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Stratigraphic and Structural Evolution of the Ouachita Mountains and Arkoma Basin, Southeastern Oklahoma and West-Central Arkansas: Applications to Petroleum Exploration: 2004 Field Symposium

The Arbenz–Misch/Oles Volume

NEIL H. SUNESON, *Editor*

Ouachita Mountains—Arkoma Basin field symposium held October 21-23, 2004, in Poteau, Oklahoma

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Cover Image

This image shows the geology and terrain of the Ouachita Mountains and southern part of the Arkoma Basin in southeast Oklahoma and west-central Arkansas. The colors represent the geology of the area distinguished by five general geologic age groups: Cambrian to Devonian—magenta; Mississippian—purple; Early Pennsylvanian—light blue; Middle to Late Pennsylvanian—dark blue; and Cretaceous to Quaternary—yellow. The geology draped over the terrain highlights the complex geologic structure. The geology was modified from Stoeser and others (2005) and the terrain is a USGS 200-meter resolution shaded relief map derived from the National Elevation Dataset.

Sources:

Stoeser, D.B.; Green, G.N.; Morath, L.C.; Heran, W.D.; Wilson, A.B.; Moore, D.W.; and Van Gosen, B.S., 2005, Preliminary integrated geologic map databases for the United States: Central States: Montana, Wyoming, Colorado, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Iowa, Missouri, Arkansas, and Louisiana: United States Geological Survey Open-File Report 2005-1351, version 1.1, http://pubs.usgs.gov/of/2005/1351/.

United States Geological Survey National Center for Earth Resources Observation and Science (EROS), 2006, Grayscale conterminous United States shaded relief–200-meter resolution, Albers projection: National Atlas of the United States, available at http://nationalatlas.gov.

- Russell Standridge

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INTRODUCTION TO THE ARBENZ - MISCH/OLES VOLUME

Neil H. Suneson
Oklahoma Geological Survey

This volume contains two papers on the structural geology of the Ouachita Mountains of Oklahoma and Arkansas. The first, by J. Kaspar Arbenz, incorporates new data and new structural concepts to explain the surface and subsurface geology of the Ouachita tectonic belt. The second paper, by Peter Misch and Keith Oles, is based on their field work for Union Oil Company of California in the early 1950s. A summary of their paper, a proprietary report completed in 1956, fueled a heated debate in the Bulletin of the American Association of Petroleum Geologists regarding the degree of thrust faulting in the Ouachitas. Their report is an "historical" document, and although their conclusions are now largely discredited, many of their field observations and detailed maps and cross sections remain insightful.

Despite hundreds of geologic investigations dating back to the latter part of the 19th century, comprehensive structural interpretations of the Ouachita Mountains of Oklahoma and Arkansas are relatively rare. One reason may be that outcrops are relatively scarce, especially in the largely forest-covered and easily eroded shale-dominated Mississippian and Pennsylvanian units that make up much of the fold-and-thrust belt. As a result, detailed geologic maps are uncommon. Also, until recently, geologists exploring for petroleum avoided the area citing over-mature source rocks, the absence of potential reservoir rocks, and the remoteness of the area. A third reason is perhaps the most compelling: the Ouachita fold-and-thrust belt is very complex. An example illustrating the complexity is Pitt's (1955) identification of the Lukfata Sandstone, which he thought was older than the Collier Shale, in the core of the Broken Bow Uplift. He failed to recognize that many of the strata in the area are subhorizontally isoclinally folded. The type section of the so-called "Lukfata Sandstone" is overturned, and the "Lukfata" probably is the Crystal Mountain Sandstone.

Many excellent papers and unpublished masters theses and doctoral dissertations, some controversial and/or now dated, describe the structural geology of parts of the Ouachita fold-and-thrust belt. Examples include the studies by Hendricks and others (1947) of the western Ouachita Mountains and by Honess (1923) of the Broken Bow Uplift. Classic papers that describe the structural geology of the entire mountain range, e.g., Miser (1929), Flawn and others (1961), and Arbenz (1989a, 1989b) typically are based on these kinds of more local studies. More recent structural interpretations of the Ouachita fold-and-thrust belt are based on the following: data from new wells, improved interpretation of new and old seismic data by the petroleum industry; reinterpretation of "existing" structural data in light of new structural concepts; and new surface information (COGEOMAP and STATEMAP programs of the Arkansas Geological Commission, Oklahoma Geological Survey, and U.S. Geological Survey). Arbenz (this volume) combines the "old" studies with new data and concepts to interpret the structural geology and history of the Ouachita Mountains. Most of his data are based on field observations. As the report by Misch and Oles (this volume) clearly illustrates, careful field observations are just as critical today as they were 50 years ago. An additional important aspect of the Misch and Oles report is that it contains field data that are no longer available because some road cuts and outcrops that they used 50 years ago are now thoroughly eroded and degraded.

Historical Background of Misch and Oles Paper

One of the most contentious questions that faces geologists working in the Ouachitas concerns the degree to which the fold-and-thrust belt has been compressed or "telescoped". Simply stated: What is the collective throw on all the thrust faults in the Ouachitas and how much shortening is represented by folds? Some seemingly simple to complex questions related to this issue are the following:

1) Does a fault exist at a particular locality?
2) What is the attitude of a fault and how does its attitude change with depth?
3) What is the throw on a particular (thrust) fault?
4) How do individual faults merge and/or are accommodated by folds?

Arbenz (this volume) provides new answers to some of these questions.

A very public and acrimonious debate on the structural geology of the Ouachita Mountains among three well-known and respected field geologists erupted in the Bulletin of the American Association of Petroleum Geologists (AAPG) in August 1957 with the publication of a "geological note" titled "Interpretation of Ouachita Mountains of Oklahoma as autochthonous folded belt: preliminary report" by Peter Misch and Keith Oles. They concluded that "the stratigraphic and structural evidence indicates that the Ouachita Mountains are an autochthonous folded system" (Misch and Oles, 1957, p. 1901). This analysis differed substantially from those of Miser (1929) and Hendricks and others (1947), who reported numerous thrust faults and allochthonous thrust sheets.

Just over a year later Tom Hendricks, who (with colleagues) had mapped a large area in the western Ouachita Mountains of Oklahoma, published a discussion (Hendricks, 1958) of the Misch and Oles (1957) paper. He concluded that "abundant evidences [sic] of low-angle overthrusting ... exist in the Ouachita Mountains structural province" (p. 2764). Hendricks strongly criticized Misch and Oles and some quotes highlight the tone of his disagreement: 1) "... such a flatly contradictory statement requires factual support if it is to be given the slightest scientific recognition" (p. 2758); 2) "... the citations of publications of previous authors are so consistently in error that it is difficult to believe that Misch and Oles actually read the works cited" (p. 2760); 3) "This statement is completely incorrect and absolutely without foundation" (p. 2760); 4) "Misch and Oles publish no data that can be reviewed critically" (p. 2757). Hendricks submitted his comments to AAPG in January 1958, about five months after the original note appeared in print.

Misch and Oles replied to Hendricks' criticism in the same issue of the Bulletin (Misch and Oles, 1958). They refuted his comments, defended their interpretation that the Ouachitas are essentially autochthonous, and noted that his discussion "goes somewhat beyond an impersonal discussion ..." (p. 2765). Although they attempted to "refrain from making any general comments concerning the character of the Discussion ..." (p. 2765), some sarcasm crept into their reply. Hendricks' "charges" were labeled "generalized" and "perhaps a trifle sweeping" (p. 2765) by Misch and Oles. One heading in his discussion was called "rather formidable" (p. 2765). They claimed that Hendricks selectively quoted the literature, which "is somewhat less than conducive to conveying an objective picture" (p. 2769), and that in other cases he quoted them "out of context" (p. 2770). Finally, one quote from Misch and Oles illustrates how they viewed their response to Hendricks' discussion: "... the absurdity of the charges has been conclusively demonstrated" (p. 2776). Misch and Oles submitted their reply to AAPG in August 1958, about seven months after they may have seen Hendricks' comment.

An interesting sidelight to the disagreement is the length of the papers. The original preliminary note published by Misch and Oles (1957) is six pages long and includes one figure. Hendricks' (1958) discussion is longer – 7½ pages and no figures. Misch and Oles' (1958) reply is almost the length of a formal paper – 18 pages including 3½ pages of figures.

Misch and Oles (1958) began their reply by stating that they planned to publish a full report on their investigations; however, that never occurred until now. The full text and accompanying figures that formed the basis of their interpretation of the structure of the Ouachita Mountains are published in this volume.

Arbenz concludes here that large-scale horizontal displacement and local rotation of thrust sheets explain the surface and subsurface features observed on geologic maps and seismic data. So in the broadest sense, Hendricks was correct: the Ouachitas are not an "autochthonous" fold belt. However, many observations reported by Misch and Oles are also correct: most thrust faults dip steeply at the surface; compressional features are controlled, to a degree, by stratal competence (see Arbenz, this volume); and the curious nature of the Johns Valley Formation as a stratigraphic unit, which commonly is shown as fault-bounded, is noted.

Editor's Notes:

Table I in the Misch and Oles report, figure 1 in Appendix A, and page 9B and the electric logs in Appendix B were missing from the files given to the Oklahoma Geological Survey by Unocal (now part of Chevron) and therefore are not included.

Only minor changes were made in the text of the original paper by Misch and Oles. Obvious spelling and grammatical errors have been corrected and the page numbers in the Table of Contents refer to this volume. The date of the report was added to the original title to avoid confusion in future citations.

Acknowledgments

The editor wishes to acknowledge and thank Chevron Corporation for permitting the Oklahoma Geological Survey (OGS) to publish (unreviewed by the OGS and with only minor editing) "Stratigraphic and structural studies in the Ouachita Mountains, Oklahoma and Arkansas" by Peter Misch and Keith F. Oles, including paleontologic data by William H. Easton and Gerald E. Marrall. Their report, no. F-154, is based on field work done from 1953 to 1955 on behalf of Union Oil Company of California.

Rene Howard read this introduction and made many helpful suggestions that improved the text. Jim Anderson of the OGS cartographic staff scanned Misch and Oles' large plates and figures on to the CD-ROMs that accompany their paper. The editor also wishes to thank Susan Cogan of OU Printing Services for the layout and design of this circular. Paul Smith (OGS) printed this volume. And the entire project could not have been completed without the encouragement of Interim Director G. Randy Keller.

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Structural Framework of the Ouachita Mountains

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Structural Framework of the Ouachita Mountains

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INTRODUCTION

The Ouachita Mountains of southeastern Oklahoma and southwestern Arkansas are the largest outcrop area of the late Paleozoic orogenic system that formed along the southern margin of the Paleozoic North American craton. The outcrop area of the thrust-and-fold belt lies between the Reelfoot–Mississippi Rift in Arkansas and the Southern Oklahoma Aulacogen and consists of a nearly east–west part in Arkansas and a northwest-facing salient in Oklahoma.

Since the early 20th century, geologists have struggled to gain an understanding of the sedimentation, regional and detailed structural geology, and deformational history of the Ouachita Mountains. Acquiring knowledge in these areas, however, remains difficult for a number of reasons: (1) the dense vegetation prevents the inspection of outcrops along strike over long distances; (2) borehole information is sparse (with the exception of the northern imbricated zone); (3) the hinterland is covered by younger rocks; (4) fossil control yields only a sparse biostratigraphic framework; (5) large amounts of seismic data are confidential; and (6) where available, seismic resolution is still limited because the highly deformed Mississippian strata of the Stanley Group are acoustically nearly opaque and prevent a clear resolution of the complex structure in the pre-Stanley Paleozoic strata.

This report presents an updated look at the structural framework and history of the Ouachita Mountains by means of ten cross sections, six in Arkansas and four in Oklahoma. Because the cross sections are, on average, ~35 km apart, they cannot present a complete three-dimensional understanding of many on-strike critical transitions occurring between them. They display, however, some of the important structural conclusions this author has drawn from the data.

The history of acquiring geological data for understanding the complex geology of this fold-and-thrust belt is over a hundred years old and can be divided into a pre-plate-tectonic period and a post-plate-tectonic period. The first period was dedicated to data collection and early interpretation, and results were published in a string of remarkable papers. The most significant of that group are Honess (1923), Miser and Honess (1927), Powers (1928), Miser and Purdue (1929), van Waterschoot van der Gracht (1931), Hendricks and others (1947), and Hendricks (1959).

The second half of the 20th century stood in the limelight of plate-tectonics concepts, progress in understanding the nature and origin of deep-water sedimentation, the discovery of major hydrocarbon accumulations in thrust-and-fold belts in western Canada, and a general rush to be on the thrust-belt bandwagon by the petroleum industry. Important publications of this period include Misch and Oles (1957), Cline and others (1959), a major attempt at a summary volume by Flawn and others (1961), Hopkins (1968), Briggs and Roeder (1975), Wickham and others (1976), Walper (1977), Viele (1973), Viele and Thomas (1989), Zimmerman and others (1982), the group of contributors to "The Geology of North America" by Hatcher and others (1989), and Roberts (1994).

In the late 1970s and early 1980s, the oil industry renewed its interest in the area during the so-called "oil boom." This interest was kindled by successful exploration programs in several thrust-and-fold belts, and—more specifically—by a number of discoveries made in the transition zone between the Arkoma Basin and the frontal elements of the Ouachita Mountains. As a result, demand increased for up-to-date and larger-scale surface geologic maps, aerial photogeologic surveys, and closer seismic coverage. Geological and geophysical contractors responded by offering large proprietary and over-the-counter surveys, and governmental agencies (the U.S. Geological Survey [USGS], the Oklahoma Geological Survey [OGS], and the Arkansas Geological Commission [AGC]) and several universities accelerated mapping efforts and research projects.

In the early 1980s, the USGS, OGS, and AGC initiated a cooperative, cost-shared geological mapping project called "COGEOMAP." The project's mission was to issue new surface geological quadrangle maps at a scale of 1:24,000 for the entire outcrop area of the Ouachita Mountains.

After roughly 12 years, the oil boom began to wane. This led to drastic reductions in federal and state funding of the ambitious Ouachita mapping project, and project leaders were forced to explore alternative solutions for bringing the results of their work to the public. Most of the results have been published as open-file reports (e.g., OGS Open-File Reports from 1989 to 1997 [Hemish and Suneson, 1997, appendix 1] that are now superceded by the Oklahoma geology quadrangle [OGQ] series; Haley and Stone, 1994) and in field-trip guidebooks by the OGS and the AGC. These publications demonstrate that great progress has been made in gathering data and understanding the region's processes of sedimentation and structural deformation.

Despite this wealth of relatively recent data, though, much critical information is still missing and serious uncertainties keep interpretations in dispute. For example, the preponderance of highly deformed ductile rocks in the deeper parts of the stratigraphic section prevents us from determining correct formation thicknesses. This alone makes the construction of cross sections quite tentative. Second, thousands of meters of the stratigraphic section are devoid of reliable fossil control needed for more accurate age determinations and correlations. Third, traceable lithologic markers are rare, making kinematic restorations difficult. Finally, because the majority of the rocks have been deposited in deep water (at least below wave base), disconformities and minor unconformities may go undetected.

MAJOR STRUCTURAL ELEMENTS OF THE REGION

From north to south, the major regional structural elements of the outcrop area in the Ouachita Mountains comprise (1) the extensionally faulted and mildly drape-folded, south-dipping part of the Arkoma Basin that abuts the compressional thrust front but still belongs to the Paleozoic North American continental platform (Regions 2W and 2E, Pl. 1); (2) a north- and northwest-facing frontal thrust-and-fold belt of varied complexity that is made up of rocks deposited on the southern platform (Regions 3W and 3E, Pl. 1); and (3) the main outcrop region of Ouachita Mountains proper, which consists of a complex set of thrust sheets made up entirely of deep-water sediments of Cambrian to Pennsylvanian age (Regions 4N, 4A, 4B, and 4C, Pl. 1). The sedimentary rocks, known as the "Ouachita facies," must have been deposited in a deep-water basin that had to lie south and east of the continental margin.

These rocks now rest as a large allochthonous mass on the rocks of the southern continental platform. A through-going fault system, the Ti Valley–Y City Fault (Pl. 2), separates the imbricated frontal belt from the allochthonous Ouachita-facies strata (hereafter called the "Ouachita Allochthon"). Some elements of an intermediate (slope?) facies appear to exist between the two domains.

At the western end of the outcrop area near Atoka, Oklahoma, the entire frontal thrust belt is absent. Here, all frontal thrust faults have merged with the Ti Valley Fault, which is the major, facies-dividing fault. Near the eastern end of the Ouachita Mountains north of Little Rock, Arkansas, the thrusts of the frontal belt lose their throw and become detached buckle folds.

STRUCTURAL PROVINCES AND THEIR BORDERS

The recognition of meaningful structural subdivisions of a larger region can best be approached by a stepwise progression from two-dimensional surface maps to first single and then serial cross sections, leading finally to three- and four-dimensional analyses of the region. Each of the steps in this approach, however, can add to the uncertainty of the results because increasing inter- and extrapolation (and creative imagination) tend to cloud the initial hard data.

To present an updated look at the region's structural fabric and history, this study uses ten cross sections (Pls. 3–7B): six in Arkansas (Pls. 4A–5C, cross sections AR1–AR6) and four in Oklahoma (Pls. 6A–7B, cross sections OK1–OK4). These cross sections contain information gleaned from published data, private communications, a few selected seismic lines, and personal observation. Although the cross sections cannot present a full three-dimensional understanding of many on-strike critical transitions occurring between them (because they are, on average, ~35 km apart), they illustrate some important structural conclusions that can be drawn from the data.

Within the Ouachita Allochthon, the deformational styles are closely related to the folding character (wavelengths and amplitudes) of competent beds of varying thickness and rigidity as they appear in the stratigraphic section (Fig. 1). As a result, subdividing the area into structural provinces by the mechanical behavior of major stratigraphic intervals may be more instructive than other classification schemes. Because of the great thickness (~10 km) of the entire stratigraphic column of the Ouachita facies, the author proposes a subdivision into at least three significantly different vertical segments.

The three proposed stratigraphic–structural style classes are described below from the base up.

1. A style of alternating ductile marine shales and competent sandstones and cherts is prevalent in the pre-Carboniferous rocks. This section is essentially shale-dominated, but the competent, folded and faulted, ridge-forming sandstone and chert formations display separate fold trains that demand much flowage in the separating shales.
2. The next style interval is confined to the highly deformed and overall ductile section of the shaly flysch facies that characterizes the lower two-thirds of the Mississippian Stanley Group (~2 km thick). Numerous thin clayey sandstone members show mappable chevron-type fold trains, but these are usually discontinuous and often disharmonic. This whole interval acts as the main zone of disharmony and detachment that exists between the pre-Carboniferous structures and the greatly different structural style of the younger turbidites.
3. The third and youngest structural style is characterized by the large- to gigantic-scale flexural folds that deform the Late Mississippian and Pennsylvanian deep-water turbidite sandstones and shales and occupy a large portion of the outcrops of the Ouachita Mountains. Turbidite sandstones form an almost continuous assemblage

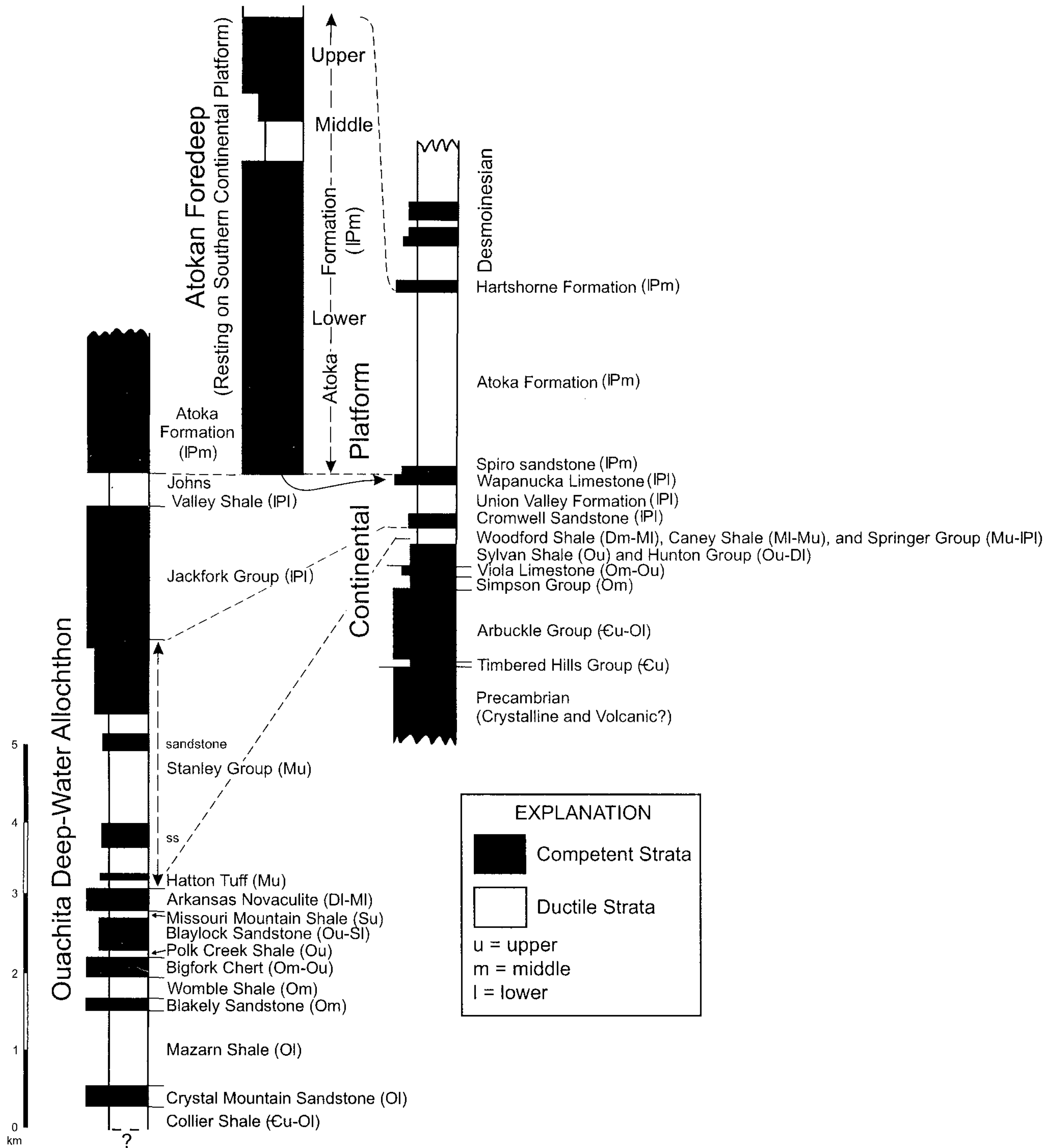

Figure 1. Generalized stratigraphy and relative competence and ductility distribution of the deep-water Ouachita-facies and continental-platform strata in the Ouachita Mountains.

from the upper Stanley Group (Mississippian), the Jackfork Group and Johns Valley Shale (Morrowan), and the overlying Atoka Formation (Atokan). The sandstone units are interbedded with countless shale partings and shale members as much as several hundred meters thick. These shale beds facilitate the mechanism of flexural folding. In the Oklahoma salient, the combined sandstone package is almost 4 km thick and appears to act as a single buckled plate. The resulting folds have wavelengths as large as 15 km and amplitudes >5 km.

The cross sections and Plate 2 contain the data for dividing the entire region of the Ouachita Mountains into the genetically related segments that are discussed next. Stone and Haley (1984) first delineated comparable segments or "belts" in Arkansas for similarity in structure, stratigraphy, and history of deformation. No major problems arise from extending most of these belts into the entire outcrop area of the Ouachita Mountains as shown, with minor modifications, on Plate 1. Because these belts had been given unique Arkansas names, the author has replaced them with more "generic" terms that could be used in the entire area of the Ouachita Mountains (Table 1).

Continental Foreland

Region 1 on Plate 1 is a small part of the North American craton that borders the Ouachita system on the north. It includes the northern Arkoma Basin and the south flank of the Ozark Uplift, the southwest extension of which becomes the Northeast Oklahoma Shelf (or Platform). The region lies north of a line beyond which we can recognize no compressional mesoscale strain of the Ouachita orogeny. The ten cross sections end as this province is reached.

The southward-tilted foreland crust consists of a Precambrian basement (~1,300–1,400 Ma) of a rhyolitic to andesitic volcanic complex that is intruded by pink granitic rocks (Denison and others, 1977) and a Paleozoic sedimentary section of dominantly carbonate rocks 3.5 to 4.0 km thick along the southern boundary of this province. The main structural attribute of the south flank of the Ozark Uplift and the Arkoma Basin is the steadily increasing southward tilt and thickening of the shallow-marine deposits that form a Late Cambrian to the Early Pennsylvanian sedimentary wedge (Haley and Frezon, 1965; Bush and others, 1977, 1978; Johnson, 1988). The only interruptions in this steady subsidence are minor events of epeirogenic unrest in the Siluro–Devonian, which caused some erosional and depositional thickness and facies variations. The last of the pre-orogenic platform sediments were deposited in the late Morrowan (Wapanucka Limestone in Oklahoma) and the earliest Atokan (Spiro sandstone).

After the early Atokan the gradual subsidence was interrupted for ~10 m.y., during which the subsidence increased markedly and sedimentation rates increased more than 20-fold. The sedimentation rates remained high throughout the Desmoinesian.

In contrast to the foreland of other thrust belts of North America, the Ozark–Arkoma basement and sedimentary cover is broken by an unknown number of extensional faults. These faults may have formed as regional basement fracture systems in the Late Precambrian, possibly in conjunction with the breakup and rifting of the southern Laurentian continental plate margin (Thomas, 1977). The most active phase of faulting affecting the Ozark–Arkoma platform rocks occurred in the Carboniferous, coinciding with the rapid down-bending of the basin flank from the early Atokan through the Desmoinesian.

Although basement faults in the Ouachita foreland strike in all directions, a large majority are oriented southwest–northeast. Many of these faults are downthrown to the south and were particularly active through much of the Atokan while sedimentation was occurring. As a result, growth faulting reinforced the accelerated subsidence and accumulation rates (Houseknecht, 1983, 1986; Johnson, 1988; Arbenz, 1989a; Perry and Suneson, 1990; Roberts, 1994). The amount of displacement on these faults varies greatly—most are tens to hundreds of meters, with a few displacements as much as several thousand meters.

Extensive modern seismic exploration and drilling for gas in Atokan and older reservoirs in the Arkoma Basin has been under way since the 1950s. This activity has resulted in a good

Table 1.—Major Structural Provinces

Designation in this Report[a]	Terminology in this Report	Terminology used by Stone and Haley (1984)
1	Continental Foreland (or platform)	Arkoma Basin
2	Southern Arkoma Basin Fold Belt	Arkoma Basin
3	Frontal Ouachita Thrust-and-Fold Belt	Rover Belt
4N	Ouachita Allochthon, northern imbrications	Aly Belt
4A	Ouachita Allochthon, upper level (Late Mississippian to Atokan)	Aly Belt
4B	Ouachita Allochthon, lower level (Early Mississippian)	Aly Belt
4C	Ouachita Allochthon, Central Uplifts (Cambrian to Devonian)	Amity, Hopper, Mt. Ida, Nixon Belts

[a]See Plate 2

understanding of the structure of the Ouachita foreland north of the compressional front as well as farther south. The style is characterized by a mosaic of fault blocks along at least three intersecting sets of basement faults. The fault blocks are usually tilted as a result of listric normal faulting. Such fault blocks have produced a large variety of combination "fault/dip/drape" traps that form most of the gas fields in the Arkoma Basin (Berry and Trumbly, 1968; Buchanan and Johnson, 1968; Haley and Hendricks, 1968, 1972; Arbenz, 1989a; Denison, 1989; VanArsdale and Schweig, 1990; Roberts, 1994).

The extensional-fault style described above continues south beneath the compressionally detached and deformed elements of the Ouachita Thrust-and-Fold Belt. Although this substrate is not exposed at the surface, seismic lines in the Ouachita Mountains show a similar extensional faulting style for at least 25 km under the thrust front. The age of the normal faulting seems to be linked to the accelerated subsidence of the Arkoma Basin and the south flank of the Ozark Uplift. Although some faulting on the platform may have happened during the drifting and cooling stage of the continental margin in the early and middle Paleozoic, no such faulting has been documented. The age of the active, down-to-south, normal growth faulting in the Arkoma Basin seems to be linked to the accelerated asymmetric subsidence of the basin, starting in the south, possibly in the Mississippian, culminating in the Atokan in the southern Arkoma Basin, and lasting into the Desmoinesian in the northern Arkoma Basin. This indicates a progressive south to north subsidence front in the Ouachita foredeep basin.

Southern Arkoma Basin Fold Belt

This province (Pl. 1, Regions 2W and 2E) is the northernmost element of the Ouachita orogen. It lies between the northernmost clearly recognizable compressional structures and the traces of the northernmost major through-going thrust faults. Early in the history of the geologic mapping in this region these border faults (Choctaw Fault in Oklahoma and Ross Creek Fault in Arkansas) were designated as the northern border of the Ouachita Mountains. As a consequence, the area of gentle compressional and drape folds north of the Choctaw Fault or the Ross Creek Fault remains, by tradition, part of the Arkoma Basin.

This fold belt consists of two structural levels separated by one or more zones of detachment in the ductile shales of the Atoka Formation. The pre-Atokan section displays a continuation of the foreland structural style, namely, a block-faulted basement covered by Cambro-Ordovician carbonates and younger platform sediments. In Oklahoma the basal Atokan Spiro sandstone typically belongs to the block-faulted infrastructure. The basal detachment of the overlying fold belt occurs mainly in the Atokan shales (Berry and Trumbly, 1968; Buchanan and Johnson, 1968; Houseknecht, 1986; Johnson, 1988; Perry and Suneson, 1990; Suneson and others, 2004).

Because most faulting in this province occurred during the deposition of very ductile Atokan shales, growth faulting (i.e., "compensatory" sedimentation) (Fig. 2A) smoothed out the structural relief by creating thick shales and sands in the structural lows. As the recently deposited sedimentary rocks laterally buckled during the latest stages of the orogeny in the early Desmoinesian, the thrust detachment was forced—by reason of least resistance—to stay in the shales and ramp over the competent structural highs in the substrate. Figure 2B illustrates that—during such ramping—the growth portion of the hanging wall rode up the detachment ramp and onto the footwall step, to form the core of a pronounced fault-bend fold. It should be pointed out that the displacements along this uneven Atokan detachment are rather local and rarely are more than a kilometer, but the amount of the added thickness contributes substantially to the height of these fault-bend folds.

In map view these fault-bend folds are not parallel. Especially in the Oklahoma salient, the lack of a parallel arrangement of the fold axes is striking and reflects the deep fault pattern.

In the northern part of the Southern Arkoma Basin Fold Belt the main detachment between the compressional folds and the extensional substrate stays in early Atokan ductile shales. Faults branching up from this detachment into the cores of emerging anticlines are common, and some of these branches are exposed at the surface. Notable examples are the Carbon Fault and the McAlester Fault in Oklahoma and numerous faults in the Ranger, Pine Ridge, and Washburn Anticlines of Arkansas (Blythe and others, 1988). The displacements along these upward-branching local thrust faults are quite small, which is demonstrated by the minor offsets of key beds at the plunging ends of the folds.

As the Choctaw Fault is approached from the north, the basal detachment of the frontal zone tends to descend southward across the base of the Atokan into shale in the Springer Group (Morrowan) and farther south into Mississippian shales. In Oklahoma this interval includes the Spiro sandstone (basal Atokan) and the subjacent Wapanucka Limestone (upper Morrowan), which together form a distinct lithologic marker in boreholes and on seismic sections, allowing more reliable structural interpretations (Perry and Suneson, 1990; Tilford, 1990).

Along the Ouachita Mountains front in Arkansas the folds in the Southern Arkoma Basin Fold Belt are long and quite parallel. With only minor en echelon offsets, the longest anticlinal trend (the Hartford–Ranger–Cadron Anticline) is ~250 km long (Pl. 2). These folds strike almost east–west; the Ross Creek Fault, which in this part of Arkansas is the frontal fault of the Ouachita Mountains, makes an acute angle of ~20° with

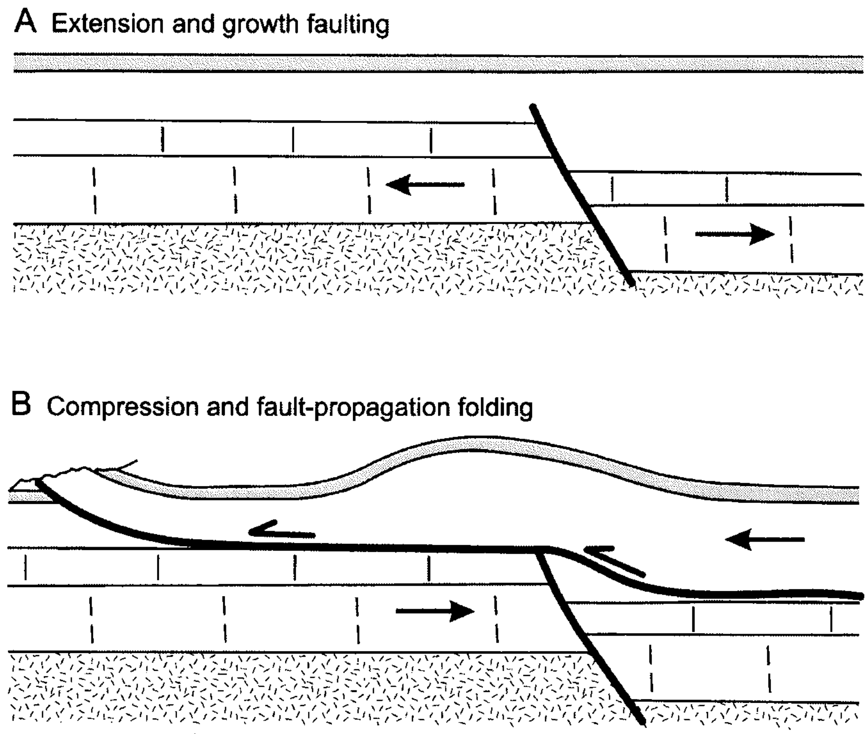

Figure 2. Diagram of Atokan growth faulting and its effect on the height of subsequent fault-propagation folds in the Southern Arkoma Basin Fold Belt. The closeness of the fold axis to the growth fault demonstrates the similarity of the fold pattern to the pattern of the basement faults.

the fold trend. Both of these trends are also evident north of the compressional front of the Ouachitas where surface faults and flexure trends form an unmistakable network of intersecting fault sets.

In the Oklahoma salient the Choctaw Fault and its related imbricate thrusts ride more obviously across the faulted foreland. Along the trace of the Choctaw Fault the angles between that fault and the fold axes in the basin are from 20° to 35° (e.g., the angle between the Choctaw Fault and the Heavener or McAlester Anticlines) (Pl. 2). These geometric relationships demonstrate that the thrust front does not control the orientation of the major folds of the Southern Arkoma Basin Fold Belt. Instead, the folds are primarily controlled by the deformational fabric of the faulted infrastructure.

Where synclines in the Southern Arkoma Basin Fold Belt abut the Choctaw Fault, we usually encounter a triangle zone (Pls. 5C, 6A, 7A, and 7B). The internal structure of these triangle zones changes rapidly (see Appendix). The variations are caused primarily by the limited lateral size and varying displacement of the multitude of small, stacked, spoon-shaped thrusts (Perry and Suneson, 1990; Tilford, 1990; Valderrama and others, 1994). These complex structures came to be better understood after intensive seismic exploration from the 1960s to 1980s, which was followed by a series of hydrocarbon discoveries in the Red Oak and Spiro sandstones (Atokan), the Wapanucka Limestone and Cromwell Sandstone (Morrowan), and the Arbuckle Group (Ordovician) along the Oklahoma salient (Suneson and others, 1990).

About 35 km east of the Oklahoma-Arkansas state line the displacement along the Choctaw Fault goes to zero and the fault disappears on the north limb of the Hon Anticline in the Waldron, Arkansas area (Reinemund and Danilchik, 1957) (Pl. 2). The role of the mountain-front thrust passes to the next southern major thrust fault, the Ross Creek Fault, ~10 km to the south. This fault becomes the northern boundary of the Ouachita Thrust-and-Fold Belt from here to the Arkansas River where it, too, loses its throw in the north limb of the Cadron Anticline (Pl. 2). This is another example where a pre-existing basement fault is reflected in the overlying anticline. Both the eastern Choctaw Fault and the Ross Creek Fault are likely to have originated near basement growth faults.

The cross sections of the Southern Arkoma Basin Fold Belt (e.g., Roberts, 1994; Pls. 4A–5C in this report) demonstrate that the levels of horizontal shortening during the folding process in this belt are only a few percent and that the rocks have not traveled far from their site of deposition. There is little doubt that this entire structural belt comprises strata belonging to the domain of the continental platform.

Frontal Ouachita Thrust-and-Fold Belt

The stratigraphy, structural style, geomorphic expression, and depositional and deformation history of the Frontal Ouachita Thrust-and-Fold Belt have the character of an orogenic foredeep. As mentioned previously, the northern boundary of this belt is the Choctaw Fault in the west and the Ross Creek Fault in most of Arkansas. Both faults come to a point of zero displacement at their east end. The Choctaw Fault ends ~30 km east of the Arkansas–Oklahoma state line and the Ross Creek Fault ends at the Arkansas River ~40 km northwest of Little Rock.

The termination of these two faults puts important constraints on the transport distance and direction of the thrust plates. At their end neither thrust fault moved more than the shortening that is required for the related folds to buckle (<10%). This reduction to zero thrust displacement proves that the rocks of this belt are part of the southern continental foreland rather than of the allochthonous Ouachita thrust complex.

The latter must have originated from a depocenter south of the continental margin, as discussed below.

The southern border of this belt is at the fault (or fault zone) where the strata of the platform sequence are juxtaposed against those that are allochthonous and were deposited in a deep-water basin of an entirely different character. These critical defining faults are the Y City Fault in the east and the Ti Valley Fault in the west (Pl. 2).

The rocks within this belt are predominantly Atokan and display facies and thickness changes that suggest a transition from platform sedimentation in the north to the rapidly subsiding Atokan orogenic foredeep in the south. Within this belt the Atokan rocks pass from a neritic environment in the north to an upper bathyal environment in the south (Cline, 1968; Bush and others, 1977; Sutherland and Manger, 1979). The subsidence was accompanied by multiple growth faults (Stone and McFarland, 1981; Houseknecht, 1986; Johnson, 1988; Visher, 1988; Roberts, 1994) and amounted to a collapse of the continental margin. This collapse was possibly triggered by thrust loading by the advancing Ouachita Allochthon or a rejuvenation of rifting north of the former continental margin. The increase in thickness across this belt is from ~600 m in the north to 3 km in Oklahoma and to ~7 km in the northeastern Ouachita Mountains of Arkansas.

The main change from neritic to deep-water sedimentation in the Atoka Formation occurred near the Choctaw–Ross Creek Faults. The southern border of the Atokan foredeep basin fell victim to erosion and/or tectonic burial by the arriving allochthonous Ouachita thrust sheet, although some southern elements of the foredeep fill may be trapped as fault slices along the Ti Valley and Y City Faults.

The structural style in the frontal thrust belt is strongly influenced by the thickness of the early Atokan turbidite sandstones. The style comprises structures ranging from massive thrust slabs and broad, lobate synclines in the thickest turbidites to thin, laterally limited thrust slices and narrow, faulted folds in the thin sandstones. At its eastern end, east of the Arkansas River, this belt cannot be separated from the fold belt to the north because no major fault separates the two. A few kilometers to the west, on the west side of the Arkansas River, the whole belt consists of one gigantic flexural-slip syncline, the 120-km-long Fourche LaFave Syncline (Pl. 2). The south limb of this single structure is made up entirely of the lower part of the Atoka Formation, which here is 4.5 km thick. The surface distance between the base of the Atokan on the two limbs of this syncline is ~20 km.

