the Criner Hills (T. 5S., R. 1E.). The better exposures occur in the central and southeastern portion of the Arbuckle Anticline and the Tishomingo Uplift (exposures from T. 1S., 1 W. to T. 1S., R. 7E. to T. 3S. R. 7E. to T. 3S., R 1 W.). Much data comes from subsurface sources such as seismic lines and well logs. Major fault systems analyzed include the Mountain View Fault, Meers Fault, Arbuckle Thrust, "Washita Valley" Fault System, and Reagan Fault (Fig. 1.2).

Methods

Portions of the study draw on field work conducted for a study on the geometry of the northwest plunge of the Arbuckle Anticline (Saxon, 1994). Field mapping, included compilation of data on 1:20,000 scale black and white aerial photographs. The bulk of the study consisted of subsurface interpretations employing the use of various well logs and seismic lines. Cross sections were drawn at the proper orientation to structural axes, to minimize plunge effects. Strict balancing was generally not possible due to deep levels of erosion; however, principles such as consistency of structural style from outcrop to the subsurface, consistent cut-off angles and cut-off lengths, and lateral consistency of style were employed whenever possible. Down-plunge projections of aerial photographs and map data were generated from a

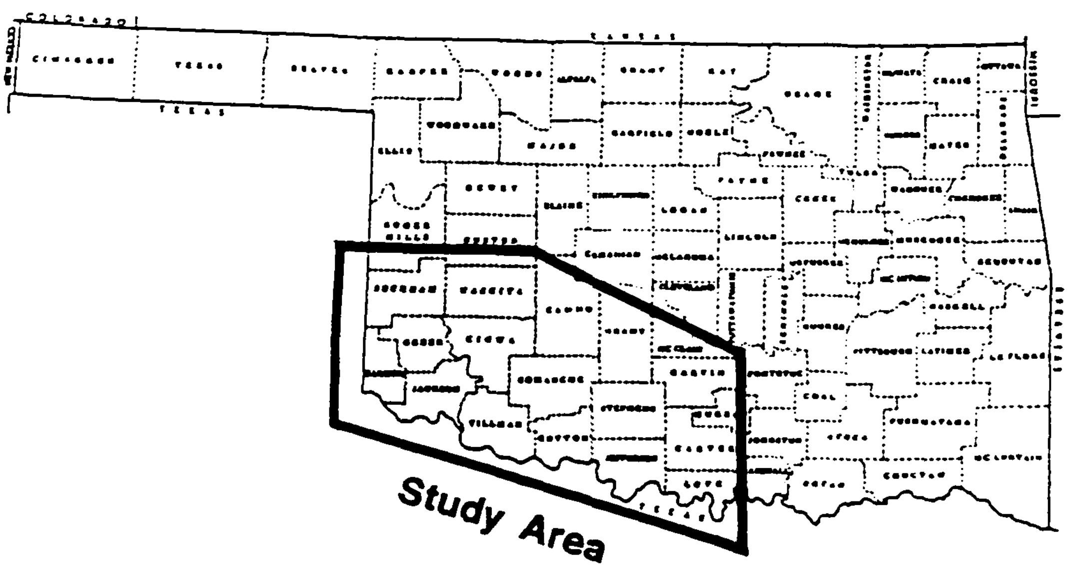
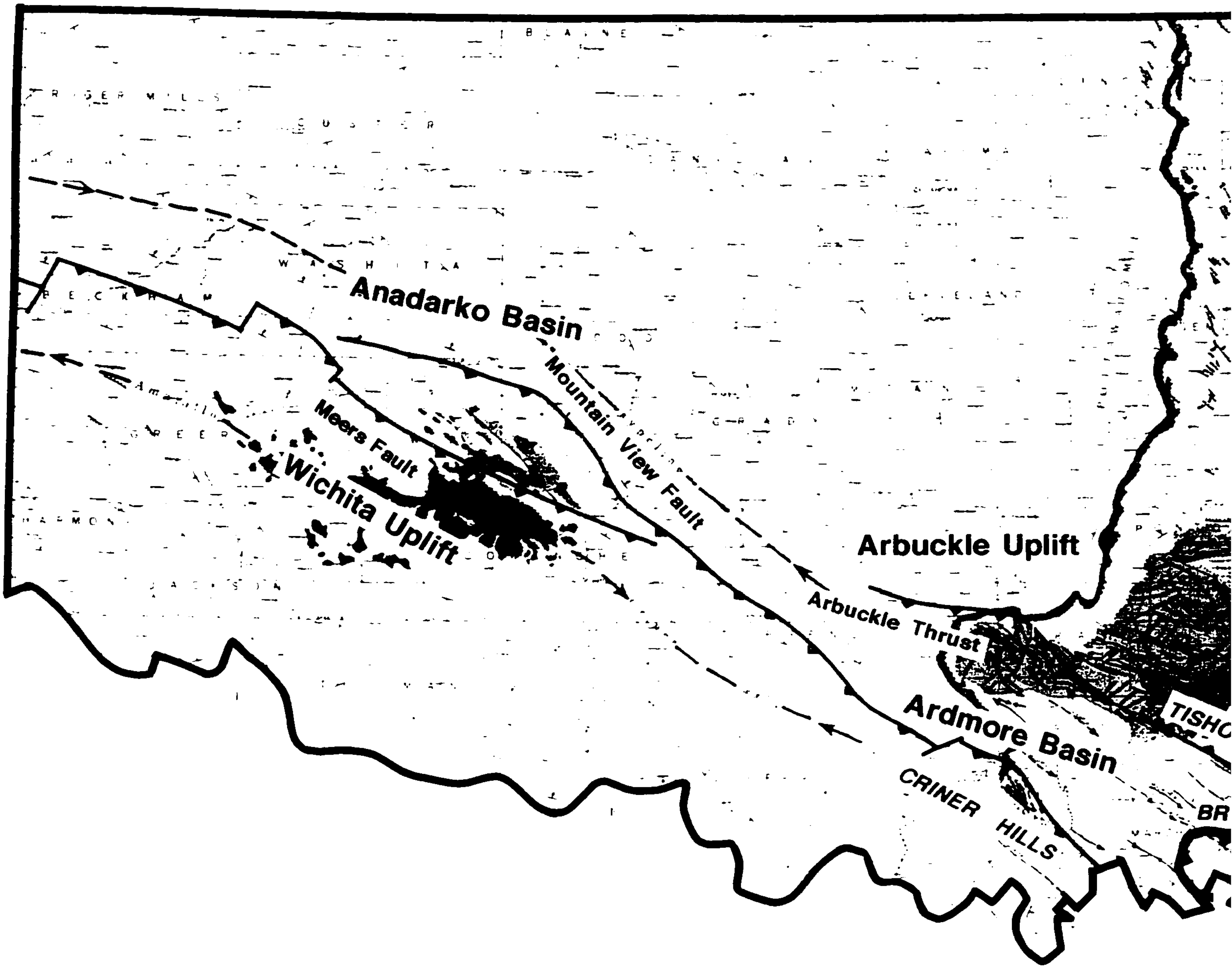
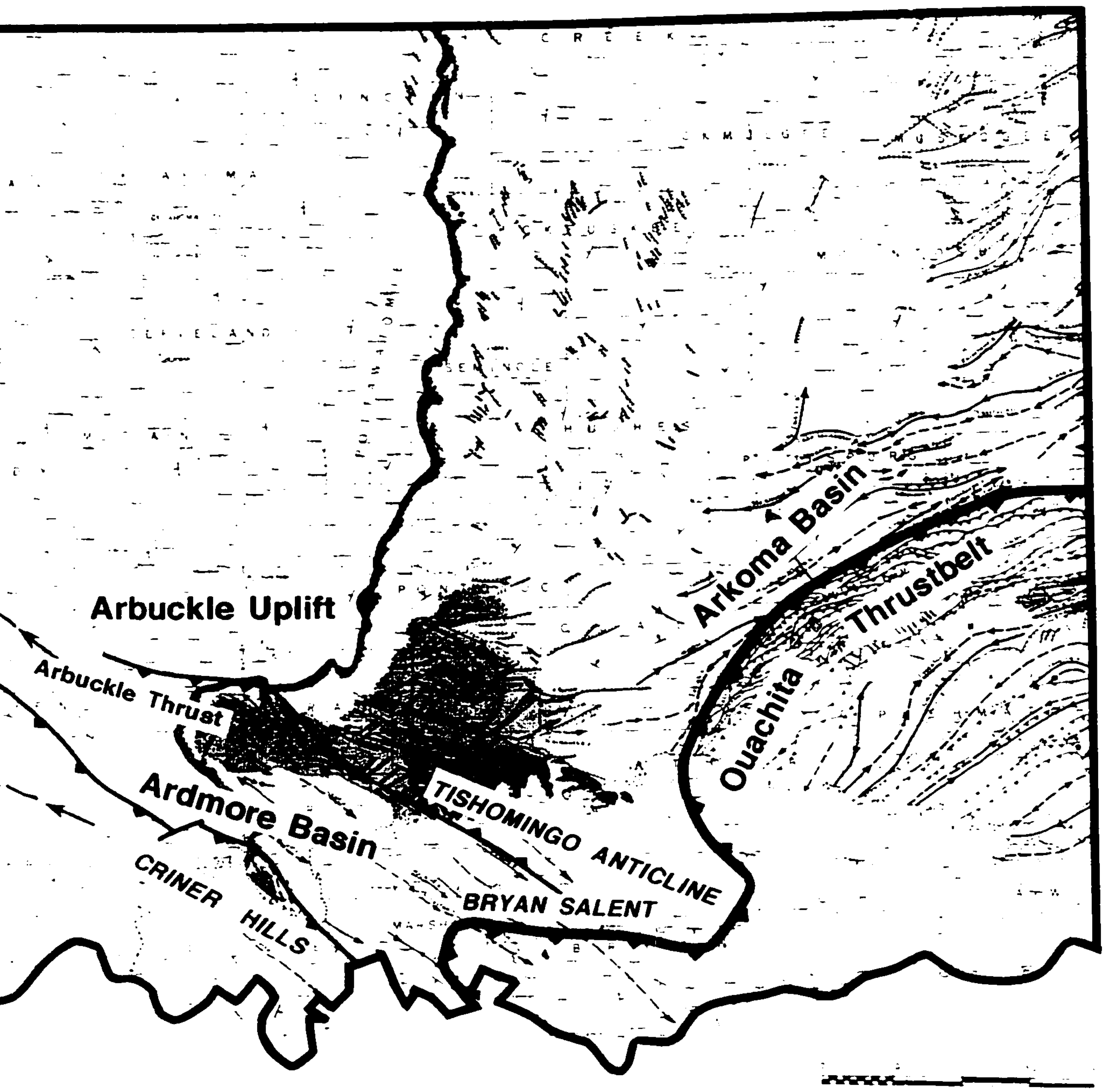


Figure 1.1. Map of southern Oklahoma showing the study area.

Figure 1.2. Tectonic map of the Southern Oklahoma Foreland showing the location of major basins, basement-involved uplifts, and the approximate subsurface trace of several of the major faults. The Wichita Uplift is bounded to the north by the Meers and Mountain View Fault systems. The Arbuckle Uplift is bounded to the north by the Arbuckle Thrust. Outcrop exposures of pre-Pennsylvanian sedimentary rock are colored. Outcrops of pre-Pennsylvanian basement rock are shaded. Note the extensive subsurface nature of the uplifts and their major fault systems. The basement-involved deformation is located foreland of the Ouachita Thrustbelt (modified from Miser, 1954).


Anadarko Basin
Mountain View Fault
Meers Fault
Wichita Uplift
Arbuckle Uplift
Arbuckle Thrust
Ardmore Basin
CRINER HILLS



(modified from Miser, 1954)

technique created by the author and used to aide interpretations of surface and subcrop maps.

Previous Works

The purpose of this section is to provide a historical perspective and temporal framework for the evolution of past structural interpretations of the study area. Detailed discussions regarding the geometry of particular tectonic models and interpretations of selected individual structures is covered in chapter 5.

Earliest Interpretations (1900-1960's)

Early interpretations of the structure and tectonics of southern Oklahoma were driven by models involving differential vertical uplift. The use of vertical uplift models indicated the lack of a plausible driving mechanism for horizontal stresses prior to the acceptance of plate tectonic theory. Large amounts of northeast-southwest directed crustal shortening could not be explained using plate tectonic models of that time. Models involving basement-thrusting did not receive popular support. By the late 1950's and 1960's, several papers introduced the concept of wrench faulting and large lateral offsets, which dominated later interpretations.

Taff (1904), the earliest documented worker in the Arbuckle Mountains, characterized the Arbuckle Uplift as a series of internally deformed blocks, divided by high-angle normal faults. Early investigators of the Wichita Uplift characterized the structural regime as due to differential vertical uplift, along high-angle normal or reverse, faults (Lang III, 1950; Harlton, 1951, 1963, 1964, 1972), or upthrust faults (Riggs, 1958).

Dott (1934) documented thrusting and compression within the Arbuckle Mountains. Swesnick and Green (1950), working with well data from the then newly discovered Eola Field, attempted to explain the surface geometry of the Arbuckle Anticline, using the subsurface data of the Eola region. By constructing properly-oriented true-scale cross sections, they were able to argue that overthrusting, along a single, basement-involved thrust (subsequently called the Arbuckle Thrust) produced the Arbuckle Uplift; and that the Eola Anticline was a footwall anticline to the buried northwest continuation of the Arbuckle Uplift. Regional work by Tomlinson (1952), in the Ardmore Basin/Arbuckle Mountain region, led to the interpretation of the exposed Washita Valley Fault as a "propeller shaped" fault, with oppositely-directed vergence which progressed outward from a null point where the fault reversed dip. It should be noted that Tomlinson considered the "propeller" shape indicative of overthrusting and rotation rather than strike-slip motion.

Based upon detailed surface mapping of the Arbuckle Anticline, Ham (1951) and McKinley (1954) and Dunham (1955) proposed left-lateral strike-slip along the Washita Valley Fault. These authors interpreted the Washita Valley Fault as the master fault of a strike-slip system and called for one-to-three miles of left-slip, a figure which represents the conservative end member of subsequent left-slip estimates.

Tanner (1967) wrote an influential paper in which he defined the lateral extent of the Washita Valley Fault System as extending from Dolye Field (northeast corner of T. 1N. R. 5 W.), across the Arbuckle Uplift to the south flank of the Tishomingo Uplift, a minimum of 150 miles in length (Fig. 1.3). Based upon apparent separation of the zero isopach of the basal Oil Creek Sandstone, Tanner ascribed 40 miles of left-slip to the "Washita Valley Fault Zone". Tanner was the first worker to attribute large amounts of lateral slip to faults in southern Oklahoma and "defined" the lateral extent of the "Washita Valley Fault". However, Tanner failed to offer evidence to document a vertical geometry for the "Washita Valley Fault" and did not recognize the presence of the subsurface Arbuckle Thrust.

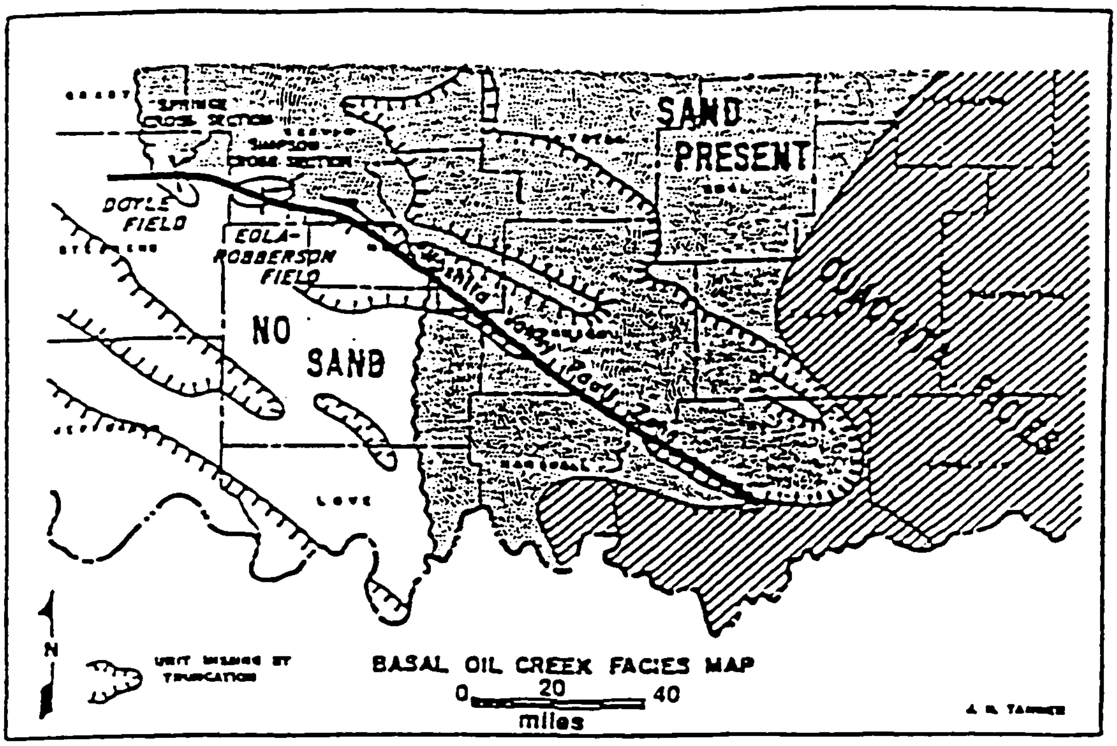


Figure 1.3. Isopach map of the basal Oil Creek Sand in the Ardmore-Arbuckle region. The apparent separation of the zero isopach line is used as a piercing point to infer 40 miles of left-slip along the "Washita Valley Fault". Note that NE-SW oriented crustal shortening is not accounted for in this restoration. This restoration ignores the presence of the well-documented Arbuckle Thrust (Brown, 1984). The zero line is not offset south of the Arbuckle Uplift where it crosses the Criner Hills, indicating no left-slip on the Wichita-Criner System. This diagram illustrates the use of apparent separation as slip. The separation shown in this illustration is predicted on the "Washita Valley Fault" as being one fault (or fault system) with the lateral extent as indicated on this map (150 mile fault length) and having a vertical dip (modified from Tanner, 1967).

Recent Interpretations (1970-present)

During the 1970's and early 1980's, models involving wrench tectonics and large amounts of left-lateral offset along vertical faults gained popularity. However, by the mid-1980's several workers presented strong evidence that deformation along the Wichita and Arbuckle uplifts involved large amounts of crustal shortening and basement overhangs on shallow-dipping faults. Currently, debate is broken into three camps; wrench fault proponents, dip-slip proponents, and oblique slip or "transpression" proponents.

Walper (1977) argued that convergence between the North and South American plates produced a series of northwest-trending megashears across Oklahoma and Texas during the Pennsylvanian. Wickham (1978) supported left-lateral offset along the Washita Valley Fault. Wiltse (1978) interpreted folding in the Southwest Davis Field, on the north flank of the Arbuckle Anticline, as the *en echelon* folding associated with left-slip on the Washita Valley Fault. Harding and Lowell (1979) presented a "flower structure" interpretation of a fold in the Ardmore Basin.

Working in the Arbuckle Mountains, Carter (1979) and Booth (1981) argued for 20 miles and 3 to 40 miles of left-slip, respectively. Haas (1979) classified the Reagan Fault on the north side of the Tishomingo Uplift, as a left-lateral wrench fault which extends in the subsurface across the Mill Creek Syncline into the Eola region. Haas states the Reagan Fault has 10,000 feet of vertical uplift, but did not address the effect of the plunge of the Tishomingo Uplift on this estimate. None of these workers offered evidence to document their assertion of vertical fault geometry.

Brownlee (1981) investigated strata of the Simpson Group occurring above the Eola Anticline and concluded that these sediments were deposited by gravity slides off the Robberson "Horst" which was uplifted by left-lateral wrenching on the Washita Valley Fault. Brownlee (1981) clearly states that she disregarded dipmeter data when the data "seemed most in error or created impossible geologic situations". She offered no explanation as to the cause of mass dipmeter error, nor what constitutes an "impossible geologic situation". Her conclusions of left-slip were based upon the previous work of others and she offered no new evidence to support her assertion.

Axtmann (1983) attributed one to three miles of left slip on wrench faults along the frontal Wichita Mountains. Axtmann stated that left-slip is more important than vertical slip. However, the documented 30,000 feet of vertical relief on the basement is more than the maximum amount of about 16,000 feet left-slip that he postulates! Axtmann failed to document his inferred structural geometries, or fault relationships with cross sections or seismic data.

Williams (1985) described deformation south of Sulfur, Oklahoma as due to right-lateral slip. Williams indicated that these findings do not match previous studies which support left-slip, so he invoked a drastic shift in the assumed paleo-stress field which, curiously, only affects his particular area of study. By reinterpreting cross sections of Harlton (1964), Phillips (1983) interpreted outcropping and sub-surface deformation north of the Washita Valley Fault to be the result of gravity-sliding of large sheets of sediments from the emerging Arbuckle Uplift.

Harding and Lowell (1979) described southern Oklahoma as a wrench system And introduced the flower structure concept to the area. They presented an interpreted seismic line over an un-named fold (probably the Madill-Aylesworth Anticline). Most of the details of their interpretation, including the dip of the controlling fault with depth, are in zones of unintelligible data.

McLean (1983) assigned the Wichita Mountains to a strike-slip system, with an upthrust-shaped fault, based upon analysis of apparent separation across fractures and fracture patterns in exposed basement rocks. McLean was not able to constrain the age of the fractures and thus was unable to specifically state which tectonic event(s) formed them. Because the fractures were measured in essentially flat igneous rock, McLean was unable to obtain a three dimension view of the fracture, and their true slip vectors.

Additioanlly, McLean was not able to show that the fracture pattern observed in the basement is present, or related to differing pattens, in the sedimentary section. The discepency indicates that the basement fractures pre-date Pennsylvanian deformation.

Brewer and others (1983) presented data from COCORP seismic profiles across the Wichita Uplift and Anadarko Basin which revealed the uplift-bounding fault to be a thrust fault, dipping southwestward at 25-35° underneath the Wichita Uplift (Fig. 1.4).

In a study using subsurface well data, properly oriented, structurally balanced cross section, and published maps, Brown (1984) showed that the Washita Valley Fault is a back-limb imbricate of the buried master fault of the Arbuckle Uplift. Brown named this fault the Arbuckle Thrust, which extends north of the Washita Valley Fault and underlies the SE Hoover and SW Davis Fields (Fig. 1.5). This interpretation was supported by a structural contour map of the Arbuckle Thrust plane based upon well penetrations of the thrust. Additionally, Brown demonstrated that apparent left-lateral offsets of the basal Oil Creek Sand zero isopach line, noted by Tanner (1967), could be accounted for by extending contours to match cut-offs on the hanging wall and footwall of the thrust plane, rather than a vertical fault plane. Brown's palinspastic restoration of the zero sand isopach line across overturned folds and reverse faults showed little or no lateral slip.

Workers such as Julliard (Dougherty Anticline, 1982); Powers (Southwest Davis Field, 1984); Ostroff (Colbert Creek Anticline, 1985); Fletcher (Caddo Anticline, 1986); Palladino (Washita Valley and Ravia Faults, 1986); and Sralla (Southeast Arbuckle Anticline, 1993), have all demonstrated that structures in the Arbuckle Mountain region have formed as a consequence of dominantly northeast-southwest oriented horizontal compressive stress. These studies emphasized the importance of parallel folding as the dominant mechanism for the deformation of the sedimentary section. Beck (1987) showed a portion of the Arbuckle Thrust in detail and presented

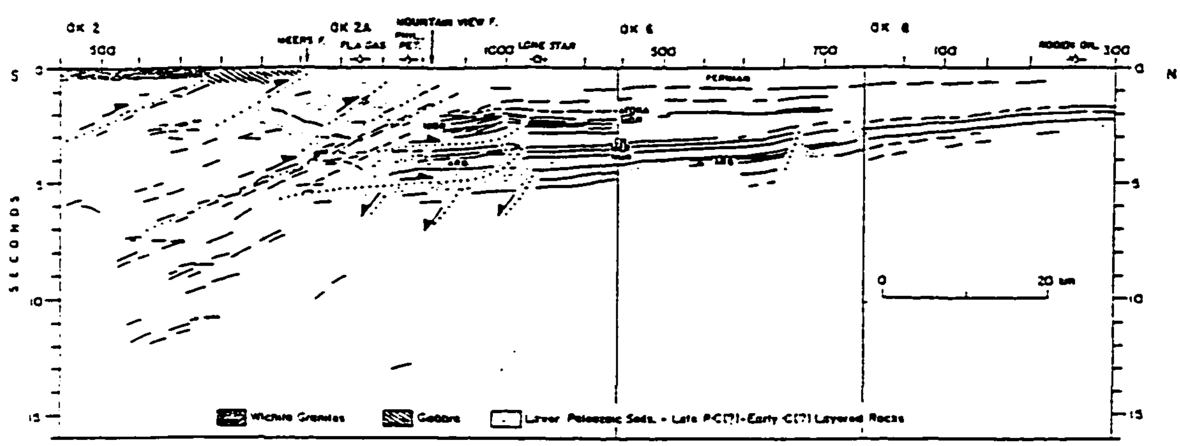


Figure 1.4. Interpretation of COCORP seismic line from Brewer and others (1983). The COCORP seismic documented the low-angle nature of the uplift-bounding faults of the Wichita Mountain Front, the asymmetric nature of the Wichita Uplift, and the presence of large basement overhangs; features consistent with NE-SW oreinted crustal shortening.

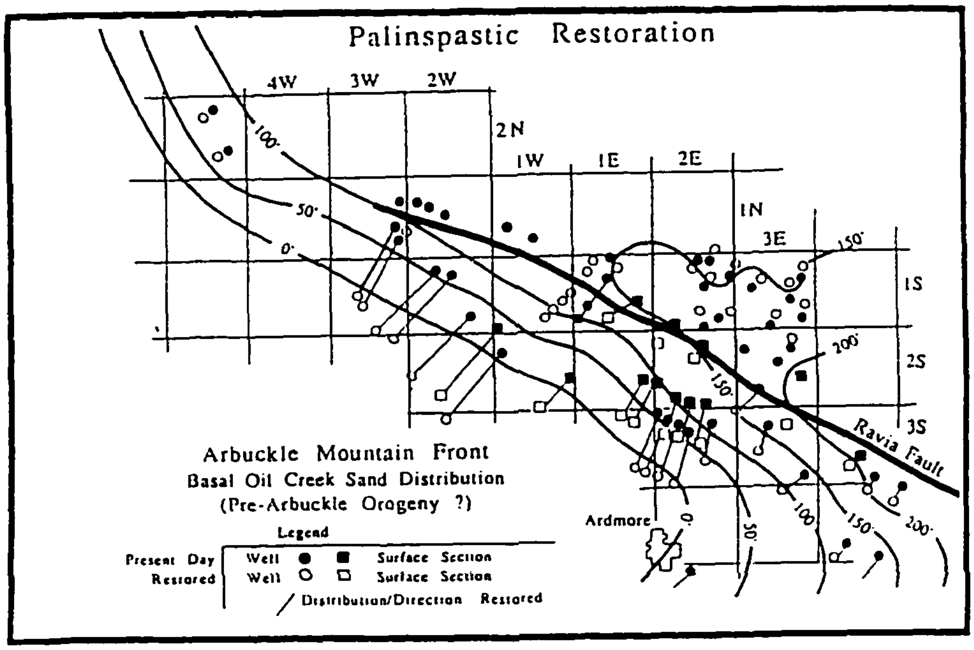


Figure 1.5. Palinspastic restoration of the Arbuckle Thrust from Brown (1984). By properly defining the fault plane with contours, and restoring hanging wall isopach contours lines to the footwall contact, Brown showed that apparent lateral offset patterns (on the "Washita Valley Fault") can be produced by dip-slip thrusting, and documented the presence, and significance, of the Arbuckle Thrust. Brown's interpretation that the Arbuckle Thrust continues south of the surface trace of the Washita Valley Fault was later confirmed by the drilling of the Hamilton Brother's Turner Falls #1-18 well. This well, located south of the surface trace of the Washita Valley Fault, drilled over 14,000 feet of basement, penetrated the Arbuckle Thrust, and encountered southwest dipping lower Arbuckle Group rocks.

well control which documented that the SE Hoover Field was a hanging wall anticline on the buried Arbuckle Thrust. Based upon well control, he showed the Washita Valley Fault to have a southwest dip of 60°.

McConnell (1987) presented a detailed examination of the Wichita Uplift from the Texas Panhandle to the vicinity of Apache Field, and concluded that the Wichita Mountains were uplifted by reverse dip-slip motion on the Mountain View Fault. However, in a subsequent article (McConnell, 1989), he used the same data to interpret slip on the Mountain View Fault as left-oblique, with a ratio of 2:1 lateral motion to dip-slip, with constant slip vectors along the length of the fault.

Hardie (1990) found that thrusts of the Ouachita System were folded in the Isom Springs Field, located in the Bryan Salient of the Ouachita foldbelt, by northeast-southwest oriented compression related to the Arbuckle Orogeny. Uplift of the Tishomingo block folded the overlying stratigraphic section, including the earlier thrust sheets; subsequent erosion resulted in their present day "reentrant" outcrop/subcrop pattern in the Bryan County salient. The Ouachita thrust sheets show no evidence of offset by widely postulated strike-slip faulting. These relationships are strong evidence that the compressive event (Arbuckle Orogeny) was not a function of, nor accompanied by, regional strike-slip motion.

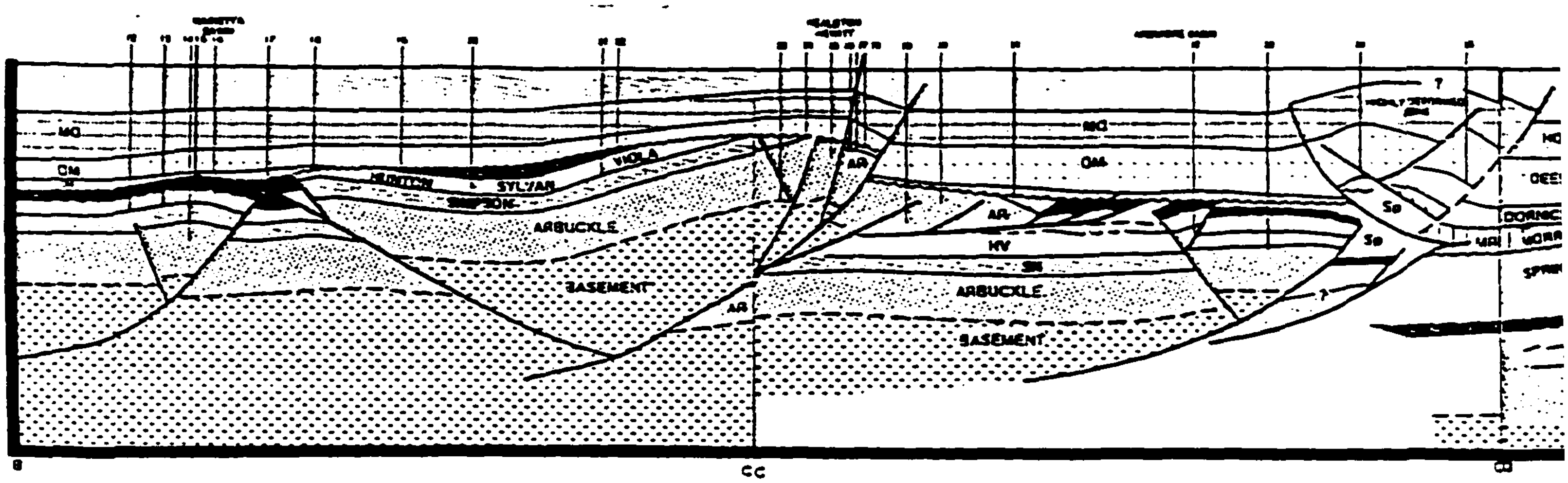
Bixler (1993) studied the geology along the Interstate 35 roadcut across the Arbuckle Anticline and documented northeast-southwest oriented shortening in the pre-Pennsylvanian sedimentary section. Saxon (1994) studied the exposed western portion of the Arbuckle Uplift and its subsurface geometry, along the northwest plunge. Saxon combined surface data, well data, and seismic to document progressive change in dip, and loss of slip, along the Arbuckle Thrust. He documented the presence of a late-stage, down-to-the-south extension fault (the Washburn Ranch Fault) on the south flank of the northwest plunge of the Arbuckle Anticline.

Naruk (1994) offered a restored cross section across the Arbuckle Anticline based upon a fault-bend fold model. Cooper (1995) presented a detailed investigation of the Criner Hills portion of the Wichita Uplift based upon several high-quality regional seismic profiles, which were integrated with closely-spaced, properly oriented structural cross sections (Fig. 1.6). He concluded that the Criner Hills were a northeast-directed foldbelt and found no evidence for left-lateral offset.

Summary

Structural styles, geometry of major uplifts and intra-basin structures, and fault geometries, relationships, and sense of slip, remain poorly defined in southern Oklahoma. Proper documentation of these aspects of southern Oklahoma structural geology are the goals of this study. Current structural understanding centers upon debate over the dominance of left-lateral strike-slip motion, along high-angle faults (wrench tectonics), versus the concept of northeast-southwest directed horizontal compression along moderate or low-angle faults, or, possibly, left-slip along low-angle faults.

Figure 1.6. Composite time-cross section constructed from seismic lines across the Wichita-Criner Uplifts and Ardmore Basin. Note the overall northeast vergence to the uplifts, the presence of southwest-dipping thrusts, and the presence of northeast-dipping back-thrusts. Several major faults appear to be detached. The style indicated in this interpretation is consistent with NE-SW oriented horizontal compression (modified from Cooper, 1995).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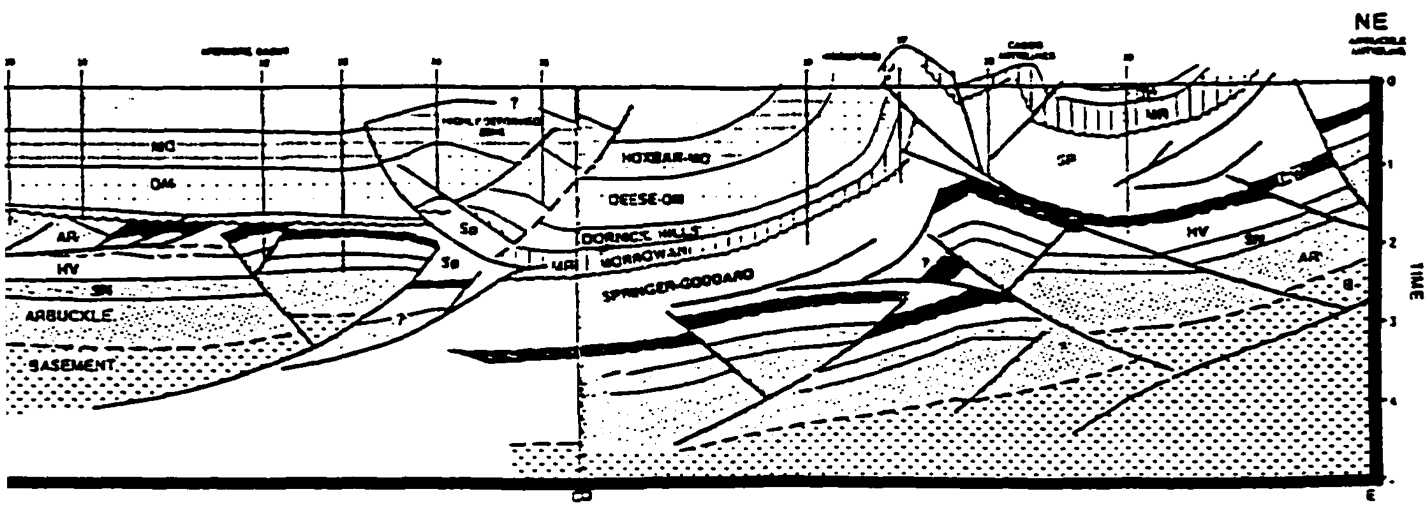
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Chapter 2

TECTONIC SETTING

Introduction

The Wichita and Arbuckle Orogenies are elements of regional late Mississippian-early Permian intra-plate deformation, which created northeast-southwest crustal shortening in the form of a series of basement-cored uplifts and coeval basins. The area of basement-involved deformation in southern Oklahoma is collectively referred to as the Southern Oklahoma Foreland and is a province of the greater Pennsylvanian Foreland. Deformation occurred north and westward of, and contemporaneous with, the emplacement of the Ouachita-Marathon foldbelt, but may not be directly causally related (Ye and others, 1996). Wichita and Arbuckle deformation was superimposed across a pre-existing extensional basement fabric created by late Precambrian-Cambrian-age rifting, oriented northwest-southeast across southwestern Oklahoma. The Wichita Orogeny occurred in late Mississippian to Atokan and resulted in northeasterly-directed thrusting of the Wichita Uplift and formation of the present-day Anadarko Basin. The Arbuckle Orogeny occurred in Late Desmoinesian to Early Permian and involved uplift of the Arbuckle Anticline and formation of the Ardmore Basin. Both uplifts involved northeast-directed crustal shortening and have produced some of the most complicated and economically significant structures in North America.

Pennsylvanian Foreland

The Pennsylvanian Foreland (Fig. 2.1) consists of the basins forelandward of the Ouachita-Marathon foldbelt. These basins and uplifts have been buried by younger

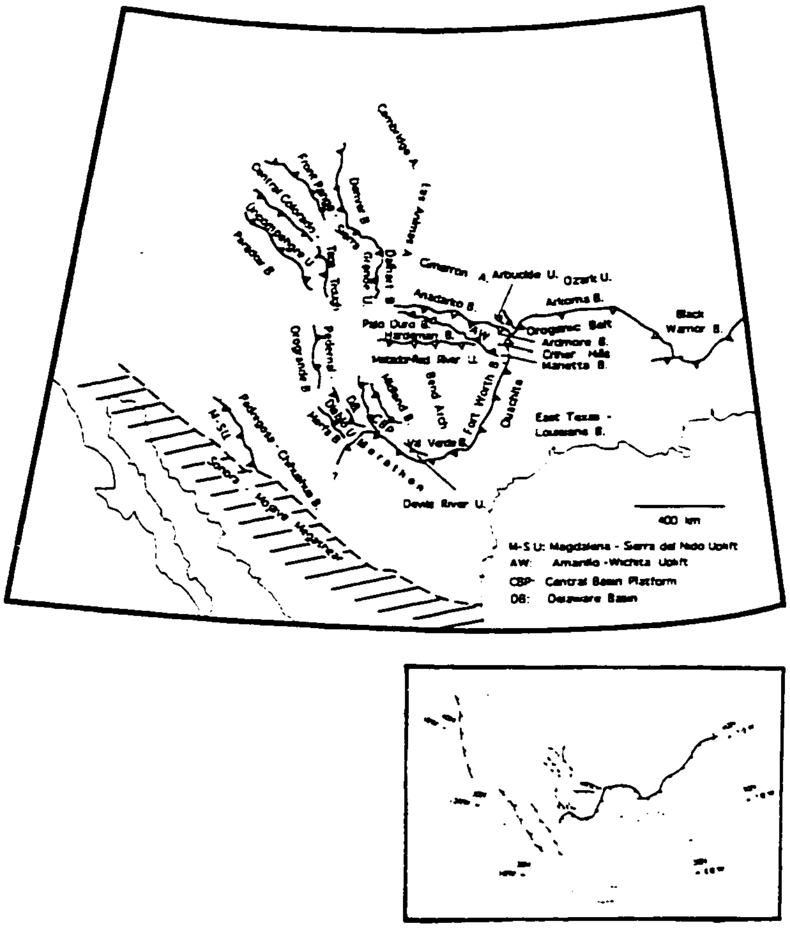


Figure 2.1. Tectonic map showing the location of the uplifts and basins of the Pennsylvanian Foreland. The Southern Oklahoma Foreland is a province of the Pennsylvanian Foreland and consists of the Amarillo-Wichita-Criner trend and the Arbuckle-Tishomingo system. These uplifts and their associated basins were re-activated by Pennsylvanian deformation across a previous northwest-southeast oriented grain of Cambrian extension (Ye and others, 1986).

sediments, and in some cases, overprinted by more recent tectonic events, obscuring the original structural geometry and relationships (Ye and others, 1996). At least two systems of deformation, the Delaware Basin of west Texas and southeast New Mexico and Southern Oklahoma Foreland, are superimposed over preexisting rifts related to extension of the southern margin of North America during the Late Neo-Proterozoic-Cambrian. The uplifts and basins are generally oriented northwest-southeast and accomodate northeast-southwest directed crustal shortening along low-angle reverse faults (Ye and others, 1986). Structural style consists of asymmetric uplifts thrust over paired basins (Fig. 2.2).

Evolution of the Southern Oklahoma Foreland

The tectonic evolution of the Southern Oklahoma Foreland can be characterized by three major stages; 1) rifting, 2) subsidence, and 3) deformation (figure 2.3). Cambrian rifting and associated magmatic activity created the initial basement fabric of southern Oklahoma, which was subsequently modified by deformation of the Wichita and Arbuckle Orogenies of the Late Paleozoic. Many details are poorly understood; however, a general tectonic framework and sequence of events can be reconstructed.

Late in the Precambrian-to-Early Paleozoic southern North America underwent rifting which separated it from its earlier position attached to the proto-Afro-South American plate (Wickham, 1978). The extension formed a series of failed rifts which extended into the craton. Dewey and Burke (1973) proposed that rifting was generated by a series of plume-generated triple junctions, which swelled and thinned the crust. The crust then broke along a series of three-armed rifts, each 120° apart. Two of the three arms experienced the majority of the extension and linked with other triple junctions to form the continental boundary. The third "arm", which extended into the

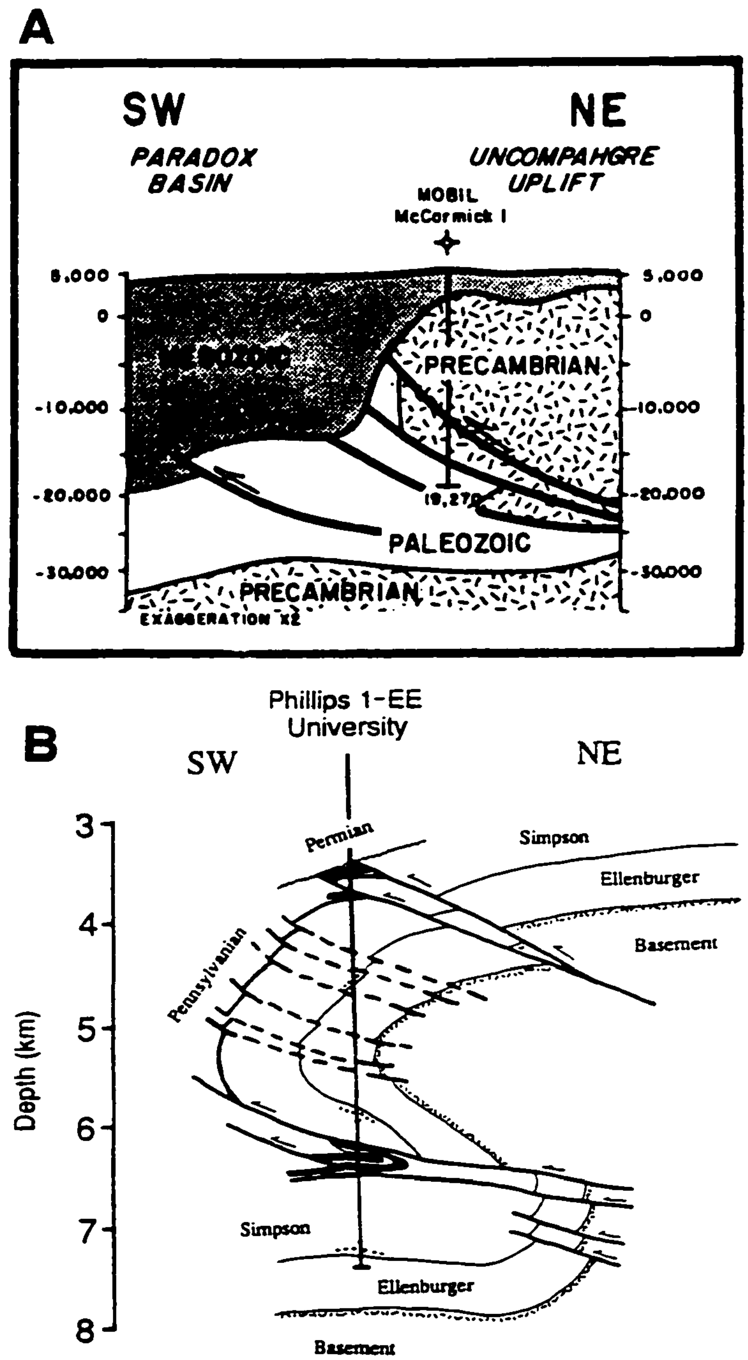


Figure 2.2 A. Cross section showing crustal shortening along low-angle mountain-flank faults of the Unompahgre Uplift, Park County, Utah (Gries, 1983). The Uncompahgre Uplift is part of the extensive Pennsylvanian Foreland (Ancestral Rockies). B. Cross section through a basement-cored uplift in west Texas (Ye and others, 1996). Both sections show the northeast-southwest directed crustal shortening which was common to uplifts of the Pennsylvanian Foreland.

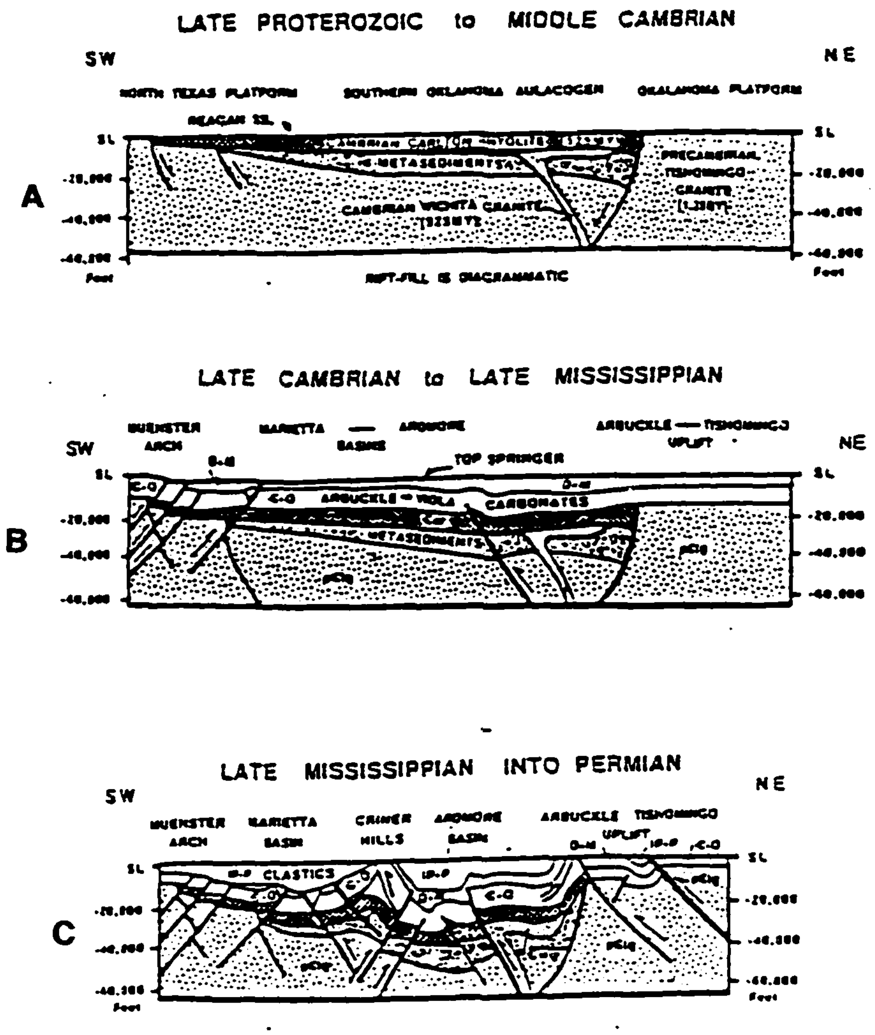


Figure 2.3 Sequential evolution of the Southern Oklahoma Rift. A. Intitial extension during the Late Proterozoic. B. Subsidence allows for the accumulatin of thick sequences of Lower Paleozoic sediments. Onset of crustal shortening in Late Mississippian. C. Late Mississippian to Permian dismemberement and shortening of the former rift during the Arbuckle Orogeny (from Brown, 1991).

continental interior, ceased rifting, creating a failed arm. Four such rifts may have been formed along the Early Paleozoic margin of North America, including thesouthern Oklahoma rift. An alternative explanation holds that the interior rifting in southern Oklahoma is the result of landward continuation of a transform fault formed by the opening of the proto-Gulf of Mexico (Thomas, 1989; Arbentz, 1989).

Magmatism accompanied the rifting in the southern Oklahoma arm; subsidence formed a deep trough, presumably along the outlines of the rift, which filled with a greatly expanded thickness of Early Paleozoic sediments. This trough, which was subsequently deformed in the Pennsylvanian has been cited as a type example of an aulocogen by Schatski (1946) and is often referred to in literature as the Southern Oklahoma Aulocogen. The term aulocogen infers a re-activation of a previous rifitning event. In order to distinguish between the rifting and later deformational events, in this study it is referred to as the Southern Oklahoma Rift.

The Southern Oklahoma rift was emplaced along the north flank of an older Proertozoic basin which is preserved south of the current Wichita Mountains under the present Hardeman Basin. The basin is inferred from pronounced, high-ampliude, laterally continous and relatively undeformed layering of the Pre-Cemabrian crust visible on COCORP data. The layering is present to depths of 13 km. The basin is probably filled with clastic sediments and felsic volcanics, though poor exposure and lack of well data preclude a better understanding (Brewer and others, 1983).

Details regarding the exact boundary and geometry of the Southern Oklahoma Rift are not well known due to deep burial and subsequent tectonic overprinting. Most evidence comes from the examination of exposures of the associated suite of igneous rocks. McConnell and Gilbert (1986, 1987) proposed normal faults to have rotated and tilted layering within near-surface intrusive rocks. According to Gilbert (1983), the initiation of the rift stage began in Early Cambrian, with the rise and emplacement of the mafic Glen Mountains Layered Complex which has been dated at 577 m.y. (Sides and

Stockton, 1981; Lambert and Unruh, 1986). This mafic complex contains many similarities to other layered mafic bodies. Dip of internal features suggests rotation along south-dipping normal faults, post-dating emplacement (McConnell, 1987). Subsequent to faulting, the Glen Mountains Layered Complex was intruded by the Roosevelt Gabbros, a series of gabbroic plutons (McConnell, 1987).

A period of erosion took place during which rocks were stripped nearly to their present-day level along a sub-horizontal unconformity (Ham and others, 1964). The Carlton Ryholite erupted and accumulated on this unconformity. The Carlton Rhyolite consists of laterally extensive layers of silicic rhyolites and ash-flow tuffs. The accumulation of the rhyolite was accompanied by emplacement of granite sills between the rhyolites and underlying gabbros. The sills are referred to as the Wichita Granite (Ham and others, 1964).

Based upon thicknesses of granite accumulation, McConnell (1987) postulated a half-graben setting with preferential subsidence to the north as the setting for the rhyolite. Based upon magnetic and gravity data, Brown (1997) proposed that the rift formed as a series of opposing half-grabens. Denison (1982) and Brown (1991) presented cross sections which contain stratigraphic relationships which suggest rift geometry across the present-day Criner Hills and Arbuckle regions was a half-graben, with down-to-the-south motion (Fig. 2.2).

Thermal cooling is thought to have controlled the relatively large subsidence rates of the rift immediately following the cessation of igneous activity. Although the same units accumulated on the craton as in the subsiding rift, the thickness of the material within the rift is substantially greater than the thickness of sediments on the craton. The Cambrian-through-Mississippian stratigraphy reflects this history, with fewer unconformities within the rift than along the rift margins (Ham, 1969).

Late Paleozoic deformation occurred throughout the interior of western North America, producing a series of paired-basement uplifts and asymmetric basins oriented north-northwest to northwest (Ye and others 1996). The intra-plate deformation was coeval with the collision of North America with the proto-Afro-South American plate which formed the Ouachita-Marathon orogenic belt during the formation of Pangea. In the Southern Oklahoma Foreland, deformation occurred in two main pulses; the Wichita Orogeny and the Arbuckle Orogeny (Fig. 2.4). The Wichita Orogeny, which began in Late Mississippian and ceased mostly by the Atokan, formed the Wichita Uplift and Anadarko Basin. The Wichita Uplift extends from the Texas Panhandle southeastward across southern Oklahoma, and into the Criner Hills of south-central Oklahoma. Initial deformation of the Tishomingo Uplift and Hunton Arch of the Arbuckle region was contemporaneous with Wichita deformation.

The Arbuckle Orogeny represents a later pulse of deformation extending from Desmoinesian to Early Permian. Uplift occurred on the Arbuckle Anticline as a result of compression of the area between the Criner Hills and the Tishomingo-Hunton system, along with major rejuvenation of the Tishomingo Uplift, Hunton Arch, and portions of the Criner Hills. The Ardmore Basin formed between the Arbuckle-Tishomingo Uplifts to the north and the Criner Hills to the south. A poorly recognized late-stage extensional system formed shortly after maximum uplift of the Arbuckle Anticline was obtained, resulting in down-to-the-south extension on the Washburn Ranch Fault on the Arbuckle Uplift (Saxon, 1994). Extension may have occurred as a relaxation of compressive stresses and/or gravity instability. The extensional phase is poorly documented and unrecognized in most literature but seems to follow the tectonic cycle of compression followed by extension which is common in the Rocky Mountains of Tertiary age.

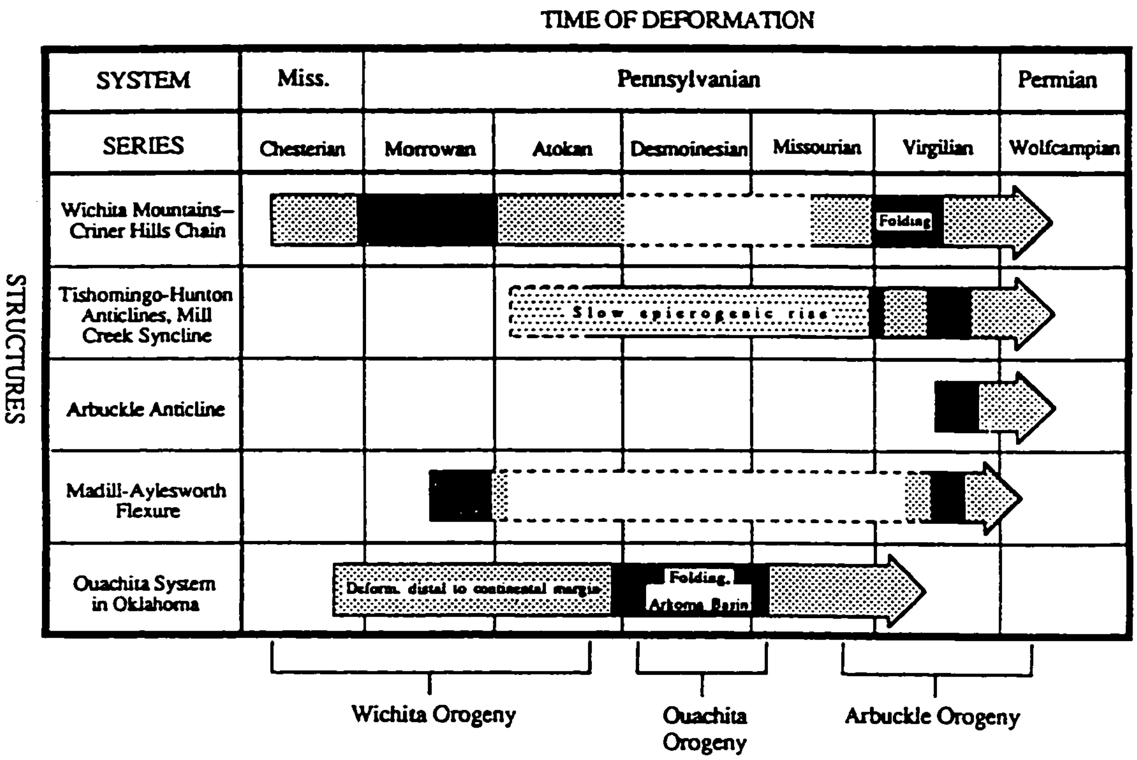


Figure 2.4 Chart of the sequential orogenic deformation of the Southern Oklahoma Foreland showing temporal relationships of the Wichita, Ouachita, and Arbuckle Orogenies. Shaded areas on arrows indicate significant pulses of deformation (from Hardie, 1990).

Relationship of the Ouachita-Marathon System to the Pennsylvanian Foreland

Details of the plate tectonic setting of the Pennsylvanian Foreland are not completely agreed upon by many authors and much speculation has centered upon the relationship of the plate-setting of the Ouachita margin and foreland deformation. Historically, most workers have related the intra-plate deformation to an assumed northwest-southeast collision of North America with the proto-Afro-South American plate (Walper, 1977; Kluth and Coney, 1980). This is complicated by the geomtery of the Ouachita-Marathon margin which contains several right-angle turns and may represent a progressive suturing of an irregular boundary through time (Kluth and Coney, 1980). Working with Kluth and Coney's plate scenario, Hardie (1990) calculated the convergence vectors for the North American and South American-African plates during the Pennsylvanian and found that by varying the rate of convergence of either plate, the resulting convergence vector changed direction with time from north-south to northwest-southeast to northeast-southwest throughout the Pennsylvanian (Fig. 2.5). Brown (1985) questioned the ability of the crust to transmit stresses over long distances and proposed that Pennsylvanian Foreland deformation was caused by horizontal compression generated as a product of ablative subduction.

Ye and others (1996) question the causal relationship of the Ouachita margin with intra-plate deformation. They point out that the Ouachita-Marathon system is more consistent with obduction of an accretionary prism than a continent-continent or continent-island arc collision, citing a lack of high-grade metamorphism, lack of extensive basement involvement, low topography, and numerous other factors. They suggest Pennsylvanian Foreland deformation was related to an Andean-type Late Paleozoic subduction zone in northeast Mexico (Fig. 2.6). They suggest a setting similar to the Laramide Orogeny, which created crustal shortening of the Rocky

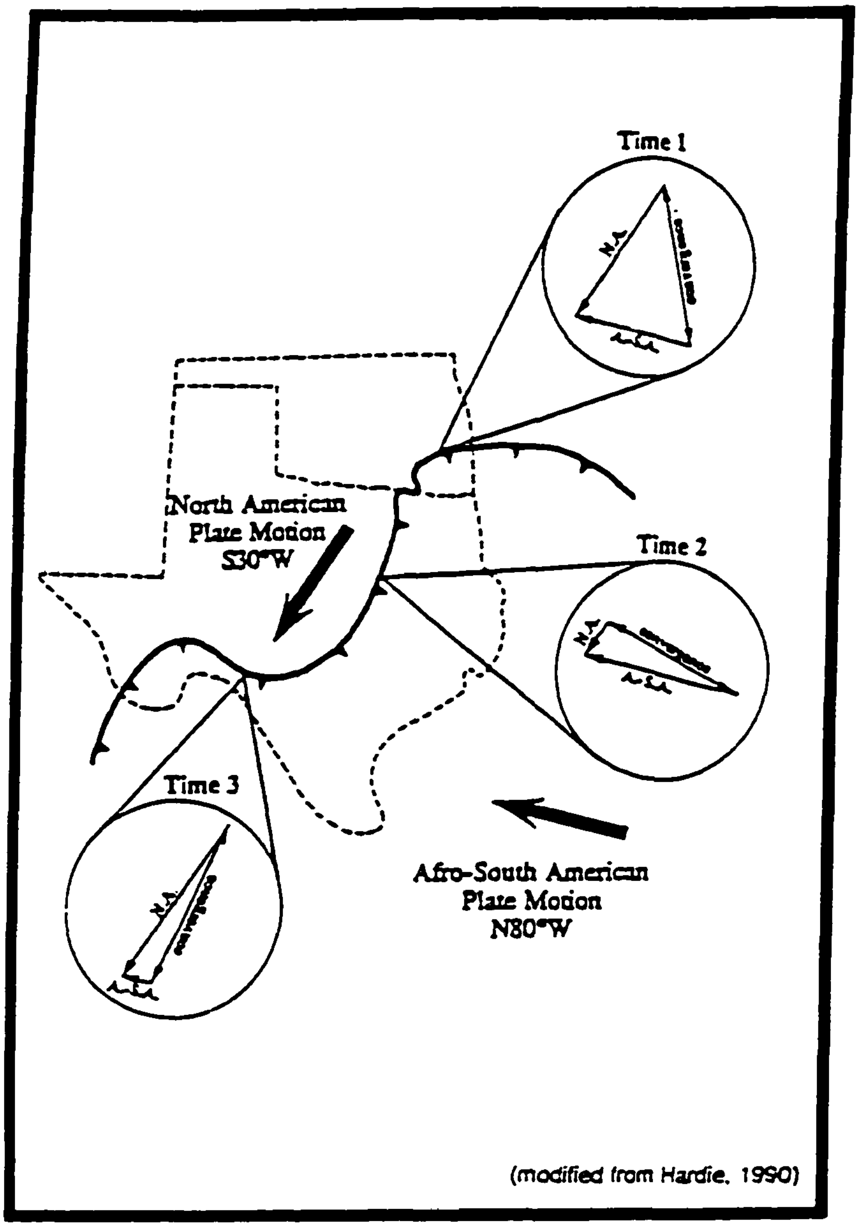


Figure 2.5 Possible convergence vectors between North and South America during the Pennsylvanian. The Ouachita-Marathon thrust front has an irregular shape with apparent multiple directions in convergence. This can be explained by resolving a N50W compressional regime into two vectoral components: a N80W direction for the Afro-South American plate, and a S30W direction for the North American Plate (from Hardie, 1990).

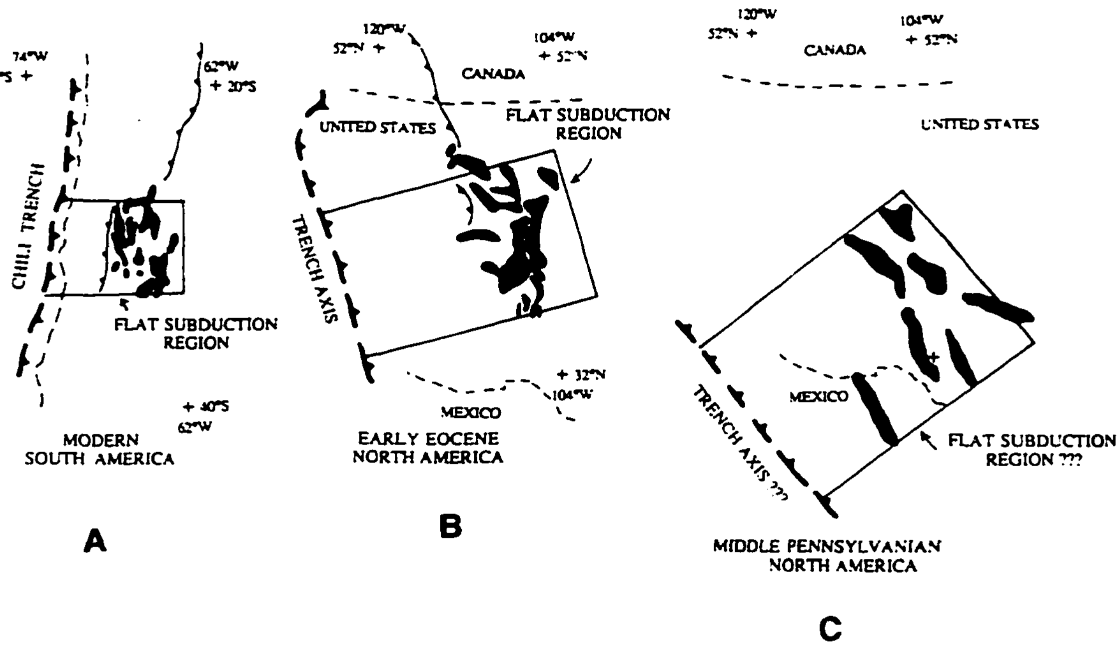


Figure 2.6 Map views comparing the modern-day basement involved deformation in the A) Sierra Pampeanas, South America to deformation of the B) Rocky Mountain Foreland and C) the Pennsylvanian Foreland. All three models may be the product of a flat subduction complex (from Ye and others, 1996).

Mountain Foreland, or modern subduction in South America, which has deformed the Sierra Pampeanas.

Summary

A late Precambrian-early Cambrian rifting, oriented northwest-southeast, with extension perpendicular to strike, formed a significant, though-poorly understood basement fabric across southern and southwestern Oklahoma. The rift imparted anisotropies into the crust, including normal faults (probably listric) and layered intrusive and extrusive igneous rocks. The rift was emplaced between the relatively stable craton and an older Proterozoic basin with layered crust, located south of the present-day Wichita Mountains. The exact boundaries and internal geometry of the rift cannot be well-documented because of deep burial and tectonic overprinting. Although they undoubtedly had a strong mechanical influence upon later Paleozoic deformation, their exact influence remains somewhat speculative. The Southern Oklahoma Foreland is a province of the Pennsylvanian Foreland which experienced crustal shortening throughout the interior of southern and western North America. Deformation of the Pennsylvanian Foreland has historically been associated with the Ouachita-Marathon fold belt, but may be more directly related to low-angle subduction in northern Mexico.

Chapter 3

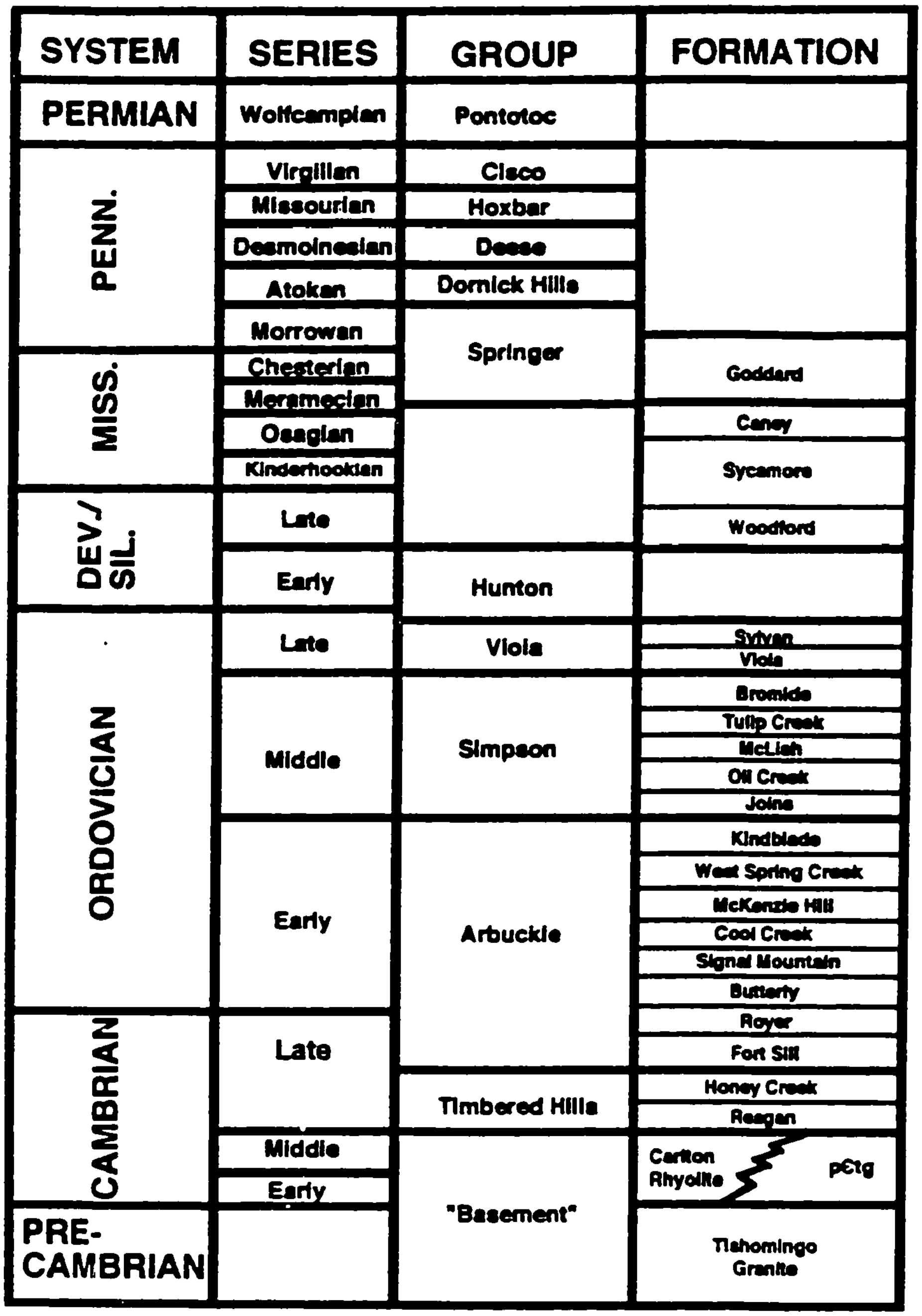
STRATIGRAPHY

Introduction

The stratigraphic column (Fig. 3.1) is represented by igneous rocks, which range from Precambrian and Cambrian in age, and a series of sedimentary rocks ranging from Cambrian through Permian in age. In the southernmost portion of the study area these rocks are overlain by a thin veneer of Cretaceous sedimentary rocks. Roughly speaking, the Paleozoic stratigraphy represents two broad tectonic influences; an early rifting and subsidence phase, and a later, shortening and uplift, phase. Mechanically, the stratigraphy can be thought of as at least three major intervals; a semi-horizontal, layered basement; a thick basal carbonate section; and a clastic basin-fill section. Orientation of deposition along the strike of the northern margin of the Southern Oklahoma Rift was probably controlled by the irregular shape of the original rift margin.