The Ross Creek Fault, the adjacent Fourche LaFave Syncline, and a number of smaller structures in the frontal Ouachita Mountains east of the state line strike slightly more northerly than does the frontal thrust-and-fold belt. This en echelon arrangement may have its origin in Precambrian basement fault patterns (Houseknecht, 1986). From its east end near the Arkansas River, the Ross Creek Fault cuts obliquely across the entire structural belt and ends at the Ti Valley–Y City Fault. The Fourche LaFave Syncline and its westward continuation, the west-plunging Black Fork Syncline (Reinemund and Danilchik, 1957) diminishes in width and disappears in more complex smaller structures near the juncture of the two faults.

North of the town of Waldron, the Choctaw Fault ends in the northern flank of the Hon Anticline, and the traditionally agreed-upon mountain front of the Ouachita Mountains moves from the Ross Creek Fault in Arkansas to the Choctaw Fault in Oklahoma. Here the scale of the deformational structures becomes smaller—as does the thickness of the entire Atokan section—and the overall sand-shale ratio decreases. The sandy and resistant lower Atoka Formation decreases from ~4.5 km thick in the central portion of the Fourche LaFave Syncline to <1.5 km thick in the Oklahoma salient. As a result the overall structural style becomes imbricated and more internally folded and disharmonic.

About 50 km west of the state line and close to the center of the Oklahoma salient, the hanging wall of the Choctaw Fault is overlain at the surface by a set of thin imbricate thrust slices, the number of which increases westward from two to eight slices near the town of Pittsburg, Oklahoma. These slices are thin, shingle-like thrust sheets and consist of a resistant center of Wapanucka Limestone and Spiro sandstone with varying thicknesses of Springer shale below and Atoka shale above. Branches of the Choctaw Fault must have peeled off these slices as they ramped northward over a growth fault into the extremely ductile early Atokan shales. The ductility contrast between the brittle limestone–chert–sandstone centers of these slices and their ductile cover and base must have been high enough to keep some of these thin slices intact for as much as 15 km along strike (Hendricks and others, 1947). These thin thrust slices pass to the north and sideways into numerous smaller, crescent- and snow-shovel-shaped thrust elements (Tilford, 1990) which were discovered mainly by seismic and drilling programs. North of the Choctaw Fault the sole fault for most of the anticlinal structures in the Southern Basin Arkoma Fold Belt remains in the ductile Atokan shales.

The uppermost (i.e., southernmost) thrust of this imbricated frontal stack brings to the surface the first thick unit of early Atokan deep-water turbidite sandstones that form the core of the northernmost Ouachita Mountains in the Oklahoma salient. The sudden appearance of these thick sandstones must have been caused by the ramping and northward transport of sandstones that had been deposited on the downthrown side of a major early Atokan growth fault that was active during the subsidence of the foredeep basin.

The southwest end of this frontal thrust-and-fold belt lies just north of Black Knob Ridge near Atoka, Oklahoma, where the Choctaw Fault and its branches appear to merge with the Ti Valley Fault (Pl. 2). From here south, the Ouachita orogenic front is the Ti Valley Fault, which carries to the surface deep-water rocks of the "Ouachita facies." These rocks crop out on Black Knob Ridge and include the Womble Shale (Middle Ordovician) at the base and all younger units. Hendricks (1943) and Hendricks and others (1947) suggested that the Choctaw Fault should be mapped in the Atokan outcrops ~3 km west of the outcrop of the Ti Valley Fault. The relatively shallow depositional environment of these Atokan beds, however, is evidence that these belong to the foreland facies.

With the exception of the frontal imbricate thrust faults that include the Wapanucka Limestone (and its cherty equivalent, the Morrowan Chickachoc Chert), this structural belt consists almost entirely of Atokan flysch. Structural interpretations in this belt suffer from the absence of reliable paleontologic or lithologic markers in the Atoka Formation. The authors of the Geologic Map of Arkansas (Haley and others, 1976) and others (Haley and Stone, 1994) divided the Atoka Formation in Arkansas into upper, middle, and lower parts by lithologic character, primarily the percentage of shale in the section. In structurally less complex regions, such as the Fourche LaFave Syncline, this subdivision works well for constructing and structurally restoring cross sections. In much of the outcrop area of the frontal Oklahoma salient, however, the structure is too complex to estimate the displacement across most faults. This inability to resolve structural geometries is particularly frustrating in a 60-km-long segment of this complex belt that straddles the Arkansas–Oklahoma state line between the longitude of Waldron (Arkansas) and Heavener (Oklahoma).

In the Oklahoma salient the topography of the deep-water Atoka Formation shows a pattern similar to that seen in Arkansas. A mountain ridge supported by ~1,000 m or more of lower Atokan turbidite sandstones forms a mountain range along the convex side of the salient. This ridge includes Pine, New State, and Blue Mountains. On the southeast side of this ridge there are at least three sets of internally faulted, east–west-striking and east-plunging anticlinal satellite folds (in the E½ T. 2 N., R.13 E.; E½ T. 3 N., R.15 E.; W½ T. 3 N., R. 17 E.). Some of these folds look like detached wrinkles in the top of the lower Atoka; others appear to cross the entire lower Atoka ridge. All these folds show easterly axial plunges and their intervening southeast-facing limbs dip toward the adjacent valley floor, which is part of a large topographic depression called Ti Valley. These folds give the appearance of a left-lateral strike-slip component along the south base of the frontal mountain range, but they could also be explained by a post-folding axial rotation caused by the uplift of the younger Arbuckle system to the south.

Ti Valley is ~60 km long and as much as 4 km wide. It harbors some of the most enigmatic geological features of the western Ouachita Mountains. On the floor of the Ti Valley Hendricks and others (1947) mapped a number of isolated outcrops of Paleozoic rocks, ranging in age from Devonian to Pennsylvanian. These rocks have been identified as Pinetop Chert (equivalent to the Haragan Formation, Hunton Group) (Devonian), Woodford Shale (Devonian–Mississippian), Caney Shale (Mississippian), and Springer Group (Chesterian-Morrowan). The rocks occur in a rather contorted matrix of Atokan shales with very little sandstone (Suneson, 1988) and contain elements of both foreland and deep-water Ouachita facies representing a transitional upper-slope environment. Outcrops of Atokan shale predominate in the Ti Valley area. The older rocks appear most often in small outcrops in creek beds and on low hills. Hendricks and others (1947) mapped these outcrops as small fault slivers in a network of thrusts and tear faults all brought up by a suggested master thrust fault, called the Pine Mountain Thrust, that they mapped along the west side of Ti Valley.

In the center of the southern part of Ti Valley (T. 2 N., R. 14 E.) we find an additional group of outcrops that contains out-of-place Ouachita-facies rocks, namely sandstones of the Jackfork Group and Johns Valley Shale. The largest of these outcrops are sandstones belonging to the deep-water flysch facies of the Jackfork that forms extensive outcrops in the Ouachita Allochthon to the south of the Ti Valley Fault. The isolated sandstone outcrops form a cluster of ~3.5 km2, show erratic attitudes, and are surrounded by poorly exposed Atokan shales. Hendricks and others (1947) interpreted these sandstone outcrops to be erosional remnants (klippen) of the Ouachita Allochthon that is exposed south of the Ti Valley Fault. The author has misgivings about the structural interpretations of the Ti Valley outcrops and the Pine Mountain Thrust set forth by previous authors (Hendricks and others, 1947; Marcher and Bergman, 1983; Suneson, 1988) and proposes an alternative interpretation. The doubts stem from the following:

1. The lower Atoka Formation of the frontal thrust complex (Katy Club Fault and Choctaw Fault) contains near its base a thin Atoka shale overlain by at least a kilometer of turbidite sandstones and shales that support the frontal mountain ranges. The lower Atoka Formation on the south side of the supposed Pine Mountain Thrust that should overlie the previously mentioned Devonian and Mississippian slivers in the southern Ti Valley should also display at least a notable section of the Atokan turbidite sandstones that are so pronounced and widespread in the frontal mountain ranges a few kilometers to the northwest. Instead we find a large outcrop area of poorly exposed, valley-forming Atokan shale.

2. If the Pine Mountain Thrust had been detached along a basal thrust in pre-Devonian rocks, we could expect that the competent Pinetop Chert would form more extensive and topographically expressed outcrops in the open valley of Atokan shale, especially in the vicinity of the Pine Mountain Thrust.

Furthermore, some of the many wells that have been drilled in Ti Valley over the last 20 years should have revealed these pre-Atokan rocks in the subsurface. To the author's knowledge, neither Pinetop Chert nor any other pre-Pennsylvanian formations have been encountered or reported. Nowhere along the northwest side of Ti Valley are there any indications that the existing structures in the lower Atoka turbidite sandstones have been clipped off or terminated by faulting (e.g., in or at the east foot of Pine Mountain). The three groups of tight, eastward-plunging and somewhat internally faulted satellite folds all appear to be diving beneath the Ti Valley floor. The topographic break at the west side of Ti Valley appears to be a normal contact between a sandstone and a shale that does not have the character of a thrust-fault contact.

3. The suggestion that the puzzling outcrops of Jackfork sandstone in Ti Valley are the remnants of a klippe is also questionable. If these outcrops really had been part of a much larger thrust sheet that was originally tied to the main Ouachita Allochthon there is little reason why they should occur in a topographic low and not at topographically higher points.

In view of all these considerations, the author has tentatively concluded that (a) the topographic depression of Ti Valley is caused by shales in the middle part of the Atoka Formation and that the hills on the south side of the Ti Valley are outcrops of structurally more complex upper Atoka Formation sandstones and shales, and (b) the middle part of the Atoka Formation in Ti Valley is therefore considered to be a large olistostrome that was deposited in the foredeep of the advancing orogen. Rivers and creeks, landslides, debris flows, mud slides, and major slope failures fed an assortment of exotic olistoliths that came to rest as clasts of all sizes in a shale-prone ocean basin during a high-standing sea level. A similar mechanism is also suggested for the larger masses of Jackfork sandstone that had reached a higher level of lithification. Such a proposition needs much field testing and requires far better detailed paleontologic and/or lithologic dating of the Atokan rocks. A structural interpretation of this entire province would gain primarily from a better biostratigraphic subdivision of the many kilometers of deep-water Atokan flysch.

Ti Valley–Y City Fault

The southern boundary of the frontal thrust-and-fold belt (Pl. 1, Regions 3W and 3E) is the Ti Valley Fault in the western part of the Ouachita Mountains and the Y City Fault in the east. These fault systems represent the most important tectonic boundary of the entire Ouachita Mountains and serve as a real "suture" along which rocks of two entirely separate depositional and structural domains are brought together:

1. On the north side we find the foreland and the orogenic foredeep provinces that are clearly sedimentary rocks deposited on the North American continent.
2. On the south side we see the large allochthonous terrane of deep-water rocks ranging from the Late Cambrian to the early Atokan, which were deposited in an oceanic basin that must have lain south of the buried continental margin (Keller and Cebull, 1973; Lillie and others, 1983; Lillie, 1984, 1985; Kruger and Keller, 1986; Keller and others, 1989; Nicholas and Waddell, 1989). These deep-water rocks, often referred to as the "Ouachita facies," were transported northward during a Pennsylvanian orogeny and came to rest on the outer continental platform. A minimum transport distance between the Ti Valley–Y City Fault and the suggested present position of the Paleozoic continental margin (Keller and others, 1989) is 70 to 150 km (Fig. 3).

The distinction between rocks of the two provinces would seem to be quite simple, but in practice is difficult because sedimentation in both domains ended in the Atokan with the deposition of deep-water flysch-like clastics. Sedimentation on the southern part of the continental platform ended in the Atokan when the continental margin subsided and a thick flysch section was deposited in the foredeep. Uplift and erosion followed. In the deep-water Ouachita basin, deposition of a thick flysch section from the Mississippian to the Atokan also ended in the Atokan with uplift and erosion.

The Atokan flysch looks very similar in the two depositional realms. The two depositional basins, the orogenic foredeep rocks on the continental margin and the final stages of the Ouachita deep-water basin, possibly merged into one basin during the northward transport of the allochthonous thrust sheet. No angular unconformity has been detected, however, in the thrust sheets of the allochthon or in the foredeep deposits. In the preceding Morrowan, however, the two basins were still separated by a structural high that may have existed near the continental margin. Figures 4A and 4B show two possible origins for the Johns Valley boulders.

The transition of the Ti Valley Fault into the Y City Fault occurs near the Arkansas–Oklahoma state line, where the north-vergent Ti Valley Fault passes into the south-vergent Y City Fault that marks the south flank of the Black Fork Syncline. This suggests the following scenario: the advancing front of the Ouachita Allochthon must have encountered massive Atokan turbidites (several kilometers thick), on the downthrown side of the basement growth fault that was to become the Ross Creek Fault. Because the leading sole fault of the Ouachita Allochton was unable to ramp over the Atoka sandstones, it formed an underthrust which lifted the south limb of the Black Fork and the Fourche LaFave Synclines. This, in turn, formed a huge triangle zone. The south-vergent thrust of this triangle zone became the Y City Fault, which emerged as a south-vergent conjugate shear of the Ti Valley Fault.

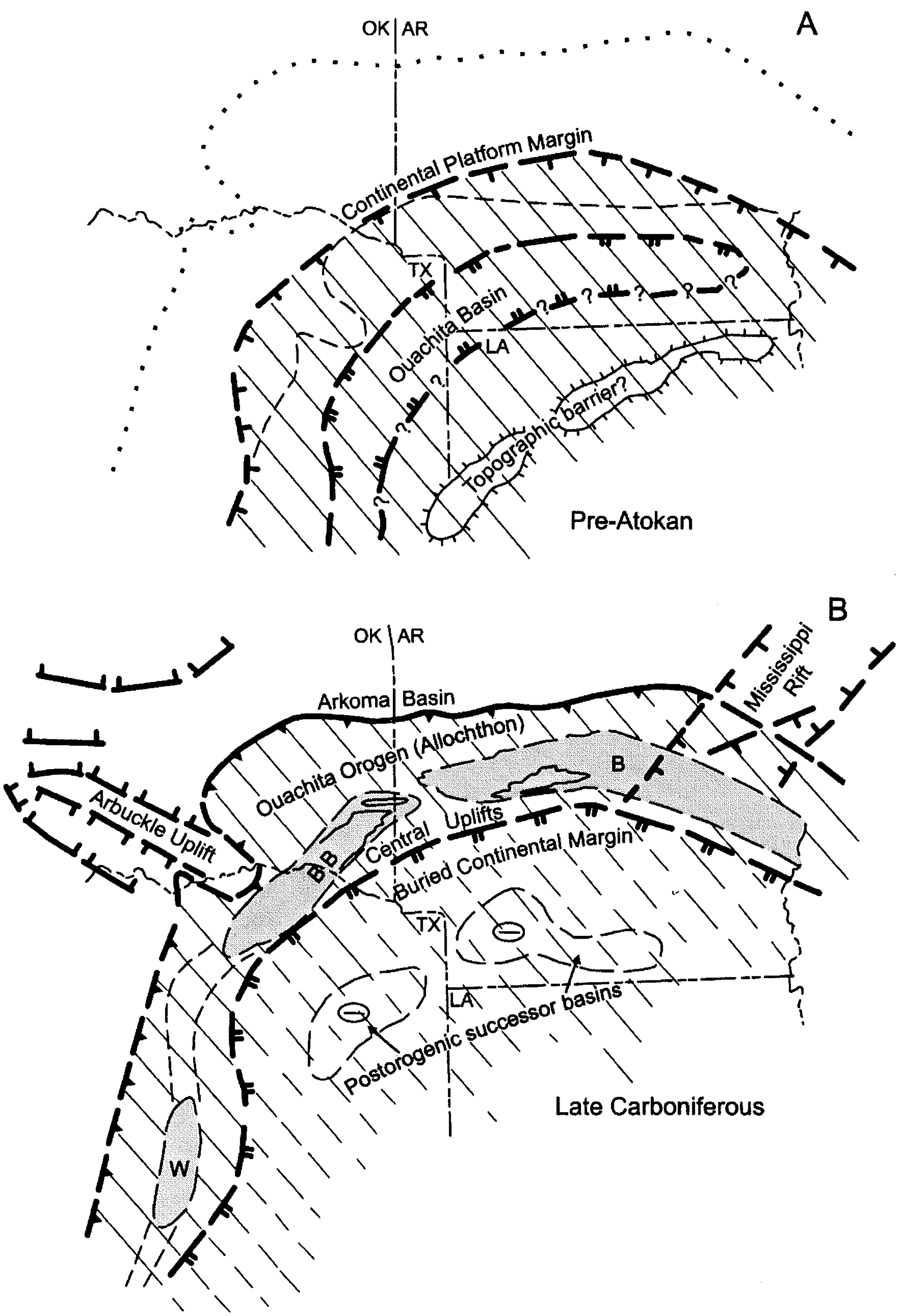

Figure 3. (A) Original pre-Atokan position of the Ouachita deep-water basin to the south of the Paleozoic continental margin. (B) Present distribution of the Ouachita Allochthon and its Central Uplifts (B—Benton; BB—Broken Bow; W—Waco). Note the erosional indentation in the thrust front caused by Early Permian uplift of the Arbuckle Mountains. Hachures: area of deep-water Ouachita facies.

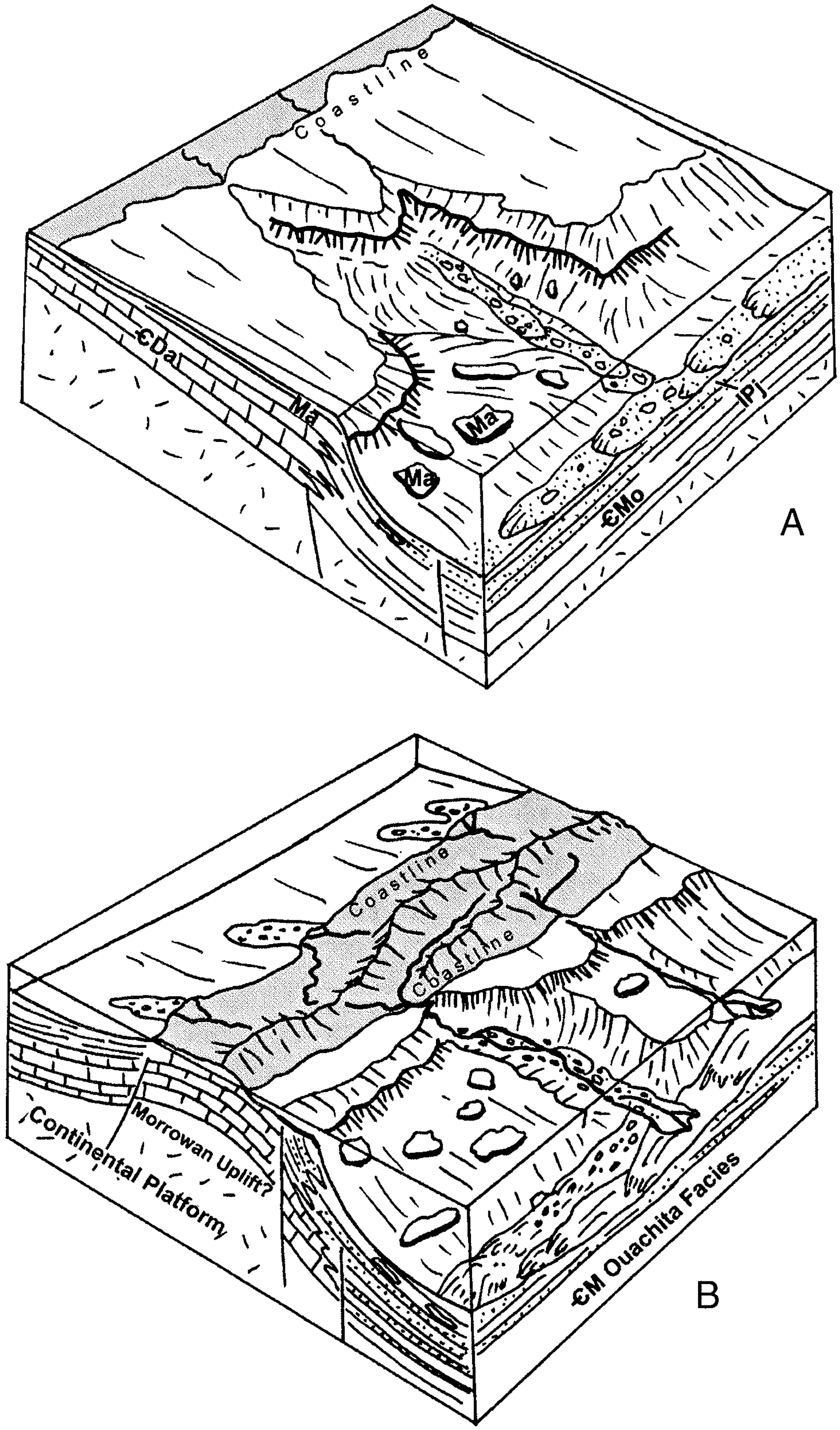

Figure 4. Block diagrams suggesting alternative origins for the source mechanism of the Johns Valley boulder beds: (A) Source areas are completely submarine from rock falls on walls of submarine canyons and slope-failure slides from the upper continental slope. ЄDa – Platform facies; Ma – Mississippian platform facies; ЄMo – deep-water Ouachita facies; IPj—Jackfork Group). (B) Submarine sources as in (A), but augmented by subaerial erosional debris from island exposures near the continental margin.

Going east from the junction of the Ross Creek Fault with the Y City Fault, the west-plunging Black Fork Syncline forms an axial culmination (near the town of Boles and near the junction of Tps. 1 and 2 N., Rs. 28 and 29 W.) and then plunges eastward as the Fourche LaFave Syncline. In the axial culmination between the Black Fork and Fourche LaFave Synclines the Y City Fault makes a reentrant to the north. In this reentrant (Pl. 1, Region 3E) underthrust east–west-striking imbrications of Ouachita-facies strata (Jackfork Group and Johns Valley Shale) are exposed. The intense fracturing and small-scale faulting of the Jackfork Group outcrops south of the Y City Fault may be related to severe compressional flowage in the underlying Stanley Group.

In Oklahoma the Ti Valley Fault seems to be a regular northwest-vergent thrust fault accompanied farther west by a complexly faulted frontal imbricate zone. The base of this zone seems to have ramped up onto the upper Stanley Group.

The Ouachita Allochthon

The largest area of the Ouachita Mountains is occupied by strata of the deep-water Ouachita Allochthon. In this region the structural style differs in separate parts of the stratigraphic column (Fig. 1). The rocks in the pre-Pennsylvanian section are shale-dominated and essentially ductile. The Pennsylvanian rocks are sandstone-dominated and competent, but capable of bending by flexural folding. These rock sequences are the product of two different depositional settings. The older portion is a preorogenic, basinal suite that was deposited in a quiet, marine, bathyal (but not necessarily abyssal) deep-water basin. Its dominant lithology is ductile, black to gray, clayey to bituminous or siliceous, fissile to blocky shale (Upper Cambrian to Lower Ordovician Collier Shale; Lower Ordovician Mazarn Shale; Middle Ordovician Womble Shale; Upper Ordovician Polk Creek Shale; and Silurian Missouri Mountain Shale). These shales are separated by six competent layers of sandstone/quartzite and chert (Lower Ordovician Crystal Mountain Sandstone; Middle Ordovician Blakely Sandstone; Middle to Upper Ordovician Bigfork Chert; Silurian Blaylock Sandstone; and Devonian to Lower Mississippian Arkansas Novaculite). The entire basinal section is ~2,500 m thick, of which ~1,000 m are represented by the competent units.

The upper part of the ductile infrastructure of the allochthon consists of an orogenic sequence of ductile shaly flysch of the overlying Stanley Group (Mississippian). This silty to sandy shale section, which contains numerous individual sandstone beds, was deposited at an accelerated rate. The ductile part of the Stanley is ~2,500 m thick and was probably deposited in a distal turbidite fan and basin-floor environment that was supplied with clastics from an unidentified distant orogenic source.

In the upper Stanley Group and overlying units mid-fan turbidite deposits reached the Ouachita basin and produced a very thick (4+ km) sequence of competent sandstones and some shale of Late Mississippian, Morrowan, and Atokan age. Over a large area of the Ouachita Mountains this combined sandstone sequence behaves as a single competent plate that has been broken into huge buckled synclines and faulted slabs.

The following sections of this text are organized by the dominant structural style of each stratigraphic level and geographic region (Pl. 1, Regions 4N, 4A, 4B, and 4C; see Table 1 for general terminology).

NORTHERN FRONTAL ZONE

A narrow and discontinuous belt of imbricate thrust slices forms the northernmost structural zone of the Ouachita Allochthon (Pl. 1, Region 4N). This belt is well developed in the Oklahoma salient between the northern end of Black Knob Ridge and the west end of Windingstair Mountain (near cross section OK1 [Pl. 6A]). East of cross section OK1 only a few outcrops are found in a similar structural setting.

At its western end this zone contains as many as four imbricate thrust slices separated by a set of anastomosing thrust and transverse faults. The rocks involved in this zone range from Stanley Group to Atoka Formation turbidites and probably belong to a transitional, basin-margin depositional setting of the Ouachita basin. It is also quite possible that the basal detachment of the Ti Valley Fault may have ramped into the upper Stanley in this belt. The Jackfork Group is considerably thinner than in the basin center and shows further thinning across several slices of this belt, indicating an approach to the basin margin (Hendricks and others, 1947). The deformational strain on this tapering wedge may be the reason for its breakup into small fragments and thin slices. Above the thin Jackfork the Johns Valley Shale in this zone contains well-developed olistostromes. Although the Atoka Formation shales and sandstones form the bulk of the rocks in this zone, their stratigraphic position within the Atokan is unknown.

TURBIDITE-DOMINATED UPPER LEVEL (LATE MISSISSIPPIAN AND PENNSYLVANIAN)

Above the Stanley Group's widespread outcrop region of shaly flysch are outcrops—frequently erosional outliers—of the mechanically different competent and massive Carboniferous turbidite sandstones (Pl. 1, Region 4A; see also Harlton, 1934, 1938, 1947; Cline, 1960; Pitt and others, 1982; Legg and others, 1990). This sandstone sequence includes the Moyers Formation of the upper Stanley Group (Upper Mississippian), the Jackfork Group and Johns Valley Shale (Morrowan), and the Atoka Formation (Atokan). The outcrop region of these rocks occupies ~50% of the entire Ouachita Mountains area south of the Ti Valley–Y City Faults and includes a variety of structural substyles. In the central synclines (the Tuskahoma, Lynn

Mountain, and Boktukola Synclines) this sandstone-dominated interval is as much as 3,500 m thick. Because the Atoka Formation occurs only as erosional remnants in the center of the synclines or as half-graben fault blocks, the original thickness of this formation is unknown. For the most part, the turbidite sandstones had their origin as deep-water fan deposits that contain abundant shale interbeds and intermittent thicker shale units.

Most of these sandstones were deposited in a deep-water trough that developed roughly parallel to and south of the now-buried continental margin. Sediment transport directions in the Morrowan are primarily from east to west (Morris, 1989). There is, however, good evidence that the northern continental shelf margin also acted as an intermittent source of clastic material (Houseknecht, 1986; Ferguson and Suneson, 1988; Lowe, 1989; Legg and others, 1990). This intermittent source was likely made up of waterborne loose sand that avalanched down the continental slope along with semiconsolidated, typically rolled clasts or contorted masses that were deposited as "intraclasts" in numerous horizons of the Jackfork Group and Johns Valley Shale. The Johns Valley is especially famous for its large quantity of rounded and angular, so-called "exotic" boulders and pebbles of pre-Carboniferous platform rocks (Shideler, 1970) and large slide masses of Mississippian black shale. Figure 4 schematically illustrates two alternate interpretations of the origin of the olistoliths. Pitt and others (1982) summarize the interpretation history in terms of the age and origin of the Johns Valley and its exotic rocks.

The line of maximum thickness (~1,700 m) of the Jackfork Group in Oklahoma strikes about parallel to the axis of the Lynn Mountain Syncline. In Arkansas the basin axis probably coincided with the axis of the later Benton Uplift. In both the northern and southern tiers of flysch outcrops in Arkansas the thicknesses of the Jackfork and Johns Valley are reduced, and most individual structures are narrow, faulted half-graben (half-syncline) structures.

The thickness variations of the Jackfork Group are evidence for an original oblong, deep-water basin. Hendricks and others (1947) recognized that the thickness in the frontal belt at the west end of the mountains northeast of Atoka is only ~350 m. South of the Benton Uplift in the Athens Plateau the Jackfork is ~1,200 m thick.

In Oklahoma the Windingstair Fault forms the boundary between the frontal imbricated zone of the Ouachita Allochthon (Pl. 1, Region 4N) and the main upper flysch province (Pl. 1, Region 4A). It is quite possible that this thrust fault is a reactivated Morrowan growth fault (Haley, 1982; Link and Roberts, 1986). This long, curved fault, which can be mapped over a distance of ~100 km, marks the northern limit of the many faulted synclines that characterize the interior structure of the Oklahoma salient. The close relationship between competent plate thickness and fold curvatures (Sherwin and Chapple, 1968) is well displayed in this part of the Ouachita Mountains (Fig. 5).

Cross sections through this region show cuspate-lobate folds (Figs. 6, 7) that form when a competent buckled plate overlies a thick ductile unit (Ramsay and Huber, 1983, 1987). Many faults of the cusp-shaped anticlines have relatively minor displacements (Cunningham and Namson, 1994) and look like bending or kinking failures rather than low-angle thrust faults. We can see this at the rarely preserved plunging ends of anticlines (such as the Pickens Anticline in T. 2 S., R. 20 E. or the Jumbo Anticline in T. 1 S., R. 15 E.; see also Fig. 7) where straight limbs turn sharply at the crest. At the plunging ends of faulted folds it also becomes evident that associated thrust faults pass quickly into ductile faults and flowage once they enter into the shales of the Stanley Group.

North of Talihina, Oklahoma, the frontal zone of imbrications ends near the eastern end of the curved part of the Oklahoma salient. East of that point the northern flysch belt continues as a set of relatively narrow and straight half-synclines and faulted Stanley Group anticlines to the eastern end of the exposed Ouachita Mountains, indicating that the overall shortening is much greater west of this point than to the east. About 15 km east of the Arkansas–Oklahoma state line, the Benton Uplift divides the flysch province into a northern and a southern belt.

The flysch belt north of the Benton Uplift comprises one to three fault slices (or half-synclines) of upper Stanley Group, Jackfork Group, and Johns Valley Shale that become increasingly narrow and structurally more complex toward the east. The section also becomes more shaly and displays an increase of internal disharmonic folding, although the synclinal origin of these thrust slices can still be detected at their plunging ends where the thrusts faults appear to have relatively small displacements.

Some of the thrust faults in the Jackfork Group of this northern flysch belt are south vergent, especially where they are near the Benton Uplift. It is unclear if the south vergence of these faults was a by-product of the underthrusting of the Y City Fault or if they developed as broken, south-facing drag folds on the north side of the Benton Uplift.

In the middle Jackfork Group of this northern flysch belt there is a massive shale member that contains one or more thick olistostromal beds. These beds contain intraformational clasts that exhibit varying degrees of preburial lithification. Because of its frontal position on the thrust sheet this shale member was subjected to intense deformation during the emplacement of the Ouachita Allochthon. As a result, the sandstone olistostoliths became severely broken up and sheared, and the shales display some schistosity and multiple slickensides. At map scale the structure of this zone can be fairly well understood as a stratigraphic unit, but at the smaller mesoscale (outcrop scale)

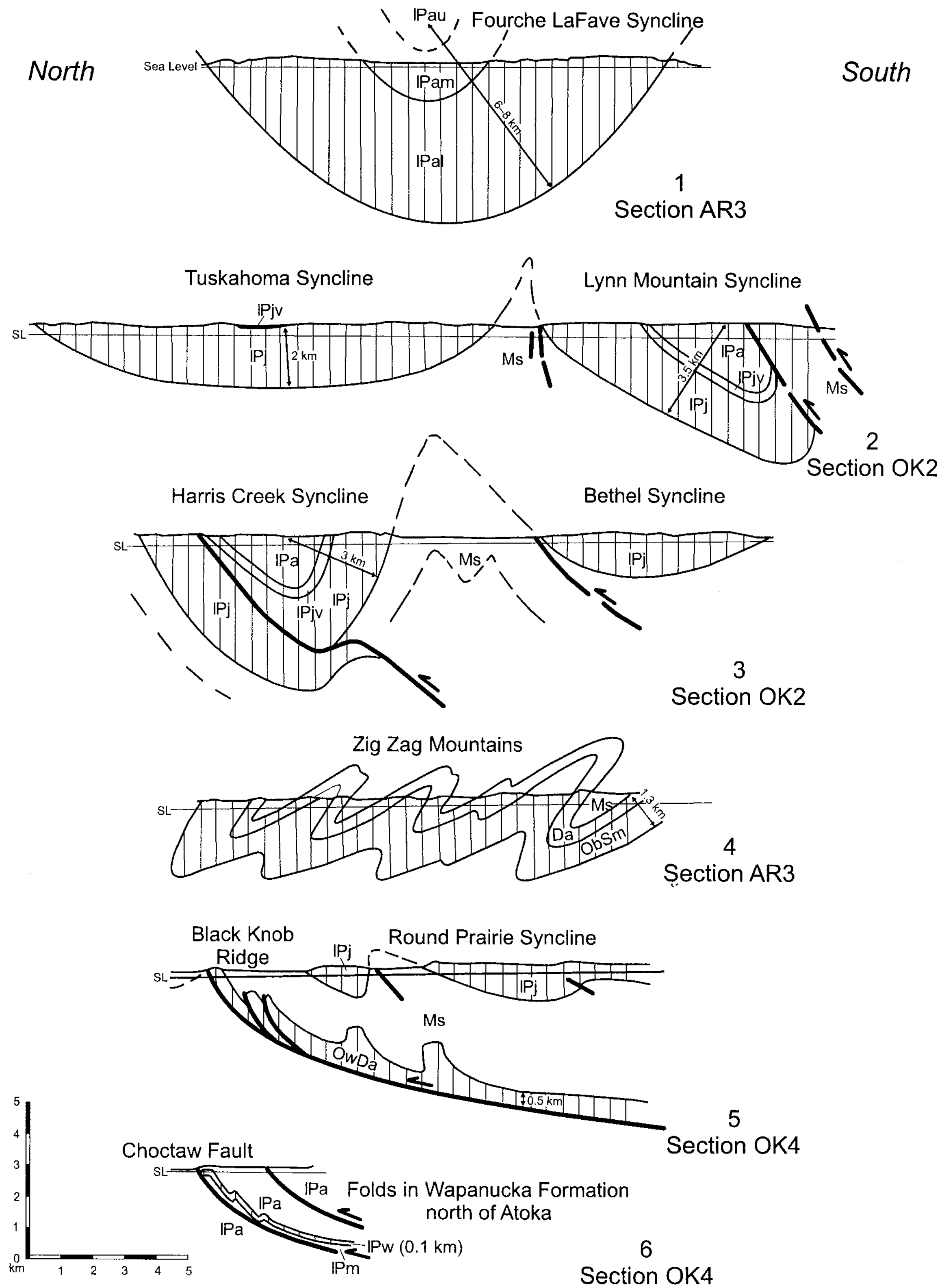

Figure 5. Examples from the Oklahoma salient of varying cuspate-lobate fold wavelengths that are controlled by the thickness of buckled competent formations. ObSm—Bigfork Chert to Missouri Mountain Shale; OwDa—Womble Shale to Arkansas Novaculite; Ms—Stanley Group; IPj—Jackfork Group; IPjv—Johns Valley Shale; IPa—Atoka Formation; IPal-IPam-IPau—Lower-Middle-Upper Atoka Formation; IPm—Springer Group; IPw—Wapanucka Limestone (after Sherwin and Chapple, 1968; Blythe and others, 1988).

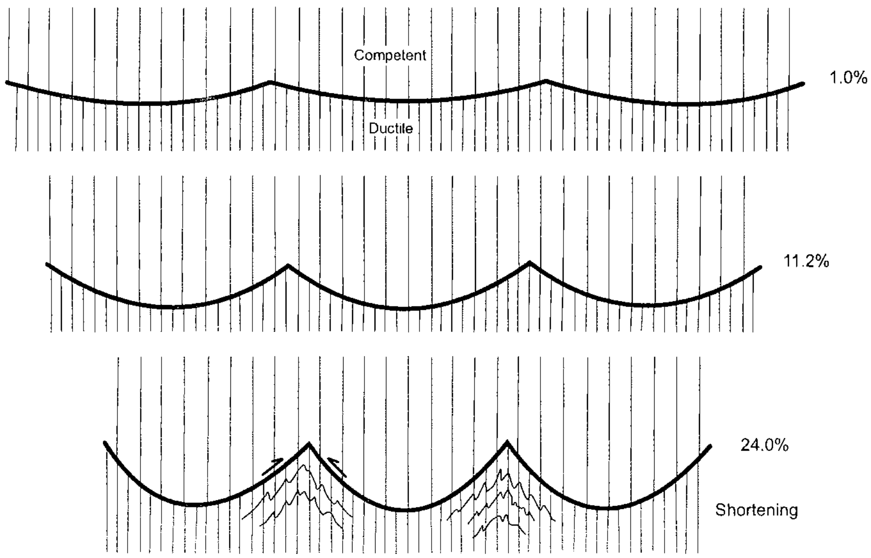

Figure 6. Schematic cross sections of the cuspate-lobate style of folding (no scale).

the structure looks highly disturbed. As a result this band of mangled rocks has been called the "Maumelle chaotic zone" or the "Maumelle mélange" (Viele, 1966, 1973; Davis, 1994). These authors interpreted the formation as a subduction mélange formed in a deep-sea trench. I prefer to interpret this disturbed assemblage as a "tectonized" olistostromal unit that may not have been completely dewatered at the time of the orogeny.

The Stanley Group flysch region on the south side of the Benton Uplift, called the Athens Plateau (Stone and Haley's (1984) "Amity Belt"; see Table 1), is a belt of tight, north-vergent chevron folds. In the more sandy upper Stanley Group and the overlying Jackfork Group sandstones, Johns Valley Shale, and Atoka Formation (Walthall, 1967; Weber and Zimmerman, 1988) the structure changes into several north-vergent thrust imbrications. As on the north side of the Benton Uplift these slices form half-synclines or half-grabens. The style, then, is quite similar to that of the flysch provinces in Oklahoma, but the structures are smaller because the Jackfork is markedly thinner in this region. The structures are also topographically more subdued because they are close to the Mesozoic erosion surface.

BASAL TURBIDITE SANDSTONE DETACHMENT

Throughout most of the Ouachita Mountains the base of the late Carboniferous massive sandstone turbidite section lies in the upper part of the Stanley Group between the very sandy mid-fan sandstones above and the much more ductile shales below. The upper, simpler structural style of the lobate synclines and peaked or faulted anticlines (Pl. 1, Region 4A) changes across a 100-to-200-m-thick detachment zone into silty shales of the middle and lower Stanley. These shales show much smaller, mostly chevron-type folds characteristic of Region 4B (Pl. 1). This boundary is not a recognized stratigraphic horizon nor does it stay necessarily at the same stratigraphic interval within the Stanley. The detachment does, however, follow the general structure of the synclinal turbidites above. It is neither a documented unconformity nor a fault surface but a widespread, regionally recognized facies change where mid-fan lobes overlie the lower distal fan sediments. It is a competence/ductility boundary where the load-bearing capacity of the overlying stiff, sandstone-rich strata ceases to exist and where thin beds of siltstone and sandstone are isolated in ductile shale beds of varying thicknesses.

This detachment zone can best be observed on aerial photographs by the contrasting fold shapes and sizes, particularly at the plunging ends of some of the big synclines (e.g., the east end of the Lynn Mountain Syncline, the Boktukola Syncline, and the Hugo Syncline). On the flanks of folds the detachment is not obvious because of similar bedding attitudes. There is little doubt that some bed-parallel displacement and flowage caused by the change of folding wavelengths must have taken place along this detachment zone, but measurable displacements or angular relationships are not evident (Ramsay, 1980). There is also no evidence that this detachment could be a major thrust surface because the detachment surface is subparallel to the bedding of the overlying Jackfork Group. It must have been initiated early in the folding process and then became folded with the overlying rocks at the base of the Jackfork.

DUCTILE FLYSCH (MISSISSIPPIAN STANLEY GROUP)

The large area of Mississippian Stanley flysch outcrops occupies most of the widespread lowlands under alluviated river valleys and low-relief erosional plateau regions lying stratigraphically below the ductile detachment (Pl. 1, Region 4B). The predominant lithology is a sandy to silty, olive-colored shale with numerous single, discontinuous sandstone layers and several sandstone units that form low ridges displaying chevron-shaped, small-scale fold trains with 2- to 3-km wavelengths. The region has been mapped by many authors, showing that, although it presents difficulties, it is not a chaotic area that cannot be mapped at all. The mapping difficulty arises from the scarcity of distinctive lithologic or paleontologic markers that would allow the larger structures to be recognized (Honess, 1923; Hendricks and others, 1947; Cline, 1960; Walthall, 1967; Zimmerman, 1984, 1986; Weber and Zimmerman, 1988).

The Stanley Group has been divided into three formations on the basis of rare but widespread siliceous shales (Harlton, 1938; Cline, 1960). The basal two-thirds have been called the

Tenmile Creek Formation and the upper third has been known as the Moyers Formation. The uppermost formation is the relatively thin Chickasaw Creek Formation. The detachment zone discussed previously occurs mainly in the Moyers Formation.

Attempts at resolving the complex structure by seismic means in and below the Stanley Group have been unsuccessful because the small-scale complex structure and the rapidly alternating siltstone-shale lithology make the entire interval nearly acoustically opaque. The structural resolution at the surface, though, is greatly enhanced by the presence of a number of rhyodacitic tuffaceous sandstone beds in the Stanley around the Broken Bow Uplift (Honess, 1923; Niem, 1977). The outcrops of these distinct and resistant markers unfortunately are restricted to a narrow halo of ~5 km around the Broken Bow Uplift. As a result, their usefulness as a mapping tool is quite local.

Where the outcrops permit a more regional observation of the structures, as in the Athens Plateau or around the Broken Bow Uplift, estimates of compressional shortening range from 25% to 35% of the original width. That range is similar to the estimates from the large cuspate-lobate folds in the sandstone-rich Late Mississippian to Atokan flysch (Pls. 6A–7B). The contact between the Stanley Group and the underlying Arkansas Novaculite appears to be conformable and no angular truncation or onlap can be seen. But it would not be surprising to encounter features of local disconformity and/or detachment on a contact with such a drastic increase in sedimentation rate. The contact zone also shows evidence of hydrothermal activity in the form of stratal and/or replacement deposits of barite on the south flank of the Benton Uplift.

PRE-LATE MISSISSIPPIAN OUTCROPS (OUTSIDE THE CENTRAL UPLIFTS)

The Potato Hills and Black Knob Ridge are the main outcrop areas of pre-Mississippian strata outside the Central Uplifts. Black Knob Ridge is a 19-km-long topographic ridge formed by rocks ranging from the Womble Shale (Middle Ordovician) to the Arkansas Novaculite (Devonian to Lower Mississippian). This ridge forms the westernmost exposure of the Ouachita Mountains and represents the steeply dipping (>60°) leading edge of the Ti Valley Fault, which brings deep-marine Womble Shale in contact with shallow-marine to continental Atokan sandstones and shales. The ridge, which represents the base of the Ouachita Allochthon at its westernmost point, marks the point of the largest displacement of the Ti Valley Thrust Fault. On a restoration of cross section OK4 (Pl. 7B), the distance between Black Knob Ridge and the interpreted Paleozoic continental margin is at least 120 km.

Black Knob Ridge strikes about north-northeast. At its north end, it displays several north-vergent, imbricated offsets and two obliquely striking complex folds that plunge steeply to the northeast (Leonhardt, 1983). These oblique folds could be interpreted as evidence for a left-lateral, strike-slip component to the regional southeast-northwest compression. The steep plunge of the folds and the steep dip of the Ti Valley Fault itself (Morrison, 1980), however, imply a late rotation of a previously

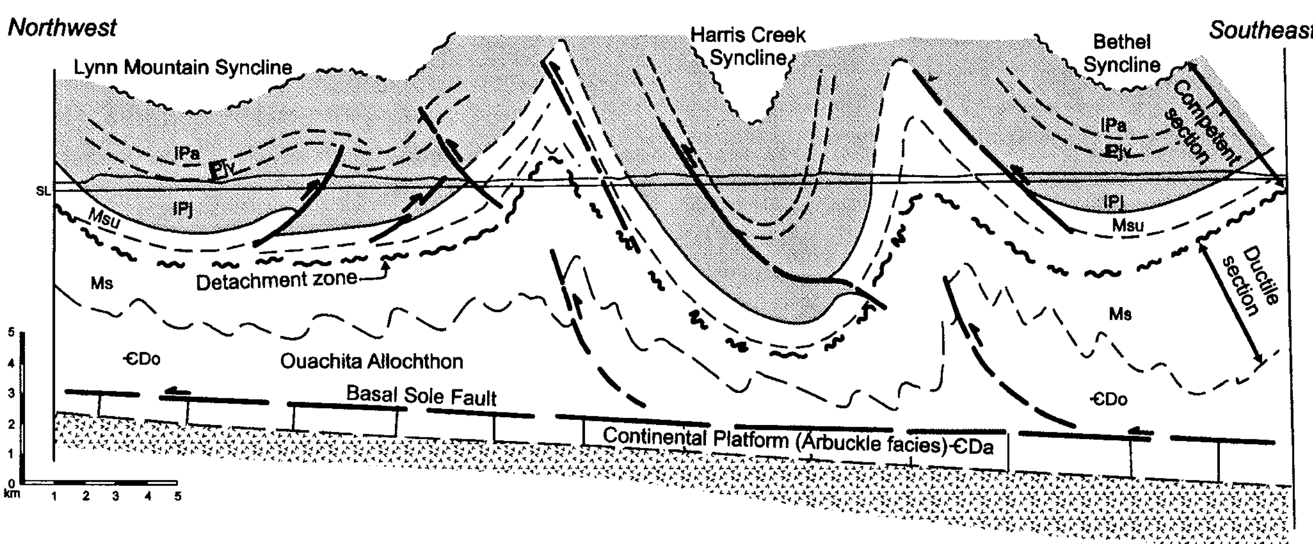

Figure 7. Cuspate-lobate style of folding in Carboniferous flysch sandstones in the Oklahoma salient, partially restored to pre-erosional state (see also cross section OK3). ꞒDa—pre-Carboniferous platform facies; ꞒDo—pre-Carboniferous deep-water facies; Ms—Stanley Group; Msu—upper Stanley Group; IPj— Jackfork Group; IPjv—Johns Valley Shale; IPa—Atoka Formation). Note the folded detachment zone between the basal Jackfork structures and the early Paleozoic strata.

folded regional group of parallel folds. Well control and seismic data confirm that the northeast flank of the subsurface extension of the Tishomingo Uplift of the Arbuckle Mountains (Pl. 1, Region 5) comprises not only a faulted drop-off but also a steeply northeast-dipping monocline. The main Arbuckle uplift occurred close to the end of the Pennsylvanian; the Ouachita thrusting appears to have ended near the middle Desmoinesian. At Black Knob Ridge this upturn produced, upon erosion, a distorted down-plunge view of the thrust front and the sole fault (Arbenz, 1989a).

The second area of pre-Carboniferous Paleozoic strata in this region of flysch is the Potato Hills (Pushmataha and Latimer Counties, Oklahoma), a 6- by 17-km oval group of low hills supported by Bigfork Chert (Middle and Upper Ordovician). This internally complex structure forms the center of a doubly plunging axial duplex culmination in the core of the most deeply eroded cuspate anticline north of the Central Uplifts. The Lynn Mountain Syncline borders the Potato Hills on the south and the Buffalo Mountain Syncline and Windingstair Fault on the north. This uplift has been the subject of much debate (Miser, 1929; Miller, 1955; Roe, 1955; Tomlinson, 1959; Arbenz, 1968; Pitt and others, 1982; Allen, 1993, 1994a,b; Smart and others, 2001; Miller, 2003).

The structure of the Potato Hills represents a partially eroded duplex structure that formed on a stack of folded and complexly faulted blind thrust slices that probably involved the Windingstair Fault and possibly the Ti Valley Fault. Strata involved in this stack of six or more slices range from Ordovician Womble Shale to Morrowan Jackfork Group. (For a simplified down-plunge projection see Plate 6B, cross section OK2). The uppermost slice crops out and forms a folded and doubly plunging thrust sheet of Womble Shale to Stanley Group. The interbedded cherty, brittle strata (Bigfork Chert and Arkansas Novaculite) and very ductile shales (Womble Shale, Polk Creek Shale, and Stanley Group) have abundant fractures and small adjustment faults and disharmonic folds that are superimposed on the larger structures. The basal thrust fault of the Ouachita Allochthon has not been penetrated by any of the exploration wells in the Potato Hills. On the south side of the main antiform the older Paleozoic strata of this slice dip south beneath the surrounding Stanley but reemerge in the north-vergent, equally doubly plunging, satellite Albion Anticline.

The Potato Hills are part of a cuspate anticlinorium that was strongly compressed after the initial duplex thrusting. As a result, the flanks of the Potato Hills have been subjected to strong flexural slip that formed satellite "drag" folds and minor crest-vergent thrust faults (Allen, 1994b). Small structures (apparently south-vergent) occur in a number of the Stanley flysch anticlines and should be regarded as by-products of cuspate folding.

Recent drilling in the Potato Hills has discovered a more complicated duplex structure at depth that will ultimately lead to a better understanding of the structure (M. Svoboda, personal communication, 2001; Miller, 2003). None of the other major anticlinal uplifts of the interior Ouachita Mountains flysch province have pre-Mississippian outcrops, but drilling on some anticlines has confirmed the presence of pre-Mississippian rocks in the subsurface (e.g., the Jumbo and Daisy Anticlines). The presence of pre-Mississippian strata in the cores of anticlines surrounded by Jackfork Group outcrops is additional evidence that a regional flat detachment level or thrust fault—which would separate an upper structural style from a different one at depth—does not exist in the Stanley Group.

CENTRAL UPLIFTS

Strata of the pre-Late Mississippian deep-water Ouachita facies crop out in two large and deeply eroded oval regions extending from near Little Rock, Arkansas, in the northeast to the southeast corner of Oklahoma. These are the Central Uplifts—Benton and Broken Bow—that comprise strata from Late Cambrian to Early Mississippian (Pl. 1, Region 4C). These deep-water deposits are devoid of any documented pre-Carboniferous orogenic events in the form of angular unconformities. With the exception of several competent chert and sandstone formations and some rare silty or limy lenses, these rocks are ductile shales and slates. The ridge-forming competent formations in the overall shaly-slaty section are in descending order as follows:

1. The section from the Bigfork Chert to the Arkansas Novaculite forms a composite ridge (or stiffer "plate") that often allows the dominant folding and faulting style to be recognized. Superimposed on the limbs of this main fold pattern are numerous smaller-scale second- and third-order mesoscale disharmonic folds. The Bigfork is typically the main resistant ridge-forming unit; however, the Bigfork is locally so thoroughly fractured that it supports only low hills (e.g., in part of the Zig Zag Mountains). In this case the Arkansas Novaculite becomes the main ridge former.
2. The Blakely Sandstone forms the second-oldest fold train. The relative thickness of this sandstone results in a somewhat smaller wavelength and spacing. Locally the Blakely is absent (e.g., Broken Bow Uplift); elsewhere it forms two sandstone ridges separated by shale (ridges to the east and south of Lake Ouachita).
3. The oldest competent formation is the Crystal Mountain Sandstone, a quartzitic, fractured and faulted sandstone that results in a topographic expression ranging from distinct high ridges or mountain groups to subdued, barely recognizable hills.

The rock sequences of the Central Uplifts are pervasively deformed into folded and faulted anticlinoria displaying a more complex structure than that seen in other parts of the Ouachita Mountains. The most important characteristics of the strata in the Central Uplifts are their mild metamorphism to greenschist facies, their widespread schistosity, and a ubiquitous south-vergence of fold geometries.

An incipient to low-grade metamorphic overprint in the Central Uplifts has also been confirmed in borehole cuttings and cores, which have revealed a nearly continuous belt of weakly metamorphosed rocks from southern Texas to the Mississippi Rift (Flawn and others, 1961; Keller and others, 1989; Thomas, 1989). This belt is ~50 km north and northwest of the geophysically identified Paleozoic continental margin, but its deep structure and associated complicated thermal history are not known well enough to arrive at conclusive answers about the true origin of the metamorphism. Attempts at dating the thermal events by radiometric-age determinations (Nicholas and Rozendal, 1975; Denison and others, 1977) have led to rather ambiguous conclusions. Analyses yielded scattered dates from the Late Proterozoic to the Silurian, but show a large and widespread cluster of dates from the Devonian into the Permian, with a peak in the Mississippian. Because there is no direct structural evidence for any orogenic events in the Ouachita hinterland between the Late Cambrian and the Pennsylvanian, the heat source may be an episodic revival of rift-related events along the southern continental margin.

The low-grade metamorphism of the Central Uplifts and nearby Stanley Group shales is associated with a pervasive network of quartz veins (Engel, 1951), as well as with the microscopic recrystallization of the Devonian cherts into the high-quality whetstones of the Arkansas Novaculite in the Benton Uplift (Miser, 1943; Houseknecht and Matthews, 1985; Arbenz, 1989b; Keller and others, 1989).

The quartz veins vary greatly in width and shape and probably represent several phases of generation. Quartz veins typically occur in fracture or fault zones, but also in zones unrelated to any obvious structural features. The veins may be meters wide and their open spaces contain fine red clay that is atypical of the flysch section. These factors lead the author to suspect that the quartz veins may be, at least in part, the result of processes that occurred late in the orogeny, possibly as late as Permian (Denison and others, 1977) when erosion had already removed a large part of the overburden so that the veins remained open. Richards and others (2002) conducted a study showing that ample molecular interchange between host silicates and veins had taken place, and Engel (1951) observed that host replacement by vein quartz was not uncommon. The presence of the famous quartz-crystal deposits and the high-quality whetstones of Arkansas (Stone and Haley, 1984) have brought much attention to this metamorphic event.

Igneous activity in the Ouachita Mountains is rare and has not contributed obviously to the orogen's structural style and makeup. Most of the known igneous activity is related to Cretaceous intrusions associated with recurring movement along the Mississippi Valley–Reelfoot Rift system and possibly in the southern Oklahoma (Arbuckle–Wichita) rifting as well.

A large, deep-seated, antiformal core reflection under the center of these two uplifts can be seen on many exploratory seismic lines as well as on the published COCORP line (Nelson and others, 1982; Lillie and others, 1983; Lillie, 1984, 1985). A similar subsurface antiformal structure, the Waco Dome in north-central Texas, was drilled to 6,190 m in the Shell No.1 Barrett. This well encountered partially marbleized platform carbonates and Precambrian basement crystalline rocks at a drilled depth of 4,145 m beneath Ouachita facies flysch-type shales (Rozendal and Erskine, 1971; Nicholas and Rozendal, 1975; Denison and others, 1977; Nicholas and Waddell, 1989). The contact between the flysch-type shales and the subjacent carbonates was interpreted as the sole fault of the Ouachita Allochthon. A generalized contour map of the sole-fault/top-carbonates surface derived from reflection seismic data (Fig. 8) shows that the Central Uplifts rise more than 5 km above the basin floor, which lies ~10 km below sea level.

One of the antiformal uplift cores in the Ouachita Mountains was also penetrated in a well, the Sohio No. 1-22 Weyerhaeuser, on top of the Broken Bow Uplift in McCurtain County, Oklahoma (Leander and Legg, 1988; Roberts, 1994). This borehole crossed the basal thrust of the Ouachita facies at ~3,840 m drilled depth and penetrated an additional 2,215 m into Ordovician(?) platform carbonates (Pl. 6A). The carbonate penetration points of these wells are still several kilometers above the floor of the Ouachita Allochthon to the north of the Central Uplifts, which lies at ~10+ km below sea level (Kruger and Keller, 1986; Keller and others, 1989). These wells suggest that not only do the platform carbonates reach all the way to the subsurface Paleozoic continental margin, but that a late orogenic process folded and uplifted the sole thrust of the Ouachita Allochthon by at least 5 km.

As mentioned above, most of the folds of pre-Mississippian strata in the Central Uplifts are south vergent, whereas most folds and thrusts outside the Central Uplifts of the Ouachita Mountains are clearly north vergent. Near the base of the Stanley flysch surrounding the Central Uplifts are exposures, a few hundred meters wide, that display the gradual transition from north-vergent to south-vergent folds (Honess, 1923; Zimmerman and others, 1982; Arbenz, 1984). In other words, the axial surfaces of these folds rotate from south-dipping through vertical to north-dipping. The geometry of these south-vergent folds ranges from south-facing asymmetric to south-overturned recumbent folding (Feenstra and Wickham, 1975; Du-

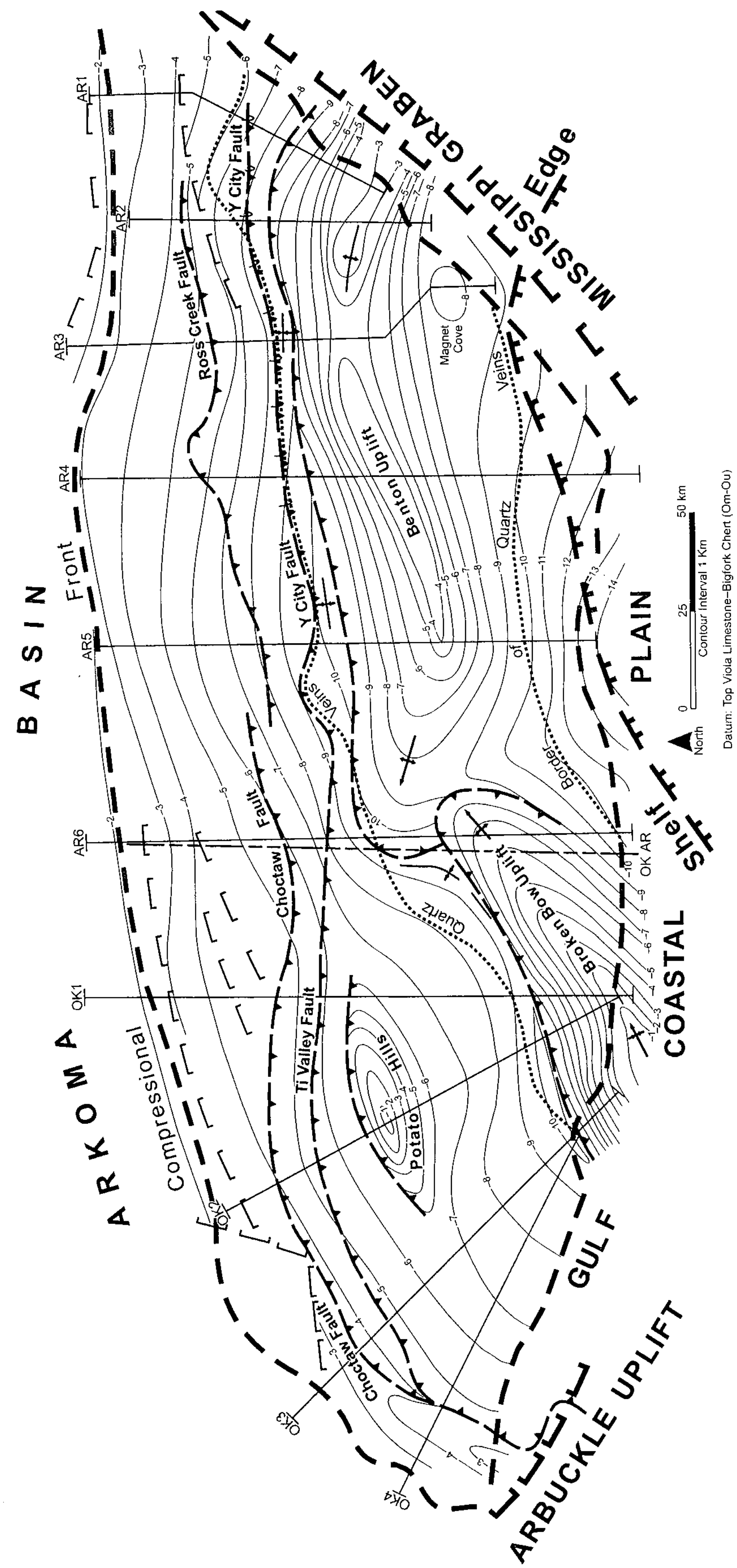

Figure 8. Structural contour map of the folded basal sole fault of the Ouachita Allochthon (which is also the top of the platform carbonate cores of the Central Uplifts) based on a distinct band of regional seismic reflections and on drilling data from the Broken Bow Uplift.

nagan, 1979) and the size varies from meter-sized to megascale. The vergence transition zone is well exposed in three areas:

1. The Cross Mountains (Fig. 9) at the northern end of the Broken Bow Uplift (cross sections H–H and J–J in Honess, 1923);
2. On the south flank of the Benton Uplift in the Caddo Mountains, particularly at the Caddo Gap (Miser, 1929; Stone and McFarland, 1981; Arbenz, 1984) and along the mountain front of the Cossatot Mountains (sections C–C', H–H', I–I', J–J' in Miser and Purdue, 1929; Weber and Zimmerman, 1988);
3. Between the Trap Mountains and the Zig Zag Mountains (Haley and Stone, 1994, and south end of cross section AR3, Pl. 4C).

Faults associated with a large number of these south-vergent folds are of special significance. Many of these faults have relatively small displacements (1 km or less) and are located on the north-dipping flanks of the folds, and most are downthrown to the north (i.e., younger over older). By their present geometry they are "normal" faults and imply an extension of the north flank of the folds (Zimmerman and others, 1982). The stark contradiction between the extensional geometry of these faults and the cross-sectional, south-vergent shape of the folds means that they cannot be the product of the same stress orientation. Recognizing this contradiction, Honess (1923) called these "normal faults" and suggested that they were the result of postorogenic uplift and extension during the Cretaceous. The outcrop sections demonstrate, however, that during the transitional rotation from north- to south-facing asymmetry, the faults on the north flank of these folds have been rotated through the vertical (e.g., at Caddo Gap), becoming "apparent normal" faults (or "overturned, former north-facing thrusts") (Fig. 10). These faulted folds suggest that the orogeny produced two stages of deformation in the Central Uplifts: first, a north-vergent deformation that affects the entire Ouachita Mountains, and second, a south-vergent overprint that was restricted to the Central Uplifts (Fig. 11).

Several major and regionally north-vergent overthrust faults in the Central Uplifts place older rocks over younger ones. North-vergent segments of such faults can be recognized in "down-plunge" view when a significant regional axial plunge makes them visible at the surface.

Two examples exist in the eastern and central Benton Uplift (Nielsen and others, 1989; Haley and Stone, 1994; Roberts, 1994). One is the northwest-trending Alum Fork Thrust, a 19-km-long north–south-striking segment, which is seen dipping gently northeast. This segment, in what is known as the Alum Fork reentrant, places Mazarn Shale (Lower Ordovician) over Stanley Group shales (Mississippian) and Arkansas Novaculite (Devonian to Lower Mississippian).

The other example is the McGraw Mountain Thrust on the south side of Lake Ouachita where folded Collier Shale (Upper Cambrian to Lower Ordovician) and Crystal Mountain Sandstone (Lower Ordovician) are thrust ~8 km northward over Mazarn Shale (Lower Ordovician) and Blakely Sandstone (Middle Ordovician) (Soustek, 1979; Nielsen and others, 1989; Haley and Stone, 1994). These overthrusts belong quite certainly to an early north-vergent phase of deformation for sev-

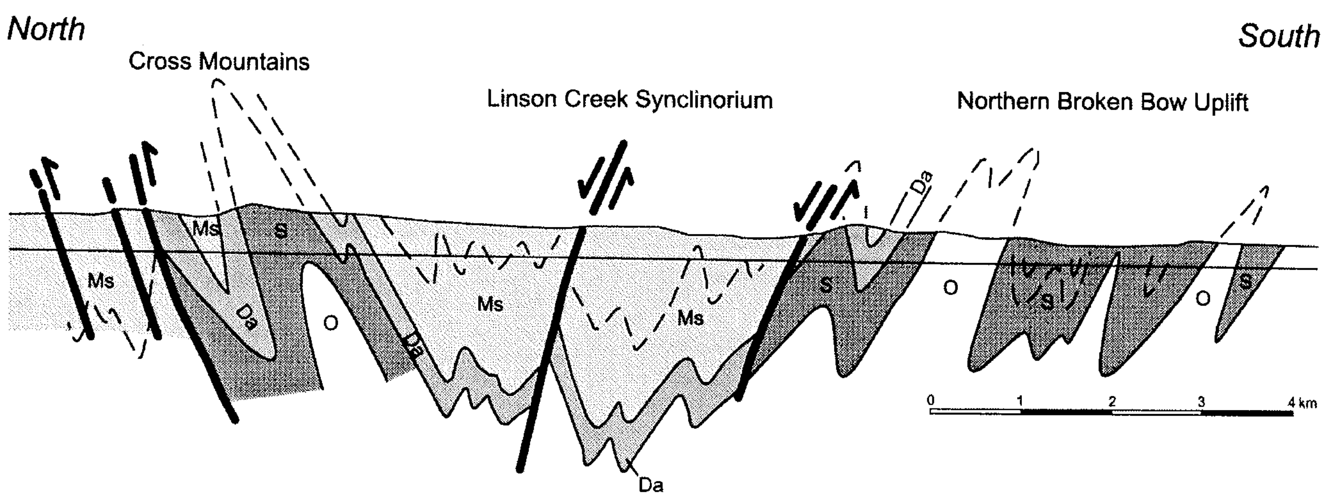

Figure 9. The reversal from north-to-south vergence as observed at many places along the edges of the Central Uplifts. This figure [modified from Honess (1923, pl. I, section H–H')] is a cross section from the northern Broken Bow Uplift to the Cross Mountains showing the rotational reversal from north vergence in the Cross Mountains to south vergence in the Broken Bow Uplift. The reversal is accompanied by a change from north-vergent thrust faults in the Cross Mountains to apparently normal faults in the south. O – Ordovician strata; S – Silurian strata; Da – Arkansas Novaculite (Devonian); Ms – Stanley Group (Mississippian).

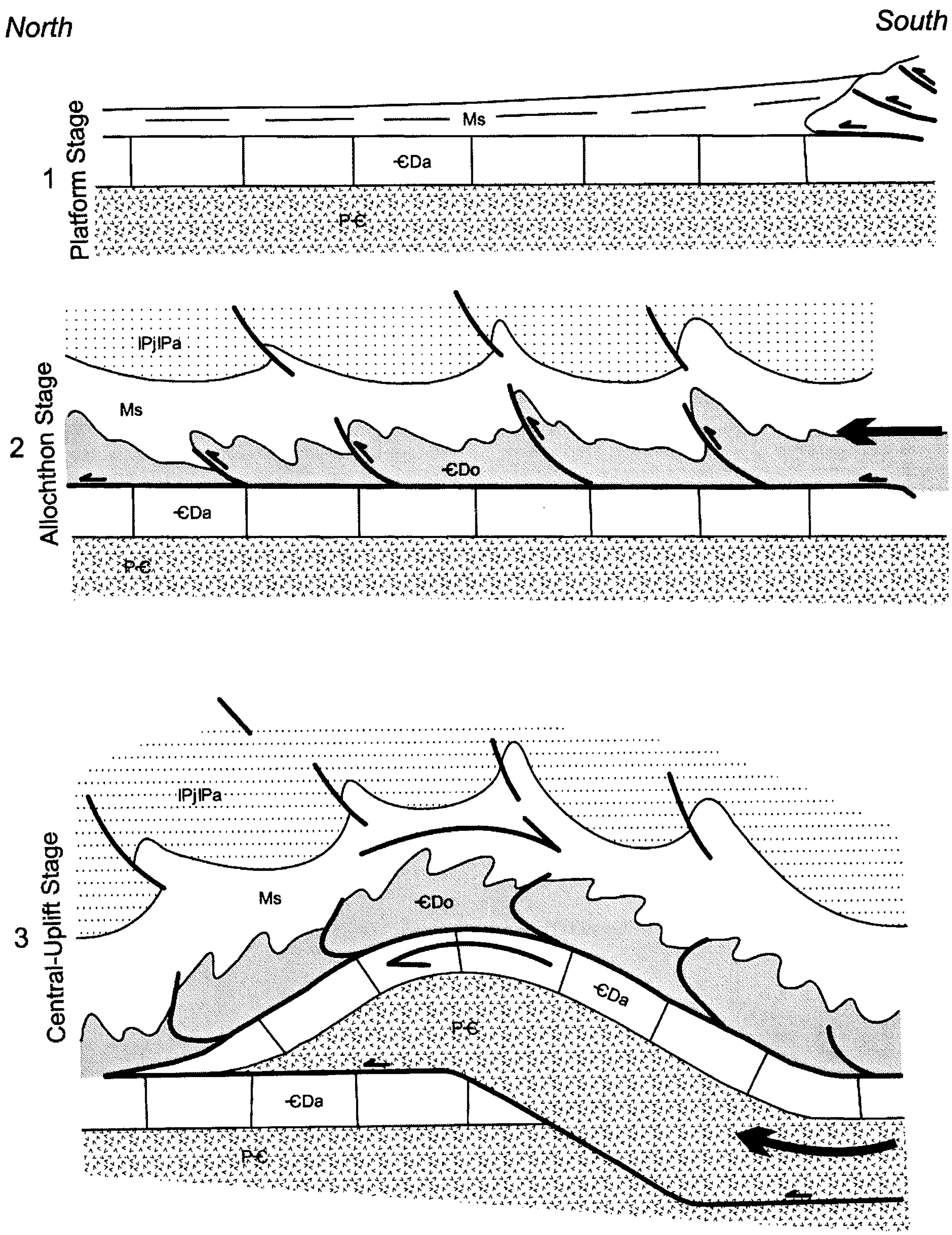

Figure 10. Diagrammatic evolution of the Central Uplifts and the origin of the south vergence of the structures on the uplifts. (1) The platform sequence at the start of overthrusting by the Ouachita Allochthon. (2) A north-vergent allochthonous fold-thrust belt above the platform carbonates. (3) An out-of-sequence fault propagation fold produces a duplex structure. Bed-parallel simple shear in the ductile part of the allochthonous thrust sheet rotates the folded units into south-asymmetric folds. P€ – Precambrian; €Da – Cambrian to Devonian platform (Arbuckle) facies; €Do – Cambrian to Devonian deep-water (Ouachita) facies; Ms – Stanley Group (Mississippian); IPjIPa – Jackfork Group, Johns Valley Shale, and Atoka Formation (Pennsylvanian).

eral reasons. Not only is the hanging wall folded into south-overturned folds, but the thrust surface itself and its footwall have also been folded into south-vergent folds that are plunging to the northeast. This fold-and-fault geometry is indisputable evidence for at least two phases of deformation, as mentioned previously.

In my opinion the north-vergent segments of right-side-up thrusts are parts of much longer thrust faults that became caught in the process of south-vergent refolding (Figs. 9, 10). In such a process the whole "sandwich" of footwall, thrust surface, and hanging wall were overturned into south-vergent segments of an overthrust. These south-overturned segments dip northward and carry younger over older rocks in apparent normal-fault geometries. North-dipping strata with apparently north-dipping faults and younger-over-older relationships have been mapped at many places in the Ouachita Mountains. Additional mapping is needed to verify that such fault segments could be overturned or recumbent parts of thrust faults. Because the south vergence is such a pervasive feature in the Central Uplifts, it is compelling that thrust surfaces have undergone the same kind of deformation as indicated schematically on the cross sections.

The geometry of the south-overturned folds and faults presents an additional dilemma. The asymmetric dip angles and the apparent limb-lengths of the folds are strong evidence for some south transport of the Central Uplifts. The overwhelming number of north-dipping, down-to-the-north faults on the northern limb of these folds, however, present a geometry indicating a lengthening of that limb that is incompatible with a compressional south vergence. This fault orientation—combined with the cross-sectional rotation of the vergence at the rim of the uplifts—implies at least two stages of deformation, an initial north-vergent stage and a second south-vergent stage. The two phases of deformation could have occurred in steps or subphases, resulting in many detailed structural analyses that indicate deformation in more than two phases (Honess, 1923; Feenstra, 1974; Feenstra and Wickham, 1975; Zimmerman, 1984; Zimmerman and others, 1984; Dix, 1985; Nielsen and others, 1989).

If the extensional faulting on the north limbs of the south-vergent folds is convincing enough to doubt an initial south-vergent deformation, what is the origin of the asymmetrical fold limbs? The fold asymmetry within the Central Uplifts is dominated by short and steep to overturned south limbs, and longer, often normal faulted north limbs. Because the hinge of a fold is stiffer than the limbs, the change from north- to south-vergence should produce (1) lengthening of the original north limbs (through normal faulting) and/or (2) a shortening of the south limbs (through thrust faulting, additional buckle folding, and/or pressure solution) as shown diagrammatically in Figure 11. Because the asymmetry of the folds is the main

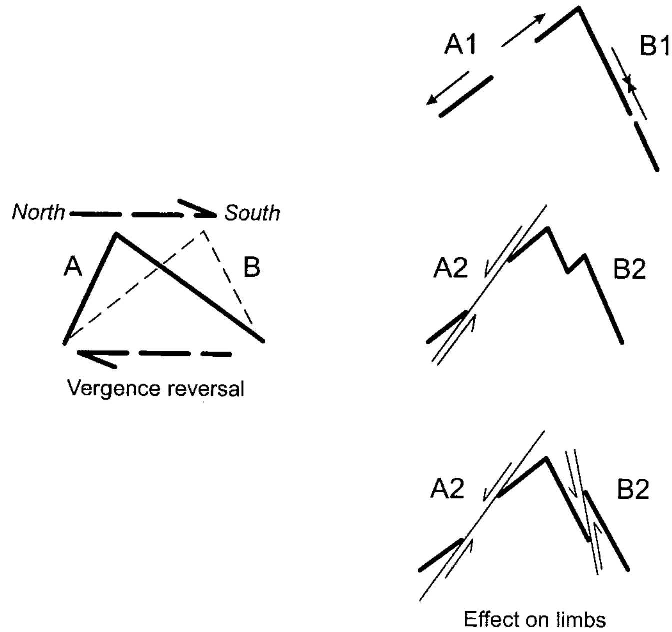

Figure 11. Geometric consequence of vergence reversal (change of sense of transport) of an existing asymmetric chevron fold with a strain-stiffened hinge. The original short limb (A) has to become the long limb through thinning (A1) or extensional "normal" faulting (A2). The original long limb (B) has to shorten (B1) by buckling (B2), faulting (B2), or both. Many folds on the Central Uplifts show features typical of at least two stages of deformation.

evidence of the south vergence and because major south-vergent overthrusting is absent, the total amount of the south-vergent displacement cannot be large (1–2 km?). Field evidence of lengthened north limbs and shortened south limbs is abundant (e.g., in the Zig Zag Mountains).

The restriction of the south vergence to the outcrops of the Central Uplifts and the narrow transition zone in which the reversal from north to south vergence takes place along their rims implies that the changing stresses that caused the reversal had to be associated with the rise of the Central Uplifts. Platform facies and possible basement rocks are present in the uplifted cores, indicating that the continental crust was involved in the rise of the uplifts. The present geophysical and borehole data in the antiformal cores, however, are not adequate to conclusively resolve the internal structure and the origin of these uplifts.

I favor an interpretation in which an originally north-vergent allochthonous thrust-and-fold belt was lifted up by a northward-moving blind duplex structure of the carbonate (and basement?) substrate, as proposed by Nicholas and Rozendal (1975). The lifting and northward movement of the "infrastructure" duplex produced a south-facing, subhorizontal simple shear in the ductile middle Paleozoic rocks against the stiff and unyielding "suprastructure" of several kilometers of turbidite sandstones. Figure 10 shows this suggested mechanism. Roberts (1994, fig. 27) suggested "counter-vergence" on the basis of conjugate, south-vergent shearing to explain the north dip of south-vergent thrusts, but does not explain the younger-over-older geometry of the apparent normal faulting (Fig. 11).

A further piece of evidence that supports a two-phase deformation of the Central Uplifts is the difference in strike between the long axis of the uplifts and the strike of the regional thrust belts (Pl. 2). This is particularly evident in the northern part of the Broken Bow Uplift, where the strike of the mesoscale folds on both sides of the uplift is close to east–west, whereas the axis of uplift is southwest–northeast. Similar angular contrasts exist on the Benton Uplift, especially at its eastern end.

Descriptions of the uplifts and their subdivisions are given in the subsections that follow (from west to east).

Broken Bow Uplift

The outcrop area of the Broken Bow Uplift is only part of a much larger axial culmination because much of it is buried beneath the Cretaceous and older postorogenic cover. A synclinorium of Stanley Group flysch—the Linson Creek Synclinorium (Honess, 1923)—separates a northern subsidiary anticlinorium of the uplift—the Cross Mountains—from the main outcrop.

The Cross Mountains are a complexly faulted group of doubly plunging, east–west-striking anticlinoria north of the Broken Bow Uplift. The intervening Linson Creek Synclinorium clearly displays in cross section the rotation from the regional north-vergent and north-thrusted anticlines to south-overturned anticlines. The latter are flanked on their north side by rotated thrust faults that now appear as normal faults (e.g., Fig. 9; Pl. 4A, T. 2 S.; Pl. 5B, T. 2 S.).

The deep structure of the uplift strikes northeast–southwest and is cored by a deep-seated antiformal seismic reflection. At the surface the uplift is expressed by outcrops of pre-Stanley strata. The mesoscale folds form a partial northwest-convex fold-belt salient striking close to east–west in the northern part of the uplift. The geometry of this doubly plunging anticlinorium shows that the thin-skin fold belt was produced by south-to-north compression, followed by uplift with a northeast–southwest axis. The resulting oblique axial culmination was followed by erosion. The end result is a vertically distorted down-plunge-viewed cross section on both sides of the uplift (Roberts, 1994, fig. 21; Pl. 6A, this report).

The largest fault of the Broken Bow Uplift is the Glover Fault (Honess, 1923; Roberts, 1994; Pl. 6A, this report), which brings the Collier Shale (Upper Cambrian to Lower Ordovician) in contact with the Bigfork Chert (Middle to Upper Ordovician) as it crosses the eastern margin of the uplift. This long, curved fault dips to the north and juxtaposes younger rocks over older rocks. Although displacement on the Glover Fault increases toward the center of the uplift, its displacement is not as large as the big faults of the Benton Uplift. In the core area of the Broken Bow Uplift the small and mesoscale south-vergent folds are nearly recumbent and isoclinal, and consequently very difficult to map (Pitt, 1955; Feenstra and Wickham, 1975; Hubert, 1984).