Pre-Mississippian Stratigraphy

Basement rocks consist of variable layered Cambrian intrusive and extrusive rocks overlaying faulted Precambrian crystalline rocks of the craton. Exposures on the margins of the Southern Oklahoma Rift are composed of Precambrian Tishomingo Granites. Within the rift, basement rocks of the Arbuckle Mountains are comprised of the Cambrian Carlton Rhyolite. Within the Wichita Mountains, multiple Cambrian igneous rocks crop out, including extensive exposures of the Wichita Granite Group and its most extensive unit, the Mount Scott Granite. The basement rocks carry a semi-horizontal layering and are highly fractured.



(Modified from Beck, 1987)

Figure 3.1 Stratigraphic column for southern Oklahoma.

The oldest sedimentary section is represented by the poorly understood Precambrian Tillman Metasediments. These sediments were deposited in a Proterozoic basin which underlies the Wichita Uplift and are most likely comprised of clastic sediments and felsic volcanics. Most evidence for the Tillman Metasediments is derived from analysis of COCORP lines (Brewer, 1983). Tillman Metasediments appear to be well developed south of the Wichita Mountain front and there is no direct evidence of them within the Anadarko Basin.

The oldest post-rift sediments are represented by the Upper Cambrian Reagan Sandstone of the Timbered Hills Group, which rests unconformably upon both the rift-filling rhyolites and the Precambrian Tishomingo Granite, separated by a 20-25 Ma ersosional interval. The Reagan is comprised of feldspathic and glauconitic, conglomeratic-to-medium-grained, immature sandstone, derived from the "basement" rocks upon which it rests. Thickness ranges from approximately 500 feet, to locally absent. The importance of the Reagan is that it was deposited continuously across rift-filling igneous extrusive rocks (Carlton Rhyolite) and the "stable" cratonic rocks (Tishomingo Granite), indicating that following the rift-fill event an unbroken depositional surface extended across southern Oklahoma. The Timbered Hills Group accumulated as part of the craton-wide transgressive Sauk sequence. The overlying Honey Creek Limestone shows great variability and is often included in the overlying Arbuckle Group in electric log picks.

Within the subsiding rift, the Arbuckle Group is an unusually thick sequence of fairly similar carbonate facies, which range in age from Late Cambrian to Early Ordovician. The Arbuckle Group consists of seven formations, in descending order: West Spring Creek, Kindblade, Cool Creek, McKenzie Hill, Signal Mountain, Royer Dolomite, and Fort Sill. Based upon observation made on outcrops of the Arbuckle Anticline, Fay (1989) places the total thickness of the Arbuckle Group at 6,700 feet.

The vast thickness and relative vertical consistency of facies suggests that the rate of deposition was near-equal to that of subsidence in the rift.

In outcrop, the Arbuckle Group was internally deformed through small-scale folding on bedding plane-slip. Folds may be tight, and often exhibit ramp-flat and fault-propagation fold geometry. Fractures and folds on the Arbuckle Anticline suggest the presence of normal faults in the lower Arbuckle Group, which may be related to subsidence (Saxon, this volume).

Overlying the Arbuckle Group is the Middle Ordovician Simpson Group. In the Arbuckle Mountains the Simpson Group consists of a series comprised of basal sand, shale, and upper limestone sequences totaling 2,330 feet. The thickness appears to decrease towards the west and become more shaly and dominated by carbonates. Within the Ardmore Basin/Arbuckle Mountains, and to a lesser degree within the Wichita/Anadarko areas, Simpson shales typically serve as important detachment horizons (Brown ,1984, 1990: Saxon, 1994).

Overlying the Simpson Group, is the Middle Ordovician Viola Group. The Viola ranges in thickness from 400 to 700 feet and is easily recognized by a "double hump" appearance in both electric-log pattern and outcrop erosional pattern. The characteristic appearance is caused by a middle shale unit. Above the Viola Group is the Upper Ordovician Sylvan Shale which acts as an important host of bedding-planar detachments.

The Hunton Group, overlying the Sylvan Shale, is a series of limestones and dolomites which were deposited during the Ordovician, Silurian and Devonian (Amsden, 1975). The Hunton Group consists of seven formations separated by multiple unconformities. In ascending order they are: the Keel, Cochrane, Clariata, Henryhouse, Haragan, Bois d'Arc, and Frisco Formations. The Hunton Group is one of the most important reservoir units in southern Oklahoma. Thickness of the Hunton ranges from zero to over 1600 feet. Following Hunton deposition, much erosional channeling occurred on the pre-Woodford unconformity. Internally, the various formations of the Hunton are separated by unconformities which represent periods of subaerial exposures and widespread development of karst features, dissolution features, and collapse breccia which reflect these exposure events (Mathews, 1994). The variations in thickness and internal characteristics in the Hunton are important to note because many workers (Carter, 1979; McConnell, 1987, 1989) have tried to construct strike-slip constraints along southern Oklahoma faults by using isopachs of the Hunton, or intervals of the Hunton. Although very general regional trends can be mapped, the Hunton contains far too many variations to make it a consistent and reliable maker (piercing points) for slip restorations, especially when the data must be made from subjective interpretations (contours).

The Woodford Formation is separated from the underlying Hunton Group by a widespread unconformity. The Woodford is comprised of cherts and siliceous shales with extremely high total organic carbon (TOC) concentrations. The Woodford is believed to be the dominate source rock for hydrocarbons generated in southern Oklahoma (Donovan, 1991). The contact between the Woodford and the overlying Sycamore Formation is an unconformity which erodes into paleovalleys. Thickness of the Woodford ranges from zero to approximately 400 feet. The Woodford is highly radioactive, giving it a distinctive very high gamma ray response on radioactive logs.

Mississippian Stratigraphy

In the eastern portion of the study area the oldest Mississippian rocks are comprised of the Sycamore Formation. Typically, the Sycamore is composed of several hundred feet of limestones, some of which are silty, with locally developing sands. Typically, it was thought that the sands were necessary for the Sycamore to be a commercial petroleum reservoir, however, significant fractured Sycamore carbonate production has recently been established at Carter-Knox, the Golden Trend, Velma, and in the Criner Hills. Further towards the west, the Sycamore grades into the "Mississippi Limestone" or "Osagean Limestone".

In the Arbuckle and Ardmore regions, the Caney Formation overlies the Sycamore. The Caney is a dark-gray fissile shale that is rarely preserved in outcrop. In the subsurface, it forms a prominent electric-log signature which distinguishes it from overlying Springer Shales.

The Springer Group is a thick sequence of shales which represent a change from the carbonate-dominated sedimentation in the stratigraphic section below it. The lower section is composed of the Goddard Formation which is Chesterian. In the western portion of the study area, the lower Chesterian is represented by a thick limestone known as the Chester Formation, which is subsequently overlain by thick accumulations of shale. The location of the Mississippian-Pennsylvanian contact is still a matter of debate with some workers assigning the higher portions of the Springer section to the Lower Pennsylvanian while other workers assign all of the Springer to the Mississippian. Springer sands are extremely important reservoir rocks. Clastic sedimentation in the Springer signals the early stage of Wichita deformation and cessation of the long-lasting subsidence in the southern Oklahoma Rift.

Pennsylvanian Stratigraphy

Pennsylvanian sedimentation took place during the Wichita and Arbuckle Orogenies. These mountain-building events uplifted large crustal blocks in shallow seas, creating isolated uplifts. These uplifts shed large quantities of synorogenic sediments into rapidly subsiding foreland basins which were progressively isolated and localized due to structural culminations and the formation of subsidiary structural uplifts. Sedimentation was clastic dominated, characterized by great thicknesses of variable, immature clastics dominated by shales. Locally thin carbonates developed. These sediments became progressively immature and conglomeratic toward the mountain front from which they were shed. Because of this, the sediments are often difficult to distinguish stratigraphically and lithologically and are often referred to collectively as "Granite Wash". Deposition occurred in four main pulses, each represented by a stratigraphic series. In ascending order these are the Morrowan, Atokan, Desmoinesian, and Virgilian. Deposition was characterized by angular unconformities, thinning over local highs, and active deformation.

Morrowan.

The Morrowan series is represented by rocks of the Lower Dornick Hills Group. During Morrowan time, the first major pulse of the Wichita Orogeny created the asymmetric Anadarko Basin, the large foreland basin north of the Wichita Mountains which were rising to the south. Exposure of Mississippian and older rocks from the rising Wichita Mountains sourced siliclastic material from the south, however, Morrowan sediments were also eroded from the exposures in the craton, Midcontinent Ridge, and other areas. Deposition occurred contemporaneously with increasing structural growth and erosion of the Wichita Uplift.

Morrowan deposition is characterized by thick sequences of marine shale, claystone, and many discontinuous coarse-grained deposits derived from the north and northwest. Near the Wichita Mountain Front, the sediments become increasingly conglomeratic, the result of alluvial fans which coalesced and prograded rapidly into a coastal marine environment.

Atokan.

Rocks of the Atokan series are separated from underlying Morrowan rocks by an angular unconformity. The Atokan Series is represented by the Upper Dornick

Hills Group. The Atokan section is comprised of non-uniform clastic shales and sands which are locally conglomeratic. The continued rise of the Wichita Mountains made the Atokan section extremely variable.

Desmoinesian.

The greater portion of the Desmoinesian Series is comprised of the Deese Group (Tomlinson and McBee, 1958). The Deese Group is separated from the underlying Dornick Hills Group by an angular unconformity. The Desmoinesian rocks are comprised of highly variable sands and shales, locally conglomeratic. The lower and middle portions of the Des Moinesian Series are truncated around major uplifts and paleo-highs; however, the upper portion, although often shortened and/or thinned, covers the crests of many smaller structures (Tomlinson and McBee, 1958). Small areas of Deese rocks are exposed on the hanging wall of the Arbuckle Thrust, indicating that the Arbuckle Mountains were partially covered, or onlapped, by Deese sedimentation.

Missourian

The Missourian Series is represented by rocks of the Hoxbar Group. By Missourian time, the Wichita Mountains had obtained considerable structural relief and most crustal shortening had stopped. Sediments of the Hoxbar Group mark the early stages of the Arbuckle Orogeny. The top of the Hoxbar Group is marked by an angular unconformity produced by the major pulse of the Arbuckle Orogeny.

Virgilian

During Virgilian time, the final major pulse of the Arbuckle Orogeny occurred(Tomlinson and McBee, 1958), accompanied by mild folding and faulting of the Wichita Uplift and smaller basinal structures in the Anadarko Basin. Thick sequences of clastic material continued to be shed from the positive Wichita and the Arbuckle Uplifts. Erosion occurred at a rapid pace. Vanoss conglomerates onlap the Arbuckle Uplift, indicating that the Arbuckle Uplift had been almost peneplaned by the end of Virgilian time. In the Anadarko Basin, the Virgilian Series is represented by clastic rocks of the Cisco Group.

Permian Stratigraphy

Permian redbeds constitute the surface exposures that cover most of the Wichita and Arbuckle Uplifts. These sediments post-date the vast bulk of deformation, with only very minor faulting and flexure present. Much of the Permian sediments are arkosic in nature, and were derived from the positive igneous areas of the Wichita and Arbuckle Uplifts.

Summary

Prior to Late Mississippian time, southern Oklahoma stratigraphy was dominated by the accumulation of large sequences of dominantly carbonate rocks. Deposition was thicker in the subsiding Southern Oklahoma rift than on the rift margins and craton, probably due to subsidence of the rift. Onset of late Paleozoic deformation is recorded by shales of the Springer Group. In the Pennsylvanian, during the Wichita and Arbuckle Orogenies, southern Oklahoma was divided into asymmetrical basins and uplifts. These basins filled with clastics shed from the near-by rising uplifts. Sedimentation was dominated by clastics. Near rapidly rising mountain fronts, these sediments often consist of conglomerates and washes whose internal stratigraphy is difficult to sort out. Much of the study area was subsequently covered with Permian red-beds following the cessation of tectonic activity.

Chapter 4

FAULT RELATIONSHIPS AND STRUCTURAL GEOMETRY OF THE WICHITA AND ARBUCKLE MOUNTAIN FRONTS

Introduction

This chapter serves as an introduction to the structural geology of the study area. The purpose is to familiarize the reader with the location and geometry of the uplifts and fault systems which will be discussed in the ensuing chapters; to define terms and fault relationships within the study area; to discuss map and subcrop patterns; and to discuss the style of deformation visible at outcrop level. The establishment and clarification of a general structural framework is necessary because in many cases there is a lack of consensus on the basic definitions of length and relationship for many major fault systems in southern Oklahoma (Table 1). This chapter presents maps and locations of cross sections and seismic lines which will be referred to in succeeding chapters and is intended to establish a frame of reference for more detailed analysis. Additional details of many areas discussed within this chapter will be presented in later chapters.

Wichita Uplift

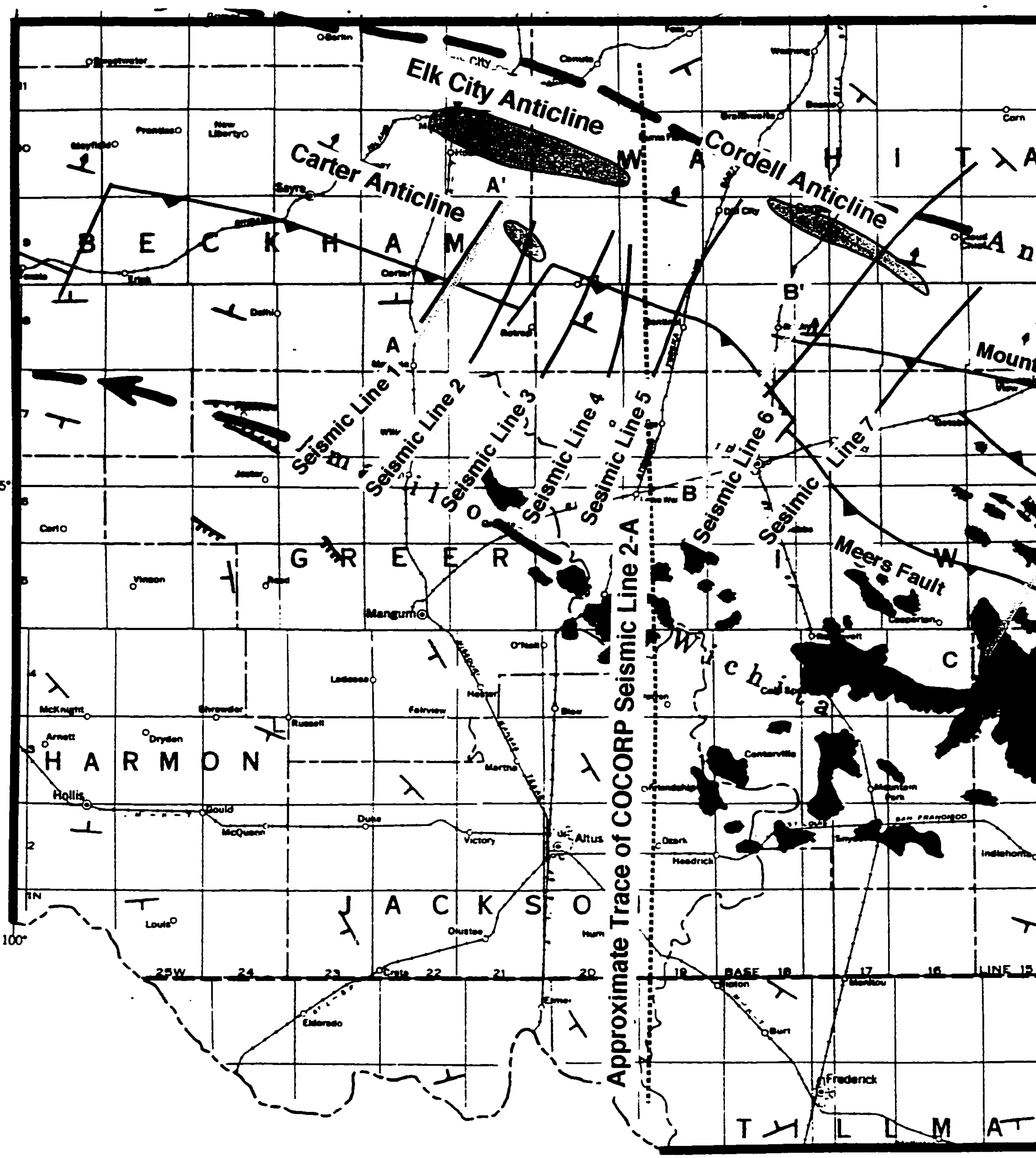
The Wichita Uplift (Figs. 4.1 and 4.2) extends from the Texas panhandle across southwestern and south-central Oklahoma. This continuous uplift is divided into three major segments based upon structural style: the "Amarillo Uplift" in the Texas Panhandle; the "Wichita Uplift" in western Oklahoma; and the "Criner Hills Uplift "in south-central Oklahoma. When this study refers to the 'Wichita Uplift', it is

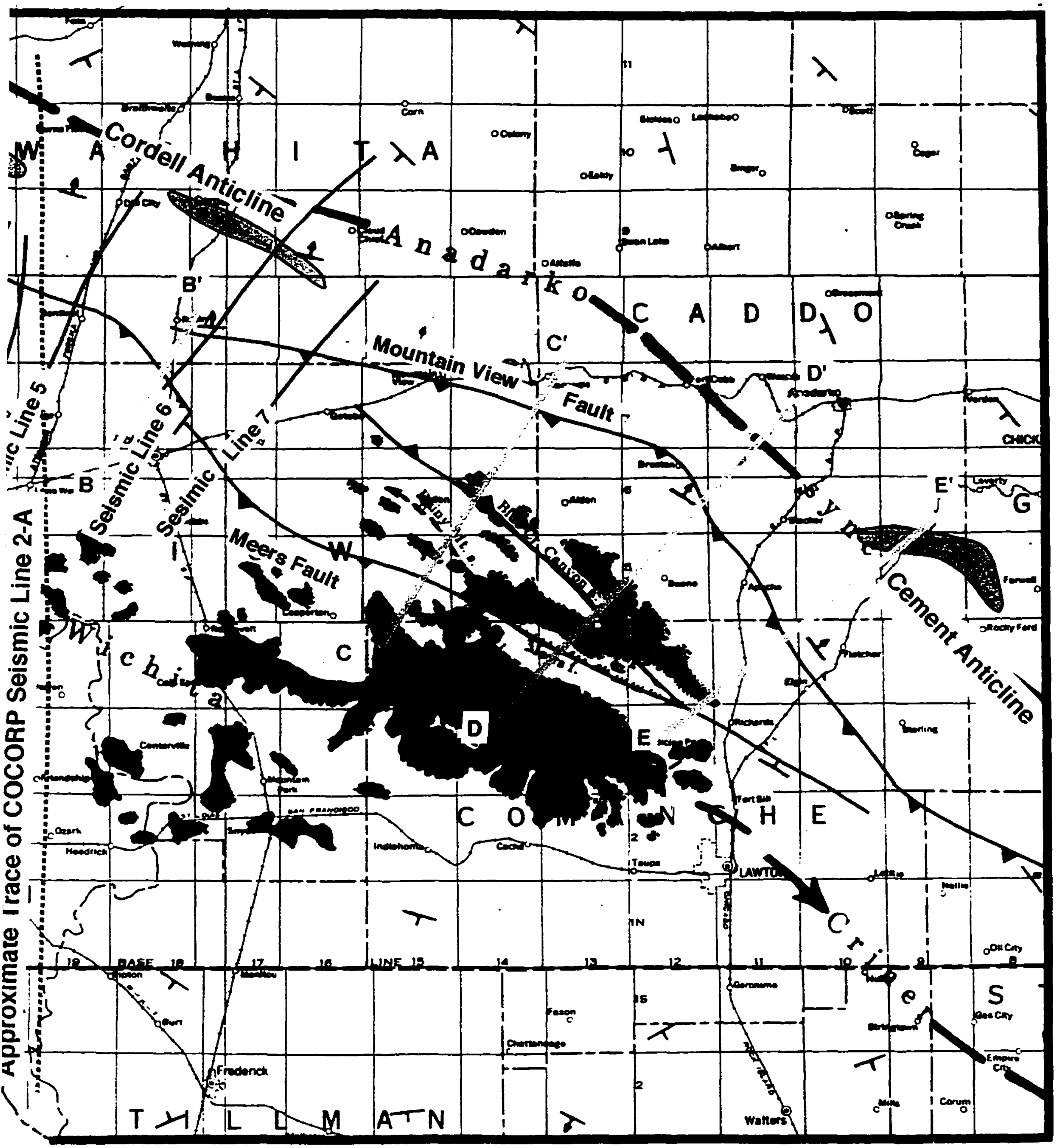
Table of Fault Geometries and Slip Estimates for the Arbuckle and Wichita Uplifts

Reference	Fault System	FAULT SLIP Amount	FAULT SLIP DIR.	RESORATION DS	RESORATION ALO	FAULT DIP	EVIDENCE AND METHODS SEIS.	X-SECT.	B-AXIS	BAL.
Budnik, 1986	WMS	60 MI	LL		Y	90				
Tanner, 1967	WVF	40 MI	LL		Y	90				
Booth, 1978	WVF	40-10 MI	LL		Y	90				
Carter, 1979	WVF	20 MI	LL		Y	90				
Ham, 1950	WVF	3 MI	LL			90				
Naruk, 1994	WVF	4 MI	DS			45 SW		Y	Y	Y
Brown, 1984	AT (WVF)	8 MI	DS	Y	Y	35 SW		Y	Y	Y
Haas, 1978	RF	10-15 MI	LL		Y	90				
Cooper, 1995	CH	6-8 MI	DS			30 SW	Y		Y	
McConnell, 1989	MVF	12 KM	LL	Y	Y	40 SW		Y	Y	Y
Axtmann, 1983	MVF	1-3 MI	LL		Y	90				
Brewer, 1982	MVF	10-15 KM	DS			35 SW	Y			

Table 1. Table of interpretations by various workers in the Wichita and Arbuckle Uplifts showing differences in terminology and interpretation, and listing data presented to document fault geometry and structural relationships. Note the lack of seismic and cross sections. Although many workers support the concept of left-slip along high-angle faults, note the general lack of consensus on the magnitude of slip. WMS is Wichita Mega-Shear, WVF is Washita Valley Fault, AT is Arbuckle Thrust, RF is Reagan Fault, MVF is Mountain View Fault, CH is Criner Hills, LL is left-lateral, DS is dip-slip, RL is right-lateral, ALO is apparent lateral offset.

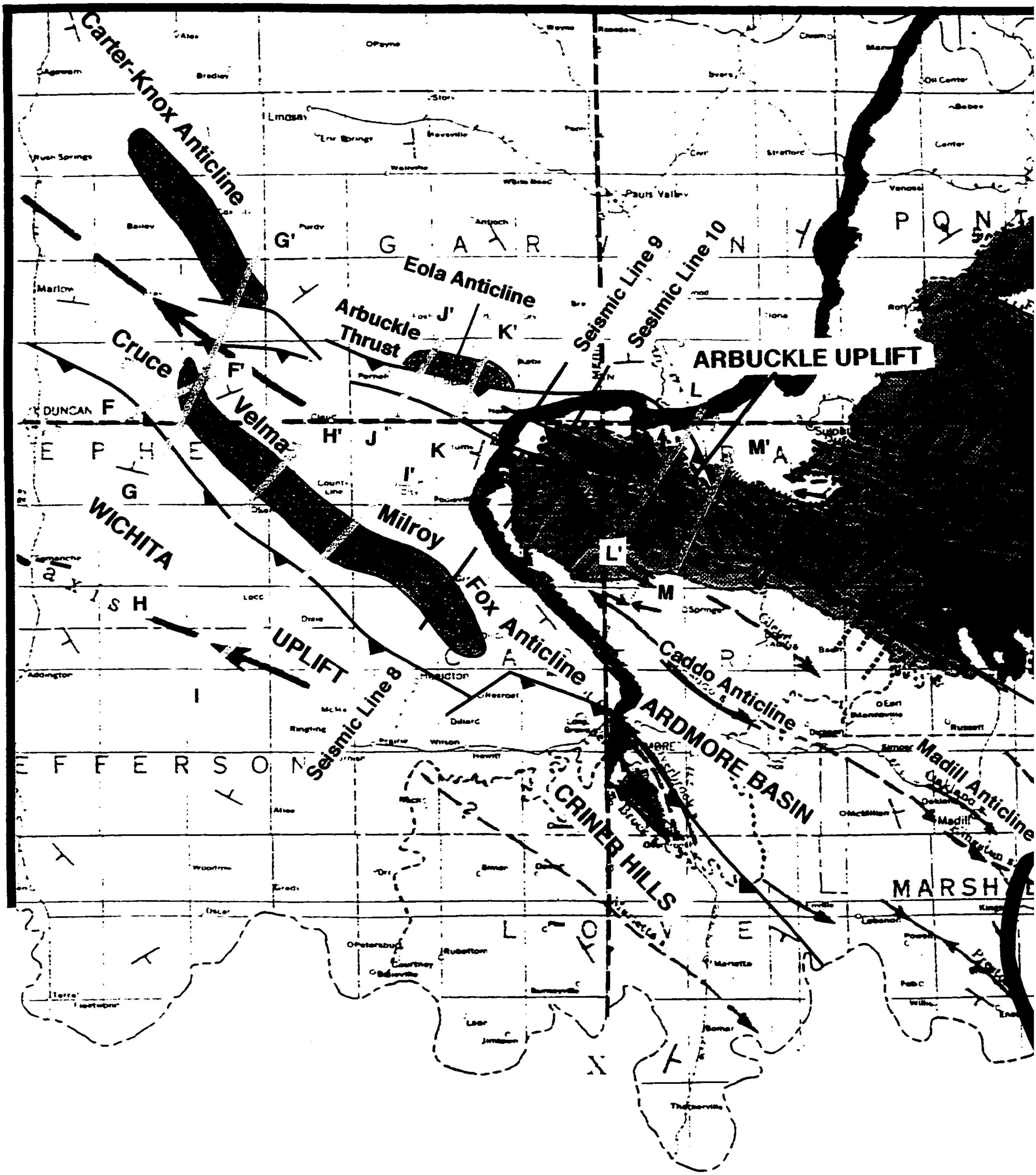
Figure 4.1. Tectonic map of the Wichita Uplift showing the location of cross sections and seismic lines used in this study (modified from Miser, 1954)

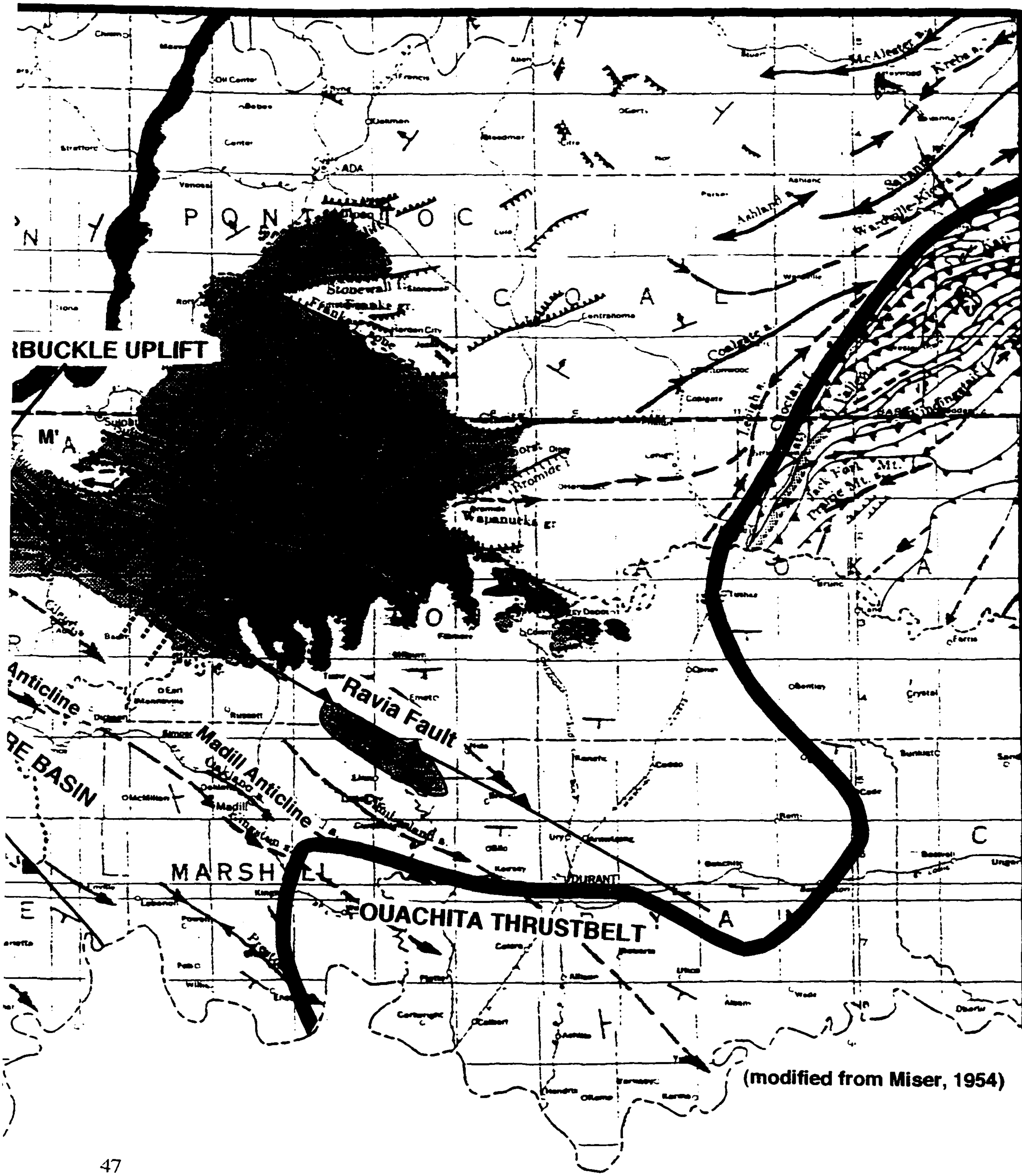

Elk City Anticline
Cordell Anticline
Carter Anticline
Meers Fault
Seismic Line 1
Seismic Line 2
Seismic Line 3
Seismic Line 4
Seismic Line 5
Seismic Line 6
Seismic Line 7
Approximate Trace of COCORP Seismic Line 2-A
A
A'
B
B'
B E C K H A M
W A S H I T A
G R E E R
H A R M O N
J A C K S O
T I L L M A N
C
Mangum
Hollis
Altus
Sayre
Frederick
Gould
Carter
Dill City
Eldorado
Olustee
Victory
Duke
Fairview
Russell
McKnight
Arnett
Dryden
Carlo
Vinson
Louis
Martha
Centerville
Headrick
Mountain Park
Tipton
Burt
Snyder
Indiahoma
Corn
New Liberty
Mayfield
Erick
Delhi
Berlin
35°
100°
25W
24
23
22
21
20
19
BASE
18
17
16
LINE 15



Approximate Trace of COCORP Seismic Line 2-A
Seismic Line 6
Sesimic Line 7
Cordell Anticline
Anadarko
CADDO
Mountain View Fault
Meers Fault
Wichita
COMANCHE
Cement Anticline
TILLMAN
B
B'
C
C'
D
D'
E
E'
LAWTON
Frederick
Walters
(modified from Miser, 1954)

Figure 4.2. Tectonic map of the Arbuckle Uplift showing the location of sesimic lines and cross sections used in this study (modified from Miser, 1954).


Carter-Knox Anticline
Eola Anticline
Arbuckle Thrust
Seismic Line 9
Seismic Line 10
ARBUCKLE UPLIFT
Cruce
Velma
Milroy
Fox Anticline
WICHITA
UPLIFT
Seismic Line 8
Caddo Anticline
ARDMORE BASIN
CRINER HILLS
Madill Anticline
DUNCAN
Pauls Valley
G'
J'
K'
F'
F
H'
J
K
I'
G
L
L'
M
M'
H
I
MARSH



(modified from Miser, 1954)

referring to the central portion of the uplift bounded by the Amarillo and Criner Hills segments, unless otherwise noted. Each major division is separated from the other by a high-angle, transverse fault (compartmental fault). The Amarillo Uplift and Wichita Uplift are bounded to the north by the Anadarko Basin. The Criner Hills are bounded to the north by the Ardmore Basin. The Sholem Alechem Uplift, a broad uplift bounded to the north by the Doyle Anticline and Doyle Thrust, separates the Anadarko and Ardmore Basins. The Wichita Uplift and Criner Hills are thrust to the north over the Anadarko and Ardmore Basins respectively, along low-angle reverse faults. Vertical offset is, in places, at least 35,000 feet. Total horizontal offset is estimated at 40,000 to 70,000 feet. Total offsets vary along strike, are often due to more than one fault, and are extremely difficult to quantify due to deep erosion of the hanging wall. Outcrops are restricted to the Lower Paleozoic rocks in the Slick Hills area and the topographic Wichita Mountains which are composed of outcrops of basement rock.

The Wichita Mountain Front is extremely complex. From the Amarillo Segment east, near the town of Lawton, Oklahoma, the mountain front trends ESE. At Lawton, the mountain front changes strike and trends SE into the Criner Hills (Fig. 4.1). The leading edge of basement-involved deformation has historically been referred to as the Mountain View Fault (Axtmann, 1983, McConnell, 1987, 1989, Brewer and others, 1983). Several workers have modeled, or assumed that, the Mountain View Fault is a single continuous fault, which extends across the entire length of the Wichita Uplift (Brewer, 1982; McConnell, 1987, 1989). This study will show that the Mountain View Fault comprises the leading-edge of the Wichita Uplift along the Blue Creek Canyon Block only and that the Wichita Mountain front consists of various leading-edge faults, some of which are separated by compartmental faults, others which die into basement-cored folds and are overridden by back-limb imbricates forming displacement-transfer zones. Much basic work still needs to be done to document and clarify fault relationships of the Wichita Mountain Front.

Between the Amarillo Uplift and Criner Hills, the Wichita Uplift can be subdivided into three general segments: the Western Wichita Segment; the Blue Creek Canyon Block; and the Eastern Wichita Segment. A subcrop map is only available for the Blue Creek Canyon area (Fig. 4.3). The *Blue Creek Canyon Block* is the basement-cored footwall block to the Meers Fault. It is the segment bounded to the north by the Mountain View Fault and to the south by the Meers Fault. The Blue Creek Canyon Block roughly corresponds with McConnell's "Lawton Segment" (McConnell 1987, 1989). The *Mountain View Fault* forms the leading edge of basement deformation of the Blue Creek Canyon Block, extending at least from T.3N., R.10 W., to the vicinity of Apache Field, and to the west near T.7N., R.17W. where it dies into a basement-cored fault-propagation fold which forms the western plunge of the Blue Creek Canyon Block. This relationship is thoroughly discussed and documented in Chapters 6 and 8. West of the Blue Creek Canyon Block, the Meers Fault overrides the Mountain View Fault to become the leading edge of the Wichita Uplift, however, the westward extent of the Meers Fault, and fault relationships in general of the Western Wichita Segment, are not thoroughly documented. The Blue Creek Canyon Block contains several prominent southwest-vergent back-thrusts including the Blue Creek Canyon Fault which places Cambrian basement against the Arbuckle Group. Paleozoic rocks outcropping in the Slick Hills are comprised mainly of Arbuckle Group carbonates. These rocks contain internal shortening by layer parallel slip, small folds, and detached thrusts (McConnell, 1987). Structures are oriented parallel to the strike of first and second-order faults and are consistent with northeast-southwest directed shortening.

The Wichita Mountain Front is poorly understood west of the Blue Creek Canyon Block to the Amarillo Uplift. This area roughly corresponds to McConnell's (1987, 1989) "Sayre Segment". Here it is referred to as the Western Wichita Segment. Although the western half of the Western Wichita Segment is not well documented the

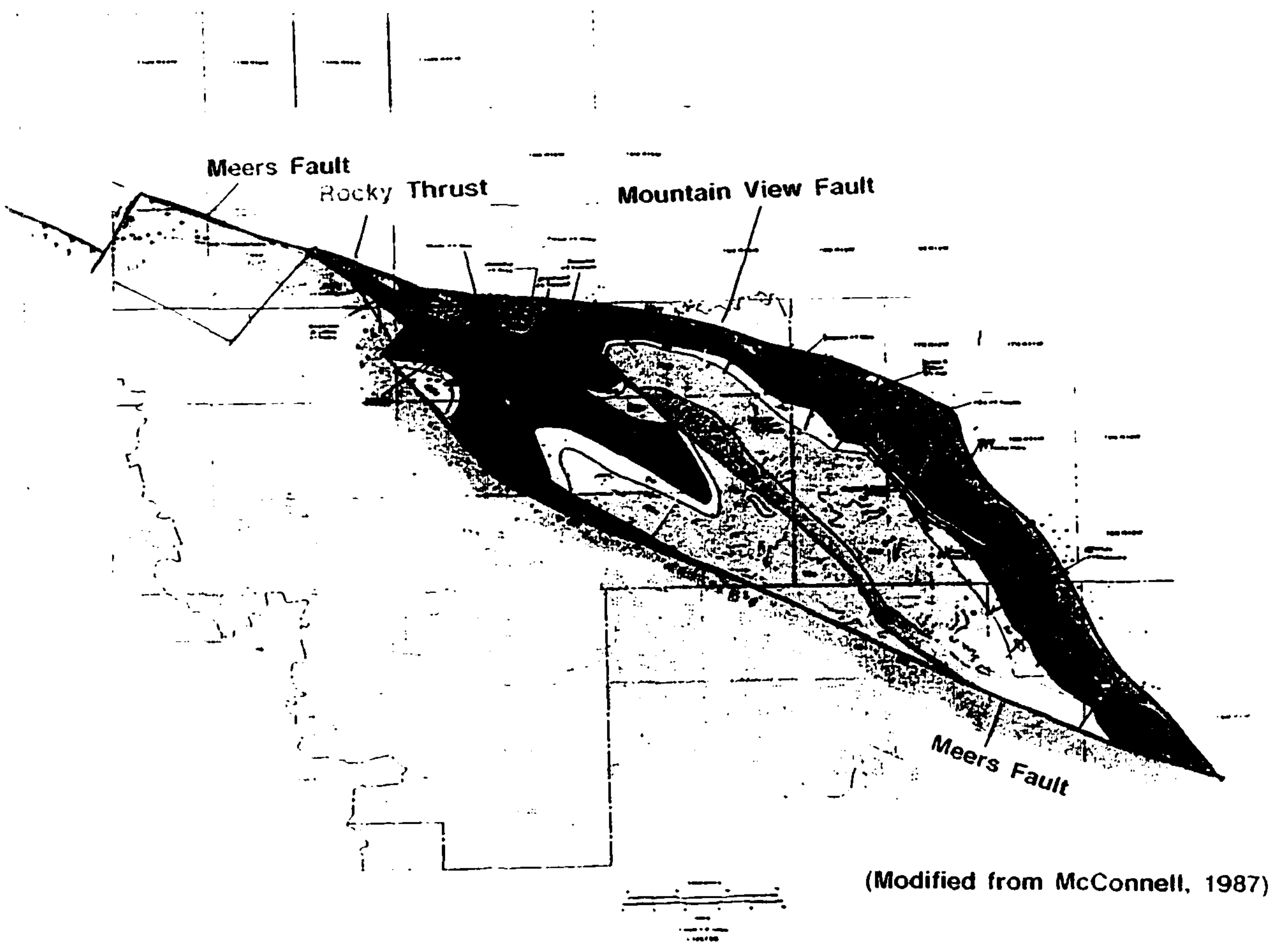


Figure 4.3. Subcrop map of the Wichita Uplift (modified from McConnell, 1987). Note the Mountain View Fault loses slip as the Blue Creek Canyon Block plunges to the west. The Meers Fault overrides the Blue Creek Canyon Block. Deep erosion of the hanging wall of the Meers Fault makes quantifying shortening difficult.

eastern portion is (Saxon, this volume). The eastern half clearly contains several major compartmental faults (Fig. 4.1) and cannot be thought of as containing a homogeneous structural style. Lack of well control makes subcrop mapping more interpretive than in the Blue Creek Canyon Block.

The eastern portion of the Wichita Mountain Front, between the Blue Creek Canyon Block to the Criner Hills, corresponds with Harlton's (1956) and Jacobson's (1984) Harrisburg Trough. This area is referred to as the Eastern Wichita Segment and plunges to the southeast, reflecting a progressive loss of slip, as the Wichita Mountain front plunges into the Criner Hills. Thus, the mountain front is progressively less deeply eroded along the southeastern plunge of the Eastern Wichita Segment. In the area near the Harrisburg Trough, near Duncan, Oklahoma, the hanging wall of the Wichita Uplift is eroded only to the lower Arbuckle Group. Farther to the southeast, Wichita termination, near Healdton Field at the transition between the Eastern Wichita Segment and the Criner Hills, the hanging wall of the Wichita Uplift is eroded only to the Simpson-Arbuckle Group level. The Brown Zone of the upper Arbuckle produces in the Healdton Field.

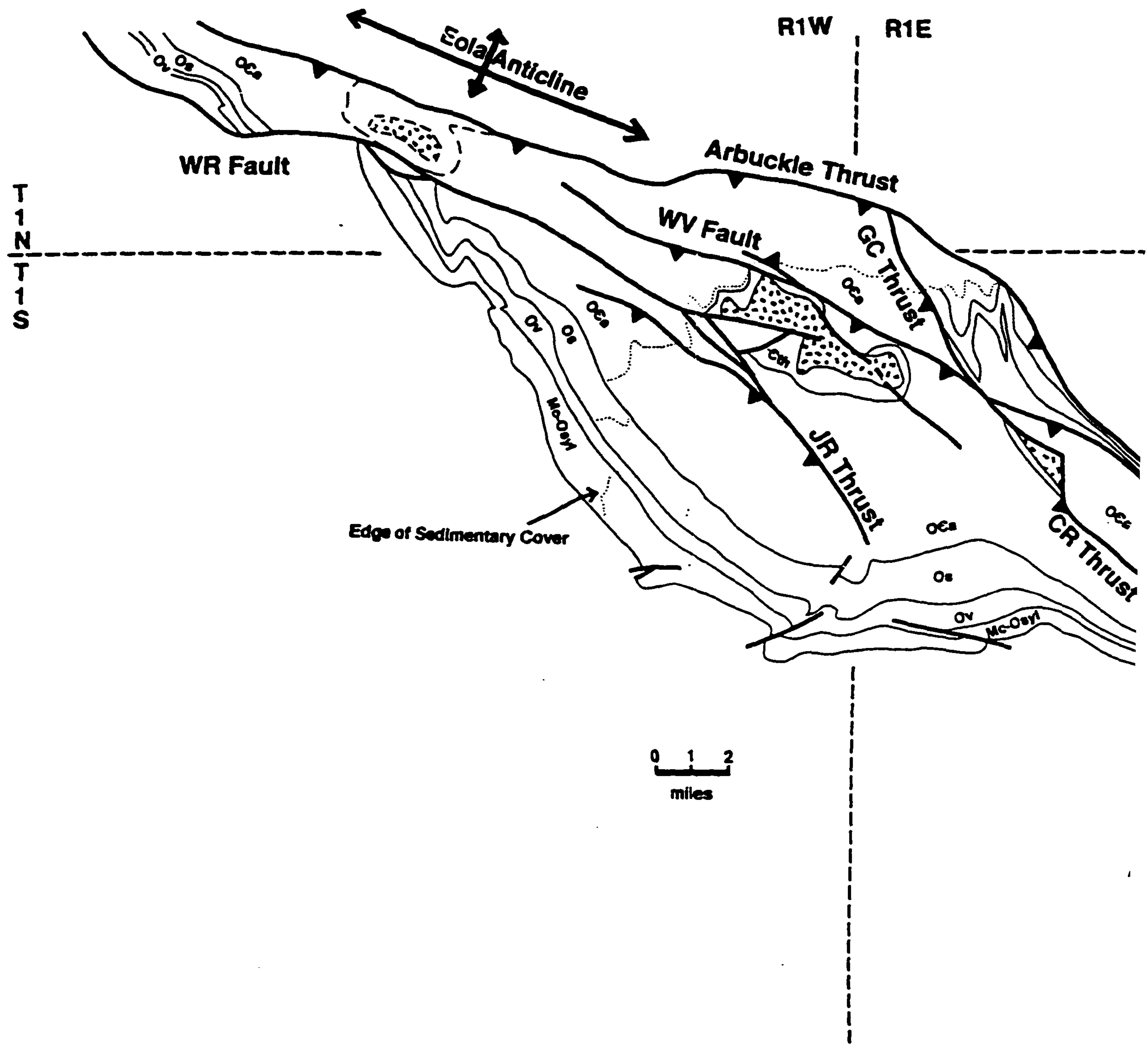
Where well documented by subcrop maps, seismic, and numerous cross sections, the Wichita Mountain Front consists of a complex, stair-step geometry and several major basement-involved thrusts, some of which terminate against compartmental faults and some of which plunge into basement-cored folds, losing slip. The Wichita Mountain Front should not be thought of as uplifted along a single, continuous thrust (Mountain View Fault) as interpreted by previous workers (McConnell, 1987, 1989). Before extensive modeling can be done for the Wichita Mountain Front, its structural geometry needs to be better documented.

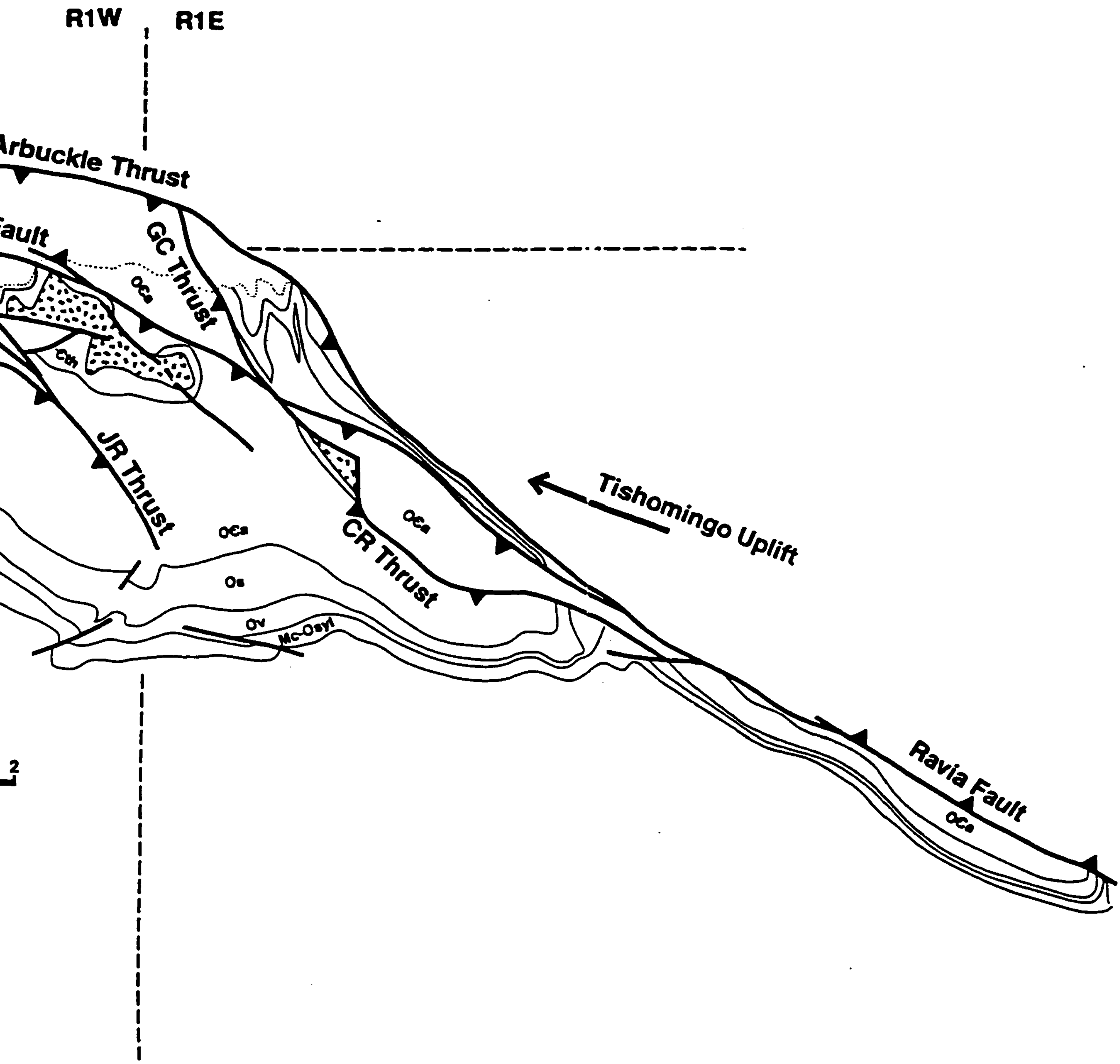
Arbuckle and Tishomingo Uplifts

The Arbuckle Mountains are a topographical series of uplifts exposed in south-central Oklahoma which include the Arbuckle, Tishomingo, and Hunton Uplifts, of which the Arbuckle is the western-most. The Arbuckle Uplift (Fig. 4.4) is the hanging wall of the buried Arbuckle Thrust which is well defined from subsurface data (Brown, 1984; Beck, 1987; Saxon, 1994). In literature, the Arbuckle Uplift is sometimes referred to as the Arbuckle Anticline. This study follows the use of Saxon (1994) and refers to the Arbuckle Anticline as the main anticline south of the Washita Valley Fault, and the Arbuckle Uplift as the entire hanging wall of the Arbuckle Thrust.

The present outcrop and subcrop pattern of the Arbuckle Uplift is dictated by the geometry and relative displacement along the Arbuckle Thrust, level of erosion, and magnitude of extension along the late-stage Washburn Ranch Fault. The pattern of the combined surface and subcrop maps (Fig. 4.4) of the Arbuckle Uplift is widest in the central portion and symmetrically tapers to both ends, forming a classic "bow and arrow- map pattern, characteristic of thrust belts (Elliot, 1976). Saxon (1994) documented the scallop shape of the Arbuckle Thrust and its relationship to the outcrop/subcrop pattern. The greatest amount of reverse dip-slip (approximately 8 miles) occurred in the area of maximum convexity of the Arbuckle Thrust and decreases toward both ends. The central portion of the Arbuckle Uplift corresponds to the greatest amount of slip, and deepest level of detachment of the Arbuckle Thrust. The northwest plunge of the Arbuckle Uplift is accompanied by a progressive loss of slip on the Arbuckle Thrust, a rise in the elevation of the detachment, and an increase in the dip of the Arbuckle Thrust (Saxon, 1994). On either side of the central "bulge", the forelimb of the Arbuckle Uplift steepens, developing a tight, overturned footwall syncline and footwall anticlines thrust out of the syncline on detachments in the lower

Figure 4.4. Combined surface and subcrop map of the Arbuckle Uplift (from Saxon, 1994).


Eola Anticline
R1W
R1E
WR Fault
Arbuckle Thrust
T
1
N
T
1
S
WV Fault
GC Thrust
JR Thrust
CR Thrust
Edge of Sedimentary Cover
Os
Ov
Mc-Osyl
0 1 2
miles


R1W
R1E
Arbuckle Thrust
Fault
GC Thrust
JR Thrust
CR Thrust
Tishomingo Uplift
Ravia Fault
OЄa
OЄa
OЄa
OЄa
Os
Ov
Mc-Osyl
2

Arbuckle Group (Eola Anticline on the northeast plunge and Dougherty Anticline along the southeast plunge).

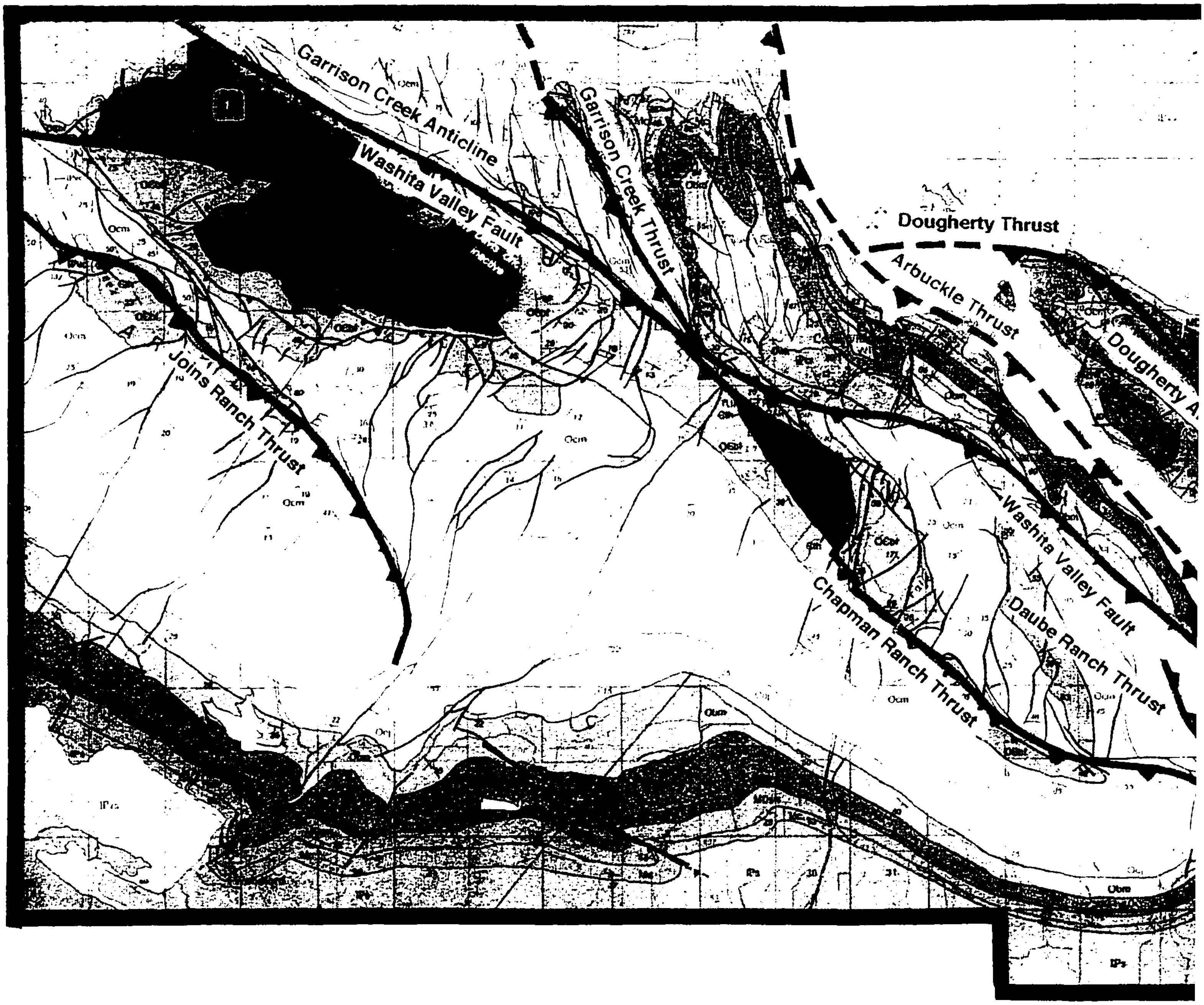
The Tishomingo Uplift (Fig. 4.5) is a broad, basement-cored uplift located to the east of the Arbuckle Uplift. The Tishomingo Uplift is bordered to the north by the southwest-dipping Reagan Fault, which overhangs the Mill Creek Syncline, and to the south by the northeast-dipping Ravia Fault, which overhangs the Ardmore Basin, and abuts against the Sycamore Creek Anticline. The Tishomingo Uplift plunges nearly due west, beneath the Arbuckle Uplift, the southeast plunge of which overrides and impinges the south flank of the Tishomingo Uplift. As the Tishomingo Uplift plunges westward, the Reagan Fault loses slip and dies out beneath the Arbuckle Uplift (Saxon, 1994).

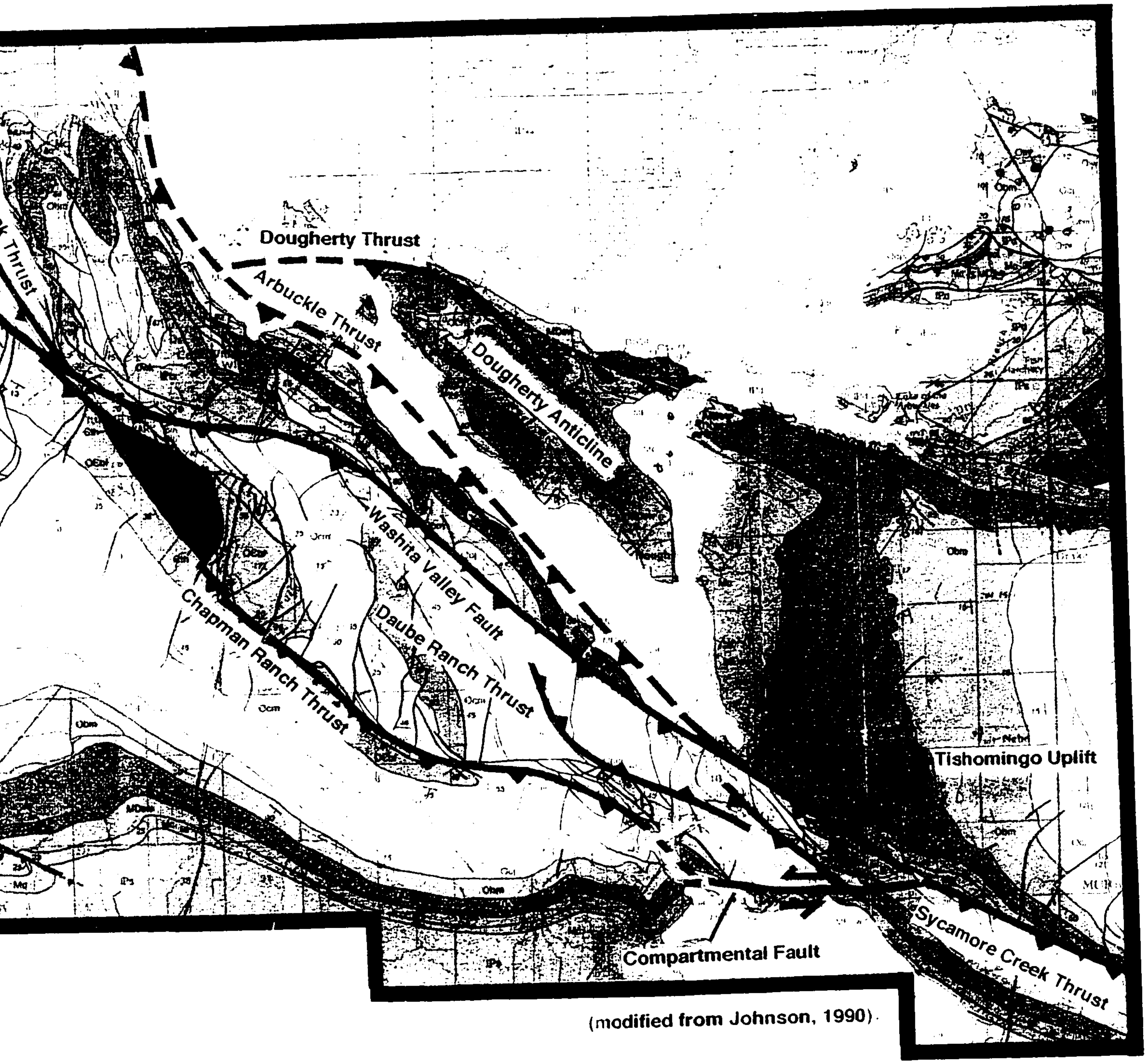
The Arbuckle Anticline is cored by Cambrian Carlton Rhyolite and has been thrust out of the old volcanic-filled southern Oklahoma Rift. The Tishomingo Uplift is cored by Precambrian Tishomingo Granite and represents shortening of the host crustal rocks which form the margin of the north flank of the southern Oklahoma Rift.

The northwestern exposure of the Arbuckle Uplift is comprised of three imbricate thrust sheets carried on the upper plate of the Arbuckle Thrust; the SE Hoover sheet, the Garrison Creek sheet, and the Arbuckle Anticline. Imbricate fault splays separate the individual sheets, each of which differs in exposed stratigraphy and style of deformation (Fig. 4.5).

The northeasternmost sheet is the SE Hoover sheet which includes the tightly folded area of Pickens, Lick Creek, and Colbert Creek Anticlines. This thrust sheet is located on the leading edge of the hanging wall of the Arbuckle Thrust. Structural style is characterized by tight folds, pervasive thrusts, and bedding plane detachments. This style of deformation, in combination with excellent reservoir rocks, has led to the trapping of hydrocarbons that have been exploited at SE Hoover and SW Davis Fields.

Figure 4.5 Geologic map of the Arbuckle Uplift (modified from Johnson, 1990).


Garrison Creek Anticline
Washita Valley Fault
Garrison Creek Thrust
Dougherty Thrust
Arbuckle Thrust
Joins Ranch Thrust
Washita Valley Fault
Chapman Ranch Thrust
Daube Ranch Thrust
Ocm



(modified from Johnson, 1990)

The Garrison Creek Thrust separates the SE Hoover sheet from the Garrison Creek Anticline (Fig. 4.5). Surface stratigraphy of the Garrison Creek Anticline consists of Arbuckle Group carbonate in a tight fold which plunges at 12° N60°W. Well control shows that the Garrison Creek sheet can be distinguished from the SE Hoover sheet by its broader folding and basement involvement.

The third thrust sheet is compromised of the Arbuckle Anticline and subsidiary structures (Fig. 4.5). It is bounded to the northeast by the southwest-dipping Washita Valley Fault. The Arbuckle Anticline is a basement-cored uplift, displaying predominately parallel folding and low-angle thrusting and contains two prominent back-limb basement-involved thrusts, the Joins Ranch Thrust and the Chapman Ranch Thrust. Other prominent subsidiary structures include the Cool Creek, Woodford, and Henry House Creek Anticlines which are thin-skinned structures detached at various horizons in the upper pre-Pennsylvanian section.

Arbuckle Thrust and "Washita Valley Fault System"

Most published articles employ the description of the Washita Valley Fault system by Tanner (1967) as a vertical fault which extends from north of Doyle Field, south of Eola Field, across the Arbuckle Anticline, and forming the south boundary of the Tishomingo Uplift. In this definition, the Washita Valley Fault is thought to be vertical, or to have a propeller-shape (Tomlinson, 1952) and to form the major uplift-bounding fault of the Arbuckle Uplift. In contrast, this study recognizes the southwest-dipping, buried, Arbuckle Thrust as the major uplift-bounding fault of the Arbuckle Uplift and bases the definition of the Washita Valley Fault on published studies by Brown (1984) and unpublished studies by Palladino (1986), Beck (1987), Bixler (1993), Sralla (1993), and Saxon (1994). These studies have documented the geometry of the Arbuckle Thrust, the Washita Valley Fault, and Arbuckle Uplift with surface mapping, plunge projections, well control, seismic data, and properly oriented balanced cross sections (Fig. 4.6).

The Washita Valley Fault is a southwest-dipping, back-limb imbricate to the buried Arbuckle Thrust with which it merges at depth (Fig. 4.2). To the northwest, in the subsurface, the Washita Valley Fault loses slip and dies out in the eastern half of T.1N., R.2W. It is in this area that the Arbuckle Thrust is commonly mistaken for the Washita Valley Fault. Along the southeast plunge of the Arbuckle Uplift, the Washita Valley Fault terminates against an un-named east-west trending compartmental fault which separates the Arbuckle Anticline from the Sycamore Creek Anticline and Sycamore Creek Thrust. The northeast dipping fault which forms the south boundary of the Tishomingo Uplift is the Ravia Fault (Fig. 4.8) which is commonly mistaken as the southern portion of the Washita Valley Fault.

The Washita Valley Fault may be a single fault or a complex series of imbricates. Surface relationships are ambiguous on this point and it is even possible that, in places, the Washita Valley Fault may subcrop beneath the Collings Ranch Conglomerate. It is possible that the Washita Valley Fault has some component of left-lateral slip, however, it cannot be of a major magnitude, nor be the dominant slip component, nor has the possible lateral slip component been conclusively proven.

Small-Scale Deformation

Observations of outcrop and roadcut-scale structures is made possible by Interstate 35 and highway 77, which provide continuous exposure across the eastern portion of the Arbuckle Uplift. These exposures are cross sectional profiles which can be correlated with outcrop patterns. Outcrops consistently reveal a fabric of northeast-directed shortening within the sedimentary section and are well documented (Bixler, 1993; Saxon, 1994). Observation of structural style at small scales is important

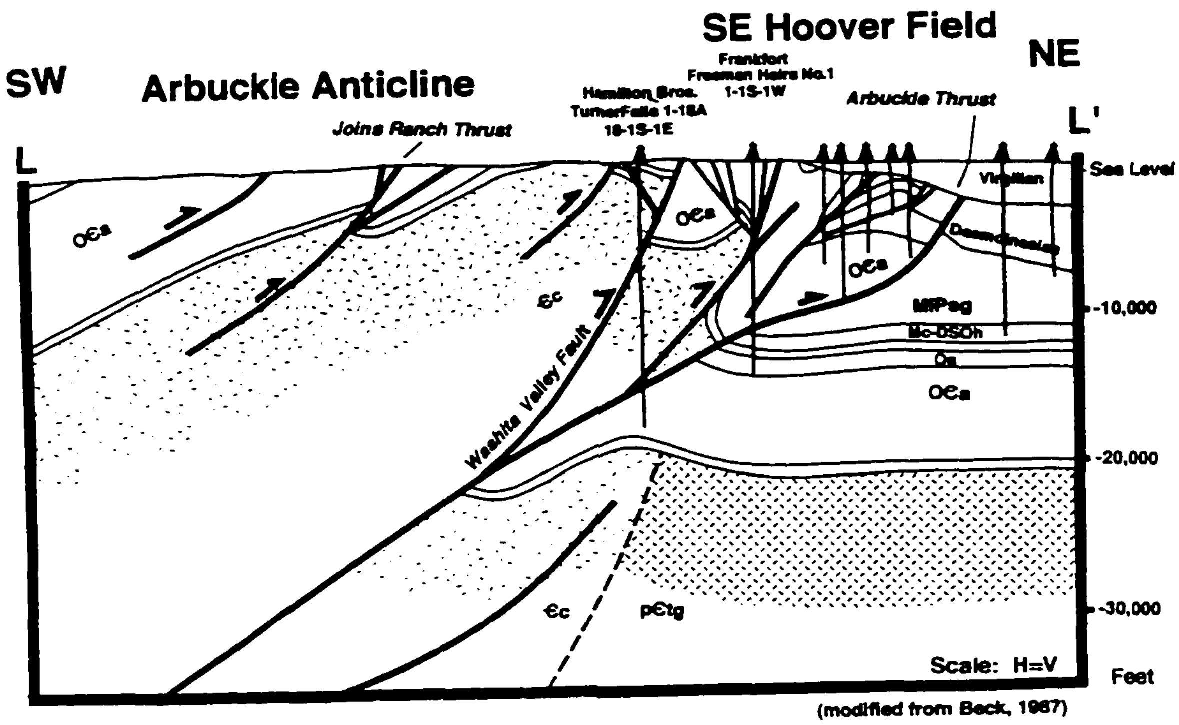


Figure 4.6. Cross section L-L' across the central Arbuckle Uplift (modified from Beck, 1987). The Arbuckle Thrust is defined from multiple well penetrations. Note the Hamilton Bros. Turner Falls well was drilled *south* of the Washita Valley Fault. This well drilled over 14,000 feet of basement rock and encountered southwest dipping Arbuckle carbonates in the footwall. This well confirmed Brown's (1984) hypothesis that the Washita Valley Fault is a back-limb imbricate to the Arbuckle Thrust.

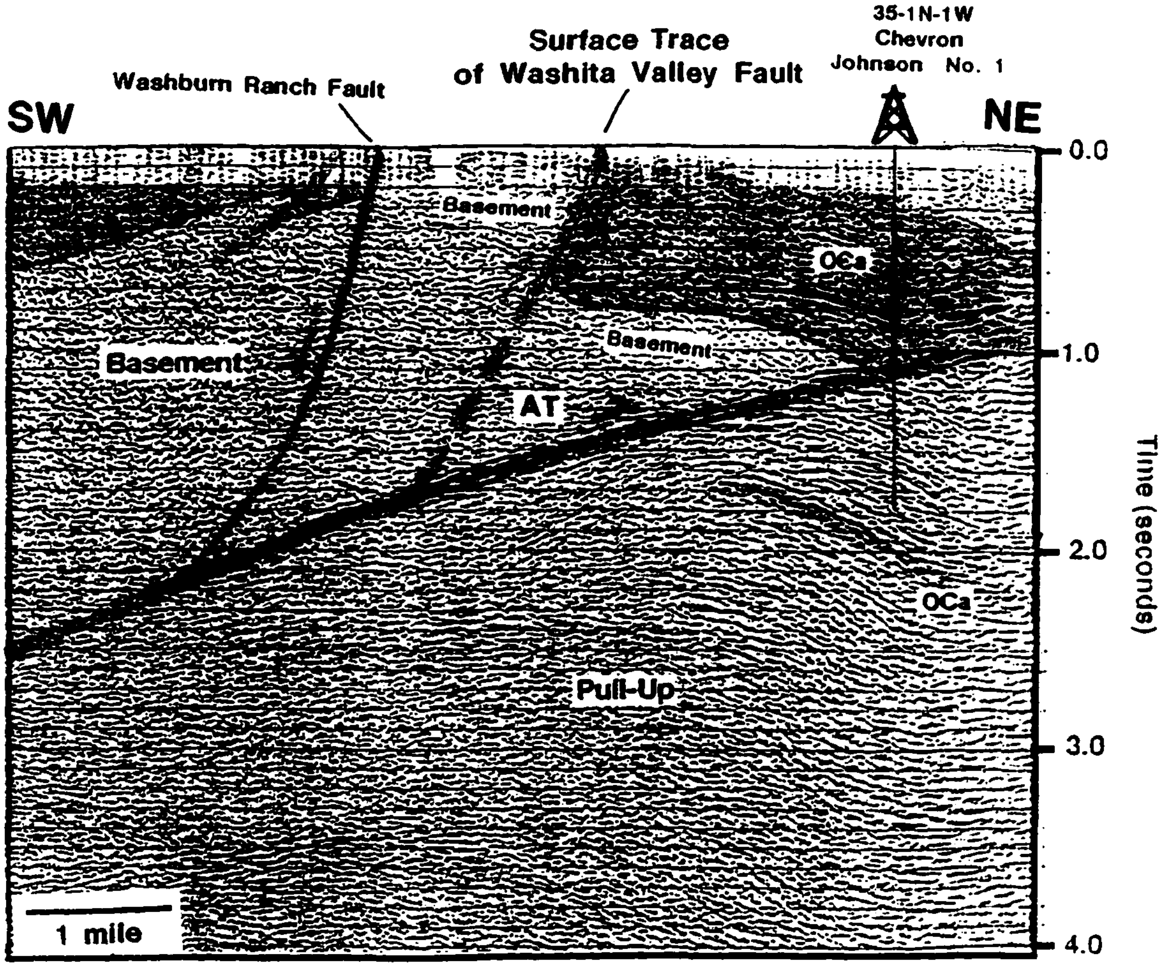


Figure 4.7 Seismic line 10 across the Arbuckle Uplift. This line crosses the far western portion of the exposed Arbuckle Uplift. Note the presence of the Arbuckle Thrust reflector north and south of the surface exposure of the Washita Valley Fault. The Arbuckle Thrust was penetrated by the Chevron Jeff Johnson #1 (siesmic courtesy of PGI and Texaco).