The Broken Bow Uplift and the Benton Uplift are separated by a broad, west–northwest-trending saddle that is covered by tightly chevron-folded and faulted Stanley flysch (Weber and Zimmerman, 1988). The folds of the Broken Bow Uplift plunge eastward beneath a large flysch expanse—the Athens Plateau—south of the Benton Uplift. The westernmost pre-Mississippian folds of the Benton Uplift plunge to the northwest toward the end of the large Lynn Mountain Syncline. In the subsurface two separate antiformal cores can be seen on unpublished seismic lines (Pl. 5C, Tps. 2–6 S.).

Western Benton Uplift

The south flank of the western Benton Uplift is bordered by a doubly plunging anticlinorium that forms the Cossatot Mountains. This group of folds is separated from the main body of the Benton Uplift by a string of very narrow and straight synclines of Stanley Group shales. This line of synclines might be the position of a right-lateral, ductile strike-slip fault.

The anticlinorium of the Cossatot Mountains narrows to the east and becomes separated from the main Benton Uplift by the wide Mazarn Synclinorium. The chevron-type folds along the Cossatot trend are approximately symmetric and can be interpreted as rotated north-vergent folds (Weber and Zimmerman, 1988). The Cossatot trend plunges to the east under Stanley Group strata but reappears south of the Mazarn Synclinorium, first as small pre-Carboniferous inliers and then as the Trap Mountains. The Mazarn Synclinorium is bordered on the northwest by the Caddo Mountains—a complex row of vertical to south-vergent anticlines that plunge to the east into the synclinorium.

The main part of the western Benton Uplift forms a broad, north-facing arcuate recess that widens to the east into a 30-km-wide thrust-and-fold belt that occupies much of the western half of the uplift. With the exception of some parts of its southern margin, all the structures of the uplift are overturned to the south. As the belt widens it exposes Cambro–Ordovician rocks in its center (near the Polk–Montgomery County line). The westernmost outcrops of Crystal Mountain Sandstone are at Bear Den Mountain, a thrust-bounded sliver that marks the western end of a major fault system. This fault system increases in throw to the east and becomes the base of a large thrust sheet, which brings Collier Shale (Upper Cambrian to Lower Ordovician) and the Crystal Mountain Sandstone (Lower Ordovician) to the surface for ~100 km in the central Benton Uplift.

Central Benton Uplift

To the east the Bear Den Mountain Thrust Fault system alternates between being upright (older-over-younger) and overturned (younger-over-older) as it meanders through the central part of the Benton Uplift. This poorly exposed fault system (and others like it) is recognized by the juxtaposition of older strata to the south against younger strata to the north.

East of Bear Den Mountain the overturned thrust fault and its thrust sheet pass just south of the town of Mount Ida, Arkansas, where its hanging (southern) wall is the Crystal Mountains Anticlinorium. South of the western end of Lake Ouachita, the fault circles the south side of an axial high and then turns northeast as the upright McGraw Mountain Fault (Soustek, 1979; Nielsen and others, 1989). The folds in the hanging wall and the footwall, as well as in the fault surface itself, are all folded together in a south-vergent geometry. This roughly 15-km-long segment of the thrust is the most convincing evidence that the south-vergent overturning and folding is a younger event than the north-vergent regional transport of the whole Ouachita system.

East of Lake Ouachita the McGraw Mountain–Jessieville Thrust nears the northern margin of the Benton Uplift. Here, this thrust is an overturned (i.e., north-dipping and younger-over-older) thrust, appearing as a north-dipping normal fault. Its thrust sheet (south of the fault) is a highly folded axial culmination and salient called the "Jessieville Dome" which displays a number of doubly plunging south-vergent folds (Hart and others, 1987; Nielsen and others, 1989). Here the structural picture is further complicated by the depositional duplication of the Ordovician Blakely Sandstone, which forms two parallel folded ridges in the region of this axial culmination.

East of the Jessieville salient the north half of the Benton Uplift plunges sharply to the northeast into a complexly faulted and folded synclinal northwest-trending reentrant, the Alum Fork reentrant. The reentrant, which is really a faulted synclinal wedge, is marked by a 12-km-long outcrop of Stanley Group and Arkansas Novaculite into the Benton Uplift. The southwest side of the reentrant is the severely deformed, northeast-dipping hanging wall of the next deeper Jessieville–McGraw Mountain Thrust. The north margin of the reentrant is the north-vergent and upright Alum Fork Thrust Sheet, which marks the base of the next higher thrust sheet (the Alum Fork "Nappe" of Nielsen and others [1989]). This undulating, east-dipping fault places early Paleozoic strata above the Stanley Group (Upper Mississippian). Near the south end of the reentrant the Alum Fork Thrust turns sharply west, where it becomes part of the now-overturned boundary between the Jessieville Dome and the Zig Zag Mountains. The thrust disappears in the bedding on the Benton Uplift's south flank.

The north flank of the central Benton Uplift is rimmed by numerous small satellite folds in the Bigfork Chert and Arkansas Novaculite. Most of these folds are south-vergent with their northern limbs dipping beneath the Stanley Group. This depositional contact is locally offset by what appear to be north-dipping normal faults that are, in fact, overturned minor thrusts. No regional faults seem to be associated with the north flank of the western Benton Uplift.

Eastern Benton Uplift

East and south of the trace of the Alum Fork Thrust, the hanging wall (i.e., the Alum Fork Thrust Sheet) forms a northwest-facing double salient containing strata from the Mazarn Shale to the Bigfork Chert. The Blakely Sandstone is thin or absent in these salients. The Mazarn and overlying Womble Shale crop out over a large, poorly exposed, low-relief plateau (the Avila Belt and part of the Hopper Belt of Stone and Haley, 1984). This region is labeled "Alum Fork Fold Belt" on Plate 2. The shaly strata of this plateau are intensely folded into south-overturned to recumbent folds in a manner similar to that seen in the center of the Broken Bow Uplift (Feenstra, 1974; Feenstra and Wickham, 1975). The topographic relief of the plateau is subdued by the closeness to the pre-Mesozoic erosion surface.

The southwestern part of the Alum Fork Fold Belt dips regionally to the southwest. Here the overlying, resistant Middle Ordovician to Devonian strata (Bigfork Chert to Arkansas Novaculite) form the spectacular southwest-plunging fold train of the Zig Zag Mountains. The folds in these mountains are overturned to the southeast and disappear in their plunge direction beneath the more tightly folded Stanley Group shales of the Mazarn Synclinorium. Because the folds of the Zig Zag Mountains have relatively gentle plunges and display more structural details of secondary folding and faulting, they may offer a good locality in which to study the mechanism of the limb-length reversal discussed previously.

On the northeast side of the Alum Fork Plateau the Benton Uplift ends in a northwest–southeast-trending thrust-and-fold belt (the "Nixon Belt" of Stone and Haley, 1984; also the "Paron Nappe" of Nielsen and others, 1989). This fold belt is ~40 km long and consists of as many as six major anticlines underlain by strata ranging from the Womble Shale (Middle Ordovician) to Stanley Group shales (Upper Mississippian). This reduced allochthonous section is similar to the strata in the Potato Hills and along the Black Knob Ridge. All structures in the Nixon Belt are south-vergent, however, and most faults seem to dip north in a younger-over-older geometry. At its west end the folds of this belt plunge steeply to the west beneath the Stanley; at the east end they disappear beneath the Tertiary fill of the Mississippi Embayment.

On the southwest side of the Nixon Belt, earlier mapping (Haley and others, 1976; Nielsen and others, 1989) indicated a major fault (the Paron Fault) between the Nixon Belt and the main body of the Alum Fork thrust sheet. Haley and Stone's

(1994) remapping of the Alum Fork Plateau, however, revealed no major fault or fault zone between the two domains. The Paron Fault is, then, either a very insignificant fault or a down-to-the-north flexure zone within the Alum Fork thrust sheet.

Viele (1966, 1973) considered the entire Nixon Belt to be an upside-down, folded klippe of an even higher and more southern thrust sheet than the Alum Fork thrust sheet. This author cannot agree with Viele's interpretation because such a wholly overturned folded thrust sheet would require all anticlines to be synforms and all synclines to be antiforms. But the plunging ends of the individual folds in the Nixon Belt clearly reveal that the folds are upright (although overturned to the south) and that antiforms are anticlines and synforms are synclines.

The leading northern fault of the Nixon Belt, called the Panther Creek Fault, is shown as a south-vergent thrust fault by Nielsen and others (1989). These authors map it as major fault separating upper Stanley and Jackfork Groups on the north from south-overturned lower Stanley and older strata on the south in a down-to-the-north configuration. If the fault is dipping to the north as the adjacent rocks suggest, the geometry of the Panther Creek Fault is again a younger-over-older normal-fault configuration that does not fit into the overall compressional interpretation. The author believes that this fault is a south-overturned, formerly north-vergent, major thrust fault that represents the overturned leading edge of the Alum Fork thrust sheet. Conversely, it could be a north-dipping but south-vergent fault of a frontal triangle zone.

The Alum Fork–Panther Creek Thrust ramps up-section in its hanging wall from the Mazarn Shale in the Alum Fork reentrant to the Womble Shale in the north part of the Nixon Belt. Near the west end of the Nixon Fold Belt the connection between the Alum Fork Fault and the Panther Creek Fault is not clear. The outcrops indicate, however, that some intraplate on-strike folding or ramping has taken place.

Summary of the Central Uplifts

From the preceding discussion, we can see some common features of the Central Uplifts that can to be summarized as follows:

1. The two Central Uplifts and their subsurface equivalents occur along a line that is ~50 km north of the buried Paleozoic continental margin.
2. Where observable in outcrop, the strata of the Central Uplifts (Upper Cambrian to Lower Mississippian) consist of deep-water sedimentary rocks, mainly shales, and a few competent units of turbidite sandstones and cherts that form topographic ridges and elucidate the structural fabric of the various domains. Their total thickness is ~3 km. Water depths probably ranged from bathyal to abyssal.
3. The uplifts have been metamorphosed to greenschist facies and display widespread schistosity. The metamorphism is most pronounced in the pre-Mississippian strata and increases gradually from the edge to the center of the uplifts. In the surrounding Stanley Group the metamorphic grade deceases rapidly. The nature of the heat source and the exact timing of the metamorphism is unknown.
4. The pre-Mississippian strata and the Early Mississippian flysch have been intruded by numerous quartz veins. These veins may be the result of the same thermal event that produced the metamorphism in the uplifts. Some evidence points to the uplift phase of the Central Uplifts as the time of maximum quartz invasion (mid-Atokan to mid-Desmoinesian). Additional intrusions may be as young as Early Permian (Engel, 1951; Denison and others, 1977; Desborough and others, 1985).
5. The uplifts that have been studied more thoroughly by seismic-reflection surveys and/or drilling are underlain by a buried, deep-seated, antiformal reflection band. In the Broken Bow (Leander and Legg, 1988) and Waco (Rozendal and Erskine, 1971) Uplifts drilling has shown that the distinct antiformal seismic-reflection band coincides with the base of the Ouachita allochthonous deep-water strata, their folded sole fault, and the top of the high-velocity platform carbonates. The interior of these antiforms shows some wedge-shaped internal reflections that suggest that the uplifts were produced by either (1) a stack of wedge-shaped depositional features or (2) fault-bounded lenticular thrust slices that constitute a blind duplex structure. The arched reflector indicates that the sole thrust of the Ouachita Allochthon and its subjacent carbonates are folded and raised ~5 km or more above the deep basin floor to the north and south.
6. The rise of the uplifts, documented by the folding of the basal detachment, is the last major documented event of the Ouachita orogeny. In the Arkoma Basin the youngest units that show gentle buckling and depositional growth affected by the orogeny are the Boggy Formation and the overlying Thurman Formation (Desmoinesian).
7. Syn- and postorogenic erosion produced the large pre-Mississippian outcrop areas of the Ouachita Mountains. Without these areas, very little would be known about the orogen's early depositional history.
8. The widespread southward overturning of the previously northward-transported thrust sheets in the Benton and Broken Bow Uplifts also must be related to the origin of the large, deep-seated antiforms. Similar south-vergent features do not exist elsewhere in the Ouachita Mountains. The areas of low-grade metamorphic rocks and of

abundant quartz veins, along with the regions of south vergence, all coincide with the outcrop areas of the pre-Mississippian strata in the Central Uplifts (Miser, 1959; Flawn and others, 1961; Houseknecht and Matthews, 1985; Arbenz, 1989b; Keller and others, 1989). We do not know why and where these features occurred near the Paleozoic continental margin.

9. Although the metamorphism of the Central Uplifts is not associated with any known or suspected intrusive events, the larger region of the continental margin has experienced considerable volcanic and intrusive activity related to the late Proterozoic to Cambrian continental breakup and its rift-like reentrants and fault systems (the Oklahoma Aulacogen, the Mississippi Rift, and the Ouachita [rift?] basin). The Early Mississippian tuffaceous deposits in the lower part of the Stanley Group are evidence of volcanic activity. This volcanism began shortly after the onset of the flysch sedimentation in the deep-water basin from a now-buried volcanic source to the south. The occurrence of a variety of mineral deposits in the Ouachita region (e.g., phosphates, mercury, barite, and manganese; Stone and others, 1995) is evidence of widespread and long-lasting hydrothermal activity.
10. More significant are the late igneous intrusive events that are linked to the Mesozoic–Cenozoic reactivation in the Mississippi Rift, such as the nepheline syenite plugs at Granite Mountain near Little Rock and Magnet Cove south of the Benton Uplift near Hot Springs, as well as the kimberlite pipes at Murphreesboro, Arkansas, and their numerous associated dikes and sills.
11. Because the entire hinterland of the Ouachita Mountains is hidden beneath the Gulf Coastal Plain, tectonic interpretations rely mainly on geophysical data and samples from some deep boreholes. Several periods of extension and subsidence are known to have occurred in the hinterland in the Desmoinesian (Pennsylvanian), the Permo–Triassic, the Mesozoic, and the Cenozoic. This repeated subsidence has obscured the direct observation of evidence that could shed light on the tectonic history in the hinterland of the Ouachita orogen.

SUGGESTED TECTONIC HISTORY

Although our knowledge of the structural history of the Ouachita Mountains is, by necessity, fragmental, we can draw the general conclusions described in this section. For recent stratigraphic and sedimentologic contributions see Johnson (1988), Suneson and Hemish (1994), Suneson and others (1990, 2004), Keller and others (1989), and Kruger and Keller (1986).

The southern continental margin of North America formed during the breakup of Pangaea in the Late Proterozoic and Early Cambrian. The history of the cooling passive margin has been studied and summarized in many publications (e.g., Thomas, 1977, 1989). Based on data from outcrops and from numerous wells, the central and northern Paleozoic continental platform was a shallow-marine, carbonate-dominated shelf. Data from the outer, southern platform and the continental margin itself are very sparse. The deep-water Ouachita facies is known exclusively from allochthonous thrust sheets that now rest on the outer platform. These deep-water strata were deposited in a basin that formed south of the newly established passive margin. The pre-Mississippian strata, which are exposed mainly in the Central Uplifts, show no orogenic interruptions or angular unconformities (Pls. 8, 9).

We do not know if the Ouachita basin was an arm of a widespread rift system that developed along the margin and extended into the continental interior or if it was part of a major oceanic basin open to the south and the east. Interpretations of sediment distribution and petrology favor an origin in a rift-like basin of bathyal depth that was bordered on the southeast by microcontinental fragments, an island arc, or some other topographic barrier. In this shale-prone basin at least three sandstone formations (the Lower Ordovician Crystal Mountain Sandstone, the Middle Ordovician Blakely Sandstone, and the Upper Ordovician to Lower Silurian Blaylock Sandstone) owe their origin to turbidity currents that were fed by deep-water sand channels and fans. Quartzose sands presumably came from the continental interior (Crystal Mountain and Blakely Sandstones) and silty-clayey arenites (Blaylock Sandstone) from an offshore island or mini-continent. Boulder-bearing debris-flow deposits that contain an assortment of igneous, metamorphic, and sedimentary clasts were derived from basement exposures in submarine canyons that had been cut into the continental platform or on continental slopes (Stone and others, 1986). Widespread chert formations are evidence of periods of clastic-influx shutoff in the Middle to Late Ordovician (Bigfork Chert) and in the Devonian to Early Mississippian (Arkansas Novaculite). Euxinic ponding produced organic-rich shale deposits in some of the Ordovician formations (e.g., the Mazarn, Womble, and Polk Creek Shales).

Late in the Early Mississippian, sedimentation rates increased from very slow to moderately fast as evidenced by a rapid influx and dispersal of primarily clayey to silty and sandy clastics of typical flysch facies (Stanley Group). The causes of this change in sedimentation rate are not evident from data within the Ouachita Allochthon west of the Mississippi Rift. Judging from the dominant westward sediment dispersal, undocumented orogenic events along the continental margin to the east or in island arcs to the south may have produced this flood of flysch-type sediments. In the Late Mississippian (upper Stanley Group) and Morrowan (Jackfork Group), a massive additional influx of quartzose turbiditic arenites appeared to come, in part, from the continental interior (Illinois Basin), entering the Ouachita Basin from the northeast. Nearby sediment sources on the northern shelf edge fed semiconsolidated and consolidated cobble- to boulder-size intraclasts to the basin, forming a group of olistostromes in the shales of the upper middle Jackfork.

The Johns Valley Shale (Morrowan) consists of flysch-like shales, sandstones, and olistostromes. The latter consist largely of foreign, mostly platform-derived carbonate olistoliths. Some of these are well rounded and conglomeratic indicating subaerial shoals or islands as sources, but a majority must have been derived from submarine canyons. The lower, shaly parts of the Johns Valley contain huge (tens of meters) slabs of semiconsolidated Mississippian shale that probably were detached by submarine slides off outcrops on the upper continental slope and margin.

Although drilling on the Central Uplifts found Ordovician platform carbonates in two wells, no younger platform or transitional upper-slope strata were found directly beneath the basal thrust of the Ouachita Allochthon. Most of the clasts derived from island(s) were shed to the south into the Ouachita basin, but some of the detritus probably also went northward into the developing foredeep. As a result, some of the Morrowan and Atokan deposits on the southern platform could contain rocks of "Johns Valley-like" facies in the frontal thrust-and-fold belt (Pl. 1, Regions 3W and 3E).

Such a source island might be located by restoring all the thrusted and folded imbrications north of the Ti Valley–Y City Fault. When we compare the southern limit of these restorations with the suggested original position of the northern limit of the deep-water Ouachita Allochthon south of the continental margin, a gap of ~50 km appears on the outer shelf where a source area for the Johns Valley clasts may have existed (Pl. 9).

The uplift of such a platform island could be a structural forerunner of the Ouachita orogeny. The pre-Johns Valley deep-water strata in the Ouachita section do not display any unconformities or other signs of orogenic deformation. The existence of an uplift of part of the continental platform at that place and time is not evident.

The next tectonic event, which is also mainly vertical, consists of the formation of a rapidly subsiding Atokan foredeep on the outer continental platform. As much as 6.5 km of deep-water sandstones and shales were deposited in this foredeep. This subsidence of the outer shelf and upper slope into an orogenic foredeep was probably initiated by thrust loading and further reinforced by sediment loading from the approaching mountain front. Based on restored sections, the width of this basin must have been at least 35 km (Pl. 1, Regions 3W and 3E).

The Atokan subsidence probably eliminated the topographic barrier that the continental slope may have presented to the advancing Ouachita Allochthon. This subsidence therefore allowed an unimpeded northward transport (or even gliding) of the more than 7,000 m of ductile, deep-water strata from the Ouachita basin onto the foundered continental platform. During emplacement the Ouachita Allochthon was transformed into a complex thrust-and-fold belt; the fill of the foredeep and its continental foreland became an imbricated and folded frontal thrust zone north of the Ti Valley Fault in Oklahoma. In Arkansas the final stages of the overthrusting by the deep-water Ouachita Allochthon formed a large underthrust triangle zone that was probably triggered by the thick mass of Atokan turbidite sandstones. The fault along which as much as 10 km of underthrusting by allochthonous Ouachita facies flysch took place is the Y City Fault.

The detachment, transport, internal folding and faulting, and final emplacement of the Ouachita Allochthon were unquestionably the most significant structural events of the Ouachita orogeny. The minimum displacement of the Ouachita Allochthon is ~150 km to the northwest as measured from the center of the Oklahoma salient (where the largest number of frontal imbrications occur) to the continental slope (Pls. 1, 3, 5A). In a south-to-north direction the displacement—some of which is disguised in out-of-section ductile strike-slip movement—is ~70 km. These distances are measured between the present leading edge of the thrust sheet at the Ti Valley–Y City Fault and its prethrust position at the geophysically recognized Paleozoic continental margin south and southeast of the Central Uplifts.

The oldest exposed formation in the Ouachita Allochthon is the Collier Shale (Upper Cambrian to Lower Ordovician). Because the continental margin had its origin between the Late Proterozoic and the Late Cambrian, it is quite plausible that the Collier was one of the first deposits in the new basin.

In the Oklahoma salient's Black Knob Ridge and Potato Hills areas, as well as in the Nixon Belt of the Benton Uplift, the oldest exposed Ouachita-facies strata are shales of the Womble Formation (Middle Ordovician). This is evidence that the basal thrust had ramped up from the Collier Shale to the Womble Shale at these western and northern positions. How much of the basin fill was left behind is unknown.

In its advance into the "Ouachita Embayment" (i.e., the original rectangular indentation of the continental margin [Thomas, 1977]), the ductile thrust sheet was pushed into a thrust-and-fold belt with a northwest-facing curved salient in Oklahoma and an east–west segment in Arkansas. The east–west segment underwent compression to the north–northwest, but also must have undergone considerable dextral ductile shear. The brittle units of the Pennsylvanian flysch (the Jackfork Group and younger sandstones), which consist of numerous tear and extensional faults as well as pervasive fracturing, present evidence of this shear. The previously mentioned en echelon arrangement of the Ross Creek and Choctaw Faults, as well as the common steep westward plunge of fold axes, offers evidence of distributive ductile dextral shearing without any obvious major single dextral strike-slip faults.

The timing of the Ouachita Allochthon's emplacement cannot be determined by geometric relationships such as angular unconformities or by the age relationships between thrusting and involved sedimentary rocks. In the Ouachita Allochthon south of the Ti Valley Fault, the youngest strata involved are early Atokan turbidites preserved in the synclines and resting conformably on Morrowan strata. These erosional Atokan remnants are never thicker than 1,500 m but cannot be dated relative to the top of the Atoka Formation.

If the middle Atokan foredeep was a depocenter for olistostromes and sizable slide masses, as suggested previously, the advancing thrust front could not have been far away. The main emplacement, then, may have occurred as early as the late Atokan, although the exact emplacement time of the Ouachita Allochton is still unresolved.

In the Arkoma Basin and on the south flank of the Ozark Uplift an initial drift stage and cooling episode lasted from the Cambrian to the Late Ordovician. This was followed by a period of minor instability which resulted in mild thickness variations in the Silurian and Devonian strata. Accelerated subsidence in the Mississippian occurred as a result of the northward migration of the orogenic foredeep that was receiving transitional and deep-water flysch deposits. Subsidence continued through the entire observable Carboniferous and reached a maximum in the Atokan (Sutherland and Manger, 1979; Johnson, 1988; Visher, 1988; Wylie and others, 1988). Well and seismic data in the Arkoma Basin show a northward migration of the extensional basement faulting that appears to have kept pace with and just ahead of the advancing thrust front. In most of the central and southern Arkoma Basin this faulting began shortly after the basal Atokan Spiro sandstone was deposited. This was followed by mild buckling and/or thrust faulting during much of the Atokan. In the northern and northwestern Arkoma Basin, extensional faulting continued on the southwest plunge of the Ozark Uplift well north of the northernmost compressional structures (Houseknecht, 1986; Link and Roberts, 1986; Roberts, 1994). The youngest extensional faulting in this part of the continental platform can be seen in the Hartshorne Formation (basal Desmoinesian) and the Bluejacket Sandstone Member (top of the lower Desmoinesian Krebs Group).

The last major orogenic event in the Ouachita Mountains was the rise of the Central Uplifts, which occurred at about the same time as the last frontal imbrications of the Southern Arkoma Basin Fold Belt were added to the Ouachita front. The last pulse of mild folding and thrusting in the Southern Arkoma Basin Fold Belt occurred in the Desmoinesian, near the contact between the Boggy Formation and the Thurman Formation. This Desmoinesian termination of folding can be seen on cross sections (for example, Pls. 5C, 7A, and 7B) and on maps (Pl. 2, this report, and Miser, 1954), which show that the Boggy Formation is clearly folded. The overlying Thurman Formation, however, is only very mildly involved in the folding.

Because the once presumably flat or gently inclined basal fault surface is folded into huge >6-km-high antiforms, the rise of the Central Uplifts (Broken Bow and Benton) evidently postdated the emplacement of the Ouachita Allochthon. Although the internal structure of the antiforms cannot be resolved, sparse geological and geophysical data suggest that the uplifts may have arisen as "out-of-sequence" deep thrusts of north-vergent, blind-duplex imbrications. With platform carbonates and possibly Precambrian basement involved, these unusual antiforms formed as imbricated fault-propagation folds (as originally proposed by Nicholas and Rozendal, 1975).

If the antiformal uplifts were produced by one or several northwest-vergent thrust slices, their crests should have moved ~15 km northward in order to rise by 6 to 8 km. It is plausible that the basal thrust of the duplex merged with the basal sole thrust of the Ouachita Allochthon, as the cross sections show. A part of this latest shortening may then have been transferred to the thrust front and even into the little-deformed Arkoma Basin, producing the mild early Desmoinesian buckle folds.

While the rigid continental carbonates of the growing antiformal duplex were being pushed relatively to the northwest, they may have produced a simple-shear couple in the overlying ductile allochthon. This simple shear, as suggested previously, may have been responsible for the south-vergent overprint of the folds on the Central Uplifts. Judging from the geometry of the south-vergent folds compared to that formed from their original north vergence, the minimum southward transport caused by the simple shear must have been 2 to 3 km.

This origin of the Central Uplifts is my preferred interpretation to solve a paradox that cannot be explained by a single deformational event—the rotated vergence from an originally north-transported thrust-and-fold belt into complex, apparently south-vergent geometries. The interpretation differs from an earlier interpretation (Arbenz, 1984) in that it sets up a bed-parallel simple shear between the basal Stanley Group and the carbonate duplex. The updated interpretation explains why the south vergence seems to disappear around the Central Uplifts within the basal few hundred meters of the Stanley. This interpretation of the origin of the Central Uplifts does not, however, address the cause of the low-grade metamorphism in the uplifts or the decrease of the metamorphic grade in the Stanley Group outside the uplifts. Likewise, a uniformly accepted explanation for the regional belt of mildly metamorphic rocks (the "Internal Zone") in the subsurface extension of the Ouachita system in Texas (Flawn and others, 1961) is still lacking.

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APPENDIX

STRUCTURES IN DUCTILE-DOMINATED ROCK SEQUENCES

Many mesoscale and outcrop-scale structures require the presence and participation of easily deformable, ductile rocks. Because such rocks make up a high proportion of the stratigraphic section in the Ouachita Mountains, it may be useful to briefly describe some common examples of deformational features found in ductile rocks so that these features are not misinterpreted.

FLOWAGE

Flowage of ductile rocks, which requires a small stress differential, is the most common mechanism of rock deformation. The most widespread flowage in clastic sedimentary rocks – known as cataclastic flow – occurs in clayey shales, in siltstones and marls, and in coal and coaly shales. Among the common evaporites, grain solution and recrystallization are the main mechanisms for ductility. Rock salt shows the greatest ease of flowage, especially under elevated temperatures. Gypsum and anhydrite are somewhat less ductile.

When faults emerge from competent, brittle rocks into under- or overlying ductile beds, the faults often change from a distinct break into a shear zone, sometimes called a "ductile fault" (Ramsay, 1980), or lose their identity altogether.

Because highly ductile sedimentary rocks are rarely devoid of some visible bedding, some degree of kinematic analysis is possible. But when exposures are rare and small, as in the Ouachita Mountains, the structural importance of rocks deformed by flowage is difficult to measure.

DISHARMONIC FOLDING

In ductile regimes with intermittent competent layers, such as the Carboniferous flysch of the Ouachita Mountains, compressional stress buckles or kinks the competent packages according to their preferred dominant wavelength (Currie and others, 1962; Sherwin and Chapple, 1968). Multiple competent layers of varying thicknesses have different fold wavelengths (Fig. 12). If the interbedded ductile shale is thick enough to accommodate the shape and volume differences by flowage, the resulting bed geometry is commonly called "disharmonic folding." If the flowage is severe, the bed succession in the flowed interval may be interrupted or repeated. Even in poor exposures such flowage should not be interpreted as faulting because a measurable displacement does not exist.

DETACHMENT OR DÉCOLLEMENT

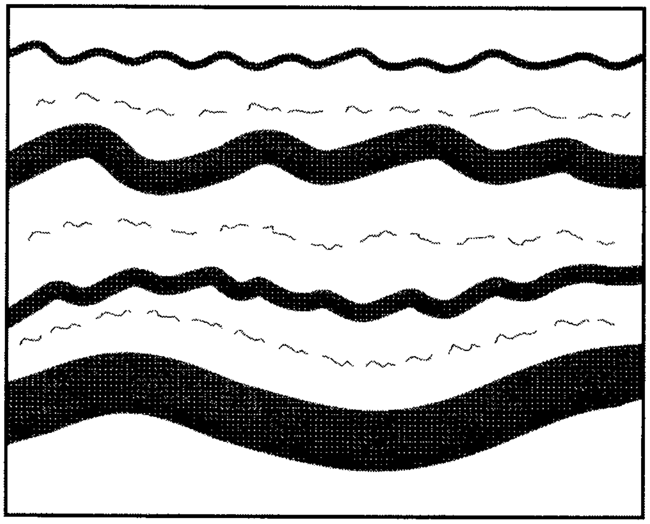
A special case of disharmonic folding is the separation of a large folded or faulted section from an undeformed or differently folded region along a distinct zone of flowage and/or faulting (Fig. 13). Such displacement surfaces are called a "detachment" (or the French equivalent, "décollement"). These terms are most often used when the deformed rocks are separated from an undeformed substrate. Detachment can also mean that apparently less-deformed rocks overlie more tightly folded or faulted rocks beneath. (We see this in the detachment between the less-deformed upper Stanley Group and younger sandstones and the locally much more crumpled shales of the lower Stanley). As long as a detachment remains at the same stratigraphic level it should not be called or mapped as a fault. When a detachment passes into a fold or thrust belt, it becomes the sole fault of the deformed unit.

Multiple-bed detachments in the limbs of folds are common and are produced by flexural slip caused by space constraints in the interior of folds. This type of displacement and its secondary strain features (e.g., drag folds) should not be interpreted as evidence for faulting because displacements may be minor and their map patterns are parallel to the strike and slip of the folded beds. Furthermore, the sense of shear is opposite in the two limbs of a fold.

CUSPATE-LOBATE FOLDING

The term for this type of folding is borrowed from paleontology and metamorphic, mesoscale structures. It refers to the scalloped or garland-shaped contacts of alternating rounded (lobes) and peaked (cusps) folds that form on contacts between competent and ductile formations (Ramsay and Huber, 1987). The lobes form on the competent side of the contacts and the cusps on the ductile side (Figs. 6, 7).

In the Ouachita Mountains, especially in Oklahoma, this kind of folding has controlled the shape of the detachment between the lower Stanley Group shales below and the overlying more-sandstone-rich section of the upper Stanley, Jackfork Group, Johns Valley Shale, and Atoka Formation. On the maps of the Ouachita Mountains (Pls. 1, 2) this scalloped contact is the boundary between two major structural-style provinces. The cuspate-lobate nature of the fold crests and troughs is best seen at the plunging ends of the folds on maps and regional cross sections. Because the crests of the majority of anticlines are eroded into the Stanley shales, the cuspate and typically



Disharmonic folding and detachment zones

Figure 12. Disharmonic folding occurs when fold trains of different wavelengths are separated by zones of flowage—rather than distinct faults—in ductile shales that are capable of adjusting to the required volume changes (modified from Currie and others, 1962).

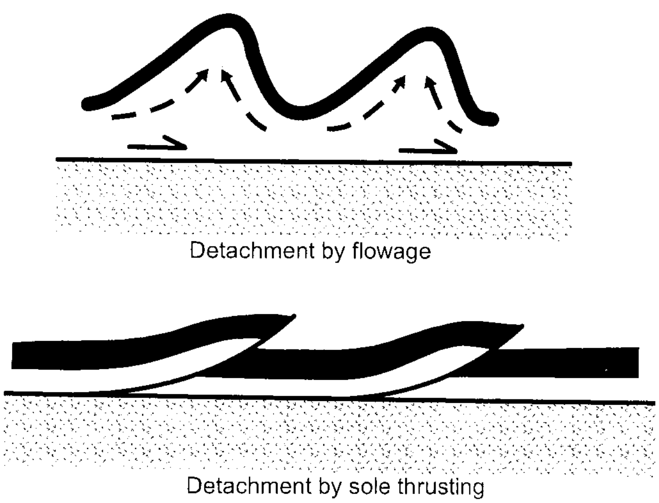


Figure 13. Detachments (or décollements) are a special case of disharmonic folding when some measurable displacement (by flowage or faulting) has taken place between deformed layers or between a deformed layer and a undeformed substrate.

faulted contact can be seen only at a few places (e.g., the Jumbo, Pickens, and Cloudy Anticlines).

"SCOOPS" OR CURVED RAMPS

In thick, uniformly ductile shale masses where widespread, tabular, competent carbonate or coarse-clastic units are absent, compressional and extensional stresses produce faults that take on doubly curved, half-bowl, scoop-like shapes. In extensional ductile systems these failure patterns will produce curved "listric" normal faults. In compressional systems the curved shapes are similar but opposite in displacement. There is much lateral overlap and strain release in both fault patterns; this is probably associated with internal flowage and possible volume dilation and compaction.

The subsurface prediction and mapping of such complex patterns is difficult and requires excellent three-dimensional seismic resolution and/or close well control. In the imbricated zone of the Oklahoma salient's frontal thrust belt, such verification is possible in the densely explored gas fields along the Choctaw Fault (Tilford, 1990). But in the early Paleozoic shales and the Stanley Group, similar control is unavailable and the existence of scoop-like faults remains hypothetical. Excellent seismic data confirming such overlapping listric-fault systems, however, are now available in the offshore Tertiary in the Gulf of Mexico and other delta regions.

UNDERTHRUSTING AND BACKTHRUSTING TRIANGLE ZONES

Many thrust belts display at their leading edge a fault zone in the footwall that dips away from the frontal thrust and has counter-regional displacement (Fig. 14). Before the 1950s field geologists could not resolve the geometry of these zones, which were usually interpreted as buckled frontal anticlines. In the 1950s, however, renewed interest in the hydrocarbon potential of thrust-and-fold belts led to new fieldwork and exploration with modern seismic techniques.

During this exploration, upturned beds were discovered at the front of the Rocky Mountains thrust belt in Alberta. These upturned beds dip away from and are not connected to the leading frontal thrust. They are also separated from the undeformed substrate (Bally and others, 1966; Jones, 1982, 1994; Arbenz, 1984; Perry and Suneson, 1990). Additional exploration revealed that these upturned footwall beds merged downdip with the undeformed, autochthonous foreland section, and that they were lifted but not otherwise moved. Thus, the layers

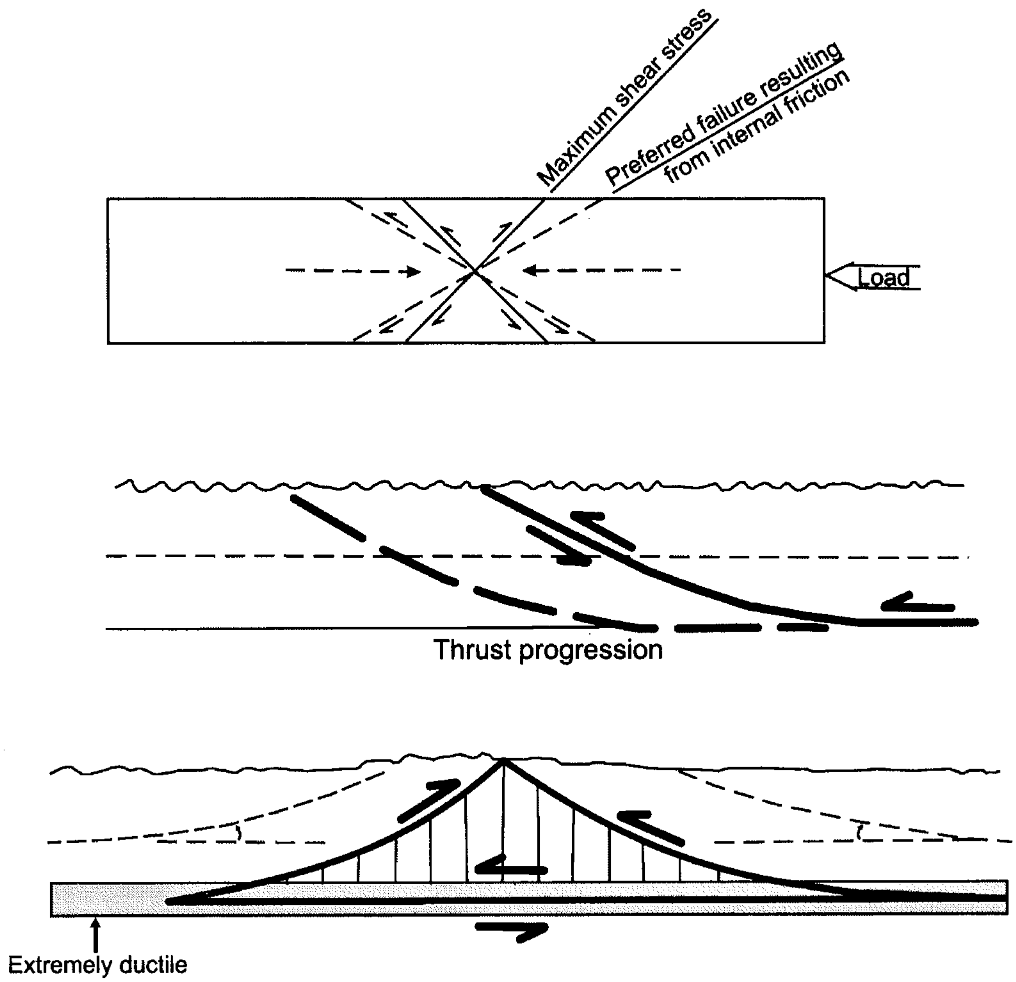


Figure 14. Triangle zones at the front of thrust systems form when a leading thrust fault passes into a nearly frictionless foreland strata instead of developing a next forward-moving thrust fault. The forward movement can then release a conjugate, counter-regional fault, isolating a triangle-shaped rock mass beneath the two opposing shears. The triangular rock mass will then move like a snowplow into the foreland section. The hanging wall of the counter-regional fault merges with the undeformed foreland section.

of the frontal thrust, the counterdipping beds of the footwall, and the flat beds of the undeformed floor formed, on seismic sections, a triangle or triangular antiform and an along-strike "triangle zone." Within a few years similar triangle zones were found along many other thrust belts.

Evidently, the upturned beds had been uplifted from below by a wedge of rocks that had been pushed, snowplow-like, into the foreland section. The contact between the wedge and the upturned segment is often a distinct thrust fault (i.e., a conjugate shear to the frontal thrust) (Jones, 1982, 1994; Arbenz, 1989b; Perry and Suneson, 1990; Valderrama and others, 1994).