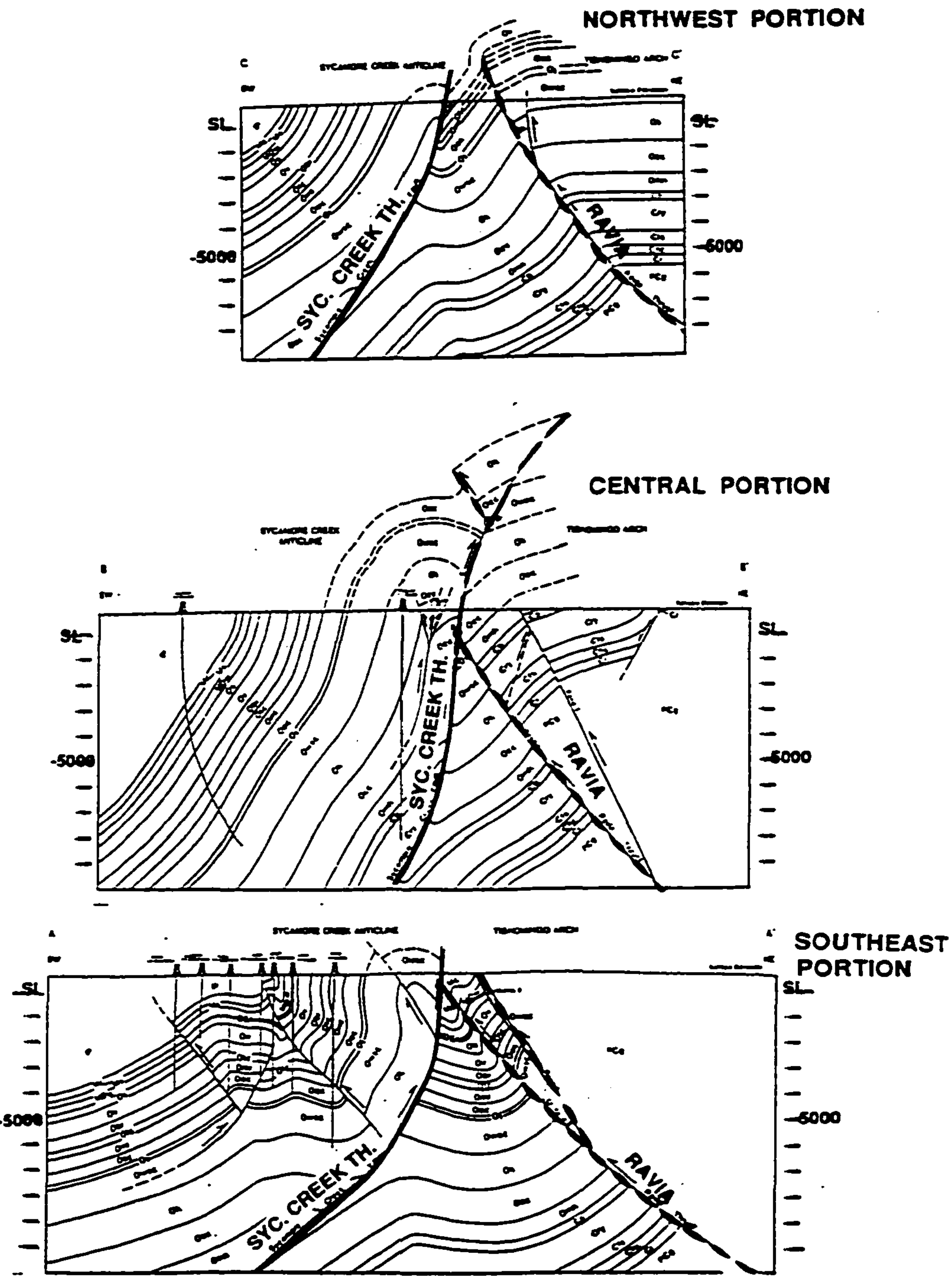


Figure 4.8. Series of cross sections showing the relationship of the Sycamore Creek Anticline to the Tishomingo Uplift (modified from Palladino, 1986). The Sycamore Creek Anticline is carried on the Sycamore Creek Thrust which separated from the Arbuckle Thrust by a compartment fault and may be either a separate fault or a continuation of the Arbuckle Thrust. In most literature, the deformation of this area is interpreted as due to the "Washita Valley Fault" and the complex surface pattern is cited as evidence of a "propeller" shape along a single master fault.

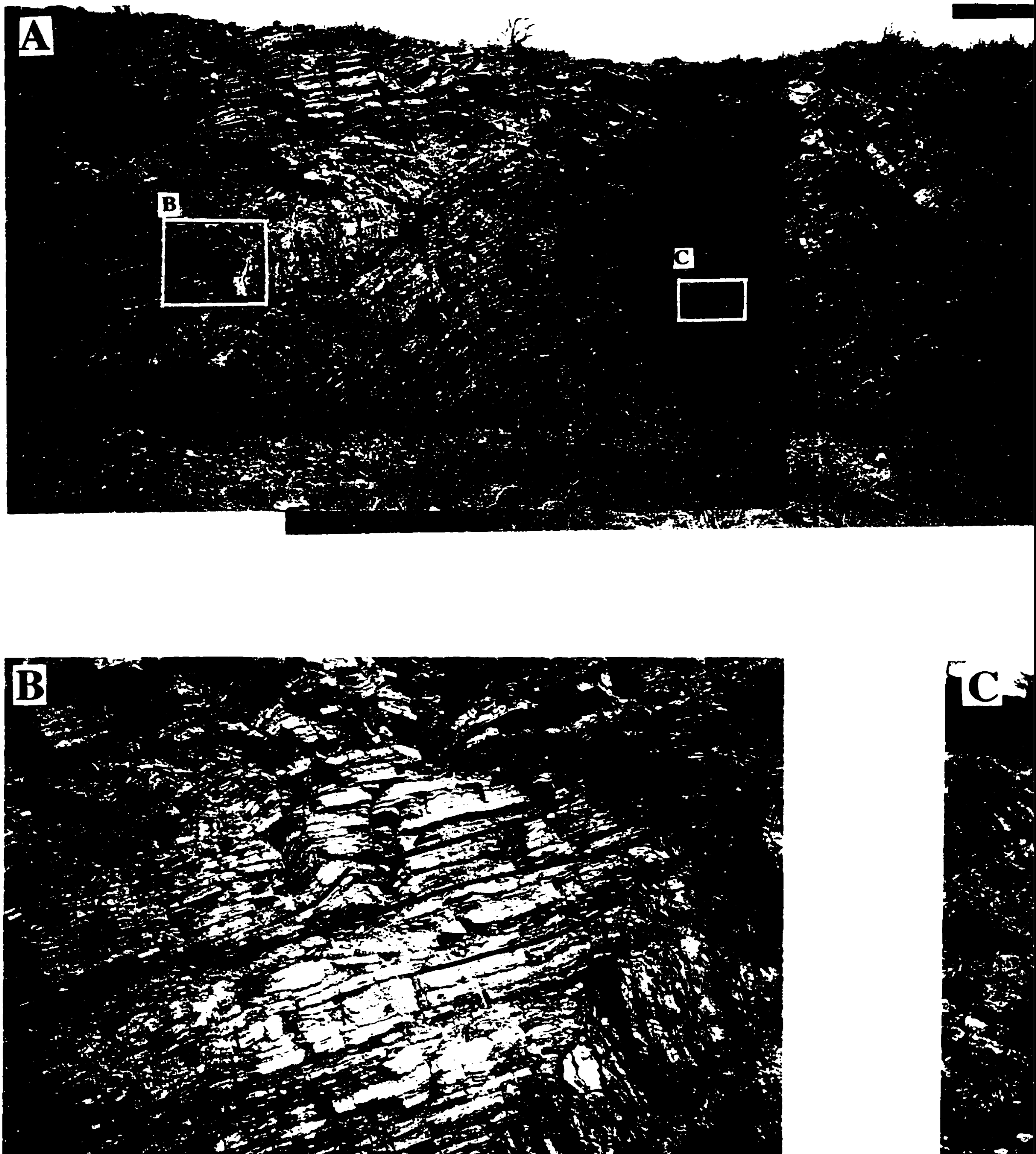
because structural style is scale independent and knowledge gained at one level of can be extrapolated into interpretations of other scales (Fig. 4.9)

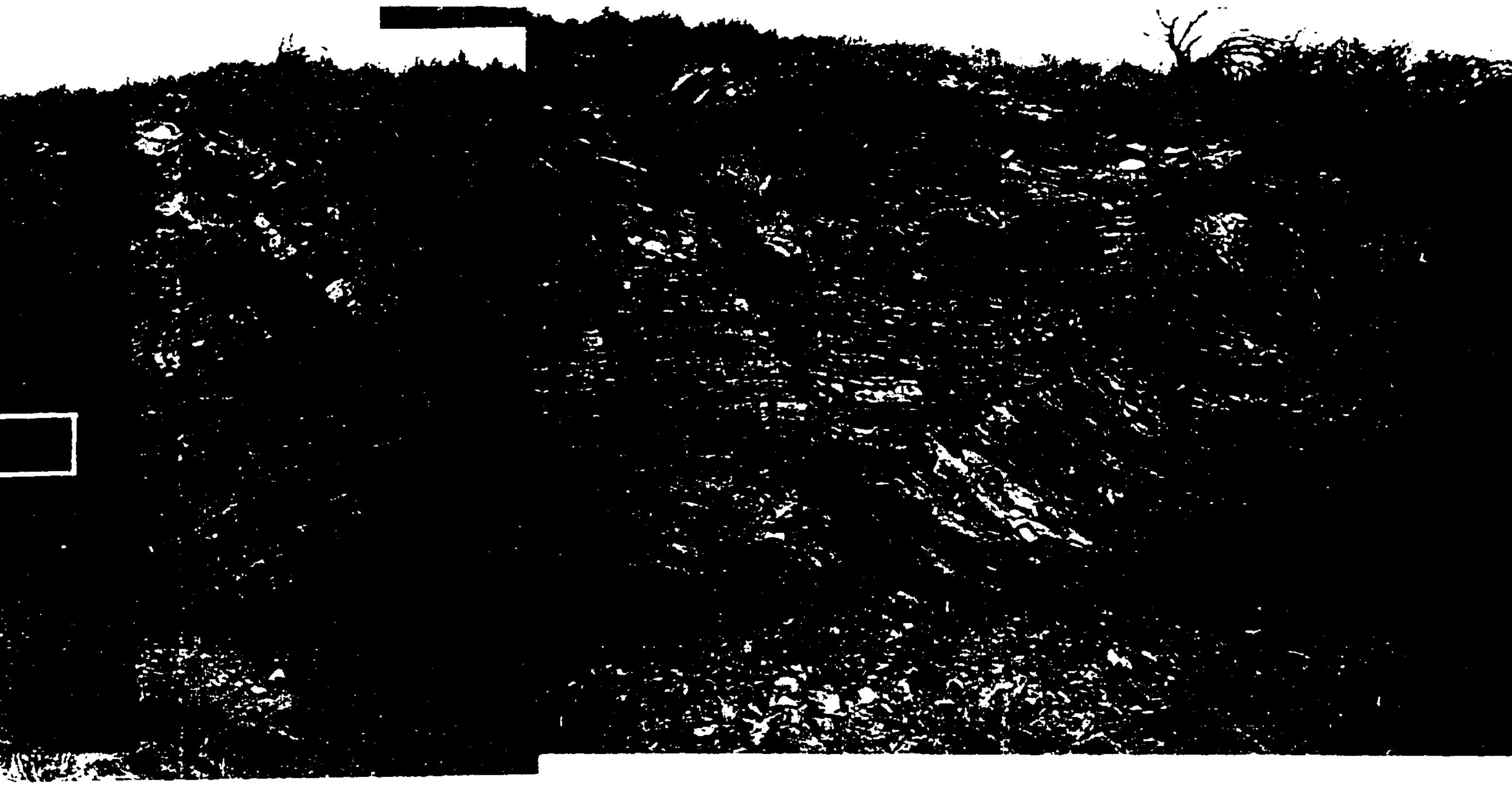
Deformation is dominated by parallel folding by bedding plane slip along layer parallel shear and layer parallel shortening. Features observed include northeast-vergent thrusting, back-thrusts, low-angle thrusting, parallel folding, fault-bend folds, fault-propagation folds, out-of-the-syncline thrusting, cross-crestal structures, back-limb structures, rabbit-ear structures, and tectonic stylolites. The tectonic stylolites are rotated across folds. Restoration suggests a NE-SW to NNE-SSW orientation of maximum compressive stress prior to folding (Bixler, 1993). Structures are dominantly northeast vergent, asymmetrical, with local overturning. Style of folding and internal deformation is partially dependent upon stratigraphy. Thick carbonates of the Arbuckle Group and older formations form broad folds, with significant pervasive small-scale folding not apparent on large-scale maps. Thin-bedded portions of the Arbuckle Group show pervasive bedding-planar slip and complex small-scale deformation (Fig. 4.9). Above the Arbuckle Group the lithology becomes more varied with a notable increase in shales. At this level detachments commonly sole-out in shales. Common detachment horizons include shales of the Simpson Group (notably the Oil Creek shales), the Sylvan shale, and the-thin-bedded Woodford cherts.

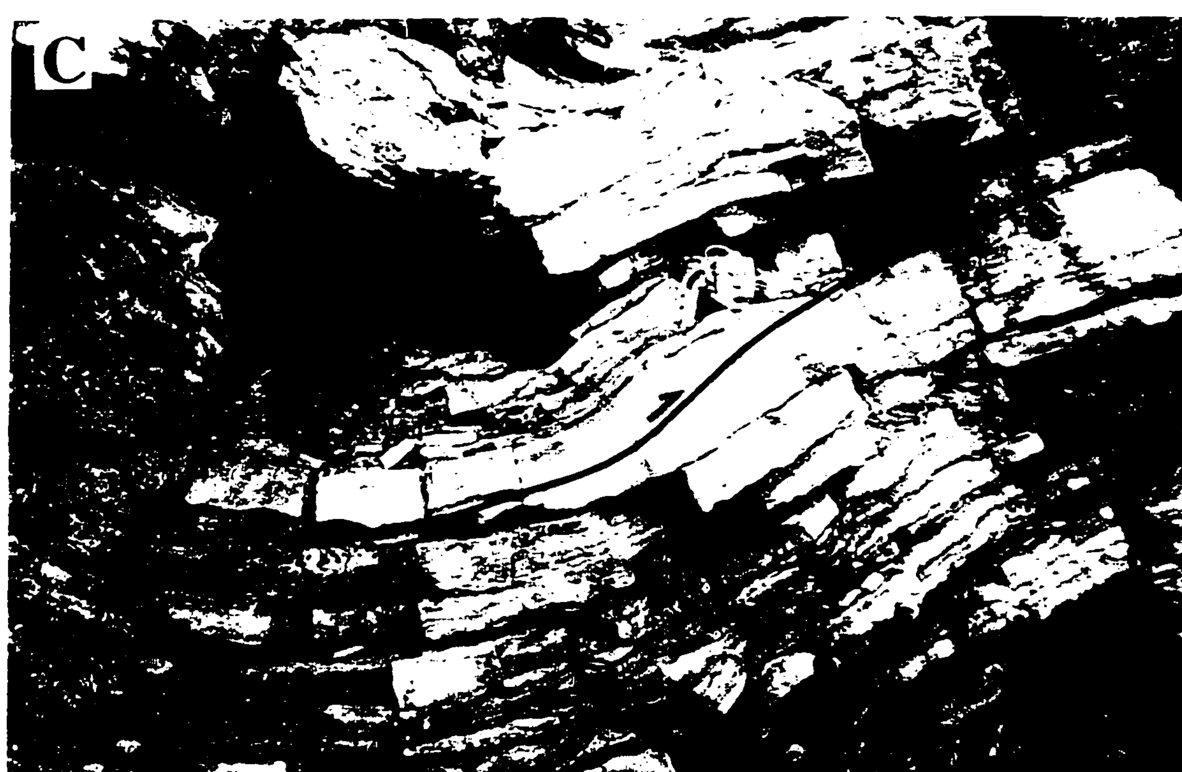
Extensional faulting

Small-scale normal faulting is visible in outcrops and map patterns on the Arbuckle and Tishomingo Uplifts. This study proposes two stages of extensional faulting. The timing of the two overprinted extensional fabrics has not been previously recognized. Previously, the presence of normal faults with compressional features has been attributed to a single episode of wrench tectonics. The first extensional event occurred prior to Pennsylvanian deformation and is related to subsidence of the Southern Oklahoma Rift. This occurred during Arbuckle Group deposition and

Figure 4.9. Montage of photographs shows small-scale structural style on the Arbuckle Uplift and illustrates scale independence of structural style. A. Parallel folding, out-of-syncline thrusting, fault-propagation folding, and other common styles of deformation in thin-bedded carbonates on the west side of the south-bound lane of Interstate 35. B. Inset showing detail of fault-propagation fold. C. Inset showing deformation at the scale of an individual layer.


A
B
C
B
C




C

established a fabric of normal faults within the upper basement surface and lower to mid-Arbuckle Group. Evidence for this is seen in the map patterns of the Arbuckle and Tishomingo Uplifts. Numerous normal faults and fractures present within the lower-to-middle Arbuckle Group show increasing loss of slip and termination in the upper Arbuckle Group, or higher. Many of these faults are have been cut by, and carried on, later Pennsylvanian thrusts which run in detachments in the lower Arbuckle Group, or lower in the section. As a result, these faults have experienced oblique slip and have compartmentalized folds. A prime example would be the cross-wise faults along the Garrison Creek Anticline (Fig. 4.5)

The second period of extensional faulting immediately post-dates the main Arbuckle orogeny and resulted in the local down-dropping along the Washburn Ranch Fault. The Washburn Ranch Fault is a large, late-stage, normal fault, which can be traced along the western Arbuckle Uplift, perhaps into the southern boundary of the Carter-Knox Anticline. Bixler (1993) documented small-scale normal faults in outcrops along Interstate 35 on the Arbuckle Uplift. Bixler interpreted this as late-stage normal faulting which occurred after the main Arbuckle orogenic event. The cause and extent of this late-stage extensional event is not well understood. Saxon (1994) speculated it may be related to relaxation of compressional forces and gravity instabilities, but much work needs to be done to document timing and geometry of this extension.

Collings Ranch Conglomerate

The Collings Ranch Conglomerate is a late-stage conglomerate deposited in the footwall of the Washita Valley Fault and preserved in a small, triangular shaped outcrop. Historically the Collings Ranch Conglomerate has been interpreted as in-fill of a pull-apart basin associated with left slip of the Washita Valley Fault (Brown, 1990; Pybas and others, 1995). Ham and McKinley (1954) mapped the southern outcrop boundary (against the Washita Valley Fault) and northeastern outcrop boundaries as having normal faulted contacts, and the western boundary as an unconformity.

Examination of air photos, outcrops, and surface mapping indicate that the northeastern boundary is unconformable. Surface exposure along Interstate 35 shows an apparent "normal fault" which offsets the unconformity by an unknown amount (Fig. 4.10). Examination of the map of the Arbuckle Anticline reveals that the apparent "normal fault" may be an overturned bedding planar thrust fault of a rabbit-ear fold (Seven Sisters Anticline) on the overturned hanging wall of the Arbuckle Thrust. This fault, which places the conglomerate in contact with pre-Pennsylvanian rocks, and offsets the unconformable contact of the Collings Ranch Conglomerate with overturned pre-Pennsylvanian rocks, contains dip-slip slickensides. If this interpretation is valid, the amount of slip on the fault is minimal and represents late-stage back-shear reactivation of the early formed detachment which carried and formed the Seven Sisters Anticline. The detachment would have propagated into, and offset, the Collings Ranch Conglomerate. A few feet away from the apparent "normal fault", a widely cited fracture contains sub-horizontal slickensides and has been cited as evidence of lateral slip (Pybas and others, 1995). However, this fracture places conglomerate against conglomerate and the magnitude of slip is unknown. Alternatively, the apparent "normal fault" may be an actual normal fault, possibly related to post-uplift extension but not the formation of a pull-apart basin nor the accumulation of the Collings Ranch Conglomerate. In either case the amount of slip on this fault is minor, and of dip-slip nature.

Along the south contact, along Highway 77, a fault can be seen in outcrop in which Arbuckle rocks override the Collings Ranch Conglomerate (Fig. 4.11). At this location, the fault contact is generally mapped as the Washita Valley Fault. The thrust fault in the outcrop may be the Washita Valley Fault or one of its imbricates. Although this outcrop does not conclusively settle the nature of the south contact of the Collings

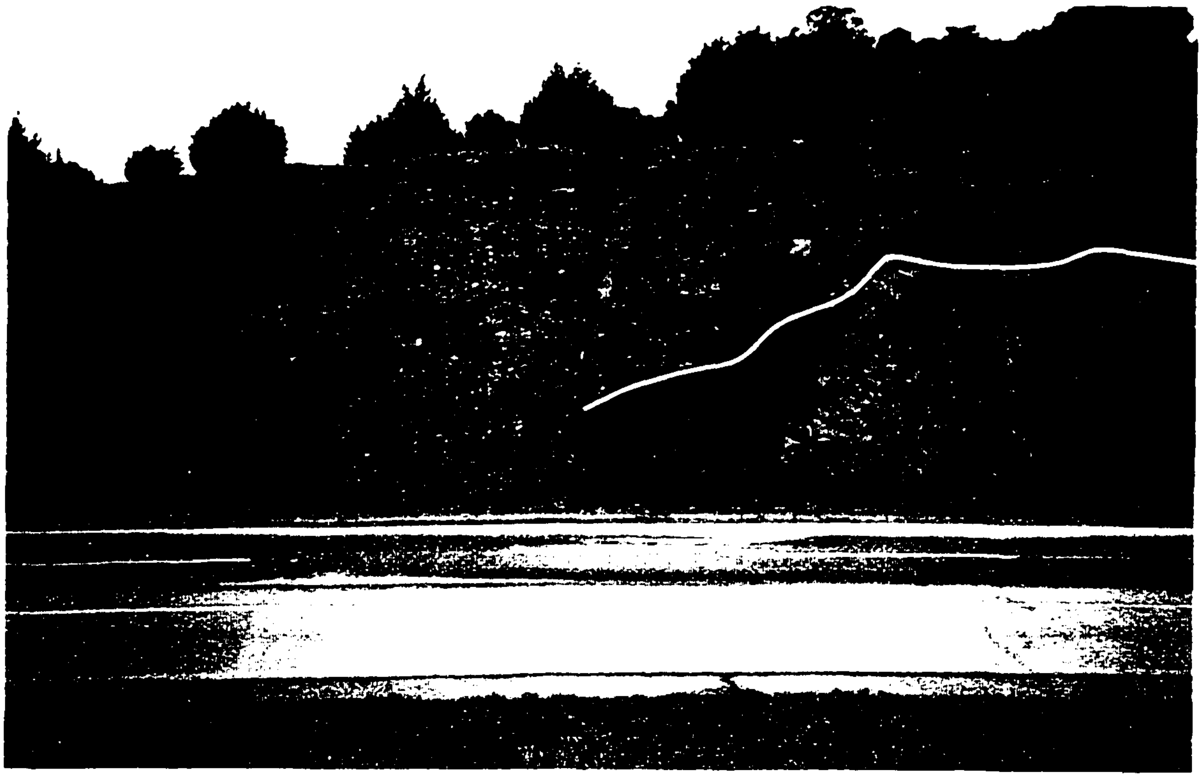


Figure 4.10. Photo of the outcrop on the west side of the south-bound lane of Interstate 35. The Collings Ranch Conglomerate lies unconformably on overturned Simpson rocks of the Seven Sisters Anticline. The apparent normal fault is an overturned thrust fault and contains dip-slip slickensides.

Figure 4.11. Photo of outcrop along highway 77 at the southern contact of the Collings Ranch Conglomerate. The Washita Valley Fault (or one of its imbricates) clearly thrusts rocks of the Arbuckle Group over the Collings Ranch Conglomerate along an extremely low-angle thrust. In most literature, this boundary has been mapped as either a normal fault contact or a strike-slip contact with associated normal faulting.

Ranch Conglomerate, it offers strong support of an overthrust, rather than extensional, or high-angle strike-slip, boundary.

Given these data, this author proposes that the Collings Ranch Conglomerate accumulated in the footwall of the Washita Valley Fault as a piggy-back basin on the hanging wall of the Arbuckle Uplift. Sediments were trapped between the paleo-high of the Seven Sisters and Honey Creek Anticlines to the north, and the Arbuckle Anticline to the south. Significant strike-slip motion is neither necessary nor geometrically feasible with the outcrop pattern. Similar relationships of sediments ponded, or trapped, on the hanging wall of uplifts between the rising main uplift and an eroded "toe" near the leading edge of a thrust is seen in several places in the Arbuckle and Wichita Uplifts, including the Harrisburg Trough (Jacobson, 1984).

Summary and Conclusions

This chapter introduced several key concepts which help establish a framework for subsequent structural analysis. Key concepts are:

1) The Wichita Uplift is thrust over the Anadarko Basin along a zone of complex basement-faulting. Several faults may be involved at any one location. Deep erosion complicates quantification of shortening.

2) The Mountain View Fault is the leading edge fault for only a relatively small portion of the Wichita Uplift and cannot be considered a single, continuous uplift-bounding fault, nor can it be considered responsible for the bulk of crustal shortening because it terminates to the west into a basement-cored fault-propagation fold.

3) The Arbuckle Thrust is the leading edge of the Arbuckle Uplift.

4) The Reagan Fault is a southwest dipping thrust which dies out with the west-plunge of the Tishomingo Uplift

5) The Washita Valley Fault is a southwest-dipping, back-limb imbricate to the Arbuckle Thrust.

6) Deformation of the Arbuckle Uplift is scale-independent and consists of northeast vergent faulting and parallel folding.

7) Two episodes of minor normal faulting alter the dominantly compressional fabric of the Arbuckle Uplift. One is related to Cambro-Ordovician subsidence and is restricted to the Arbuckle Group. The second is a post-orogenic extension which resulted in localized large-scale extension on the western plunge of the Arbuckle Uplift. The presence of extensional fabrics with compressional fabrics does not constitute proof of wrench tectonics.

8) The Collings Ranch Conglomerate was deposited on the footwall of the Washita Valley Fault. The Collings Ranch Conglomerate could not have accumulated in a pull-apart basin as a result of strike-slip motion.

Chapter 5

MODELS OF BASEMENT-INVOLVED DEFORMATION APPLIED TO THE SOUTHERN OKLAHOMA FORELAND

Introduction

This chapter presents a critical review of previous models of foreland deformation applied to the Southern Oklahoma Foreland. It is the intention of this chapter to examine some of the structural models proposed for the Southern Oklahoma Foreland and to explore the implications of proposed geometry and slip. In some cases the tectonic model itself comes under close scrutiny; in other cases, specific interpretations are examined. This chapter is not meant to be a comprehensive evaluation of all previous structural studies and some of the same studies are more fully discussed in other portions of this dissertation.

The classification and analysis of structural models applied to the Southern Oklahoma Foreland can be very challenging. The structural geology of southern Oklahoma is extremely complex and much data comes from subsurface sources and is subject to interpretation. Steep dips and massive faulting create areas of poor seismic imaging. As a result of these factors, a wide variety of structural models have been applied to this province. Analysis and debate of structural models has not been as formal or systematic as in better studied structural provinces such as the Rocky Mountain Foreland or San Andreas System. Models for southern Oklahoma have been proposed by workers with a variety of backgrounds other than structural geology. Concepts such as structural balancing have rarely been used. In the literature, terminology sometimes disagrees with the model depicted in a given article. Often there is lengthy discussion of structural movement in the text, but a lack of cross sections and seismic lines to document a given interpretation. When provided, cross sections often contain distortion due to improper orientation and construction.

Despite these challenges, models may be broadly sorted by fault geometry and slip: faults which are vertical or steepen with depth (non-crustal shortening models); and faults which are inclined or shallow with depth (crustal shortening models), and by dominant directions of slip: dip-slip, both reverse and normal, and strike-slip models. The geometry of the faults and the slip vectors assigned them carry strong implications of what styles of deformation are possible.

Models of Foreland Deformation

Models applied to the southern Oklahoma foreland can be placed into four broad categories based upon geometry and fault-slip direction.

1) Models of differential vertical uplift: Involves dip-slip motion along high-angle faults or, faults which steepen with depth. Includes drape folding, upthrusts, and most gravity-slide models.

2) Wrench tectonics: Involves dominantly lateral slip along high-angle to vertical faults. Includes oblique upthrusts and flower-structure models.

3) Basement-involved thrusts: Involves dominantly reverse dip-slip motion on low-angle faults or faults which shallow at depth. Includes fold-thrusts, thrust uplifts, and basement fault-bend fold models.

4) Oblique-thrusts or "transpression": Involves oblique-slip on low-to-moderate-angle fault, or faults which shallow with depth, in which the lateral slip component is greater than, or equal to, the dip-slip component. Includes most "transpressive" models.

The four categories can be broken into two broad classes based on fault geometry; 1) faults which are vertical, or steepen with depth, and 2) faults which flatten with depth. Faults whose dips steepen with depth are incapable of significant crustal shortening by nature of their fault geometry. Faults which flatten with depth (and which contain a component of dip-slip motion) shorten the crust. This division, based upon fault geometry, was noted by Brown (1984) in his comparison of fault models of the Rocky Mountain Foreland (Fig. 5.1.). Stone (1984) also contains a discussion of the geometry of faults whose dips steepen with depth versus faults which flatten with depth.

Analysis based upon fault geometry is often the most practical way of dividing models because fault geometry has certain geometric consequences that may be independent of the direction of fault slip (dip-slip versus strike-slip). This is especially important for southern Oklahoma because fault geometry is often better documented than the direction, or magnitude, of fault slip. Each of the structural models is reviewed in terms of structural geometry and examples of interpretations based upon these models in southern Oklahoma are examined.

Non Crustal-Shortening Models

Non crustal-shortening models, or models in which the fault is vertical or steepens with depth include differential vertical uplift along block faults (drape folds), upthrusts, and wrench tectonics. Both differential vertical uplift and upthrusts are vertical tectonics models, driven by differential vertical forces, whereas wrench tectonics models are driven by horizontal shear. Because of the differences in driving mechanisms, vertical uplift and wrench models are generally thought of as unrelated. However, although they differ in slip direction, both models share essentially the same fault geometry, and thus some common basic geometric constraints. This is especially true of upthrusts and wrench structures; geometrically they are nearly identical, the major difference between them being the direction of slip. Although the implications of

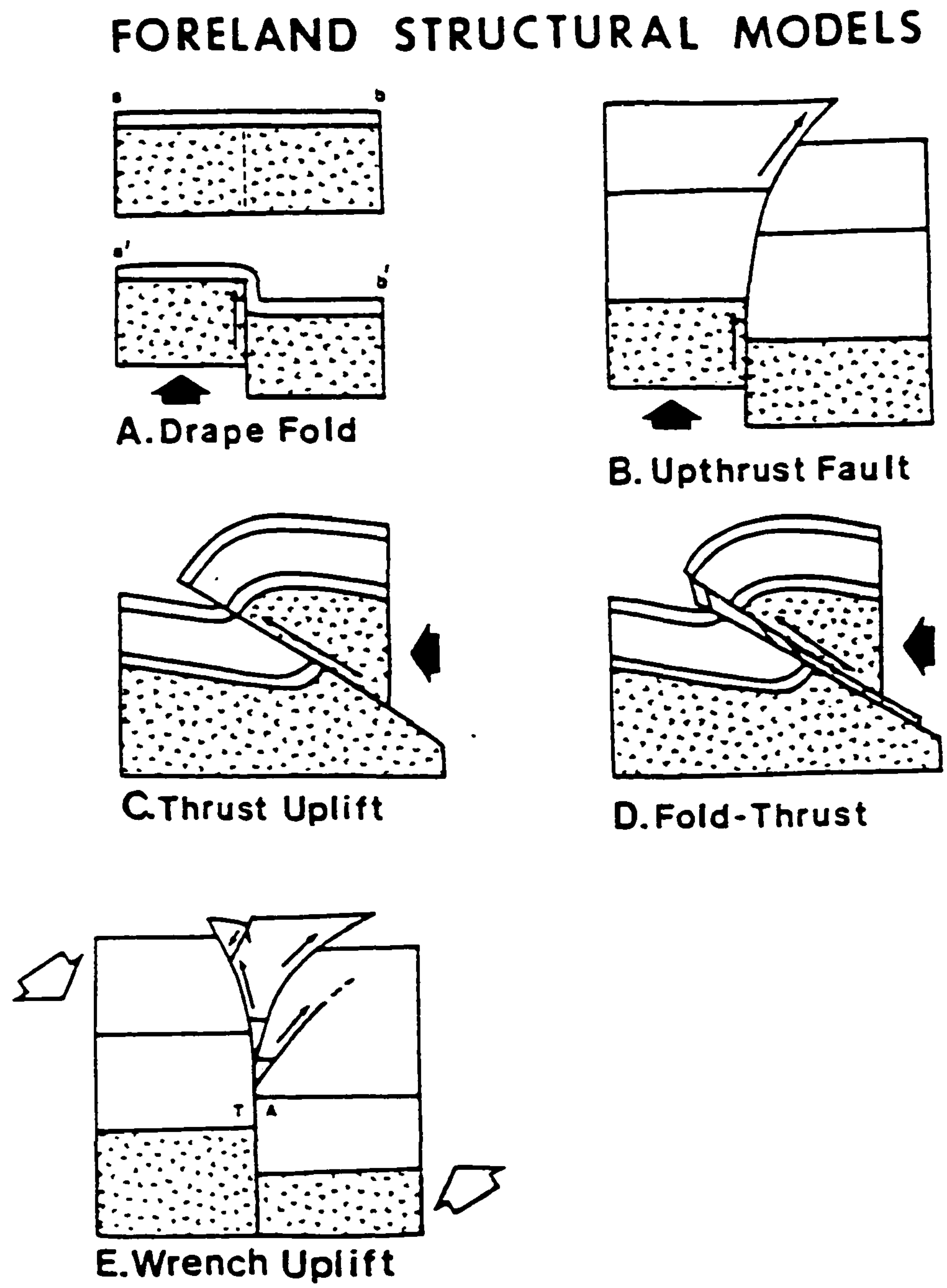


Figure 5.1. Five basic models of foreland deformation. Based upon the fault geometry at depth these five models can be broken into shortening and non-shortening categories. A and B are models of differential uplift. Models C and D are basement-involved thrusts. Model E is based upon wrench tectonics. If oblique-slip occurs on the fault, model D may be related to transpressive deformation. Note the similarity between geometries of B and E (modified from Brown, 1988).

vertical and/or steepening fault geometry have been explored for vertical uplift models (Stone, 1984; Brown, 1984, 1988), wrench structure and flower structure models have not come under the same scrutiny. Because of this disparity of analysis and the prevalence of wrench fault interpretations in Oklahoma, particular attention is given to the geometry of wrench fault models.

Vertical Uplift Models (Drape Folds, Upthrusts, and Gravity Slides.

Differential vertical uplift models dominated the interpretations of Oklahoma workers of the 1950's and 1960's. In both drape folds and upthrusts, deformation is controlled by a vertical or near-vertical fault, which rises up from the basement (Fig. 5.1). In an upthrust, the fault progressively shallows as it rises, forming a concave downward shape. Local shortening may exist where the fault is shallow and forms an overhang. However, in order to maintain structural balance, any shortening caused by overhang in the upthrust must be balanced by hanging wall extension (Fig. 5.2). In a drape fold, the fault maintains a steep dip. In order to maintain structural balance the sedimentary section must involve one of the following mechanisms: 1) tectonic thinning 2) extension of the sedimentary section 3) pulling away a portion of the sedimentary section along a detachment (Fig. 5.2) (Brown, 1988).

Riggs (1958) applied an upthrust geometry to the Wichita Mountain Front (Fig. 5.3a). Although he termed the faults "thrust faults", he interpreted them as steepeing with depth, depicting an upthrust-style geometry. According to Riggs, initial deformation of the Wichita Uplift and Anadarko Basin was caused by normal faulting. The normal faults were subsequently rotated into "apparent" thrust shapes as the basement ductilely "flowed" laterally over the basin.

Harlton (1951, 1963, 1964, 1972) presented numerous interpretations of geometry and fault relationships of the Wichita and Arbuckle Mountain Fronts (Fig. 5.3b). Harlton interpreted deformation as occurring along a series of basement blocks

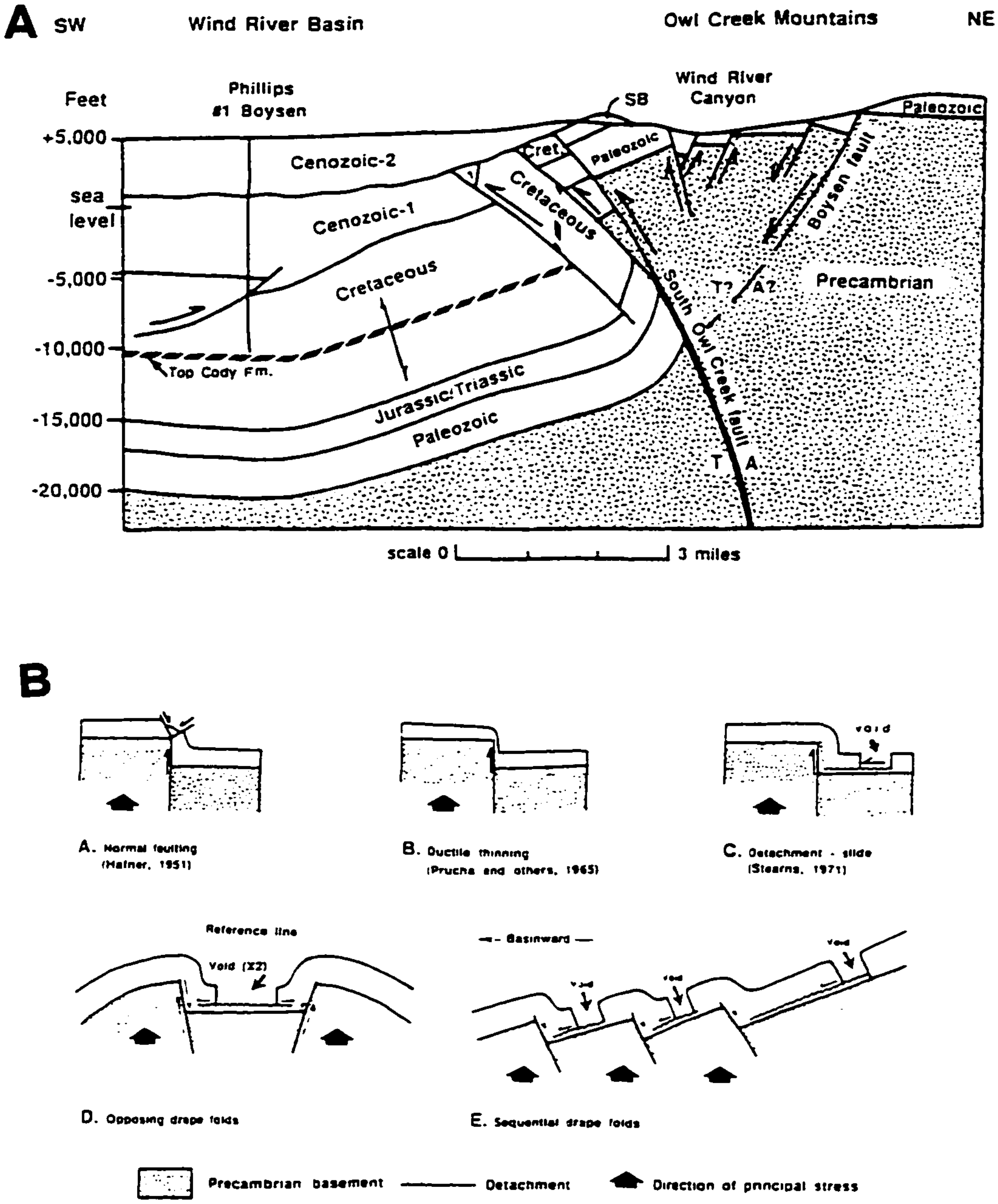


Figure 5.2. Balancing problems for models involving differential vertical uplift. A. In an upthrust hanging wall shortening must balance with extension. This example is from the south flank of the Owl Creek Mountains, Wyoming. In this case, the upthrust shape occurs with a component of left-slip (Brown, 1993). B. Drape folds must compensate by tectonic thinning, extension of the sedimentary section, or pulling along a detachment (Brown, 1993).

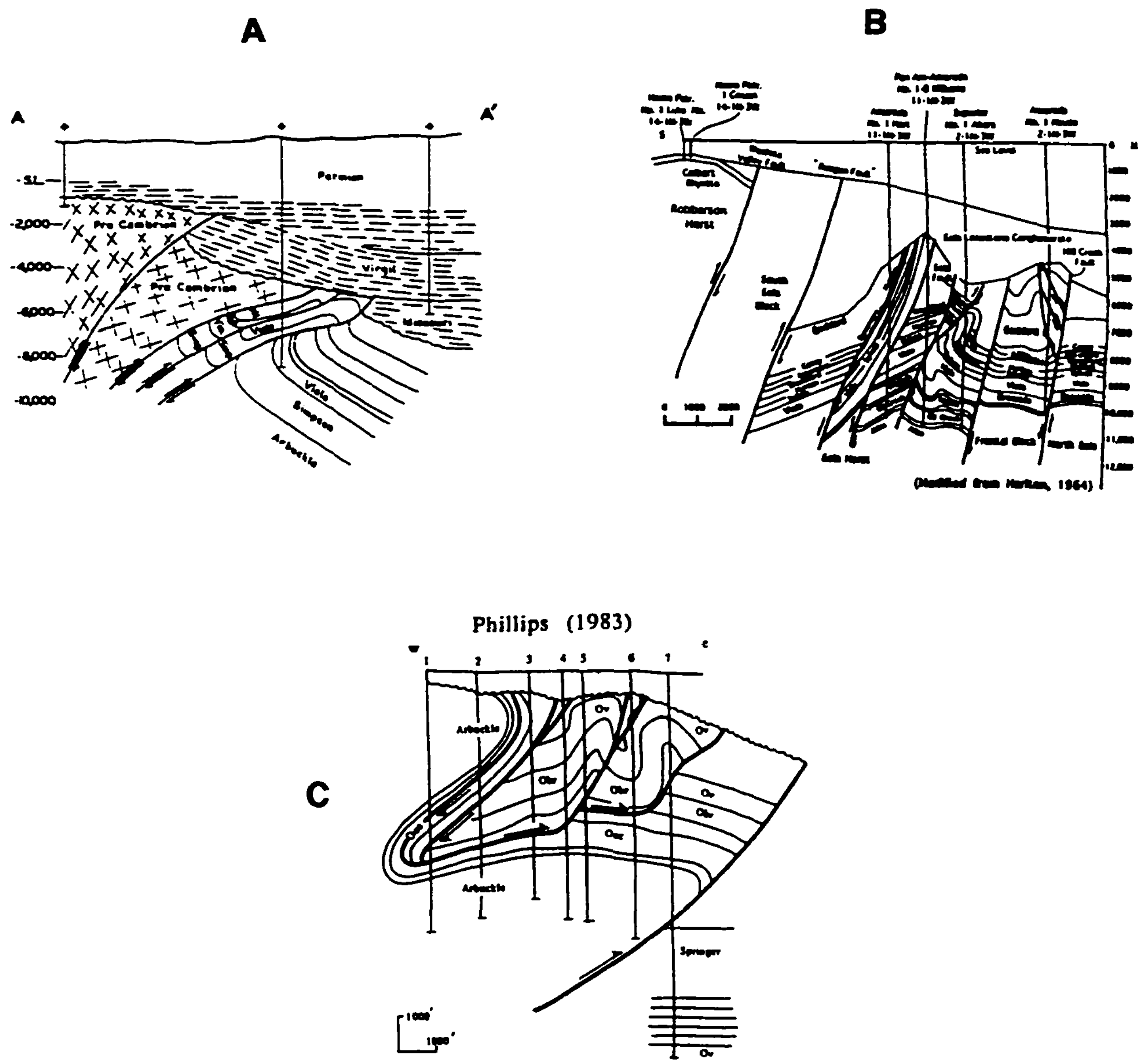


Figure 5.3. Vertical uplift models of the Wichita and Arbuckle Uplifts A) Cross section across the western portion of the Wichita Uplift from Riggs (1958) depicting an upthrust deformational style. B) South-north cross section across the Arbuckle Mountain Front and Eola Field (from Harlton, 1964). The north-south orientation of this cross section is incorrect for the northwest-southeast trend of the system. as a result, the cross section contains distortions and does not properly represent the structural style. Faulting is interpreted to have occurred along high-angle faults reactivated from older normal faults. Note the mismatch between cut-offs on either side of faults. Several prominent faults, such as the Reagan Fault, are illustrated although there is no data to suggest they are present. C) Gravity slide model from Phillips (1983).

which were upthrown along a series of vertical, or near-vertical, faults. Harlton's sections do not balance and are not restorable. Problems with this style of interpretation include inconsistencies of bed-length cut-offs on opposite sides of the same fault, inconsistencies in the vertical change in the sense of throw along the same fault, and linking faults of markedly differing style.

Working along the central and western plunge of the Arbuckle Uplift, Phillips (1983) modified Harlton's (1964) interpretation of the SE Hoover Field and Eola Field areas using a gravity-slide model. Phillips interpreted folding of the north flank of the Arbuckle Uplift and footwall of the Arbuckle Uplift as gravity slides along detachments from vertically uplifted blocks (Fig. 5.3c). Phillips model suffers from mis-matched cutoffs. Phillips' model requires the geologically unrealistic condition of virtually no erosion of the hanging wall during the initial uplift despite attaining over 10,000 feet of elevation above sea level, but massive amounts after uplift and deformation along the "Washita Valley Fault" cease. Additionally, although Phillips recognized bedding-plane slip in rocks of the Arbuckle Uplift, his interpretation of gravity sliding is in error. His figure of a fold on the north flank of the Arbuckle Uplift (Fig. 5.3c) was in overturned rocks, and the sense of vergence was down, not up, the steep flank.

Vertical uplift models can not account for the presence of large basement overhangs documented by seismic lines (Brewer, 1983; Saxon, 1994) and drilling (Brown, 1984; Beck, 1986; Saxon, 1994), and provide no mechanism to generate net shortening of the hanging walls of uplifts because any shortening created by the upward flattening of an upthrust must be balanced by hanging wall extension. It is also difficult to explain the driving mechanism for vertical stresses in the terms of plate tectonics. Strong vertical forces should result in regional doming, however, adjacent to the mountain uplifts are coeval basins which experienced subsidence. It is difficult to reconcile how vertical stresses could operate in the opposite directions in the same area.

Wrench Tectonics.

During the 1970's and 1980's the majority of workers in southern Oklahoma attributed Pennsylvanian deformation to strike-slip or "wrench" tectonics (Tanner, 1967; Lowell and Harding, 1979; Walper, 1977; Wiltse, 1978; Haas, 1979; Carter, 1979; Booth, 1981; Axtmann, 1983; Budnik, 1986). Most workers categorized deformation as due to left-lateral wrenching. These studies vary widely on estimates of slip magnitude (Table 1); however, all agree that deformation was characterized by dominantly left-slip along vertical, or nearly-vertical, faults. Few of these studies contained documentation of interpretations of fault-linkage and fault-geometry with cross sections, or seismic lines. Many interpretations were based upon restoration of lateral slip of offsets of isopach contours (interpretational data) and assumed vertical fault geometry. None of the wrench fault articles attempt to restore crustal shortening and are therefore based upon incomplete restorations.

By definition, wrench faults (Fig. 5.4) are a class of strike slip faults differentiated from other faults with lateral slip by their basement involvement and the steep angle of the master basement fault (Wilcox and others, 1973). Wrench faults are a type of simple shear in which initial deformation occurs by folding and fracturing along a zone of deformation which narrows as deformation increases, eventually resulting in slip along a few closely spaced faults, or along a through-going wrench fault (Wilcox and others, 1973). In contrast, strike-slip faults driven by pure shear are non-rotational and deform along a single fault plane. Historically, the geometry of wrench fault style of deformation has been characterized by:

1) large-scale lateral offsets along primarily vertical faults

2) greater lateral slip than dip-slip motion

3) "flower" or "palm tree" structures

4) *en echelon* folds.

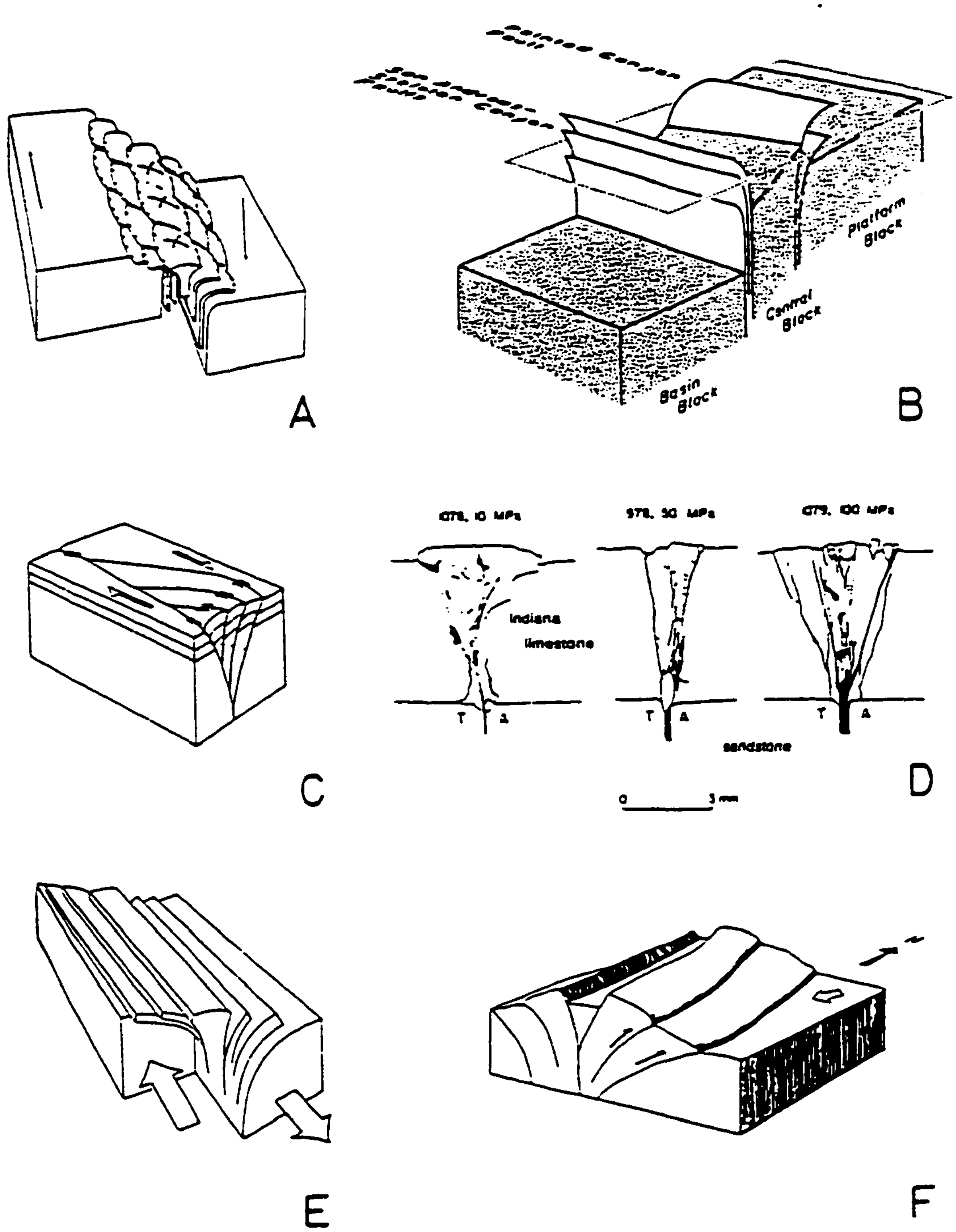


Figure 5.4. Several schematic variations of wrench systems models. Note most are essentially dual-upthrusts with lateral motion. Only one model (B) is based upon a real geologic situation (Sylvester and Smith) and that interpretation is not supported with subsurface control. Compare Bartlett model (D) to schematic models. Note that D is not an upthrust shape narrow band of basement deformation (Sylvester, 1989).

Modern thinking about wrench tectonics is largely based upon clay modeling experiments (Moody and Hill, 1956; Wilcox and others, 1973) rather than type examples of specific structures. Models typically consist of clay cakes which are placed across two underlying rigid boards. The boards are slid past each other to simulate lateral movement on basement faults. Low amplitude, symmetric, *en echelon* folds form as the result of detachment of the clay from the underlying boards. Some clay models enhance folding by using plastic sheets to create an artificial detachment surface. The association of structures generated from clay cake experiments, especially the 2-D map patterns, are then compared against tectonic map patterns of actual fault systems (Wilcox and others, 1973). Significance of the horizontal detachment in the models cannot be overstated because it is the mechanism which allows the clay to form *en echelon* folds. Although cited as diagnostic to wrench zones, *en echelon* arrangements of folds are common in many other structural settings such as fold and thrust belts (Dahlstrom, 1970) and compressive basement provinces and is diagnostic of detachments, not just wrenching or simple shear.

Clay models, in the author's opinion, are poor analogs to actual layered rock systems. Their physical properties arenot representative of the stratigraphic layering of real rock systems, nor can they model anisotropies and pre-existing structural grains. Rock model experiments which can approximate sedimentary layering, mechanical stratigraphy, and which can be run under real rock confining pressures may be better analogs. Suprisingly, very few of these experiments have been conducted to simulate a wrench system; however, those that have been run (Loagan and others, 1978; Bartlett and others, 1981), show a strong variance from the results of clay models.

Bartlett and others (1981) created a model which is essentially the rock-model equivalent of a standard clay-cake model (Fig. 5.5). The model consists of a slab of sandstone, which simulated basement rock, and contained a vertical pre-cut oriented

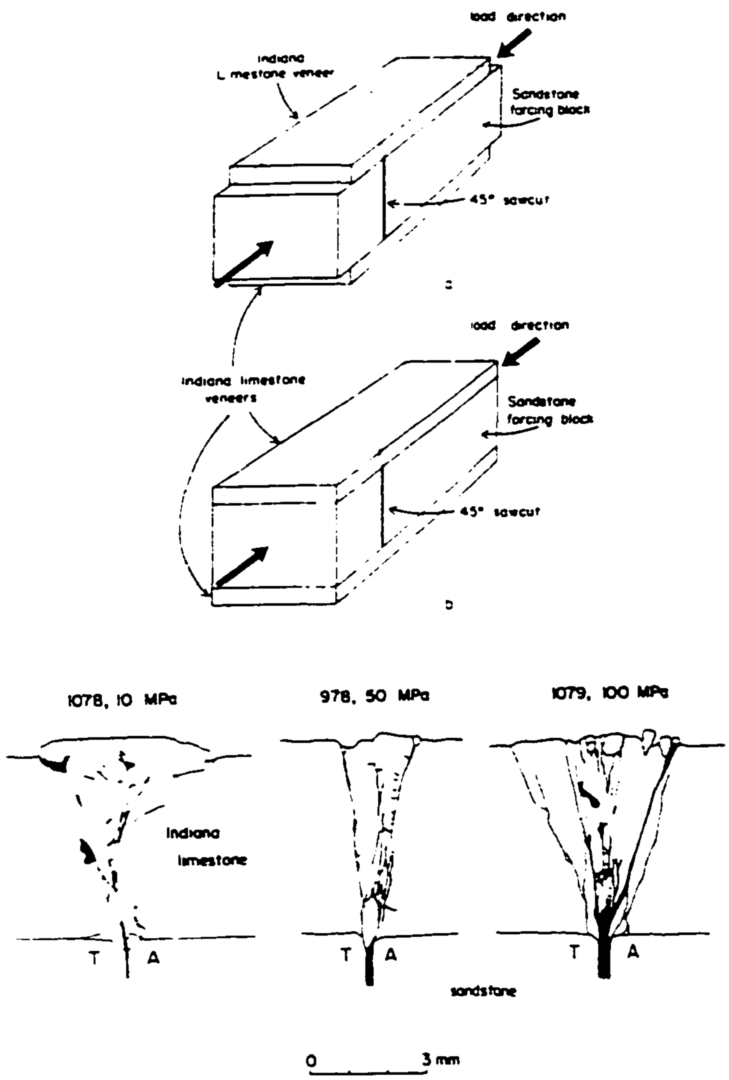


Figure 5.5 Rock model of a wrench zone designed by Bartlett and others (1981). This model is similar in design to clay-cake models of wrench systems, but yields a different suite of structures. A notable difference is the failure of *en echelon* faults to develop in the real rock models. This is because no detachment forms in the rock model along which folds can develop. The detachment is a function of the material used (clay) and not the wrench system. The zone of deformation in the rock models is narrow; less than the width of the "sedimentary column" (limestone thickness). No crustal shortening is generated due to the vertical nature of the basement fault.

45° from the edge of the block which simulated the wrench fault. An uncut layer of limestone was placed across the top of the sandstone, and used to simulate the sedimentary cover (Fig. 5.5b). The model was then subjected to end-loaded compression, resulting in shearing along the pre-cut fault, creating a wrench system.

Examination of the deformed model (Fig. 5.5c,d,e) revealed several important features:

1) No net shortening occurred across the wrench fault.

2) Deformation in the "sedimentary" section was confined to a narrow band of anastamosing faults which widened upward from the basement.

3) The "sedimentary" section did *not* detach and nor did it produce the *en echelon* arrangement of folds typical of clay models.

4) Deformation of the "sedimentary" section consisted of fault gouge.

5) No net vertical offset occurred on the basement sedimentary contact.

By comparing real rock models to clay models, one can see each generated substantially different suites of structures, simply as a result of variation of the material and confining pressures used in the models.

Logan and others (1978) modeled uplifts on which combined lateral slip and differential vertical uplift (Fig. 5.6) occurred on a vertical fault. In these models, a forcing block was designed with two pre-cut faults. The first was oriented parallel to the direction of end loading to accommodate lateral slip. The second was a ramp oriented perpendicular to the direction of shortening, to simulate a high-angle (60°) reverse fault and to introduce a component of differential vertical uplift along the vertical lateral-slip fault. The forcing block was then overlain with thin layers of uncut rock to simulate the sedimentary section. End loading of the model forced the pre-cut block to move up the ramp, forming a high-angle reverse fault and created differential vertical uplift and lateral (oblique) slip along the vertical fault. The model was repeated

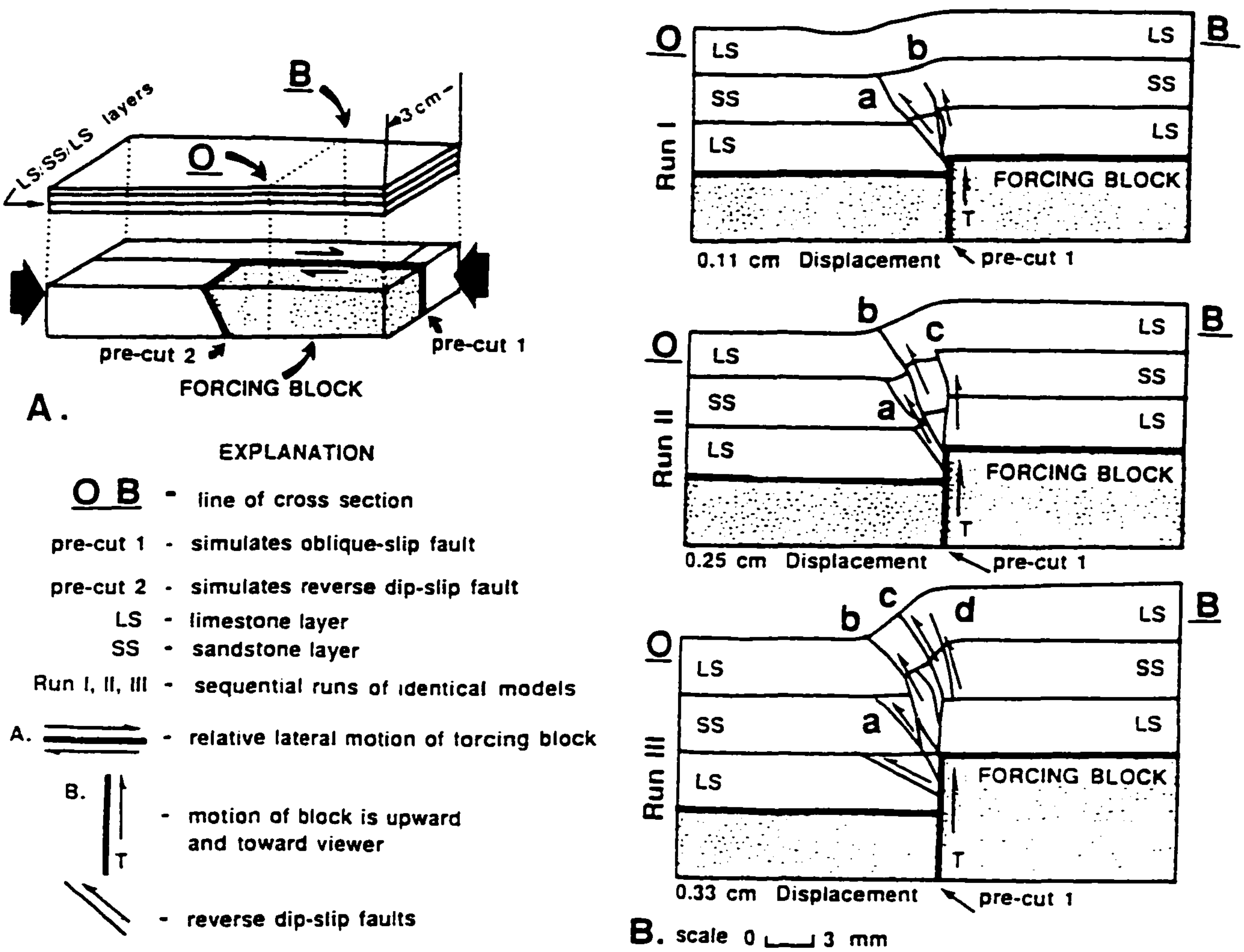


Figure 5.6 Rock models experiments by Logan and others (1978) which simulate lateral slip combined with differential vertical uplift. A. Model is designed so that a vertical fault (precut 1) is transverse to a ramp (precut 2). End-loading forces the block to move up the ramp, generating right-oblique slip along the vertical fault. B. Results of repeated experiments with increasing displacement (runs 1, 2, 3), illustrate progressive development of an upthrust-shaped -fault with right oblique slip. No net crustal shortening is generated due to vertical dip of the fault at depth. Sedimentary layers in monocline are tectonicly thinned (from Brown, 1993).

several times with varying amounts of displacement producing a sequence of development.

In cross section profile (Fig. 5.6) splay faults formed off the vertical pre-cut fault and flattened into the sedimentary section forming an upthrust geometry. The resulting uplift had a monoclinal shape. No folding, other than passive drape, occurred in the sedimentary section. Although there was motion in and out of the plane of the section, reasonable balance was maintained across the fault. The lack of crustal shortening within the basement was accommodated by thinning of the sedimentary section. Because the sedimentary section did not detach, no *en echelon* folding developed. *Both rock models illustrate that vertical faults, even with lateral motion, are incapable of shortening the crust or generating significant net shortening of the overlying sedimentary section.* Additionally, both models illustrate the concept of balance across a vertical fault.

Flower structures.

One of the most common models applied to wrench tectonics is the "flower" or "palm tree" structure model. Geometrically, flower structures are dual-sided upthrusts which accommodate lateral slip. Like an upthrust, the vertical nature of the flower structure master fault precludes net shortening of the crust, and overlying sedimentary section, by its vertical geometry. Flower structures can only form local shortening in the sedimentary section where the vertical fault flattens into a thrust. However, because the fault ultimately steepens with depth, it cannot create net crustal shortening and must contain an amount of extension within the hanging wall which balances any shortening created by thrusting. Flower structures are routinely depicted as large folds in the sedimentary section located over, and cored by, a master fault which becomes vertical at depth. Such an interpretation necessitates a greater amount of shortening of the sedimentary section than in the basement below the fold, and presents serious problems in restoration and balancing. The oft-cited argument that such a geometry is permissible due to fault motion in and out of the line of section is misleading. *Even for a situation in which there has been motion out-of-the-plane of section there still must exist a cut-off, somewhere along the strike of the fault, which matches one side or the other of a fault.* If a "flower structure" interpretation consists of a large fold in the sedimentary section located over, or cored by, a vertical basement fault, the interpretation is out of balance, because the sedimentary section has been shortened but the basement has not. Additionally, each half of the flower structure (or either side of the flower structure) will be out of balance if considered individually. Thus, the "flower structure" is composed of two sides of a master fault, each of which is incapable of balance. The geometry of the other side to which each "half flower" must restore, by necessity, must also be out of balance. The basement cut-off will restore against a vertical fault (no shortening) but the sedimentary section will restore against a fold (shortening). Thus, even with out-of-the plane slip, the total "restored" section will be out of balance (Fig. 5.7). Faults cannot accommodate shortening at, and below, the level at which they become vertical and interpretations, such as flower structures, which depict large amounts of shortening above a vertical fault (even with lateral slip) are geometrically untenable.

When considering flower structures, it is important to keep in mind that they are most commonly known from interpretations of seismic data. No definitive "type" example field structure has ever been pointed to in the literature which is based upon indisputable field evidence. There is seldom a flower structure where an alternative explanation for the geometry of the seismic image isn't possible (Fig. 5.8). This is underscored by an article by Harding (1990) who listed thirteen widely different structures which could be mistaken for a flower structure (Table 2).

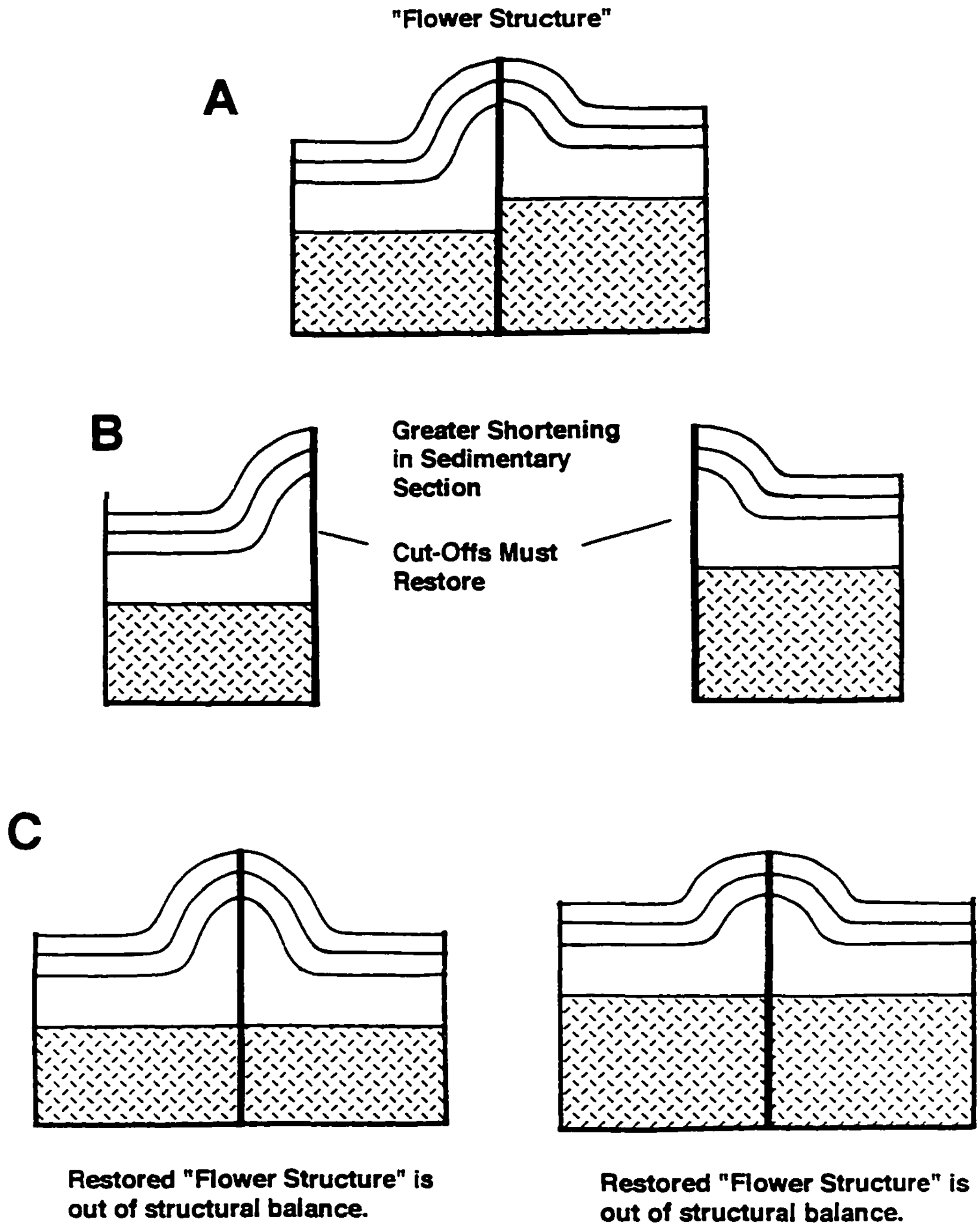


Figure 5.7. Schemactic diagram illustrating restoration problems with "flower structures".

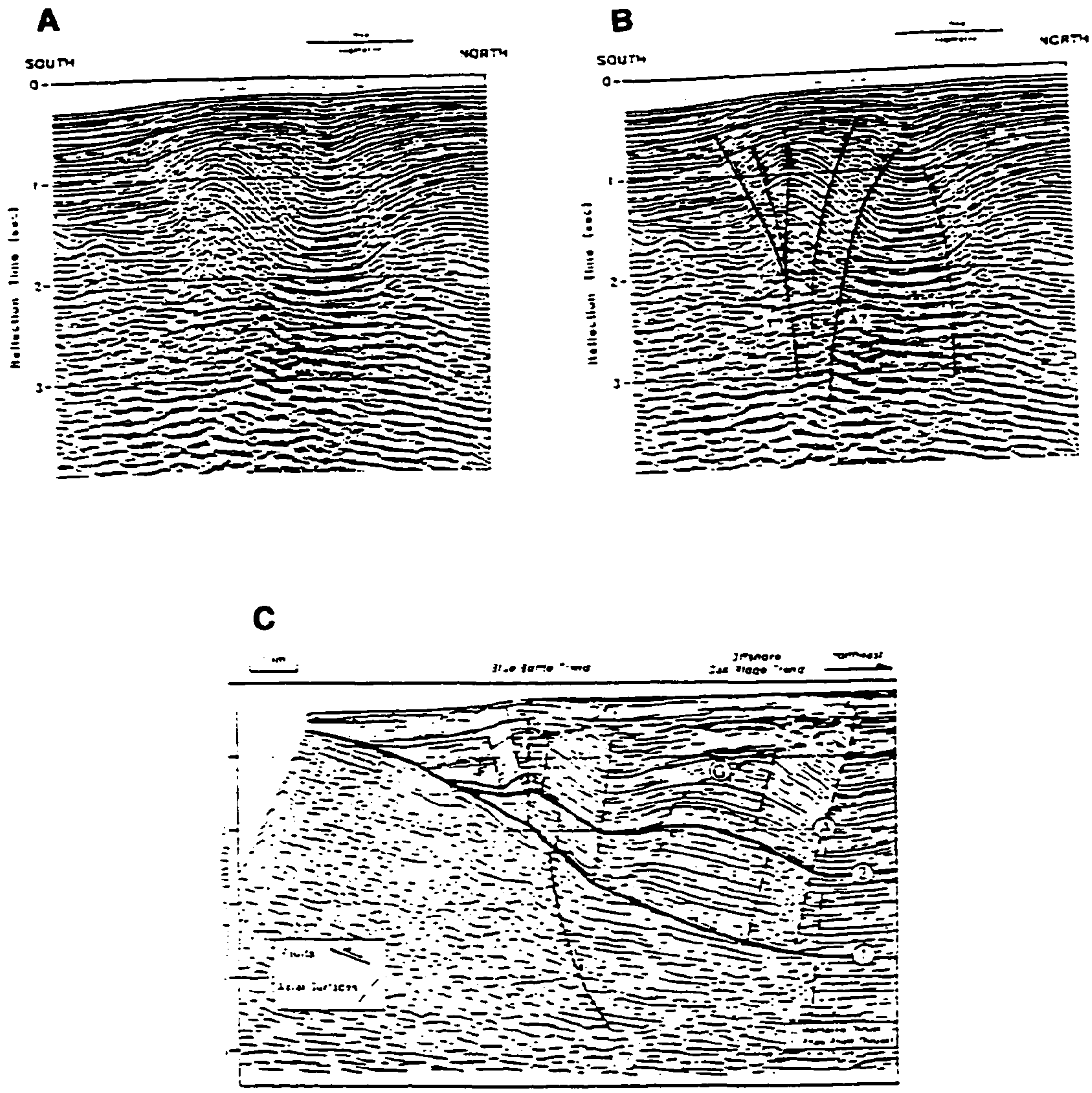


Figure 5.8 One seismic line offshore in the Santa Barbara Channel, California. A is uninterpreted seismic data. B is interpreted using the flower structure model. Note that the faults in this interpretation do not break the surface and many show no offset of reflectors A and B from Sylvester, 1988). C is an alternate explanation in which fault-bend folding creates the folding. Note that this model also explains the geometry of the growth sediments. Many structures, such as the Blue Bottle fold, which were once held as type examples of flower structures are interpreted as forming in other ways (from Shaw and Suppe, 1994).

Structure	Compressional Setting	Extensional Setting	Neotectonic Setting
Basement Horst or Graben	Horst or Box Fold	Extensional Graben	
Basement Faults and Splays	Reverse Step Faults	Normal Step Faults	
Faulted Anticline	Faulted Anticline	Faulted Syncline	
Inverted Basement Blocks	Prior Contractional Block	Prior Extensional Block	
Detached Box Fold	Detached Folds		
Salt-Intruded Fault	Salt-Intruded Fault	Salt Intruded Fault	
Linked Fault Systems	Two-Sided Orogen	Rift Basin	
Misc. Structures			Large Joints Solution Collape

Table 2. List of different structures which could be mistakenly identified as a "flower structure" (list complied from Harding, 1990).

Examples of Wrench Models Applied to Southern Oklahoma.

Tanner (1967) introduced the concept of large-scale lateral displacements and wrench tectonics to southern Oklahoma, proposing 40 miles of left-lateral offset along the Washita Valley Fault which he traced for 150 miles (Fig. 1.3). Tanner used offset (separation) of the zero-sand isopach of the basal Oil Creek Sand to determine offset (slip). However, he failed to address shortening. His interpretation was predicated upon the assumption that the Washita Valley Fault is vertical and extends for a length of 150 miles. However, he offered no evidence to support that assumption. Tanner's article was remarkably influential, not only in terms of its conclusions, but in serving as a template for subsequent workers, and in "defining" the lateral extent of the "Washita Valley Fault".

Lowell and Harding (1979) presented a flower structure interpretation of an un-named fold in the Ardmore Basin (probably the Aylesworth-Madill Anticline) which has been subsequently cited by many as a type example of a "positive" flower structure (Harding, 1985) (Fig. 5.9). This interpretation shows a vertical fault beneath a large fold in the sedimentary section. The fault rises vertically from the basement to the middle Arbuckle Group level, above which it splits and branches in a complex manner. The large fold is obviously a result of the lower-angle portion of the fault zone located directly above the first split in the vertical fault which branches into the fold. The basement on the north side is vertically offset from the basement on the south side, and is therefore not shortened. The tips of the various splays of the wrench fault terminate within the sedimentary section and are therefore "pinned" and unable to accommodate significant lateral slip. Only one strand of the fault reaches the surface (unconformity) and it's pathway is extremely tortuous and complex. The sedimentary section from the mid-Arbuckle Group level upward is shortened (folded), whereas the basement and lower Arbuckle are not shortened. Each side of the "flower structure" is out of balance

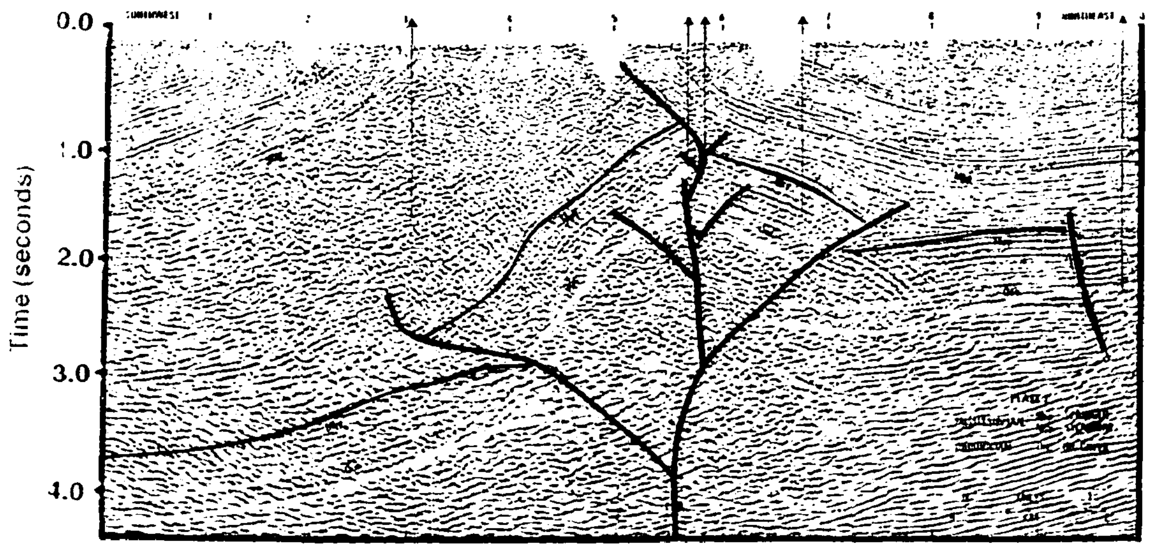


Figure 5.9 Flower structure interpretation of a fold in the Ardmore Basin (Lowell and Harding, 1979). The lower Arbuckle and basement are out of balance with the overlying section which is shortened by folding. Because each half is out-of-balance independent of the other half, and must restore to matching cut-offs, there exists no match out of the plane of motion which will present a balanced section. Note the fault tips are pinned within the sedimentary section and are incapable of accommodating lateral slip.

because each side must restore against a fold over a vertical fault, and will be further out of balance when restored! Thus, the interpretation will not balance even if "out of the plane motion" exists. Additionally, the style of folding depicted in the interpretation is not the same style of parallel folding visible on the exposed Arbuckle Anticline located a few miles away.

Carter (1979) argued for 20 miles of left-slip on the Washita Valley Fault, based upon offsets in contours of the Hunton Group isopachs and apparent surface offsets of fold patterns. He assumed a vertical dip for the Washita Valley Fault. Though his interpretation was based on offset of fold patterns, Carter failed to address the ratio of the shortening component to the assumed lateral slip. Furthermore, he used "separation" as equivalent to "slip" (two dimensions versus three dimensions), failing to take into account the effect of plunge and erosion on apparent separation. The Hunton Group is extremely variable in thickness and contains numerous (at least five) unconformities, and contains local paleo-karsting. Carter showed that the Hunton may double in thickness and change lithology in as little distance as one-quarter mile on a non-faulted block. All of these considerations leads to the question of the validity of offset based upon interpretive isopachs of the Hunton Group derived from random drilling.

Booth (1981) presented stereonet plots of slickensides for three portions of the "Washita Valley Fault Zone". Booth described the slickensides as "horizontal" and claims that their presence supports left-slip along the Washita Valley Fault Zone which she described as a vertical fault. However, in two of three plots, she indicated that the slickensides plunge to the southwest at a moderate dip. This orientation is perpendicular to the strike of the Washita Valley Fault (Fig. 5.10). It is impossible for slickensides of this orientation to be contained on the Washita Valley Fault if the fault is vertical. However, the slickenside data are compatible with low-angle thrusting in a northeast-southwest direction on a southwest dipping fault plane. Booth's analysis

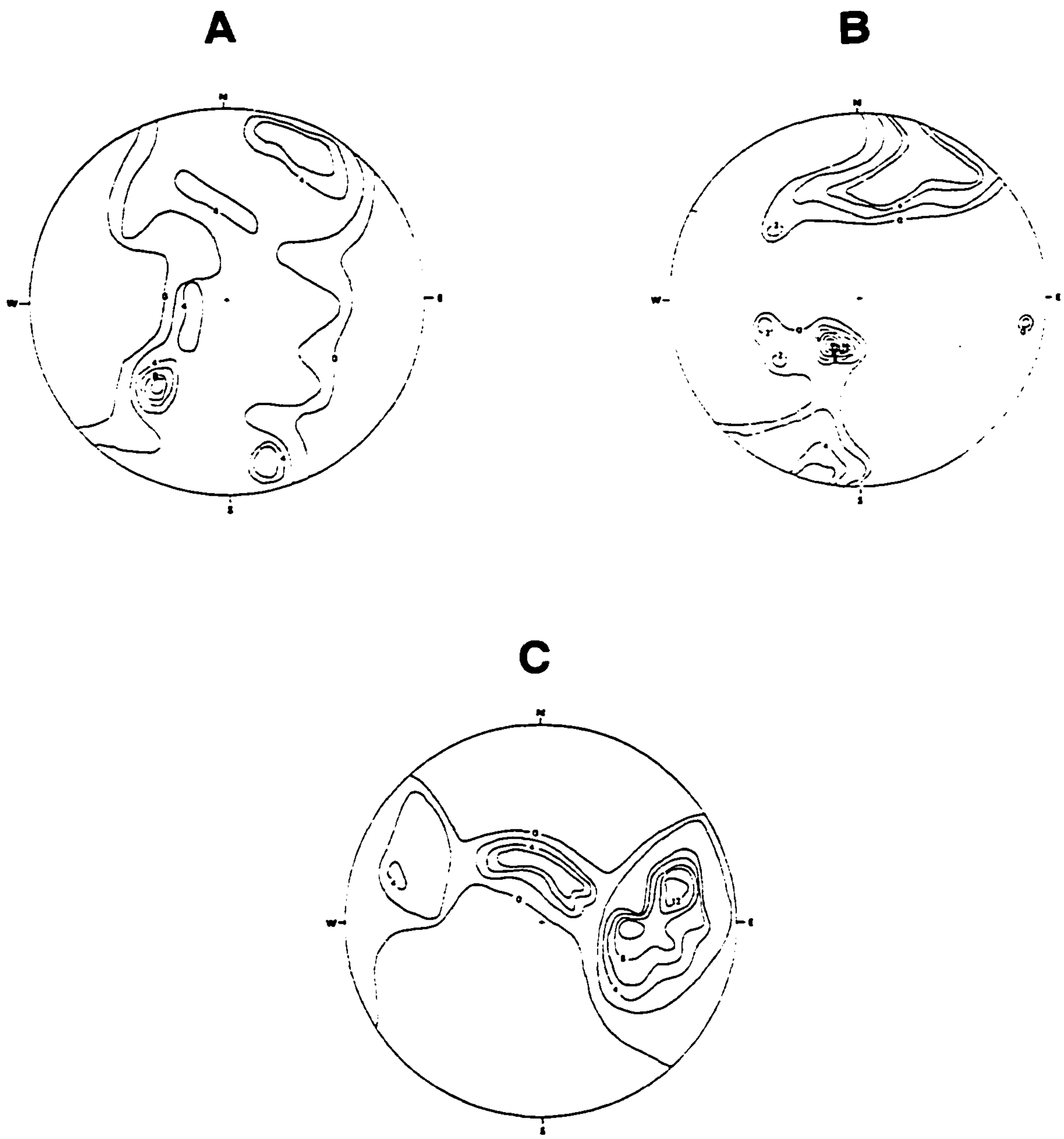


Figure 5.10. Three stereonet plots of slickensides from various faults along portions of the "Washita Valley Fault Zone" which strikes roughly northwest for all plots (Booth, 1981). The greatest concentration of slickensides in plots A and B plunge to the southwest at less than 45 degrees, indicating NE-SW oriented dip-slip faulting. Slickensides in plot C are collected along Interstate 35. The lack of a coherent direction probably reflects overturned bedding and plunge from subsidiary parallel folds.

illustrates some common problems with map analysis of "wrench" zones. First, the analysis ignores the third dimension. Second, because wrench systems are thought to generate compressional, extensional, and shear fabrics, the wrench model can "absorb" kinematic data from a multitude of orientations. Data which support alternate interpretations are thus used to support the wrench model.

Crustal Shortening Models

Shortening of the crust in southern Oklahoma has been documented by the COCORP seismic lines, which imaged large basement overhangs (Brewer and others, 1983). Numerous wells have been drilled, and thousands of feet of basement overhang documented (Brown, 1984; Beck, 1986; Saxon, 1994). Although there is a growing consensus that the Wichita Mountain Front and Arbuckle Uplift are bounded by low-angle faults, there is a lack of consensus to the style of faulting and, importantly, to the amount of lateral-slip versus dip-slip. Workers who favor crustal shortening can be broken into two camps; those who favor equal or greater amounts of lateral slip (oblique or "transpressive" motion) and those who favor a dominantly dip-slip interpretation.

Models of crustal shortening depend upon basement behavior. Workers who favor rigid basement models, contend the basement is incapable of folding. In contrast, some workers have argued on the basis of overall geometry of basement-involved uplifts that the

crystalline basement must experience relatively continuous folding. Arguments over basement behavior for the crustal shortening models have been more thoroughly explored by workers in the Rocky Mountain Foreland (Stone, 1984, 1988; Brown, 1988; Schmidt and others, 1993). Many workers in southern Oklahoma do not directly address basement mechanics and present interpretations with elements of more than one model.

Dip-Slip Models

Thrust Uplift. Thrust uplift deformation is typified by forced-folding of the sedimentary section by a basement block carried along a low-angle thrust. The concept of low-angle basement faulting was popular in the Rocky Mountain Foreland for many years but Berg (1962) appears to be the first to define and name this style in the literature. The thrust uplift is essentially the same style as the thrust-fold model of Stone (1984), who in turn, borrowed from Blackstone (1940). Schmidt and others (1993) documented an end member of basement deformation which could be described as a thrust uplift.

The thrust uplift model involves little to no folding of the basement prior to the development of a low-angle, or listric, basement fault which transports the hanging wall over the developing basin. Characteristic of the thrust uplift style is a single major fault plane and minor basement folding (if any) prior to thrusting. The dual fault zone, characteristic of fold-thrust deformation, is generally not present, although Stone (1993) demonstrated how a poorly developed "dual fault zone" can be developed by imbrication of the basement thrust. In the thrust uplift model, no mechanism exists to generate significant amounts of folding of the footwall syncline. As a result, volumetric crowd structures such as rabbit-ear folds and foreland detachment structures are either poorly developed or not present. If the basement behaves in a particularly rigid manner, the forced fold of the thrust uplift is associated with thinning of the forelimb of the fold.

Thrust uplift models are favored by workers who believe in a rigid-basement response to regional horizontal compression. Thrust uplift models are more readily balanced than vertical uplift models (Brown, 1988). In many cases, it is difficult to differentiate between thrust uplift and fold-thrust structures. Different portions of the mountain front may exhibit characteristics of either style. Sometimes regions of different style may be separated by compartmental faults, however, it is possible that these styles may laterally grade into one another; an idea that is examined in chapter 8. Many areas in southern Oklahoma show characteristics of the thrust uplift model. Deep basement drilling along the central portion of the Arbuckle Uplift (Hamilton Brothers Turner Falls #1-18) has encountered a single major thrust (Arbuckle Thrust). Aspects of thrust-uplifts in southern Oklahoma are more thoroughly addressed in chapter 8.

Fold-Thrust. Fold-thrust deformation has not been formally applied to the southern Oklahoma foreland, although it has been implied in the cross sections of workers such as Brown, (1984), Beck (1987), and Saxon, (1994). Fold-thrust deformation is explored in detail in chapter 6 and is therefore, only discussed briefly here. In the fold-thrust model, deformation occurs by initial folding of the basement, forming asymmetric anticline-syncline pairs. Upward volumetric crowding of the forelimb syncline generates detachments within the sedimentary section. Once the basement reaches it's mechanical threshold, faulting replaces folding and the anticline is carried over the syncline along a low angle thrust. No single mechanism is proposed to facilitate "folding" of the basement although Chase and others (1993) and Schmidt and others (1993) have documented a variety of mechanisms which allow for the folding of a variety of basement compositions.

The fold-thrust model (Berg, 1962) allows individual faults to terminate laterally into fault/fold interchanges (fault-propagation folds) and provides a geometric basis for the formation and timing of detachments which generate subsidiary structures in the sedimentary section. Detachments (subsidiary structures) are formed early, prior to faulting, as a result of volumetric folding, and may be carried on the hanging wall of a fault which cuts the detachment, creating a fault block with excess line length in the sediments above the detachment.

Fault-Bend Fold. Fault-bend fold modeling is a quantitative approach to a qualitative model of ramp-anticline proposed by Rich (1934). In the fault-bend fold model (Suppe, 1983), folding is passive, caused by the translation of the hanging wall over a bend, or ramp, in the fault. Ramp anticlines form over ramps which allow for a vertical rise in the fault over a short horizontal distance. The size of the hanging wall anticline (fault-bend fold) is a function of depth of the thrust, dip and width of the ramp, and amount of slip of the hanging wall over the ramp. If slip decreases laterally along strike, the fault-bend fold may terminate into a fault-propagation fold. Back-thrusting may develop at the inflection point of the lower flat and ramp.

Fault-bend folding may modifiy a thrust-uplift of fold-thrust style of deformation. The main basement-thrust may have a fault-bend fold shape at depth, but reach the surface as a fracture tip which propagates as either a thrust uplift or fold-thrust. The fault-bend fold geometry of the uplift is created by the translation of the hanging wall, modifying the geometry of the uplift created at the fault-tip (mountain-flank). A fault-bend fold geometry may develop a fault splay at a ramp-to-flat bend which shallows the fault by "clipping off" the ramp. The fault-bounded block becomes a "horse" in the footwall and may be translated along with the hanging wall. Footwall horses may be misinterpreted as portions of the extremely thinned dual fault zone charateristic of the fold-thrust model. Beck (1987) interpreted a horse in the footwall of the Arbuckle Thrust. Saxon (1994) interpreted a horse in a sesimic line along the subsurface northwest plunge of the Arbuckle Uplift (Fig. 5.11).

Brown (1984) and Saxon (1994) presented cross sections of the Arbuckle Anticline which incorporated elements of fault-bend folding and fold-thrust modeling. Saxon (1994) described the change in outcrop/subcrop pattern of the Arbuckle Anticline from its central portion to its northwest plunge in terms of changing fault geometry and progressively decreasing slip along plunge. Naruk (1994) presented a rigid fault-bend fold interpretation of the Ardmore Basin and Arbuckle Uplift.

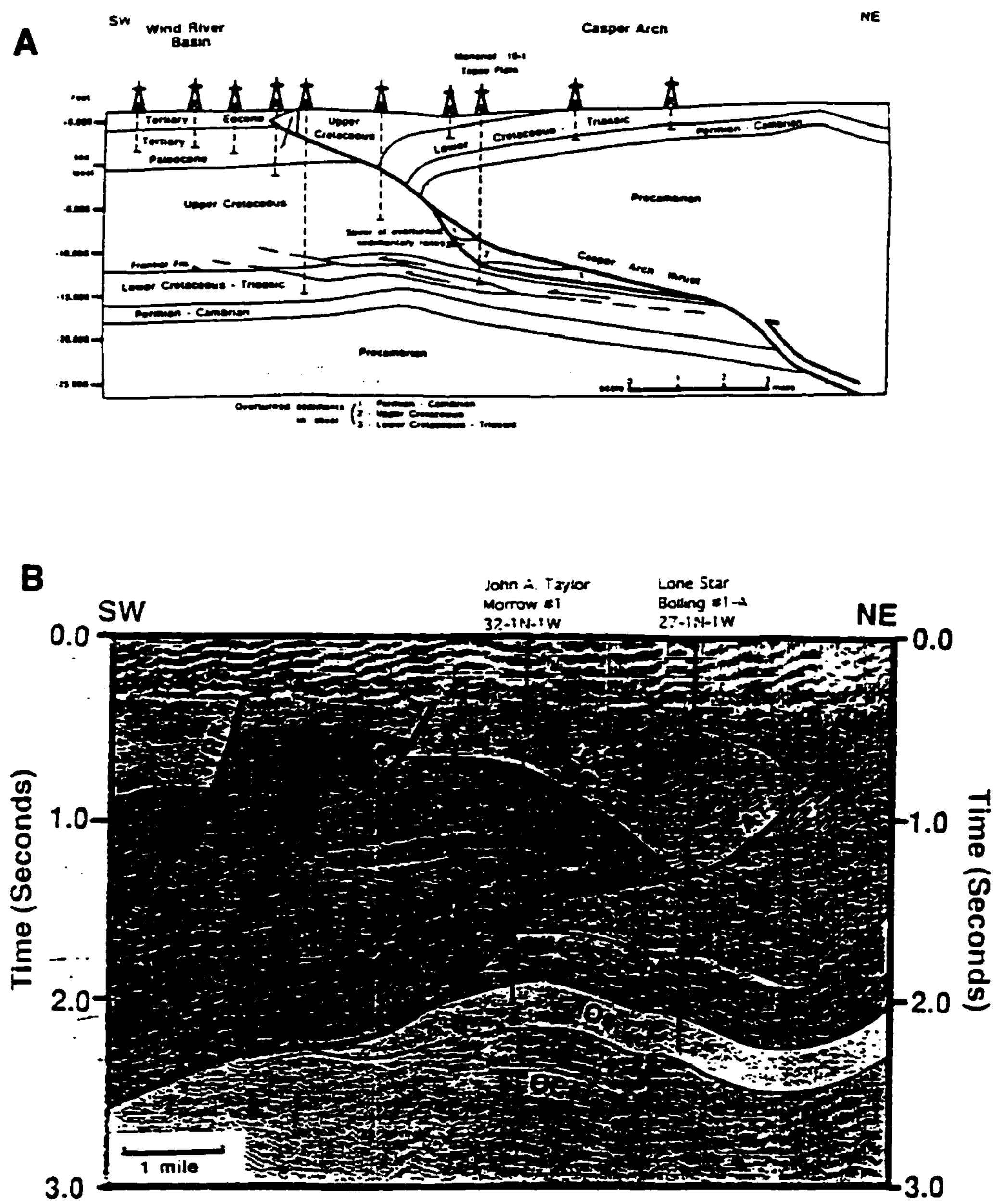


Figure 5.11. A. Cross section across the Casper Arch, Wyoming showing a basement-involved uplift with a modified fault-bend fold geometry and footwall horse block (Skeen and Ray, 1983). B. Unmigrated seismic line from the Arbuckle Uplift, east of Eola Field. Note the footwall block interpreted as a horse (modified from Saxon, 1994). Sesimic line courtesy of Texaco.

Examples of Dip-Slip Models Applied to Southern Oklahoma.

In a study using subsurface well data, properly oriented and structurally balanced cross sections, and accurate published maps, Brown (1984) showed that the Washita Valley Fault is a back-limb imbricate to the buried master fault of the Arbuckle Uplift. Brown named this fault, which subcrops north of the Washita Valley Fault and underlies the SE Hoover and SW Davis areas, the Arbuckle Thrust. Brown's interpretation was supported by a structural contour map of the Arbuckle Thrust plane based upon well penetrations of the thrust. Additionally, Brown demonstrated that apparent left-lateral offsets of the basal Oil Creek Sand zero isopach line noted by Tanner (1967) could be accounted for by extending contours to match cut-offs on the hanging wall and footwall of the thrust plane, rather than against a vertical fault plane (Fig. 1.3). Brown's palinspastic restoration of the zero sand isopach line across overturned folds and reverse faults showed little or no lateral slip. Brown's interpretation was supported by studies by Saxon (1994) and Beck (1987).

McConnell (1987) applied the rigid basement model based upon Spang and others (1985) to the Wichita Uplift (Fig. 5.12). In this model, curvature of the basement surface is only "apparent", due to distributed motion on discrete, closely spaced basement-faults. The basement faults abruptly die into the overlying sedimentary section in the footwall syncline of the basement uplift, creating a highly faulted, non-continuous basement-sedimentary contact in the syncline. Because the rigid basement model does not allow for folding of the basement (other than as a ramp anticline) it provides no mechanism for the generation of out-of-the-syncline thrusting near or just above the basement-cover-rock boundary. McConnell states that the Arbuckle Group is "welded" onto the surface of the basement and the first zone capable of detachment is the Simpson Group (McConnell, 1987). Thus, McConnnell interprets fault displacement as being completely absorbed within the Arbuckle Group, the upper

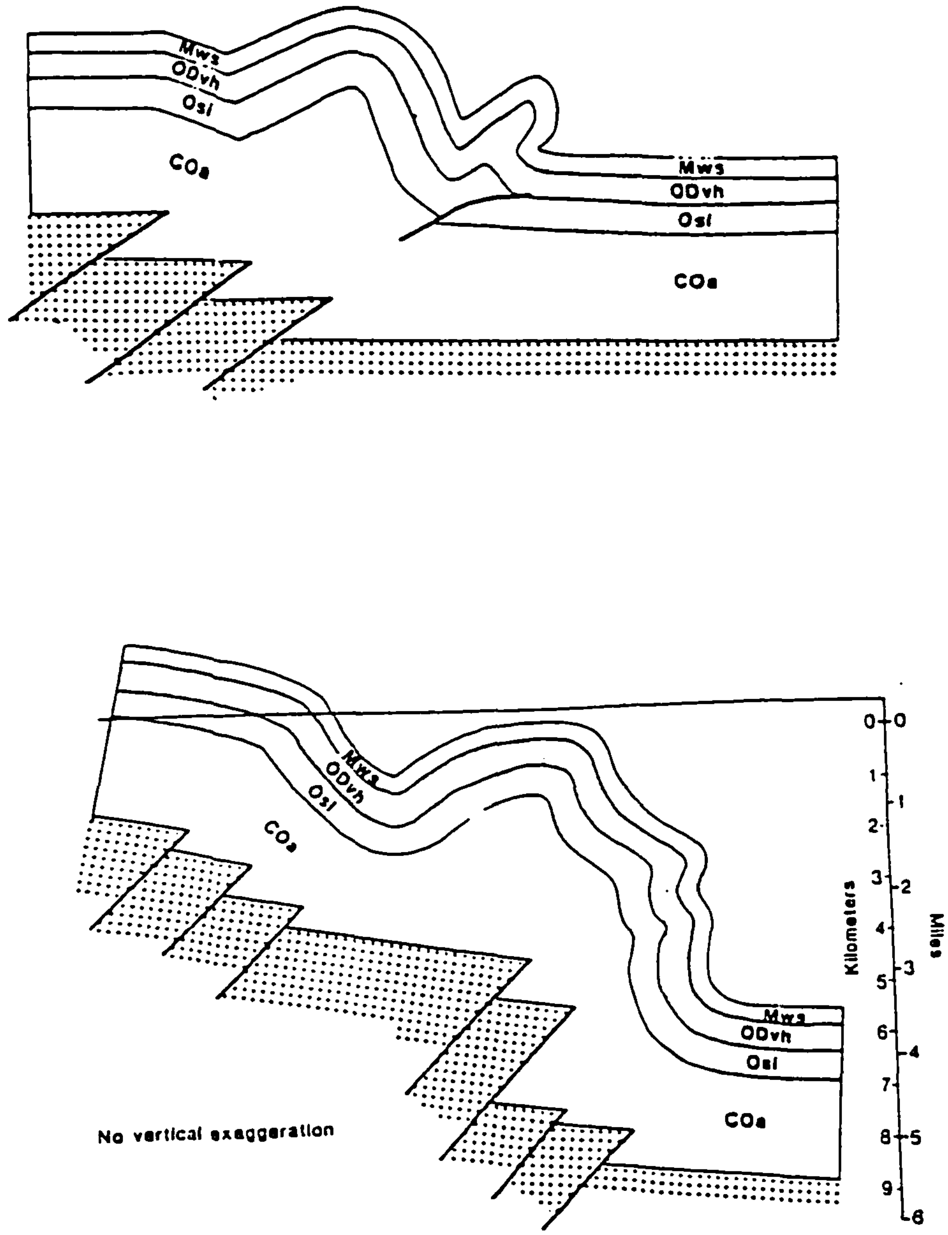


Figure 5.12. Cross section across the Wichita Uplift from McConnell (1987) depicting basement deformation as a series of closely-spaced parallel thrusts. The majority of the thrust terminate within the lower Arbuckle Group. Fault termination is inconsistently depicted as the majority of thrusts end with no effect on the Arbuckle whereas some form prominent fault-propagation folds. The upper portion of the Arbuckle is unbroken whereas the lower portion is broken up by numerous faults and must contain a detachment which allows to the differential deformation of the upper and lower Arbuckle Group section.

contact of which is not offset and forms an uninterrupted synclinal surface. In McConnell's model, the base of the Arbuckle is not folded by flexural slip, therefore it provides no mechanism to create detachments necessary for out-of syncline thrusting within the Arbuckle Group. As a result, in this interpretation, flexural slip folding and out-of-syncline thrusting is only possible in sediments above the Arbuckle Group. Because this model provides no mechanism to create detachments in the Arbuckle, it necessitates that all Arbuckle folds must be interpreted as cored by basement involved thrusts. This is contrary to the deformational style of the Arbuckle Group as evidenced by outcrop pattern in the Arbuckle and Wichita Uplifts. These outcrops clearly show the the lower Arbuckle Group is capable of sustaining long detachments.

McConnell's model is inconsistent in its depiction of the geometrical and mechanical response of the Arbuckle Group to basement faulting. According to McConnell's model, within the synclines, basement faults die into the outer arc of the footwall syncline. If the upper Arbuckle Group is folded into a uninterrupted, continuous syncline and the lower Arbuckle Group is not folded, and is offset by numerous parallel faults, (as McConnell interprets) a detachment surface is necessary to allow for the differences in deformation style and mechanisms between the upper and lower Arbuckle Group. However, a main premise of McConnell's model is that the Arbuckle Group is welded to the basement and is incapable of supporting a major detachment. No difference in lithology in the Arbuckle Group is present to form a mechanical basis for such a differentiation of structural styles between the upper and lower layers. In the end, McConnell's model, which is based upon the inability of the Arbuckle to sustain a major detachment, invokes the very detachments he argues against!

McConnell's model depicts fault slivers which deform the lower Arbuckle and terminate over a very short distance. The faults do not generate fault-propagation folding. No mechanism is offered to explain their nearly instantaneous loss of slip.

Although McConnell shows the synclines offset by basement faults which do not terminate as fault-propagation folds, he shows the opposite for Arbuckle-cored anticlines. All Arbuckle-cored folds are depicted as fault-propagation folds, formed as the result of loss of slip on basement faults. But perhaps the biggest problem is that the Arbuckle Group is quite clearly capable of supporting large detachments as evidenced in outcrops from the Slick Hills and Arbuckle Anticline and from the subcrop map and well data from McConnell's study.

Oblique-Slip or Transpression

The term "transpression" (and it's companion term "transtension") can have many different meanings to different workers (Saxon, 1994). In the sense used in this study, it is meant to imply a low-angle fault with oblique slip such that there is an equal, or greater, amount of lateral slip than dip slip. However, caution must be used when encountering this word. "Transpression", as first used by Harland (1971), refers to stress oblique to a plane across which it acts. Though inherently a term used to describe a broad range of stress vectors, it has been popularly used to explain a variety of geometries (strains) and to infer structural style. The term has been used to describe local geometry on a wrench fault (Sylvester and Smith, 1976), oblique low-angle basement-thrusting (Donovan, 1986), or strain partitioning invoking the co-development of strike-slip faulting and basement-involved fold and thrust belts (Namson and Davis, 1988). Saxon (1994) has argued for the removal of this term from the geologic vocabulary based upon the lack of consensus of definition.

Several workers have proposed oblique slip across the Wichita Mountain front along a shallow dipping fault(s), even though they may not have used the term "transpression". McConnell (1989) proposed that the Wichita Mountain front in the Lawton segment (Blue Creek Canyon Block) consisted of one major continuous basement thrust plane, the Mountain View Fault, which contained a univariant slip vector along the entire length of the fault. McConnell (1989) proposed 12-26 km of left slip on the Mountain View Fault based upon restorations of interpretive isopach contours of the Hunton Group. In an earlier study, McConnell (1987) used *the same data to show no lateral offset* in the Hunton isopach. McConnell proposed that fault geometry and slip vectors have two important consequences. First, the Wichita Mountain front changes strike from WNW to NW in the vicinity of Apache Field. By maintaining a single fault plane and a constant NE oriented slip vector, this model predicts the greatest amount of fault overhang will occur east of the bend in the mountain front (eastward from Apache). The greater the lateral component of left-slip, the greater the overhang east of the bend in the mountain front. In fact, the opposite relationship occurs; the Wichita Uplift loses slip and plunges to the east from the Apache region. Second, the presence of vertical tear (compartmental) faults in the western portion of the Wichita Uplift preclude large amounts of lateral slip. Slip vectors with a large left-slip component would result in massive crustal extension by pull-apart basins in areas of documented crustal shortening (Fig. 5.13). Additionally, in the Criner Hills, large amounts of lateral offset is precluded because the zero sand isopach of the Oil Creek Sand shows no offset across the Criner System (Remmer, 1989).

Summary

A wide variety of structural models have been applied to southern Oklahoma, though few have been well documented. Models in which the structural geometry precludes crustal shortening, are not appropriate to southern Oklahoma, because they cannot account for basement overhangs and shortening of the sedimentary section.

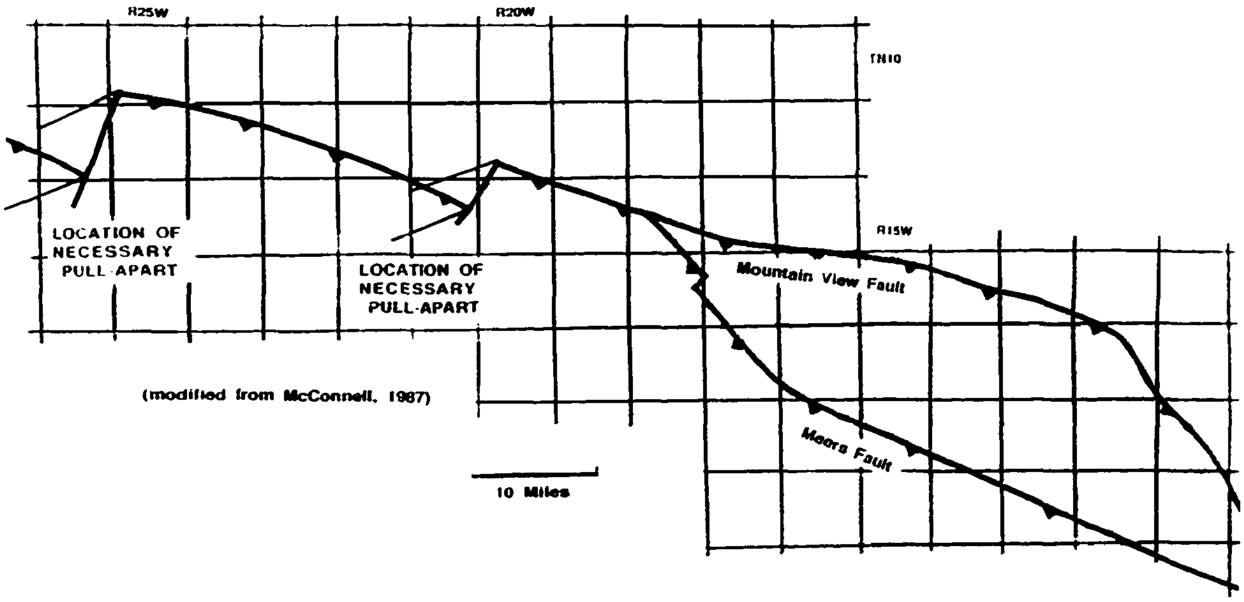


Figure 5.13 Map of the Wichita Mountain Front showing constant oblique left-slip vectors and a single thrust plane (Mountain View Fault) (based upon McConnell, 1989). Oblique slip shown is of 7.5 miles, corresponding to the direction and magnitude for the *least* amount of left-slip calculated by McConnell (1989). Slip vectors are shown in red at the corners of compartmental faults. Note that the slip vectors shown would result in crustal extension in the form of rhombic pull-aparts at the corners. The magnitude of crustal extension at pull aparts predicted for these areas would increase with increasing values of left-slip. Crustal extension is not present at these corners, thus left-slip, even oblique left-slip, is incompatible with the fundamental geometry of the Wichita Uplift.

Many popular concepts of wrench tectonics, such as flower structures, are not based on clear geologic analogs and may be invalid. Wrench tectonics and strike-slip systems are some of the least documented and poorly understood structural styles. The general concept of crustal shortening along low-angle faults is well documented in the Rocky Mountain Foreland. However, there is little consensus among workers as to the amount of lateral slip and structural style in the Southern Oklahoma Foreland. Proper documentation of structural geometry with magnitude and direction of slip, is crucial to the development and application of a proper structural model for southern Oklahoma.

Chapter 6

FOLD-THRUST DEFORMATION IN THE SOUTHERN OKLAHOMA FORELAND

Introduction

This chapter provides an overview of the fold-thrust model of mountain-flank deformation (Berg, 1962; Brown, 1988; Willis, 1993) and documents and examines fold-thrust deformation along portions of the Wichita and Arbuckle Mountain Fronts.

Various portions of the Wichita and Arbuckle Mountain Fronts exhibit evidence of folding prior to the development of mountain-flank faulting. In these areas, early stages of the deformation were characterized by shortening of the crust through the formation of asymmetric basement-cored anticline-syncline pairs. Many of the anticlines were subsequently broken by mountain-flank faults and thrust over footwall synclines as asymmetric basement-cored overthrusts. Volumetric crowding of the forelimb synclines, prior to faulting, resulted in the development of out-of-the syncline thrusts along detachments. The general style of deformation in many ways resembles that of the fold-thrust model proposed by Berg (1962) and later modified by Brown (1983) and Willis (1993) for the Rocky Mountain Foreland. Areas of fold-thrust deformation in southern Oklahoma most closely resemble the late stage of fold-thrust development. These areas are characterized by a stair-step mountain front geometry, foreland detachment structures, rabbit-ear folds developed on an over-steepened hanging wall and/or footwall, and a tight footwall syncline. The well-developed, thinned, sheared dual fault zone characteristic of advanced stages of fold-thrust development has not been documented in southern Oklahoma. Full documentation of the structural style of mountain-flank deformation in southern Oklahoma is difficult because of the sub-surface nature of the uplifts. Few sub-thrust wells in the Wichita

Uplift have drilled the basement overhang. Although numerous wells have drilled basement overhang in the Arbuckle Uplift, these wells tend to reach total depth shortly after encountering the footwall block, and thus give little perspective on the character of the footwall and/or dual fault zone. Mountain-flank-uplifts of southern Oklahoma may contain characteristics of several styles of foreland deformation, thus making it difficult to establish, based upon limited well control and seismic data, which is the dominant deformation mechanism.

Overview of the Fold Thrust Model

Fold-thrust deformation, or key characteristics of the fold-thrust model, have been documented in the Rocky Mountain Foreland by workers such as Willis (1993), Schmidt and others (1993), Chase and others (1993), and Miller and Lageson (1993). Although not limited intrinsically to the Rocky Mountain foreland, the fold-thrust model has remained associated with that province. A rigid-basement model, in which the basement does not fold, but develops a series of parallel planar faults which die into the folded basal sedimentary unit (Spang and others, 1985), was described as a "fold-thrust" model and applied to the frontal Wichitas by McConnell (1987). However, because this model involves rigid basement deformation and does not involve folding of the basement (a key criteria of Berg's original fold-thrust model). Despite its description as a "fold-thrust", not be considered a variation of the original fold-thrust model (Berg, 192), but rather regarded as a separate model.

Fold-thrust deformation can be divided into three stages; begining, intermediate, and late. Each is associated with a distinct style of deformation and deformation mechanisms. These divisions are based primarily upon observations made in the Rocky Mountain Foreland (Berg, 1962; Brown, 1983, 1984, 1988; Willis, 1993). However, it should be noted that fold-thrust deformation is a continuous process, and

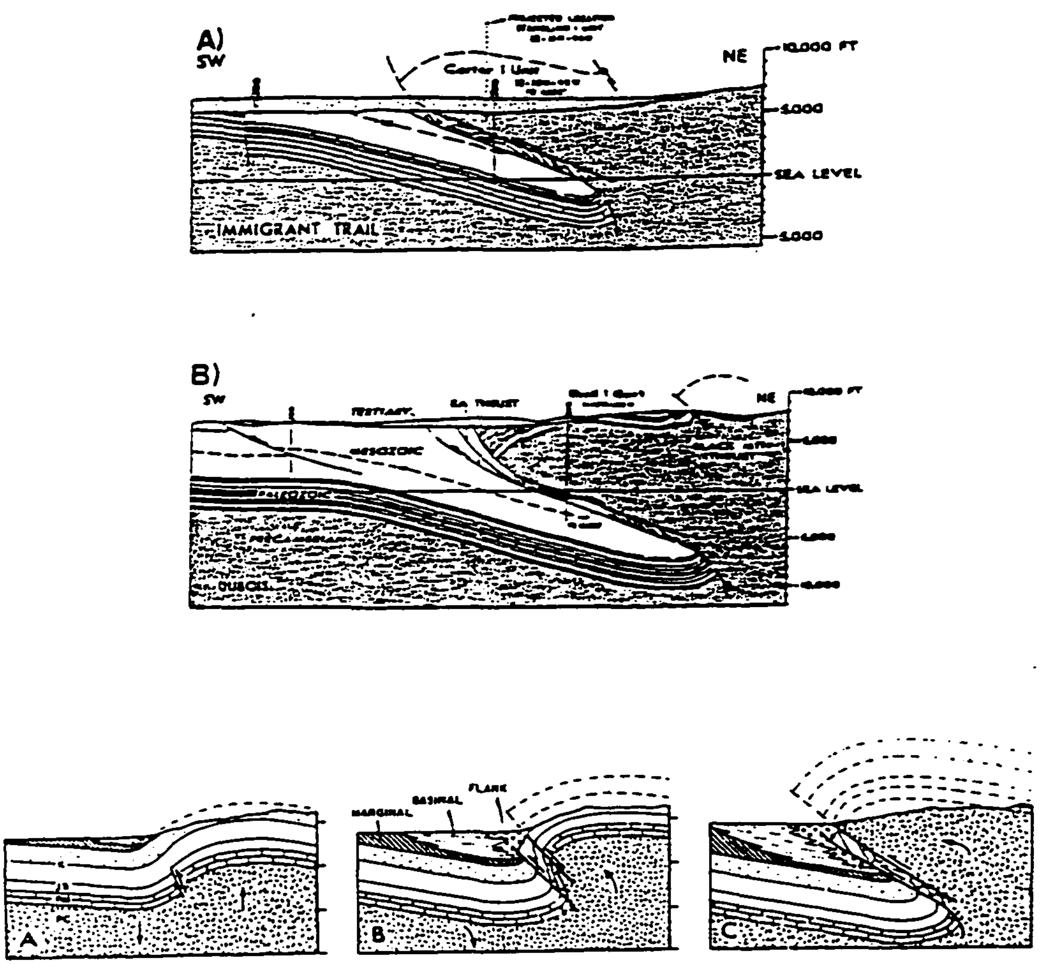


Figure. 6.1 A. Fold-thrust interpretation of the Immigrant Trail area, central Wyoming and sequential development of the fold-thrust model of Laramide structures in the Rocky Mountain Foreland (modified from Berg, 1962).

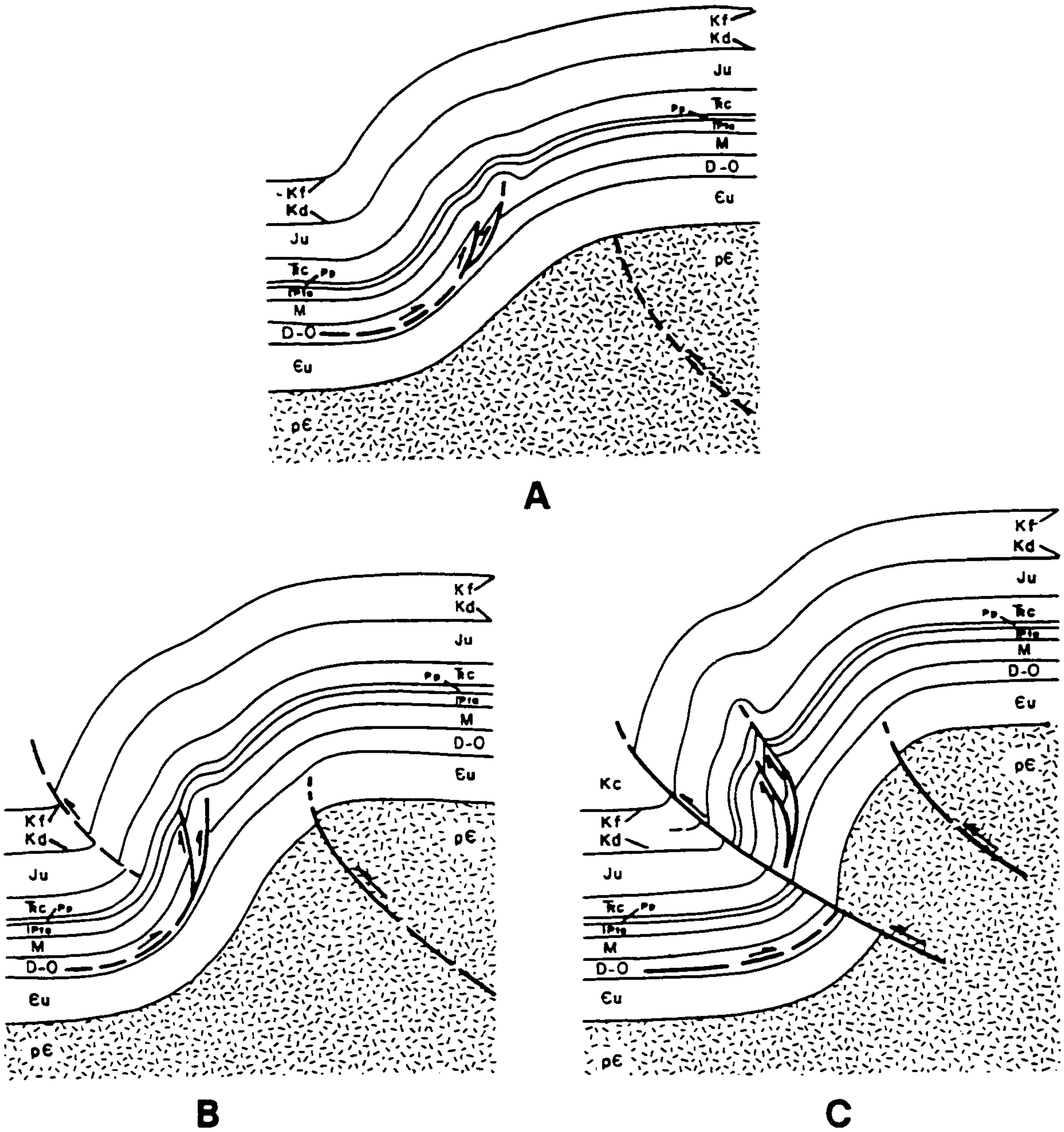


Figure. 6.2. Modified fold-thrust model by Brown (1983) illustrating the response of sediments through flexural slip to crowding of the forelimb syncline. Volume resolution is depicted in this example by the development of a detached thrust up the steep flank, however, crowd structures may also thrust along the shallow (basinal flank of the forelimb syncline. Once the sedimentary section is cut by the syncline-hinge fault, faulting replaces folding as the main mechanism for shortening and major development of subsidiary features ceases. Recognizing the early development of synclinal crowd features can be crucial in establishing structural style (modified from Brown, 1983).

that the stages of deformation amy not represent abrupt changes in development or "pulses" of deformation.

Early-Stages of Deformation.

Initial deformation is characterized by the development of an asymmetric, basement-cored anticline and it's paired forelimb syncline (Brown, 1983). The anticline is a fault-fold interchange (Fig. 6.3) where an upward propagating basement reverse fault dies-out into a basement-cored fold (fault-propagation fold). The upward propagating reverse fault may form a monocline rather than an anticline-syncline pair if the back-limb dip remains at regional dip, however, both anticlinal and synclinal hinges will eventually form as the structure progresses (Willis, 1993) (Fig. 6.4). Basement rock are generally folded in conformity with the overlying sedimentary section, producing a "fold" of the basement surface at some level of observation. "Folding" of the basement may occur by a variety of brittle mechanisms; including cataclastic deformation (microfracturing), slip along favorably oriented foliation and/or basement fabrics, and rotation of blocks between fault or shear zones (Brown, 1988; Schmidt and others, 1993). The exact mechanism(s) of basement deformation will depend upon local geology. Basement deformation mechanisms are discussed more thoroughly in a later section of this chapter.

In the early stages, the sedimentary section is deformed by folding, with volumetric crowding of the forelimb syncline. Crowding is relieved by slip along bedding-parallel detachments and may be resolved on the shallow flank of the basin, as foreland detachment structures (Petersen, 1983), or up the steep flank as rabbit-ear structures, or as numerous other crowd structures (Fig. 6.3). Shortening in this stage is accomplished by folding. In the sedimentary section, shortening is accomplished by flexural slip folding processes and occurs prior to the development, and offset along, the mountain-flank fault(s).

Early-Stage Fold-Thrust

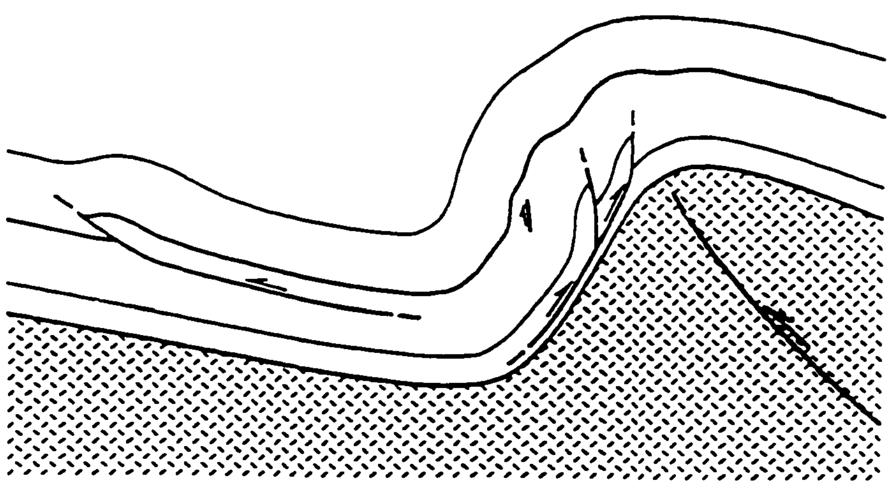


Figure. 6.3. Schematic illustration of a fold-thrust in an early stage of devlopment. At this stage the fold-thrust is a fault-fold interchange of an upward propagating basement reverse fault (fault-propagation fold). Crustal shortening is dominated by folding processes. Subsidiary flank structures develop due in response to volumetric synclinel crowding (from Willis, 1993).

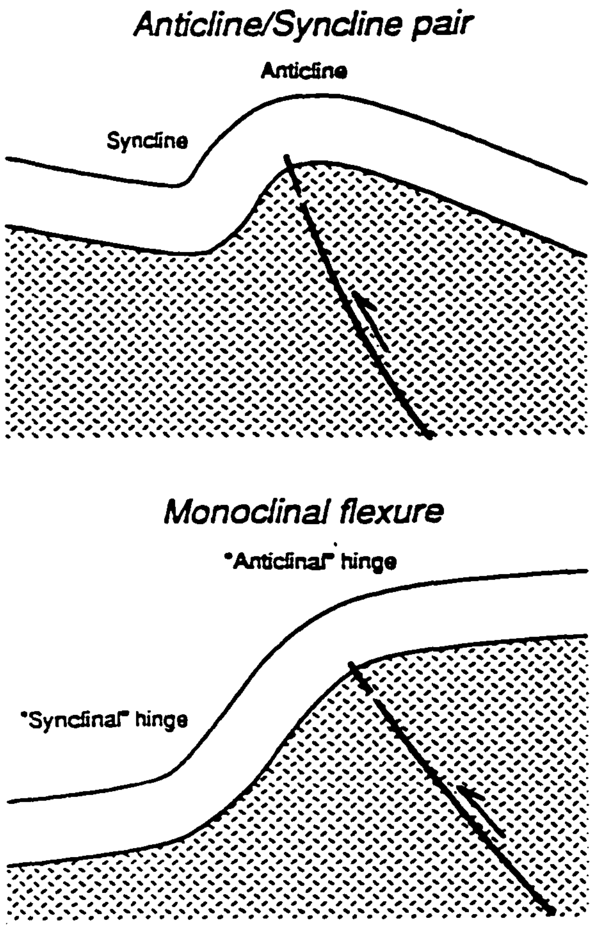


Figure. 6.4. Early stages of fold-thrust development may develop as either an anticline-syncline pair or as a monocline. In either situation, both develop a synclinal and anticlinal hinge (from Willis, 1993).

Intermediate Stages of Deformation.

The intermediate stages (Fig. 6.5) are characterized by the development of the mountain-flank faults which separate the hanging wall from the footwall, cutting and offsetting bedding slip planes, effectively ending the development of the crowd structures. In this stage, faulting replaces folding as the dominant crustal shortening mechanism. Often, a dual fault system develops in which the main basement-fault originating at, or near, the axial hinge of the anticline, propagates from the basement into the sedimentary section; simultaneously, a parallel fault develops in the sedimentary section along the synclinal hinge of the forelimb syncline, and propagates down toward the basement. The strata between the two faults represents the dual fault zone. The synclinal-hinge fault develops initially in the upper sedimentary section and loses displacement down-section as it propagates into the syncline (Willis, 1993). The downward propagation of this fault reflects the tighter crowding of the core of the syncline in the upper portion of the sedimentary section..

Late-Stage of Deformation.

During the late stages of fold-thrust deformation (Fig. 6.6), faulting has replaced folding as the dominant shortening mechanism. The steep flank is usually vertical to overturned and the overall structure continues to develop asymmetry by the upward propagation of the primary basement fault. Both the synclinal hinge fault and the primary basement fault offset the basement contact. Together, the primary basement fault and synclinal hinge fault form a dual fault system. The dual fault system will vary in initial thickness, but with progressive deformation will become narrower and the strata between progressively more sheared. Rabbit-ear structures on the steep limb may be rotated such that the detachments (which are at a low-angle to bedding) are overturned and form *apparent* normal faults.

Intermediate-Stage Fold-Thrust

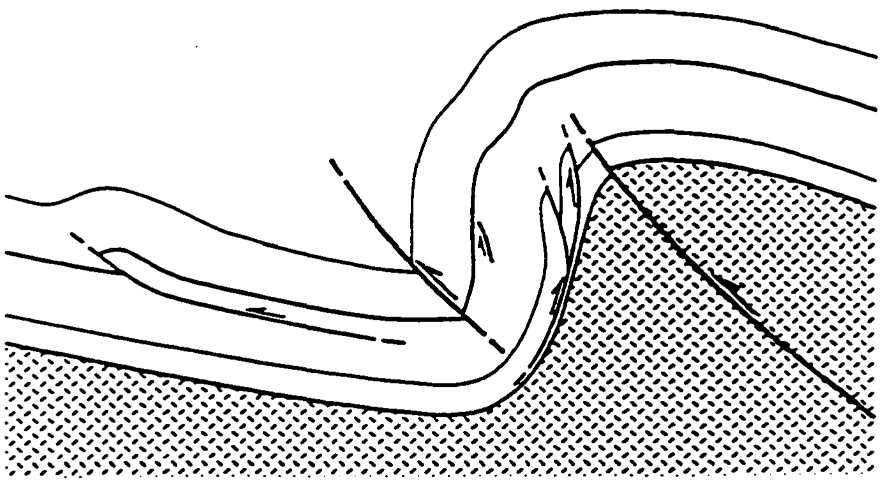


Figure. 6.5. Schematic illustration of a fold-thrust in an intermediate stage of development. Volumetric crowding of the syncline progresses to the point that a downward-propagating synclinal -hinge fault develops (from Willis, 1993).

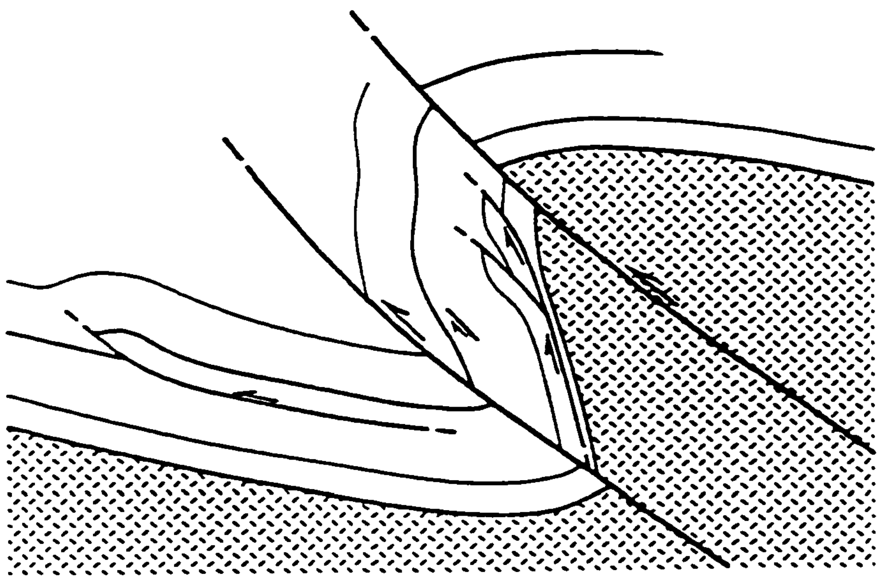


Figure. 6.6. Schematic illustration of a fold-thrust in the late stages of devlopment. Faulting replaces folding as the primary deformation mechanism. The dual fault system is now well developed. The steep limb is vertical to overtutned. Subsidiary structures (rabbit-ear faults) may appear as normal faults due to the rotation of the steep limb (from Willis, 1993).

Advanced Stages of Deformation

Fold-thrust structures in the advanced stage of development (Fig. 6.7) are characterized by continued translation of the hanging wall of the primary and synclinal-hinge faults producing significant basement-overhangs, and the progressive thinning, shearing, and rotation of the dual-fault zone. Rigid and brittle sedimentary rocks such as dolomites may be broken by crushing and fracturing, whereas more ductile rocks, such as shales, may undergo extreme thinning, both in the dual-fault zone, and along the steep flank.

Control of Basement Folding in the Fold-Thrust Model

Deformation of the Basement

The overall style of mountain-flank deformation is controlled by the amount of folding the basement can accommodate prior to faulting and by the mechanical and lithologic composition of the sedimentary section. The less the basement folds, the less the volumetric constriction of forelimb syncline, and hence, the lower the amount of material displaced from the syncline. The mechanism of basement folding has been the source of much debate. Working with twelve basement-cored anticlines across the entire Rocky Mountain foreland, Schmidt and others (1993) and Chase and others (1993) have shown that the mechanical behavior of the basement is significantly affected by the presence and orientation of basement fabric, directly supporting the work of Brown (1988). They found four categories of folds (Fig. 6.8) based upon the role of pre-existing layering and foliation: 1) Foliation and/or layering present, but ineffective, 2) Foliation and/or layering at low angle to sedimentary cover and rotated in forelimb domain with flexural slip, 3) Foliation and/or layering favorably oriented for slip parallel to anticlinal hinge surface, 4) Foliation and/or layering absent. The igneous basement of parts of southern Oklahoma associated with rifting contain a sub-horizontal

Advanced-Stage Fold-Thrust

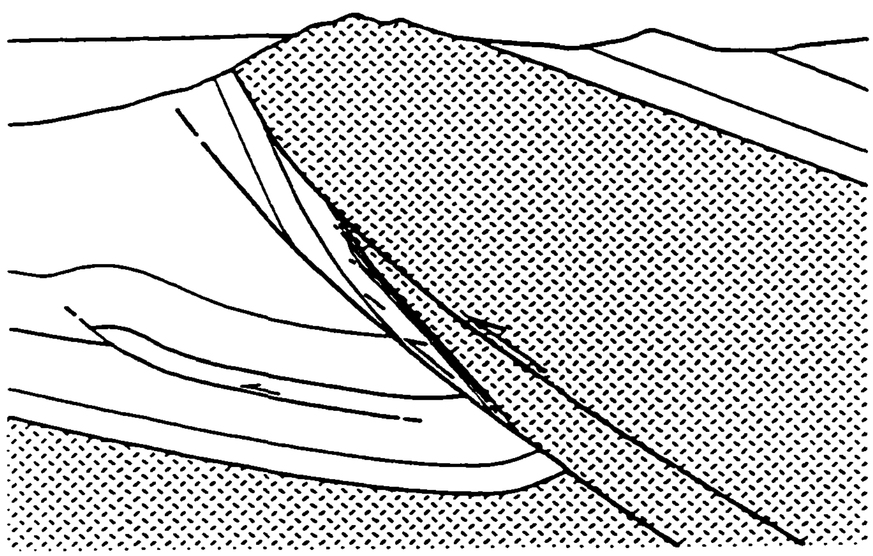


Figure. 6.7. Schematic illustration of a fold-thrust in the advanced stages of devlopment. The dual fault system is highly sheared and thinned (from Willis, 1993).

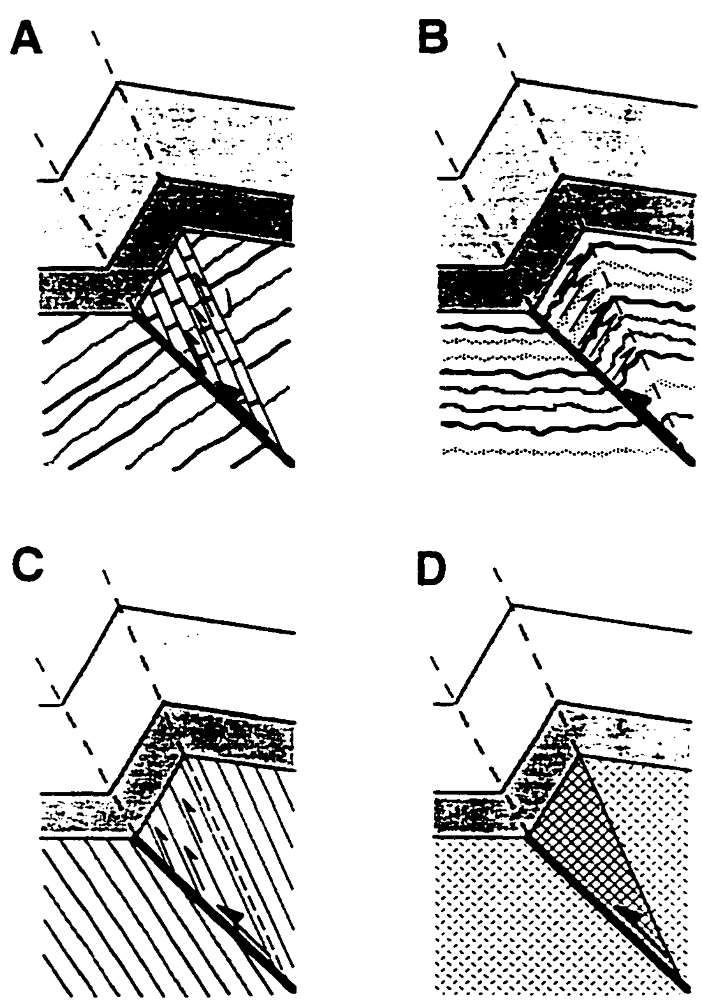


Figure. 6.8. Four examples of the role of basement fabric in the nature of basement deformation on the forelimb of basement-cored folds of the Rocky Mountain Foreland. A: Foliation present but ineffective. B: Foliation and/or layering at low angle to cover and rotated in forelimb domain with flexural slip. C: Foliation and/or layering favorably oriented from slip parallel to anticlinal hinge surface. D: Foliation and/or layering absent. Layered volcanic and intrusive rocks in southern Oklahoma may form anisotropy such as example B (From Schmidt and others, 1993).

fabric resulting from layering of the intrusive and extrusive Cambrian igneous rocks and most closely resemble the conditions in category 2 where the foliation and/or layering are at a low-angle to the sedimentary cover. The Precambrian host rocks contain no definable regional structural grain, however, they are cut by a variety of dikes which show a marked northwest strike (Denison, 1995). Along the margins of the Sothern Oklahoma Rift, the host rocks were very likely cut by normal faulting at the margins of the rift. Closer to the Ouchita System, the Precambrian basement is cut by a series of northeast trending normal faults (Johnson, 1990). This pattern of faulting may be related to down-to-the-south extension associated with loading of the Arkoma Basin from the advancing Ouachita Thrust Sheets.

Basement Fabrics in Southern Oklahoma

Basement rocks in southern Oklahoma are known from relatively sparse outcrops in the hanging walls of deeply eroded uplifts. These rocks record an important Late Proterozoic-Early Paleozoic extensional rifting event which imparted an important fabric(s) to the basement of southern Oklahoma. General features of the rift are known; many important details, especially regarding fault and rift geometry, remain obscured by Paleozoic sedimentation and tectonic overprinting, and thus care must be taken in the analysis of basement fabrics.

The specifics of the geometries of the rift, especially the nature of the bounding faults, and amount of slip are not well defined. Several workers (Brown, 1997) have proposed that the rift occurred in a series of opposing half-grabens. In this case, the faults would be listric with depth, perhaps linking with a low-angle crustal detchment at depth. Undoubtedly the pre-existing fabric has had an important mechanical influence upon subsequent Paleozoic deformation and many workers have speculated that some (or most) faults were re-activated normal faults associated with Cambrian rifting

(Denison, 1995). However, no conclusive evidence has been offered to document these speculations.