Depending on the strength and ductility of the rocks involved, the size and internal structure of triangle zones can vary greatly, ranging from a nearly intact triangular piece of the foreland to an intensely deformed mass. The most critical factor in the origin of a triangle zone is the presence of a nearly frictionless, highly ductile detachment surface at the base of the triangle. The energy required to trigger a "conjugate" backthrust, therefore, must be less than that required to form a forward-stepping, "in-sequence"-vergent thrust fault. In the Ouachita Mountains part of such an underthrust complex of Johns Valley Shale is actually exposed in the reentrant of the Y City Fault near Boles, Arkansas.

STRATIGRAPHIC AND STRUCTURAL STUDIES IN THE OUACHITA MOUNTAINS, OKLAHOMA AND ARKANSAS (1956)

By

Peter Misch and Keith F. Oles

With Paleontological Data

By

William H. Easton and Gerald E. Marrall

UNION OIL COMPANY OF CALIFORNIA

May 1956

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ILLUSTRATIONS

STRATIGRAPHIC AND STRUCTURAL STUDIES IN THE OUACHITA MOUNTAINS, OKLAHOMA AND ARKANSAS (1956)

by

Peter Misch and Keith F. Oles

INTRODUCTION

Location of Area Investigated (See Fig. 1 and Geologic Maps of Arkansas and Oklahoma)

The Ouachita Mountains occupy an elongate belt extending from the Mississippi Embayment in central Arkansas to the town of Atoka in southeastern Oklahoma. The southern and eastern boundary of the Ouachita Mountains coincides with the contact between the Paleozoic rocks of the mountains and the Cretaceous rocks of the Coastal Plain. In Oklahoma the western and northern boundary has been considered to be the Choctaw Fault Zone (Plate I). In Arkansas the northern boundary coincides with the cropping out of rocks of Des Moines and younger age in the Arkansas Coal Basin.

Purposes of the Investigation

The original purposes of this study were: (a) to evaluate the long-accepted overthrust hypothesis for the origin of the Ouachita Mountains; (b) to map the reported thrust faults; and, (c) to determine whether structural traps favorable to the accumulation of petroleum could be expected in the Arbuckle "facies" which were presumed to underlie the overthrust rocks of the Ouachita "facies."

Discovering that there was no evidence for overthrusting, and that the long-accepted concepts were in error, this project was continued:

(a) To determine the structural pattern of the region;
(b) To determine and evaluate the stratigraphy of the area in terms of oil possibilities;
(c) To locate and map structures favorable for the accumulation of oil.

Recommendations

The recommendations that follow are based partly on detailed mapping, and partly on general reconnaissance. Reference should be made to the geologic map of the Western Ouachita Mountains of Oklahoma (Plate I) for geographic locations.

(I) It is recommended that the Jumbo anticline (T. 1, 2, and 3 S., R. 15 E.) be drilled.

(II) If the Jumbo test is successful, the following program is suggested:

- (A) Land should be acquired and these two structures drilled:
  - (1) Bald Mountain anticline (T. 1 and 2 N., R. 15 E.);
  - (2) Potapo Mountain anticline (T. 2 S., R. 13 and 14 E.).
- (B) The Buffalo Creek anticline (T. 2 S., R. 25 and 26 E.) should be mapped in detail. This doubly-plunging anticline has been established by rapid field reconnaissance. The rocks exposed are middle or lower Stanley (Mississippian) and a test here would penetrate the entire pre-Mississippian section.
- (C) The following areas should be investigated for possible anticlines and fault traps. The selection of these areas for investigation is based on general reconnaissance and/or aerial photographic interpretation.
  - (1) The Kiamichi River valley east of the Potato Hills. The main area of interest lies between the St. Louis and San Francisco Railway line in T. 2 and 3 N., R. 21 E., and the town of Muse in T. 2 N., R. 24 E. Other boundaries are the Jackfork rocks of the Kiamichi Mountains on the south, and the projected trace of the Windingstair fault on the north.
  - (2) The Kiamichi River valley between Kosoma (T. 2 S., R. 16 E.) and Clayton (T. 1 N., R. 18 E.). This part of the Kiamichi valley coincides with the Moyers anticline. Major strike faults near Kosoma, which eliminate the northwest limb of the Moyers anticline, may provide fault closure. Farther to the northeast, near Clayton, the anticline apparently is complete.

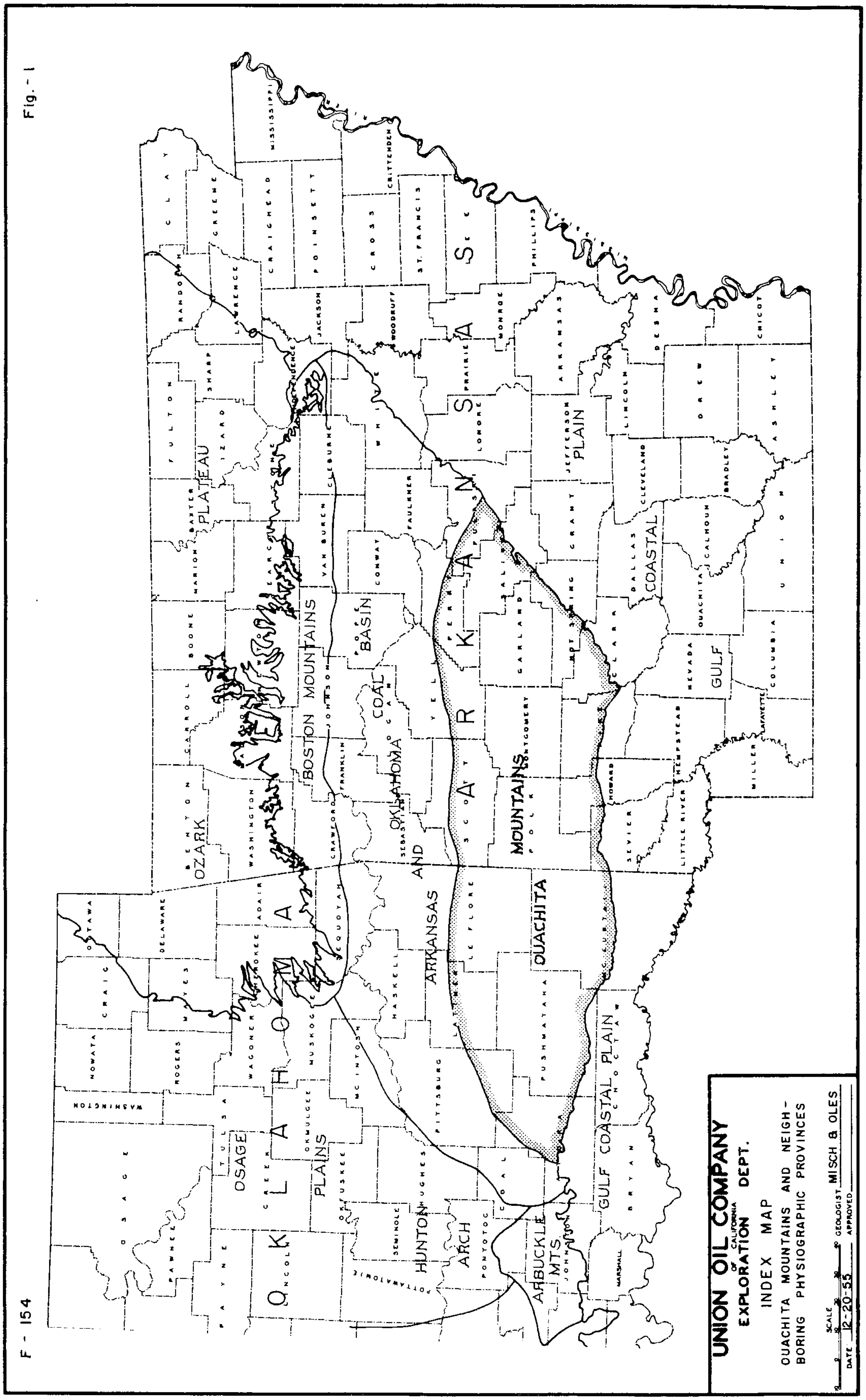
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Fig. - 1
OKLAHOMA
ARKANSAS
OZARK PLATEAU
BOSTON MOUNTAINS
ARKANSAS AND OKLAHOMA COAL BASIN
OUACHITA MOUNTAINS
GULF COASTAL PLAIN
OSAGE PLAINS
HUNTON ARCH
ARBUCKLE MTS.
UNION OIL COMPANY OF CALIFORNIA
EXPLORATION DEPT.
INDEX MAP
OUACHITA MOUNTAINS AND NEIGHBORING PHYSIOGRAPHIC PROVINCES
GEOLOGIST MISCH & OLES
DATE 12-20-55

(3) The Kiamichi Mountains lying within the confines of T. 2 to 4 S. and R. 16 to 20 E.

(D) Seismic studies should be made to determine whether there are reversals of plunge of those anticlines which are overlapped by Cretaceous rocks along the southern border of the Ouachita Mountains. Specific anticlines to investigate are:

(1) The Jumbo anticline and its southward extension beneath the Cretaceous overlap. If the Jumbo and Moyers anticlines join beneath the Cretaceous rocks there may be an axial culmination in T. 3 or 4 S., R. 14 or 15 E.;

(2) The southwest-trending Antlers anticline in T. 3 and 4 S., R. 16 E.;

(3) The anticline which, in sec. 2, T. 4 S., R. 17 E., is overlapped by Cretaceous rocks.

Discussion of recommendations:

Jumbo anticline: This is a major doubly-plunging fold which has been mapped in detail. A high-angle, east-dipping reverse fault along the western flank of this structure is construed as enhancing the closure. The details of structure are shown on the geologic map, Plate V; on the structural contour map, Plate VI; and on nine cross sections, Plate VI, a through i.

The rocks exposed in the crestal region belong to the lower Stanley (Mississippian) group. Thus, a well on the Jumbo anticline will test the Ordovician to Mississippian section.

If the Jumbo test is successful, it is recommended that two other structures be drilled. These are: (1) Bald Mountain anticline, T. 1 and 2 N., R. 15 E.; and, (2) Potapo Mountain anticline (T. 2 S., R. 13 and 14 E.).

Bald Mountain anticline: Photo-interpretation indicates this is a small structure about two miles long, with a reversal of plunge and presumed closure, but a lack of outcrops does not permit confirmation by surface mapping. The rocks exposed are upper Stanley and a well on this structure would test most of the Stanley group as well as the older formations. There are several shallow wells and an abandoned gilsonite mine on the presumed crest of this structure. The available surface details are shown on the geologic map, Plate III.

Potapo Mountain anticline: This is a major structure lying between the Lane and Pine Springs synclines. The rocks exposed along most of its length are those of the Jackfork group, but at the axial culmination the uppermost Stanley rocks crop out. A major reverse strike fault cuts out part of the northwest flank and might provide fault closure. Practically the entire Stanley section could be tested on this structure. At least seven shallow wells are producing near the crest of this structure. Details of structure are shown on the geologic map, Plate IV, and cross sections, Plate IV, a and b.

Additional Surface Mapping: If Jumbo anticline should be a favorable structure, and drilling activities are transferred to the Bald Mountain and Potapo Mountain structures, it is recommended that active surface mapping be done in the general areas previously listed. A study of the aerial photography, coupled with a knowledge of the regional structure, indicates these areas probably contain structures favorable to the accumulation of oil.

Time Expended and Main Emphasis

The field work began on June 15, 1953, and continued to November 1, 1955. The greatest time was spent, and the more detailed work done, in the Oklahoma segment of the Ouachita Mountains, particularly within Atoka, Latimer, Le Flore, Pittsburg, and Pushmataha counties.

Methods

Photographic coverage (stereoscopic pairs, scale 1:20,000) was obtained for much of the western Ouachitas and for substantial areas in Arkansas. Township mosaics were obtained later for parts of the Oklahoma Ouachitas. Large areas were mapped in the field by reconnaissance methods. Additional information was gained by a detailed study of vertical aerial photographs. Smaller areas which were deemed crucial to an understanding of the whole were mapped in detail. Detailed cross sections were prepared from traverses along Oklahoma Highway 2 and certain county roads which cross the regional strike (Plates VII, VIII, X, XI, and XII).

Maps and Literature Utilized

Maps:

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(3) Hendricks, T. A., et al, Preliminary Map 66 (in 3 sheets), Oil and Gas Investigations, U.S. Geological Survey, 1947.

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A large part of this report has been abstracted from the senior author's 1953 Progress Report, which contains a fuller discussion of the previous work in the Ouachitas and of certain of the concepts developed during this project.

STRATIGRAPHY

A composite stratigraphic section (Plate VIJ) is appended to show both the surface and the presumed subsurface column of the Jumbo anticline, Pushmataha County, Oklahoma. The Womble (Ordovician) through basal Stanley (Mississippian) section is a composite of measurements made in the Potato Hills and Black Knob Ridge. Most of the Stanley group was measured in Jumbo Valley. Additional data have been borrowed from the work of Honess (11, 12) and Harlton (10). This section shows the thicknesses and nature of the units to be expected in the areas of Pattern III and IV structures.

No one section is applicable to the entire Ouachita Province, inasmuch as there is both a marked thickening of section and an increase in coarser clastics from northwest to southeast across the mountains. Moreover, certain formations, present in southeastern Oklahoma and Arkansas, are absent in the western Ouachitas of Oklahoma (cf. below).

Description of Rock Units

For the discussion that follows reference should be made to the state geologic maps of Arkansas and Oklahoma, to the geologic map accompanying Honess' report (12) on McCurtain County, and to the stratigraphic section, Plate VIJ.

Collier formation

This is the oldest formation which crops out in the Ouachita Mountains. There are two areas in which rocks of this formation have been recognized. These are: (1) the "heart" of the Ouachita anticlinorium of Arkansas, south and west of Mt. Ida in Montgomery County; and, (2) the center of the Choctaw anticlinorium of McCurtain County, Oklahoma.

The base of the Collier formation is nowhere exposed, and only the top 400 feet can be described. The following is a composite description based on the writers' investigations and on Honess' work (12).

The lowest part of the section known to the authors crops out in an abandoned quarry (Section 32, T. 2 S., R. 25 W.) about 4 miles southwest of Mt. Ida, Arkansas. This quarry is not generally known, and no published reference to it has been found. A very small outcrop along State Highway 8 south of Mt. Ida is visited on geological field trips and is considered to be the "Core of the Ouachitas" (Section 26, T. 2 S., R. 25 W.). However, in the quarry and immediately to the south are exposed approximately 200 feet of contorted and fractured, dark gray, argillaceous, thinly-bedded and banded limestone, with intercalated shaly partings. A flat shearing has been superimposed upon the sub-isoclinally folded limestone, and subsequent near-vertical fractures are filled with milky quartz and calcite.

Honess (12; p. 34) has described a section which conformably overlies the limestone in McCurtain County, Oklahoma. This is a sequence of black, carbonaceous shales with minor lenticular cobble conglomerates which contain limestone, sandstone, and black chert fragments. Thin limestones are interbedded in this shale section. The thickness of the shales is estimated by Honess to be at least 200 feet. Here, as well as south of Mt. Ida, Arkansas, the shales have been metamorphosed into phyllitic rocks.

In both McCurtain County, Oklahoma, and Montgomery County, Arkansas, the uppermost 25 to 30 feet of the Collier formation is thinly-bedded, dense, fine-grained, dark bluish-gray limestone.

Folding, a superimposed flat shearing, and subsequent fracturing have probably obliterated most fossils that may have been present. Honess does describe (12; p. 44) some non-diagnostic siliceous algae. However, no fossils have been found which might determine the age of this formation. The assigned Cambrian age is subject to question, and will be discussed in a later chapter.

Crystal Mountain sandstone

This formation crops out in the same localities as the Collier. The formation is divided into two units.

Basal conglomerate: Discomformably (12; p. 46) overlying the upper Collier limestone is a conglomerate up to 14 feet thick. This contains pebbles of quartz, sandstone, limestone, black shale, slate, and quartzite. Bedding is not apparent. The cementing material is described by Honess (12) as ranging from a "fine-grained, dense, siliceous limestone" to a "calcareous sandstone."

Upper sandstones: The sandstones overlying the basal conglomerate and forming the bulk of the formation are estimated by Honess (12) to be at least 500 feet thick, and by Miser and Purdue (16) to be 850 feet thick. These are generally massive, fine- to coarse-grained, dark-gray, and quartzose. Honess (12) describes rutile, apatite, and zircon inclusions within the usually well-rounded quartz grains. The cementing material is silica, and many of the sandstone members are true quartzites.

This formation has been assigned an early Ordovician age. No fossils have been described from it.

Mazarn shale

Apparently conformable with the underlying Crystal Mountain sandstone is a sequence of shales estimated (Honess, 12; Miser and Purdue, 16) to be about 1,000 feet in thickness. This formation is mapped on the Arkansas and Oklahoma state maps with the overlying Blakely and Womble and its exact area of outcrop is not well defined. To the writers' knowledge the Mazarn does not crop out in the western Ouachitas, but is restricted to the eastern and southern Ouachita Mountains in the Ouachita anticlinorium of Arkansas and the Choctaw anticlinorium of Oklahoma.

The dark bluish-gray to black, carbonaceous shales have been subjected to flat shearing which has produced a slaty cleavage. In the past, this cleavage has been interpreted as bedding. Much of the formation, as a result of the shearing, has been converted to low-grade metamorphic rocks, some of which are phyllites. Honess (12; p. 33) notes that because both the Mazarn and the Collier have been metamorphosed one is often mistaken for the other.

Subordinate amounts of sandstone and limestone occur in lentils within the shales, and locally are found as lenses within the zones of flat shearing. The limestone is dark-gray to black, dense, thinly-bedded, and occurs in bands up to 15 feet thick (16). A minor quantity of the limestone is a granulite composed of clastic limestone fragments. The sandstone occurs in beds up to 2 feet thick and is gray, fine-grained, thinly-laminated, and locally approaches a quartzite in composition.

Only rare graptolites have been found. Miser and Purdue (16) give a list of graptolites and have assigned these a Beekmantown (early Ordovician) age. The writers believe that Miser and Purdue may have mistaken the Mazarn for the Collier, however, and believe that there is a possibility that the graptolites were collected from the older formation.

Blakely sandstone

Overlying the Mazarn shale with apparent conformity is a sequence which, in McCurtain County, Oklahoma, is the lateral equivalent of at least part of the Womble Shale of Arkansas and Oklahoma. Miser and Purdue (16) note that in the vicinity of Hot Springs, Arkansas, a local basal conglomerate may indicate unconformity.

Honess (12) describes the Blakely as a fine- to coarse-grained quartzitic sandstone lying beneath the readily recognizable Big Fork formation. Miser and Purdue (16) describe the Blakely in the Caddo Gap quadrangle, Arkansas, as shale with interbedded sandstones. This formation quite probably represents a sandy facies of the Womble Formation. However, this formation does not crop out in the western Ouachitas and is therefore not shown on the stratigraphic column (Plate VIJ).

Womble shale (Womble "schistose sandstone", Stringtown shale)

In conformity with either the Blakely or the Mazarn, apparently dependent upon geographical location, is a variable sequence of rocks. In McCurtain County Honess (12) described the Womble as a "mass of green (invariably weathered red) schistose, micaceous, fine-grained sandstones and grits." Miser and Purdue (16) describe the Womble as hard, black, splintery shale, the upper part very carbonaceous, with thin fine-grained quartzose sandstone layers throughout the formation and sporadic lenses of fine-grained, even-bedded limestone in the upper 150 feet.

The Womble is predominantly shale in the Potato Hills and along Black Knob Ridge (Plate I). The shale is black, thinly platy, fissile, or papery, and highly carbonaceous. There also are silty shale and siliceous shale intercalations. In the upper part of the formation interbedded thin black cherts are transitional with the overlying Bigfork formation. The full section of the Womble is not exposed in the westernmost Ouachitas, and its thickness is an estimate. Miser and Purdue (16) estimate the thickness in the Caddo Gap area as 1,000 feet. Honess (12) did not estimate a thickness in the Choctaw anticlinorium because of poor exposures. Because of marked thinning of many of the higher formations in a westward and northward direction, a lesser and arbitrary thickness of 500 feet has been depicted on Plate VIJ. This figure may be in considerable error.

Graptolites are common in some members. Ulrich (16) has assigned ages to various collections from the Womble which range from upper Chazy to Trenton (early Middle to late Middle Ordovician).

Bigfork chert

This formation transitionally overlies the Womble shales. Excellent exposures occur in the Ouachita anticlinorium of Arkansas, and in the Choctaw and Potato Hills anticlinoria and along the Black Knob Ridge of Oklahoma. Miser and Purdue (16), in the Caddo Gap (Arkansas) area, have assigned a thickness of about 700 feet; Honess (12), in the Choctaw anticlinorium, about 800 feet. The writers' observations in the Potato Hills indicate a thickness of about 600 feet.

This formation differs little from the Viola limestone, and faunal evidence indicates this is its equivalent in the Arbuckle region. In most places where the writers have seen the Bigfork it contains only a moderate to small amount of pure black cherts. Much more common are impure rocks which contain varying amount of limestone, siltstone, and siliceous material. The proportion of silica varies greatly. The formation includes thin-bedded, finely-textured, locally silty limestones and calcareous siltstones with subordinate beds of shale.

The fossils collected from the Bigfork are chiefly graptolites, although other invertebrate remains, such as sponge spicules, crinoid stems and brachiopods, have been found. Ulrich (Miser and Purdue, 16) considers the graptolites to be Trenton (late Middle Ordovician) age.

Polk Creek shale

In the various anticlinoria the Bigfork formation is overlain conformably by a sequence of shales and subordinate siltstones, with interbedded cherts near the base. The shales are thinly-platy to fissile, usually dark gray or black, and carbonaceous. The estimated thicknesses are: Miser and Purdue (16), in the Caddo Gap area, up to 175 feet; Honess (12), in the Choctaw anticlinorium, 100 to 200 feet. In the Potato Hills and along Black Knob Ridge folding makes difficult a calculation of thickness, but 150 feet is an estimate. For convenience the writers have mapped the Polk Creek and the overlying Missouri Mountain shale together (Plates I, II).

Graptolites are abundant in some of the shale beds and have been assigned a late Cincinnatian (Upper Ordovician) age (16).

Blaylock sandstone

The Blaylock sandstone lies conformably between the underlying Polk Creek shales and the overlying Missouri Mountain's shales. This formation has been described in Arkansas by Miser and Purdue (16) and in McCurtain County, Oklahoma, by Honess (12). The formation is not present in the western end of the Ouachita Mountains.

The strata composing this formation are described by Honess (12) as ".....thin-bedded, fine-grained, greenish-gray, hard sandstones and interbedded shaly sandstones and dark shales." Honess has measured an 804 foot thick section near Hochatown, Oklahoma. About 5 miles north of this section Honess notes (12; p. 95) that the formation has thinned to 670 feet.

Fossils are rare. E. O. Ulrich[1] has assigned a Silurian age to seven species of graptolites from this formation.

Missouri Mountain shale

The Missouri Mountain shale is conformable with the underlying Polk Creek shales in the westernmost Ouachitas. The transition is gradual, and for this reason the two formations were mapped together. The bulk of the Missouri Mountain formation is fissile and platy shale. The shales are mostly dark gray, although maroon or grayish-green shales also occur. Thin bands of chert are present in the upper part of the formation. The amount of chert increases upward as the base of the Arkansas novaculite is approached. Intricate folding makes difficult an accurate estimate of thickness, and an arbitrary thickness of 150 feet has been assigned.

No fossils have been described from this formation, and the assigned Silurian age is based upon stratigraphic relations.

Arkansas novaculite, Pinetop chert, and Woodford chert or shale

In the outer parts of the Ouachita anticlinorium of Arkansas, and in the Choctaw anticlinorium, Potato Hills, and Black Knob Ridge of Oklahoma, the Missouri Mountain shales are overlain conformably by the Arkansas novaculite. This is a sequence of generally thin-bedded, black, gray, green, reddish, and light colored, locally banded cherts, with subordinate amounts of dark and greenish shale. The writers believe that in the Potato Hills this formation is about 400 feet thick. Conodonts have been collected from the upper middle part of the novaculite, and these have been assigned a Kinderhookian (early Mississippian) age. However, Honess found a Leptocoelia flabellites (12; p. 117) in the upper part of the lower novaculite. This definitely dates this part of the formation as being of Oriskany or Onondaga age (early Devonian). Therefore, the novaculite is probably Devonian and early Mississippian in age.

The cherts of the novaculite differ from the Bigfork rocks by their much higher degree of purity and by their variegated coloring. However, much of the novaculite consists of dark-colored rocks, and these have been mistaken in the past for the Bigfork cherts.

In the marginal belt at the western end of the Ouachitas—but not along Black Knob Ridge where there is typical novaculite—the correlatives of the novaculite are the Pinetop chert and Woodford chert. The former corresponds to the Devonian part of the novaculite, and the latter to its early Mississippian part, although the contact between the two may not coincide exactly with the Mississippian-Devonian boundary.

Where the writers have observed these two formations (Sec. 3-5, T. 2 N., R. 15 E.; Sec. 32, T. 3 N., R. 15 E.) their names appear to be rather misleading. The lower part of the "Pinetop chert" contains limestone which is similar lithologically to the Hunton of the Arbuckle region. The upper part contains light-colored cherts similar to those of the novaculite. The partial silicification of some of the limestones indicates that at least part of the chert is secondary.

If the term Pinetop chert is to a certain extent a misnomer, this is to a greater extent true of the Woodford "chert" of the westernmost Ouachitas. The Woodford near Pinetop School (T. 2 N., R. 15 E.) is a siltstone which is in part limy, and characteristically contains very limy and phosphatic concretions. Chert is almost absent, and generally is restricted to a few bands just below the top. Some of the siltstones are partly siliceous, and there are shaly interbeds within the siltstones. At the top, the so-called Woodford "Chert" passes conformably into greenish and black fissile shales. In the westernmost Ouachitas these shales are mapped as Caney shale, but they most probably are the lower Stanley shale (cf. below).

Stanley group

Overlying the Arkansas novaculite is the Stanley shale which is one of the thickest and most widespread units in the Ouachita Mountains. It is the great valley-former of the Ouachita Mountains. The Stanley Formation can be subdivided, and can be considered to merit the rank of a group. Harlton (10) has subdivided the Stanley group, basing his division on distinctive black, partly siliceous shales. Harlton's formations, in ascending order, are: Ten Mile Creek, Moyers, and Chickasaw Creek.

The Stanley is conformable and transitional with the underlying Arkansas novaculite. For a full description of the Stanley in the southwestern Ouachitas, Harlton (10) should be consulted. In brief, the lower 750 feet is composed of siliceous and/or cherty green shale and siltstone, with minor intercalated sandstones. The siliceous content decreases upward.

Above this lower siliceous unit is a sequence which, in the Jumbo—Moyers area of Pushmataha County, Oklahoma (Plate I), is about 7,000 feet thick. This is a sequence of dominantly gray to dark-gray fissile and platy shales, with subordinate silty shales, arenaceous shales, siltstones, and fine-grained sandstones. Characteristically the Stanley sandstones and siltstones weather to an olive drab color, and the shales to an olive green color. Bluish, partly silicified shales are convenient key members for mapping, and form the basis for Harlton's subdivision

[1]Miser, H. D., U.S.G.S. Bull. 660-C, P. 66.

of the group. Tuffaceous layers occur locally near the base, and, in their optimum development in eastern Oklahoma and Arkansas, are termed the Hatton tuff lentils. Thin chert conglomerates occur in the Chickasaw Creek and Moyers formations (Harlton, 10) and may represent unconformities.

Microfossils are rare and usually non-diagnostic. Reference should be made to the appended paleontologic report of Gerald E. Marrall. An effective zoning based on spores probably could be worked out.

Honess has found the only megafossils known to the writers. Ulrich (12; p. 178) believed that some of the brachiopods found by Honess belonged to a species of Chonetes of an age older than Warsaw (i.e., older than Meramec, Mississippian). Ulrich then ignored his paleontologic determination by writing: ".....it is almost too much to concede that the Stanley can be lower Mississippian, then these fragments may be used to point toward the Pennsylvanian rather than Mississippian." Honess' collection was from a zone about 25 feet above the base of the Stanley, not far above the top of the Arkansas Novaculite in which fossils of Kinderhookian age have been found. It is conceivable that Ulrich's paleontological determination is more valid then his pre-conceived opinions.

Jackfork group

The shales, siliceous shales, and lenses of chert conglomerate of Harlton's uppermost Stanley formation—the Chickasaw Creek siliceous shale—are overlain conformably by thin-bedded, fine-grained quartz sandstones of the lower Jackfork group. Harlton (10) has assigned a group rank to the Jackfork, and he has divided the group into four formations (10). These formations have an aggregate thickness in the type sections of 8,750 feet. The Jackfork is the dominant ridge- and hill-former of the Ouachita Mountains.

The Jackfork is characterized by its heavy sandstones, although thin-bedded sandstones, siltstones, and interbedded shales make up a considerable part of the sequence. The Jackfork also contains "boulder beds."

Harlton's sequence (10) can be utilized for mapping purposes, though some of his highest Jackfork and boulder bed data are confused and subject to different interpretations.

Wapanucka limestone and Chickachoc chert

In the northern- and westernmost parts of the Oklahoma Ouachitas there is a limestone, siltstone, and shale sequence which, through high-angle reverse faults, has been repeated as many as six times (Plate I), forming a number of resistant, parallel ridges.

The Wapanucka typically consists of highly fossiliferous, locally crinoidal limestones with interbedded siltstones and shales. The complete sequence, as exposed at Limestone Gap (Section 29, T. 2 N., R. 13 E.) north of Stringtown, Oklahoma, consists of an upper, dominantly calcareous unit, a thick medial shale unit, and a lower dominantly calcareous unit. This sequence approximates 500 feet in maximum thickness. This threefold division occurs throughout the calcareous outcrops of the Ouachita Mountains, as well as in the subsurface and on the surface of the Coal Basin. The persistent unit in the Ouachitas is the medial shale. Both of the calcareous units change in lithology both along and across the strike. Rapid changes from limestones to calcareous siltstones, sandstones and shales occur.

A few of the localities where these marked facies changes may be seen are: (cf. Plate I)

(a) In an abandoned limestone quarry, Section 17, T. 4 N., R. 17 E. Here, as in the quarry approximately one mile farther west along the strike, limestones change to sandstones within a distance of 50 feet;

(b) In Section 14, T. 4 N., R. 17 E., where the limestone of the lower calcareous unit has changed to a coarse-grained, glauconitic sandstone;

(c) In the northeast quarter of T. 4 N., R. 18 E., where a ridge with the characteristic sharp, linear expression of the limestone ridges was found to be composed of medium-grained, white, clean, quartzose sandstone of upper Jackfork type. Paleontologic evidence from samples collected along Oklahoma Highway 2, immediately to the east, indicates that these beds are correlative to the Wapanucka;

(d) At the eastern end of the Wapanucka outcrop (east of Wilburton, Plate I), the ridges, though still possessing the topographic expression of the limestone ridges, are composed dominantly of medium-grained quartzose sandstone;

(e) South of Limestone Gap, in T. 1 N., R. 12 E., where the lower calcareous unit is transitionally overlain by shales and siltstones, and the upper unit has lost its calcareous character.

The term Chickachoc has been used by most authors to indicate the clastic equivalent of the Wapanucka. Harlton (10) dispenses with the name, and sets up a new terminology in which the lower calcareous unit (cf. above) is the Wapanucka, and the upper calcareous unit, together with the medial shale, is the Barnett Hill formation.

In most localities the Chickachoc "chert" is not chert, but is a slabby, dark gray siltstone, which is in part limy, and locally is silicified. Much of it is rich in sponge spicules. True chert is restricted to a few bands and concretions. Some of the Chickachoc is sandy (cf. above); some, as at Limestone Gap is dominantly limestone; and some grades into shale.

Field studies by Dr. Easton, coupled with his and Mr. Marrall's paleontologic determinations, prove that the confu-

Figure 2.

INDEX MAP

OUACHITA MOUNTAINS

OKLAHOMA

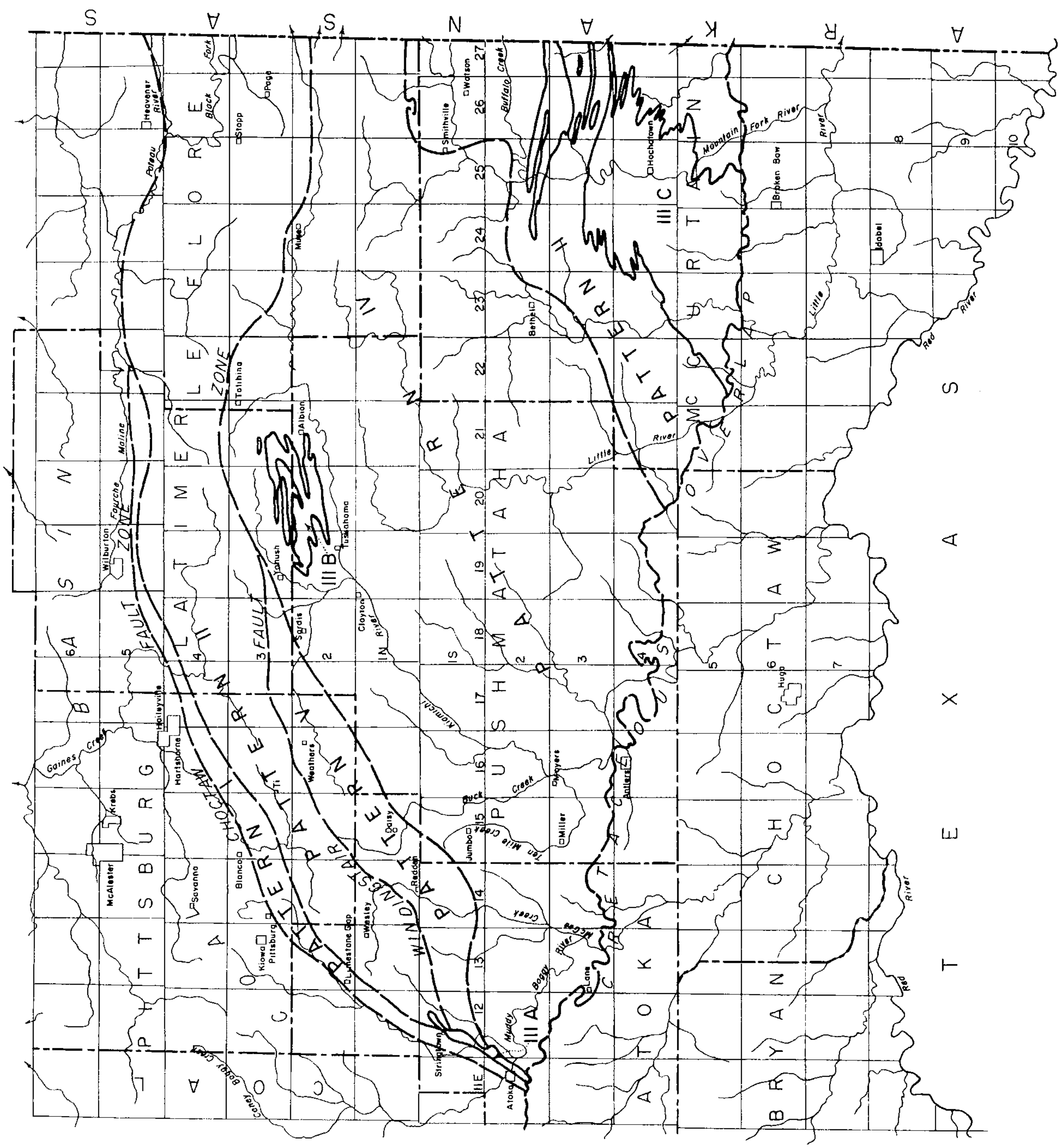
SHOWING PATTERNS OF DEFORMATION

P. Misch & K.F. Oles

UNION OIL COMPANY OF CALIFORNIA

1956

PATTERN I – The belt of imbricate faulting.
PATTERN II – The belts of tight folding.
PATTERN IIIA – Black Knob Ridge.
PATTERN IIIB – Potato Hills
PATTERN IIIC – Choctaw anticlinorium.
PATTERN IV – The area of open synclines and more tightly folded anticlines.
PATTERN V – The faulted belt north of the Pattern IV area.



sion in terminology and stratigraphy was not eliminated by Harlton's work (10). As an example, Harlton's Barnett Hill ranges in age and lithology from early Des Moines sandstones at his type locality near Clarita, Oklahoma (T. 1 S., R. 8 E.), to middle Morrow limestones in the westernmost part of the Ouachitas, as at Limestone Gap. Dr. Easton's work, based on "walking-out" of beds and fossil collections, shows that the upper calcareous unit of the western Ouachitas is the true Wapanucka, and corresponds to the Wapanucka limestone at Taff's presumed type locality just west of the town of Wapanucka (T. 2 S., R. 8 E.). Moreover, the lower calcareous unit, lying beneath the persistent medial shale, is the Chickachoc. Both the Wapanucka and the underlying Chickachoc grade along and across the strike into more clastic rocks. In general, the two formations become more and more clastic (cf. above) as either the eastern end (east of Wilburton) or the southwestern end (north of Atoka) of their outcrops are approached. The culmination of this increase in clastic materials cannot be seen to the southwest because of truncation by the Choctaw fault (Plate I). However, at the eastern end of the outcrop area, in T. 5 N., R. 21 E. east of Wilburton, Oklahoma, the Wapanucka and Chickachoc become sandstones which lose their identity in the upper Jackfork sandstone sequence.

Honess (12) recorded an identical conclusion. He obtained a large fauna from the Jackfork about midway in the sandstone series which forms the Boktukola syncline in McCurtain County. Honess is quoted by Miser and Purdue (16; pp. 71-72): "The fauna is regarded as definitely Morrow and equivalent to the Wapanucka. The Morrow fauna occurs about midway in the sandstone series which forms the Boktukola syncline. The sandstone series overlies the Stanley shale in normal sequence and is 13,618 feet thick.....From the point of view of the lithology there is no difference between that part of the formation which lies below the fauna and that part which lies above it.....and no part of this vast series looks like or resembles in any way the Caney shale or the Atoka formation. The Wapanucka limestone is wanting, and in its stead there are fine-grained ferruginous sandstones. The entire series (13,618 feet thick) is one continuous and uniform whole, and this being a fact, the writer does not see fit to do otherwise than to speak of a lower Jackfork (that portion which lies below the Morrow fauna) and an upper Jackfork (that part which lies above it)."

Dr. Easton and Mr. Marrall have determined that the Wapanucka and Chickachoc are of middle Morrow age (cf. Appendix A), and are correlatives of the Marble Falls formation of Texas and the Brentwood limestone of Arkansas.

Atoka formation

Much of the Atoka formation of early Des Moines (Pennsylvanian) age has been mapped on the basis of the presumed overthrusting in the Ouachita Mountains (cf. Oklahoma Geologic Map and Hendricks, 3). The writers' structural studies, coupled with paleontologic evidence (Appendix A), indicate that much of the mapped Atoka is Jackfork (cf. Structure, Pattern I and II).

However, Atoka is probably present in the cores of certain of the major synclines. For example, in the cores of the Prairie Mountain and Lane synclines (Plate I, T. 1 and 2 S., R. 12 and 13 E.) there are several hundred feet of shales, siltstones, and sandstones. The sandstones are ripple-marked, fine-grained, mostly ferruginous, argillaceous and carbonaceous. Locally, these sandstones contain a profusion of plant debris. These sandstones differ markedly from the more thickly-bedded, coarser-grained, highly quartzose, "clean" sandstones of the upper Jackfork.

Atoka rocks probably are present in the core of a large syncline in T. 3 N., R. 16 E. (Plate I) where a sequence of thin-bedded sandstones, siltstones, and shales lies unconformably upon rocks of Jackfork age.