Further complicating matters is the presence of layered intrusive and extrusive Cambrian syn-rift volcanics (Denison, 1995). These rocks contain an imperfectly understood layering related to their emplacement. They may be interbedded with volcaniclastic rocks, and certainly the extrusive rocks are unconformably deposited over older rocks, imparting additional semi-horizontal anisotropies. Denison (1995) documented linears and fractures present within both the younger Cambrian basement and the older host rocks. Fractures in the host rock both trend N60°W, however, they are of two differnt ages. The oldest is near the age of the host rock (1,350-1,400 Ma) and the others are Cambrian. The East and West Timbered Hills of the Arbuckle Uplift are cored by Camian Carlton Rhyolite and contain a complex pattern of linears. The linears of the East Timbered Hills have a dominat east-west strike, wheras the linears ofthe West Timbered Hills folow the refional N60°W grain. The east-west pattern in the East Timbered Hills is incompatible with previous interpretations of the Washita Valley Fault as a left-slip wrench fault (Denison, 1995). The linear patterns are restricted to the basement rocks and do not extend into the overlying sedimentary section. The linears may predate the overlying sedimenats, in which case they may not be directly related to Pennyslvanian deformation. Alternatively, the linears may have formed during the Pennsylvanian in response to tectonism, in which case the basement would have to be "decoupled" from the overlying sedimentary rocks to account for the observed differnences in structural response between the basement and the sedimentary cover. Denison (1995) proposed the east-west orientation of the East Timbered Hills was due to local shear formed by the minor rotation of the East Timbered Hills as the Arbuckle Uplift was thrust to the northeast and locally abuted against the resistant buttress formed by Precambrian rocks on the rift margin. If the linears represent a series of fractures and/or faults which predate the sedimenatyr rocks hey may have provided sanisoptropies which would allow for "folding" of the basement on some scale. The timing of basement linears and their role in Pennyslvanian deformation is an area which needs much further investiation.

A well-defined picture of the host and rift-basement anisotopies is not available, however, the following general picture can be described; the upper portion of the basement of southern Oklahoma consists of a series of fractured, sub-horizontal, intrusive and extrusive rocks overlaying down-faulted rocks, which may be in the form of opposing half-grabens. The basement of southern Oklahoma is anything but homogenous and isotropic, and should not be modeled as such. Numerous horizons exist into which reverse faults might sole, including listric normal faults associated with rifting and mechanical boundaries such as the intrusive-host rock boundary. Old fault scarps, which place volcanics against host Precambrian rock, might serve as mechanical buttresses, influencing the position and geometry of ramps in basement cored faults. One needs to bear in mind that there is no control at these depths and these mechanisms, however appealing to invoke, will remain impossible to fully document in the foreseeable future.

Role of Cover-Rock in Development of Fold-Thrust Deformation

An important factor in the control of the style of deformation of basement-cored uplifts is the thickness and lithology of the sedimentary package. The lithologies and distribution of lithologies within the cover rock determines its mechanical competence. A strong contrast between the competence of the cover rock and basement reduces "folding" of the basement, whereas a low contrast enhances basement folding. In their study of twelve basement-cored folds of the Rocky Mountain Foreland, Schmidt and others (1993) observed that the greater the percentage of carbonate rocks in the first 330 meters of stratigraphic cover, the greater amount of folding of the basement (Fig. 6.9).

This has significant implications for southern Oklahoma where much of the basement has a strong horizontal anisotropies due to igneous layering and is overlain by an extremely thick carbonate sequence (Arbuckle Group). The mechanical contrast between basement and cover rock in southern Oklahoma is extremely low relative to the Laramide province. The presence of sub-horizontal anisotropy in the basement may further diminish the mechanical contrast between the basement and cover rocks. These factors imply, that under horizontal compression, the crust of southern Oklahoma is susceptable to significant folding prior to faulting.

Deformation of the Sedimentary Section

Volumetric Constriction of the Syncline

Deformation of the sedimentary section occurs through parallel folding and flexural slip (not kink-folding) as a response to tightening of the forelimb syncline. Faults are either directly linked back to major basement-involved faults or are detached and rooted within the sedimentary section. Detached, non-basement-involved faults are generated by volumetric constrictions that develop in upward tightening synclines (Fig. 6.10). The severity of folding of the sedimentary section is, in part, controlled by the amount of basement folding. The basement deforms by methods other than the sedimentary section, and is generally able to accomadate less "folding" than the sedimentary section.

Synclines tighten upward, creating progressively more volume constriction higher in the section. These must be relieved by means of an upper detachment, bedding plane-slippage, or out-of-the syncline faulting (Fig. 6.11). These mechanisms, or combinations of them, form five common volume-adjustment structures in the sedimentary section as a response to volumetric constriction of the syncline (Fig. 6.12). These include rabbit-ear faulting, back-limb faulting, cross-

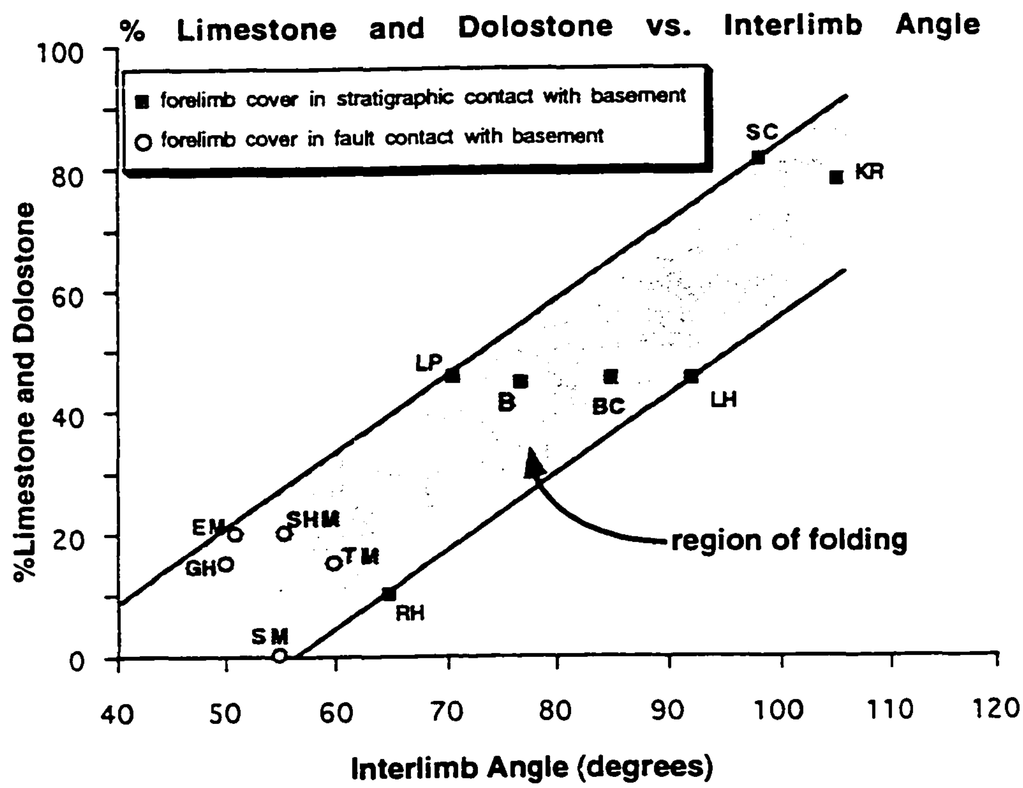


Figure. 6.9. Graph of fold interlimb angle versus percent carbonate rock in the first 330 m of stratigraphic section for twelve basement-cored folds of the Rocky Mountain Foreland. The data suggests that a strong cover-rock section of massive carbonates may produce a wide zone of deformation in the forelimb domain of basement-cored anticlines. In southern Oklahoma, 6,000-7,000 feet of limestones of the Arbuckle Group directly overlie the basement (From Schmidt and others, 1993).

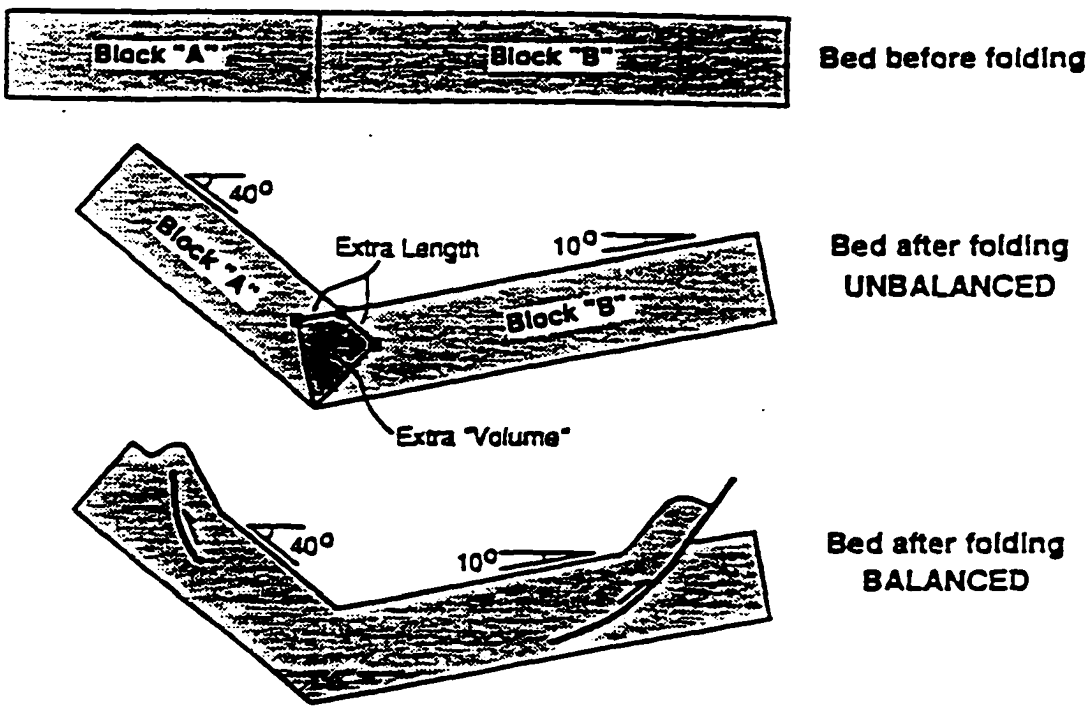


Figure. 6.10. Schematic illustration showing how excess area and line-length are related in the generation, and relief, of syncline crowding (from Willis, 1993).

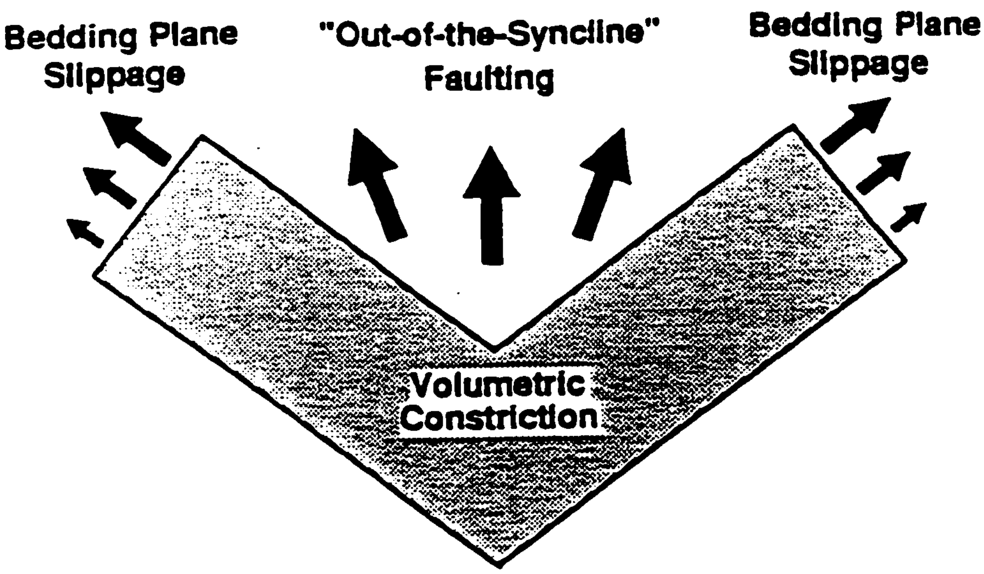


Figure. 6.11 Potential paths for transport of excess volume out of a synclinal hinge (ffom Willis, 1993).

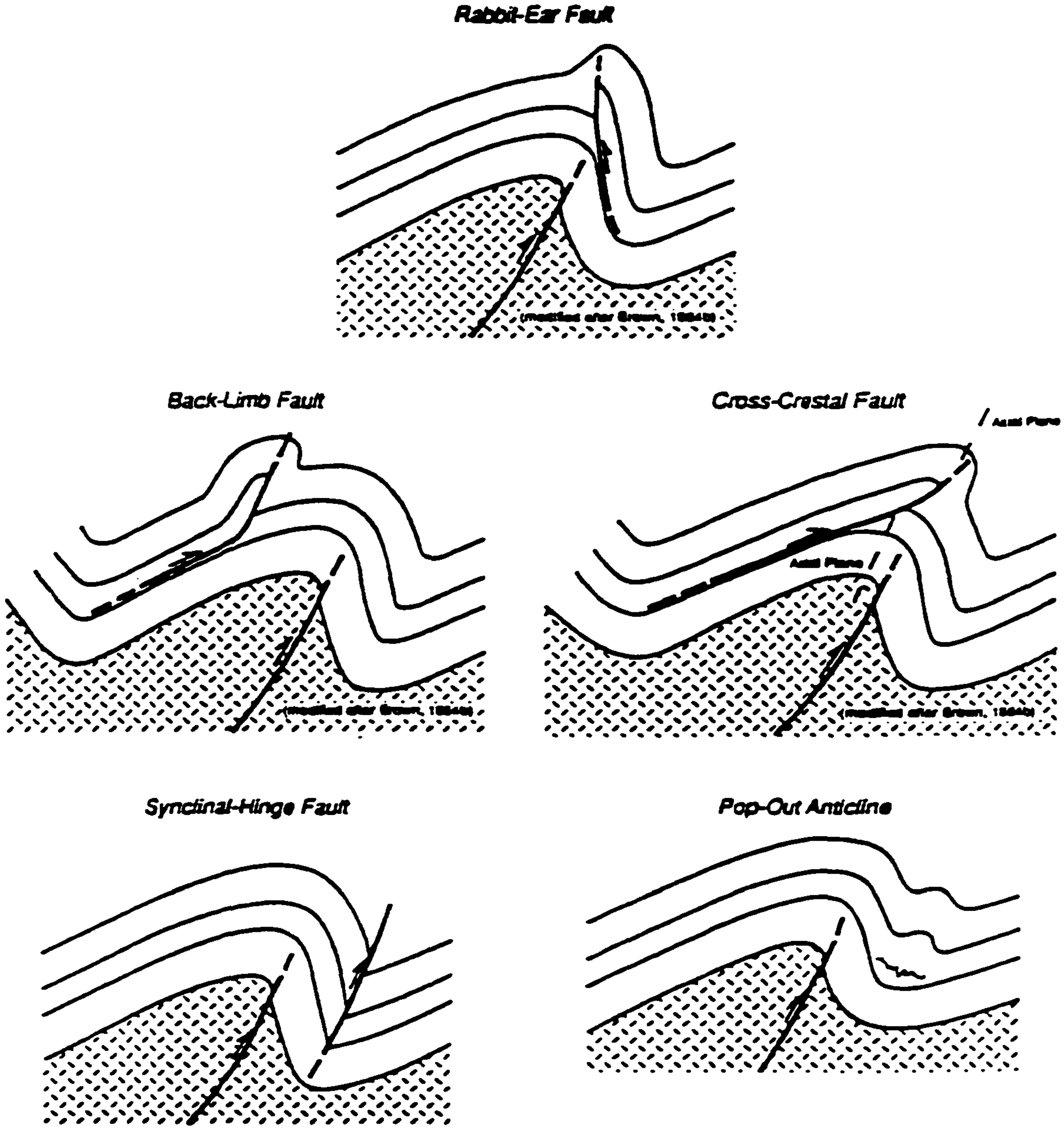


Figure. 6.12 Five types of volumetric crowd structures formed in the sedimentary section as a response to volumetric constriction of the syncline (from Willis, 1993).

crestal-faulting, pop-out anticline, and syncline-hinge faulting. All of these structures are detached and the result of volumetric crowding of synclines. The presence of these structures and detachments within the Arbuckle Group, especially along detachments in the lower Aruckle Group, geometrically implies folding near the base of the sedimentary section to generate detachments in the lower Arbuckle. This provides strong geometric evidence for basement folding.

Foreland Detachment Structures

Foreland detachment structures are a special type of cross-crestal fold related to crowding of the mountain-front syncline. Foreland detachment structures are strong indicators of fold-thrust deformational style becasue they are generated by large-scale synclinal crowding. Some of the most economically important structures of the Anadarko Basin are foreland detachment structures (Fig. 6.13). Examples include Cordell, Elk City, Carter-Knox, Cement, Fox, Milroy, Velma, and Cruce Anticlines. The Carter-Knox structure was recognized as a foreland detachment structure by Petersen in 1983. Foreland detchment structures form in response to volumetric crowding of the footwall syncline of the mountain front. A detachment typically forms within the lower to middle portion of the Arbuckle Group and thrusting is directed out of the basin, up the shallow flank where it ramps up-section, terminates in a fault-fold interchange (fault propagation fold) within the pre-Pennsylvanian section. The location of the ramp and it's associated fault propagation fold is often at an inflection point or hinge on the basement surface. The inflection may be a fault-bend fold in the basement, or an older normal fault boundary related to earlier rifting. Above the fault-propagation fold, there is a major detachment within Springer shales creating a cross-crestal anticline, the hanging wall of which may contain further detachments rooted in Springer or younger rocks. This creates a two-tiered structure which differs in deformation style above and below the cross-crestal detachment. Above the

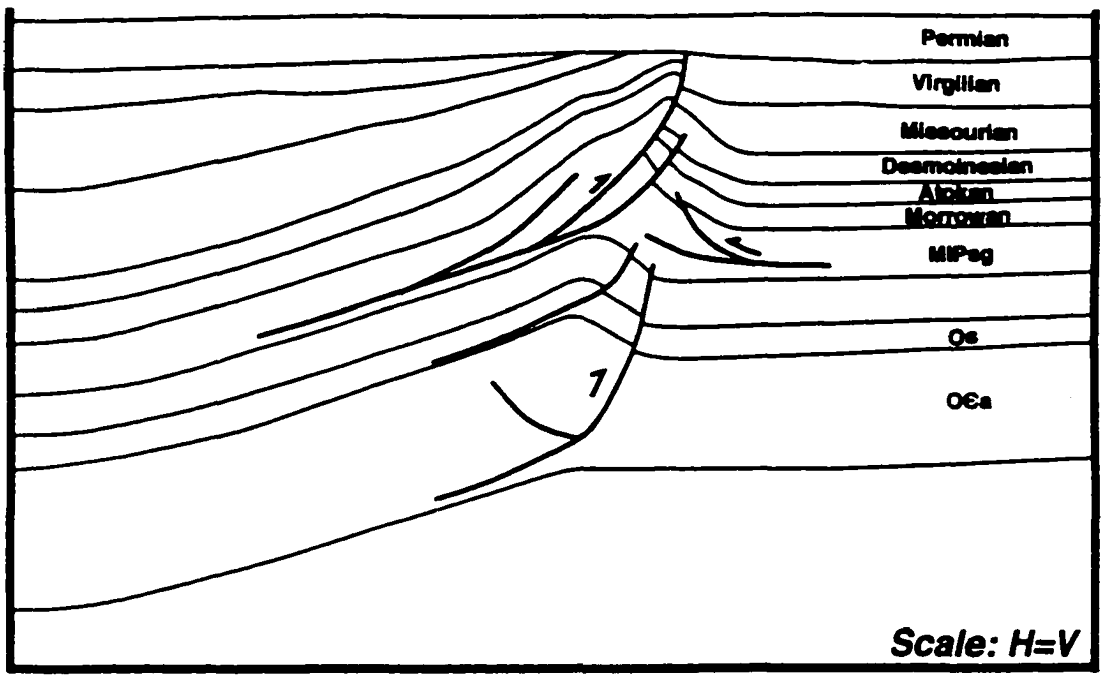


Figure. 6.13. Schematic foreland detachment structure of the Anadarko Basin. The structure is two-tiered consisting of a fault-fold interchange (fault-propagation fold) in the carbonate-dominated pre-Pennsylvanian section and a cross-crestal fault detached in Springer shales which contain growth structures in the synorogenic Pennsylvanian clastics of the hanging wall. The lower fault-propagation fold often forms over a hinge in the basement.

detachment, Pennsylvanian synorogenic sediments often thin toward the crest, reflecting the growth history of the structure. Balancing foreland detachment structures may be challanging because of the complex relationship between thrusting and accumulation of growth strata and the fact that the deep and shallow folds may differ in amounts of shortening. However, when they are considered as part of an increasingly tightened mountain-flank syncline, they make sense. Foreland detachment structures are discussed in greater detail in Chapter 7.

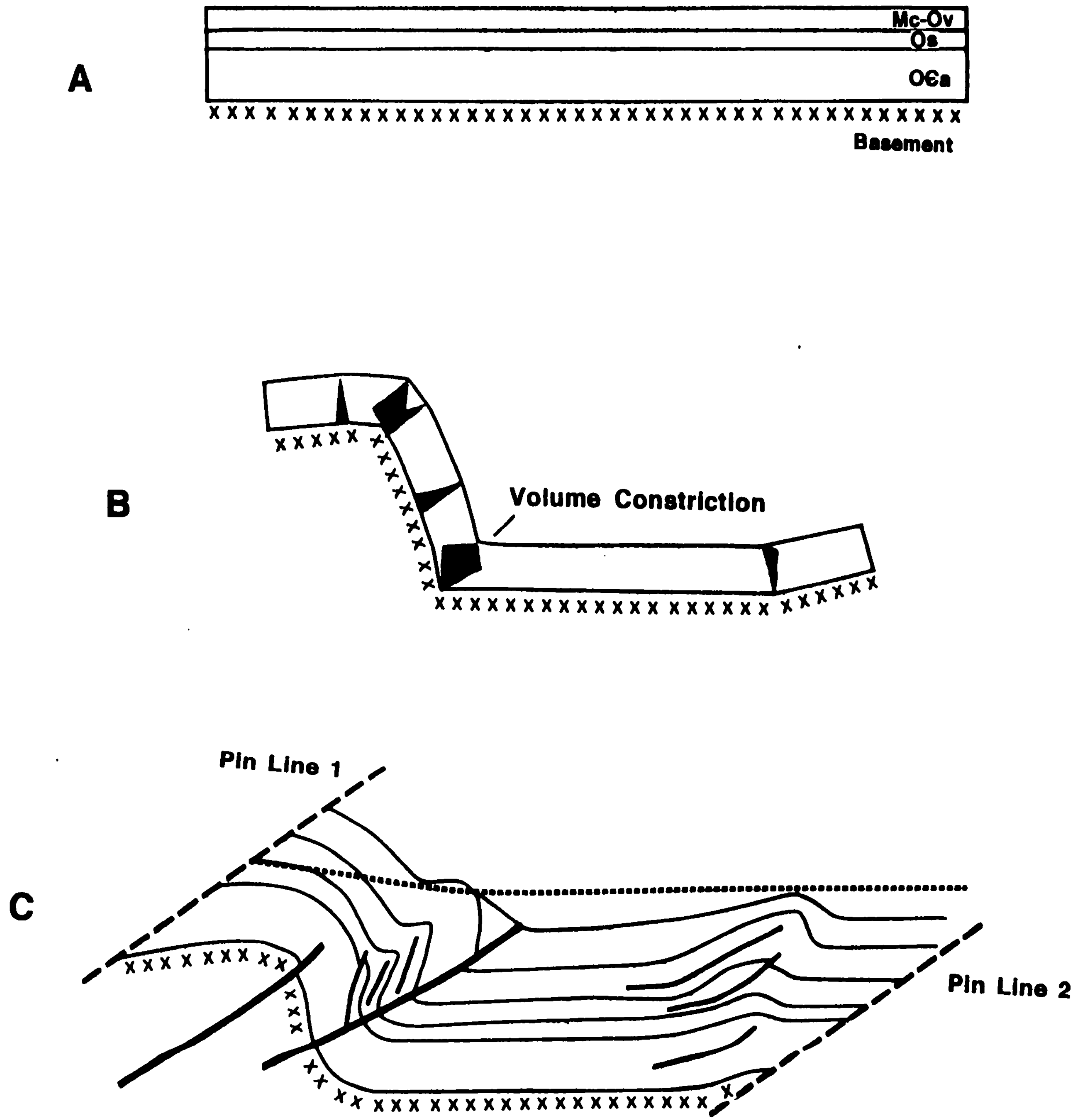
Sequential Development of the Fold-Thrust Model in southern Oklahoma

The Wichita and Arbuckle Mountain Fronts and their respective basinward synclines contain suites of structures which can be explained in terms of fold-thrust deformation. Fig. 6.14 presents an idealized model portraying the development of the Wichita Mountain Front and Anadarko Basin as the result of fold-thrust deformation. This schematic illustration shows many of the typical structures that develop from fold-thrust deformation. Specific examples of individual structures are presented later.

Fig. 6.14a presents an undeformed sequence of pre-Pennsylvanian section with a given line-length and area. In Fig. 6.14b, the sequence undergoes folding. Folding is initially simulated by dividing the "Arbuckle Group" into rectangles and rotating the rectangles into one another. This is done to illustrate volume problems associated with folding at hinges. Notice that the folding produces "overlap" within the syncline and that the amount of "overlap" increases in the upper portions of the syncline. If the thickness of the beds is kept uniform, the upper line length will exceed the horizontal distance of the lower line length. These are two geometric illustrations of the volume problem created in generating a fold. The kink-like geometry is depicted for ease of illustration and is not meant to infer kink-like folding as the mode of formation.

Fig. 6.14c is a balanced cross section depicting the Wichita Uplift and Anadarko Basin at approximately Morrowan time. The style of deformation is an

Figure. 6.14 Schematic diagram showing the evolution of the Wichita Mountain Front. A. Given volume and line length of pre-Pennsylvanian sediments pinned at either end for balancing purposes. B. The given volume is broken into rectangular blocks and rotated into place. Only the Arbuckle Group is depicted. Note the overlap (shaded areas) which indicate volumetric constriction at the fold hinge. C. Balanced cross section showing the mountain front as an intermediate stage fold-thrust in Morrowan time. Volumetric crowding is relieved as rabbit-ear folding and foreland detachment structures.. D. The mountain front portrayed in a balanced cross section as it might look today. Style of deformation is a late-stage fold-thrust. Note late Pennsylvanian shortening produces detachments high in the Pennsylvanian section in the syncline created between the foreland detachment structure and the steep limb of the mountain-flank.


A
Mc-Ov
Os
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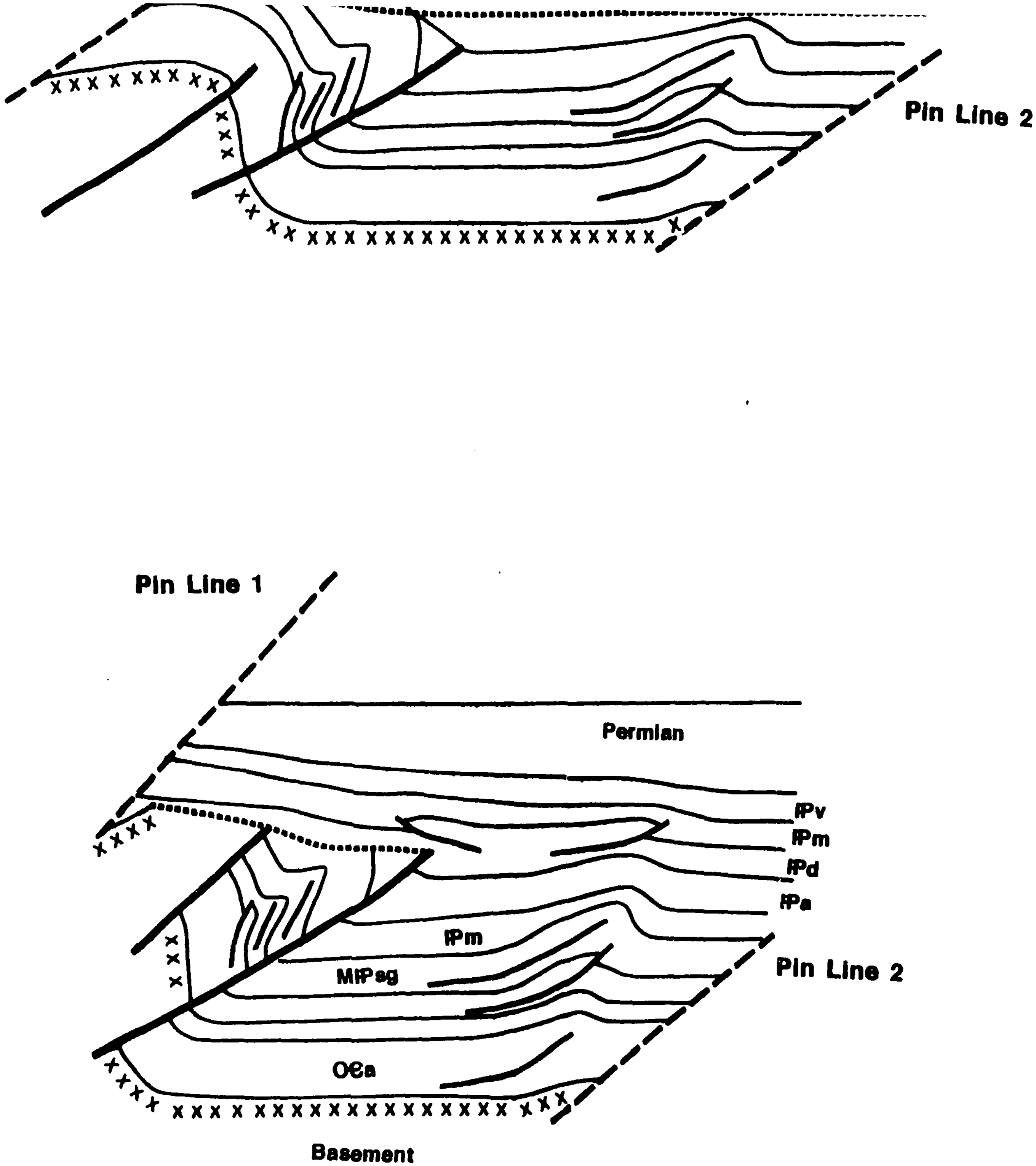
Basement
B
Volume Constriction
C
Pin Line 1
Pin Line 2

C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Permian
IPv
IPm
IPd
IPa
IPm
MIPsg
OЄa
Pin Line 2
Basement

D

intermediate-stage fold-thrust. Deformation has been accomplished by the creation of an asymmetric basement-cored uplift. Pin lines 1 and 2 are drawn parallel to the axes of the forelimb syncline and the axial hinge of the asymmetric basement anticline. The inclination of the pin lines to the basement accounts for layer-parallel shear in the flexural folding process. Excesses in volume and bedding line-length problems are resolved by the generation of a rabbit-ear on the steep limb and a foreland detachment structure by means of out-of-the-syncline thrusting.

Fig. 6.14D is a balanced cross section depicting the Wichita Mountain Front-Anadarko Basin as it looks today as a late-stage fold-thrust. Pin line 1 is rotated into place by faulting. Uplift of the hanging wall has stripped of the line lengths which intercept the pin line in the illustration. Typical features of the Wichita Mountain Front depicted in this illustration are the stair-step mountain front, the steep forelimb, rabbit-ear folds, foreland-detachment structures, and detached out-of-the-syncline crowds high in the Pennsylvanian section reflecting local late-pulses of deformation (in this case, in the Des Moinesian). Timing of the deformation of the mountain front, discussed later in the dissertation, will significantly impact the structural style and association of structures, especially detached structures in the Pennsylvanian sediments.

Examples of Fold-Thrust Deformation From Wichita Uplift

Eastern Wichita Mountain Front. Fig. 6.15 is a regional cross section extending to the northeast from the Harrisburg Trough area of the eastern portion of the Wichita Uplift, across Cruce and Anticlines to the southern end of the Carter-Knox Anticline. This section illustrates variations of fold-thrust deformation and is based upon a regional seismic line (not presented). The Atokan sediments ponded on the hanging wall of the Wichita Uplift form the Harrisburg Trough (Jacobsen, 1984) and unconformably overlie folded pre-Pennsylvanian rocks on the hanging wall of the

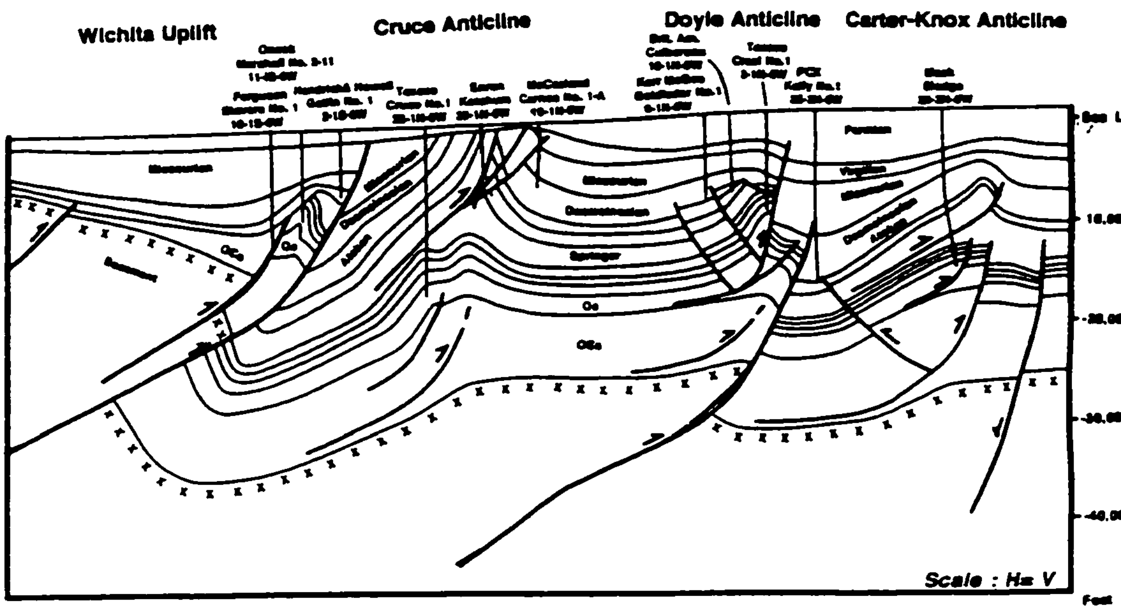


Figure. 6.15. Cross section G-G' across the Wichita Mountain Front between the Harrisburg Trough and Doyle Field. Note the remnant of a detached fold on the eroded lip of the hanging wall of the Wichita Uplift. The fold is overlain with Atokan sediments which partially overlay and partially pond against the eroded fold, all of which a carried on the hanging wall of the major thrust. The fold had to form early, prior to the deep erosion and deposition of Atokan sediment and subsequent overthrusting. The timing and style are consistent with a fold-thrust model of deformation. Cruce Anticline is a detached basin structure generated from crowding the forelimb syncline of the Wichita Mountain Front.

Wichita Uplift. Along the northeast edge of the trough, the Atokan rocks onlap against a preserved toe of imbricated and folded pre-Pennsylvanian sedimentary rocks. Folding and faulting of the pre-Pennsylvanian rocks had to occur prior to the subsequent deposition of Atokan rocks, and overthrusting. Such a sequence of events can only be explained by a model in which folding precedes faulting.

Cruce Anticline is a foreland detachment structure which has been thrust over the shallow limb of the forelimb syncline of the Wichita Mountain Front. Cruce Anticline consists of a fault-propagation fold within the pre-Pennsylvanian sediments, above which is developed a cross-crestal fold, rooted on a detachment in Springer shales. Pennsylvanian sediments, especially the Atokan, thin against the crest, providing evidence that structural growth initiated relatively early. Cruce Anticline is located over an inflection point in the basement, where it breaks over to form steeper dip. Several other foreland detachment structures appear to be located over hinge lines in which they have been thrust up the steep flank. Examples include Cement and Cater-Knox Anticlines. These hinges are located at great depth and are not always imaged by seismic. Possible causes of "basement hinges" include axial planes associated with fault-bend folds, old normal fault boundaries and SW verging thrusts (or back-thrusts).

Blue Creek Canyon Block. Cross section D-D' (Fig. 6.16) is located across Apache Field, a highly complex structure located on the Blue Creek Canyon Block in the hanging wall of the Wichita Uplift. The Blue Creek Canyon Block is the portion of the hanging wall of the Wichita Uplift bounded between the Mountain View Fault, which is locally the frontal edge of the Wichita Uplift, and the outcropping Meers fault to the southwest. Significant overhangs on the Mountain View Fault have been established on the Blue Creek Canyon Block by the Wagner and Brown (Sohio) Traub No. 1-1 well (not on cross section, located in Section 3 T. 6N., R. 14 W.) which drilled 12,530 feet of basement overhang and encountered Ordovician carbonates (Arbuckle?) in the footwall.

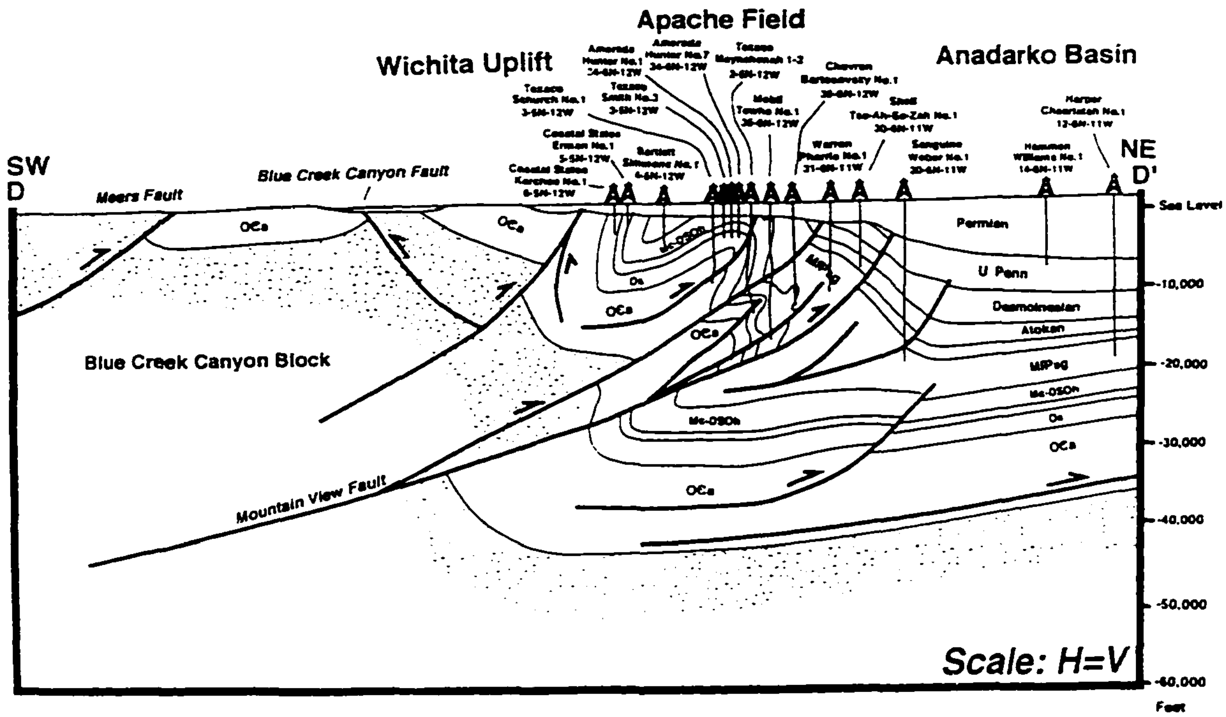


Figure. 6.16. Cross section D-D'across the Blue Creek Canyon Block at Apache Field. Apache Anticline is an extremely tightly folded Arbuckle-cored fold which is detached within the Arbuckle. Note the line lengths in the sedimentary section between the Mountain View Fault and Meers Fault are greater than the line length of the top of the basement. The sedimentary section must have folded and detached prior to separation along the Mountain View or Meers Faults, strongly implying a fold-thrust origin.

Apache Field is located on the crest of an extremely tight Arbuckle-cored fold. The tightness of the fold dictates that it must be detached within the Arbuckle Group. This is supported by a subcrop map by McConnell (1987) which shows ApacheAnticline to be a narrow, doubly plunging fold. The Meers and Mountain View Faults to the northeast, separate the Blue Creek Canyon Block from the Anadarko Basin, and the southwestern portion of the Wichita Uplift. Becasue of this, they be used as end points for bedding line lengths. Measuring bedding line lengths of the Blue Creek Canyon Block reveals that the basement line length is significantly less than the line length of the cover rocks. Because this discrepancy in line lengths is internal and restricted to the Blue Creek Block, arguments of out-of-plane motion to explain the line length discrepancy are not applicable. The difference in line lengths can be explained by folding of the basement prior to faulting according to a fold-thrust model. Tight folds were generated by detachments in response to volumetric crowding of synclines. The sedimentary section was "stacked" over the incipient Blue Creek Block which was isolated by late-stage basement-involved faulting.

Western Wichita Mountain Front. Cross section A-A' (Fig. 6.17) and seismic line 1 (Fig. 6.18) are located in Beckham County along the western portion of the Wichita Mountain front. Here, the mountain front is relatively narrow, and consists of a faulted basement block overhanging an overturned forelimb syncline which contains complex deformation on the steep flank. Well penetrations of the overturned synclinal limb encounter detached folds in the Arbuckle (Union Texas Simpson well). Penetration to the north outlines a complex overturned rabbit-ear which has been formed by progressive cross-crestal detachments in the upper portion of the pre-Pennsylvanian section. Note that the internal characteristics of the footwall deformation are not imaged in the seismic line, due to steep dips. This area serves as an excellent example of the pitfalls of relying on seismic images to interpret structural style in complexly deformed areas with steep dip.

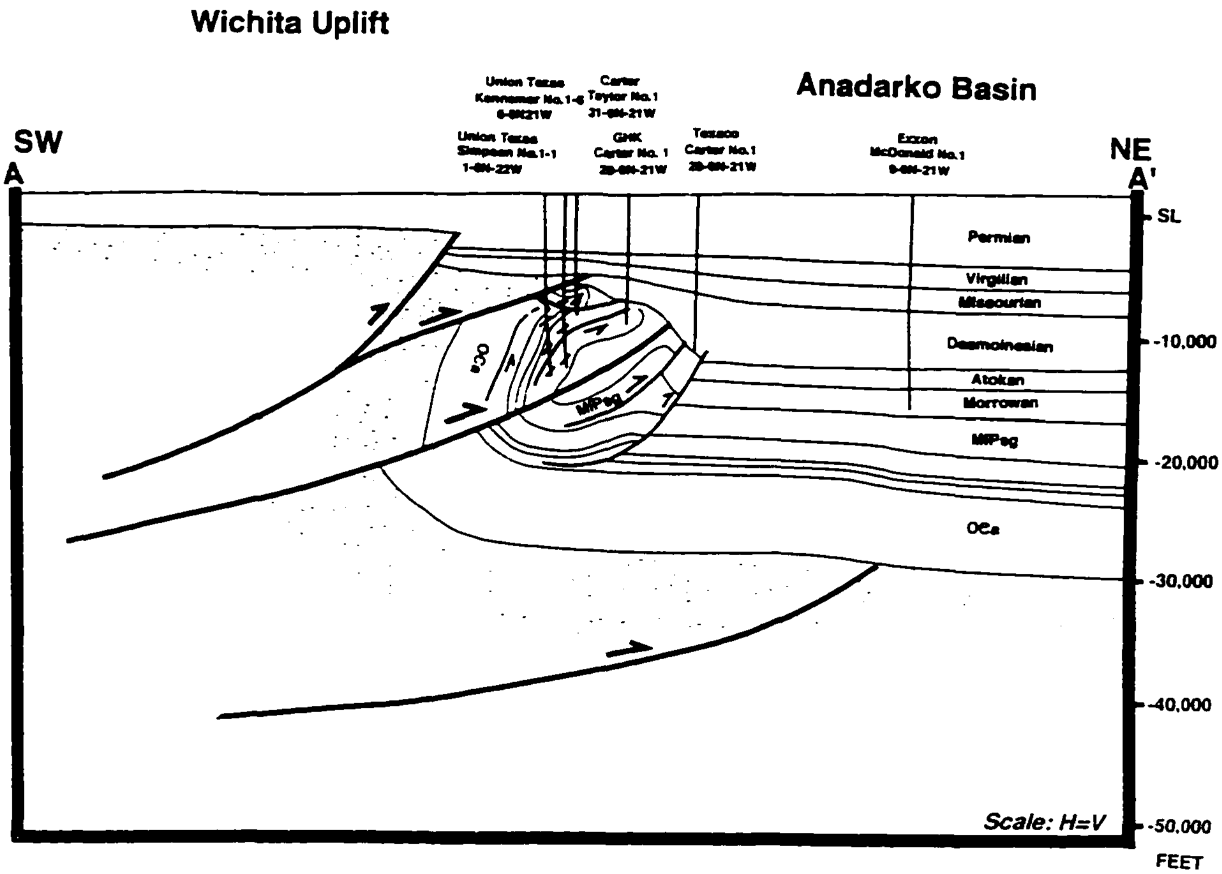


Figure. 6.17. Cross section A-A' across the Wichita Mountain Front in Beckham County, Oklahoma. Note the complex crowd structure on the overturned forelimb of the footwall syncline caused by progressive upward cross crestal detachments. Lack of well control make the geometry of the footwall speculative and deep erosion make quantitative balancing impossible. However, knowledge of structural style strongly implies that the shallow limb will mirror the structural style of the steep limb, providing several potential exploration opportunities.

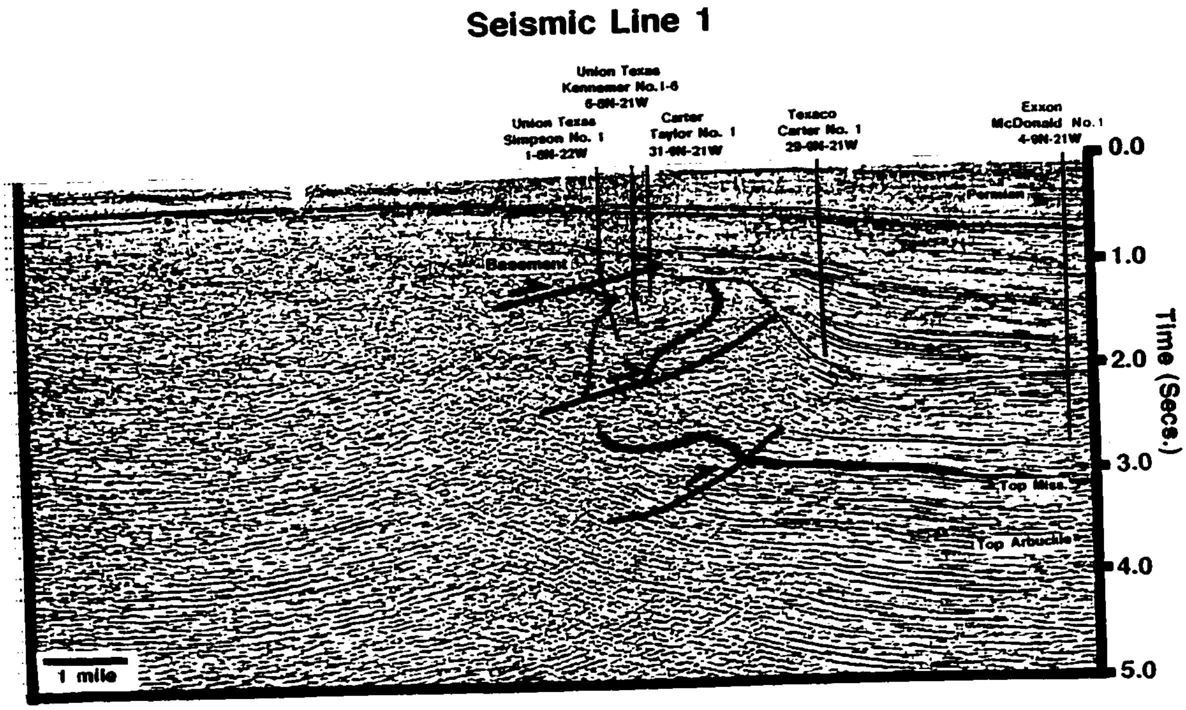


Figure. 6.18. Seismic line 1 located across cross section A-A' in the western portion of the Wichita Uplift in Beckham County.

Examples of Fold-Thrust Deformation From the Arbuckle Uplift

West Timbered Hills. Examples of folded basement can be seen in portions of the exposed Arbuckle Mountains where the basement is composed of fractured Cambrian Carlton Rhyolite. The basement is exposed in two areas on the Arbuckle Mountains, the East Timbered Hills Anticline along the Chapman Ranch Thrust and in the West Timbered Hills in the hanging wall of the Washita Valley Fault. Fig. 6.19 is a down-plunge projection of geologic map of the West Timbered Hills. The map was scanned, imported into a drafting program, oriented so that the Y-coordinate system was aligned with the plunge direction, and foreshortened by the calculated amount to create a "true" or right-section cross section in order to better provide an undistorted view of the fold geometry. The basement-sediment contact is clearly folded at this level of observation.

Northeast Flank of the Arbuckle Anticline. Fig. 4.5 is a geologic map of the Arbuckle Anticline. The major uplift-bounding fault is the buried Arbuckle Thrust, the subcrop trace of which roughly follows the outcrop trace of the north limb of the Arbuckle Anticline. The north flank of the Arbuckle Anticline is vertical, to overturned, from just west of Interstate 35, southeastward to where the Washita River cuts across the Arbuckle Anticline. This steep forelimb contains several detached subsidiary anticlines (Honey Creek Anticline, Seven Sisters Anticline, and Deel Creek Anticline) which have been thrust up the steep north flank of the Arbuckle Anticline along detachments in the Oil Creek Shale. Geometric constraints of data from wells drilled in the Collings Ranch Conglomerate indicate that the Oil Creek detachments are cross-crestal to a lower (probably detached) Arbuckle fold.

The Dougherty Anticline and Vines Dome are east of the Washita River, in the footwall of the Arbuckle Thrust. Dougherty Anticline is a doubly-plunging structure, eroded to upper Simpson Group rocks; cross-crestal faults developed over the Arbuckle fold. Numerous wells have penetrated the Dougherty Anticline in search of

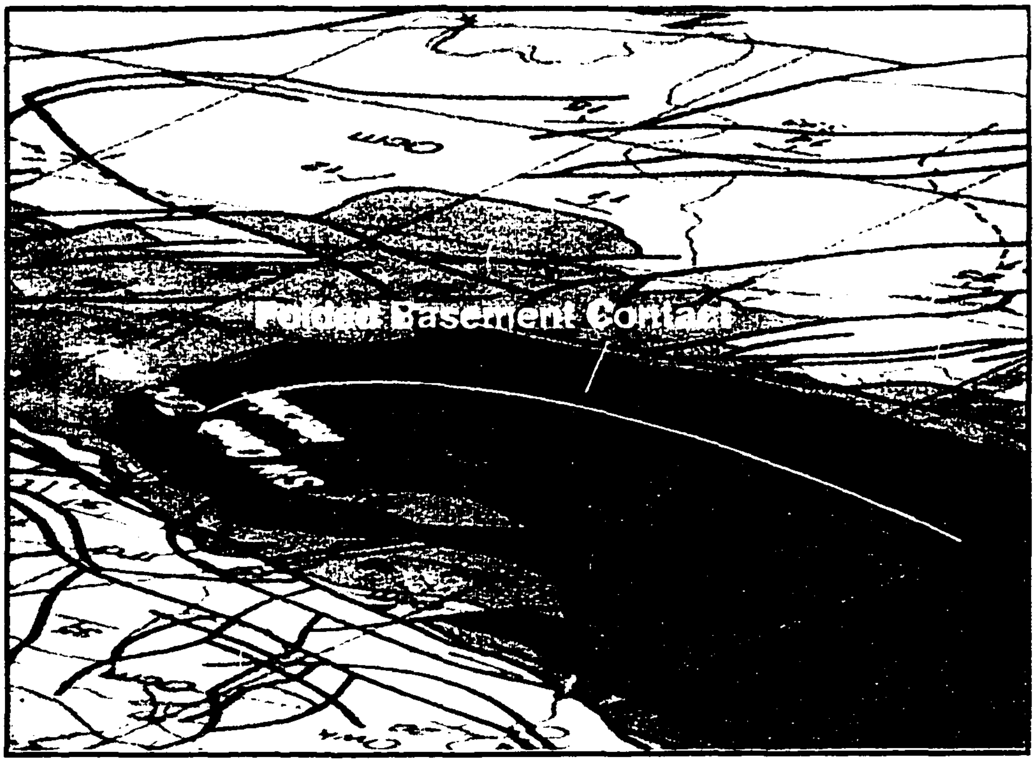


Figure. 6.19 Foreshortened plunge-projection of a geologic map across the southeast plunge of the West Timbered Hills area of the Arbuckle Mountains. The map has been foreshortened into a "right" cross section view. Note the basement-Timbered Hills contact is clearly "folded" at this level of observation (modified from Johnson, 1990).

hydrocarbons. One of the most import, the Placid Geis No. 1 (Section 20, T.1 S., R.2 E.) was spudded on the south flank of the Dougherty Anticline and drilled to a total depth of 9,910 feet, in the Oil Creek Sandstone (Fig. 6.20). The dipmeter for this well indicates a continuous 60° dip for the south flank of the Dougherty Anticline, to the depth of the basal Oil Creek Sand. Thus, the 60° south-dipping panel of Dougherty Anticline (north flank of the Washita Valley Syncline) down to the level of the Oil Creek Sand, partially constrains the geometry of the Washita Valley Syncline. Dougherty Anticline is virtually the mirror image of the Seven Sisters Anticline both in terms of structural style and relative position in the Washita Valley Syncline. Both the Seven Sisters Anticline and the Dougherty Anticline were generated by volumetric crowding of the Washita Valley Syncline during the early stages of fold-thrust deformation.

Eola Area. Cross section K-K' (Fig. 6.21) is constructed across Eola and Robberson Fields, located along the subsurface northwest plunge of the Arbuckle Uplift. The Arbuckle Uplift has been deeply eroded due to elevation of the hanging wall along a steeply dipping ramp in the Arbuckle Thrust and overprinted by the late-stage extensionl Washburn Ranch Fault (Saxon, 1994). The highly shortened footwall of the Arbuckle Thrust contains an overturned syncline and the complex Eola Anticline. A series of wells drilled by Pan America (Amoco) drilled through the Carlton Rhyolite basement overhang and established production in overturned footwall beds of the Bromide Formation of the Simpson Group. Saxon (1994) described the Arbuckle Uplift in this region as a basement-cored, fault-propagation fold, in which the thrust had broken through, carrying the hanging wall over the overturned footwall syncline.

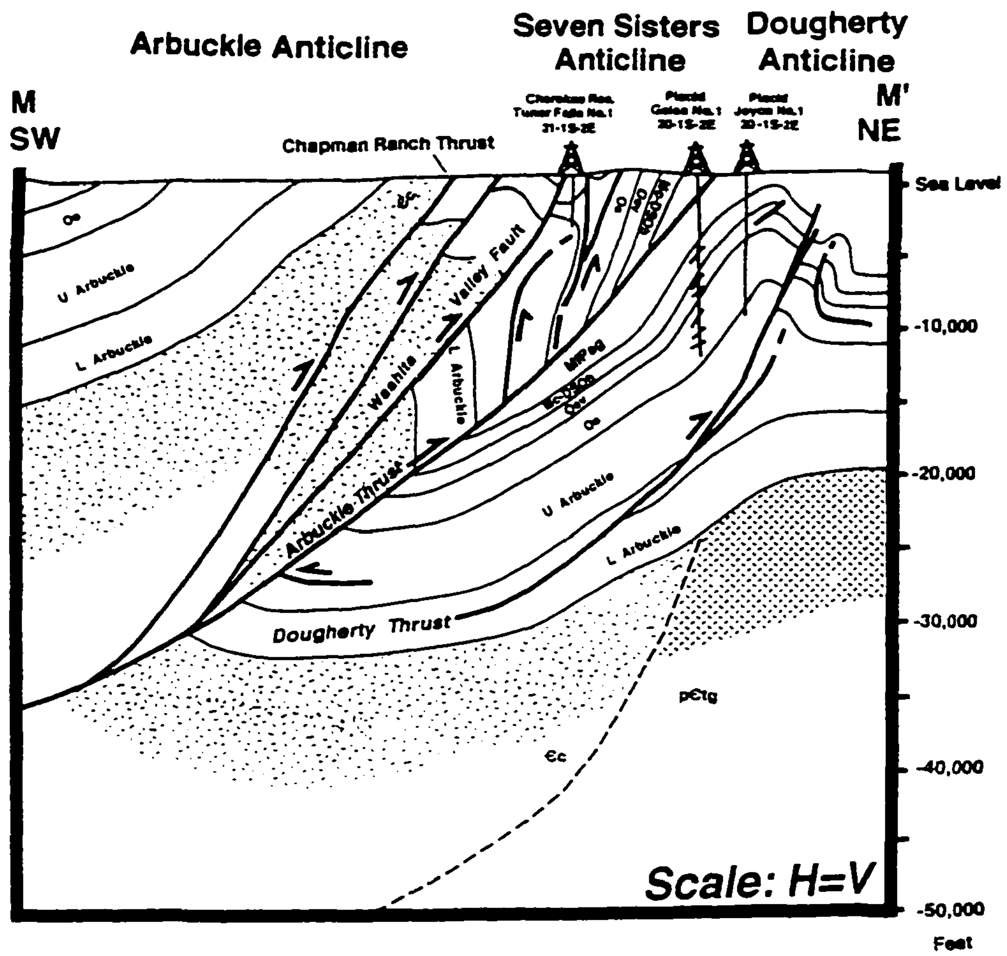


Figure. 6.20. Cross section M-M' across the Arbuckle Anticline and Dougherty Anticline. The Seven Sisters Anticline and Dougherty Anticline were formed as crowd structures developed out of the Washita Valley Syncline. The Placid Geiss No. 1, drilled on the south flank of the Dougherty Anticline, contains a nearly constant 60 degree dip panel.

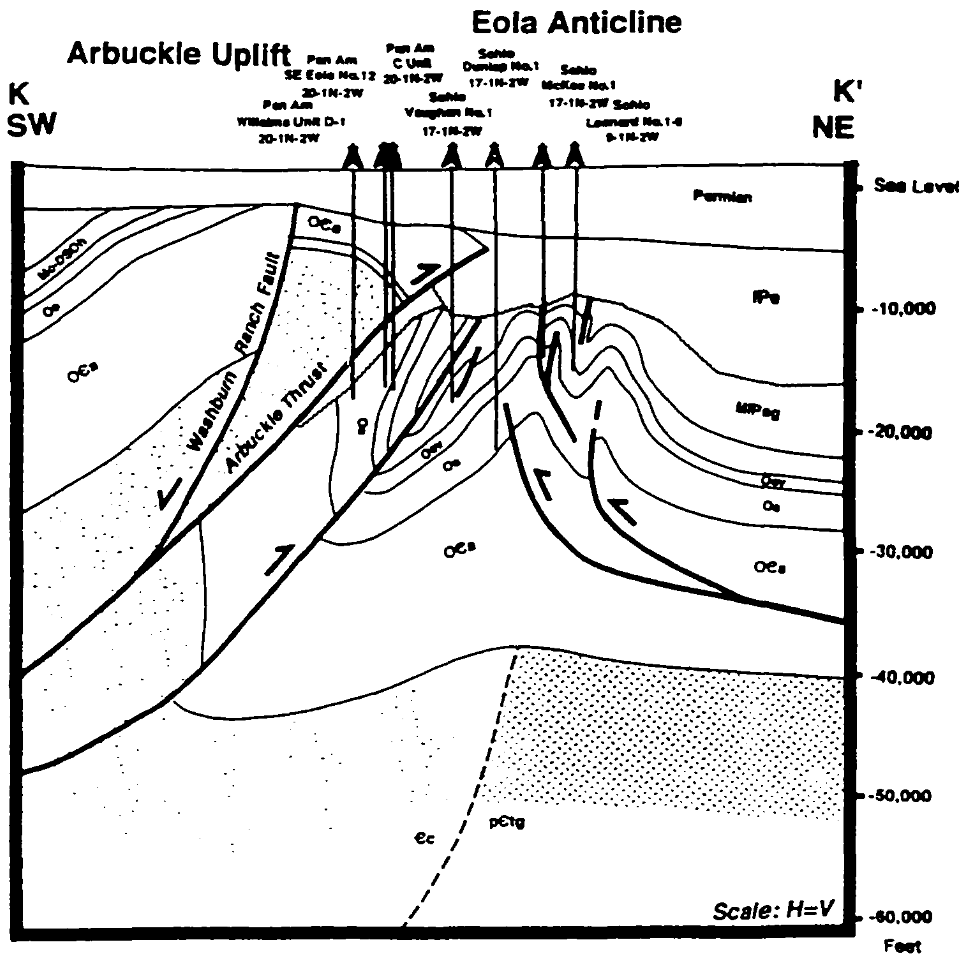


Figure. 6.21. Cross section K-K'through Eola Field.

Why Fold-Thrust Deformation in Southern Oklahoma?

Southern Oklahoma lacks the high-quality surface exposures of the Rocky Mountain Foreland where the fold-thrust theory of mountain flank deformation has been documented with surface and subsurface examples of early, intermediate, late, and advanced stages of deformation (Berg, 1962; Brown, 1983, 1984, 1988; Willis, 1993). Determination of structural style is often more dependent upon subsurface and interpretational data such as well-logs, interpretational (though constrained) cross-sections, and seismic data. Strong evidence for fold-thrust deformation comes from the deformation style and history of the sedimentary section; steep to overturned limbs containing rabbit-ear folds and foreland detachment structures in particular require folding of a mountain-flank syncline early in their history of formation. These features are very difficult to explain by passive folding as a response to force-folding of a basement-block (thrust-uplift model).

In the Rocky Mountain Foreland, some of the best subsurface evidence for fold-thrust deformation comes from the dual-fault shear zone which forms the mountain-flank fault zone. In advanced-stage fold-thrust deformation, the dual fault zone is a well developed, overturned, thinned, sheared zone of material which has been recognized in well-logs. In the Southern Oklahoma Foreland, no advanced-stage dual fault zone has yet been encountered by drilling. Where present, fold-thrust deformation in southern Oklahoma exhibits styles closer to intermediate and late-stage style fold-thrust deformation (Willis, 1993). Such areas include the Eola-Robberson area of the northwest plunge of the Arbuckle Uplift and the Blue Creek Canyon Block on the Wichita Mountain Front. This leads to the question; are there areas in southern Oklahoma typified by advanced-stage deformation? Clearly areas in which large amounts of basement overhang exist could be associated with an advanced-stage fold-thrust style. But are these areas typified by fold-thrust deformation? No well evidence is available in these areas because a deep sub-thrust (sub-basement) play has not yet developed along the Wichita Mountain Front. Many of these areas of large, continuous basement overhang appear to have undergone less folding than the areas previously documented in this chapter. More significantly, the areas of large overhang are often associated with frontal imbricates in which the main thrust runs for a significant length as a flat (or low-angle ramp) in the Arbuckle Group (Saxon, this volume). Such a geometry is difficult to reconcile with large amounts of basement folding, but is better explained by fault-bend folding and thrust uplift models. Cross sections by Saxon (1994) suggest a progressive variation in style along the northwest Arbuckle Uplift from a fault-bend fold to a fold-thrust, with both areas showing attributes of the other style. Chapter 8 addresses lateral changes in style of the mountain front and offers models to explain variations in structural style of the mountain front along strike as a consequence of variations in the amount of folding along strike. Clearly, a better understanding of mountain front geometry is needed.

An additional consideration is the distribution of well data along the mountain flanks of southern Oklahoma uplifts. Suprisingly, relatively few wells have been drilled through the Wichita Uplift. Most wells which have drilled through basement overhangs in southern Oklahoma have been drilled on the Arbuckle Uplift and the majority of these wells are located in the Eola-Robberson area of the northwest plunge of the Arbuckle Uplift. This area is typified by intermediate-stage fold-thrust deformation and would not likely encounter a highly sheared dual fault zone. Many of these wells were drilled to established production in overturned beds of the steep-limb which were sealed against the fault-plane. As a result, these wells may have reached total depth without continuing through to the lower fault of the dual fault zone. The only well to drill through a substantial amount of basement overhang in the Wichita Uplift is the Sohio Traub which was drilled through an area characterized by intermediate fold-thrust. It too reached total depth shortly after cutting the basement overhang and may not have penetrated enough of the footwall and dual fault zone to provide a full picture. Thus, wells may have not been drilled in areas typified by late-stage fold-thrust deformation, and those that have been drilled, may have not been drilled deep enough to provide enough conclusive information about the geometry of the footwall.

Summary

The southern Oklahoma foreland contains a sub-horizontally layered basement which accommodated Pennsylvanian crustal shortening through fold-thrust deformation. The layered igneous basement of Oklahoma, combined with the overlying strong layer of Arbuckle Group limestones, may have served to lower the mechanical contrast between basement and sedimentary cover, allowing for a more homogenous response between crust and cover. The fold-thrust deformation can be documented along portions of the Wichita and Arbuckle Uplifts and their associated basins. Tight folding, of forelimb synclines of asymmetric basement-cored anticlines, during the early stages of fold-thrust deformation, created complex detached subsidiary structuresin order to resolve synclinal crowding. Footwall synclines may be locally overturned and contain "rabbit-ear" structures on the steep flank. Detached foreland structures are commonly generated by out of-the syncline crowding of the shallow (basinal) limb of the footwall syncline. These complex structures are typified by fault-propagation folds in the pre-Pennsylvanian section and cross-crestal thrusts which transport Pennsylvanian growth structures. Where documented in southern Oklahoma, fold-thrust structures show late-stage deformation. The highly-thinned and sheared dual fault zone characteristic of advanced stages has not been documented. Fold-thrust deformation may be an end member of a continuous range of styles of basement deformation which may include, or be modified by (or modify) thrust uplifts and fault-bend folds.

Chapter 7

FORELAND DETACHMENTS STRUCTURES OF THE ANADARKO AND ARDMORE BASINS

Introduction

Foreland detachment structures are an economically significant class of intra-basinal structures which are common in the Anadarko and Ardmore Basins. Foreland detachment structures are complex cross-crestal folds, typified by a two-tiered geometry, consisting of two fault-propagation folds, stacked vertically over each other. Each fold is rooted in a different detachment horizon and the crests of the two folds are offset by bedding-plane slip, resulting in a cross-crestal fold. The deep fold is a fault-propagation fold in the pre-Pennsylvanian section which is detached in the Arbuckle Group. The deep fault-propagation fold may be cross-crestal to, or located above, an even deeper hinge, or flexure, of the basement-sediment contact. The shallow fault-propagation fold, which deforms the Pennsylvanian section, is cross-crestal to the deep fault-propagation fold and is offset along a detachment rooted in Springer shales. The shallow fault-propagation fold is a growth structure consisting of complexly imbricated Pennsylvanian growth sediments which thin against, or over, the crest. Foreland detachment structures are accommodation features of the mountain-flank syncline and must be considered in the context of regional balancing. When balanced "locally", many foreland detachment structures may show a greater amount of shortening in the shallow, cross-crestal fault-propagation fold than in the underlying deep fault-propagation fold of the pre-Pennsylvanian rocks. However, the "imbalance" is only an apparent artifact of local balancing, and is regionally compensated for by structural adjustments along the mountain-flank syncline. *In order to achieve structural balance,* *the foreland detachment structure must be integrated with the forelimb of the mountain-flank syncline from which it was generated.*

Foreland Detachment Structures

The foreland detachment structures examined in this chapter are second-order intra-basin folds. Foreland detachment structures occur within the basin, forelandward of the mountain-flank syncline which is the footwall of basement-cored uplifts (Figs. 4.1 and 4.2). Foreland detachment structures were generated as crowd structures, and were thrust out of the shallow limb of the mountain-flank syncline, during early stages of fold-thrust deformation. Foreland detachment structures are typified by the following general characteristics.

1) They are present within the basin, on the shallow limb (of a mountain front syncline).

2) They are vergent away from the hinge of the syncline from which they were generated.

3) They typically exhibit cross-crestal folding in which the syn-orogenic sediments are off-set from a lower fold by a detachment in the Springer shales.

4) They form a "sub-basin" between themselves and the deformed mountain front.

Examples of detachment structures in the southern Oklahoma foreland include Carter-Knox Anticline, Cordell Anticline, Elk City Anticline, Cement Anticline, Fox-Milroy-Velma-Cruce Trend, and Carter Anticline. They are set apart from other detached structures by their common characteristics, size, and economic significance.

Petersen (1983) first used the term "foreland detachment structures" in southern Oklahoma in a study of detached second order structures in the Wyoming Foreland and Anadarko Basin. Petersen (1983) noted that detachment structures formed by concentric folding through flexural slip, are principally the result of changes in synclinal geometry, and exist over several orders of magnitude. Brown (1984, 1988) related the development of detachment structures in the sedimentary section of the Wyoming Foreland to out-of-the-syncline crowding. Brown recognized three styles of structures which result from bedding plane slip; the back-limb fold, the cross-crestal fold, and the rabbit-ear fold (Fig. 6.12). In the cross-crestal fold, bedding plane slip shifts the crest of a shallow anticline with respect to a deeper anticline. Basin detachment structures of the southern Oklahoma foreland fit into both Petersen's (1983) general description of foreland detachment structures and Brown's (1984) cross-crestal style of fold. This chapter examines characteristics of style and structural position which are unique to detachment structures of the Anadarko and Ardmore Basins.

Geometry of Foreland Detachment Structures

The foreland detachment structures of southern Oklahoma are complex cross-crestal folds which differ in structural style above and below the offsetting detachment (Fig. 7.1). Fold geometry is controlled by two main detachments, each generated from different structural levels of the mountain-front syncline. The lower detachment is rooted in the Arbuckle Group. The upper detachment is rooted in Springer shales. The Springer is several thousand feet stratigraphically higher in the section than the Arbuckle Group and closer to the core of the mountain front syncline. Because of upward tightening of the mountain flank syncline, a greater amount of out-of-the syncline thrusting will occur in the Springer than the lower Arbuckle Group. Thus, the same syncline will generate thrusts of increasingly greater displacement higher in the section (closer to the core of the syncline).

The shallow fold above the Springer detachment, and the deep fold below, are both fault-propagation folds; however, the exhibit differing structural styles because of

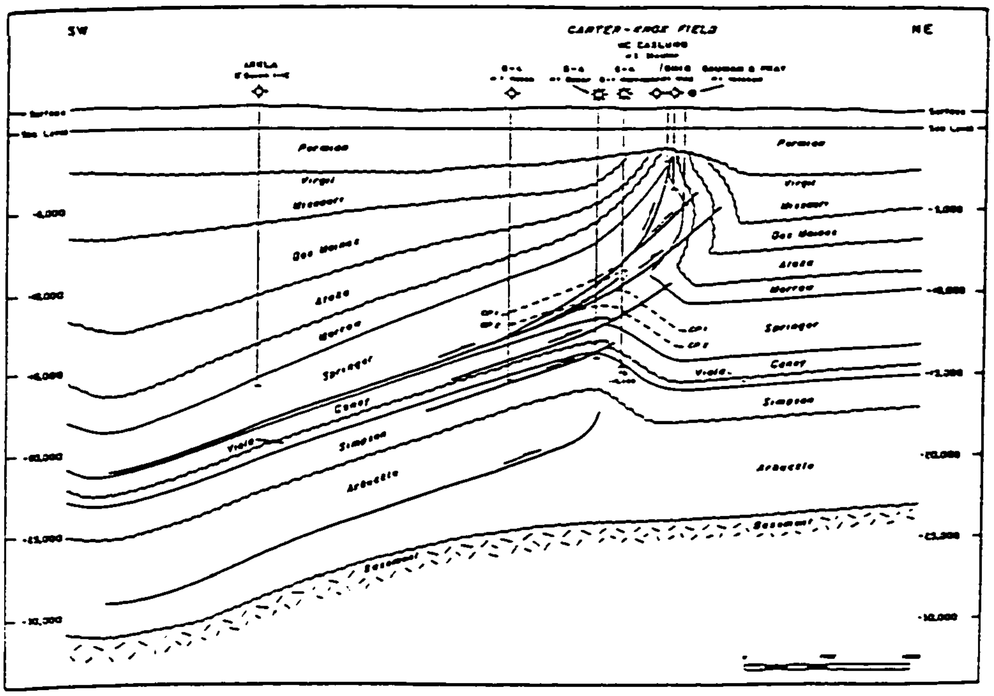


Figure 7.1 Cross section of Carter-Knox Anticline in the Anadarko Basin. Carter-Knox is a typical basin detachment structure in southern Oklahoma. The shallow fold in the pre-Pennsylvanian sediments is cross crestal to a deep fault propagation fold. Structural style differs between the upper and lower folds. Shortening is greater above the upper detachment than in the deep fault-propagation fold, but is balanced at the basin syncline. Note that the basement continues beneath the structure which is detached in the lower Arbuckle Group (from Petersen, 1983).

mechanical and lithological differences between the pre-Pennsylvanian and Pennsylvanian sections. In the following discussion, these offset folds will be referred to as the shallow fault-propagation fold and the deep fault-propagation fold. The pre-Pennsylvanian section consists of a dominant Cambro-Ordovician carbonate section and inter-layered carbonates and clastics in the Ordovician-Mississippian section. The Pennsylvanian section is comprised of shales, sands, and washes which reflect the in-filling and structural evolution of the basin. In between are approximately 1,000 feet of shales of the Mississippian-Pennsylvanian Springer Group; which are conducive to the formation of detachments.

Deep Fault-Propagation Fold.

The deep fault propagation fold, cored by rocks of the Arbuckle Group, is characteristically concentric, doubly-plunging, and generally has a large length-to-width ratio. Smaller subsidiary detachments, especially in the Simpson and Sylvan shales, may modify the fold, and small reverse faults may locally duplicate a horizon. Local variations in detachments form culminations and saddles. Fractures and normal faults which run transverse to the main structural trend may compartmentalize the fold. Some folds, such as the south plunge of Carter-Knox Anticline, may terminate against a compartmental fault. The deep fault-propagation fold may contain back-thrusts, formed as a consequence of Arbuckle rocks moving up the ramp of the detachment. Because the Arbuckle detachment is a product of synclinal crowding, and was generated during the early stages of mountain-flank folding, the deep fold is formed in the earliest stages of basin development. Growth of the deep fault-propagation fold ends when the mountain-flank fault breaks through the mountain-flank syncline and faulting replaces folding as the main deformation mechanism.

For some foreland detachment structures, it is not always clear whether or not the deep fault-propagation fold is basement involved. This is generally due to lack of deep well control and poor seismic imaging. Petersen (1983) and Stone (1993) illustrated examples from the Bighorn Basin in which foreland detachment structures were rooted in basement thrusts, and are, essentially, basement fault-propagation folds. The examples from the Bighorn Basin verge up the shallow flank (back-limb) of a gentle basin whereas the majority of detachment structures in the southern Oklahoma foreland are generally located close to the mountain front syncline. Thus detachment structures of the Big Horn basin and southern Oklahoma, despite certain genetic similarities, may not represent equivalent structural position. In some cases, such as the Carter-Knox Anticline, the deep fault-propagation fold has a high length-to-width ratio typical of non-plunging concentric folds in detached thrust sheets, or, such as the case of the Velma Anticline, the deep fault-propagation fold is too tightly folded to accommodate basement involvement at greater depth. Determinations of basement involvement may be made with depth-to-detachment calculations. However, this analysis is not always definitive, as the Arbuckle Group-rooted detachments may be cross-crestal to lower basement involved thrusts.

In many cases foreland detachment structures form across a hinge or inflection in the basement surface, which may serve as a ramp, controlling the formation of the deep fault-propagation fold. The flexure of the basement may be caused by a variety of means, including a fault-bend fold over a basement ramp, south-directed back-thrusting, or the erosion of the fault scarp of an older (Precambrian or Cambrian) normal fault (Fig. 7.2). Basement flexures add to the degree of curvature, and thus the tightening, of the syncline between the back-limb of the foreland detachment structure and the mountain-flank syncline. Each successive detachment steepens the dip of the back-limb of the foreland detachment structure and must be added to the regional dip of the basement. The syncline between the back-limb of the foreland detachment structure and the mountain-flank syncline can become very tight. The upward tightening of this

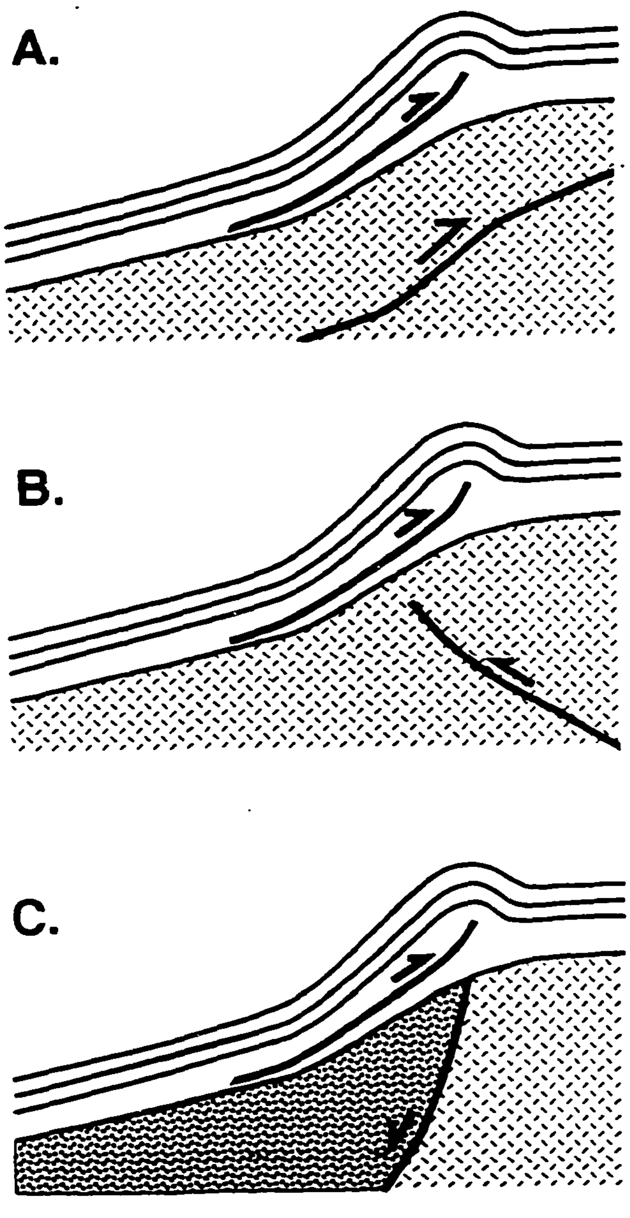


Figure 7.2. Possible mechanisms for the creation of inflection points or hinges in the basement surface which may serve as a locus for the development of foreland detachment. A. Fault-bend fold over a basement ramp. B. South-directed basement back-thrusting C. Eroded normal fault scarp from old rift boundary.

syncline may generate detachments which are thrust out of either side of the "basin" between the mountain front and the foreland detachment structure.

Shallow Fault-Propagation Fold.

The fold above the Springer detachment is the most complex portion of the foreland detachment structure. The Springer detachment can be highly imbricated and, in many cases, ramps up steeply over the crest of the deep fault-propagation fold. The imbrications die out into a complex Springer-cored fault-propagation fold. In some cases, crowding of the forelimb syncline of the deep fault-propagation fold may generate a hinterland-verging Springer detachment, forming a triangle zone. Imbrication and generation of detachments in the Springer, and higher formations, is a function of tightening the sub-basin (syncline) formed between the mountain-flank syncline and the back-limb of the deep fault-propagation fold of the foreland detachment structure (e.g. Cyrill Basin between the Wichita Mountain front and Cement Anticline). Each detachment of the foreland detachment structure progressively adds dip to that limb of the syncline, tightening the syncline and generating further detachments to relieve volumetric crowding (Fig. 7.3).

Pennsylvanian sediments are synorogenic strata, deposited across the actively growing shallow fault-propagation fold of the foreland detachment structure (Figure 7.4). Pennsylvanian beds thin against the structural crest, may be truncated by angular unconformities, and record progressively less shortening with rising stratigraphic position. These synorogenic sediments fit many of the characteristics of growth strata (Suppe and others, 1992). Growth structures can be observed over many orders of magnitude. Small, detached, growth structures are common in the syncline between the foreland detachment structure and the mountain front. Growth structures record the interaction between sedimentation and fold growth. Where sedimentation rates are known, the growth structures can be used to determine the rate of structural growth.

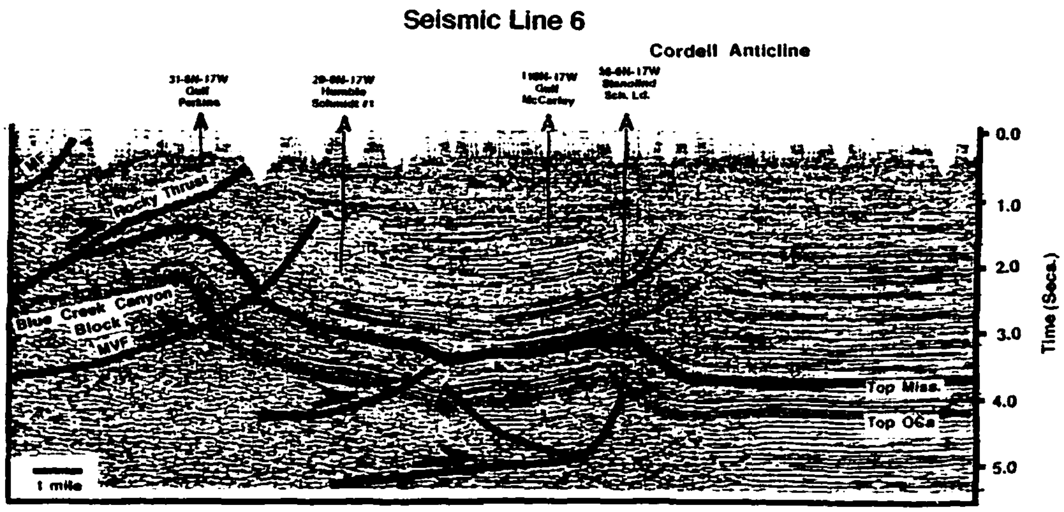
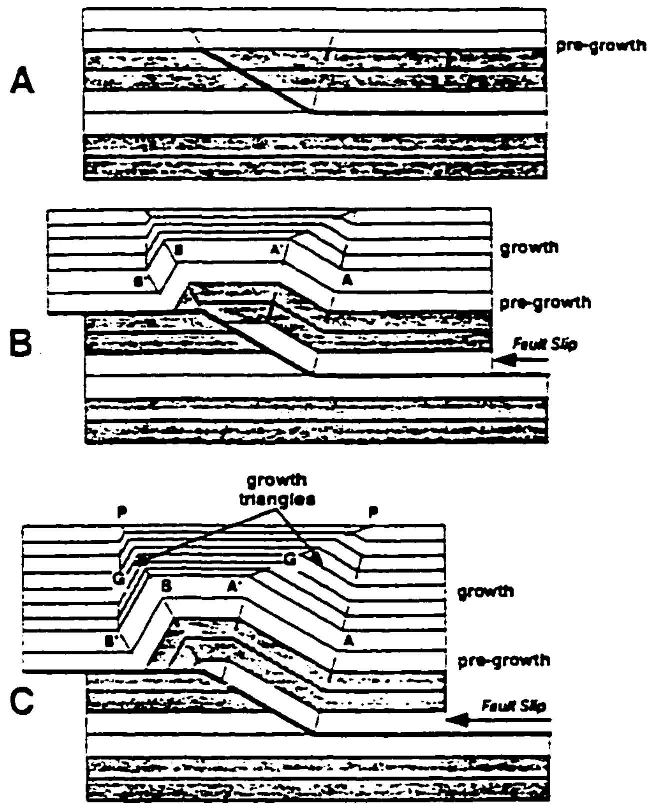


Figure 7.3. Seismic line 6 across Cordell Anticline. Cordell Anticline is a foreland detachment structure generated from folding of the forelimb syncline of the plunging Blue Creek Canyon Block of the Wichita Mountain Front. Note the syncline formed between the mountain front and the detachment structure is progressively tighter up section. Upward syncline crowding has led to the development of multiple levels of detachments (seismic courtesy of Vestige).



(A-B) = Active axial surfaces
(A'-B') = Inactive axial surfaces
(G) = Growth (inactive) axial surfaces
(P) = Surface deformation

Figure 7.4. Growth structures (Shaw and Suppe, 1994)

Relationship to the Mountain Front Syncline and Timing of Growth

Foreland detachment structures are generated from volumetric crowding of the mountain-flank syncline. In the Wichita and Arbuckle Uplifts, this was accomplished by fold-thrust deformation. In the early stages of fold-thrust deformation, shortening is accomplished by the creation of a basement-cored anticline and it's forelimb syncline. Folding of the syncline creates volumetric crowding which is relieved by out-of-the-syncline thrusting. During the intermediate and late-stages, the syncline is cut by faults, shutting off the folding mechanism for the generation of crowd structures. In the Wichita Uplift, the major uplift along mountain flank faults occurred by the end of the Atokan. Foreland detachment structures of the Anadarko Basin show evidence of early growth by the thinning or absence of the oldest growth sediments (Springer, Morrowan, Atokan) against the crest of the shallow fold. However, many foreland detachment structures, particularly in the eastern portion of the Anadarko Basin, show continued growth, with strata through Virgilian thinned, folded, and offset by faulting. This structural growth continued as slip along the early formed Springer detachment which must have been cut, and therefore "shut-off" from slip, by the major mountain-flank fault. Clearly, in these cases, the footwall syncline of the mountain flank must have experienced continued shortening after the development of the major mountain-flank faults in order to generate slip on the Springer detachment. This can be accomplished by forward-breaking thrusts in the footwall of the major mountain-flank fault and/or rotation of the steep limb by sheer between a dual fault zone. In these areas, the main uplift of the mountain-flank has occurred by Atokan time, but persists with minor footwall shortening throughout the Pennsylvanian. Foreland detachment structures of the western Wichita Uplift generally do not display this growth, and, in general, appear to have ended growth by the Desmoinesian. Both foreland detachment structures and the mountain flank of the eastern Wichita Uplift show continuous growth throughout the Pennsylvanian. This may indicate a tectonic front in which deformation of the Wichita Uplift moved from the west to east, or at least continued for a greater length of time, to the east.

Balancing Considerations

Foreland detachment structures should not be "locally" balanced; that is, balanced as isolated folds outside of their regional context. When foreland detachment structures are balanced locally, with pin lines fixed between synclinal axes, the shallow and deep folds may not contain the same line lengths and thus may appear to not balance. *In order to achieve structural balance, foreland detachment structures must be regionally balanced, with the mountain flank-syncline from which they were generated included in the scope of the balance.*

The Pennsylvanian section of a foreland detachment structure consists of synorogenic sediments which may contain eroded beds, complex detachments, and formations which thin towards the fold crest. Successively younger synorogenic sediments do not record shortening which occurred prior to their deposition. As a result, synorogenic sediments are not suitable for balancing. The Pennsylvanain setion may, however, yield insights into important factors of growth history such as growth rates.

Highly imbricated and internally stacked shales, such as the Springer, may "wad up" and thus are unsuited for line-length balancing techniques. In such cases, area balancing techniques may be more appropriate.

Examples of Foreland Detachment Structures

Carter-Knox Anticline

Carter-Knox Anticline (Figs. 7.1 and 7.5) is located in Grady and Stephens Counties in the southeastern portion of the Anadarko Basin. Abundant well control and seismic data make the Carter-Knox Anticline the most well-documented example of a foreland detachment structure in southern Oklahoma. Production exists from multiple horizons in both the shallow and deep folds. The shallow fold crest is offset from the deep fold crest by a mile along the Springer detachment. The shallow fault-propagation fold experienced continuous growth through the entire Pennsylvanian and had the greatest movement in Late Pennsylvanian time (Petersen, 1983).

Cement Anticline.

Cement Anticline (Figure 7.6) in the southeastern Anadarko Basin, is a typical, well-developed foreland detachment structure. The shallow fault-propagation fold occurs above a detachment in the Springer shales. The detachment becomes complexly imbricated as it dies upward into the fold, with several imbricates breaking the forelimb of the fold. A southwest-verging thrust, detached in the Springer, creates a triangle zone above the forelimb syncline of the deep fault-propagation fold. Morrowan and Atokan sediments thin against the crest, indicating rapid early growth. the back-limb of the shallow fault-propagation fold is deformed by small thrusts detached in the Deese. These faults were active until, and perhaps during, the Permian, indicating continuous growth. The overlying Permian beds are very gently folded, producing a surface anticline, which is one of the oldest producing fields in Oklahoma.

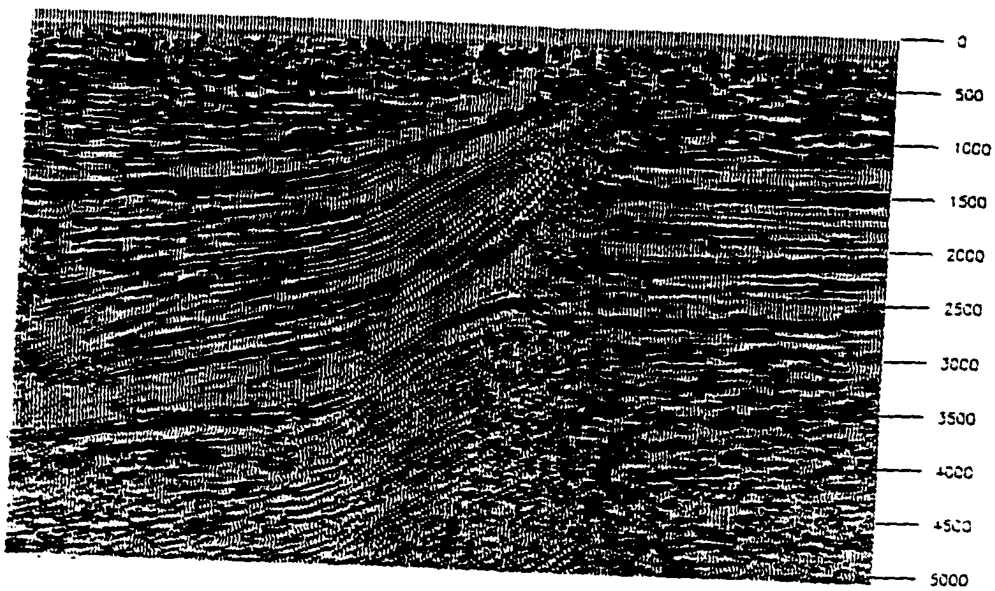
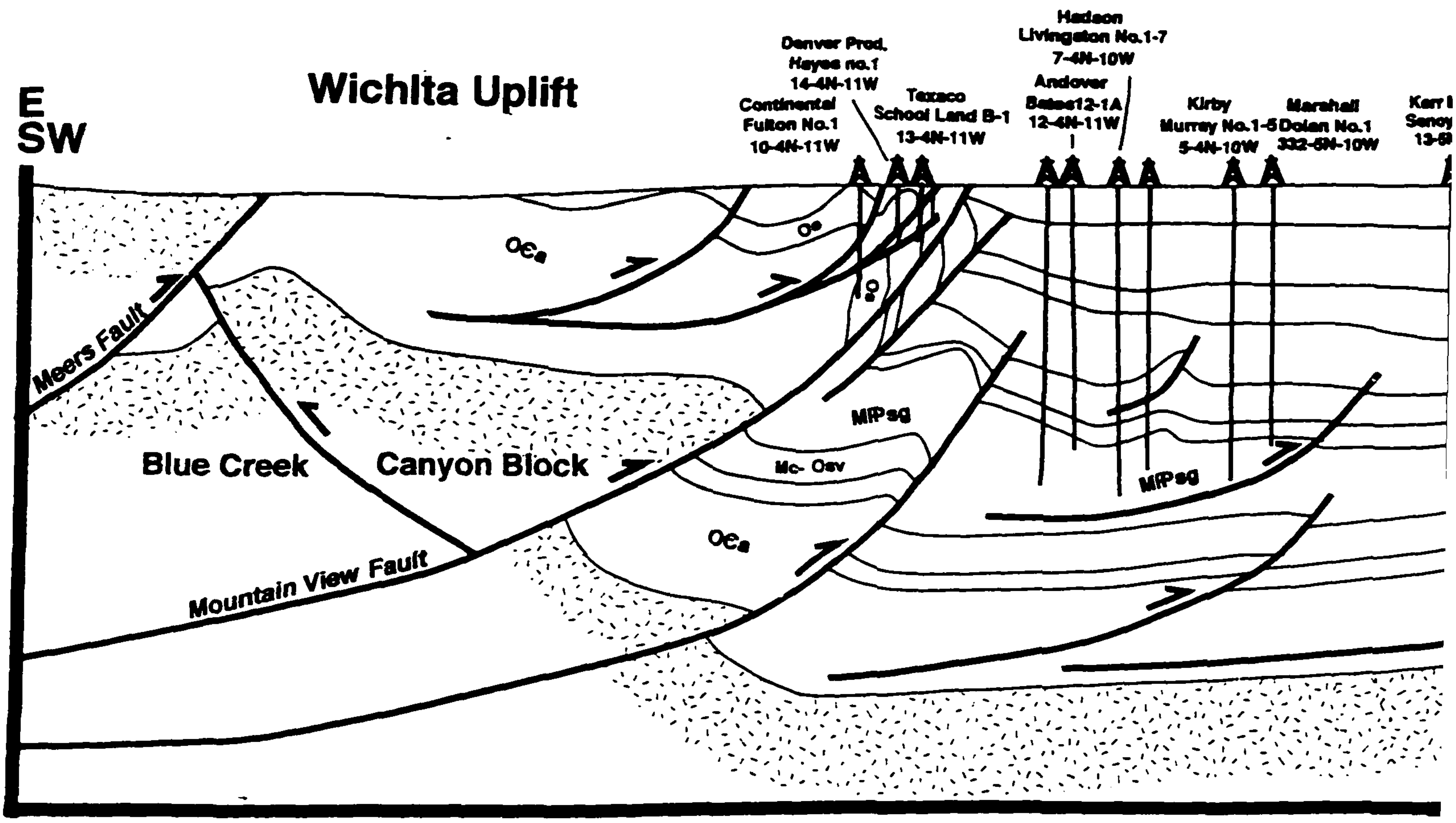
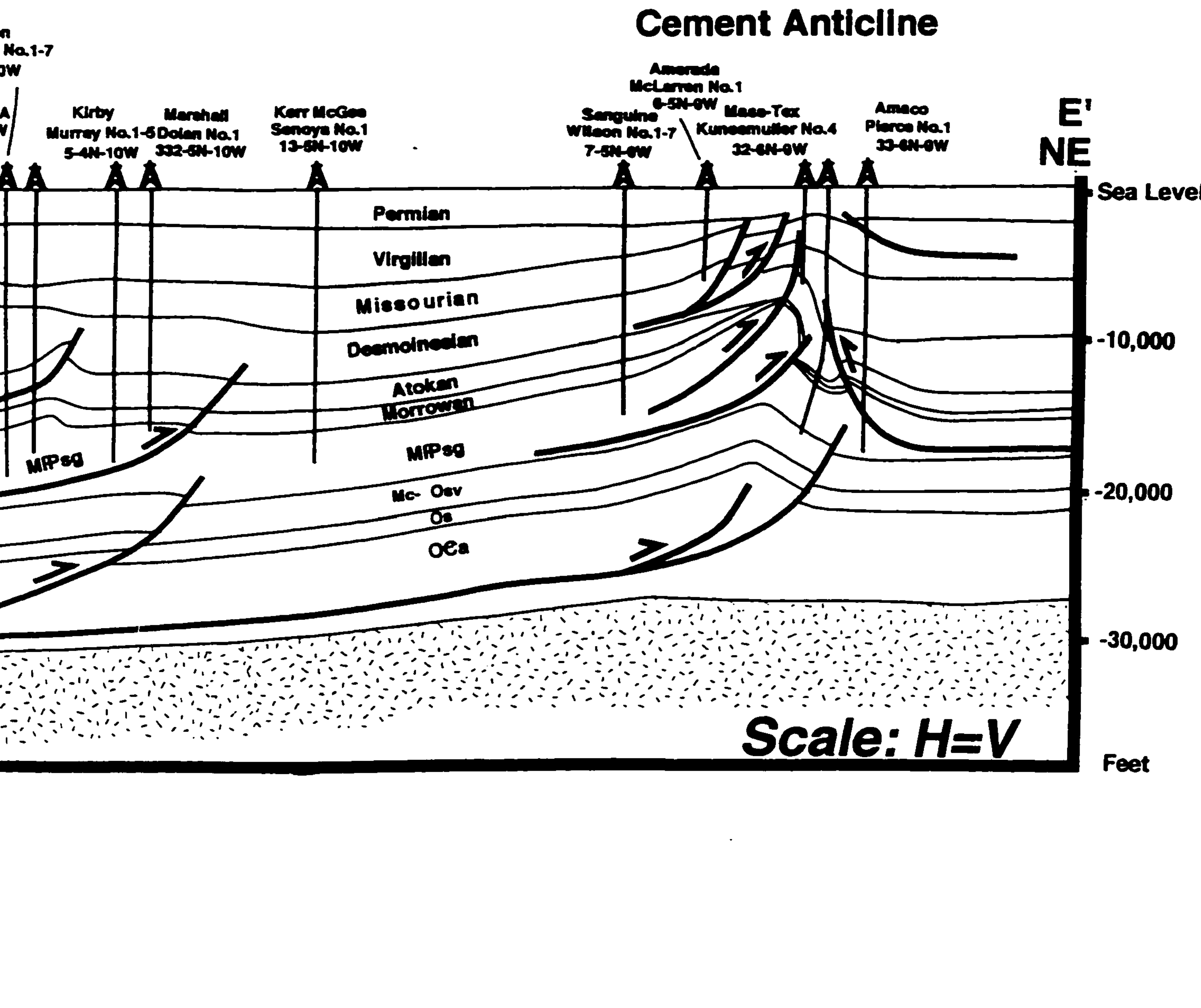


Figure 7.5. Seismic line through Carter-Knox Anticline.

Figure 7.6. Cross section E-E' through Cement Anticline.



E
SW
Wichita Uplift
Denver Prod.
Hayes no.1
14-4N-11W
Continental
Fulton No.1
10-4N-11W
Texaco
School Land B-1
13-4N-11W
Hadson
Livingston No.1-7
7-4N-10W
Andover
Bates12-1A
12-4N-11W
Kirby
Murray No.1-5
5-4N-10W
Marshall
Dolan No.1
332-5N-10W
Meers Fault
Blue Creek
Canyon Block
Mountain View Fault
MPsg
Mc- Osv



Cement Anticline
Kirby
Murray No.1-5
5-4N-10W
Marshall
Dolan No.1
332-5N-10W
Kerr McGee
Senoya No.1
13-5N-10W
Amerada
McLarren No.1
6-5N-9W
Sanguine
Wilson No.1-7
7-5N-9W
Mass-Tex
Kunsemuller No.4
32-6N-9W
Amaco
Pierce No.1
33-6N-9W
E'
NE
Sea Level
-10,000
-20,000
-30,000
Feet
Permian
Virgilian
Missourian
Desmoinesian
Atokan
Morrowan
MPsg
Mc- Osv
Os
OCa
Scale: H=V

Carter Anticline

Fig. 7.7. is a seismic line over Carter Anticline, located on the boundary between Beckham and Washita Counties. Carter Anticline is a poorly developed foreland detachment structure. The deep fold is a fault-propagation fold having a ramp-flat geometry. The shallow fault-propagation fold is detached within the Springer shales and is cross-crestal to the deep fold. In the case of Carter Anticline, structural growth ended in the Des Moisesian as upper Des Moinesian and younger beds are not folded. Caret Anticline may have stopped growing because the forelimb of the mountain-flank may have been broken by faulting during the Des Moinesian, shutting off the mechanism for generating syncline tightening. Minor growth of the mountain front continued during the Des Moinesian as is evidenced by the detached, southwest-verging growth fold detached in the Deese. The exact relationship between the mountain front and the detached structures is difficult to establish from this seismic line due to the low-quality of resolution of the mountain front and the lack of well data to aid in structural interpretation.

Fox-Milroy-Velma-Cruce Trend.

The Fox-Milroy-Velma-Cruce trend is the largest, most complex, and the most economically important foreland detachment structure in southern Oklahoma. The Fox-Milroy-Velma-Cruce trend is a long, tight, doubly-plunging, NW-SE striking subsurface uplift. It is located in the footwall of the eastern flank of the Wichita Uplift, and extends from near Duncan, Oklahoma, to the Criner Hills. The structure is broken into four domains based upon similar structural style and elevation; Fox Anticline, Milroy Anticline, Velma Anticline, and Cruce Anticline. Differences in structural geometry between each segment are caused by differences in amount of slip on the Fox Thrust, style of the deep fault-propagation fold, structural elevation, level of erosion, and plunge. Each segment is bounded by transverse faults which compartmentalize the

Seismic Line 2

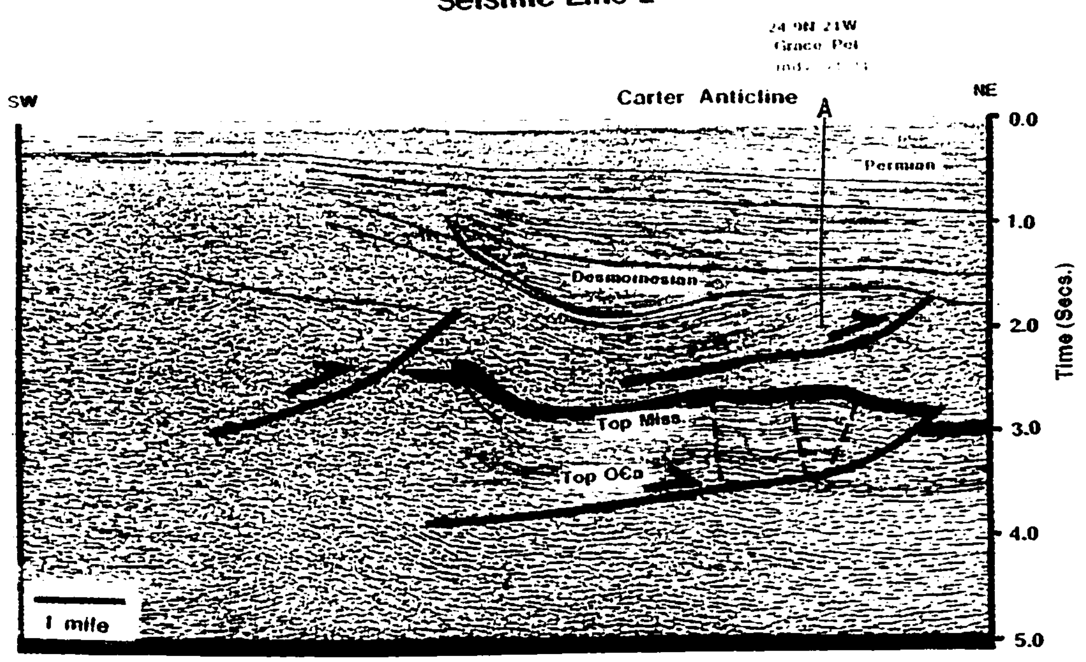


Figure 7.7. Seismic line 2 across Carter Anticline, Beckham and Washita Counties, Oklahoma (Seismic courtesy of SEI).

deformation and allow each segment to deform independently. Progressing from Fox Anticline, in the southeast, to Cruce Anticline in the northwest, slip on the Fox Thrust is decreased as it dies into a fault-propagation fold and loses structural elevation. The hanging wall fold becomes progressively tighter.

Fox Anticline. The Fox Anticline (Fig. 7.8) is the complex hanging wall anticline of the low-angle Fox Thrust which is detached in the Arbuckle Group. The Fox Anticline is thrust northeast over the Ardmore Basin. The central Fox Anticline was deeply eroded in Morrow and Atokan time, with erosion cutting into the upper portion of the deep fault-propagation fold which is unconformably overlain by Deese sediments. The narrow Oil City Anticline, located on the north flank of the Fox Anticline, is a rabbit-ear formed along a detachment in the Springer as a result of compressing the Ardmore Basin during the Arbuckle Orogeny. The eroded back-limb of Fox Anticline produces from the Sycamore Formation which has been unconformably trapped by Deese sediments which thin and overlap the uplift. To the north of Fox Anticline is the deep Ardmore Basin. The Fox Anticline plunges to the southeast, either merging with, or plunging under, the Criner Hills Uplift.

Milroy. Milroy Anticline (Fig. 7.9) is located to the northeast of, and down-plunge of, the Fox Anticline. The Milroy Anticline is cored by a fault-propagation fold developed from a back-limb imbricate of the Fox Thrust, which has lost slip continuously to the northeast from the location of the Fox Anticline. Milroy Anticline is at a lower structural elevation and is less deeply cut by post-Atokan erosion than the Fox Anticline. A deeply eroded, cross-crestal, Springer detachment is preserved on the back-limb of the Milroy Anticline. Milroy Anticline is more tightly folded than Fox Anticline because a greater amount of shortening is accommodated by folding as the Fox Thrust loses slip to the northeast. The Milroy Anticline is cross-crestal to a hinge in the basement which forms the south-dip of the Sholem Alechem Uplift.

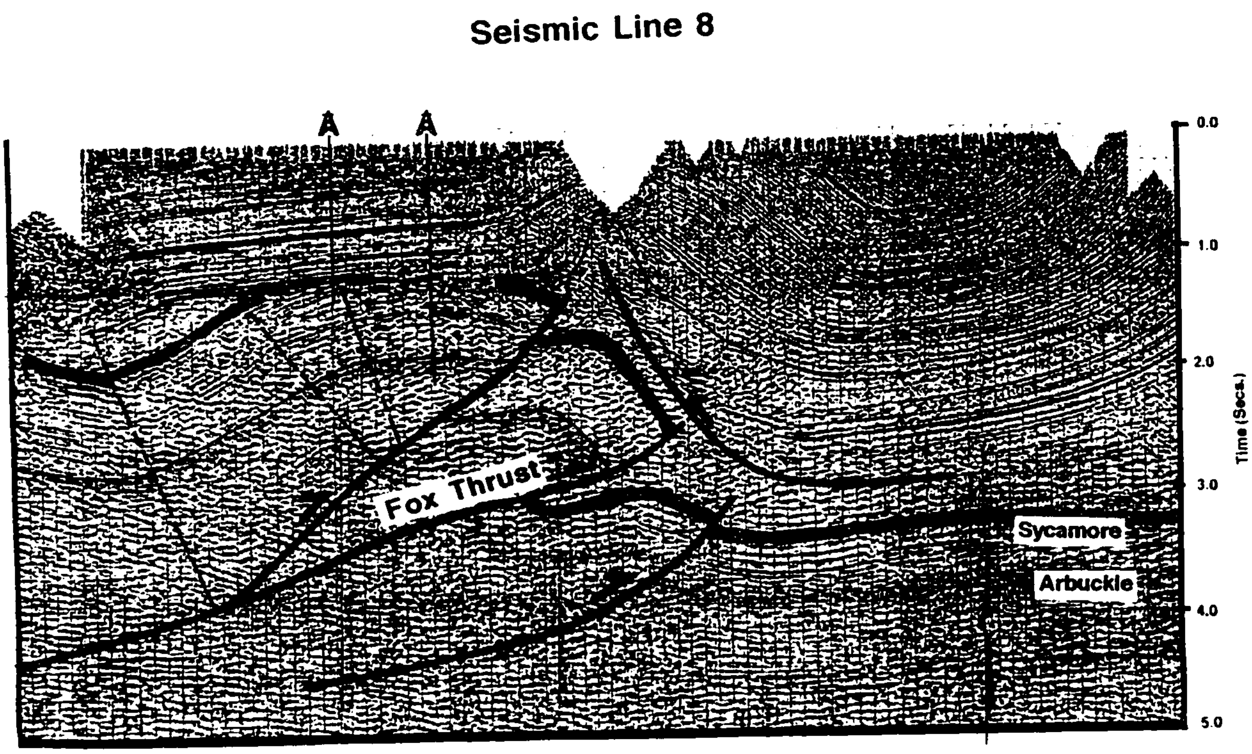
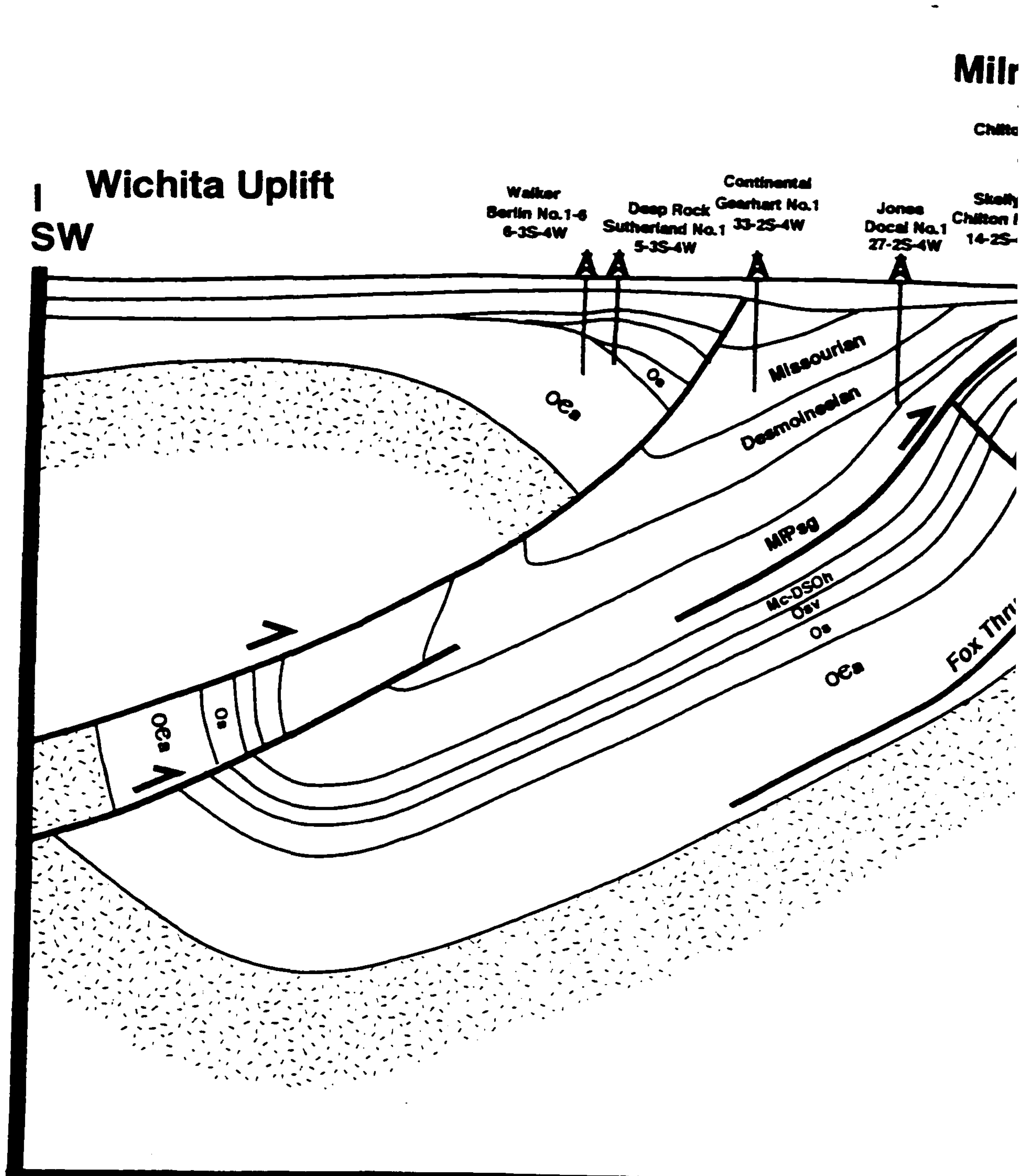
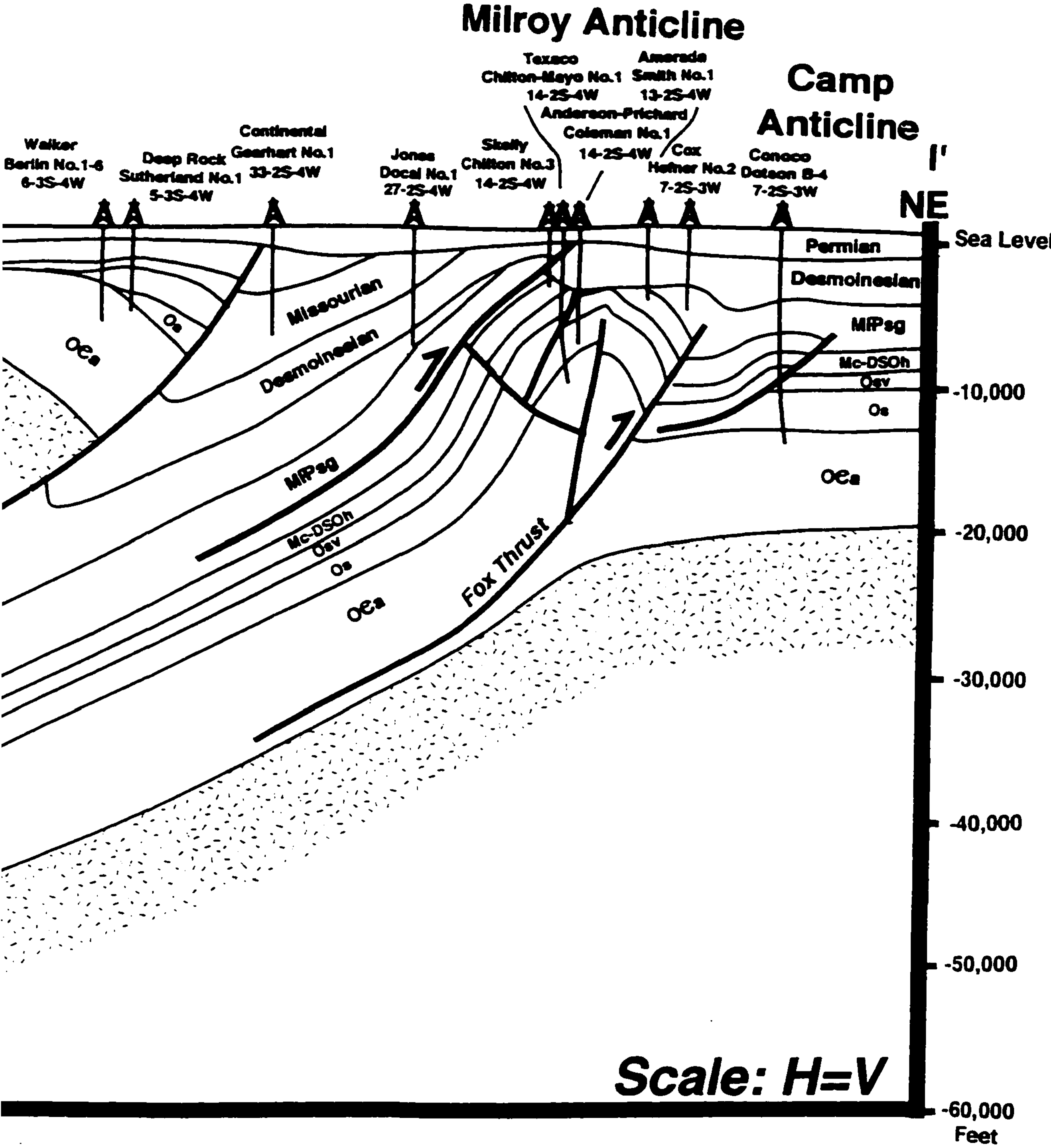


Figure 7.8. Seismic line 8 across Fox Anticline. Seismic courtesy of the Ardmore Geological Society.

Figure 7.9. Cross section I-I' across Milroy Anticline. Milroy Anticline is a fault-propagation fold generated by the northwestward loss of slip on the Fox Thrust. Milroy is a typical detachment structure of the Southern Oklahoma Foreland. The cross-crestal detachment in the Springer has been deeply eroded. Camp Anticline is a small footwall feature to the Fox Thrust.


Wichita Uplift
SW
Milr
Chilto
Walker
Berlin No.1-6
6-3S-4W
Deep Rock
Sutherland No.1
5-3S-4W
Continental
Gearhart No.1
33-2S-4W
Jones
Docal No.1
27-2S-4W
Missourian
Desmoinesian
MPsg
Mc-DSOh
Osv
Os
OЄa



Milroy Anticline
Camp Anticline
Texaco Chilton-Mayo No.1 14-2S-4W
Amerada Smith No.1 13-2S-4W
Anderson-Prichard Coleman No.1 14-2S-4W
Walker Berlin No.1-6 6-3S-4W
Deep Rock Sutherland No.1 5-3S-4W
Continental Gearhart No.1 33-2S-4W
Jones Docal No.1 27-2S-4W
Skelly Chilton No.3 14-2S-4W
Cox Hefner No.2 7-2S-3W
Conoco Dotson B-4 7-2S-3W
I'
NE
Sea Level
Permian
Desmoinesian
MIPsg
Mc-DSOh
Osv
Os
OЄa
Missourian
Desmoinesian
Fox Thrust
-10,000
-20,000
-30,000
-40,000
-50,000
-60,000
Feet
Scale: H=V

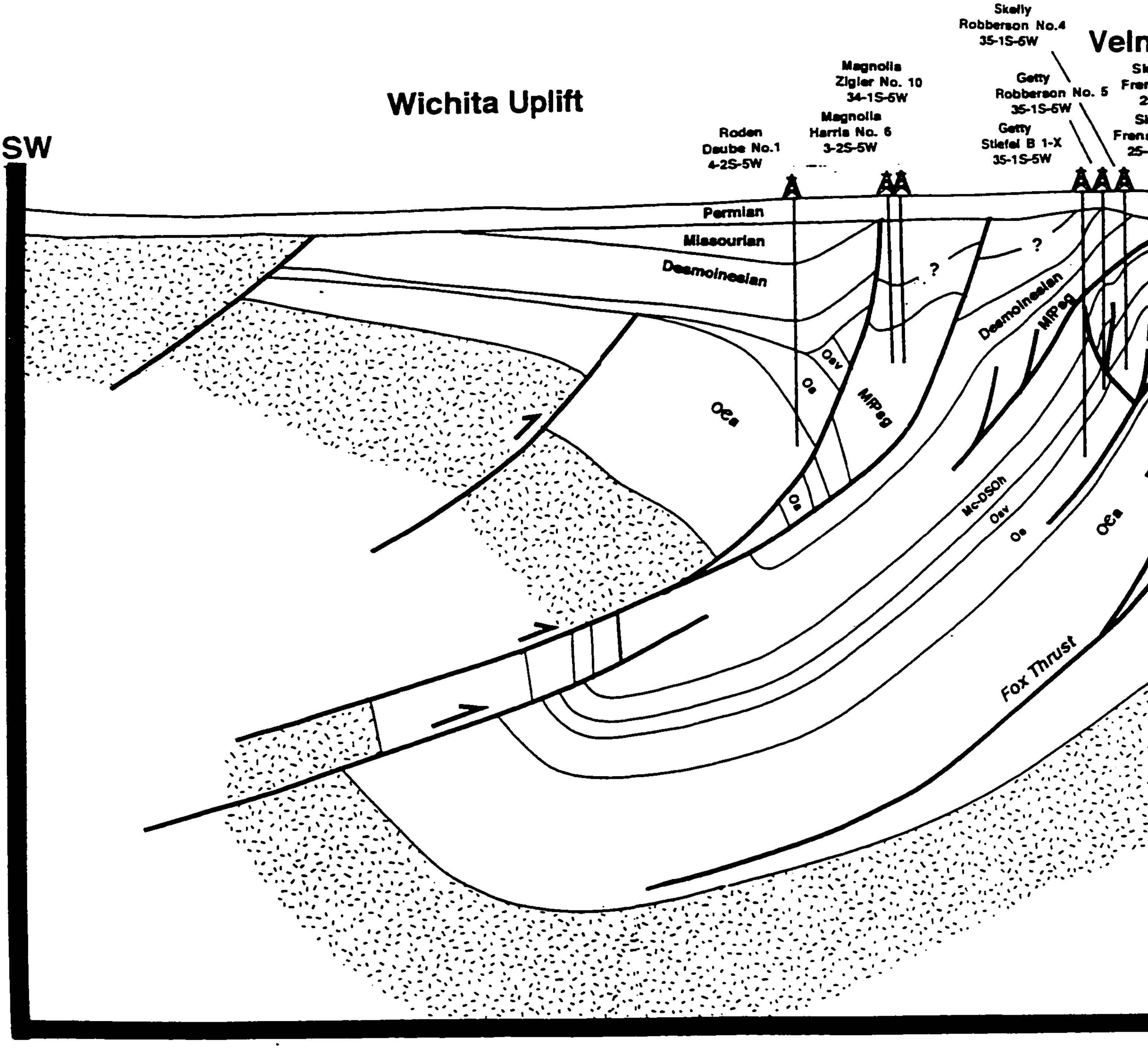
Velma. Velma Anticline (Figure 7.10) is located to the northwest of, and down-plunge from, Milroy Anticline. Velma Anticline is a fault-propagation fold which is cross-crestal to the inflection of the south flank of the Sholem Alechem Uplift. Velma Anticline is structurally lower than Milroy Anticline and is eroded to the level of the Springer Group. At Velma Anticline, the Fox Thrust has lost slip from its position at Milroy Anticline and, as a result, is a tighter fold than the Milroy Anticline. Back-thrusting and rabbit-ear structures are well-developed on the Velma Anticline as a consequence of the tightness of folding.

Cruce. The Cruce (Fig. 7.11) portion of the uplift is separated from the Velma portion by a series of tear faults, which strike to the northeast. At the Cruce segment, the Fox Thrust is a fault-fold-interchange (fault-propagation fold) which plunges to the northwest. Due to a lack of well penetrations, and reliable seismic data, plunge rates on the pre-Pennsylvanian fold are not known. The cross-crestal detachment in Springer Shales spectacularly over-rides the lower fold, forming a structure which is similar to that of any other small-scale Anadarko basin feature (Carter-Knox, Cement, Cordell). Evidence from current drilling programs suggests that the cross-crestal thrusts at Cruce become very complex and plunge at very high rates to the northwest, perhaps eventually reaching vertical.

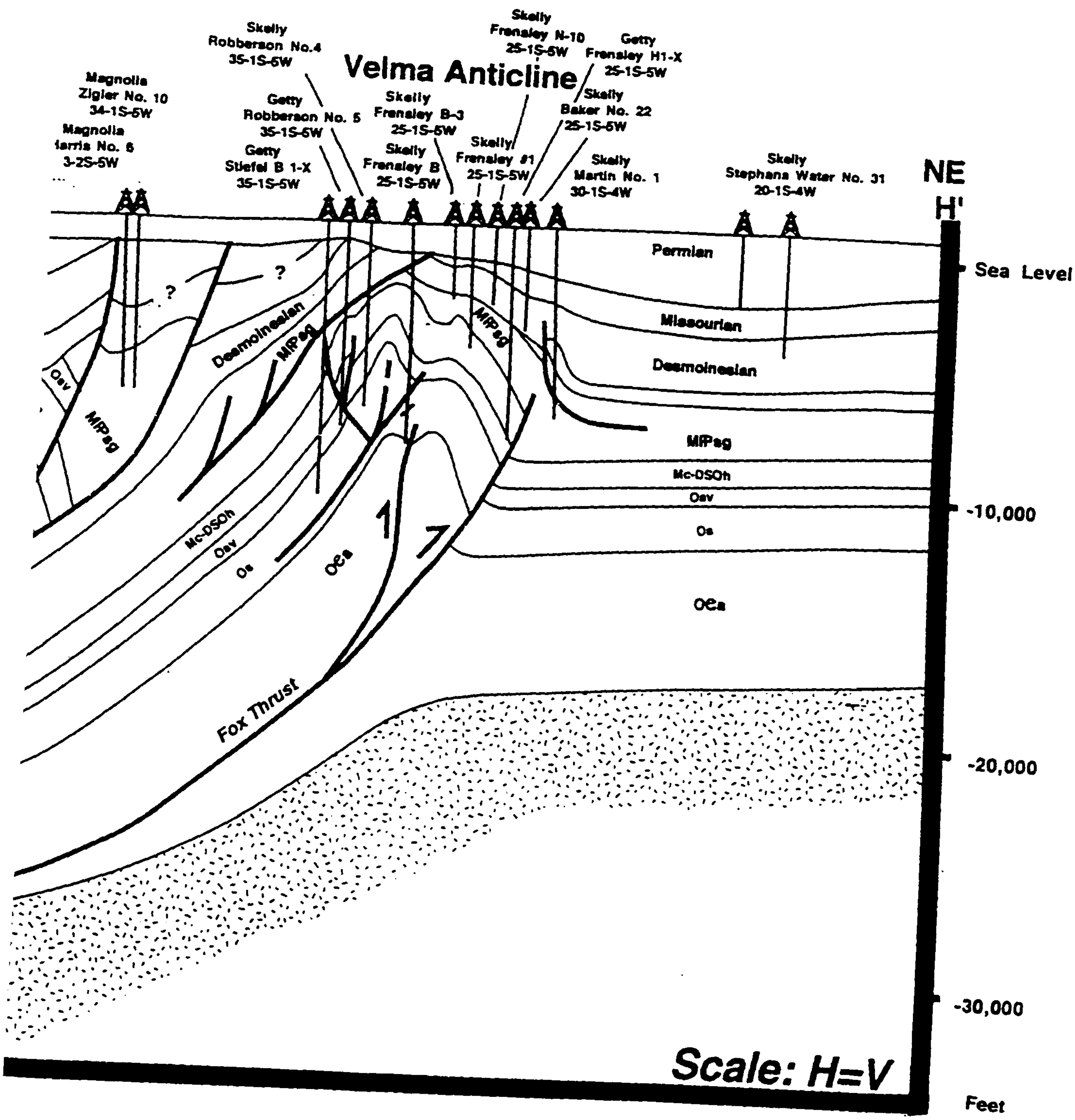
Tectonic and Economic Significance of Foreland Detachment Structures

Documentation of the structural geometry of foreland detachment structures is crucial in order to understand their relationship to the overall structural style of Pennsylvanian tectonics in southern Oklahoma. Previously interpretations of foreland detachment structures as flower structures, or subsidiary reverse faults associated with inferred restraining bends, were based upon structural analysis which did not include documentation of structural geometry. The cross-crestal geometry, and detached style

Figure 7.10. Cross section H-H' located across Velma Anticline. Velma Anticline is a tight fault-propagation fold cross-crestal to a hinge on the south flank of the Sholem Alechem Uplift. Velma Anticline is at a lower structural elevation than Milroy Anticline and is eroded to a higher stratigraphic level. Numerous detachments are developed at a variety of stratigraphic level. The cross-crestal Springer detachment crosses the lower fault-propagation fold.



Wichita Uplift
SW
Roden
Daube No.1
4-2S-5W
Magnolia
Zigler No. 10
34-1S-5W
Magnolia
Harris No. 6
3-2S-5W
Skelly
Robberson No.4
35-1S-5W
Getty
Robberson No. 5
35-1S-5W
Getty
Stiefel B 1-X
35-1S-5W
Veln
Permian
Missourian
Desmoinesian
Fox Thrust


Velma Anticline
NE
H'
Magnolia
Zigler No. 10
34-1S-5W
Magnolia
Harris No. 6
3-2S-5W
Skelly
Robberson No.4
35-1S-5W
Getty
Robberson No. 5
35-1S-5W
Getty
Stiefel B 1-X
35-1S-5W
Skelly
Frensley B-3
25-1S-5W
Skelly
Frensley B
25-1S-5W
Skelly
Frensley N-10
25-1S-5W
Getty
Frensley H1-X
25-1S-5W
Skelly
Baker No. 22
25-1S-5W
Skelly
Frensley #1
25-1S-5W
Skelly
Martin No. 1
30-1S-4W
Skelly
Stephans Water No. 31
20-1S-4W
Permian
Missourian
Desmoinesian
MIPsg
Mc-DSOh
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Os
OЄa
Fox Thrust
Sea Level
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-20,000
-30,000
Feet
Scale: H=V

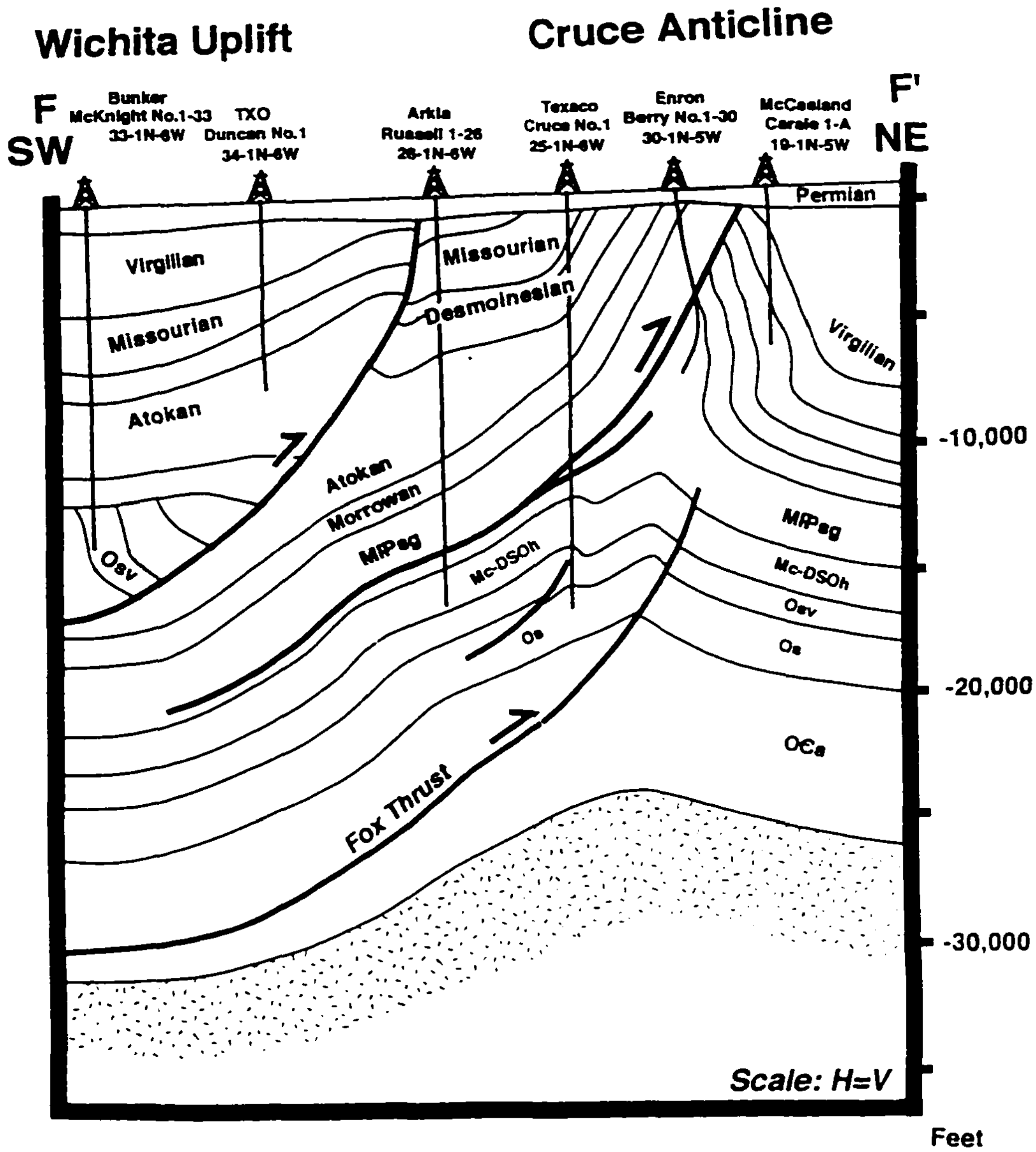


Figure 7.11. Cross section F-F' across Cruce Anticline. Cruce Anticline forms the northwest plunge of the Fox-Milroy-Velma-Cruce Trend. The crest of the lower fault-propagation fold is at the deepest structural elevation. The cross-crestal Springer detachment is preserved and well-developed. Note the thinning of Atokan Sediments on the south flank (from French, unpublished).

of these structures, may be their most significant features. This style of deformation, combined with the observation that there is a greater amount of shortening above the Springer detachment than below, can only be explained in terms of out-of-the-syncline crowding of a mountain-flank syncline. This is strong, if indirect, evidence which supports the fold-thrust style of mountain flank deformation. Cross-crestal folding, especially with greater shortening in synorogenic sediments than in the deep fold, is difficult, if not impossible, to reconcile with any other structural model. The fact that foreland detachment structures are not basement involved has strong implications for the presence and location of many interpretations of basement faulting in southern Oklahoma. The presence of a detachment structure can not be used as evidence of a through-going basement fault, and basement faults should not be interpreted as linking, or passing through, foreland detachment structures.

From an economic point of view, foreland detachments structures are some of the most important basin structures in Oklahoma. They provide a variety of traps at nearly every structural and stratigraphic level, including mild folding of overlying Permian sediments above shallow folds, stratigraphic traps due to pinch-outs of flank sands, imbriacate and footwall plays, and crestal plays on the fault-propagation fold. 3-D seismic imaging is helping to resolve these structures better.

Summary

Foreland detachment structures are complicated, cross-crestal folds, generated from crowding of the mountain-flank syncline during the early stages of fold-thrust deformation. Foreland detachment structures consist of a deep fault-propagation fold detached in the Arbuckle Group and a shallow fault-propagation fold which is detached in the Springer shales and is cross-crestal to the deep fold. The shallow fold is a growth structure, which deforms syn-tectonicly with deposition. When considered individually, foreland detachment structures may contain greater amounts of shortening in the shallow fold. However, when viewed in a regional context, the differences in shortening can be related to differential amounts of crowding of progressively higher portions of the mountain-flank syncline. Although foreland detachment structures are not basement-involved, their location and style appear to be often controlled by the geometry of the basement below. Additionally, foreland detachment structures are highly influenced by differences in mechanical stratigraphy within the basin which the basement-Mississippian section is dominated by carbonates and the remaining section by sands and shales. Thus the location of the deep fault-propagation fold is determined by inflections in dip of the basement surface which acts as a ramp. In turn, the deep fault-propagation folds in the carbonate section serves as a ramp for the shallow fold in the Pennsylvanian section detached in the Springer shales. Foreland detachment structures form some of the most economically important exploration opportunities in southern Oklahoma. Advances in 3-D seismic imaging are showing that even "a mature" foreland detachment structures (e.g. Carter-Knox Anticline) may be more complex and compartmentalized than previously thought, providing economic opportunities.

Chapter 8

VARIATIONS IN STRUCTURAL STYLE ALONG THE ARBUCKLE AND WICHITA MOUNTAIN FRONTS

Introduction

Dramatic variations in structural style occur along the Wichita and Arbuckle Mountain Fronts with successive position of cross sections. Overall structural style at any given location is controlled by the amount of folding which the basement underwent, prior to faulting, and the geometry of the uplift-bounding fault(s). Lateral variations in structural style may be either gradual, or abrupt. Abrupt changes often occur across transverse compartmental faults. Mechanisms which allow for gradual variations in structural style include variations in magnitude of folding during early stages of fold-thrust deformation, lateral changes in displacement along thrusts, lateral fault-to-fold interchanges, lateral displacement transfer zones including; imbricate thrusting, back-thrusts, and *en echelon* patterns of faults, and gentle lateral ramps. Mechanisms which allow for abrupt lateral variations include steep lateral ramps and compartmental faults. Compartmental faults allow for instant plunge, changes in fault vergence, and facilitate abrupt changes in fold asymmetry. This chapter describes the mechanisms which dictate changes in structural style along the mountain fronts of southern Oklahoma uplifts, and provides examples from the Wichita, Arbuckle, and Tishomingo systems.

Style of Deformation

Knowledge of basement-involved structural styles has greatly increased in the past twenty years. Most knowledge has been derived from the Rocky Mountain

Foreland, the San Andreas System, and to a lesser extent, the southern mid-continent. Part of the confusion in assessing the structural style(s) of basement-involved areas may lay in the diversity of factors within any given province which affect structural style such as basement composition, orientation of pre-existing basement-trends, stratigraphy, amount of shortening, and depth of burial. Within the Rocky Mountain Foreland, dominant models include the fold-thrust model (Berg, 1962: Brown, 1983, 1988), the thrust uplift (or thrust-fold) (Blackstone, 1940; Stone, 1984), and variations of fault-bend folding (Narr, 1993). Recent work of Brown (1988) and Schmidt and others (1993) concluded that structural style needs to be assessed independently for individual structures, and that more than one style of deformation may occur in areas of compressional basement-involved deformation.

The style of deformation of the Southern Oklahoma, and larger Pennsylvanian Foreland has been poorly documented. Typical features include large basement overhangs, growth structures in synorogenic sediments, overturning of footwall synclines and hanging- wall forelimbs, back-thrusts, compartmental basement faults, detachments and parallel folding of the sedimentary sections, and progressive steepening of structure through stacked-cross crestal faults. Many of the intra-basin structures appear to be generated as a consequence of out-of the syncline crowding (Petersen, 1983; Saxon, this volume). Saxon (1997, this volume) has documented the presence of a version of fold-thrust deformation for large portions of the Arbuckle and Wichita Uplifts. The presence of detachments is extremely important in understanding the structural style of southern Oklahoma. The area below a detachment may have a completely different geometry than above, and may mask, or obscure, the lower structure. Most importantly, detached structures are capable of rapid lateral changes in geometry, such as fault-fold interchanges, transfer of displacement between faults, development of subsidiary structures (e.g., rabbit-ear folds, cross-crestal folds), and plunge termination of folds.

Within the pre-Pennsylvanian section, detachments are common in the middle of upper Arbuckle Group and shales of the Simpson Group (especially Oil Creek Shale). Shales of the Springer Group often form prominent, splintered thrusts, especially cross crestal thrusts on deeper folds. Other units which may locally form important, though less extensive, zones of detachment are the Sylvan Shale and the Woodford Formation.

Gradational Lateral Variations in Structural Style

Many portions of the Arbuckle and Wichita Mountain fronts are characterized by variations in structural style which change *gradationally* along strike. Gradational changes may be relatively dramatic, occurring over short lateral distances, or very gradual, occurring over long distances. Structural geometry may grade from one structural model to another, or vary between end-members of a given structural model. If the variation occurs over a short distance, a structural model which may be valid at one location may be in-appropriate, even misleading, when applied to a different location a few miles along strike. Extreme change in style may occur despite an apparently continuous map or subcrop pattern. Segments of the mountain front divided by compartmental faults may exhibit gradational variations in structural style within blocks bounded by basement tear faults.

Structural Style As a Consequence of Variations in Magnitude of Basement Folding

The structural style of basement-cored uplifts may vary as a function of the amount of folding which the basement undergoes, prior to faulting. The development of detachment structures in the sedimentary section is controlled by the creation of basement-involved synclines; therefore the amount of folding the basement undergoes (creating the forelimb syncline) will have a significant impact on the structural style(s) of the detachment structures and mountain front geometry. As a result, geometry of the mountain flank may vary laterally as a consequence of lateral changes in the amount of folding in the early stages of fold-thrust deformation.

This study identifies two dominant end-member styles of basement deformation in southern Oklahoma, which have been observed in combined outcrop-well log cross sections and in seismic surveys. These end-member styles are designated Mode I and Mode II. The two structural styles vary as a consequence of the magnitude of early basement folding. Mode I and Mode II styles generally correspond to the fold-thrust and thrust uplift (Berg, 1962) models respectively. However, each can be modified by fault-bend folding. Most areas along the Wichita and Arbuckle Mountain Fronts probably contain a mixture of characteristics of both Mode I and Mode II deformation.