Trinity group

The Lower Cretaceous (Comanchean) Trinity sandstone lies with angular unconformity upon much-weathered Stanley, Jackfork and older formations along the southern border of the Ouachita Mountains. Where this formation is observed a cobble- to boulder-conglomerate lies at the base, succeeded by lenticles of fossiliferous limestone interbedded in a ferruginous coarse-grained sandstone.

The Boulder Beds of the Ouachita Mountains

Introduction

In many places in the Ouachita Mountains of Oklahoma and as far east as Boles, Arkansas, there are Pennsylvanian shales, ranging from a few feet to one hundred feet in thickness, which contain pebbles, cobbles, and boulders. These exotic rocks vary greatly in lithologic type and size, and range in age from Ordovician to Mississippian. Though the shales are continuous for many miles along the strike, the boulders are sporadic in occurrence. Some boulders occur in pods or lenses which are less than 100 feet in longest dimension. In Pounds Valley (T. 2 N., R. 14 and 15 E.), the boulder shale was traced along the strike for about 4 miles.

Ulrich (18) lists 42 localities at which these boulder shales crop out. Woodworth (19) described the boulders which crop out in the St. Louis and San Francisco Railroad cut 1/2 mile north of Compton, Oklahoma. Harlton (10) mentions the boulder shales at the Compton railroad cut; in a road cut near Stapp, Oklahoma; in a creek in the NE¼, NW ¼, Sec. 14, T. 3 N., R. 19 E.; at the junction of Oklahoma Highways 2 and 63 (SE¼, SW1/4, SW¼, Sec. 27, T. 4 N., R. 19 E.); and in the Prairie Mountain syncline (NE¼, NE¼, SE¼, Sec. 2, T. 2 S., R. 12 E.).

In Oklahoma the Jackfork group has been mapped only south of the alleged Ti Valley thrust (Hendricks, 3; Geologic Map of Oklahoma, 2). North of this "thrust" only Atoka has been mapped. Hendricks (3) has designated the Johns Valley shale as the formation which contains the boulder shales, and he considered it as the interval between the Jackfork group and the overlying Atoka formation. Where outcrops of boulder shale were found or imagined, the boulders apparently have been considered by Hendricks as ball bearings which, rolling along a fault zone or "friction carpet," were brought up from depth along major thrusts. The astonishing complexity of Hendricks' map is based largely on the occurrence of these boulder shales.

Stratigraphic Position

Previous workers mapped on the basis that the Johns Valley shale occupied the same stratigraphic position throughout the Oklahoma Ouachitas, and marked the boundary between the Jackfork and the Atoka. Moreover, every outcrop of the boulder shales was interpreted as indicating the presence of a "friction carpet" and a major thrust.

However, structural studies and paleontologic evidence developed in this study show that there are three boulder shale zones, and that all three occur within the Jackfork group. The lowest boulder shale is near the base of the Jackfork, and is exposed south of Pinetop School (Secs. 8 and 9, T. 2 N., R. 15 E.: Plate VIII) and north of Maud School (Secs. 11 and 12, T. 2 N., R. 14 E.; Plate XI). Both the stratigraphic position and the microfauna indicate that this lowest shale is a part of the lower Jackfork.

The medial boulder shale crops out south of the Hairpin Curve (Sec. 10, T. 3 N., R. 19 E.) and near the Baskett Ranch in the Johns Valley syncline (Secs. 3 and 4, T. 2 S., R. 16 E.). The shale matrix of this boulder shale contains a Morrow microfauna which is characteristic of the upper Jackfork rocks. These fossils are slightly older than those found in the Wapanucka formation (middle Morrow).

The upper boulder bed crops out (1) In the creek east of Oklahoma Highway 2 (NE¼, NW¼, Sec. 14, T. 3 N., R. 19 E.); (2) In the highest boulder bed exposed on the north side of the Hairpin Curve (SE¼, SE¼, SE¼, Sec. 3, T. 3 N., R. 19 E.); (3) At the junction of Oklahoma Highways 2 and 63 (SE¼, SW¼, SW¼, Sec. 27, T. 4 N., R. 19 E.); (4) On the Potapo Mountain anticline (Sec. 34, T. 2 S., R. 13 E.). The shales enclosing the boulders at each of these localities contain a microfauna identical with that found in the Wapanucka formation (middle Morrow). In addition, megafossils collected from locality (1) confirm a Brentwood (i.e., Wapanucka) age for the shales.

The Shale Matrix

The matrix of the boulder beds consists of thin-bedded to fissile black shale, with subordinate intercalations of dark-green and dark-gray shale. There are subordinate sandstones which are thin-bedded, in part silty, and locally quartzitic. The sandstones occur as stringers, a few inches thick, within the boulder-bearing shales or, locally, as thicker members, up to 3 feet thick, which are intercalated in adjacent boulder-free shales.

The boulders are restricted to the dark fissile shales. Generally the volume of shale greatly exceeds the volume of boulders, although locally the reverse is true. In a road cut south of Stapp (Sec. 13, T. 3 N., R. 25 E.) which has been described by Harlton (10), most of the exotics are widely separated in a sequence which is dominantly shale. However, at this locality there is a zone about 50 feet thick which consists of a closely-packed, uncemented mass of boulders, cobbles, and pebbles (Figure 3). At the margins of this mass the black shale of the matrix projects into the spaces between individual fragments.

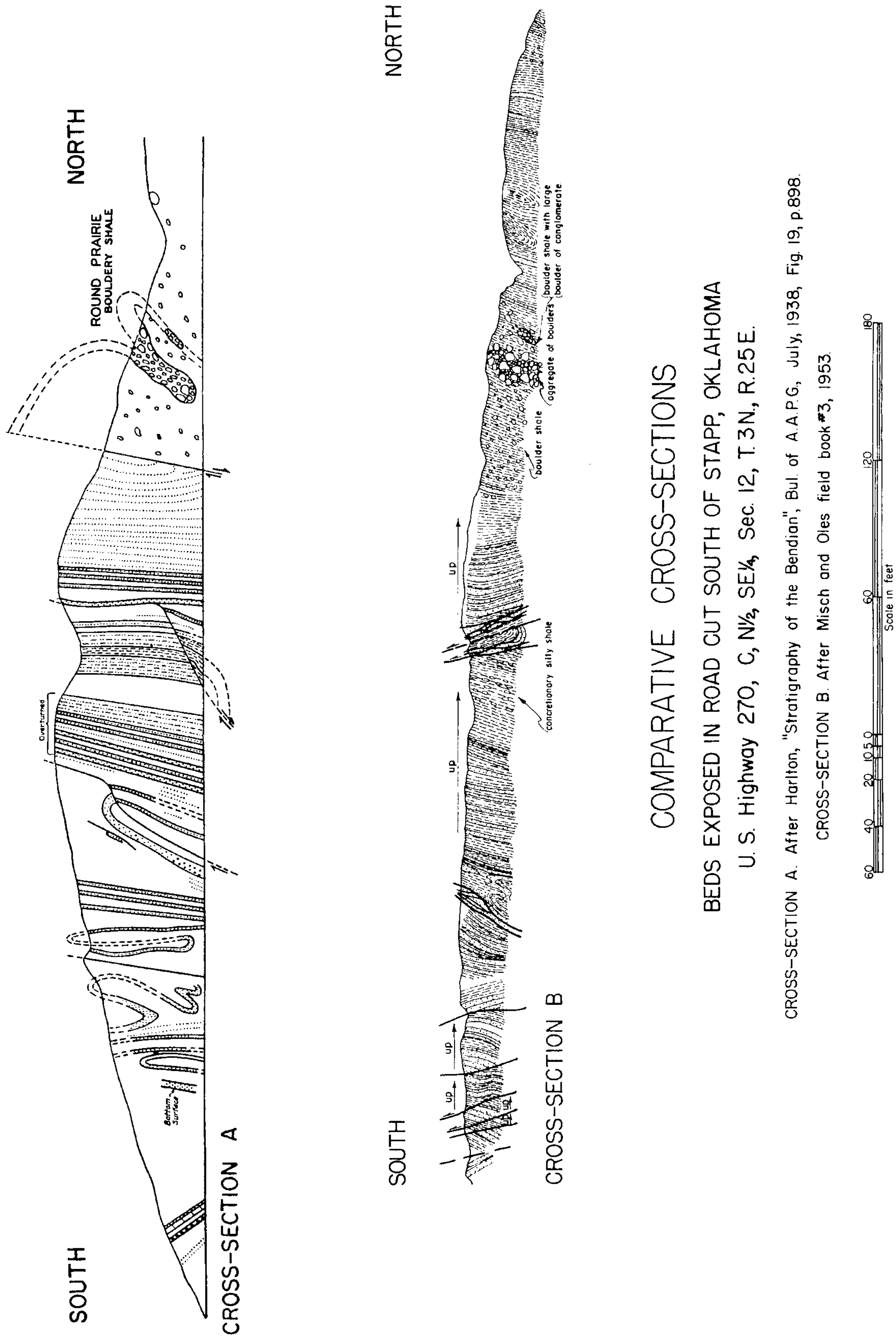
About 25 feet to the north there is an isolated boulder of conglomerate. This boulder is represented on Harlton's cross section (10, p. 398; Figure 3, A) as a band of individual boulders connected to the larger mass of uncemented boulders by an isoclinal fold. However, the solitary boulder of conglomerate, unlike the larger mass of boulders, has a sandy matrix and obviously was cemented prior to deposition in the shale. This boulder apparently was derived from an older conglomerate, and it is not a band of individual boulders (Figure 3, B).

Exotic Boulders

The exotics are irregularly scattered in the dark shales (which also are rich in concretions which can be mistaken for exotics). Apart from sandstones which could have been derived from strata in the vicinity, the exotics consist of Arbuckle-region rocks ranging from Arbuckle limestone (Cambrian-Ordovician) to Caney concretions (Mississippian). Ulrich (18) gives a description of the faunas on which these age determinations have been based. Chert always is present, and locally is the only rock type represented in the shales. Some of the chert varieties are obviously silicified limestones.

The exotics range in size from small pebbles to large boulders. The largest boulders the writers have seen crop out in Johns Valley syncline (Sec. 3, T. 2 S., R. 16 E.). These boulders are composed of Arbuckle, Viola, and Hunton limestones, Caney concretions, chert, and silicified limestone. One boulder, though incompletely exposed, has one dimension exceeding 100 feet. However, boulders measuring more than 10 or 15 feet in longest dimension are rare, and pebbles and cobbles are most common.

The exotics generally are subrounded to subangular, a few are well-rounded, and exceptionally they are angular. The larger boulders generally are slab-shaped, with subrounded to subangular edges. The slabs invariably lie with the long axis



F-154 Figure 3

COMPARATIVE CROSS-SECTIONS

BEDS EXPOSED IN ROAD CUT SOUTH OF STAPP, OKLAHOMA

U. S. Highway 270, C, N½, SE¼, Sec. 12, T. 3N., R. 25 E.

CROSS-SECTION A. After Harlton, "Stratigraphy of the Bendian", Bul. of A.A.P.G., July, 1938, Fig. 19, p.898.

CROSS-SECTION B. After Misch and Oles field book #3, 1953.

parallel to the bedding of the enclosing shale. The shape of the largest boulders is difficult to determine inasmuch as they generally are incompletely exposed.

Locally the smaller boulders have polished surfaces which are scratched. These striations have been described by Ulrich (18). In the road cut immediately south of Harlton's Stapp locality (10) there is a limestone boulder about 10 feet long with a prominent striated surface. The striations are in parallel arrangement and extend across the surface from edge to edge.

Deformation in the Boulder Beds

The shales containing the exotics, as well as the intercalated boulder-free shales and sandstones, are evenly bedded and undisturbed. Locally, minor faulting and shearing are present, phenomena which are common to all the more tightly-folded rocks of the Ouachitas. However, these local disturbances are unrelated to the occurrence of the exotic boulders. The only deformation in the shales related to the boulders occurs at the lower edges of the larger slabs, where the shale is wrapped around the fragment. This very local deformation generally disappears immediately beneath the slab, and dies out laterally within a few inches. Apparently this deformation occurred when the slab was dropped into mud, with the result that the sediment wrapped around the lower edges. No deformation of the enclosing shales was noted adjacent to the smaller pebbles and cobbles. There is never deformation in the shales overlying the exotics, and any local minor faulting and shearing is clearly secondary.

Origin of the Boulder Shales

There are a number of hypotheses to explain these exotics. Some of the most pertinent ones follow.

Ulrich (18) recognized a depositional origin for the boulders, and advanced the ice-rafting hypothesis to account for the transportation of fragments of Arbuckle rocks into the Ouachita geosyncline. Ulrich theorized that shore ice formed along a coast of Arbuckle rocks, and that fragments of these rocks dropped onto the ice from cliffs and were carried away on ice rafts when the ice broke up. The striations are accounted for in the following way: smaller fragments, frozen into the ice, were scratched by being dragged over the shallow bottom of the sea during movement of the ice rafts.

There are minor objections to this explanation of the striations. First, it is questionable that fragments dropped on the surface of shore ice would be frozen into the lower part of the ice. Second, it is probable that the shallow sea floor was mantled with soft sediment incapable of scratching these fragments. Third, this explanation does not account for the subrounded to subangular shape of many of the exotics, or for those individuals which have two or more abraded or polished surfaces.

Despite these minor objections, Ulrich's hypothesis is noteworthy in that it recognizes a depositional origin for the exotics and considers ice to be the agent of transportation.

Subsequent to Ulrich's work, the overthrust hypothesis of the Ouachitas was invented. As a result, the exotics were considered to be of tectonic origin, having been thrust up along "friction carpets" from underlying Arbuckle "facies." Based on this origin of the exotics, a huge thrust of Arbuckle rocks to the southeast was conceived. This "Powers thrust" (Hendricks, 3) is supposed to be older than the emplacement of the exotics in the Johns Valley shale. This assumption was necessary to make Arbuckle rocks available at depth so that during the Ouachita orogeny fragments of Arbuckle rocks could be carried upward by the later thrusts which moved toward the north and northwest.

In support of the overthrust hypothesis, all the boulder shales have been considered to be of the same age. The theory is that one formation, the Johns Valley shale, took up most of the thrusting during the Ouachita orogeny, and thereby became loaded with exotics brought up from depth.

Field evidence condemns a tectonic origin for the boulders. Everything observed confirms Ulrich's hypothesis (18) that the boulders are depositional. The undeformed shale matrix and the regular bedding of the associated shales and sandstones exclude the possibility that these boulder beds could be of tectonic origin. The paleontologic evidence shows that there are at least three different ages for the shales enclosing the boulders, thus negating the theory that the Johns Valley shale is a single stratigraphic unit of limited age. Moreover, even lacking paleontologic evidence for more than one boulder bed, it would be unreasonable to assume that all thrusting would occur in one unit to the exclusion of the numerous other shale units present in the Jackfork.

Harlton (10) suggests a different origin for the boulder shales. This hypothesis considers the Stapp conglomerates (SW¼, SW¼, Sec. 7, T. 3 N., R. 26 E.) to be the source of the exotics. Harlton believes that the conglomerate was unconsolidated during the time the exotics were eroded, transported a short distance, and redeposited in the shales. However, in other parts of his paper (10) the term "friction carpet" is used, as if the tectonic explanations of others were being followed.

Harlton's premises will be discussed on a two-fold basis. First, on the assumption that his hypothesis applies only to the Stapp area, and, second, on the assumption that the hypothesis applies to all of the Ouachitas.

Concerning the first, the boulder shale near Stapp (Sec. 13, T. 3 N., R. 25 E.) contains a large boulder of conglomerate. This boulder is identical with the Stapp conglomerate, and has probably been derived from it. Harlton considers the

Stapp conglomerate as having been unconsolidated at the time of reworking and deposition in the boulder shales. Actually, the conglomerate boulder at the Stapp locality was indurated prior to deposition in the shales. Moreover, some of the boulders, even in the vicinity of Stapp, are far larger than any found in the Stapp conglomerate, and some display surface polishing and parallel striations. Thus, it is not likely that the Stapp conglomerate was the source for many of the exotics.

Second, the Stapp conglomerate is supposed to be widely distributed, with the implication that it was available throughout the Ouachitas as a source for the exotics. Certain facts conflict with this assumption. First, there is no evidence for a wide distribution of the conglomerate. In fact, the type locality at Stapp seems to be the only locality, the conglomerate having the characteristics of a local stream deposit. Second, even if the conglomerate were extensive, it could not furnish boulders which, in the Johns Valley syncline, are at least 100 feet long. Even the more common boulders up to 15 feet in length are too large to be moved by water from the Arbuckle region into the Ouachita geosyncline, be formed into a conglomerate, and then be reworked to form the boulder shales. In addition, the boulders in the Stapp conglomerate rarely exceed two feet in longest dimension. Third, the structural and paleontologic evidence shows that there are at least three different boulder shales, one of which pre-dates the Stapp conglomerate. Fourth, the striations and polished surfaces of some of the boulders cannot be explained by stream transport.

The Iceberg Hypothesis

What is the origin of the exotic boulders? First, all of the observed boulder shales are of depositional origin. Then, the question arises, what erosional agents can transport rock fragments of size of the larger Ouachita exotics? There are only two: gravity and ice. Gravity can effect transport of large fragments for short distances only, and only where there is steep relief. Neither applies to the Ouachita exotics. Transport has been all the way from the Arbuckle region or, in the case of the exotics near Boles, Arkansas, from the Ozark region, and the character of the Jackfork lithology does not indicate steep relief at or near the sites of deposition. It might be argued that the exotics have fallen off the steep front of a thrust sheet. However, a thrust sheet of Arbuckle rocks advancing within the Ouachita geosyncline is out of the question. Thus, ice must have been the agent of transportation. On this the writers agree with Ulrich (18).

A minor modification of Ulrich's hypothesis is proposed. This is that transportation was by icebergs which calved off the snouts of glaciers which reached the sea in an area of Arbuckle rocks. Glacial transport would account for the subrounded and subangular shapes of many of the exotics, for the occurrence of polished surfaces on some of the boulders, and for the striations. There are boulders which no one familiar with glaciated regions would hesitate to describe as glacial erratics.

If the exotics were transported by glaciers, would the bouldery shales be tillites? The answer is no. The well-bedded nature of the shale matrix, the boulder-free shales and the sandstones indicate that these are water-laid sediments. Moreover, the fauna indicates a marine environment. Apparently the exotics were dumped into a marine mud.

Transportation by icebergs is a well-known geological process, and glaciation of the Arbuckle region in early Pennsylvanian time is not unreasonable. Glaciation about this time has been reported from several parts of the world. Individual ice ages are short, in terms of geologic time, and this would account for the restriction of the boulder shales to thin members in the Jackfork. The fact that boulder shales are found at more than one stratigraphic position would indicate several glacial periods—an assumption which is supported by known multiple glaciations of Pennsylvanian age in other parts of the world.

The ice-rafting hypothesis of Ulrich (18) does not explain the restriction of the exotics to shaly sediments. The conditions under which shore ice would form and then break up into rafts would indicate a reasonably cold winter, with a summer warm-up which would permit normal erosional activity and, presumably, some deposition of sand. Under conditions of ice-rafting alone, some of the exotics should have been dropped into sand.

Does this same objection apply to iceberg transportation during a glacial period? A definite answer would remain with the glacial sedimentologist. However, with glaciers extending to the sea, the bulk of the sedimentary material released for deposition might be limited to two grain sizes: (1) the very fine-grained material which has been ground up (i.e., glacial flour), and, (2) the coarse size of the remaining boulders, cobbles and pebbles. It is believed that little sand would be produced during the height of glaciation of the source area. If this reasoning is valid, then it might explain the fact that all the exotics occur in shaly sediment.

Some ice rafting probably occurred. The small boulders of Caney shale might have been transported in this fashion. If the Caney boulders had been included in moving glacial ice they would have been broken up. However, they may have been dropped onto the glacier surfaces and ultimately carried on the surface of icebergs.

Stratigraphic Correlation and Facies Relationships

General Discussion

Table I (ed. note – missing) presents an outline of the customary stratigraphic correlation, as compiled from various sources. The minor subdivisions have been omitted. Most of this nomenclature, and part of the correlations, are governed by the hypothesis that there exist two strongly contrasted facies: the "Ouachita facies" and the "Arbuckle facies." This hypothesis concludes that these two facies have been brought into juxtaposition by tectonic means, and that the "Ouachita facies" rocks overlie "Arbuckle facies" rocks at a huge, flat overthrust (Plate IX). Based on this interpretation all formations have been given different names in the Ouachita and Arbuckle Mountain regions.

In the westernmost part of the Oklahoma Ouachitas an intermediate facies has been recognized by several authors, yet this part of the Ouachitas has been considered to be a part of the same huge allochthonous Ouachita thrust sheet. The differences between the rocks of this outer belt and those of the main "Ouachita facies" have been attributed to separation along the alleged Ti Valley overthrust (3). On this basis an entirely different stratigraphic nomenclature has been used for the outer belt, although several units are identical on opposite sides of the "thrust," and others exhibit gradational facies relationships in the field.

Table I shows that the sharpest facies contrast is averred to be between the Arbuckle limestone on the one hand, and the supposed Cambrian-early Ordovician section of the Ouachitas on the other hand. If the customary correlation is correct, this is a very important facies contrast.

No one familiar with both the Ouachitas and the Arbuckles can deny that there are considerable facies differences in parts of the section. However, after consideration of the field data, it is suggested that:

(1) There are also many similarities between Ouachita and Arbuckle formations;

(2) Some alleged differences are based on words rather than reality, insofar as identical units are named differently in different areas, and some formational units have been given misleading names (cf. discussion on Pinetop "chert," Chickachoc "chert");

(3) The considerable differences in facies which do exist in parts of the Ouachita and Arbuckle sections commonly are bridged by transitions;

(4) Such transitions, in part gradual, in part rapid, have been accentuated by the considerable shortening brought about by tight folding and steep imbricate slicing;

(5) None of the differences exceed those encountered in other areas where adjacent and connecting depositional basins were subjected to different types of tectonic regimes;

(6) The differences in facies are not confined to those between Arbuckles and Ouachitas, or between marginal and inner Ouachitas, but differences also occur along the strike in the Ouachitas (e.g., Wapanucka-Chickachoc discussion), and distinct changes in facies also occur within the formations of the Arbuckle area (Table II).

Table II presents the correlation which has resulted from the writers' field work. According to this interpretation the unfossiliferous lowest part of the Ouachita section—the Collier shale and Crystal Mountain sandstone—should not be considered as being Cambrian or earliest Ordovician age. Instead of being correlative to most of the Arbuckle limestone it is suggested that the Collier shale and Crystal Mountain sandstone are probably altogether Ordovician and mainly younger than the Arbuckle limestone.

Furthermore, it is suggested that the exposed Ouachita section is underlain by a massive limestone comparable to the Arbuckle limestone. Substantiating this suggestion are:

(1) The structural conditions (cf. Structure), especially in the Arkansas and Choctaw anticlinoria, which indicate a horizon of disharmonic shearing-off below the Collier shale and stratigraphically above lower massive rocks which were mechanically too strong to participate in the tight folding of the overlying section. This lower massive section, therefore, would have participated with the basement during orogenic deformation;

(2) Regional stratigraphic considerations which suggest that these non-exposed massive sediments are probably limestone. This limestone is suggested as being comparable to the Arbuckle limestone in stratigraphic position, though not necessarily in the exact age of its upper and lower boundaries. This assumption is supported by:

   (a) Large blocks of massive limestone which have been brought up from depth by the intrusives of Magnet Cove, Arkansas (T. 3 S., R. 17 W.). Here, thrusting of the Ouachita over Arbuckle rocks has not been claimed so that this limestone need not be considered as coming from beneath an overthrust;

   (b) The several hundred feet of Collier limestone exposed southwest of Mt. Ida, Arkansas. This limestone, lying beneath the Collier shale, probably represents the top of the limestone section which is postulated to be present at depth as the Arbuckle correlative.

If these correlations are correct, the most important difference between the "Ouachita facies" and the "Arbuckle facies" disappears.

Table II is based on the facts and suggestions discussed below.

F-154 Table II

System	Series	Arbuckle Mountains, Oklahoma Stratigraphy: Western Area (Arbuckle Anticline)①	Arbuckle Mountains, Oklahoma Stratigraphy: Eastern Area (Belton Anticline)①	Ouachita Mountains, Oklahoma—Stratigraphy of Structural Units (See Figure 2): Belt I	Belt II	Belt IV and Potato Hills	Choctaw Anticlinorium②
CRETACEOUS	Lower					Trinity sand (basal only)	Trinity sand (400'±)
PENNSYLVANIAN	Lower Des Moines (Atoka)			(top not exposed) Atoka formation (? up to 1000')	(top not exposed) Atoka formation (? up to 1000' preserved)	Atoka formation (basal 500'± exposed)	
PENNSYLVANIAN	Morrow	Springer formation	Springer formation	Upper Jackfork shale (300'(+) exposed); Wapanucka limestone (0-200'); Medial shale (30-130'); Chickachoc "chert" (0-275'); Middle Jackfork shale (1000'± present) (base not exposed)	Jackfork sandstone (3,500'+) (become sandstone members in upper Jackfork)	Jackfork sandstone (3,750'± in Prairie Mountain Syncline)③ (10,000'± in Johns Valley Syncline)③	Jackfork sandstone (5,000'-13,618') (the larger figure may include part of the Atoka formation)
?	?—? Chester						
MISSISSIPPIAN	Meramec	Caney shale (275'-820') (thickens to west and north)	Caney shale (375')		Stanley shale (4000'±)	Stanley shale (7600'±)③	Stanley shale (6,000'±)
MISSISSIPPIAN	Osage	Sycamore limestone (300'-350')	not developed				
MISSISSIPPIAN	Kinderhook	Woodford chert/shale (285'-390')	Woodford chert/shale (250'-560') (thickens to east)		Woodford "chert" (165'±)	Arkansas novaculite (400'±)	Arkansas novaculite (250'-600')
DEVONIAN					Pinetop "chert" (120'± exposed) (base not exposed)		
SILURIAN		Hunton group (0-350') (absent locally by pre-Woodford erosion)	Hunton group (125'-210')			Missouri Mountain shale (150'±)	Missouri Mountain shale (60'-100'); Blaylock sandstone (670'-800')
ORDOVICIAN	Cincinnati	Sylvan shale (250'-335')	Sylvan shale (150')			Polk Creek shale (150'±)	Polk Creek shale (150'±)
ORDOVICIAN	Champlain	"Fernvale"-Viola limestone (600'-800') (thickens to west)	"Fernvale"-Viola limestone (430'-520')			Big Fork chert (600'±) ("Fernvale" correlative not recognized)	Big Fork chert (800'±) ("Fernvale" correlative not recognized)
ORDOVICIAN	Champlain	Simpson group (2000'-2300'): Bromide formation; Tulip Creek formation; McLish limestone; Oil Creek formation; Joins limestone	Simpson group (1500'): Bromide formation; McLish limestone; Oil Creek formation			Womble shale (100'±) (base not exposed)	Womble shale (1,000'±); Blakely sandstone (0-15'); Mazarn shale (1,000'±); Crystal Mountain sandstone (500'±)
ORDOVICIAN	Beekmantown	Arbuckle group: Upper and Middle (5,000'-5,200') (all limestone except for thin dolomite)	Arbuckle group: Upper and Middle (3,300') (dolomite; much more sandstone than to west)				Collier formation (shale 200'±) (limestone 200'±) (base not exposed)
CAMBRIAN		Arbuckle group: Lower (1,500') (mostly limestone in west dolomite in east)	Arbuckle group: Lower (600'-875') (mostly dolomite)				
CAMBRIAN		Honey Creek limestone (90'-110')	Honey Creek dolomite (115'-250')				
CAMBRIAN		Reagan sandstone (230'-460') (thickens to west)	Reagan sandstone (50'-140')				
PRE-CAMBRIAN		crystalline basement	crystalline basement				

①Ham, Wm. E., Guide Book III, Okla. Geol. Survey, 1955. ②Honess, C. W., Bul. 32, Okla. Geol. Survey, 1923. ③Harlton, B. H., Bul. of AAPG, July 1938.

CORRELATION OF ARBUCKLE AND OUACHITA MOUNTAINS SECTIONS OKLAHOMA

The pre-Bigfork part of the Ouachita section comprises Collier shale, Crystal Mountain sandstone, Mazarn shale, and Womble shale. If the customary classification of the Collier as Cambrian and the Crystal Mountain as basal Ordovician is accepted, then there is a great contrast between the Ouachita section and the Arbuckle section. But what is the evidence for this age classification? No fossils have ever been found in either of these two formations. In fact, no Cambrian or earliest Ordovician fossils are known from the Ouachitas. Apparently the age determination of the Collier and Crystal Mountain rests on the undisputed Ordovician age of the Womble and Mazarn, in which fossils have been found, and on the assumed necessity for a facies contrast between the rocks of the Ouachitas and the Arbuckles.

This evidence for dating of the Collier and Crystal Mountain is inconclusive. These two formations lie conformably beneath a section of known Simpson (Middle Ordovician) age, and are likely to be of Ordovician age also. If this is correct, the pre-Bigfork Ordovician section of the Ouachitas comprises Collier through Womble, is correlative with the Simpson group of the Arbuckles, and the Crystal Mountain sandstone corresponds to some sandstone of Simpson age.

The Ouachita rocks which are correlative to the Simpson group of the Arbuckles differ in that black shales predominate, limestones are uncommon, and sandstones, with the exception of the Crystal Mountain sandstone, are subordinate. This contrast is real. But it is not so strong that it could not be bridged by a transition zone. The Ouachita rocks correlated with the Simpson are exposed at a considerable distance from the Arbuckle rocks of Simpson age, with the exception of the highest part—the top of the Womble shale exposed in Black Knob Ridge. For the highest Womble, then, the transition must be fairly rapid, although the transition has been greatly accentuated by a strong shortening achieved by tight, steep folding and imbricate slicing along Black Knob Ridge (Plate XIII). As far as the pre-highest-Womble part of the Ouachita Simpson section is concerned the transitional zone might be wider. The differences between the Simpson group and its Ouachita correlatives do not exceed the differences of facies commonly found within one and the same geosyncline within comparatively short distances.

An examination of well logs from the Marietta Basin west of Ardmore, Oklahoma, is pertinent to this problem. Within a distance of six or eight miles, the typical sandy Simpson of the Ardmore Basin has undergone a rapid facies change. The proportion of shale has increased greatly and the typical Simpson sandstones have practically disappeared. This is noteworthy for it concedes rapid facies changes within the Simpson group in an area where a hypothesis of overthrusting has not been invoked to account for such change.

The Bigfork chert of the Ouachitas does not differ greatly from most of the Viola limestone, its Arbuckle correlative. In most places the Bigfork actually contains only a moderate to small amount of pure black cherts. Impure rocks which contain limestone, siltstone and siliceous material in various proportions are much more common, and the siliceous component is absent in part of these rocks. Thin-bedded, finely textured, locally silty limestones occur, as do calcareous siltstones, with or without a siliceous admixture. There are also subordinate shaly intercalations.

Most of the Bigfork rocks resemble the Viola rocks. However, there is one rock type in the Viola which, though subordinate, is rather characteristic and is entirely absent in the Ouachitas. This is the "Fernvale" limestone (Table II)—the shallow water, biogenic, locally clastic and granular limestone which has its main development at the top of the Viola. This particular shallow water environment which existed temporarily in the Arbuckle region obviously did not extend into the Ouachita region. However, the similarity of the Bigfork and Viola rocks indicates that both were deposited in the same major basin.

The Upper Ordovician Polk Creek shale of the Ouachitas differs little from the Sylvan shale, its Arbuckle correlative. The differences, such as the dolomitic character of certain parts of the Sylvan shale, are insignificant. Deposition in the same basin cannot be doubted.

The Silurian Missouri Mountain shale of the Ouachitas, however, differs from the Silurian of the Arbuckles. The Arbuckle Silurian is calcareous; the Ouachita Silurian, argillaceous. In both regions the Silurian is very thin, an indication that the major subsiding movements of the crust were of the same magnitude in both areas during this period. Moreover, it is not yet clear whether the two Silurian sections are complete or not.

The Devonian is thin both in the Arbuckles and Ouachitas. The rocks occurring in both regions probably were deposited in the same basin. The Devonian limestones of the Arbuckles (i.e., the Hunton group) are correlative with the Pinetop "chert" in the northwestern part of the Oklahoma Ouachitas. This "chert" actually contains much limestone comparable to that of the Hunton, and locally displays secondary silicification. In the main part of the Ouachitas the Arkansas novaculite has taken over altogether, although some limestone beds have been reported.

It is of interest to compare three Ouachita formations—the Arkansas novaculite, the Pinetop "chert," and the Woodford "chert"—with their Arbuckle correlatives. In the Arbuckles the Silurian rocks are overlain by the Devonian Hunton limestone and the lower Mississippian Woodford chert and/or shale. The Hunton differs from the Devonian part of the Arkansas novaculite, but is comparable to the limestones of the Pinetop "chert," especially if the secondary character of at least part of the chert in the Pinetop is considered. Much of the Woodford of the eastern Arbuckles is identical with the upper novaculite of the Ouachitas. Moreover, the Woodford of the eastern Arbuckles comprises the same two facies which occur in the Ouachita rocks of the same age. North of Ardmore, Oklahoma, the Woodford consists of thin-bedded cherts with shaly interbeds and is indistinguishable from parts of the Arkansas novaculite. Farther north (as south of Ada in T. 1 N., R. 7 E.) the Woodford is silty which is also characteristic of the Woodford in the northwestern part of the Oklahoma Ouachitas. Even the calcareous and phosphatic concretions in the siltstones and silty shales are identical in character, size, and shape.

Thus, for the lowest Mississippian rocks there is a more or less east-west trending facies boundary between cherty rocks on the south and silty rocks on the north. This facies boundary is clearly defined both in the western Ouachitas and in the eastern Arbuckles. An analogous situation exists in the lower Pennsylvanian rocks. Much of the Wapanucka of the Coal Basin—Arbuckle Mountain area (as near the town of Wapanucka) is lithologically and faunally identical to the Wapanucka of the Ouachita Mountains (as at Limestone Gap). This east-west equivalence of units is incompatible with the hypothesis that the Ouachitas have been thrust in from far distant regions.

The post-novaculite Carboniferous rocks of the Ouachitas are similar to the rocks of the Arbuckle region. The supposed sharp and abrupt facies contrasts are based solely on the different nomenclature used at opposite sides of the mapped overthrusts. Some factors of major significance are:

(1) The gap of Caney age in the Ouachita section (Table I) is nonexistent. The section is continuous, the novaculite gradually passing into the Stanley. The writers have seen this conformity in many places, and the transition is such that an arbitrary boundary must be selected as the contact between the two formations;

(2) The Caney shale is represented in its entirety within the Stanley shale, the upper portion of the Stanley probably extended higher in the section than the top of the Caney. The Sycamore limestone of the Arbuckles (not developed everywhere there) has its approximate correlative in the basal part of the Stanley. The Sycamore mapped at Pinetop School (Sections 4 and 5, T. 2 N., R. 15 E.) is nonexistent. There the highest layer of Woodford siltstone which weathers blue-green, is in part limy, and contains some limy concretions, has been called the Sycamore;

(3) The inner part of the northwestern Ouachitas (as south of Pinetop School), which is mapped as having Caney and Springer above the Sycamore limestone, actually contains a typical Stanley-Jackfork sequence, with black shales somewhat more prevalent than in the townships farther south. Whether the Arbuckle-Coal basin or the Ouachita nomenclature should be applied in the outermost part of the northwestern Ouachitas is purely arbitrary. However, heavy Jackfork sandstones still exist on Pine and Blue Mountains in the northwestern part of the Oklahoma Ouachitas (Plate I). And in the Arkansas Ouachitas the Ouachita nomenclature definitely applies to the northern margin of the system, and possibly beyond, where sections (13) show typical Stanley and Jackfork in the subsurface of the Arkansas Valley;

(4) The Chickachoc "chert," which supposedly takes the place of the Wapanucka immediately south of the faulted limestone ridges, is a misnomer. The Chickachoc rocks change markedly in facies, both along and across the strike. Moreover, the Chickachoc is not the lateral correlative of the Wapanucka, but is a separate, mappable unit underlying the Wapanucka;

(5) Black shales with exotic boulders are not restricted to the post-Jackfork Johns Valley shale as has been assumed, but occur in at least three zones, the lower two being pre-Wapanucka in age, the upper, a Wapanucka correlative. This indicates a Jackfork age for these three boulder zones;

(6) All the boulder shales are of depositional origin and are not "friction carpets" formed by overthrusting;

(7) Much of what is mapped as Atoka is Jackfork;

(8) Several facies boundaries in the Carboniferous rocks of the Ouachitas do not parallel the structural trend, but cross it in an east-west to northeast-southwest direction.

Summary

The sharp and abrupt facies contrast emphasized by Miser (14) and Hendricks (3) does not exist. Part of the supposed contrast is based on differing nomenclature rather than lithologic differences. Some units are identical in both the Arbuckle and the Ouachita regions; some units differ only slightly; other units differ considerably, although transitional relationships are indicated. In a number of cases the transition is gradual and can be traced in the field. In other cases transitions, mostly from limestone to shale to sandstone, are rapid. Such occur in the Wapanucka-Chickachoc ridges of the northwestern Ouachitas, and they do not exceed similar facies changes described from other geosynclines and basins. Moreover, the comparatively rapid facies changes occur where there

has been a considerable shortening by steep folding and imbricate faulting. A number of facies boundaries do not parallel the structural trend but transect it. Examples are: the boundary between Woodford shale and siltstone to the north, and Woodford chert and upper novaculite to the south—a boundary which can be traced from the eastern Arbuckles into the western Ouachitas; the gradational facies boundaries in the Wapanucka-Chickachoc sequence; the increase in a southeasterly direction in the sandstone content of the Stanley and Jackfork formations; and the appearance in the southeastern Oklahoma Ouachitas of the Blaylock and Blakely sandstones.

STRUCTURE

Introduction

In Part I of the senior author's progress report (21) individual areas and traverses were described briefly. Subsequent field work has confirmed the writers' belief that large, flat overthrusts do not exist in the Ouachita Mountains. The studies of the structure, and the paleontologic determinations do not support the thesis that the Ouachitas are an overthrust complex.

The questions then arise: What is the structural type of the Ouachitas? What general interpretation can be given? What kind of structural features can be predicted to occur in the nonexposed, deeper parts of the Ouachita system?

In the absence of subsurface data, answers must be based on an analysis of the surface structures. The analysis must attempt to clarify the mechanism of deformation of the rocks, and attempt to predict the types of structure to be expected at depth. The latter is not easy to do, because of the very low relief which does not offer much of the third dimension to direct observation. Fortunately, many of the folds plunge sharply. As a result, part of the third dimension becomes visible.

The Generalized Structure (See map, Plate I, and Geologic Map of Arkansas)

The Ouachitas are a folded system; in most parts tightly folded, in other parts more openly folded. Faults generally are close to the vertical, and include strike and cross-faults. In general, however, faults are of secondary importance compared to folds. The exception to this is the northwest marginal belt of Oklahoma (Figure 2, Belt I), where strike faulting is a major factor. As a whole, the structural pattern of the Ouachitas resembles that of the folded Appalachians (Valley and Ridge Province). Regionally, the Ouachitas appear to be the frontal belt of a broader geosynclinal system, the interior parts of which are concealed beneath the Cretaceous and Tertiary rocks of the Gulf Coastal Plain. Moreover, it appears likely that the Ouachita rocks have been sheared-off disharmonically from their basement (evidence for this concept is discussed in a later chapter). Flat thrusts of any size were not observed anywhere.

The use of the term "basement" in this report is not restricted to the pre-Cambrian crystalline rocks, but includes any sedimentary rocks older than those exposed which might, for reasons of their massive and mechanically resistant character, have acted with the crystalline basement instead of entering into the folds of the visible suprastructure.