Mode I Deformation. Mode I style generally corresponds to the fold-thrust model of basement deformation (Berg, 1962). In the Mode I model (Fig. 8.1), the basement is able to accommodate a significant amount of folding prior to faulting. Both the asymmetric basement-cored anticline and its forelimb-syncline are tightly folded, with the steep forelimb dipping vertical to overturned. The intense folding of the forelimb syncline generates out-of-the-synclines crowd structures along detachments which verge up both the steep and shallow flanks of the syncline. The uplift-bounding fault may have a "sled-runner" shape which shallows with depth. Translation of the hanging wall up the steepening curvature of the fault plane may induce back-shear up the steep flank, reactivating the rabbit-ear structures along existing detachments. The tight fold and moderate angle of the mountain-flank fault produce an uplift with a relatively high ratio of vertical uplift to horizontal displacement. The result is a mountain front which is often quite narrow in map-width. Deep erosion of the hanging wall is typical. Often the hanging wall is eroded to the basement, in which case the portion of the mountain front available for hydrocarbon exploration consists of the complexly deformed footwall syncline. These areas are extremely

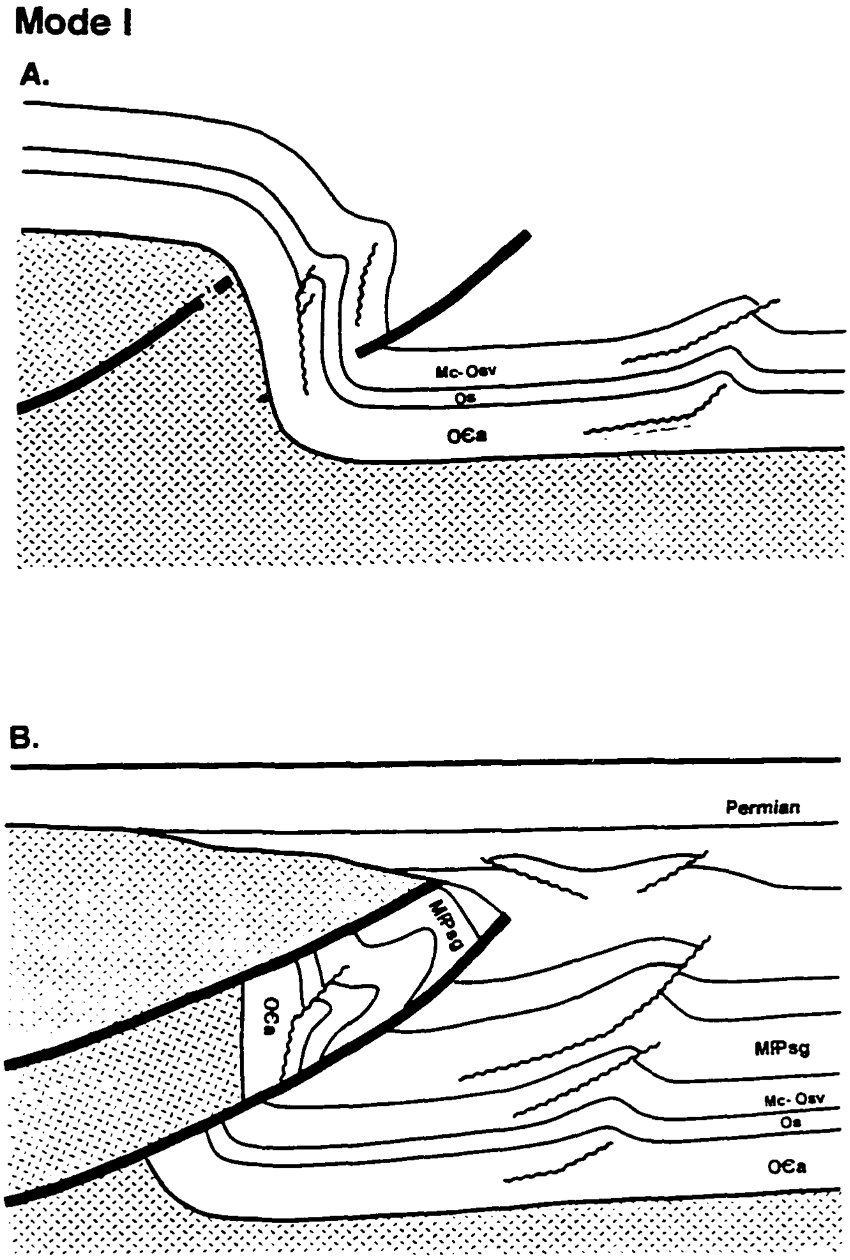


Figure 8.1 Sequential development of a Mode I model of mountain-front deformation. Mode I deformation is a fold-thrust style of deformation (Berg, 1962). A. Initial deformation involves a substantial amount of basement folding. B. In the final stage of deformation, the mountain-flank contains a tightly folded footwall syncline. Rabbit-ear folds, and other syncline volumetric crowd structures, are often found in areas of the mountain-flank which fit Mode I deformation.

difficult to image seismicly because of the steep dip, vertical limbs, complex crowd structures, and deep level of erosion.

Mode II Deformation Mode II style of deformation shows characteristics of thrust uplifts, fold-thrusts, and, at times, fault-bend folding. Ultimately this style is most closely modeled as a thrust uplift. Mode II style of deformation (Fig. 8.2) are formed when the basement accommodates a relatively small amount of shortening through folding prior to faulting. The gentle folding of the basement results in a relatively open forelimb syncline. The relatively open syncline does not fold enough to generate as many, or as complex, syncline crowd structures, as in the Mode I style. The primary basement fault ramps up through the upper basement and, near the syncline hinge, enters the Arbuckle Group where it shallows, forming a relatively low-angle ramp, or flat. Often the fault continues at a low angle within the Simpson Group and cuts up more steeply within the upper pre-Pennsylvanian carbonates. The effect is to create a bend in the fault which, upon translation of the hanging wall, forms a fault-bend fold that modifies the already partially folded hanging wall. Small basement back-thrusts are common to this style of deformation. In map view, portions of the mountain front deformed in a Mode II style are typically much wider than in areas deformed by Mode I style. The major mountain-flank thrust contains a long basement overhang which, due to its relatively low-angle of fault, obtains a lesser degree of elevation, and may be less deeply eroded. Sedimentary rocks of the Arbuckle Group or higher may be preserved. The broad, arching shape of the hanging wall may create conditions suitable for the formation of erosional strike-valleys and the preservation of complex "toes" near the lip of the hanging wall.

Mode II style of deformation closely resembles that created by a pure fault-bend fold geometry. However, there are two reasons why I believe that early folding of the basement took place prior to modification by fault-bend-folding. The first argument involves back thrusting. In a pure fault-bend fold model, the ramp anticline would be

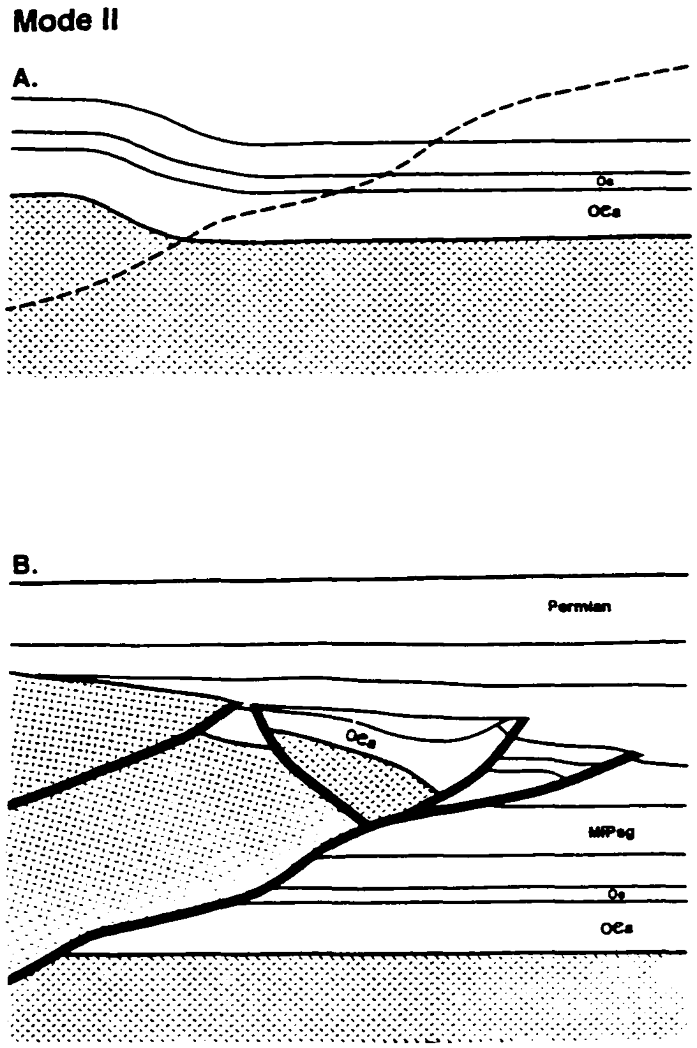


Figure 8.2 Schematic sequential development of an idealized Mode II structure. A. The basement accommodates only a small amount of folding, creating a relatively open forelimb syncline. The future trace of the uplift-bounding fault has a moderate dip in the basement and shallows in the sedimentary cover. Note that in this model the basement is folded generating potential room problems which may be resolved as basement-back-thrusts. B. Translation of the hanging wall along the fault modifies the original fold-thrust by fault-bend folding. Note the long flats with the sedimentary section. The low nature of the fault results in long low overhangs.

entirely generated as the result of translation of the hanging wall. In this case, the folding of the basement surface of the would be passive, and generate outer-beam extension (Fig. 8.3). However, in many instances, the Mode II model is associated with basement back-thrusts. Back-thrusts are generated in fault-bend folds by back-shear at the inflection point where a low-angle fault steepens (flat-to-ramp transition). However, in a Mode II model, the fault plane is steeper in the basement and flattens in the sedimentary section, forming a ramp-to-flat transition. If the basement were folded in early stages of deformation, the back thrusts could be generated by out-of-the-syncline crowding. The second reason is that, in at least one instance, the transition from mode I to mode II can be shown to take place laterally, without compartmentalization to differentiate areas of differing style. Thus Mode I and Mode II styles must be able to blend into each other laterally.

Examples from the Wichita Uplift. Cross section A-A' (Fig. 8.4), located in the Western Wichita Segment, displays most of the characteristics of a Mode I style of deformation. The hanging wall is deeply eroded. The mountain front consists of basement overhanging a tight, faulted forelimb footwall syncline. The mountain front has a narrow width in map view. The steep flank and deformed footwall syncline is the only preserved portion of the mountain front. The several wells which have drilled through the basement overhang encountered an overturned limb which contains a complex rabbit-ear fold detached in the Arbuckle Group. Well control shows detachments at several stratigraphic horizons and tight folding of the rabbit-ear structure. The rabbit-ear, which is cut, and over-ridden, by the main mountain-flank fault, formed prior the development of the main mountain-flank fault as a result of tight, early crowding of the forelimb syncline.

Seismic line 4 (Fig. 8.5), also located along the Western Wichita Segment, displays most of the characteristics typical of Mode II deformation. The mountain front is broad in map view. The main mountain-flank (Meers) fault dips to the southwest at

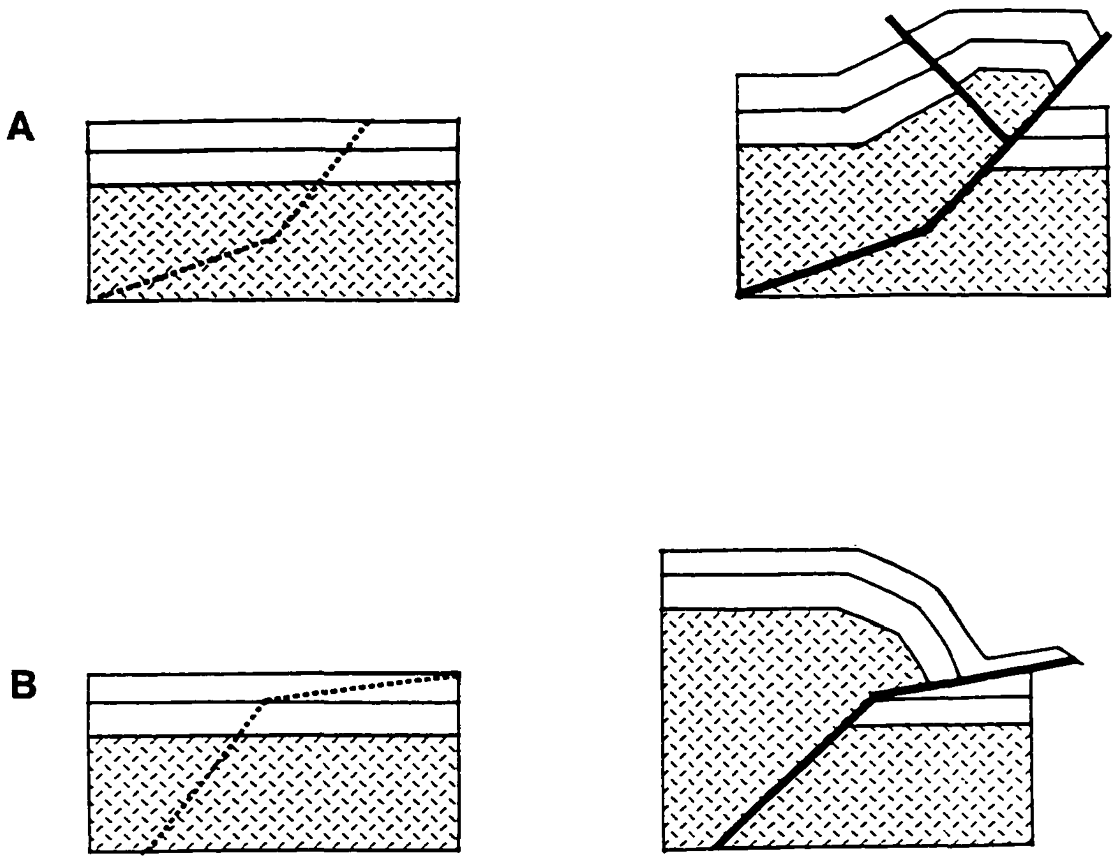


Figure 8.3. Schematic models of different basement uplifts caused by fault-bend folding over faults with differing geometries. A. The fault forms a ramp-to-flat transition. The hanging wall produces a ramp anticline. Extension occurs on the outer arc of the fold as it rotes through the hinge. B. The fault makes a flat-to-ramp transition. The hanging wall anticline develops back-thrusting at the inflection point in fault dip and the resulting uplift is a pop-up block.

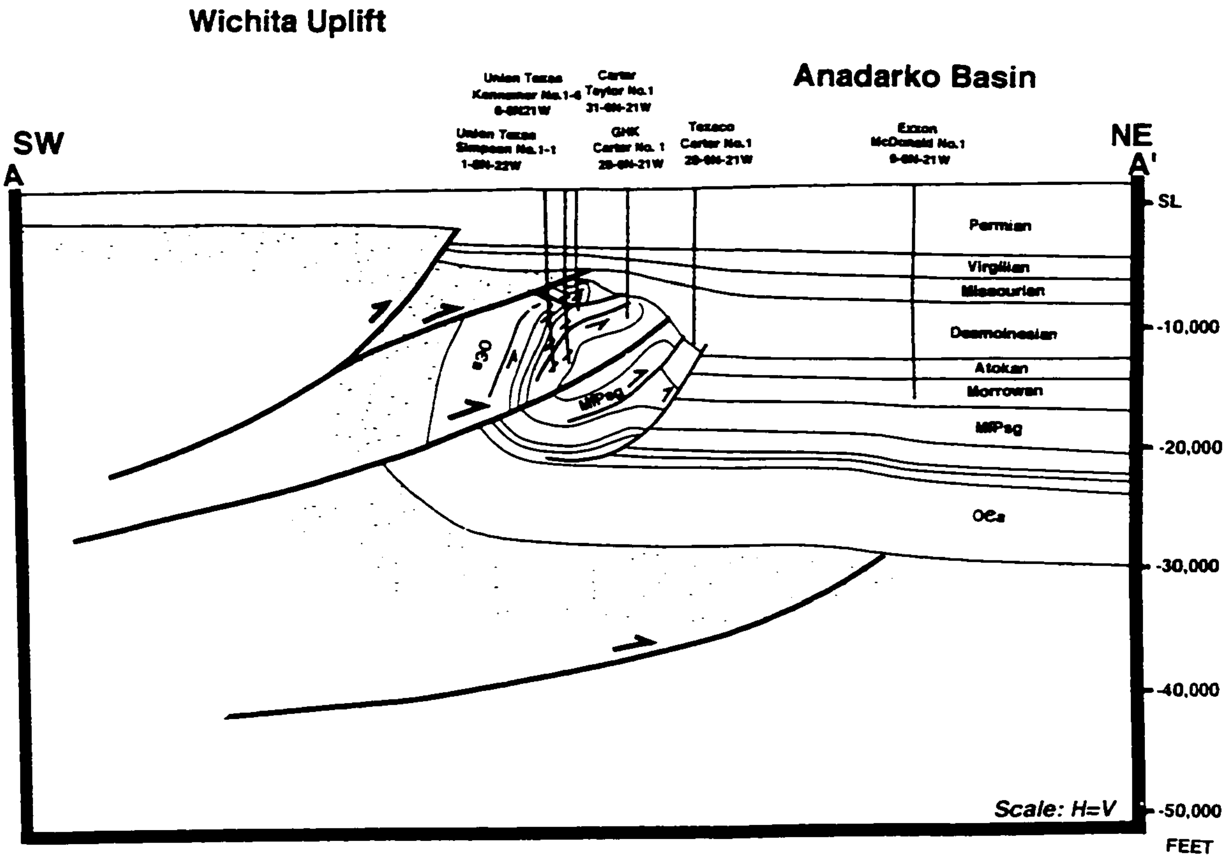


Figure 8.4. Cross section A-A' in the Western Wichita Segment exhibiting a Mode I style of mountain-flank deformation. Three well penetrate a basement overhang along a thrust with shallow southwest-dip. The complex footwall syncline contains a rabbit-ear fold on the intermediate block.

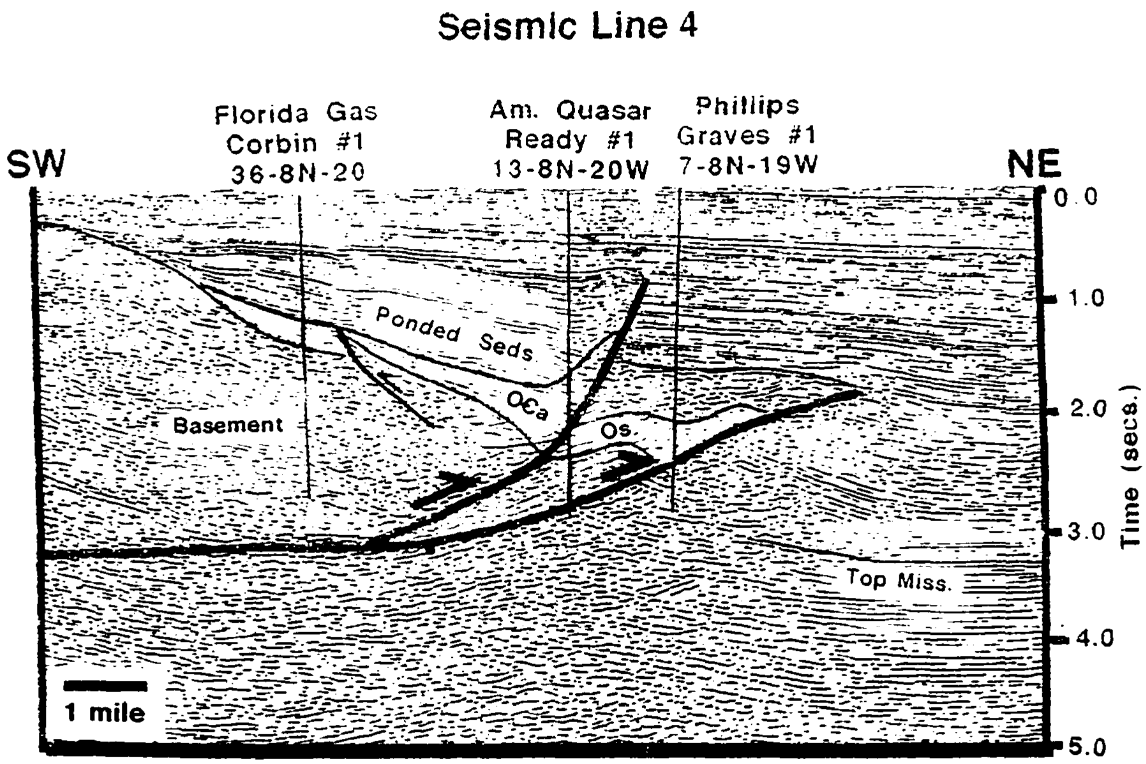


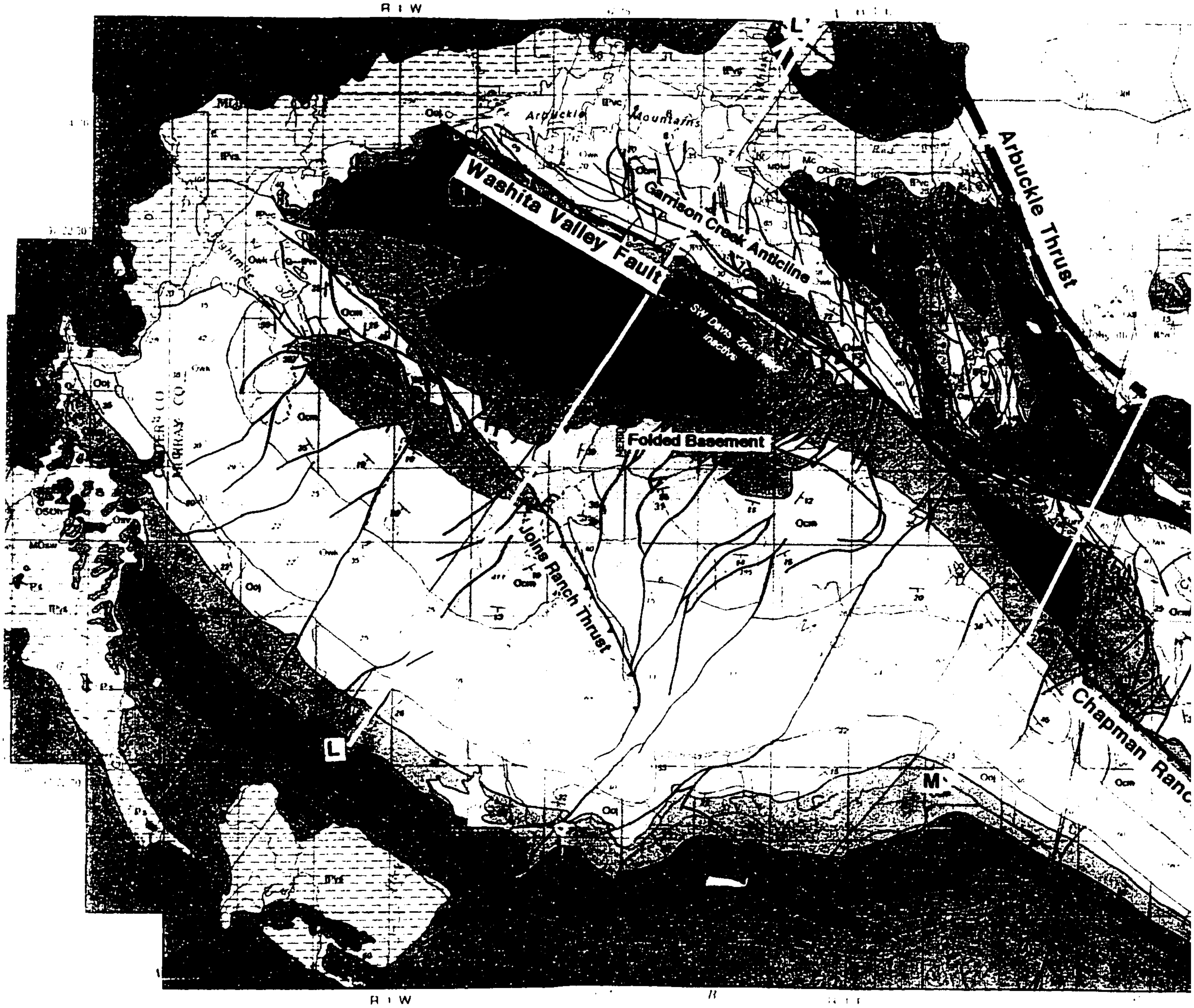
Figure 8.5 Seismic line 4 located along the Western Wichita Segment. The mountain front is deformed in a Mode II style. Note the long flat in the Arbuckle Group in the hanging wall. This flat must restore to a flat in the footwall. The mountain front is eroded only to the level of the Arbuckle Group because the shallow dip of the mountain-flank fault (seismic coutersy of SEI).

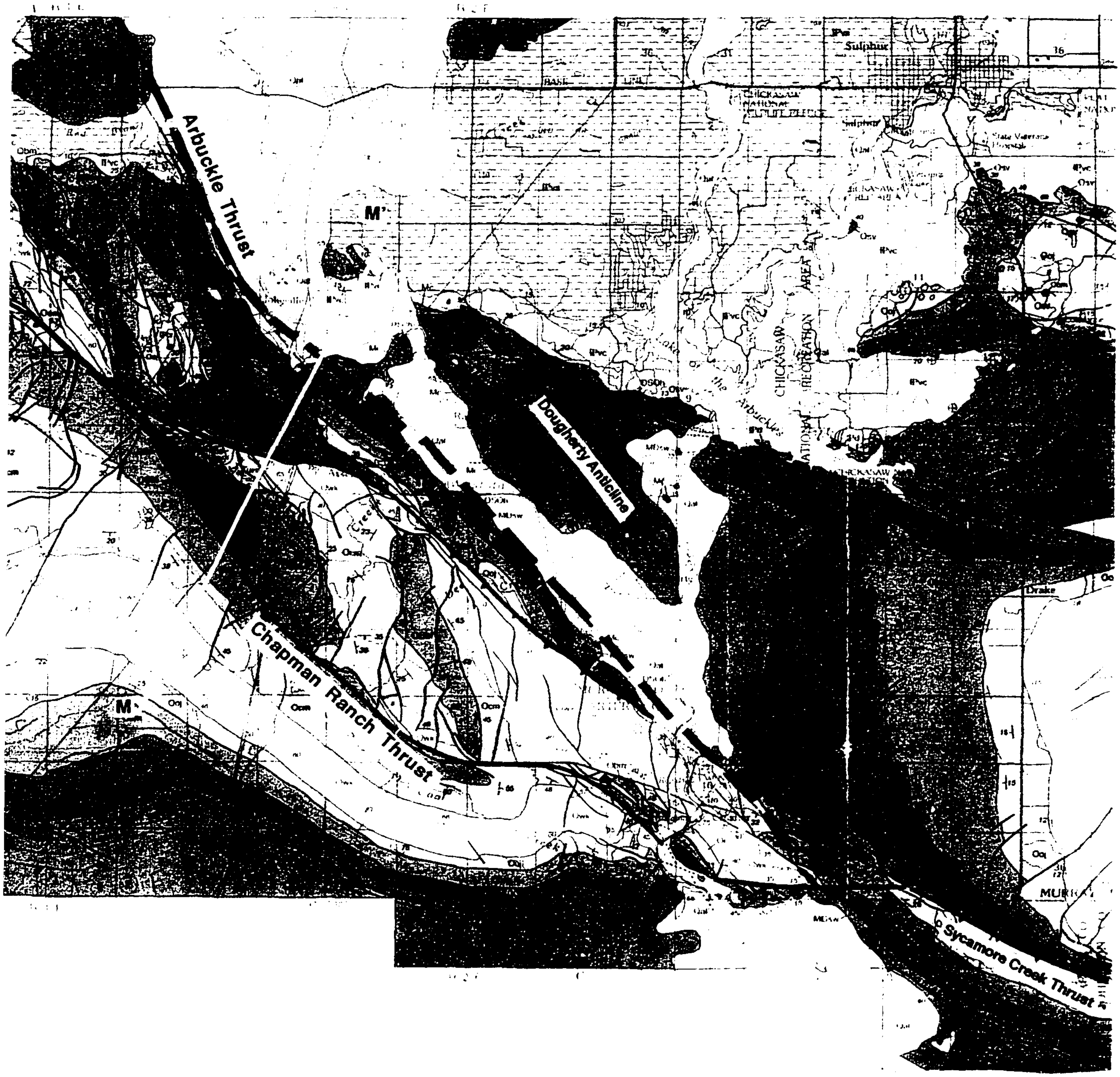
a shallow angle and contains a long flat in the Arbuckle Group on the frontal imbricate (A). The hanging wall flat in the Arbuckle Group must restore to a flat in the Arbuckle Group on the footwall. A back-limb imbricate (B) carries the basement over the frontal imbricate. The basement block contains a back-thrust. The hanging wall has been carried far over the Anadarko Basin along a shallow fault. As a result of the low fault dip, the hanging wall has not been raised as structurally high as other portions of the Wichita Uplift, and has only been eroded to the Arbuckle Group. Erosion proceeded from the core of the uplift towards the north, ponding against an erosional "toe" near the frontal imbricates, forming a "piggy-back" basin.

Examples from the Arbuckle Uplift. The area between the SE Hoover region in the central "bulge" of the Arbuckle Uplift and Interstate 35 (Fig. 8.6) provides an excellent example of *gradational* lateral changes in structural style dictated by variations in magnitude of basement folding. The gradational nature is shown in map pattern and cross sections. Near the vicinity of SE Hoover Field, near its central portion, the Arbuckle Mountain Front contains three major imbricate faults: 1) the buried Arbuckle Thrust, which forms the leading edge of the Arbuckle Uplift. 2) the Garrison Creek Fault. 3) the Washita Valley Fault. The SE Hoover sheet is the hanging wall of the Arbuckle Thrust and consists of tight detachments and rabbit-ear anticlines. Well data shows that, on the SE Hoover sheet, the Arbuckle Thrust forms a flat in the upper Arbuckle Group carbonates and is not basement-involved. Fig. 8.7 is a cross section located on the central portion of the Arbuckle Uplift which illustrates these structural relationships. At this location, the Arbuckle Uplift shows many characteristics of Mode II deformation.

Moving from cross section L-L' southeast, toward cross section M-M' (Fig. 8.8), the mountain front between the Arbuckle Thrust and Washita Valley Fault narrows and shows the following changes in map pattern and structural geometry: 1) the trace of the Garrison Creek Fault merges with the trace of the Washita Valley Fault,

Figure 8.6 Geologic map of the Arbuckle Uplift. Note continuous outcrop pattern between cross sections L-L' and M-M'. No visible compartmental, or tear fault exists between the two lines of cross section. However, the mountain front does become more narrow toward M-M' and the dip steepens to overturned, indicating a change in structural style (modified from Johnson, 1990)


Washita Valley Fault
Garrison Creek Anticline
Arbuckle Thrust
SW Davis Zinc
inactive
Folded Basement
Joins Ranch Thrust
Chapman Ranc
L
L'
M
Arbuckle Mountains


Arbuckle Thrust
M'
Dougherty Anticline
Chapman Ranch Thrust
M
Sycamore Creek Thrust
Sulphur
CHICKASAW NATIONAL RECREATION AREA
Drake

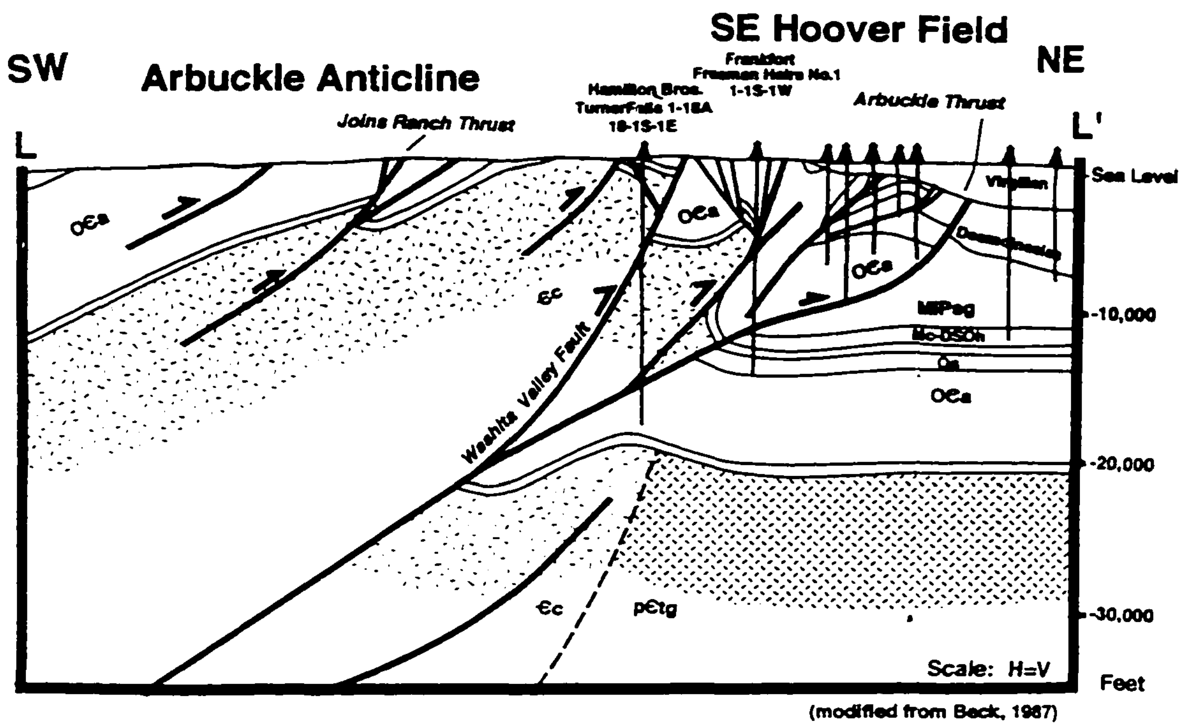


Figure 8.7. Cross section L-L' across the Arbuckle Mountain Front. This section shows a Mode II style of deformation. Note the flat in the Arbuckle Group in the leading imbricate (modified from Beck, 1986).

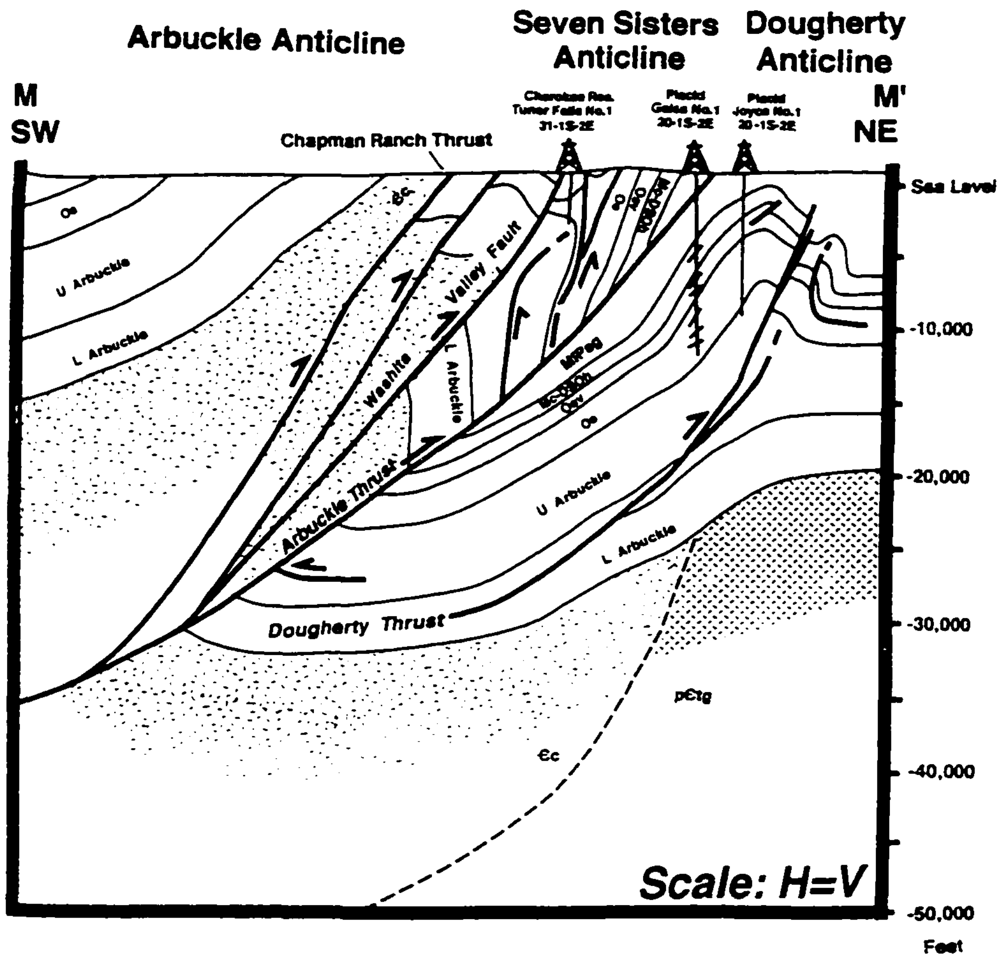


Figure 8.8. Cross section M-M' across the region near Interstate 35 on the Arbuckle Anticline. The style of deformation in this cross section is Mode I. Note the overturned rabbit-ear fold (Seven Sisters Anticline) and tightly folded footwall syncline.

and the Colbert Creek and Lick Creek Anticlines merge and are obscured by the unconformable Collings Ranch Conglomerate, 2) the frontal limb of the Arbuckle Anticline progressively steepens until, near Interstate 35, it becomes overturned and develops rabbit-ear folds (overturned Honey Creek and Seven Sisters Anticlines). Cross Section M-M' (Fig. 8.8) depicts the structural geometry across this region. The Arbuckle Uplift over-rides a narrow, tight forelimb syncline with an overturned steep limb. Out-of-the-syncline crowding has generated the rabbit-ear structures up the steep limb and the Dougherty Anticline out the shallow limb. The through-going basement fault cuts the synclinal hinge with a sled-runner geometry. The structural geometry most closely matches that of a Mode I structural style.

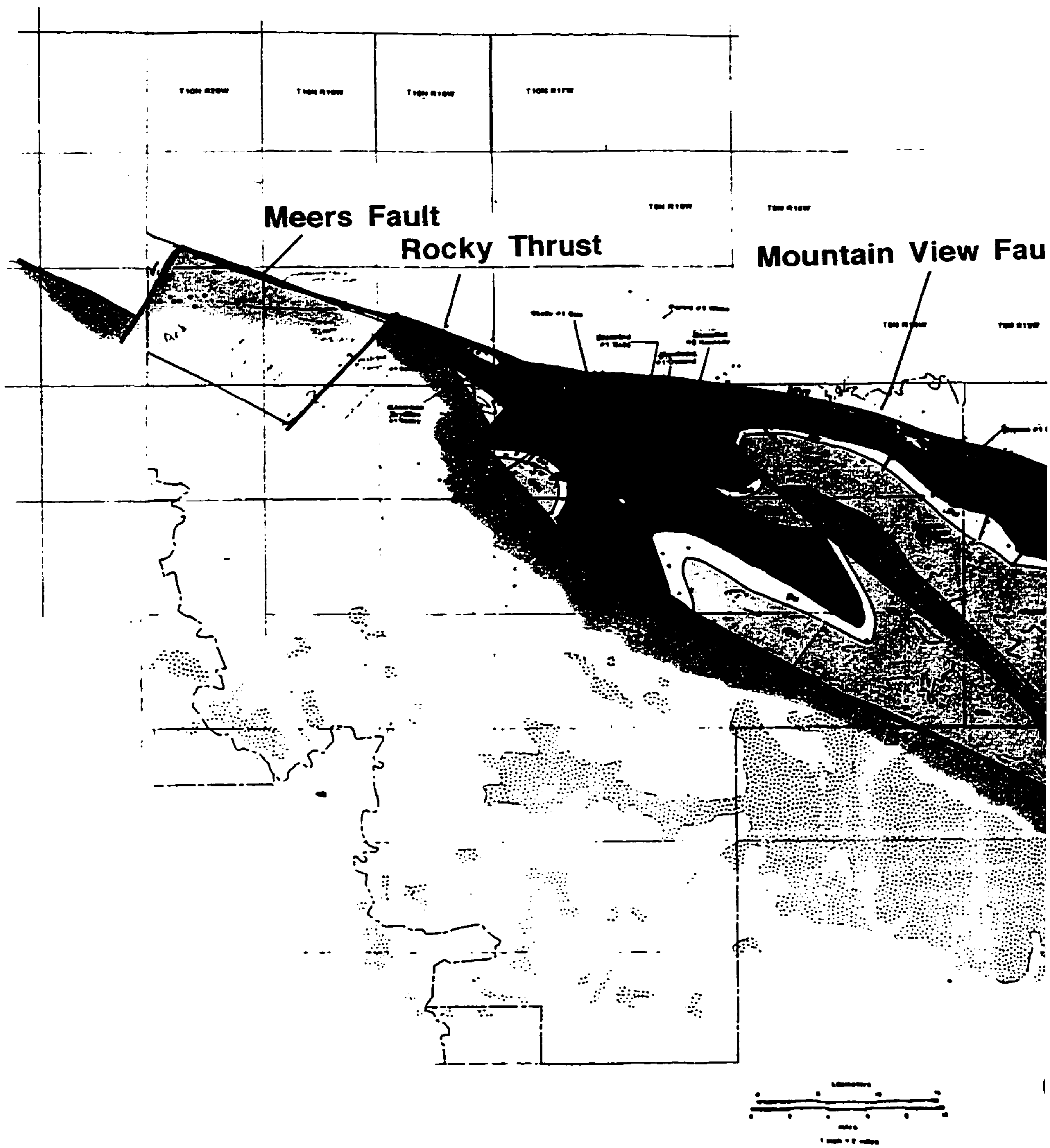
Both cross sections are only a few miles apart, yet contain different structural styles. The map pattern between them is continuous, indicating that the geometrical changes are gradational. Saxon (1994) documented similar gradational changes along the northwest plunge of the Arbuckle Uplift.

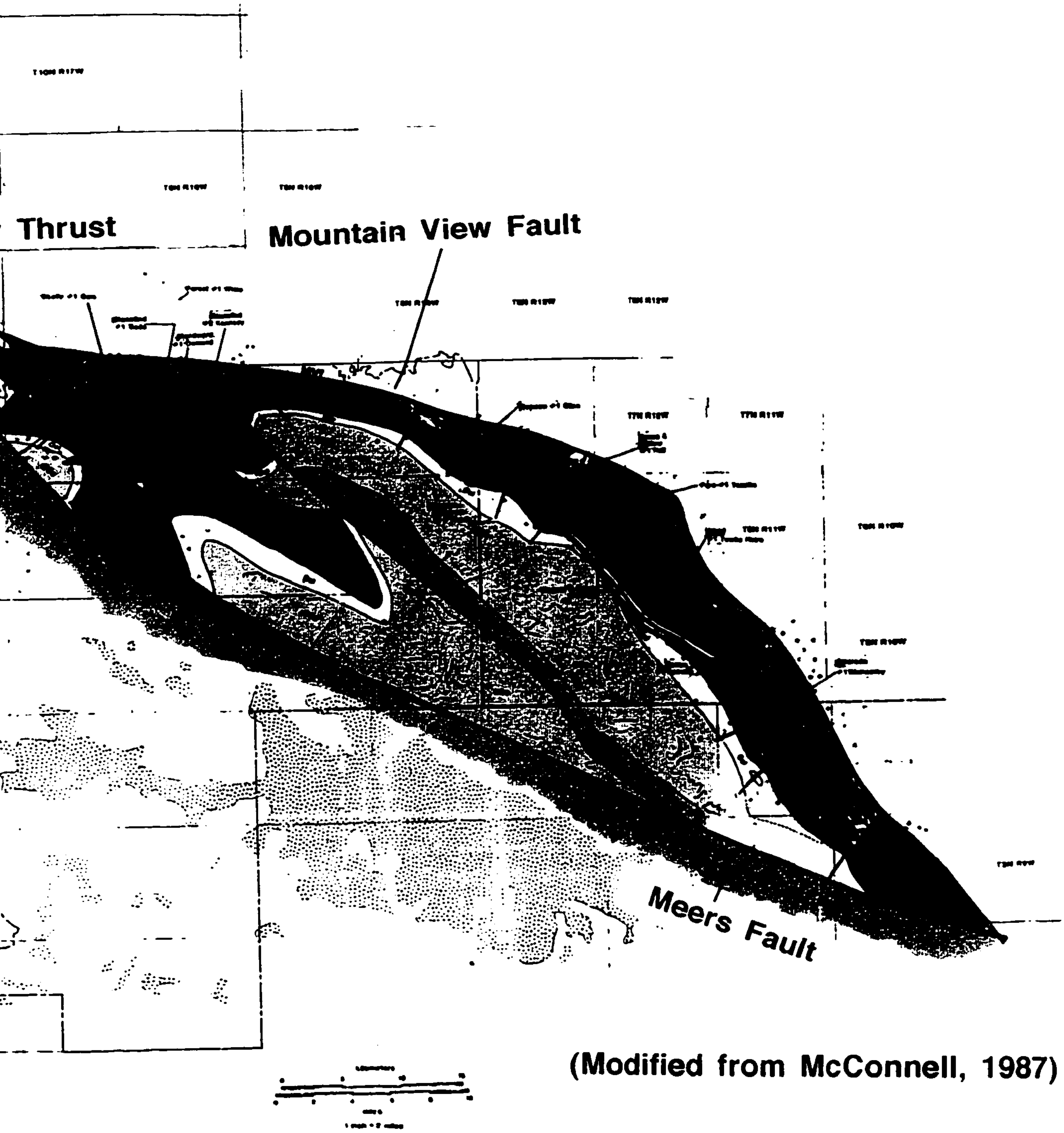
Gradual Loss of Displacement Along Thrust

Individual thrusts do not continue indefinitely, nor do they maintain constant slip. Thrusts commonly lose displacement along strike, often in conjunction with changes in thrust geometry, such as lateral rises or decreases in the level of detachment, local folding of thrusts, and changes in ramp geometry. Depending upon fault geometry, loss of slip can affect the hanging wall geometry. In a situation in which a hanging wall is translated over a ramp, a progressive loss of slip can result in the failure to translate the hanging wall up and over the ramp, causing a progressive change from a fault-bend fold (ramp anticline) to a fault-propagation fold. Loss of slip decreases the amount of thrust overhang and the subthrust area available for exploration. Loss of dip-slip may continue until the fault completely loses slip, often in a fault-fold interchange (fault-propagation fold). Fault-to-fold interchanges are important because they "pin" fault slip at the fault tips and constrain fault motion to dip-slip thrusting. Thrusts are often concave in shape and form a "bow and arrow" outcrop pattern (Elliot, 1976) in which slip decreases from maximum displacement at the center to a null point at the termination of the fault trace. The rate of loss of slip can help determine the rate of plunge of the hanging wall fold.

Examples from the Wichita Uplift. The Mountain View Fault, which is the frontal thrust of the Blue Creek Canyon Block, progressively loses slip to the west, eventually terminating in a fault-fold interchange (Fig. 8.9). Cross section C-C' (Fig. 8.10) is located across the central potion of the Blue Creek Canyon Block. Basement overhang on the Mountain View Fault is confirmed by the Sohio (Wagoner and Brown) Traub #1 well which drilled over 12,000 feet of basement rocks before cutting the Mountain View Fault, then reaching total depth in Ordovician carbonates. Seismic line 7 (Fig. 8.11) is located 14 miles west of cross section C-C'. This line shows a marked decrease in the overhang of the Mountain View Fault. Seismic line 6 (Fig. 8.12) is located 10 miles to the west of seismic line 7. At this location, the Mountain View Fault contains virtually no overhang and has terminated into a fault-propagation fold in the footwall of the Meers Fault. The Blue Creek Canyon Block has plunged into the Anadarko Basin as the Mountain View Fault has lost slip westward. Cross section B-B' (Fig. 8.13) is located adjacent to seismic line 6. This cross section covers Rocky Field, located in a cross-crestal thrust (Rocky Thrust) of the plunging fault-propagation fold of the Blue Creek Canyon Block. Note that the Rocky Thrust is not the leading edge of a basement-involved imbricate. It is located in the footwall of the Meers Fault and should not be mapped as part of the Mountain View Fault. Note the flat in the Simpson Group must restore to a flat in the footwall. In doing so, a minimal cut-off line length in the Arbuckle Group is generated for the hanging wall of the Rocky Thrust. In order to make an admissible cross section which accounts for minimal fault cut-off lengths in the Rocky Thrust (derived from well data) the Blue Creek Canyon

Figure 8.9. Subcrop map of the Wichita Uplift (modified from McConnell, 1987).


Meers Fault
Rocky Thrust
Mountain View Fau



(Modified from McConnell, 1987)

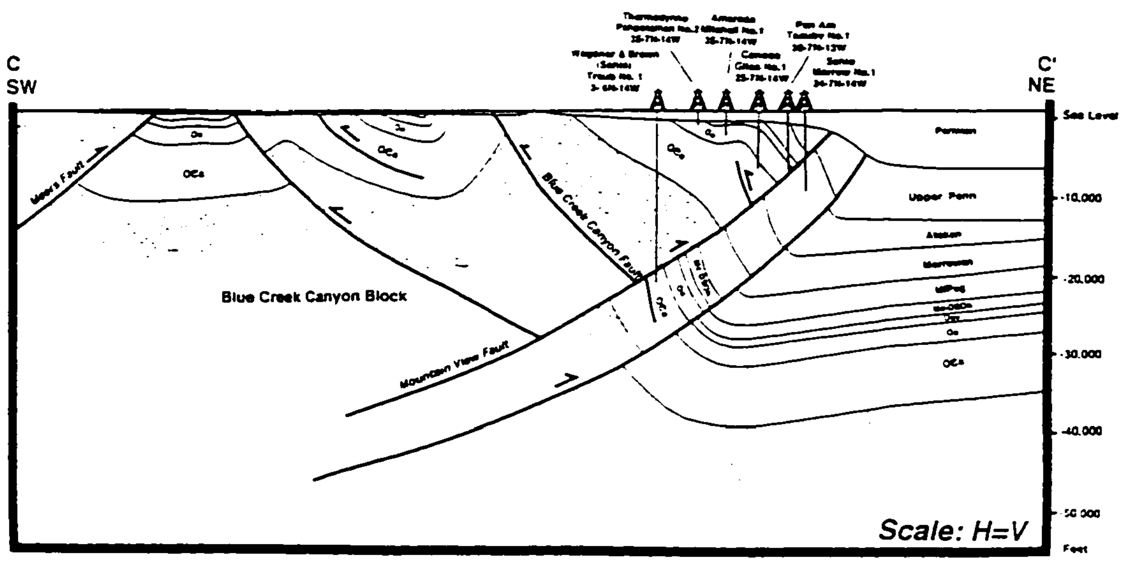


Figure 8.10. Cross section C-C' located across the central portion of the Blue Creek Canyon Block. The Sohio Traub #1 drilled over 12,000 feet of basement rock and established significant overhang on the Mountain View Fault.

Seismic Line 7

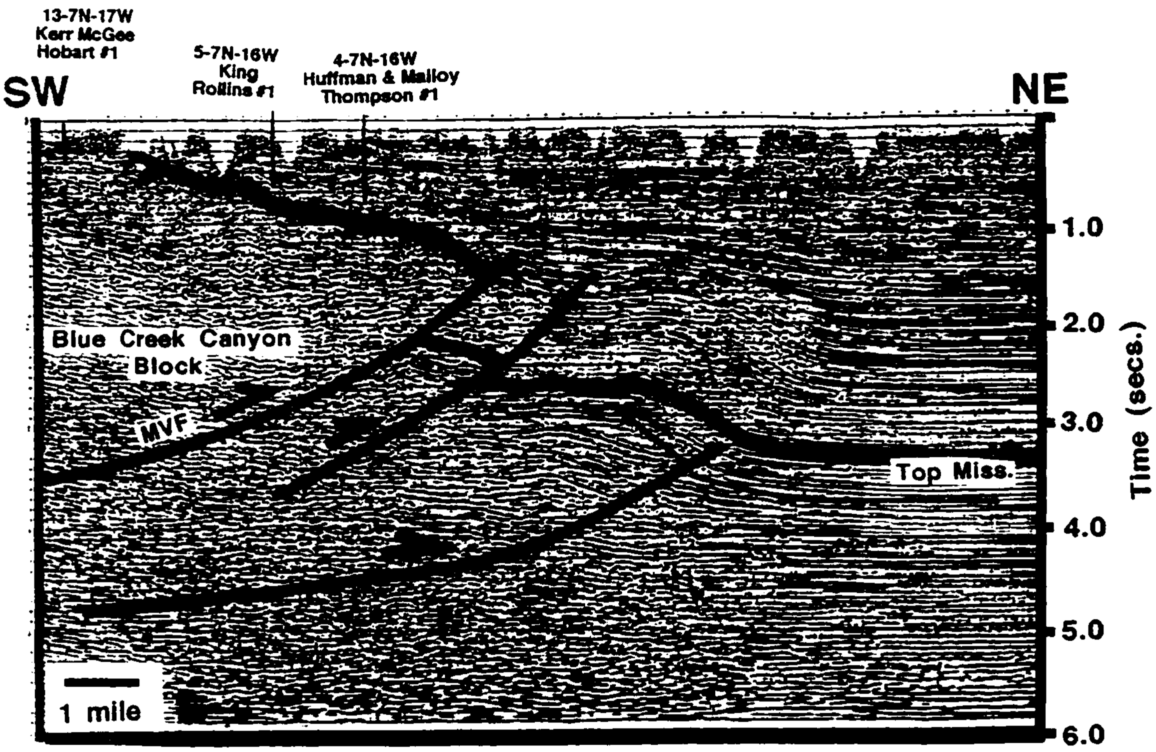


Figure 8.11. Seismic line 7. Note the decrease in slip on the Mountain View Fault from cross section A-A' (seismic courtesy of Vestige).

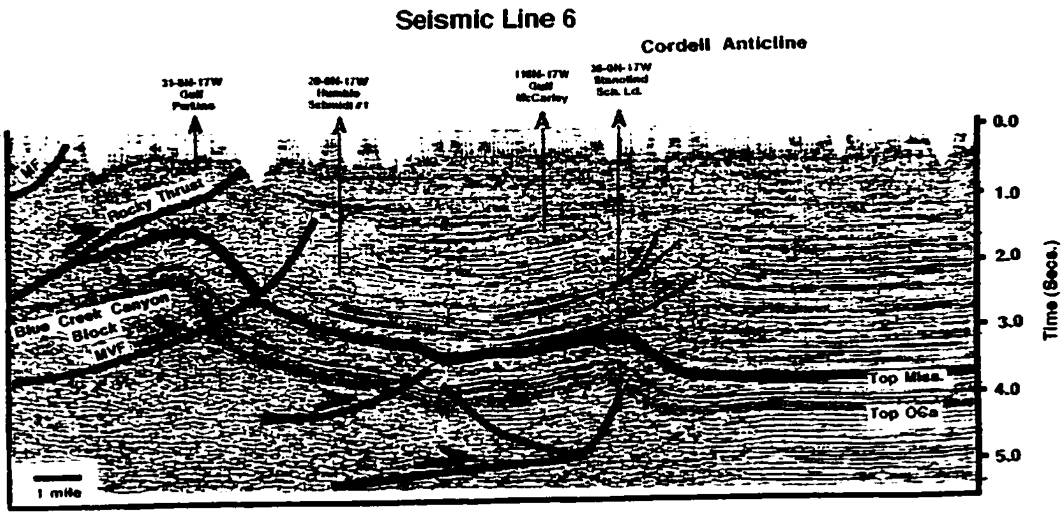


Figure 8.12. Seismic line 6 along the Wichita Mountain Front (Sesimic courtesy of Vestige).

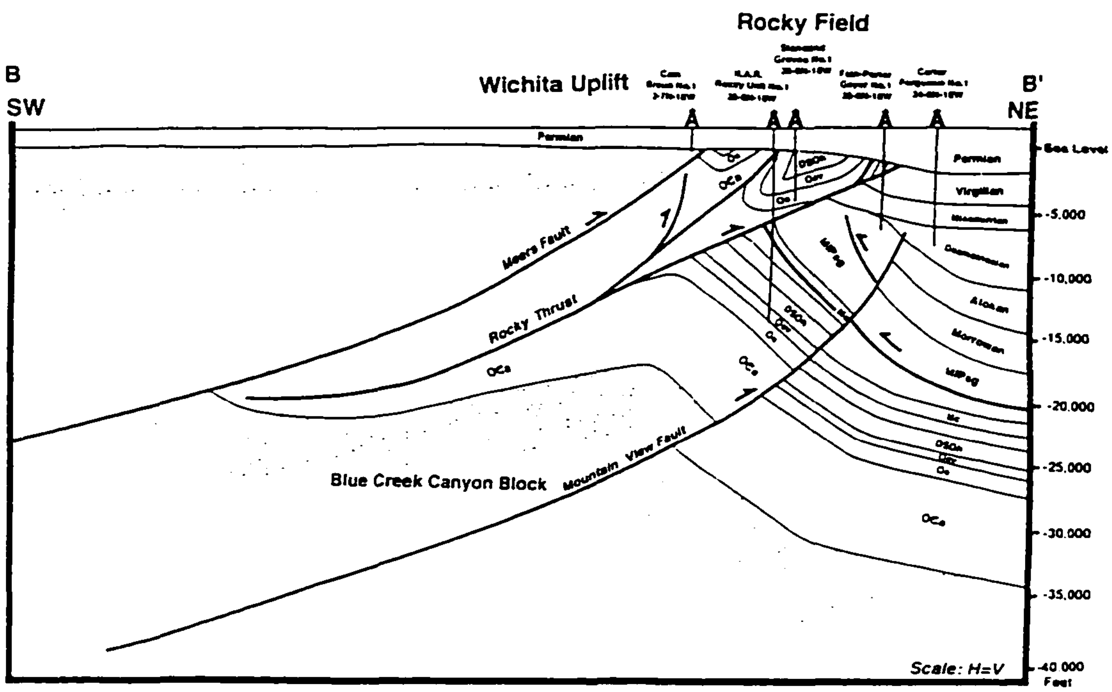


Figure 8.13. Cross section B-B across the Wichita Mountain Front. The Rocky Thrust is a cross-crestal thrust to the plunging Blue Creek Canyon Block, which terminates as a basement-cored fault-propagation fold. Restoration of the cut-offs along the Rocky Thrust controls the interpretation of the southwestward extent of the footwall beneath the overhanging Meers Fault. Note the Rocky Thrust is *not* part of the Mountain View Fault.

Block must extend underneath the basement overhang of the Meers Fault for several miles (30,000 feet or more).

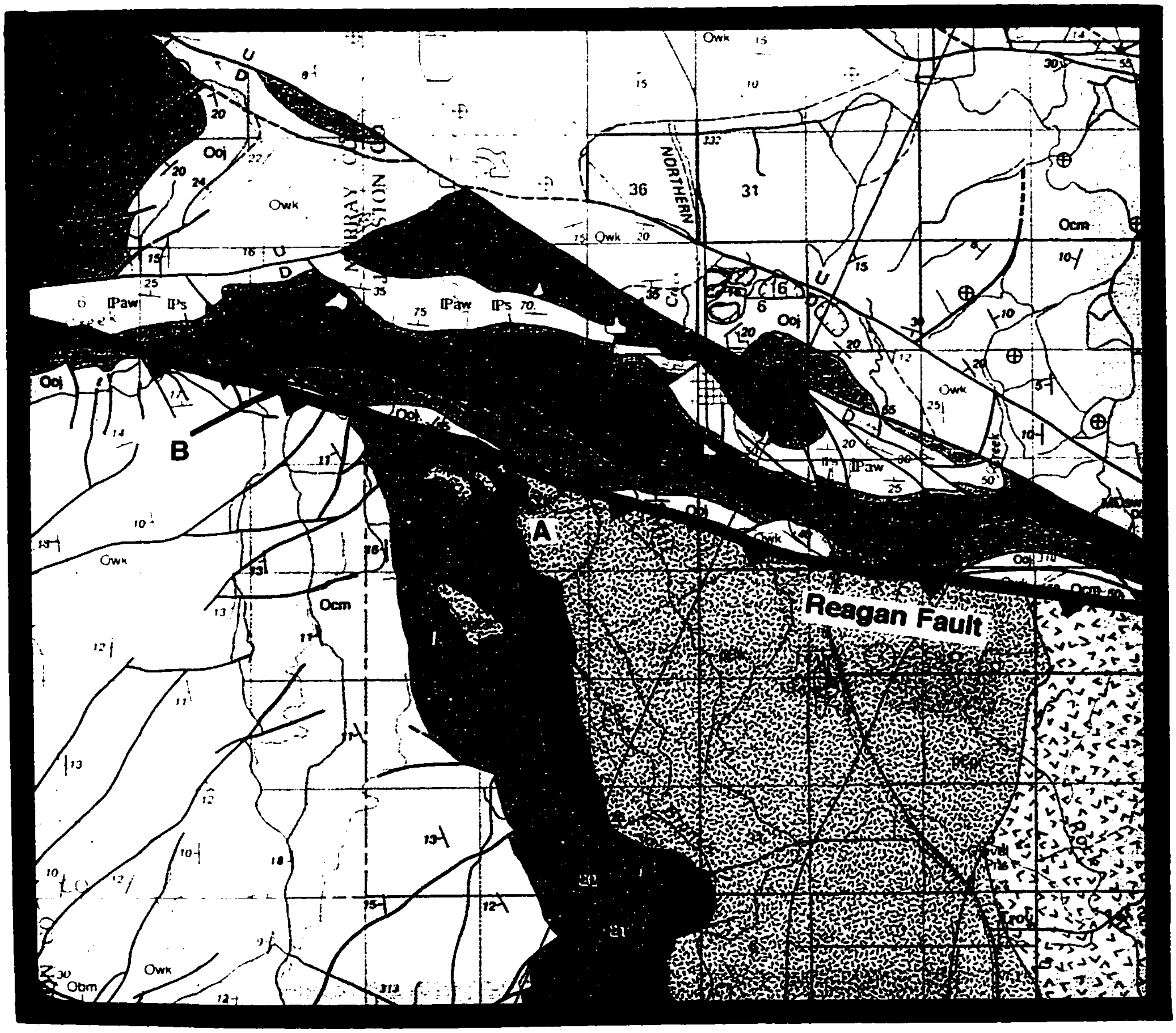
The westward loss of slip on the Mountain View Fault is reflected in the subcrop pattern (Fig. 8.10) of the Blue Creek Canyon Block which shows the distance narrowing between the traces of the Meers and Mountain View Faults and a progressive rise in the stratigraphic level exposed in the subcrop of the Blue Creek Canyon Block.

Examples from the Arbuckle Uplift. The Reagan Fault is the northern border of the Tishomingo Uplift and displays a continuous westward loss of slip (Fig. 8.14) associated with the western plunge of the Tishomingo Uplift. In one three-mile stretch the Reagan Fault loses about 3,000 feet of stratigraphic offset, and goes from placing the basement-sediment contact against the Ordovician Simpson Group, to placing Simpson Group over Caney.

Along its northwest plunge, the Arbuckle Anticline changes structural geometry as the result of progressive loss of northeast-directed slip, the lateral elevation of the depth of detachment of the Arbuckle Thrust, and progressive elevation of the dip of the Arbuckle Thrust (Saxon, 1994). The result is a change in hanging-wall geometry from a fault bend fold near the center of the uplift, to a "snakehead" fault-propagation fold in the Eola region (Fig. 8.15). The change between the western exposed Arbuckle Uplift to the Eola region, reflects a continuous and gradational change from a Mode II to Mode I style of deformation.

Lateral Fault-to-Fold Interchanges

As a reverse fault loses slip, it may terminate in a fold. In cross section view, the fold generated at the fault tip is commonly referred to as a "fault-propagation fold" after the model by Suppe and Medewedeff (1984). Less commonly realized is that faults may die laterally into folds as well. Such a termination is a lateral fault-to-fold interchange (Brown, 1984). Progressive decrease in dip-slip along a ramp may change



(modified from Johnson, 1990)

Figure 8.14. Map view of the Reagan Fault and the Tishomingo Uplift. The Reagan Fault loses slip west as the Tishomingo Uplift plunges to the west (modified from Johnson, 1990).

A

B

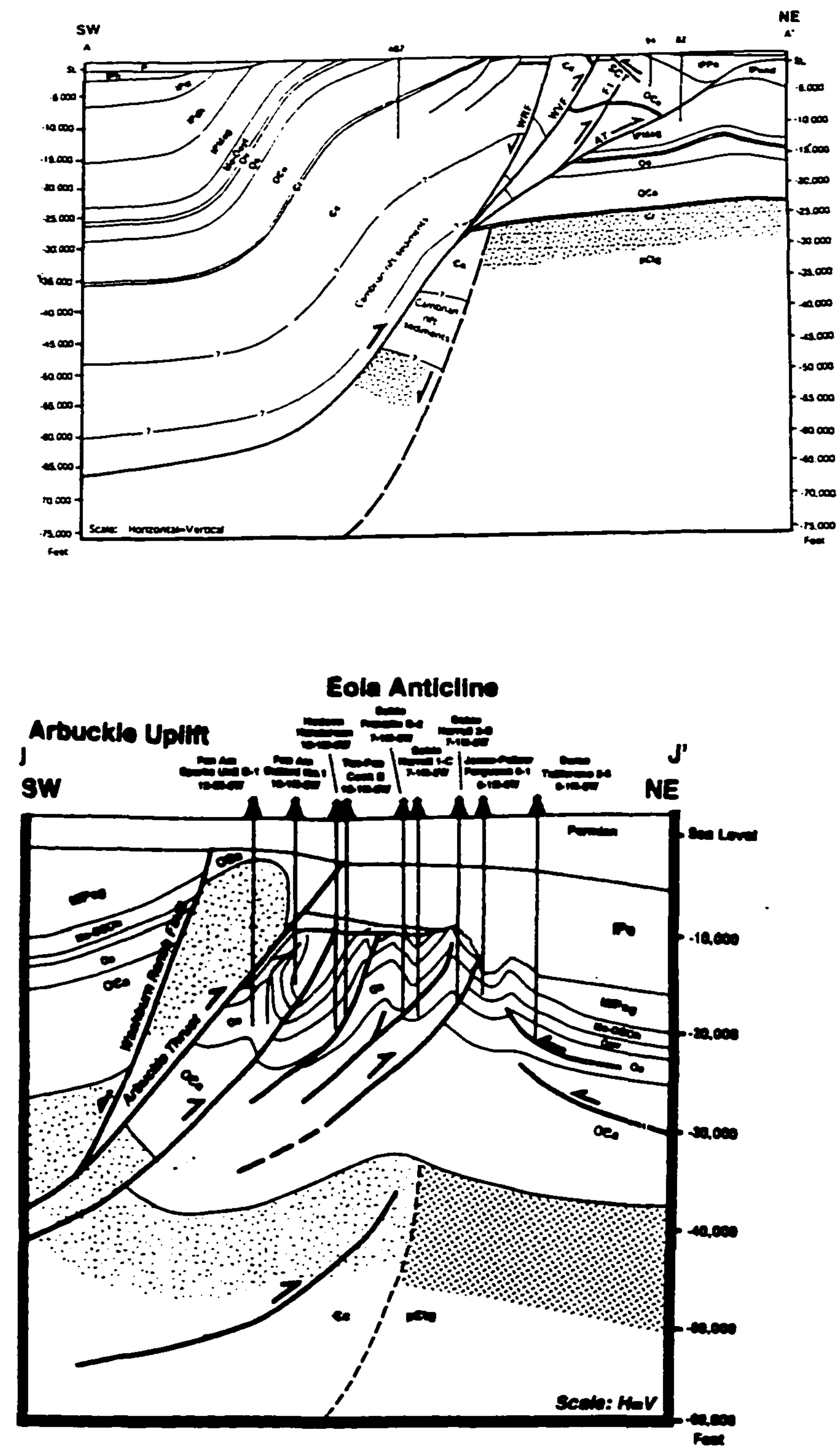


Figure 8.15. A. Cross section across the central Arbuckle Anticline. Note the Mode II style of deformation and the fault-bend fold geometry of the Arbuckle Uplift (modified from Saxon, 1994). B. Cross section J-J' across Eola Field. Note the mode I style of deformation.

fault geometry from a fault-bend fold to a fault-propagation fold as the hanging wall fails to be transported over the ramp. Fault-to-fold interchanges are indicators of dip-slip fault separation. Startiing on a fault and moving towards a fault-fold interchange, dip-slip is progressively lost on the fault and taken up as folding. The fold "pins" the fault at the fault-to-fold interchange, marking a point of zero fault slip.

Examples from the Wichita Uplift. As documented in the previous section, the Mountain View Fault loses slip westward and terminates as a fault-propagation fold. Seismic line 5 (Fig. 8.16), located 7 miles to the west of seismic line 6, (Fig. 8.12) shows the Blue Creek Block plunging-out westward as a footwall fold, to the overriding Meers Fault.

Examples from the Arbuckle Uplift. The southeastern plunge of the Arbuckle Uplift terminates into a plunging fold as dip-slip is lost on the Arbuckle Thrust and it's imbricates. The Chapman Ranch Thrust, a back-limb imbricate of the Arbuckle Thrust, and Joins Ranch Thrust provide excellent map-view examples of faults terminating into a fold (Fig. 8.17). The Chapman Ranch Thrust terminates as a cross-crestal fold. The western plunge of the Tishomingo Uplift ends in the Reagan Fault losing slip and terminating in a fold with progressive cross-crestal detachments (Fig. 8.18).

Zones of Lateral Displacement Transfer

Working in the Canadian Thrust Belt, Dahlstrom (1970) noted that while thrust systems may show continuous shortening, or gradual regional changes in shortening, the individual structures which make up a thrust system show gradual variation at a higher rate than the regional variation of the system. In order to maintain the regional rate of change, individual structures must accomplish a transfer of displacement from one structure to another. Dahlstrom termed these areas "displacement transfer zones".