The Dominant Structure

In order to evaluate the surface structures exposed in the Ouachitas, five dominant structural patterns or types of rock deformation will be described (Figure 2). These represent different types of response of the rocks to the same compressive stresses. The contacts between the patterns of deformation are not sharp, but grade one into another. However, the structures typical of Pattern I, II, and V deformation are found in fairly well-defined elongate areas or belts. In the discussion that follows, the terms Belt I, Belt II, and Belt V are utilized to designate areas in which structure of Pattern I, II, or V deformation are found.

(1) Pattern I: The Belt of Imbricate Faulting (Figure 2) This belt, characterized by steep strike faults, begins at Atoka, (Plate I), is fully developed north of Stringtown, continues from there to the area southeast of Hartshorne, becomes less fully developed south of Wilburton, and disappears between Wilburton and Heavener. It is not present in Arkansas. The surface rocks are mostly Pennsylvanian.

(2) Pattern II: The Belt of Tight Folding (Figure 2) This belt of Carboniferous rocks begins northeast of Stringtown (Plate I) and continues the entire length of the Ouachitas to south of Little Rock, Arkansas. This belt is absent between Atoka and Stringtown, Oklahoma, where its place is taken by the narrow Black Knob Ridge of older rocks. Steep strike faults and some cross-faults occur in this belt, but in general they are subordinate to the tight folds. In the middle part of the Oklahoma Ouachitas, the Windingstair fault approximates the southern border of this belt. The change in structural pattern across this fault is not sharp, the transition being mainly south of the fault. In Arkansas, this belt lies between the Arkansas Valley and the Arkansas anticlinorium.

(3) Pattern III: The Ouachita Anticlinoria (Figure 2, Plate I and Geologic Maps of Arkansas and Oklahoma)

The anticlinoria do not occupy a continuous belt, nor are they lined up along one major axis. They occur individually in various parts of the Ouachitas, forming roughly elliptical units which plunge at both ends beneath younger rocks. The anticlinoria are:

(a) The Potato Hills anticlinorium in the central part of the Oklahoma Ouachitas (T. 2 and 3 N., R. 19-21 E.).

(b) The Choctaw anticlinorium of McCurtain County, Oklahoma, (T. 2-6 S., R. 22-27 E.) which lies southeast of the Potato Hills and southwest of the Arkansas anticlinorium. This anticlinorium lies farther south than the others and, excepting the Arkansas anticlinorium, is the largest.

(c) Black Knob Ridge (T. 1 and 2 S., R. 11 and 12 E., Oklahoma), an incomplete anticline, which extends from near Atoka to northeast of Stringtown, lies much closer to the Ouachita front than any of the other anticlinoria. On its interior side it passes through plunging folds into an area characterized by Pattern IV structures (cf. below).

(d) The Arkansas anticlinorium extends nearly all the length of the Arkansas Ouachitas. It rises from younger rocks in westernmost Arkansas and disappears to the east beneath the sedimentary rocks of the Gulf Coastal Plain. It is the largest of the anticlinoria. On the north it is bordered by rocks with Pattern II deformation, and on the south by folded Carboniferous rocks of Pattern II-type deformation.

(4) Pattern IV: The Open Synclines and More Tightly Folded Anticlines (Figure 2, Plate I, and Geologic Map of Oklahoma)

This pattern of deformation is characterized by large, open synclines of Jackfork rocks and more tightly folded anticlines of Stanley rocks. In addition there are subordinate tight folds. This structural pattern is not found in a continuous belt, but occurs in broad areas which, along the regional strike, pass into areas of different structural pattern. In Oklahoma, areas characterized by Pattern IV pass along the strike into areas of more tightly folded Carboniferous rocks or into anticlinoria (i.e., Potato Hills, Choctaw). The main development of Pattern IV is from south of the Potato Hills to east of Stringtown and Atoka, where axial plunge causes Black Knob Ridge to rise from this area of simple folds. This pattern also occurs on the west side of the Choctaw anticlinorium, more or less in continuation of the area mentioned above.

(5) Pattern V: The Faulted Belt North of the Pattern IV Area

This type of deformation is found in a narrow belt which extends from northwest of the Potato Hills to east of Stringtown. This area is characterized by several major strike faults, by a large number of cross faults, and by subordinate tight folds.

These structural patterns will be discussed separately. For convenience, the terms Belt I, II, and V are used occasionally in this paper to refer to areas in which Pattern I, II, and V structures, respectively, are developed. Emphasis will be on the Oklahoma Ouachitas since apart from several traverses in Arkansas the detailed work has been restricted to Oklahoma.

Pattern I: The Belt of Imbricate Faulting (Plate I; Figure 2)

This pattern of deformation is a characteristic element of the western Ouachitas, and its absence is equally characteristic of the Ouachitas from easternmost Oklahoma through Arkansas, where the tight folds of Pattern II (cf. below) directly pass into the gentler folds of the Arkansas Valley. The fullest development of Pattern I deformation is from north of Stringtown (T. 1 S., R. 12 E.) to southeast of Hartshorne (T. 4 N., R. 18 E.). In the northwestern Ouachitas this belt of imbricate faulting is separated from the younger Coal Basin rocks by the Choctaw fault zone (Figure 2).

Characteristic of this belt are the Wapanucka and Chickachoc (lower Pennsylvanian) rocks which form parallel resistant ridges. These rocks occur in a series (up to six) of long and narrow, steeply tilted, imbricate slices which are separated by near vertical, reverse faults (Plates VII, VIII, and X). The mechanical relation of local folds to the faults suggests that these imbricate slices were formed from a sequence of north- and northwest-overturned, steep, isoclinal and sub-isoclinal folds. The northern and northwestern limbs of the folds were eliminated at most places by faulting. The relatively steep dips in the southern and southeastern limbs, and the even steeper dips of the reverse strike faults, indicate that yielding in this tightly compressed belt was predominantly upward and only to a minor degree to north and northwest (i.e., outward). This pattern of yielding at the margin of a folded system indicates an obstacle or buttress in the forward direction (Plate XIII). That every one of the slices contains a band of Wapanucka and/or Chickachoc as a "backbone" indicates that these competent stratigraphic units determined not only the pattern and size of the steep folds, but that of the imbricate slices into which these folds developed.

North of Stringtown (T. 1 N., R. 12 E.) most of the imbricate slices become faulted out toward Black Knob Ridge. Only one elongate fault block continues through Stringtown south to

Atoka (Plate XIII). On the east this block is in contact with Black Knob Ridge along a steep reverse strike fault. Here Ordovician Womble is brought up against lower Pennsylvanian Atoka, and the stratigraphic throw of this fault is at least 8,000 feet. Regionally, it is assumed that this one major fault substitutes for the several faults which occur within the zone of Pattern I deformation farther northeast. Here also a buttress in front of the Ouachitas is indicated at the time of orogeny. The fact that Belt I becomes narrowed and partly suppressed by a major reverse strike fault may indicate that between Stringtown and Atoka the frontal buttress was an especially strong obstacle.

Between Hartshorne (T. 4 N., R. 17 E.) and Wilburton (T. 5 N., R. 19 E.) Belt I narrows and is restricted to a single Wapanucka-Chickachoc ridge (Plate VII). The reduction in width of this belt is not interpreted as a compressive reduction opposite a frontal buttress, but as a dying out of this type of deformation through an eastward disappearance of the postulated buttress. This is supported by the fact that east of Wilburton (in T. 5 N., R. 22 E.) Belt I disappears altogether, and south of Heavener (T. 3 and 4 N., R. 25, 26 E.) the tight folds of Pattern II deformation (cf. below) apparently pass into the Pennsylvanian rocks of the Arkansas Valley without any major faulting at the Ouachita front. This transition is certainly true for the Ouachita front all the way from the Oklahoma-Arkansas state line to Little Rock.

Although Belt I consists mostly of homoclinal faulted slices, folding occurs locally along or at the ends of ridges of Wapanucka-Chickachoc rocks. There is an excellent example southwest of Hartshorne in the southernmost part of the belt (Secs. 27 and 28, T. 4 N., R. 16 E.). Other examples occur south of Pittsburg (Sec. 33, T. 3 N., R. 14 E.), with the innermost Wapanucka-Chickachoc ridge participating (Plate X); north of Stringtown, where a series of south-plunging folds are terminated by one of the faults in the Choctaw fault zone (Sec. 14, 15, 21, 22, T. 1 N., R. 12 E.); and southeast of Hartshorne where there is an elongate domal anticline which lies between the outer Wapanucka ridge and the main Hartshorne sandstone ridge north of it (Sec. 9, T. 4 N., R. 17 E.). Here some of the folding apparently is pre-Hartshorne, inasmuch as there is an angular unconformity between the Atoka and the Hartshorne formations.

Belt I has been interpreted by the proponents of the overthrust hypothesis as a great thrust front (3 and 16), with the Choctaw fault representing the sole thrust on which the entire Ouachita system of Oklahoma "floats" on the Arbuckle-Coal Basin section (see Plate IX, Howell's cross section). This interpretation is difficult to accept inasmuch as even the proponents of the overthrust hypothesis have prolonged their Choctaw thrust only to the Oklahoma-Arkansas boundary and have not questioned the perfectly normal relationship between the Ouachita folds and the Arkansas Valley folds in Arkansas (Plate XII). It is difficult to conceive of one and the same folded system floating as a huge allochthonous thrust mass on one side of a state line, while it is perfectly autochthonous on the opposite side.

The writers examined Pattern I areas for indications of large-scale overthrusting. The results were negative. Many indications of the absence of overthrusting were found. Foremost among these is the characteristic outcrop pattern and the lack of any violent rock deformation, even in sensitive shale sequences (Plates VII, VIII, X). An outcrop pattern of steeply inclined, long and narrow, regular, parallel ridges, which usually vary little in width, does not support the hypothesis that this zone represents the frontal portion of a great allochthonous thrust mass. There should, if this were the case, be violent rock deformation—shearing, squeezing, mutual overriding, and breaking-up of the stratigraphic sequence—especially in view of the great differences in competence of the rocks composing the belt. No feature of this kind occurs.

The conclusive evidence against overthrusting lies within the shale sequences. Wherever these are exposed they are merely tilted, as are all the rocks in this belt, and are devoid of shearing, squeezing, tectonic thinning and thickening, and complex minor folding. It is inconceivable that these shale members could have maintained their regularly bedded and undisturbed character if they had participated in large-scale horizontal overthrusting. In this respect, the shale members intercalated within the Wapanucka and occurring immediately beneath it are particularly impressive (Plates VII, VIII, X). In spite of the extreme contrast between the strong Wapanucka-Chickachoc rocks and these soft fissile shales, the even bedding of the shales and the regularity of the entire sequence have remained intact.

There are no signs of the flat movement which would be associated with horizontal transport along major overthrusts. There are no flat shear planes or minor thrusts, and no recumbent minor folds. Minor structures, flat or steep, are generally absent. The major structures are all steep, indicating a minor component of yielding to the west and north, and a major component of yielding in the upward direction. Shortening, therefore, was not achieved by horizontal transport along overthrusts, but by the compression into a much narrower belt of strata which, in their original flat-lying condition, occupied a vastly wider area. This compression into a much narrower belt resulted in a great thickening of the section by the piling-up of steeply inclined fault slices of great vertical extent.

Two other facts militate against the overthrust hypothesis. The first is the facies distribution, especially in the relatively well-exposed Wapanucka-Chickachoc units. Facies changes occur not only across the belt, but also along the strike. The changes occur both along and across individual Wapanucka-Chickachoc ridges, with limestones passing into shales, siltstones, and even sandstones in short distances. The facies boundaries are at an angle to the Ouachita trend, running more northeasterly than the structural trend. Consequently, facies zones, which east of Wilburton, for example, lie north of the Ouachitas, intersect and enter the Ouachitas farther west.

If the overthrust hypothesis were correct, the facies zones probably would parallel the Ouachita trend, each thrust being characterized by one distinct facies. This has been claimed but is not confirmed by the observed facts. In the event that the overthrust hypothesis were correct, and that the facies boundaries were at an angle to the outcrops of the thrust sheets, the trend of the facies boundaries would most likely be more easterly or southeasterly than the Ouachita trend. This would be necessary because the overthrust hypothesis requires that the distance of horizontal thrusting be greatest on the west, less to the east, and zero across the state line in Arkansas. However, the facies boundaries in Belt I trend more northeasterly than the Ouachitas, thus trending the wrong way for confirmation of the overthrust hypothesis.

The major point, however, is that there is as much change along the strike as across the strike. If the strongly compressed structures of Belt I are flattened out, the facies changes across the Ouachita trend become about as gradual as those along it.

The second fact is that at some places Belt I still "hangs together" with the southern margin of the Coal Basin. It is questionable that the Choctaw fault is actually as continuous from Atoka to the Arkansas boundary as has been claimed and required for the overthrust hypothesis, for the major faulting at the front seems to die out altogether between Wilburton and Heavener (Plate I). At Atoka, the southwestern extremity of the Ouachitas (Plate I), the Choctaw fault has been mapped with the same Atoka formation on both sides. This is improbable for a huge sole fault with dozens of miles of horizontal displacement. A local steep strike fault, with diminishing throw, would more probably place the same formation on both sides.

Pattern II: The Belt of Tight Folding (Plate I; Figure 2)

Northern Boundary

This pattern of deformation is not developed in the southwesternmost Ouachitas where Black Knob Ridge is faulted up against Belt I on the west, and plunges down to structure of Pattern IV (cf. below) on its east side. To the north and east of Black Knob Ridge, Belt II is bordered on the outside (west and north) by rocks of Belt I. Still farther east, where the Pattern I structures die out, Belt II is directly adjacent to the rocks of the Arkansas Valley. Here the relationship is one of structural continuity, the intensity of folding diminishing as the Pattern II structures pass into the folded younger rocks of the Arkansas Valley.

Southern Boundary

The southern boundary of this pattern of deformation is indefinite. From Black Knob Ridge to north of the Potato Hills, this boundary approximates the Windingstair fault, a major strike fault. However, there is no sharp structural change across this fault. Immediately north of the Windingstair fault the steep folding pattern of Belt II is typically developed. South of the Windingstair fault this folding pattern gradually passes into the simpler folds of Pattern IV. At some places, however, elements of Pattern IV occur immediately south of the Windingstair fault. This is the case north of the Potato Hills where the broad, open Buffalo Mountain syncline (Plate I; T. 3 and 4 N., R. 20 and 21 E.) of Jackfork rocks occurs just south of the fault. This is also true in the southern part of T. 3 N., R. 18 E., where a syncline formed in Jackfork rocks is cut off on the south by the steep, reverse, North Jackfork fault. At still other places folds of Pattern II occur south of the Windingstair fault. This is the case southwest of Counts (T. 2 N., R. 16 E.) in the eastern prolongation of the block of Jackfork rocks which is bounded by Windingstair and North Jackfork faults. Steep folding occurs also south of the intersection of the trace of the Windingstair fault and Oklahoma Highway 2 (T. 3 N., R. 19 E.). These folds lead directly to the tighter folds of the Potato Hills anticlinorium (Plate II).

East of the Buffalo Mountain syncline the southern boundary of Belt II again seems to be gradational, with some relatively simple folds to the south. In the Kiamichi Valley (Plate I), east of the Potato Hills, Belt II passes through some major faults into the Pattern IV structure of the Kiamichi Mountains.

A study of the aerial photographs, coupled with a general reconnaissance, indicates there is a broad area in the southern Ouachita Mountains of Oklahoma in which there is Pattern II-type of deformation. This area lies between the Choctaw anticlinorium and the area of Pattern IV deformation. Figure 2 shows the approximate boundaries of this second area of Pattern II deformation.

Rocks

The rocks composing Belt II belong predominantly to the Jackfork group of early Pennsylvanian (Morrow) age. The Jackfork section thickens, and the quantity of heavy sandstones increases from northwest to southeast across the western Ouachitas (Table II). Boulder shales occur at many places in Belt II. Stanley (Mississippian) rocks also occur, but are subordinate. The Stanley rocks are most widely exposed in Pounds Valley (T. 2 N., R. 14-16 E.) south of Pine Mountain and the Pine Mountain fault. Basal Mississippian rocks occur only locally, and are represented by the Woodford and lowest Stanley in the vicinity of Pinetop School (Sec. 32, 33, T. 3 N., R. 15 E.) (Plates I, VIII, X, XI). The basal Mississippian rocks come to the surface once more in a narrow slice against the next strike fault north of Pinetop School (Plate I, Plate VIII). Pre-Carboniferous rocks are exposed only locally in Belt II. A narrow belt of Pinetop "chert," its base faulted out, underlies the Woodford at Pinetop School.

Folds

Belt II is characterized by folding which formed tightly compressed anticlines and synclines (Plates I, VII, VIII, X). The dips in the limbs are generally steep, and locally are vertical. Few of the major folds are isoclinal, but many of them approach this state. Others are somewhat more open. The crests of the anticlines and the troughs of the synclines are usually narrow, the reversals in dip taking place within a very short distance. Rarely there are somewhat wider belts of gentler dips in the cores of the folds. Because the dips are often close to the vertical, and there is overturning to both north and south, mere reversal of dip is generally not sufficient to determine the position of the axis of a major fold. Sedimentary structures, such as bottom markings, cross-bedding, slip-bedding, and graded-bedding must be used to ascertain which side is up for a determination of the position of the fold axes. Fortunately, such sedimentary structures are widely developed in the northern, more thinly-bedded shaly part of the Jackfork sequence. Only in the more massive Jackfork sandstone members farther to the south are such structures lacking.

All of the folds in Belt II have steep axial planes, and part possess gentle axial plunge. Recumbent or strongly overturned folds are absent. Many of the folds are upright, their axial planes being more or less vertical. Others are overturned, but the axial planes remain steep, being rarely less than 70 or 75 degrees. There is no uniform direction of overturning, it being partly to north, partly to south. In some sections, as from south of Stapp (T. 3 N., R. 25 E.) to south of Heavener (T. 5 N., R. 26 E.), northward overturning is more common. In other sections, as along Oklahoma Highway 2 (Plate VII), northward and southward overturning are about equally common. In the northwestern part of Belt II a broad zone south of the Windingstair fault has a tendency to be steeply overturned to south (Plate VIII).

Minor folding is common in Belt II. There are comparatively few large outcrops in the more thin-bedded rocks of this belt which do not show at least a few minor folds. The folds display a variety of pattern which is controlled by the relative competence of the folded sedimentary beds and by local adjustments to space requirements.

These minor folds have certain features in common. They are generally tightly compressed; only a very few are gentle. In most cases the anticlinal crests and the synclinal troughs are narrow, just as in the case of the major folds. Many of the minor folds are isoclinal, especially where they occur in shales and in thinly-platy argillaceous or silty sandstones. Others are more open, resembling in shape the majority of major folds in this belt. The minor folds are generally steep; no recumbent folds were observed. Many are upright, with more or less vertical axial planes. Others are overturned, either to north or to south (Plate VII). In other cases, overturning repeatedly alternates from north to south, usually with intervening upright folds. At some places minor anticlines, overturned in opposite directions, face each other in such a manner that the intervening syncline is fan shaped. In most aspects the minor folds are rather faithful models of the major folds with which they are associated.

Most of the minor folds show axial plunge. Some of them plunge rather steeply, and exceptionally the axes of the minor folds are close to vertical. These steeply plunging minor folds are the result of differential compressive stresses set up during the adjustment of the rocks to space requirements, and represent the filling-in of "pockets" of lesser stress by tectonic accumulation through minor folding. Most of the plunges of the minor folds, however, are relatively gentle. The plunge of a group usually is more or less uniform, and is then related to the plunge of the major structures. Locally, the plunge of a group of minor folds lacks uniformity. This is relatively rare, and is again caused by differential adjustment to space requirements.

The minor folds are best developed in the thin-bedded rocks of Belt II. Their size is related to the relative competence of the beds. The thinner and weaker the beds, the smaller the minor folds; and vice versa. In the massive, heavy sandstones minor folding usually is absent. This particularly applies to the Jackfork Sandstone members in the southern part of Belt II, but also to heavy Jackfork sandstones which crop out farther north, as at Pine and Blue Mountains (Plates I, VII, X).

This description of the major and minor folds of Belt II is based on studies in the Oklahoma part of the belt. However, the reconnaissance traverses made in the Arkansas part of the belt indicate a similar over-all structural pattern (Plate XII).

The Oklahoma segment of Belt II widens from west to east (Plate I; Figure 2). This is caused partly by the reduction of Belt I east of Hartshorne, and partly by the eastward fanning-out of the Ouachitas. As a result, the main belt of Stanley (Mississippian) shales, which for many miles are bounded on the north by the Pine Mountain fault zone, lies farther and farther south of the northern boundary of Belt II in an eastward direction (Plate I).

Faults

The Oklahoma part of Belt II contains a number of strike faults (Plate I). A few of them, as the Windingstair and Pine Mountain, have stratigraphic throws of several thousand feet. However, faults generally are subordinate to the tight folding which represents the main kind of deformation in this belt. These strike faults have been considered to be major northward overthrusts (3 & 14), running the entire length of the Oklahoma

Ouachitas, then disappearing at the Arkansas border. Hendricks has mapped an astonishing number of "overthrusts" in this belt. Most of these are non-existent. A few exist but are very high angle reverse faults, not overthrusts.

The strike faults generally are not exposed. But the straight outcrop patterns, delineated on the air photographs, their relation to the topography, and the structures of the adjacent rocks indicate that they are close to the vertical. Most are probably reverse faults, inasmuch as they appear to form part of the compressive pattern of deformation which predominantly consists of tight folds. In all observed cases the northern block is downthrown.

The Pine Mountain fault south of Pittsburg lies very close to the northern margin of Belt II (Plates VIII, X). In fact, here this fault might be considered as the northern border of the belt. South of the Pine Mountain fault there is a thick Stanley shale sequence, with the Caney equivalent in its northern and lower portion (Plate VIII). This shale sequence, as well as the Jackfork sequence to the south, is very steeply tilted and in part slightly overturned to the south. Both sequences form the northern limb of a major syncline (Plate I), the axis of which apparently coincides with the alleged Ti Valley overthrust. The southward overturning (Plate VIII) of the beds south of the Pine Mountain fault militates against this fault being a northward overthrust of great horizontal displacement. In addition, the outcrop pattern clearly indicates that the fault is very steep.

From south of Pittsburg the Pine Mountain fault continues to south of Blanco as a double fault (Plate I). The northern branch of the fault brings Woodford (lower Mississippian) in contact with upper Jackfork (Pennsylvanian). The southern branch brings up Pinetop "chert" (Devonian) in addition to Woodford (Plates I, VIII). The Pinetop and Woodford here are conformably overlain to the south by the Stanley and Jackfork groups.

From south of Blanco the belt of Stanley shales continues to south of Hartshorne and disappears farther east (in T. 4 N., R. 19 E.). This shale belt probably is bounded on the north by the Pine Mountain fault, evidence for a branch of which is based on paleontological samples collected along Highway 2 south of Wilburton. The fault apparently dies out somewhere east of Highway 2.

About midway between the northern and southern boundaries of Belt II the Ti Valley overthrust has been mapped by previous workers (2, 3). This thrust has been interpreted by Miser (14) as a flat overthrust with many miles of horizontal displacement. Hendricks (3) has mapped a detailed solid-line picture of this thrust, a considerable number of subsidiary thrusts, and a large "klippe" south of Pittsburg (T. 2 N., R. 14 E.). It was on this "klippe" that the Southwest Exploration Company #1 Hoehman was drilled.

The Ti Valley thrust, whether it be considered an overthrust or a steep, reverse, strike fault, is non-existent at those places where the writers made detailed cross sections. The same is true of the supposed subsidiary overthrusts and the "klippe." South of Pittsburg there is a regular, tightly compressed, slightly southward-overturned major syncline where the Ti Valley thrust is alleged to reach the surface (Plate XI). Individual beds can be traced from the supposed lower plate right into the "klippe." Cross-faulting of considerable complexity is present within and at the western side of the "klippe" (Plate I).

South of Blanco a normal and continuous section, in part steeply overturned to south (sic), is present where the Ti Valley thrust has been mapped (Plate VIII). South of Hartshorne (Plate I) the Ti Valley thrust is also absent. The same is true at the famous Hairpin Curve (Plate I; Sec. 2 & 3, T. 3 N., R. 19 E.) of Oklahoma Highway 2. Here there is a regular, tightly compressed anticline flanked by synclines (Plate VII). These folds are well-exposed in the road cuts of this highway.

The straight trace of the Windingstair fault indicates that it is not an overthrust, but a steep fault with essentially vertical displacement. It probably has a very steep dip to the south. Such a dip is locally expressed at the next strike fault to the south, the North Jackfork fault (Plate I). The interpretation of the Windingstair fault as a major overthrust is based on the view that the Potato Hills contain a tectonic window formed by this thrust. However, the Potato Hills window is non-existent (Plate II).

In the area where the Windingstair fault, North Jackfork fault, and South Jackfork fault follow each other from north to south (Plate I), there is considerable cross-faulting. This cross-faulting partly displaces the steep strike faults; partly it does not. The cross-faults are almost invariably steep, approaching the vertical.

Evidence Against the Overthrust Hypothesis

Neither the major nor the minor folds display those recumbent structures which might be expected if this belt were part of a great sequence of thrust sheets which has traveled northward dozens of miles. All folds are very steep, although tightly compressed. The steeply overturned folds do not display uniform yielding to the north but are overturned both to north and to south (Plates VII, VIII). In some places the one direction predominates, in some places the other, and locally the two opposite directions of yielding are intermingled. This is incompatible with the hypothesis that this folded belt is one of huge overthrust sheets.

The number of strike faults is considerably smaller than previously presumed. This is especially true in reference to the map by Hendricks (3) which depicts a complex pile of slices which has no resemblance to the actual pattern of tight folds. The strike faults actually present are steep, reverse, and displacement is mostly vertical.

Near the alleged major overthrusts the rocks display no sign of the intense deformation—shearing, lensing, intensified minor folding—which one would expect adjacent to overthrusts. Even the shale members have maintained their regular bedding and sequence. There are no signs of the flat or gently inclined shearing and minor thrust planes normally associated with thrust sheets. All minor faults observed are very steep, except for two local examples. These are exposed along Oklahoma Highway 2, and are small scale disharmonic shearing-off planes in shales and very thin-bedded sandstones which are overlain by heavy sandstones.[2] In both cases, the underlying, easily deformed rocks have been compressed into tight minor folds, while the overlying heavy sandstones, not being readily compressed, were disharmonically sheared-off. Such minor disharmonic features are common in areas where interbedded rocks of greatly contrasted competence are intensely folded.

Certain areas of Atoka rocks, customarily mapped north of the "overthrusts" (2, 3) prove to be Jackfork (Morrow) rocks (Plate I). Distinctive fossils of the Wapanucka-Chickachoc section have been found in horizons high in these "Atoka" rocks. This confirms the hypothesis that the Wapanucka and Chickachoc, through facies change, become "lost" in the upper Jackfork, and indicates that the undisturbed sequences beneath these Wapanucka-correlative horizons are of Morrow or Jackfork age and not of Des Moines, or Atoka age. The rather high and continuous ridge known variously as Pine Mountain and Blue Mountain (Plate I) is an example of Jackfork rocks mapped as Atoka.

Pattern III: The Ouachita Anticlinoria

The Potato Hills Anticlinorium (Plates I, II, II a and b)

The Potato Hills have been described by Miser (16) as the type "window" of the Ouachitas and have since been considered as the conclusive proof of the overthrust interpretation of the Ouachita Mountains. The authors mapped this critical region and believe that the window hypothesis is erroneous. A geologic map of the Potato Hills with two structure cross sections is in the appendix.

The rocks exposed in the Potato Hills are, in ascending order, Womble shale, Bigfork chert, Polk Creek shale, Missouri Mountain shale, Arkansas novaculite, and Stanley shale with its interbedded sandstones. The thin bedded character of this sequence, and the large amount of pliable shales in the section, allow these rocks to be folded without permitting folds of very large dimensions. Of these formations the Bigfork and the Arkansas novaculite are the most competent, the rest being dominantly shale. Therefore, these two formations have determined the folding pattern. Neither of these formations is very thick, and though mechanically strong, they are thin-bedded. Thus the individual folds are of comparatively small size, being much smaller than those folds formed in the heavy, resistant Jackfork sandstones. The folds are tight and their axes are usually considerably curved, leading to pronounced axial plunges.

Where caught in or between tightly compressed folds of the two competent formations, the shales have undergone a secondary change in thickness. This includes both tectonic reduction on the flanks and tectonic accumulation in the crests of the folds. These thickness changes were controlled by local space requirements as the rock masses contended for room during compression. The shales between the Bigfork and Arkansas novaculite, i.e., the Polk Creek and Missouri Mountain, are particularly susceptible to these tectonic changes in thickness. Most of the minor folds in these shales are tight, and many are isoclinal.

Tectonic accumulation is not restricted to the less competent shale formations. Such accumulation is widespread in the more competent Bigfork and novaculite, especially in anticlines. This accumulation is produced by tight minor folding. Many of these minor folds have extremely sharp crests and troughs, and form a zig-zag pattern. Some of the major folds have similar sharp crests. Other folds have more rounded shapes. In several anticlines there are not only one major fold and numerous minor folds, but also folds of an intermediate size. This results in not one single fold axis but a composite of several parallel axes. In this manner the Bigfork, actually a thin formation, is accumulated to form wide areas of outcrop (Plate II, Secs. 24, 25, T. 3 N., R. 20 E.).

Most of the folds have steep flank dips. Some folds are upright; some are overturned. The overturning is partly to north and partly to south, locally with opposing directions alternating. There is a definite tendency for overturning against synclines occupied by Stanley shales, the stronger anticlines of chert "overpowering" the more easily yielding synclines in the shales. This principle is displayed on a large scale where the Round Prairie synclinorium of the east central Potato Hills has been overfolded from both sides, causing it to have a fan-shaped pattern (Plate II, a). Though most of the overturned folds have remained very steep, at a few places overturning has become stronger so that the overturned limbs dip less steeply. This occurs in the limbs of overturned anticlines which are adjacent to synclines formed in shales, the rocks of which yielded more easily. A notable example of this is the southern limb of the big anticline (Plate II, Sec. 29, T. 3 N., R. 20 E.) which borders the Round Prairie synclinorium on the north (to the east the overturned limb is faulted out, cf. below).

The axial plunge of the Potato Hills folds is not restricted to the general plunge which is easterly at the east end and westerly at the west end. There are variations in plunge within the Potato Hills. Along a longitudinal section through the Potato Hills the direction of the plunge reverses itself several times. Usually adjacent folds have their axial culminations and de-

[2]Cross section, Plate VII: @ distances 25,800′ and 43,000′.

pressions in common. But this does not hold true all the way across the Potato Hills. Adjacent groups of folds locally have opposite directions of plunge (Plate II). Where this has happened torsional forces acted, in some cases being released by yielding along hinge or pivot faults. There are reverse faults inasmuch as they formed a field of compressive stress. A notable example of this is the fault which borders the Round Prairie synclinorium on the south (Plate II). The torsional effect is not apparent at the south side of Round Prairie, where much of the folded section has been faulted out. It becomes obvious farther west where the throw of the fault diminishes to zero at the hinge in the west central Potato Hills (Plate II, Sec. 6, T. 2 N., R. 20 E.).

The repeated reversals of plunge along the strike, combined with the reversals of plunge of adjacent folds across the strike, complicate the folding pattern of this anticlinorium. As an example, several anticlines rise from the western part of the Round Prairie synclinorium (Secs. 26, 35, T. 3 N., R. 20 E.). Farther west, several of these anticlines combine into a tightly packed secondary anticlinorium (Plate II, Sec. 4, T. 2 N., R. 20 E.). These folds also are present in Round Prairie, but entirely within the Stanley shale. The Ringling and Brooks Well (Plate II, Sec. 30, T. 3 N., R. 21 E.), which drilled about 3,000 feet of Stanley shale, lies just off the axis of one of these folds—the main syncline of the Round Prairie synclinorium.

An example of lack of uniform plunge is an anticline which, in the northwestern Potato Hills, rises from a syncline, with the result that the synclinal axis bifurcates to the west (Plate II, sec. 32, T. 3 N., R. 20 E.). The adjacent folds north and south of this anticline do not display the same plunge. This is a small-scale duplication of the Round Prairie region.

The anticlines which plunge beneath the Stanley shale at the outer borders of the Potato Hills continue for several miles within the Stanley. However, with increasing distance away from the pre-Mississippian rocks of the Potato Hills these anticlines lose their identity and large numbers of smaller, minor folds replace the major fold. This is confirmatory evidence that the Bigfork and novaculite chert formations control the folding pattern of the overlying Stanley for a certain vertical distance. With increasing vertical distance this control weakens and disappears, and the Stanley reacts according to its own mechanical properties.

An understanding of this change of control is necessary to interpret the broad synclines of Jackfork rocks which border the wide areas of Stanley outcrop. What has been described above in terms of increasing horizontal distance, is probably a change based on decreasing tectonic and stratigraphic depth. In the lower part of the section, the Bigfork and novaculite control the folding pattern, as observed in the Potato Hills and in the other anticlinoria. These two competent formations control the folding pattern in the overlying Stanley for a certain vertical distance. Higher in the section the thick and massive Jackfork rocks assume control. The Jackfork is much stronger than the Bigfork and novaculite; i.e., its relative competence is greater. Therefore, it is incapable of duplicating the intricate tight folding patterns of the Bigfork and the novaculite. Instead, it forms folds of much larger dimensions, and exerts control over a certain thickness of the underlying Stanley shale.

Not all of the Potato Hills folds are parallel. Although trends close to an east-west direction predominate, there are many deviations which add to the complexity of the folding pattern. Most of these deviations are southwest-northeast, as on the southwest side of the Potato Hills near Tuskahoma (Plate II, Secs. 13, 14, T. 2 N., R. 19 E.). Locally, northwest-southeast folding occurs, as on the northeast side of Round Prairie (Plate II, Sec. 30, T. 3 N., R. 21 E.). The pronounced axial plunges and the diagonal folds apparently indicate that compression did not operate in a north-south direction alone, but also with an east-west component.

A few strike faults, which are of secondary important to the folding, occur in the Potato Hills. There are four main strike faults. The first is the northern border fault of the Round Prairie synclinorium (Plate II). This fault occurs in the south limb of a southward overturned major anticline, and dies out to the west (Plate II, Sec. 30 T. 3 N., R. 20 E.) near the west-plunging nose of this anticline. North of Round Prairie most of the overturned limb of the anticline appears to have been eliminated by this fault. Here the major anticline north of the fault acquires a composite character.

The second strike fault occurs in the northern limb of a steeply north overturned anticline in the northwest central Potato Hills (Plate II, Sec. 36, R. 19 E.; Secs. 28-30, R. 20 E., T. 3 N.). This fault brings Missouri Mountain shale up against the lower Stanley rocks. This reverse fault is very steep, as are the beds in the northern anticlinal limb. The fault dies out both to east and to west, giving way to normal sequences.

The third strike fault forms the southern border of the Round Prairie synclinorium and of that bundle of folds which rises from this synclinorium farther west (Plate II). This steep reverse fault is probably the result of torsion produced by the opposing plunges of two adjacent groups of folds. On the west this fault dies out in the south limb of a syncline (Plate II, Sec. 6, T. 2 N., R. 20 E.), the sequence being normal farther west. This zero point is the hinge. From the hinge the throw of the fault increases to the east. On its north side the folds plunge to east, and on its south side the folds plunge to west, being at the same time successively cut out to the east. Steep overturning to the north occurs on both sides of the fault. The fault attains its maximum throw near the southeast corner of Round Prairie (Plate II, Sec. 31, T. 3 N., R. 21 E.), where Womble (Ordovician) is brought up against Stanley (Mississippian). Here the plunge of the folds south of the fault becomes easterly as the torsional effect disappears. South of the fault and west of "The Narrows" (Plate II, Sec. 36, T. 3 N., R. 20 E.) an anticline and syncline, cut out farther to the west, appear to the east. The anticline immediately bordering the fault is incomplete and its northern limb is faulted-out. From "The Narrows" the fault turns to the northeast and cuts off the northern border fault of the Round Prairie synclinorium in Sec. 29, T. 3 N., R. 21 E. As a result the easternmost part of this synclinorium is reduced to a sharp down-faulted wedge of Stanley. Northeast of the end of this wedge the southern border fault continues and is in contact with the anticlinal unit which, farther west forms the northern border of the Round Prairie synclinorium (Plate II). The fault is still reverse, though the throw, bringing Womble of the southern anticline over Bigfork of the northern anticline, has markedly decreased. The fault continues northeast out of the Potato Hills across the valley west of Talihina, and, having truncated the east end of the Buffalo Mountain syncline, presumably runs into the Windingstair fault (Plate II).

The fourth strike fault borders the westernmost Potato Hills on the south (Plate II, Secs. 9, 10, T. 2 N., R. 19 E.), though it does not reach Oklahoma Highway 2. This fault is in the south limb of a major anticline, and brings the southern anticlinal limb up against Stanley. This fault dies out both to northwest and to southeast.

In addition to the four larger strike faults, there are numerous very steep cross faults. These cross faults range from fractures with a displacement of a few inches to those with a displacement of several hundred feet. The displacement ranges from vertical to essentially horizontal. Most of the cross faults are related to the folding, being caused not only by local vertical and horizontal shearing stresses, but by local longitudinal tensional stress. Groups of parallel cross faults, of dominantly vertical displacement, occur in the plunging parts of folds. Associated with the cross faults are groups of diagonal faults which share the characteristics of the cross faults. Locally, these diagonal faults have a displacement (up to 1,000 feet) of the strike-slip type and displace entire folds. The best examples of the diagonal faults are in the west central Potato Hills (e.g., Sec. 36, T. 3 N., R. 19 E.). Their origin is not quite clear. Perhaps lateral torsional forces have been responsible.

The general description of the Potato Hills structure outlined above confirms the fact that this anticlinorium does not contain a tectonic window (14). The most significant facts that disprove the window are: (1) the wedge east of Round Prairie, the truncation of the northern border fault, and the continuation out of the Potato Hills of the southern border fault; (2) the dying out of both northern and southern border faults along the strike to the west; (3) the occurrence of as much northward as southward overturning—especially the overturning to south on the north side, and the overturning to north on the south side of the belt of folds which prolongs to the west the Round Prairie synclinorium.

Certain structural features in the Potato Hills suggest that between the folds and the basement there occurs a horizon of disharmonic shearing-off. Similar features are developed in the other Ouachita anticlinoria, and they will be discussed in a later section of the report.

The Choctaw Anticlinorium (Plate I)

This anticlinorium lies in southern McCurtain Country, Oklahoma, and has been mapped and described by Honess (12). Honess' work undoubtedly is the best which has been published on the Oklahoma Ouachitas. His map has been reproduced on Plate I.

The type of folding encountered in the Choctaw anticlinorium is the same as that of the Potato Hills. The folds are carried by the two relatively competent formations, the Bigfork and the novaculite. The major folds are of moderate size (Plate I) owing to the thickness and mechanical properties of these two formations. There are secondary changes in the thickness of the shale formations, brought about by tectonic reduction along the flanks of folds and accumulation in the crests. There are numerous minor folds, not only in the shales but also in the chert formations. The patterns and shapes of both major and minor folds are similar to those in the Potato Hills. Axial plunge of the folds is widespread, and faulting is subordinate. Part of the folds are upright, and part are overturned. In these ways the Choctaw anticlinorium resembles the Potato Hills. There the similarity ends.

Whereas in the Potato Hills northward and southward overturning are about equal, southward overturning appears to be predominant in the Choctaw structure (12, structure cross sections). Moreover, slaty cleavage occurs in the argillaceous formations of the Choctaw anticlinorium. This slaty cleavage generally has a steep northerly dip, indicating yielding to south, and not to north. The relation of the slaty cleavage to the folds is usually that of axial plane cleavage. Thus the steeply dipping cleavage and tight folding are expressions of the same deformation by the same compressive stress.