Seismic Line 5

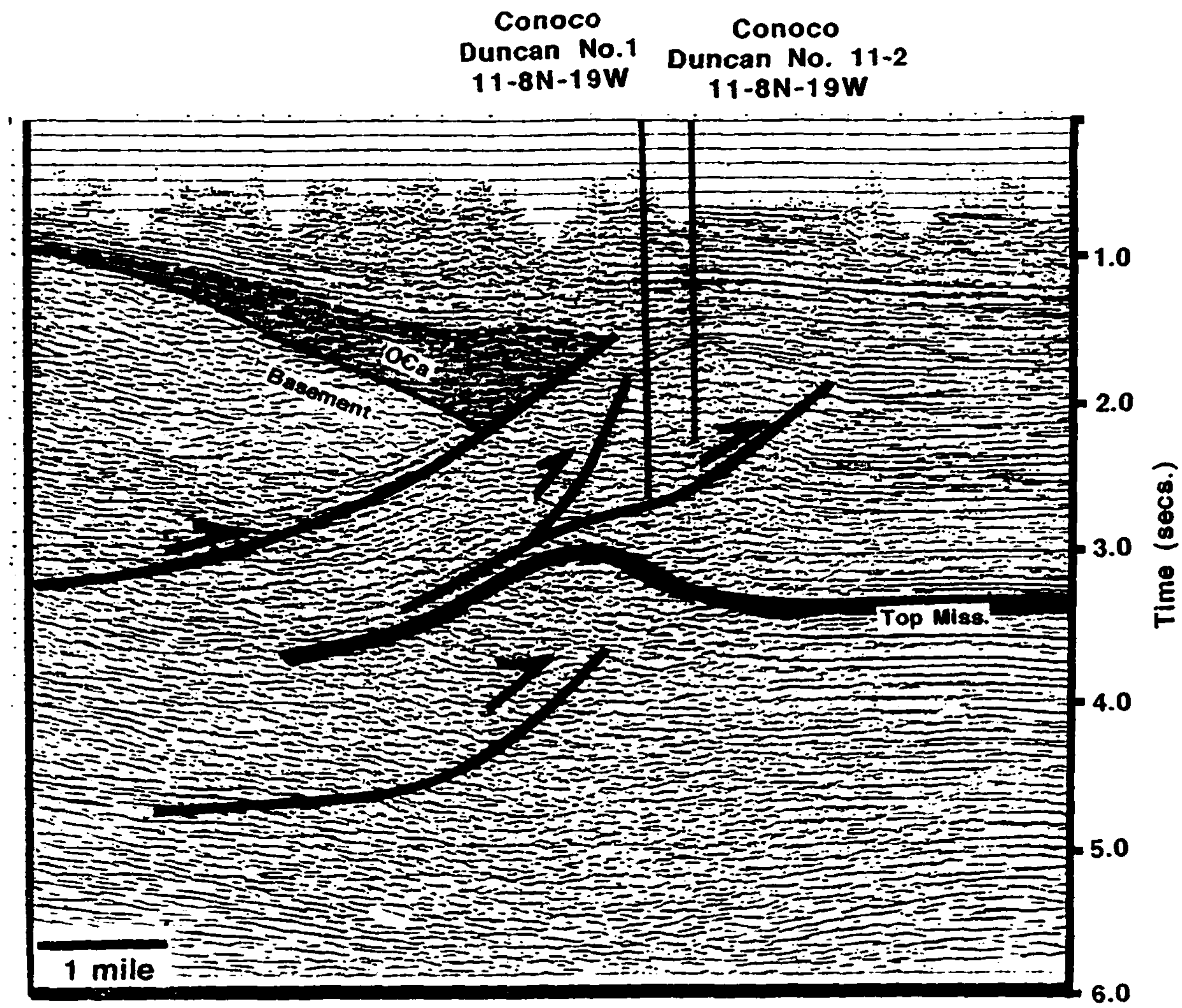
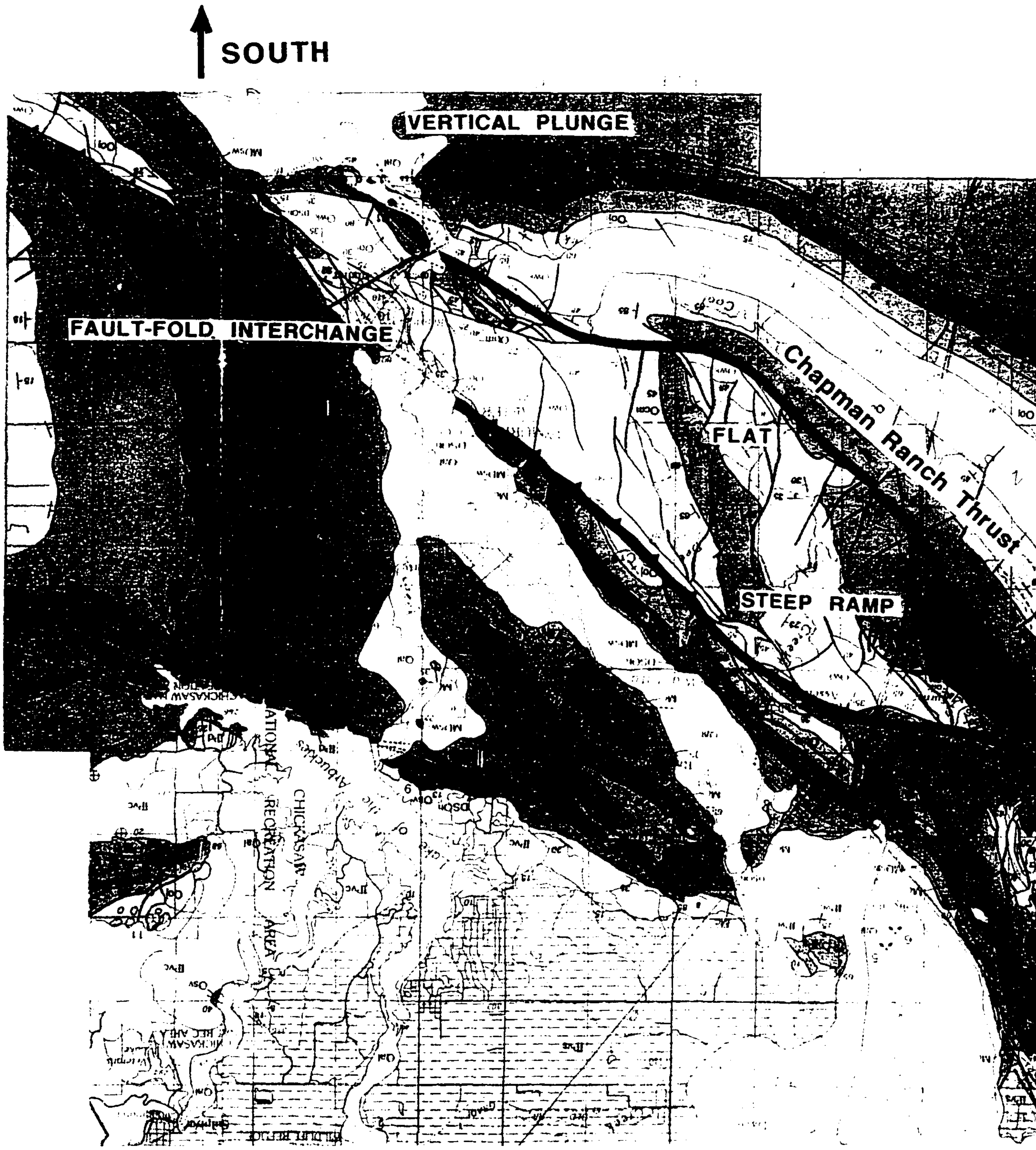


Figure 8.16. Seismic line 5 located in the Western Wichita Segment (seismic courtesy of Vestige).

Figure 8.17. Map view of the southeastern plunge of the Arbuckle Uplift (Johnson, 1990).


SOUTH
VERTICAL PLUNGE
FAULT-FOLD INTERCHANGE
FLAT
STEEP RAMP
Chapman Ranch Thrust


VERTICAL PLUNGE
Chapman Ranch Thrust
FLAT
STEEP RAMP
GENTLE RAMP
MOUNTAIN
SW Dens Zinc Field
Inactive

Figure 8.18. Foreshortened plunge-projection of the western plunge of the Tishomingo Uplift. The Reagan Fault terminates in a fold as the result of the progressive westward loss of dip-slip. Shortening is taken up by cross crestal detachments (modified from map by Johnson, 1990).

Dahlstrom's observation were made in a thin-skinned fold and thrust belt, where fault systems are linked by a common regional detachment. In southern Oklahoma, individual major thrusts, such as the Arbuckle Thrust, are large-scale basement-involved detachments which contain imbricates and internal variation. Although it is not certain whether large basement uplifts are directly linked by a regional basement detachment, the concept is supported by the similarities from the Thrust Belt. Nonetheless, the concept of displacement ending on one system and picking up on another such that their is overlap is applicable to southern Oklahoma. When systems verge in a common regional direction (such as in a fold-belt), displacement transfer zone produce an *en echelon* arrangement of fold patterns. In southern Oklahoma, structures show a predominant northeast vergence. However, occasionally significant southwest verging systems develop, usually as back-thrusts.

Imbricate Thrusts Shortening along a major detachment may be distributed between multiple imbricate faults which splay off the master detachment. Along strike, imbricate splays may merge with other imbricates, or with the master fault. Entire thrust slices, or sheets, may "disappear" laterally as their foreword bounding imbricate dies out. In thin-skinned thrusting, imbricates commonly break foreword, so that the order of development is for younger faults to develop in the footwall of the older fault. This sequence is not always observed and sometimes the opposite relationship occurs (Dahlstrom, 1970).

Examples from the Arbuckle Uplift. Many examples of imbricate thrusting exist in the Arbuckle Mountain Front (Fig. 8.6). The Garrison Creek Fault merges with the Washita Valley System to the east and disappears. The most famous imbricate fault is the Washita Valley Fault which is a back-limb imbricate to the buried Arbuckle Thrust (Brown, 1984; Beck, 1987; Saxon, 1994). The Washita Valley Fault itself may be several faults which are an imbricate system. Along the southeastern

Arbuckle Anticline, the Chapman Ranch Thrust splays off the Washita Valley Fault as an imbricate.

Back-Thrusts. Back-thrusts are reverse faults which verge in the opposite direction as the main thrust. Back-thrusts are conjugate shears to the main fault and often root into a detachment at the flat-to-ramp interchange. Back-shear then activates the conjugate which may subsequently be transported up the ramp. Back thrusts may act as transfer displacement features, accommodating shortening that is being lost on the main thrust tip. These features create structures which verge the opposite direction of general transport and vergence.

Example from the Wichita Mountain Front. Back-thrusts are common in the Wichita Uplift. The Burch Fault (Fig. 1.4) imaged in the COCORP seismic shoot is probably a large back-thrust to the Wichita System. Another prominent example is the exposed Blue Creek Canyon Fault in the Slick Hills which is the back-thrust to the Mountain View Fault. In the Criner Hills, the Joiner City Thrust is a south-directed back-thrust of the northeast-verging Criner Hills Fault.

Examples from the Arbuckle Uplift. Back-thrusts occur on the south and southeastern flank of the Arbuckle Uplift. As the Arbuckle Uplift plunges to the southeast, it loses slip on the Arbuckle, Washita Valley, and Chapman Ranch Thrusts. A line of back-thrusting is developed from behind the central portion of the Arbuckle Anticline near Woodford, OK, and continues to the southeast, supporting Springer Field and forming the Caddo Anticline (Fig. 8.19). The line of back-thrusting may represent one continuous fault or several related back-thrusts. The back thrusts are related to the position of the ramp of the Arbuckle Thrust. As slip decreases along the frontal Arbuckle System, the slip increases on the back thrust toward Caddo Anticline. Back-thrusts in these locations can be mis-identified as "flower structures" in seismic profiles (Fig. 8.20).

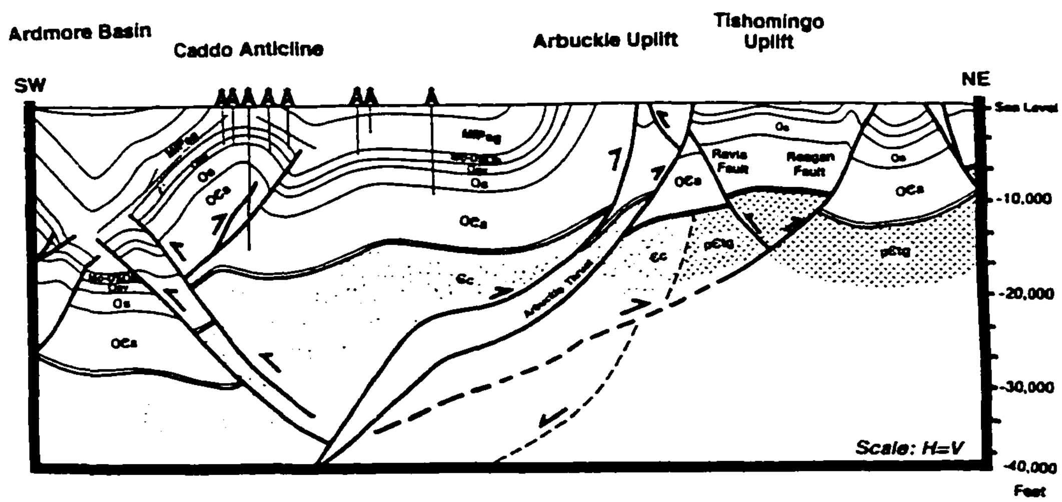


Figure 8.19. Cross section from the Arbuckle Uplift to the Caddo Anticline. The Caddo Anticline is a back-thrust to the Arbuckle Thrust. At the tip of the Arbuckle Thrust a back thrust in the Arbuckle is developed. The Ravia Fault is a back-thrust to the Reagan Fault (modified from Fletcher, 1986).

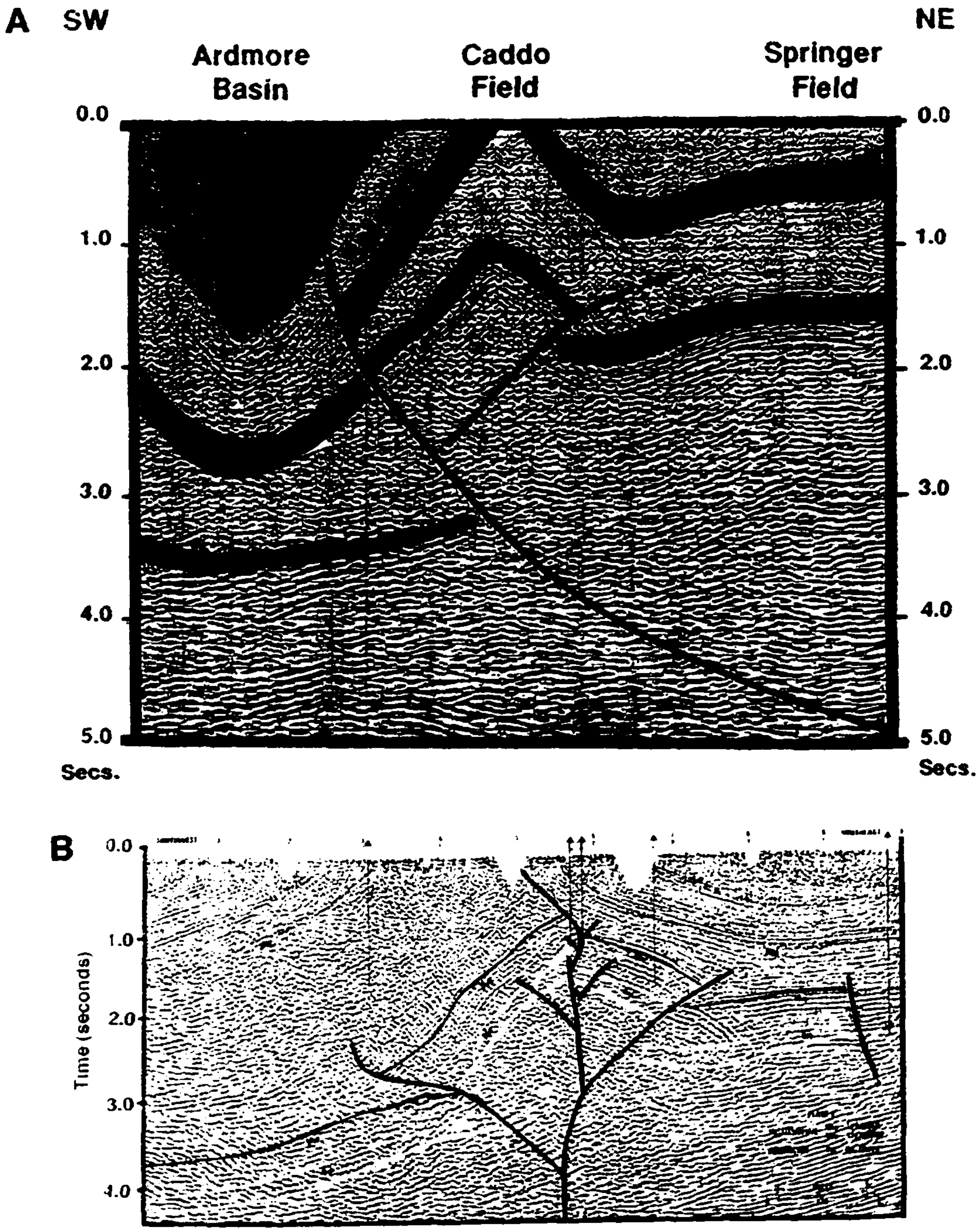


Figure 8.20. A. Seismic line through Caddo Anticline (Brown, 1990). B. Interpretation of a "flower structure" in the Ardmore Basin (Lowell and Harding, 1979). Note the similarity between this interpretation and the back-thrust at Caddo Anticline.

***En echelon* Patterns.** *En echelon* patterns of folds and faults are often thought of as diagnostic indicators of wrench systems (Wilcox and others, 1973), however, they are actually quite common in systems not associated with lateral slip, such as fold and thrust belts and compressive basement tectonics. Interestingly, only clay models of wrench systems, in which the clay detaches from the underlying material, form the *en echelon* fold patterns. Rock models, in which no detachment occurs, consistently fail to develop the "diagnostic" *en echelon* pattern. *En echelon* patterns are the result of one system taking up slip as another dies. This may occur on faults linked to the same detachment. Dahlstrom (1970) described four different *en echelon* fold patterns in the Canadian Foothills and related their patterns to displacement transfer between thrusts related to a basal detachment, structural position, and level of erosion. *En echelon* patterns are visible at various scales in southern Oklahoma uplifts. The most prominent *en echelon* patterns occurs between largebasement-bounded blocks and may indicate a common fault-linkage (regional detachment) at depth.

Examples from the Wichita Uplift. In the Wichitas, the westward loss of displacement on the Mountain View Fault and concurrent gain in slip on the Meers fault constitutes an *en echelon* pattern.

Example from the Arbuckle Uplift. The northeast-vergent Arbuckle Thrust, and the southwest-vergent Ravia Thrust forms an *en echelon* pattern between the Arbuckle and Tishomingo Uplifts.

Gentle Lateral Ramps. All faults change stratigraphic position in the direction of tectonic transport, while some faults change stratigraphic position laterally. This may be accomplished through either a gradual change in elevation of the fault plane along strike, or an abrupt change in elevation of the fault plane which may abruptly link flats or low-angle ramps of different elevations. Such ramps are termed lateral ramps (Dahlsrom, 1970). Lateral ramps may be oriented parallel, or oblique, to the direction of transport of the overriding thrust sheet. The orientation of ramps in thrust sheets control the orientation of fault-bend folds in the hanging wall. Lateral ramps also control the position of plunge in the hanging wall fault-bend anticline. Oblique ramps will generate hanging wall anticlines which may be oblique to the general direction of tectonic transport. Anticlines formed by oblique ramps may create *en echelon* arrangements of anticline oriented at some degree to the a fault trace. Such a map pattern could easily be mis-interpreted as diagnostic of wrench tectonics (Wilcox and others, 1973).

Example from the Arbuckle Uplift. The Chapman Ranch Thrust is a back-limb imbricate of the Arbuckle Thrust, exposed on the southeastern plunge of the Arbuckle Anticline (Fig. 8.6). Where it splays off the Washita Valley Fault, the Chapman Ranch trends northwest-southeast, placing lower Arbuckle Group rocks over lower Arbuckle Group rocks. Along strike to the east it cuts down section at a low angle, eventually placing basement rocks over lower Arbuckle Group rocks, forming the East Timbered Hills culmination. Continuing to the east, the fault takes an abrupt north-south trend, ramping up-section into the lower Arbuckle Group forming a slightly-oblique lateral ramp. The Chapman Ranch Thrust then resumes it's original northwest-southeast trend as a low-angle flat in the lower Arbuckle Group, continuing to the southeast where it is folded by a footwall anticline and dies out as a cross crestal fault-propagation fold. The footwall anticline is oriented north-south, parallel to the strike of the lateral ramp and may be the product of an unexposed oblique lateral ramp at depth.

Lateral changes in fault geometries and fault-plane elevation are important in constraining slip vectors of the hanging wall of the Arbuckle Thrust (Saxon, 1994). In the area of the westward rise in the Arbuckle Thrust, the lateral ramp dips to the southeast. Left-lateral slip of the hanging wall parallel to the trace of the Arbuckle

Thrust would result in moving the hanging wall obliquely down the dip of the lateral ramp. The result of such movement would be crustal extension of the hanging wall. The extension would be contemporaneous with, and balance the shortening on, the Arbuckle Thrust, resulting in no net crustal shortening. Late-stage extension occurred along the Washburn Ranch Fault which merges with the Arbuckle Thrust at a ramp (Saxon, 1994). However, extension along the Washburn Ranch Fault post-dates shortening; therefore extension occurs west of the lateral ramp in an orientation which is unfavorable to left-slip (Saxon, 1994).

Abrupt Lateral Variations in Structural Style

Steep Lateral Ramps

Steep lateral ramps are abrupt lateral rises in elevation of a fault plane which link detachments of differing structural and stratigraphic position. Lateral ramps are often oriented parallel to the direction of tectonic transport, however, they may be oriented at some angle other than parallel, in which case they are oblique ramps.

Example from the Arbuckle Uplift. The southeast flank of the East Timbered Hills provides an excellent outcrop example of a sharp lateral ramp (Fig. 8.6). The Chapman Ranch Thrust cuts up-section sharply from the basement to the lower Arbuckle Group, then trends to the southeast as a flat in the lower Arbuckle Group.

Compartmental Faults

Faults transverse to the trend of the mountain front which serve to allow differential shortening or modes of deformation along either side, are termed compartmental faults (Brown, 1984). Compartmental faults are present in the Wichita and Arbuckle Uplifts. They may represent primary extension fractures oriented parallel to the direction of maximum horizontal stress, or they may be a relict zone of basement weakness which has been re-activated by favorable stress orientation. It is difficult to determine the relationship of basement fabric to compartmental faults in southern Oklahoma (if any direct link exists) because of the subsurface nature of the uplifts. Compartmental faults serve to allow equal amounts of shortening on either side of a fault through different folds and faults, or to allow a lateral termination of a structure, or to separate areas of differential shortening as part of a plunge adjustment mechanism. The nature of the subsurface uplifts and lack of reliable measuring of shortening on either side of a compartmental fault may make exact function(s) unknown. Compartmental faults oriented in the direction of tectonic transport provide a geometric constraint on the range of possible slip-vectors along a mountain-flank fault. Compartmental faults in southern Oklahoma which are generally oriented northeast-southwest. Their orientation is incompatible with left-slip solutions for northwest-southeast trending fault planes.

Examples from the Wichita Uplift. Compartmental faults are most common on the western portion of the Wichita Uplift. A major compartmental fault separates the Wichita Uplift from the Amarillo Uplift (Fig. 4.1). The sense of structural vergence is diametrically opposed on the two adjacent blocks across this fault. Fig. 8.21 is a cross section across the Mills Ranch Field in Wheeler County, Texas, on the Amarillo Uplift. The mountain flank dips gently to the northeast and subsidiary detachment structures verge southwestward. To the east of the mountain front compartmental fault, the Wichita Uplift verges to the northeast. Figs. 8.22 and 8.23 are seismic lines on opposite sides of a compartment fault in the Western Wichita Segment. The compartment fault separates Mode I from Mode II style deformation.

Examples from the Arbuckle Uplift. Compartmental faults do not appear to be as common in the Arbuckle Anticline as in the Wichita Uplift. Brown

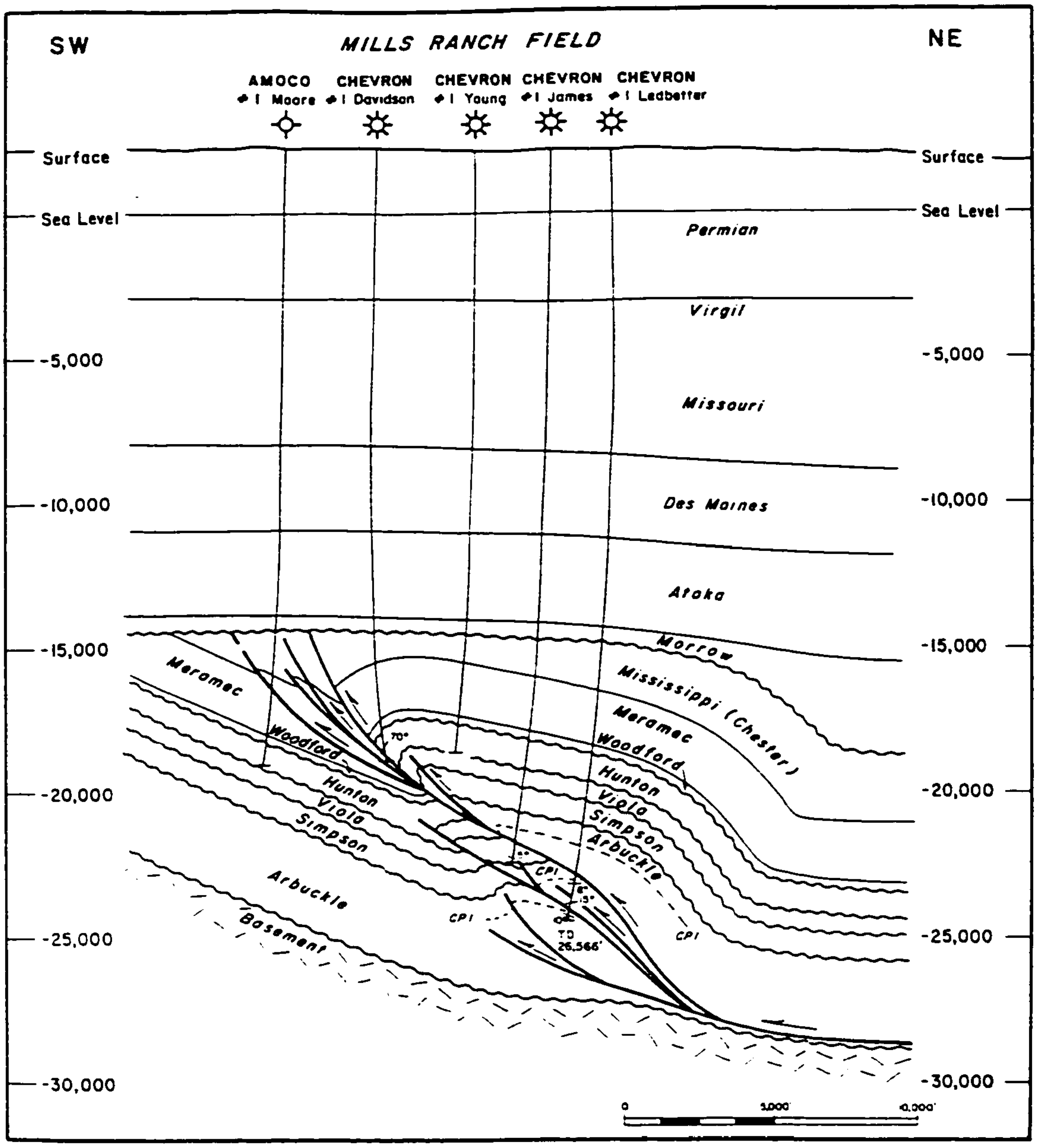


Figure 8.21. Cross section across Mills Ranch Field on the Amarillo Uplift of the Texas Panhandle. The structural vergence in the Amarillo Uplift is opposite of the Wichita Uplift. The two areas of differing style are separated by a compartmental fault (from Petersen, 1983).

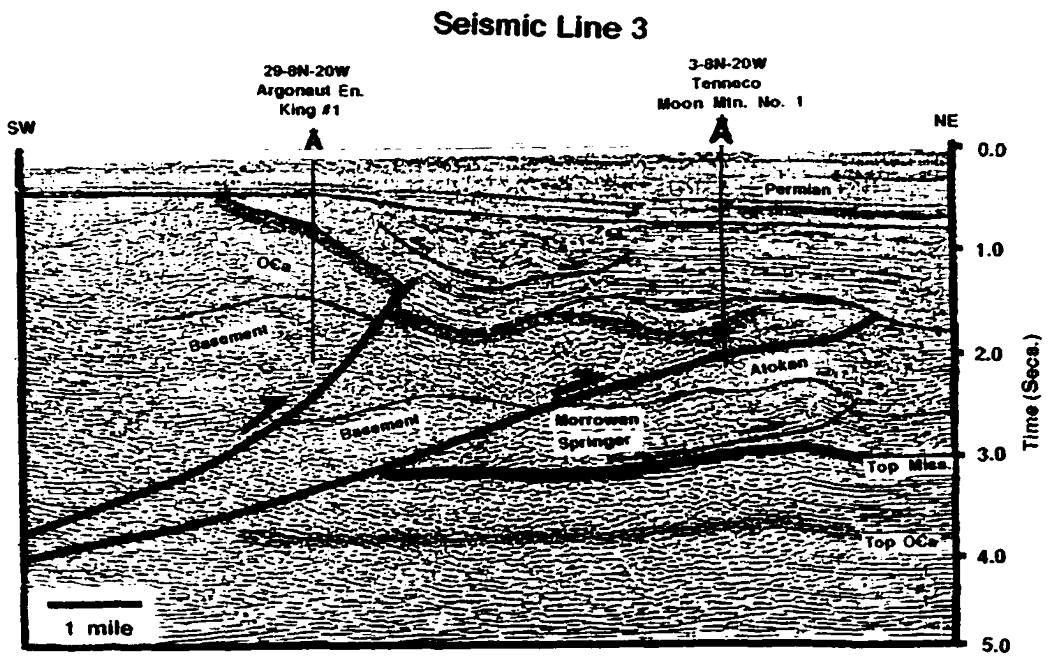


Figure 8.22. Seismic line 3 located in the Western Wichita Segment. This line shows a Mode II style of deformation. Note the long flat in the Arbuckle Group. Contrast this line with that in Figure 8.22 (seismic courtesy of SEI).

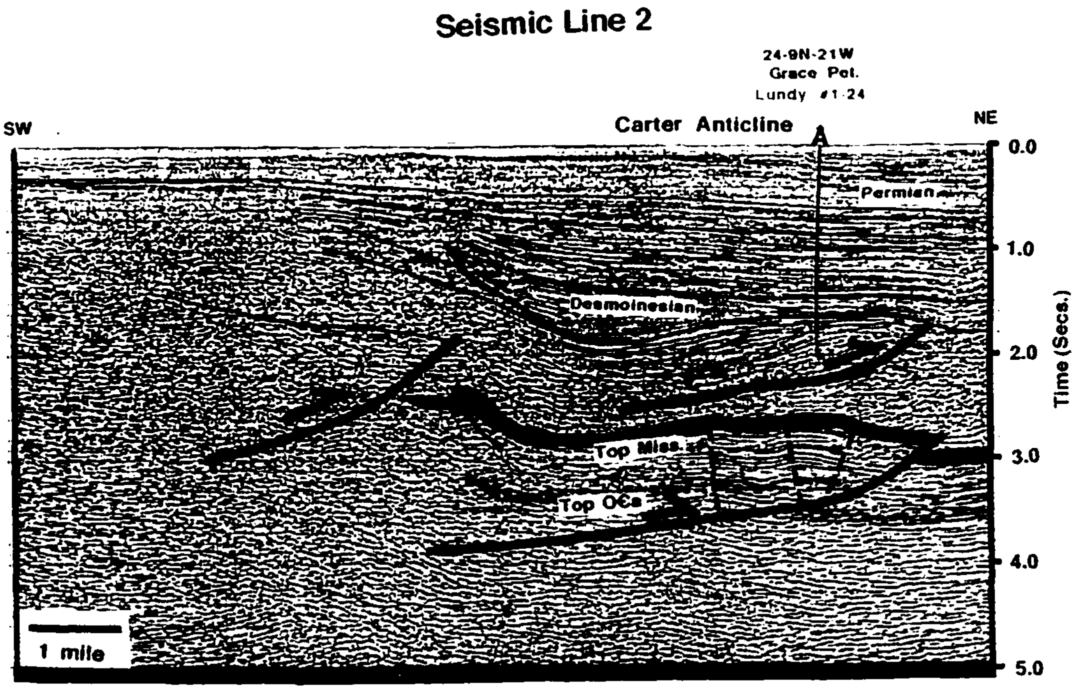


Figure 8.23. Seismic line 2 located in the Western Wichita Segment. Although the style of deformation of the mountain front is not well imaged by this seismic line, the area in front does not contain the long flat seen in seismic line 3 (Figure 8.21). Clearly, this line shows the mountain front is well to the southwest of it's position in line D and does not contain the same Mode I style of deformation with a long, low-angle overhang extending far over the basin. These lines are only a few miles apart but contain radically differing structural styles, separated by a compartmental fault (seismic courtesy of SEI).

(1984) showed a tear in his structural contour map of the Arbuckle Thrust which may serve as a compartmental fault. An east-west trending compartmental fault forms the southeast termination of the Arbuckle Uplift, separating it from the Sycamore Creek Anticline (Fig. 8.17).

"Instant Plunge" Across Compartmental faults

Structural style of a basement-cored uplift may vary as a function of plunge rate. When plunge rates steepen sharply to vertical over very short distances, a structure is said to create "instant plunge" (Brown, 1987). At the point of instant plunge, a structure usually terminates abruptly, and disappears. Instant plunge occurs as a fold develops over a high-angle fault, which is oriented parallel to the direction of transport. The instant plunge is a reflection of the monoclinal shape along a longitudinal cross section. Basement-cored uplifts which terminate in such folds often show a lateral succession in which a fault-bounded uplift changes into a fault-to-fold interchange, and ultimately terminates in instant plunge. The geometry of the termination fold is a function of variations in plunge rate. Brown (1987) documented the effects of variations of plunge rate upon the termination of basement-cored uplifts in the Rocky Mountain Foreland. Brown determined four empirical rules regarding plunge rates and structural style: 1) as long a plunge rates do not exceed 20 degrees, vertical cross sections do not overly distort the geometry of a structural cross section; 2) when plunge exceeds 25 degrees, detachments develop in the stratigraphic section on the down-plunge end of a fold; 3) when plunge approaches 45 degrees, the structure becomes conical and disappears rapidly; and 4) when plunge is accomplished by a transverse fault at depth, the fold experiences "instant plunge" of 90 degrees.

Example from the Arbuckle Uplift. The southeastern end of the Arbuckle Anticline terminates in instant plunge (Fig. 8.17). The southeast end of the Arbuckle Uplift is a lateral fault-to-fold interchange, with slip decreasing to the southeast along the Arbuckle, Washita Valley, and the Chapman Ranch Thrusts. The terminal southeastern fold almost instantly attains vertical plunge as it passes over an east-west trending compartmental fault which separates the Arbuckle and Sycamore Creek Anticlines. Because the fold attains vertical plunge, the map pattern southeast plunge of the Arbuckle Uplift is essentially a true, right cross section.

Abrupt changes in vergence

In general, abrupt changes in vergence are not seen in southern Oklahoma with one major exception. The compartmental fault which separates the Amarillo and Western Wichita Segments facilities a change from northeast vergence of the Western Wichita Segment, to gentle, southwest vergence of the Amarillo Segment. The basement on the north flank of the Amarillo Segment dips to the northeast, forming a broad, open syncline into the Anadarko Basin. Out-of the syncline thrusts, detached in the Arbuckle Group, are directed to the southwest, up the shallow flank of the Amarillo Mountain Front. Mills Ranch Field (Fig. 8.21), in Wheeler County, Texas, is an example of a southwest-verging structure.

Summary and Conclusions

A variety of factors enable structural styles of the mountain flank uplifts of southern Oklahoma to vary with lateral position. Many changes are the result of the termination of a structure. Dramatic changes occur along plunge where a variety of mechanisms may facilitate rapid change in structural style. Because structural style and structural geometry change rapidly, one must apply caution in trying to force a single model to the entire length of an uplift. Documentation of structural geometry and structural styles are necessary before meaningful interpretation, or slip estimates, can be made. Knowledge of structural geometry may serve as a useful constraint on the models of deformation, or interpretive slip vectors proposed across a fault. As a fault loses slip, other mechanisms, may compensate for the loss of slip. Changes in style may be abrupt or gradual depending upon the presence of compartmental faults and rates of plunge.

Chapter 9

TECTONIC ARGUMENT AND SUMMARY

Introduction

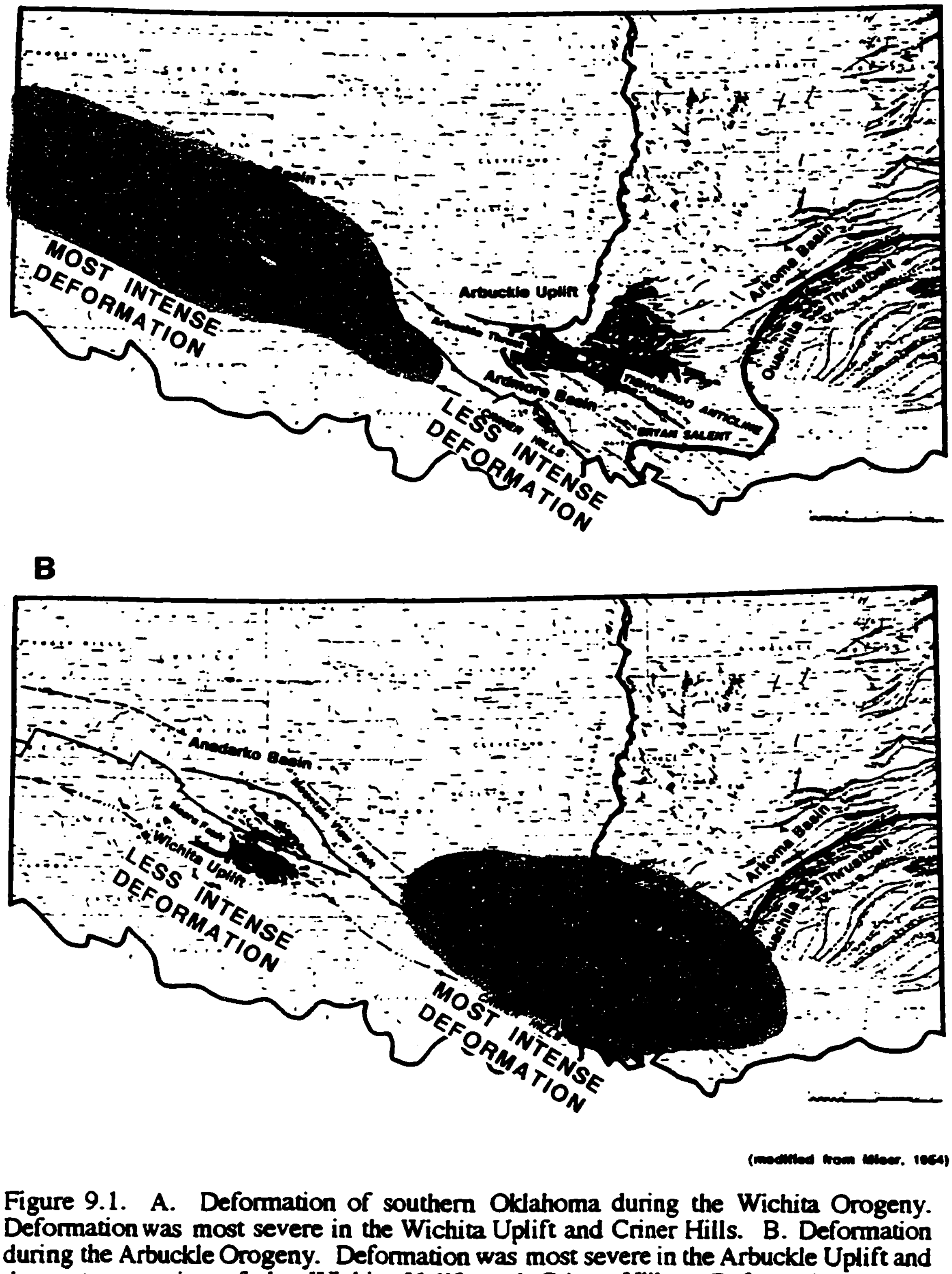
This section addresses the tectonic and regional aspects of Pennsylvanian deformation of the Southern Oklahoma Foreland. Observations and arguments made in previous chapters are summarized and placed into proper perspective to address the overall style of deformation, with particular reference to the debate of strike-slip versus horizontal compression. The debate is viewed in terms of both wrench tectonic (simple shear) and strike-slip faulting (pure shear) interpretations as well as horizontal compression. Fundamental techniques of analysis, structural interpretations, and basic assumptions of strike-slip settings are questioned and a strong case is made in favor of horizontal compression. Lastly, this chapter summarizes the contribution of the dissertation.

Timing of Deformation

Deformation of the Southern Oklahoma Foreland occurred in two pulses; the Wichita Orogeny, which initiated in the Chesterian and culminated at the close of the Atokan, and the Arbuckle Orogeny, which began in the Virgilian and ended in the early Wolfcampian. These orogenic events passed through southern Oklahoma as a tectonic front, moving from southwest to northeast, and west to east. Fig. 9.1a shows deformation during the Wichita Orogeny. The pattern of heavy-shading indicates major uplift and shortening; the light pattern indicates minor faulting and folding. The Wichita Orogeny resulted in the major uplift and deformation of the Amarillo-Wichita-Criner System and early folding, and minor shortening, of the Arbuckle, Tishomingo, and Hunton Uplifts. Fig. 19b shows deformation during the Arbuckle Orogeny during which, deformation was concentrated on the eastern portion of the Wichita Uplift, the

A

B



(modified from Miser, 1954)

Figure 9.1. A. Deformation of southern Oklahoma during the Wichita Orogeny. Deformation was most severe in the Wichita Uplift and Criner Hills. B. Deformation during the Arbuckle Orogeny. Deformation was most severe in the Arbuckle Uplift and the eastern portion of the Wichita Uplift and Criner Hills. Deformation passed northeasterly through southern Oklahoma along a northwest-southeast-oriented tectonic front.

Criner Hills, and the Arbuckle, Tishomingo, and Hunton Uplifts. This period resulted in the main uplift of the Arbuckle and Tishomingo Uplifts and the closing and shortening of the Ardmore Basin. These pulses of deformation were bridged by minor flexing during the Middle Pennsylvanian and the emplacement of the Ouachita Thrust System in the southeast during the most severe portion of the Ouachita Orogeny in the Desmoinesian. The northeast-moving tectonic front is consistent with the general northeast vergence of the basement uplifts of southern Oklahoma and the foreland-breaking sequence of deformation associated with compressional fold-belts (Fig. 9.2).

Strike-Slip versus Horizontal Compression

Framework of the Debate

Discussion of structural geology of the Southern Oklahoma Foreland has centered on the controversy as to whether the area is a province of wrench, or strike-slip faulting typified by large amounts of left-slip, or that of horizontal compression resulting in large-scale crustal shortening along low-angle thrust faults. Some of the argument has played out in the literature; however, given the commercial interest in the area, and the hesitancy of industry to publish proprietary data and interpretations, much the debate has been "informal". Workers in the strike-slip camp have offered interpretations based upon both wrench tectonics, with high-angle strike-slip faults (simple shear), and low-angle, or oblique, strike-slip faults (pure shear). These arguments focus upon apparent lateral offset of interpretive isopachs or facies lines on subsurface maps. Structural arguments often hinge upon subsurface fault mapping (often highly interpretive) and assumptions of fault geometry, which are typically not well-documented.

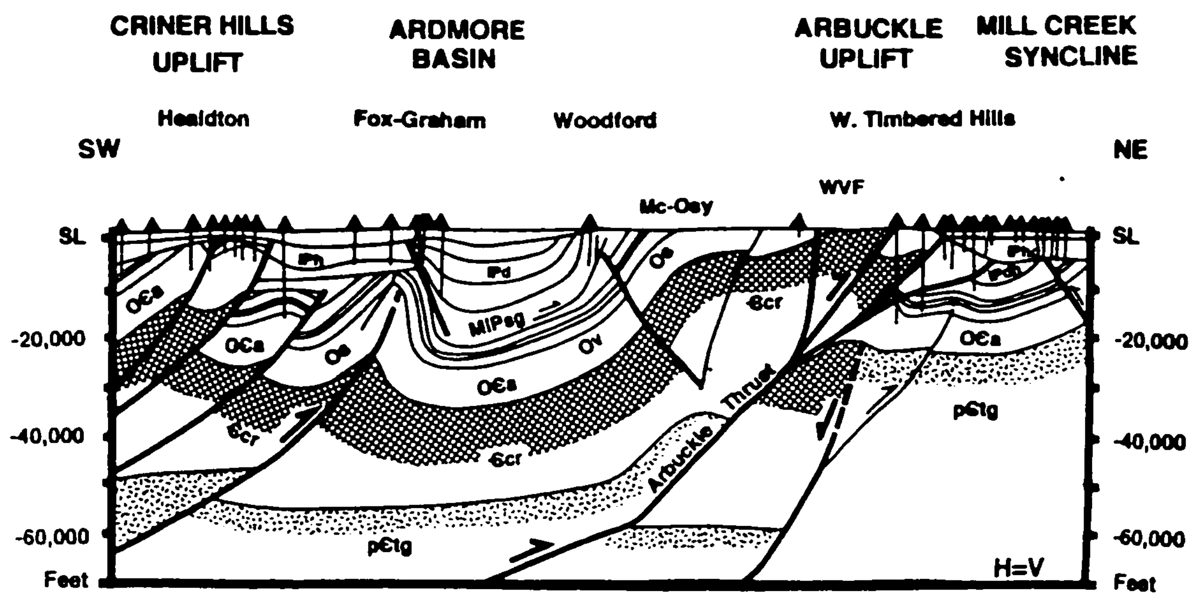


Figure 9.2. Regional cross section from the Healdton Uplift to the Arbuckle Anticline. This cross section shows the extreme northeast-vergence of southern Oklahoma deformation. The faults are linked at depth, interpreting a possible regional decollment (modified from Brown, 1990).

Problems Associated with Wrench Tectonics.

The idea that large amounts of strike slip motion occurred in Southern Oklahoma gained prominence in the late 1960 and 1970's. At this time, southern Oklahoma was generally described as a province of wrench tectonics. The wrench tectonics interpretation was centered upon:

1) Assumption of vertical master faults

2) Restoration of interpretative contours against vertical faults, such that map separation equals fault slip.

3) Comparison of tectonic map patterns with general associations predicted by the strain ellipse for left-lateral wrenching.

4) The assumption that *en echelon* fold patterns are diagnostic of wrench systems exclusively.

5) The plate -tectonic setting of the southern mid-continents assumed by many to support only strike-slip deformation at the detriment of northeast-southwest directed crustal shortening.

Beginning in the early 1980's, the first two arguments were seriously brought into question by workers who presented well and seismic data which clearly demonstrated that the major fault systems of the Wichita Uplift and Arbuckle Uplift were of a low-angle nature (Brewer, 1983; Brown, 1984). Most importantly, Brown (1984) documented that the presence of a major fault which he named the Arbuckle Thrust, which had not been previously recognized. Although Brown did not stress this point, his interpretation clearly documented the assumed shape and lateral extent of the "Washita Valley Fault System" as defined in the standard literature, was clearly misinterpreted, as was its assumed amount and magnitude of slip. Additionally, Brown demonstrated the dangers of using map separation as slip, and the failure of previous workers to account for crustal shortening in their restorations of "piercing points".

The third point, that map patterns, especially tectonic map patterns, can be "analyzed" to see if general orientations "fit" a strain ellipse, represents a common, but unreliable method of structural "analysis". There are several problems with this mode of analysis. First, all deformed rocks fit a strain ellipse. Simply fitting a strain ellipse to an area of deformation by itself does not imply a wrench or strike-slip origin for the deformation. Secondly, the identical strain ellipse pattern can be generated with the sigma one principle stress at different orientations. The strain ellipse in Fig. 9.3 could be generated by either a left-lateral wrench or northeast-southwest directed horizontal compression. Thus, even if an area "fits" a strain ellipse, a unique sigma one principle stress direction has still not been defined. Perhaps the most overlooked problem with the technique of "fitting" an area to a strain ellipse is that the ellipse predicts associations of structures which should arise as the result of deformation of a previously non-strained medium. Quite clearly, southern Oklahoma contains established structural grains and fabrics which pre-dated Pennsylvanian deformation and may have had an important control on the Pennsylvanian deformation. The orientation of the Pennsylvanian deformation fabric may be more reflective of, or controlled by, previous structural trends as oppose to a primary fabric which would be generated by wrenching of a setting devoid of a previous structural grain. Yet another consideration is that previously existing structural fabrics, such as minor extensional faults in the Arbuckle Group related pre-Pennsylvanian subsidence, or the post-Pennsylvanian extension fabric, may be assumed to be the result of Pennsylvanian deformation and "fitted" into the strain ellipse, providing false data. By providing a neat "catch-all" explanation for structural fabrics, strain ellipse explanations can miss important timing relationships of structural fabrics and mistakenly incorporate data from unrelated tectonic events.

The fourth point, that *en echelon* fold patterns are diagnostic of wrench systems exclusively, is misleading. In clay model experiments of wrench systems

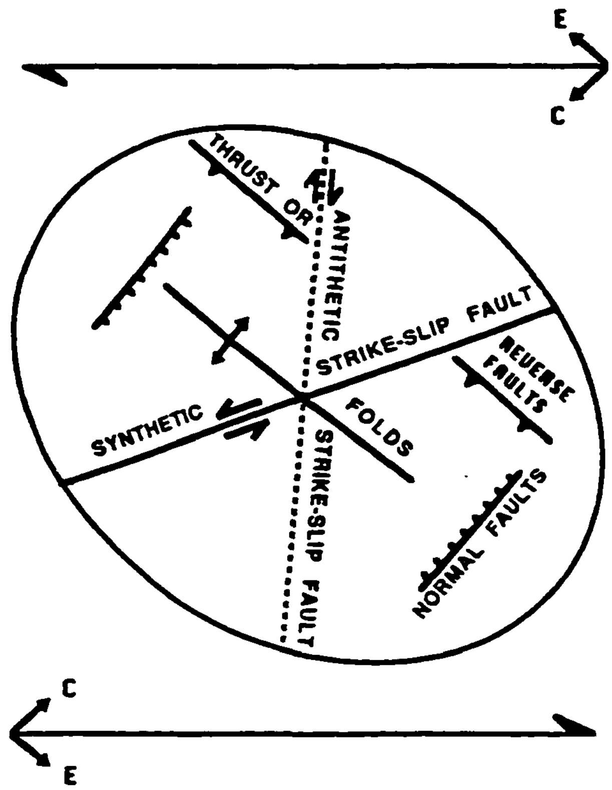


Figure 9.3. Strain ellipse for a left-lateral wrench couple. This is also the strain ellipse for northeast-southwest oriented compression. Different primary stresses can be fitted to this strain ellipse. Stating that an area can be "fitted" to a strain ellipse does not constitute rigorous structural analysis.

(Wilcox and others, 1973), a certain linear, *en echelon* arrangement of fold patterns forms as the clay detaches from the underlying boards. As examined in Chapter 5, this pattern fails to develop in real rock model experiment of strike-slip faults (Logan and others, 1978; Bartlett and others, 1981) where the sedimentary section does not detach. *En echelon* fold arrangements are related to detachments rather than simple shear. The development of *en echelon* folds is a geometrical manner of transfer of displacement from one structure to another. They are a common feature in fold and thrust belts (Dahlstrom, 1969) and provinces of compressive tectonics. Additionally, *en echelon* folds generated in clay wrench models tend to be early formed, asymmetric folds which are broken by a thoroughgoing master wrench fault if substantial lateral displacement occurs. Such a pattern is not seen in the folds of southern Oklahoma. The mere presence of an *en echelon* fold pattern does not mandate a wrench origin. The arrangement, timing. and asymmetry of the *en echelon* fold pattern must also be considered when trying to establish the structural style of the region.

The fifth argument is a case of the "tail wagging the dog". It is the attempt to argue present-day strains from an assumed paleo-stress setting. This process is always a dangerous approach to structural analysis. The strike-slip argument assumes that the Wichita and Arbuckle Uplifts were directly caused by stresses transmitted to the interior of the continent from the active southern margin and that those stresses were at a direction parallel to the direction of tectonic transport of the Ouachita Thrust Sheets. Unfortunately, the Ouachita System itself is difficult to explain as the result of a single non-variant stress field (direct strain to stress relationship) because it contain numerous right-angle bends. Stresses generated by the collision of North America with the proto South America-African Plate are dependent upon the magnitude and direction of plate motions (vectoral sums). Variation of the rate of plate motion greatly affects the resultant vector (and thus stress direction and magnitude). Hardie (1990) demonstrated this for the closing of the Ouachita System. Ye and others (1996) presented a strong argument that the deformation of the Pennsylvanian Foreland was related to subduction off the coast of Mexico, in which case, the argument regarding the Ouachita System becomes mute. Looking for evidence to support a preconceived tectonic setting is dangerous.

More importantly, the stress system needed to create a left-lateral strike-slip fault with the general N50°W trend of the major faults of southern Oklahoma, could not have been generated by the Ouachita collision. Fig. 9.4 shows the various sigma one directions needed to generate the primary faults of southern Oklahoma as right-lateral strike-slip, left-lateral strike-slip, and northeast vergent dip-slip faults. The left-lateral interpretation would require sigma one to be oriented nearly due east-west; a direction highly oblique to the Ouachita Thrust Front! and incompatible with vectoral sums of the collision of North America with South America-Africa (Hardie, 1990).

Other serious problems with the wrench tectonic interpretation is that wrench systems start as a zone of widely distributed shear which narrows with progressive deformation. Deformation in southern Oklahoma does not show a pattern of continuously narrowing deformation. In fact, deformation progresses as a northeast-vergent tectonic front. Intra-basin folds, such as Cordell, Cement, and Carter-Knox Anticlines show continued growth through the entire Pennsylvanian, and thus cannot be explained as the product of wrench tectonics.

In the early 1980's workers such as Brewer (1983) and Brown (1984) documented the presence of low-angle basement overhangs along the Wichita and Arbuckle Mountain Fronts. Although these findings took away the very basis for wrench fault interpretations, the concept of southern Oklahoma as a strike-slip or wrench province remained. Several workers have tried various explanations to reconcile the low-angle of the mountain-flank faults with assumed left-slip. Budnick (1986) simply stated that compressive features are found in association with wrench setting. He offered no documentation of how such an association would work in the

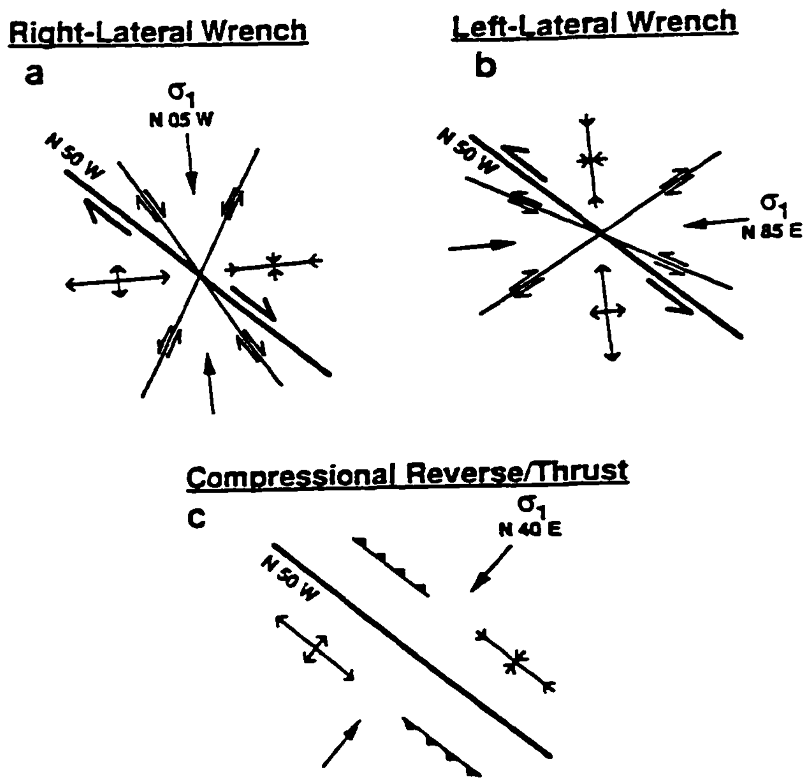


Figure 9.4. Diagram showing the orientation of the principle stress required to create a N50W trending fault with A) right-lateral slip B) left-lateral slip and C) northeast-southwest shortening (from Bixler, 1993).

Wichitas. His description of the Mills Ranch Field in Wheeler County, Texas as either a "flower structure" or a "trap-door structure" is arm-waving. In fact it is neither (Petersen, 1983). In Budnick's mega-shear model, the lack of documentation and the interpretation of any structural model does not constitute "proof" of wrench faulting.

Problems Associated with Strike-Slip and Transpressive Arguments

1) There is no credible stratigraphic evidence that left-slip has actually occurred on either the Arbuckle Thrust or along the Wichita Mountain Front. Brown (1984) showed that the apparent separation of the zero-sand isopach of the Oil Creek Sand along the "Washita Valley Fault" was actually due to reverse dip-slip motion along the Arbuckle Thrust. The same raw data McConnell used to argue for pure dip-slip motion in the Wichitas (McConnell, 1987), was then later used by McConnell to argue for 20 miles of left-slip (McConnell, 1989). Problems with McConnell's restorations include the use of highly interpretive isopachs of the extremely variable Hunton resulting from a lack of data points in the footwall (four control points in 900 square miles). McConnell's data regarding offsets of Hunton isopachs is certainly not definitive since his own interpretations show offset that can be interpreted with a 20 mile variance. Using the zero sand isopach of the Oil Creek Sand, Remmer (1989) demonstrated that no lateral offset could have occurred in the Criner Hills Segment of the Wichita Uplift. All previous estimates of large amounts of lateral offset in southern Oklahoma have been shown to be accountable for by reverse dip-slip or can be based upon unreliable or questionable methods.

2) Major amounts of left-slip is incompatible with compartmental faulting. Several large compartmental faults exist in the Wichita Uplift, especially in the Western Wichita Segment. The most prominent of which runs approximately parallel to the Texas border and separates the Wichita Uplift from the Amarillo Uplift. If substantial amount of left-slip occurred along the Wichita Mountain Front, these areas would be

the location of pull-apart basins resulting in massive amounts crustal extension equal to the component of left-slip. Although a considerable amount of vertical separation exists along the compartmental faults, no net crustal extension occurs because of the fault-plane is essentially vertical. Additionally, the structural style on either side of the compartmental fault is of northeast-southwest net crustal shortening; a fabric, and structural orientation, incompatible with localized extension predicted by left-slip along the mountain front.

3) Several major basement faults in the Wichita and Arbuckle Mountain Fronts lose slip along strike and terminate as fault-propagation folds. Faults which terminate into folds are pinned at the fault-fold interchange and are incapable of significant amounts of strike-slip.

4) Thrust sheets of the Ouachita System, which predates the Arbuckle Orogeny, are not offset by Arbuckle-aged strike-slip faults. The entire Bryan County Salient has been synclinally folded coaxially along the axis of the Ardmore Basin and this folding has caused syncline crowding of folds of the Ouachita Thrust Sheet. In the Isom Springs area, several thrusts sheets have been folded along a northwest trending axis by crustal shortening (Hardie, 1990) during the Arbuckle Orogeny.

5) Previous strike-slip interpretations (Tanner, 1976; Carter, 1979; Booth, 1981; Haas, 1981; Axtmann, 1983; McConnell, 1989) have been dependent upon fault linkages and subsurface interpretation which have been shown to be incorrect (Brown, 1984; Palladino, 1986; Saxon, 1994, this volume). Interpretations of large strike-slip offset involving the Arbuckle Anticline (Tanner, 1967; Carter, 1979; Booth, 1981) are predicated upon Tanner's (1967) definition of the "Washita Valley Fault Zone" as a 150 mile, vertical fault. The zone of faulting indicated by these authors is, in fact, comprised of several different southwest- and northeast-dipping thrust faults including the Arbuckle Thrust, Washita Valley Fault, Doyle Fault, Sycamore Creek Thrust, and Ravia Fault. In the Wichitas, strike slip estimates have been predicated upon the

assumption that the Mountain View Fault is a continuous fault or fault system which forms the northern boundary of the Wichita Uplift (Axtmann, 1983; McConnell, 1989). Saxon (this volume) documents the Wichita Mountain Front as composed of several southwest-dipping basement thrusts (Mountain View Fault, Meers Fault) which loses slip and terminate against compartmental faults and/or die out into basement-cored folds. Axtmann (1983) incorrectly links the basement-involved Mountain View Fault with the Wayne Fault by running a connecting segment through the north portion of Cement Anticline, a non-basement-involved foreland detachment structure! Axtmann also attempts to link the Wichita and Arbuckle Uplifts by extending the already mismapped "Washita Valley Fault Zone" into the Meers Fault. These interpretation of fault linkage are offered without the slightest bit of evidence to support them. Such linkages are picked up by others (Budnick, 1986) and are parleyed into regional wrench systems.

6) Strike-slip faults cannot simply terminate at an end point, with strike-slip diminishing to zero without transferring slip to other fault systems. Strike slip faults can terminate (to zero slip)by: 1) turning into a basement-thrust or normal fault at right angle to the strike-slip fault, or 2) creating a large anticline or syncline at the end. Strain at these terminations must equal the amount of strike-slip along the fault. Thus, large strike-slip offsets, such as the 40 miles suggested by Tanner (1967) must be balanced by crustal shortening by 40 miles, at nearly right angle to the strike-slip trace. Such amounts of shortening would create structures right angles to (as well as dwarf) the Wichita and Arbuckle Uplifts. An example of a real-world strike-slip fault maintaining structural balance is the San Andreas system in California which is driven by crustal extension in the form of sea-floor-spreading at its southern termination, and transference of slip to a transform at it's northern termination. Because supposed strike slip in southern Oklahoma was not part of an overridden transform, like the San Andreas System, it lacks the plate tectonic, mechanical, and kinematic driving

mechanisms of the former to generate, and transfer, large amounts of strike slip at fault tips.

Case for Horizontal Crustal Shortening

The Southern Oklahoma Foreland contains an undeniable component of northeast-southwest crustal shortening. Seismic and well data have clearly established the presence of low-angle, basement-involved faulting along the Wichita and Arbuckle Mountain Fronts. These overhanging thrust sheets contain internal fabrics of shortening that are consistent with crustal shortening models. The mountain-flank faults terminate by loss of slip at fault-fold interchanges or abrupt lateral terminations at compartmental faults. Reverse dip-slip faulting can account for all geometries observed within the Southern Oklahoma Foreland, including the structural geometry of the mountain fronts and detached basin structures, as well as adequately explain the apparent lateral offset of facies and the deformational style of growth sediments.

The argument for horizontal compression can be outlined by the following observations:

1) Presence of large basement overhangs. These overhangs contain an internal fabric of shortening and could only be generated by crustal shortening.

2) Southwest and northeast dip on the moderate- to low-angle thrusts. These faults form a conjugate system, indicating northeast-southwest directed horizontal stress.

3) Presence of lateral motion across transverse, or compartmental faults, parallel to the direction of tectonic transport. The lack of crustal extension, and the presence of crustal shortening, on either side of these faults is consistent with differential amount (and style) of horizontal compression parallel to the trend of the compartmental fault.

4) The basement and sedimentary section are deformed, with the basement acting as the forcing-block folding the sedimentary section.

5) Basement-involved thrusts which die-laterally into folds.

6) Northeast-southwest oriented cross sections across the Wichita and Arbuckle Mountain Fronts can be structurally balanced.

7) There is a direct correlation between the style of deformation of the hanging wall and footwall across the mountain front. This is important because the structural style can vary quickly along the mountain front. If even small amounts of strike-slip were present, there would be no such correlation immediately across the hanging wall and footwall of the mountain flank.

8) Palinspastic restoration of numerous "piercing points" can be explained with dip-slip models along low-angle thrusts.

9) Portions of the mountain front have undergone fold-thrust deformation.

10) Northeast verging fault-bend folds.

11) The "bow and arrow" pattern of the Arbuckle thrust is consistent with the map pattern of a thrust sheet.

12) Strong asymmetry of southern Oklahoma deformation to the northeast. The asymmetry is consistent with the known southwest -dip of the major fault systems of southern Oklahoma.

13) Gradual lateral variation in the depth of the major basement thrusts (especially the Arbuckle Thrust) are consistent with northeast-directed tectonic transport. Significant left-slip along the northwest-rise in the Arbuckle Thrust would translate the hanging wall obliquely down-dip, and result in crustal extension synorogenic to the creation of the Arbuckle Uplift. Late-stage extension (post Arbuckle Uplift) is present as the Washburn Ranch Fault, however, it's timing post-dates significant crustal shortening of the Wichita and Arbuckle Orogenies and its orientation is incompatible with left-slip along the Arbuckle Thrust (Saxon, 1994).

14) Northeast-southwest directed horizontal compression is compatible with possible plate tectonic scenarios for the Pennsylvanian postulated by Kluth and Coney (1981) and Ye and others (1996).

15) Progressive deformation across the Southern Oklahoma Foreland from southwest to northeast. Migration of foreland tectonic fronts has been documented in the Rocky Mountain Foreland (Brown, 1988). If the deformation of southern Oklahoma were attributable to simple (wrench tectonics) deformation would start as a wide band and progressively narrow to a through-going master fault. If deformation were attributable to pure shear, a system of conjugates distributed across the entire foreland would have to be simultaneously active.

16) The Southern Oklahoma Foreland is part of the overall, widely-distributed, northeast-southwest oriented crustal shortening of the Pennsylvanian Foreland.

These observations argue strongly the case for northeast-southwest directed horizontal compression as the cause of Pennsylvanian deformation in southern Oklahoma. However, care must be taken in trying to establish a direct correlation between present-day geometry (strain) and paleo-stress. Structures of the Southern Oklahoma Foreland record the strain and the local stress field(s) the structure formed under, but may not record the regional stress which acted upon the margins of the old Southern Oklahoma Rift boundary during the Pennsylvanian. Stresses at a variety of angles to the Southern Oklahoma Rift boundary could have caused out-of-the-syncline crowding, and the exact amount of influence of the tectonic fabric of the rift on Pennsylvanian deformation is not well understood. If old rift-bounding faults were low-angle at depth, it is possible they could be reactivated during the Pennsylvanian as thrusts. Restoration of the plate-setting by Kluth and Coney (1981) and Hardie (1990) indicate that if deformation was caused by the Ouachita collision, the stress field would have undergone significant rotation during the course of the Pennsylvanian. Thus the principle stress may have been directed at a variety of angles to the old rift margin, and been further "refracted" across the margin of the rift, presenting a complicated, non-static stress field.

Structural style of the Southern Oklahoma Foreland shows a variety of styles which may vary quickly with changes in lateral position. However, all styles are compatible with some amount of initial basement folding and overall crustal shortening. The style of deformation incorporates aspects of fold-thrust, thrust-uplift, and fault-bend folding, with any of these three styles becoming more dominant at any given location. The presence of the fault-bend fold style in the Southern Oklahoma Foreland may indicate that deformation may be linked at depth by a common detachment (Brown, 1990; Saxon, 1994; Copper, 1995), however this has not been clearly established.

Conclusions

1) The southern Oklahoma Foreland underwent northeast-southwest directed crustal shortening during the Pennsylvanian.

2) Initial deformation occurred during the Wichita Orogeny and proceeded to move to the north and east as the Arbuckle Orogeny, passing through as a tectonic front.

3) Deformation occurred on low-to-moderately-dipping basement involved thrusts.

4) Deformation style varies along strike and is primarily directed by the amount of folding the basement underwent in early stages of deformation.

5) Areas of fold-thrust deformation resulted in the generation of foreland detachment structures and complex mountain fronts typified by overturned flanks and tight mountain-flank synclines.

6) Areas of the mountain fronts which underwent thrust-uplift deformation are typified by large overhangs and less deformation of the footwall than areas of fold-thrust deformation.

7) Both fold-thrust and thrust-uplift styles of deformation may be modified by fault-bend folding.

8) Deformation occurred along several faults in the Wichita Mountain front, the Mountain View Fault dies out westward into a fold and cannot be considered the single fault plane which was responsible for the uplift of the entire Wichita System.

9) Structural style varies laterally along strike in both gradual and abrupt manners.

10) The presence of large compartmental faults rules out the possibility of strike-slip motion along the Wichita Mountain Front.

11) The Washita Valley Fault System, as is commonly referred to in the literature, is in fact several different reverse dip-slip faults.

12) Deformation along the Arbuckle Mountain Front occurred along the buried Arbuckle thrust.

13) The Collings Ranch Conglomerate is on the footwall of the Washita Valley Fault, which was subsequently thrust over the conglomerate.

13) Structural style in wrench systems are poorly understood because many of our main concepts are not founded upon real-world analogs.

14) Rock-model of strike slip systems do not match clay models.

15) Flower structure interpretations must be held accountable to the rules of material balance.

16) Extensional fabrics in southern Oklahoma occurred as the result of post-compression extension and subsidence.

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IMAGE EVALUATION TEST TARGET (QA-3)

1.0 1.1 1.25 1.4 1.6 1.8 2.0 2.2 2.5 2.8 3.2 3.6 4.0 4.5 5.0

150mm

6"

APPLIED IMAGE . Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989