This slaty cleavage is best developed in the pre-Carboniferous formations, although the Stanley and Jackfork rocks locally participate.[3] This indicates that the cleavage appears with increasing stratigraphic depth. As a result of differential shearing, the argillaceous rocks have undergone a mild degree of dynamic metamorphism. Slates, phyllitic slates, and occasional phyllites have been formed, with the production of new minerals such as sericite and chlorite. There is no such dynamic alteration in the Potato Hills; there the argillaceous rocks have remained shaly. Although the slaty cleavage is mostly restricted to the argillaceous rocks of the Choctaw anticlinorium, it locally is developed in the more resistant sandstones. However, this cleavage is never as closely spaced as in the slates, and generally there is a parallel joint or fracture pattern, with a tendency for the cleavage to deviate from parallelism to the axial planes of the folds and to assume a position more nearly perpendicular to the bedding of the sandstones or other more competent strata.[4]

In the Choctaw anticlinorium there is a stratigraphic and tectonic depth not exposed in the Potato Hills. Here, the formations underlying the Womble come to the surface with a very significant change in the style of deformation. The tightly compressed folds disappear and the slaty cleavage, for the most part, becomes gently inclined. The rocks have not accumulated in a pile of steeply inclined tight folds which yielded predominantly in the upward direction. Instead, the rocks have yielded by sliding along a gently inclined set of shearing planes. This sliding usually parallels the bedding. There is a normal stratigraphic sequence from older rocks below to younger above, even though bedding planes have been converted into shearing planes. This is noted especially where beds of different mechanical strength overlie one another. The sliding along gently inclined shearing planes has in many cases produced lenticular bodies formed from individual beds or groups of beds. Honess (12) has given an excellent description of the type of deformation which characterizes the central, and stratigraphically and tectonically deepest part of the Choctaw anticlinorium. Everything observed during the writers' brief reconnaissance fully confirms Honess' conclusions.

Miser (14) has suggested that the central part of the Choctaw anticlinorium represents a tectonic window beneath a major flat overthrust (geologic map of Oklahoma, 2). This thrust is supposed to be identical with the Boktukola fault which has been mapped north of the Choctaw anticlinorium in an area of Stanley and Jackfork rocks (Plate I). It may be assumed that one reason for Miser's suggestion was that he felt certain that he had established a tectonic window in the Potato Hills. As has been shown previously the Potato Hills window does not exist.

The structural features in the central Choctaw anticlinorium do not support the window interpretation. There are no older rocks overlying younger rocks anywhere, as a true overthrust would require. If the alleged thrust be considered as one of younger over older rocks, there is no evidence for a single major movement plan of great horizontal displacement. There is no tectonic break in the stratigraphy at the borders of the "window," the general sequence being normal and complete. There is simply a change in the mode of reaction of the rocks to compressive stress at greater stratigraphic and tectonic depths. The preponderant southward overturning of those steep folds which are not upright, coupled with the southward yielding demonstrated by the slaty cleavage, militates against the window interpretation. According to the window hypothesis the steeply folded rocks which surround the generally gently dipping older rocks of the central anticlinorium form a huge thrust plate which has traveled a considerable distance to the north (14, Fig. 7). It is mechanically impossible that southward overturning and southward yielding along cleavage planes can characterize a thrust plate which has moved to the north. It may be added that the Boktukola fault—which would represent the front of this thrust plate—displays no sign of the strong rock deformation which would be expected from a major overthrust.

It is of interest to note that Dr. Lewis Cline[5] of the University of Wisconsin, and his assistant, William Pitt, will shortly publish on the Choctaw anticlinorium, proving the window does not exist.

The downward change to a deformation pattern of gliding along gently inclined shearing planes is one of the main arguments in favor of a disharmonic relationship between the folded Ouachita structure and the underlying basement.

Black Knob Ridge (Plates I, XIII)

Black Knob Ridge (T. 1, 2 S., R. 11, 12 E.) lies very close to the Ouachita front, yet displays the same Ouachita section of pre-Stanley rocks which is typical of the Potato Hills anticlinorium. This has been interpreted as evidence for long distance overthrusting of the Ouachitas over the Arbuckle-Coal Basin section (3).

Black Knob Ridge is not quite comparable to the other Ouachita anticlinoria. It is not a true anticlinorium, but is a narrow anticlinal belt bordered on the western side by a major reverse strike fault (Plate XIII) which cuts out part of the anticlinal structure. This fault forms the inner boundary of Belt I, the width of which is greatly reduced in front of Black Knob Ridge (Plate I). The fault is not exposed, but its straight trace and its relation to the topography indicate that it is steep. The fault brings Womble (Ordovician) up against Atoka (Pennsylvanian).

There is no indication that the border fault of Black Knob Ridge is a flat overthrust, nor that it is a flat overthrust which subsequently became steeply tilted in its frontal portion. There is none of the intense rock deformation which would exist if this were the frontal outcrop of an overthrust of large horizontal

[3] Slaty cleavage is developed in the lower Stanley rocks in McCurtain County, Oklahoma, in most of the Stanley rocks in the central part of the Ouachita anticlinorium of Arkansas, and in the lower Jackfork rocks immediately north of Little Rock, Arkansas.

[4] Similar phenomena in the Arkansas anticlinorium are depicted on cross section, Plate XII.

[5] Oral communication: Ouachita Foldbelt Symposium, New Orleans, La., Nov. 10, 1955.

displacement. The shale formations associated with the cherts of Black Knob Ridge generally have maintained their regular bedding, even in the immediate vicinity of the frontal fault. This comparative lack of strong deformation holds true also for the Pennsylvanian rocks of Belt I on the western side of the fault. The fault apparently is one of great vertical displacement combined with a smaller amount of horizontal displacement. This is in harmony with the intense compression and strong shortening characterizing Belt I of the westernmost Ouachitas.

Along Black Knob Ridge there are a number of second order folds which, trending more nearly east-west, are at an angle to the main axis of the ridge (Plate I). These folds are of generally the same trend as the folds in the Stanley and Jackfork rocks east of the ridge. In size and pattern they are similar to the folds in the other Ouachita anticlinoria, but are much shorter. This shortness is due to a strong plunge off the main axis of Black Knob Ridge toward the interior of the Ouachitas. Thus the anticlinal noses of the pre-Stanley rocks disappear rapidly beneath the Stanley shale. The plunge of these folds coincides with the regional dip off the back (east) side of Black Knob Ridge into the Ouachitas.

The Stanley crops out in a belt on the back side of the ridge (Plate I). An easterly plunge persists across this belt, and a number of east-plunging synclines of Jackfork rocks appear on the east side, being separated by narrower and steeper anticlines within the Stanley rocks. Some of these east-west trending folds are incomplete, the southern limbs having been eliminated by steep reverse strike faults. Part are complete, a notable example being the broad and open Prairie Mountain syncline (Plate I). These structures in the Stanley and Jackfork rocks are of Pattern IV-type and will be discussed later.

There apparently is a structural continuity from the east slope of Black Knob Ridge and its eastward plunging folds through the Stanley belt to the eastward-plunging folds in the Stanley and Jackfork rocks. In fact, some of the individual folds seem to be continuous from the east slope of the ridge eastward into the Jackfork rocks. Not every one of the folds runs through inasmuch as the size of the folds descending from Black Knob Ridge is generally smaller than that of the folds in Stanley and Jackfork a mile farther east (Plate I). This size is a function of the differing thicknesses and competence of the formations which carry the folds.

Hendricks (3) has mapped a number of overthrusts along the belt of Stanley rocks between Black Knob Ridge and folds farther east. The overthrust hypothesis of the Ouachitas requires this interpretation. However, where the Stanley is studied in detail there is no evidence for repeated thrust sheets. Neither is there the intense rock deformation and shearing which would be expected. Nor do the attitudes in the Stanley rocks fit a scheme of thrusting; instead, they support structural continuity.

The question remains whether the rocks of Black Knob Ridge make it necessary to assume that this unit has been emplaced by long distance overthrusting. The rocks are certainly of Ouachita type, and do not differ materially from those exposed in the Potato Hills anticlinorium. The oldest exposed formation is the Womble, but it is probable that the rocks underlying the Womble are likewise of Ouachita type. This difference between the Black Knob Ridge section and that of the Arbuckle-Coal Basin would in itself support an overthrust hypothesis, but the structural features do not give any indication that large scale overthrusts exist at either the western border of the ridge or the western margin of Belt I. Apparently the facies differences must be accounted for without recourse to long distance thrusting.

This is possible, and has been discussed under Stratigraphy. It has been suggested that the existing facies differences do not exceed what is often observed in closely adjacent areas of deposition, if tectonic regime and conditions of sedimentation vary. Moreover, extreme shortening in the westernmost Ouachitas has been achieved by tight folding, reverse faulting, possible shearing-off, and possibly some true overthrusting (Plate XIII). As a result, contrasted facies were brought more closely together than they were at the time of deposition. If it is correct that in the westernmost belt steep imbricate slices were piled up against a frontal buttress, lateral shortening could account for the apparently rapid change in facies. In particular this is true if the disharmonic shearing-off hypothesis, to be discussed later, is accepted. If so, the following hypothetical structural history is outlined:

(1) The Ouachita sediments were compressed into a pile of folds without participation of their basement, the basement for mechanical reasons being unable to join in the intense folding;

(2) This disharmonic behavior produced shearing and sliding in a stratigraphic horizon below the steeply folded section and above the massive underlying rocks;

(3) Presumably due to the presence of a frontal buttress, which impeded the smooth and gradual dying-out of the waves of the Ouachita folds, the mass of folded rocks above the shearing-off horizon was especially compressed and shortened in its westernmost part;

4) As a result, the folds broke into tightly packed, steep imbricate slices.

This interpretation would permit maximum shortening in the westernmost belt and a certain amount of lateral displacement, without invoking any large flat overthrust for which there is no field evidence.

The Arkansas Anticlinorium

This is the largest of the anticlinoria, extending almost the entire length of the Arkansas Ouachitas (geologic map of Arkansas, 1). It rises from Carboniferous rocks at its plunging ends, and is concealed on the east by the sediments of the Gulf Coastal Plain.

The folding pattern (Plate XII) is of the same type as that of the Potato Hills and of the Choctaw anticlinorium. This applies to the size of the individual major folds which are carried by the competent Bigfork and novaculite and, in part, by the Crystal Mountain sandstone. The shape and plunge of the folds, the behavior of the weak shale formations, the widespread minor folding, and the generally tight and steep nature of the folds all resemble the folds in the Potato Hills and the Choctaw anticlinoria. Steep overturning, reminiscent of the Potato Hills, occurs both to north and to south. Not all of the folds are parallel; some of them trend diagonally. There are several axial culminations in the anticlinorium, the highest being south of Mt. Ida where the Collier limestone, the lowest known part of the Ouachita section, is exposed.

Certain parts of the argillaceous formations have acquired slaty cleavage. Where there is slaty cleavage the rocks range from indurated shales to true slates, phyllitic slates, and, locally, phyllites (Plate XII). Generally, the degree of cleavage and of dynamic rock alteration appears to increase with stratigraphic and tectonic depth. There are exceptions. On the north side of the anticlinorium (Plate XII, mile 28), there is a fully developed slaty cleavage with an alteration to phyllitic slates of rocks of Stanley age.

The highest degree of dynamic rock alteration is in the Collier shales in the axial culmination south of Mt. Ida (Plate XII). The shale has in large part been converted into silvery sericitic phyllite. This area is interesting from a structural standpoint. The old rocks exposed in the core of this culmination do not occur in steeply inclined tight folds, but in a more gentle anticline in which the slaty cleavage or phyllitic foliation is gently inclined. As in the core of the Choctaw anticlinorium, this apparently indicates that not much farther down there is a horizon of disharmonic shearing-off. It should be emphasized that a normal and unbroken stratigraphic sequence leads from the gently inclined structures of the core of this culmination to the normal steep tight folds of the remainder of the anticlinorium. This matches those occurrences in the Choctaw anticlinorium which militate against the window interpretation.

There is one locality in the Arkansas anticlinorium which offers indirect evidence as to what rocks lie beneath the exposed Ouachita section. This is Magnet Cove (Arkansas, T. 3 S., R. 17 W.) southeast of Hot Springs where large blocks of contact metamorphosed limestone have been brought up by basic alkaline magma. This seems to indicate that the exposed folded Ouachita section is normally underlain by a massive limestone formation equivalent to the Arbuckle limestone or a part of it. It is suggested that the shearing-off horizon, which probably underlies the folded Ouachitas, should be near the base of the Collier shale and above this massive limestone. The possibility exists that the top of this massive limestone is the Collier limestone exposed in the quarry southwest of Mt. Ida (Arkansas, Sec. 32, T. 2 S., R. 25 W.).

Pattern IV: The Open Synclines and More Tightly Folded Anticlines

The Open Synclines

The characteristic structures of this pattern consist of very broad and open synclines and of narrower, more highly compressed anticlines. Generally, Jackfork rocks are exposed in the synclines and Stanley rocks in the larger anticlines. A number of the synclines are very wide and have gentle dips in their interior portions, whereas at the rims the Jackfork rocks dip in most cases between 30 and 50 degrees (Plates V, XIII). Individual synclines often occupy large areas, the Jackfork outcrop in the Johns Valley, or Tuskahoma syncline (Plate I) being more than 30 miles long and up to 8 miles wide.

All of the broad open synclines have a limited longitudinal extent because of marked plunges which eventually bring Stanley rocks to the surface along the continuation of the synclinal axes. Most of the synclines are elongate and doubly plunging, thus forming an oval outcrop pattern (Plate I). Locally, the plunge at the ends is almost as strong as the dips in the limbs so that the inner part of the syncline has a more or less circular pattern. An example of such a round, shallow, structural basin is the large Prairie Mountain syncline southeast of Stringtown (Plate I). Some synclines do not show double plunge because part of the syncline is concealed beneath the Cretaceous overlap. Examples of these partly concealed structures occur in the vicinity, and east, of Antlers (Plate I).

Generally, the large broad synclines have only two directions of plunge, and these flatten out in the central part of the synclinal basin. Locally, there are secondary axial culminations, and the syncline then contains two basins separated by a moderate structural high. These secondary culminations locally continue across the strike into adjacent anticlines in the Stanley rocks. The Johns Valley syncline has such a constriction representing a culmination (Plate I, Sec. 33, T. 1 S., R. 16 E.). By following this culmination across the strike into the adjacent anticline, the Jumbo anticline (Plate V) was located.

The axial depressions represented by the deepest parts of the syncline often continue across the strike into adjacent anticlines. Where the axial depressions line up across the strike of two neighboring synclines, and the depression is continuous across the intervening anticline, the axial depression locally is deep enough to permit the Jackfork rocks of the two synclines to connect across the depressed anticline. An example occurs north of Jumbo (Plate V, T. 1 N., T. 1 S., R. 15 E.) where the Jackfork of the Johns Valley and Pine Springs synclines is connected across the plunging northern nose of the Jumbo anticline, the Stanley rising once again farther to the north (Plates I, V).

The trend of the large synclines is not always the same (Plate I). This is to be expected, in view of the important role played by axial plunge (i.e., deformation transverse to the main fold axes). In this, as well as in other aspects, the areas characterized by Pattern IV structures differ from the Pattern II with their tightly compressed and generally sharply parallel folds. The most common trends of the large synclines in areas of Pattern IV are east-west to northeast-southwest, but there are places where the trend becomes nearly north-south. In some major synclines different parts trend differently. The Johns Valley syncline (Plate I) in its main, northeastern portion trends about east-northeast, but to the southwest, beyond the axial culmination, the trend is nearly north-south.

The More Tightly Folded Anticlines

The anticlines of Stanley rocks in areas of Pattern IV deformation are generally much narrower, and almost invariably more tightly compressed than the large synclines. Thus, the anticlines have steeper dips and narrower crests. A reconstruction of the structure which existed prior to the erosion of the Jackfork cap over the anticlines shows that Pattern IV folding is of the "ejective" type (Plate VI-g). The thick and massive Jackfork warped down into broad, gentle, basin-shaped synclines, while between the synclines it buckled up in much narrower, tighter, and steeper anticlines, often accompanied by reverse strike faulting. This ejective type of folding cannot be attributed to the mechanical properties of the Jackfork rocks. It must be related to the fact that beneath the Jackfork there is a thick shale sequence, with subordinate, easily folded but competent chert formations. These formations tended to accumulate and squeeze upward in the anticlinal cores. This deformation probably involved the pre-Carboniferous portion of the section to a greater degree than the Stanley shale which, in areas of Pattern IV, generally does not have the large amount of minor folding which is assumed to exist at a greater stratigraphic depth.

The conclusion is reached that beneath the Stanley shales of the anticlines the structures probably become more complex. This downward increase in complexity may be visualized in the following manner: the usually quite simple and regular anticlines probably pass downward into tightly compressed composite anticlines possessing numerous minor folds. It appears likely that this change to complexity occurs not farther down in the section than the novaculite—Bigfork interval. This is indicated by the relationships which exist at the surface along the general axial plunge from the folded novaculite of the western Potato Hills through the broad Stanley belt into the area characterized by Pattern IV (Plate I). The interpretation of this horizontal change in tectonic style in terms of a change with stratigraphic and tectonic depth has been discussed on page 72.

However, such a change in pattern of folding is likely to occur only beneath the anticlines in the areas of Pattern IV, and not beneath the large synclines. This is suggested by the ejective character of the folding. If this deduction is correct, the shape of an anticline, as mapped on the surface, cannot be projected to great depth with accuracy. However, it cannot be doubted that the major structures will be the same in the lower (i.e., pre-Stanley) part of the section. In other words, anticline probably remains anticline, and plunge in a certain direction probably remains plunge in that direction. What probably changes in the lower part of the section is the detail, especially insofar as simple anticlines at the surface probably become complex or composite anticlines at depth. This ejective folding pattern is difficult to visualize mechanically unless a horizon of disharmonic behavior exists at depth.

Minor folding is not common in the anticlines of Pattern IV. It occurs, but is not as widespread as the minor folding which characterizes the Stanley, as well as other shale formations, in areas of intense folding. On the Jumbo anticline, for example, there is local minor folding, and in the southward plunging part of the anticline there are several plunging folds in the Stanley (Plate V, Sec. 20, T. 2 S., R. 15 E.). But, as a whole, and removing the faulting, the Jumbo anticline is rather regular. In the Moyers anticline (Plate I), which borders the Johns Valley syncline to the southeast, there are secondary complications, comprising both folding and faulting, but as a whole the anticline is also rather regular, persistently plunging to the northeast. In a similar way the two tilted faulted blocks (Plate I) north of the Johns Valley syncline are remarkably regular and generally free of minor folds.

The trend of the anticlines varies. Most trend east-west or northeast-southwest, but some, as the Jumbo anticline, trend nearly north-south. A factor which contributes to the variation in trend of the anticlines is the pronounced axial plunge of the large synclines, which represents an element of transverse deformation. At strongly inward plunging noses of broad synclines the two adjacent anticlines tend to converge. An excellent example occurs at the southwestern end of the Johns Valley syncline. Here the north-south trending Jumbo anticline and the northeast-southwest trending Moyers anticline almost meet (Plates I, V), and it is possible that beneath the overlapping Cretaceous to the south the two anticlinal axes actually merge.

The pattern which results from the divergence, convergence, and branching of anticlines is that of a network of generally connecting, mostly narrow, anticlinal zones of Stanley rocks. This network winds around the large, broad, mostly oval-shaped, plunging synclines. This peculiar structural pattern could not be due to a linear compressive stress which acted in only one direction. There also must have been compressive stress in a transverse direction. It is probably more reasonable to speak of an "all-sided" horizontal field of stress, with the strongest component operating in a north-south to northwest-southeast direction. Somewhat similar conclusions were reached when the structural pattern of the Potato Hills was discussed. Regionally, this stress distribution would account for the arcuate pattern of the western Ouachitas.

Faults of Pattern IV

The open synclines and the narrower anticlines constitute the dominant structural elements of Pattern IV. There are, however, other structures present. These are strike and cross faults, and tighter folds in which not only the anticlines but also the synclines are relatively strongly compressed.

Faults generally are rare. Steep reverse strike faults, paralleling the local folding trend, are encountered, usually at or near the margins of anticlines (Plates I, V, VI), or at places where locally tighter folds occur in the Jackfork rocks. None of these strike faults appear to continue for great distances. They usually are absent in the larger synclines. Local exceptions to this occur within the Prairie Mountain and Lane synclines (Plates I, IV).

Cross faults, transecting the local folding trend, are rare where the typical Pattern IV is developed. However, they do occur and exceptionally may be of great magnitude. One example (Plate I, T. 1 N., R. 19 E.) is the north-south trending fault which, east of Clayton, cuts off the large and wide syncline of the Kiamichi Mountains. Where folding trends diverge, one and the same fault may be transverse with regard to one folding trend and longitudinal with regard to another. This is the case north of Jumbo (Plates I, V; T. 1 N., R. 15 E.) where a strike fault of the Jumbo anticline is a cross fault with regard to the Daisy anticline. All the faults observed are steep, and where dips were measured they were rarely less than 75°. The displacement is mainly vertical. None show any indication of overthrusting.

Tighter Folds in the Jackfork Rocks

Tight folding is rather subordinate in the Jackfork rocks, and it is absent over large areas. Locally, however, it is prominent. Such tight folding is usually close to major anticlines, not in the interior of the large synclines. These tighter folds are much smaller than the dominant major folds. They are rather narrow, and usually have a limited longitudinal extent. Examples are found north of Jumbo in the Daisy Valley (Plate I, T. 1 N., R. 15 E.), and elsewhere.

These tighter folds are of interest in that they demonstrate that the Jackfork, in spite of its massive character, can be folded into tight anticlines and synclines. The broad and open character of the large synclines cannot, therefore, be attributed entirely to the mechanical properties of the Jackfork. Rather, it is concluded that these synclines actually represent areas of relatively weak compression. It may be deduced that beneath these synclines the deformation remains weak at depth, even in the older formations.

Pattern V: The Faulted Belt North of the Pattern IV Area of the Western Ouachitas

Eastern Part

This belt lies north of the wide area of typical Pattern IV structures (Figure 2). It is characterized by several major strike faults, and by a large number of cross faults. The strike faults are reversed, all have the north side downthrown, and all of them are steep as demonstrated by their straight outcrops.

The eastern part of this belt extends from northwest of the Potato Hills to north of Jumbo (Plate I). Here two large tilted fault blocks occur between the Johns Valley syncline on the south and the Windingstair fault to the north.

The northern fault block is bounded on the north by the Windingstair fault and on the south by the North Jackfork fault. This southern fault brings Stanley of the second and southernmost block up against upper Jackfork. This fault is exposed in a road cut[6] and is a very steep reverse fault, dipping about 80° to the south. Though mapped as an overthrust (3) there is no indication of any large horizontal displacement. At both ends of the block the fault dies out within the Stanley rocks. Near the western end of this tilted block the throw of the North Jackfork fault decreases until the base of the Jackfork runs into the fault at a very small angle (Plates I, III). This sharp and narrow wedge of nearly vertical lowest Jackfork makes it obvious that the fault is not an overthrust.

The dip of the beds composing this northern block is to the south-southeast. In the northern part of the block the Stanley conformably underlies the Jackfork, and is faulted up against probable Jackfork along the Windingstair fault. The Windingstair fault is alleged to be a major overthrust (3, 14), and to appear in the "window" in the core of the Potato Hills farther east. It has been shown that this "window" does not

[6]Immediately west of 1/4 cor. between Secs. 25 and 26, T. 2 N., R. 15 E., on the Welcome Valley to Counts road.

exist. Nor does the Windingstair fault have the appearance of a large overthrust. Its straight outcrop pattern and its relation to the topography indicate that it is very steep, displacement being essentially vertical. The fault is not exposed, but it is assumed that it is a high-angle reverse fault similar to the North Jackfork fault on the opposite side of this same tilted block.

Although the dip of this block is homoclinal to the south, there are several minor folds (Plates I, III, T. 2 N., R. 15 E.). These die out to the east in a low-dipping homocline which has steeper dips only in the immediate vicinity of the North Jackfork fault. These gentle structures in the Jackfork recall Pattern IV, though strongly modified by strike faults. Farther east, southwest of Counts, several folds of small magnitude appear in the Jackfork rocks of the fault block (Plate I, T. 2 N., R. 16 E.). They are much more distinct than those near the western end of the block, being more tightly compressed. In the vicinity of Counts (Plate I, Sec. 1, T. 2 N., R. 16 E.) the fault block is interrupted by a zone of cross-faulting and transverse tilting which is probably of horst-like character. East of this transverse zone the fault block continues, with the same characteristics as the block farther west.

The southern tilted fault block is bounded on the north by the North Jackfork fault and on the south by the South Jackfork fault (Plate I). This block includes Jackfork Mountain. The Stanley and Jackfork rocks of this block are also tilted to the south, the Jackfork on the south being faulted down against the Stanley. This fault is straight and steep, and probably is a high-angle reverse fault. It gives no indication of being an overthrust, and dies out to the east and to the west (Plate I). On the east it dies out (T. 3 N., R. 18 E.) as the tilted block changes to a syncline which is relatively tightly compressed. This change is accompanied by a zone of cross-faulting. On the east the syncline ends because of westerly plunge off the Potato Hills anticlinorium.

South of the South Jackfork fault and the southern fault block is a belt of Stanley rocks which dips south into the Johns Valley syncline. This belt is in part an incomplete anticline with its northern limb faulted out. To the east the anticline may be complete where the throw of the South Jackfork fault decreases to zero (Plate I).

The structures of these two blocks may be interpreted in terms of moderately steep to gentle, large synclines and steeper, narrower anticlines in which the northern anticlinal limbs, and the southern synclinal limbs, generally have been eliminated at high-angle reverse faults. In the easternmost part of this belt (T. 2, 3 N., R. 19 E.) a smooth folding pattern leads all the way from the south side of the North Jackfork fault to the Johns Valley syncline.

Cross faults are very common in this belt. All are steep and near vertical. Many of them have a strike-slip movement. A major cross fault (Plates I, V, T. 1 N., R. 15 E.) cuts off the Jackfork Mountain (i.e., the southern) block on the west. It is one of a group of cross faults which are prominent in the westernmost part of this block.

There are also many cross faults in the northern block. A number of them at which strike-slip movement predominates have displaced the North Jackfork fault as well as the axes of the folds which occur in the Jackfork rocks southwest of Counts (Plate I). Several of these cross faults line up with faults in the southern block, apparently being continuous across the intervening belt of Stanley.

It is of interest that the large cross fault which forms the western end of the southern block, some faults farther northwest on the opposite side of the wide Stanley outcrop area, and the north-south trending faults which are associated with the anticlinal zone north of Jumbo, all lie within one meridional belt (Plate I). This may indicate control through block movements at depth.

Western Part

The western part of the faulted belt displays the same general features which have been described from the eastern part. The pattern is the same. There are very steep, reverse strike faults, with downthrow on the north; southward tilted blocks of Stanley and Jackfork rocks; transitions from homoclinal Jackfork sequences to synclines, and from homoclinal Stanley sequences to anticlines; and smaller folds, in the Jackfork rocks, which are partly tightly compressed and partly more open. In the southern part of this belt lies the wide band of Stanley rocks which includes the Redden oil field (Plate I).

There are structures which recall Pattern IV. East of Stringtown is an easterly plunging Jackfork syncline. To the east its southern side is faulted against the anticlinal zone of Stanley which separates this syncline from the Prairie Mountain syncline. At the same place, several folds of second magnitude appear in the southern portion of this Jackfork unit. Another Pattern IV structure occurs west of Bald Mountain. Here is a doubly plunging Jackfork syncline of moderate size, trending northeast-southwest (Plate I). This syncline is elongate in shape, and is cut by several cross faults.

Pattern IV structures of this kind, combined with the interpretation of the fault blocks as anticlines and synclines which have had part of their limbs faulted out, indicate that this area represents a transitional faulted belt which is related to the large Pattern IV region immediately south.

The westernmost part of this belt extends to east and northeast of Stringtown (Plate I). It ends in the folds which plunge off the eastern side of Black Knob Ridge. There is structural continuity from Black Knob Ridge across the belt of Stanley rocks into the Pattern IV and V structures, and there is no indication of the overthrusts which have been postulated

(3). There is a divergence in strike between the folds in the Jackfork and Stanley rocks, which trend nearly east-west, and the northeast strike of Black Knob Ridge. The link between these divergent trends is the folding which plunges off the east side of Black Knob Ridge at an angle to the main axis (Plate I). This divergence in trend supports the interpretation that the folded rock mass of the Ouachitas is underlain by a horizon of disharmonic shearing-off, and that at the margin of the westernmost Ouachitas the rock mass above the shearing-off horizon broke up into steep slices as it encountered a strong buttress. The trends of the main axis of Black Knob Ridge and of the outer marginal faulted belt would have been determined by the trend of the border of this buttress, which possibly coincided with the border of the Ouachita geosyncline.

Structural Interpretation of the Ouachitas

The Ouachita Mountains were considered originally to be an autochthonous folded system. Subsequently the Oklahoma part of the mountains has been interpreted as a huge allochthonous mass floating on a sole thrust—the Choctaw fault—with a number of higher overthrusts of large magnitude. This overthrust hypothesis, conceived by Miser (14), has been expanded by Hendricks (3). Hendricks has assumed a horizontal displacement of "tens of miles," bringing the whole Ouachita system from an area altogether to the south of its present location. To accompany this magnification of the displacement, Hendricks has increased the number of overthrusts within the Ouachitas. However, no one has applied a similar interpretation to the Arkansas part of the Ouachitas. This state of affairs is contradictory.

This overthrust hypothesis has been discussed in the various parts of the Ouachita system previously described. The evidence demonstrates that this hypothesis must be discarded. Thus, the Ouachita Mountains are returned to their original status of an autochthonous folded system comparable to the folded Appalachians. But the autochthonous interpretation permits of (sic) two concepts:

(1) That the surface structures continue harmonically to depth. This would require harmonic participation of the non-exposed lowest units and basement with the exposed section. This concept is that of a harmonic autochthonous folded system;

(2) That the surface structures do not continue indefinitely to great depth, but are disharmonic with regard to the structures in the mechanically strong basement and in the massive pre-Collier sedimentary rocks presumably overlying the basement. This concept is that of a disharmonic autochthonous folded system. This requires a horizon of disharmonic shearing-off above an infrastructure and beneath the tightly and steeply folded suprastructure, the mechanical responses of these two major units to orogenic stress having been altogether different. This interpretation is one of disharmonic shearing-off. Many structural features favor this interpretation.

Evidence for the Disharmonic Shearing-off Hypothesis

The evidence for this hypothesis includes the following:

(1) Pre-Collier rocks do not appear in any of the anticlinoria, not even in the highest axial culminations. This cannot be mere coincidence. The overthrust hypothesis also could account for this except that it cannot be reconciled with numerous other structural features;

(2) In the axial culminations of the Choctaw and Arkansas anticlinoria the steep and tight folding characteristic of these areas is replaced by gently-dipping shearing. This zone of flat shearing is interpreted as lying immediately above a horizon of disharmonic shearing-off. A plane of overthrusting beneath the surface also could account for this flat shearing, but is discarded on other grounds;

(3) The behavior of the folds in the anticlinoria indicates a disharmonic relation between the exposed suprastructure and an infrastructure of mechanically much stronger rocks. The great accumulation of rock masses in the steeply folded anticlinoria represents compressive upward yielding such as would be expected above a horizon of disharmonic separation, and actually has been observed above shearing-off planes in other regions. This feature cannot be reconciled with either a harmonic autochthonous folded system or an overthrust;

(4) The horizontal component of yielding in the steep folds of the anticlinoria is small, and lacks uniformity. There is as much of a southern as of a northern component in the Potato Hills and Arkansas anticlinoria, and the southern component is dominant in the Choctaw anticlinorium. This pattern of non-uniform yielding often is found above a plane of disharmonic separation where the individual folds are free to choose the easiest direction of yielding—a direction which in each case depends on the local distribution of rock masses contending for space. This non-uniform yielding cannot be reconciled with the hypothesis of flat thrust sheets. Such would require uniform yielding in the direction of thrusting;

(5) The complex pattern of plunge in the anticlinoria is best explained by the disharmonic shearing-off hypothesis which gives the folds in the suprastructure independence and permits adjustment to local space requirements. This pattern cannot be reconciled with a harmonic autochthonous folded system. It might be reconciled with an underlying overthrust, but a flat thrust representing a large horizontal displacement should have forced a high degree of structural uniformity on the rocks of the overthrust plate;

(6) Not only the anticlinoria, but the entire Ouachitas display a lack of uniformity in the horizontal component of yielding. Overturning occurs both to north and to south. This lack of uniformity is incompatible with the overthrust hypothesis, and is not easily reconciled to a harmonic autochthonous folded system in which the folds, extending down to the basement, probably would have acted more uniformly under the control of their deep cores of mechanically strong basement rocks;

(7) The ejective folding pattern characteristic of the Pattern IV areas typically occurs above disharmonic shearing-off planes. This pattern cannot be reconciled with harmonic folding extending into the basement. It is also incompatible with the overthrust hypothesis, as is the weak over-all shortening in the Pattern IV areas. Thrust plates lack strong internal shortening only if they are composed of mechanically strong, massive rocks. This does not apply to the Ouachitas as is clearly illustrated at numerous places by the Jackfork group which, with its interbedded shales and thin-bedded sandstones, has been able to form very tight and steep folds.

The Theory of Disharmonic Shearing-off

Fundamental differences exist between disharmonic shearing-off and overthrusting. Any large thrust sheet has come from elsewhere. None of its rocks are still where they were formed, irrespective of whether older rocks have been thrust over younger, in a true overthrust, or vice versa. Shearing-off, on the other hand, occurs between different parts of one and the same section, and is essentially slippage along the bedding. This is caused by different tectonic responses of parts of the section which have different mechanical properties. The rocks above a shearing-off plane are at or near the point where they were deposited, and they still overlie those rocks which were their original substratum.

If a thrust plate is of large extent across the strike, large horizontal displacement is indicated. A shearing-off plane may be very extensive, yet the actual horizontal displacement may be very small. Along a cross section of a thrust plate the direction and amount of relative movement are more or less constant. Along a cross section of a shearing-off plane both the amount and the direction of relative displacement may change from place to place, dependent upon the amount of shortening in the suprastructure compared to that in the infrastructure.

Every overthrust plate has a frontal break-through to the surface, unless its front is covered by a later thrust sheet or concealed by younger sediments. A shearing-off plane often does not break through at all, but dies within the bedding, being laterally replaced by an undisturbed section.

The behavior of a shearing-off plane depends upon the shortening ratio of the rocks above and below the plane. In extreme cases the infrastructure has suffered little or no shortening, whereas the suprastructure has been strongly shortened by folding. This is possible only if deeply rooted thrust masses have pushed the "back side" and peeled-off the sediments of the suprastructure from their substratum. In this case, displacement at the shearing-off plane is greatest on the back side, and steadily decreases to a zero line at the outside. At the zero line the movement plane may die out within the bedding, or it may break through to the surface, causing a reverse fault which cuts across the bedding. Frontal buttresses favor such a breaking-through.

In other cases the shortening in the infrastructure and in the suprastructure on opposite sides of a shearing-off plane is about equal, although the mechanisms of shortening differ. In this case the horizontal displacement at the shearing-off plane remains small everywhere, and its amount and direction changes from place to place, with intervening "zero points" at which there is no displacement. Eventual breaking-through can occur, but is less common in this case.

Between the two extremes above there are all transitions. Moreover, there are cases in which shortening by folding is greater in the lower unit than in the upper, and a certain amount of true overthrusting necessarily results. This does not concern the Ouachitas, inasmuch as the suprastructure displays strong shortening.

Application of Disharmonic Shearing-off to the Ouachitas

(For purposes of this discussion, it will be assumed that the disharmonic shearing-off hypothesis is the correct interpretation of the Ouachitas).

In Arkansas and easternmost Oklahoma no frontal break-through has occurred. Here the Ouachita folds pass transitionally into the folds of the Arkansas Valley (2). Thus, the shearing-off dies out along the bedding, being replaced by an undisturbed section to the north (Plate XII). The "zero line" must lie near or at the northern border where the tight Ouachita folds of Pattern II change into the gentle folds of the Arkansas Valley. The latter probably extend harmonically to the basement.

From east of Wilburton (Plate I) to the southwestern end of the Ouachitas at Atoka a marginal break-through of the shearing-off plane has occurred. It is represented by the faulted border of Belt I. The steep reverse faults which lie inside Belt I are closely related to the break-through, even though several—and probably most of them—have formed from strongly compressed steep folds which are an expression of the strong stress which operated in back of the frontal break-through. The amount of compression is strongest in the western part of Belt I near Black Knob Ridge, less strong in the eastern part near Wilburton, where Belt I becomes reduced in width and complexity, and least strong between Red Oak and Heavener where Belt I is absent (Plate I; Figure 2).

The reason for the break-through in the west, but not farther east, may be conjectured. The Arbuckle region (geologic map of Oklahoma, 2) to the west formed a buttress of resistant rocks which forced the shearing-off plane to break through. This produced a sharply marked Ouachita front in this area, and prevented both a more gradual underground dying out of the shearing-off plane and a more gradual dying out of the strong folding of the suprastructure.

The buttress included the present eastern Arbuckles as well as adjacent areas which might be described as "buried Arbuckles"—areas where the resistant Arbuckle rocks, relatively high at the time of the Ouachita folding, subsequently were buried under post-Ouachita basin deposits. There is no reason why the buttress should have extended as far east as Belt I does, for the break-through would have extended beyond the limits of the frontal buttress which caused it. The fact that compression in Belt I is strongest on the west, and decreases to the east until Belt I dies out, indicates that the buttress was located to the west.

This interpretation does not imply that the reduction in width of Belt I in front of Black Knob Ridge (Figure 2) is caused by less intense compression. On the contrary, especially strong compression caused a narrowing of this belt through imbricate slicing and suppression of some of the folds at reverse faults. In this area, the component of horizontal shortening at the reverse faults is probably greater than elsewhere.

The interpretation suggested above would account for the contrast between the north-northeast strikes of Belt I and Black Knob Ridge (Plate I and Figure 2), and the more east-westerly strikes of the less compressed folds to the east. The latter represent the normal folding pattern of this part of the Ouachitas above the underlying shearing-off plane. The former are an expression of the frontal buttress to the west which prevented the normal Ouachita folds from continuing in a north-westerly direction and, instead, forced the shearing-off plane to break through in a narrow and tightly compressed zone.

The Probable Structure Beneath the Shearing-off Plane

(In the absence of subsurface data this discussion is purely speculative).

The first possibility is that the resistant rocks of the infrastructure have undergone little or no shortening. In this case the amount of displacement at the shearing-off plane would systematically increase to the south. A pattern of this kind is only possible if to the south there were large, deeply rooted, thrust masses which exerted a northward push. These now would be concealed beneath the sediments of the Gulf Coastal Plain. None of the available subsurface data south of the Ouachitas seem to permit an accurate appraisal of this concept. A comparison with the major zones of the Appalachian system favors this interpretation. Yet the predominance of southward overturning in the Choctaw anticlinorium is unfavorable to the interpretation that a northward push was exerted by now concealed thrust masses.

The second possibility is that the infrastructure has undergone shortening. This is supported by certain features of the surface structures. First, the horizon of disharmonic shearing-off is not flat (Plates IX, XIII). This plane must lie at different depths beneath different portions of the Ouachitas. The depths may be estimated as follows: about 3,000 to 4,000 feet below the Bigfork chert of the anticlinoria; considerably less beneath the culminations within the anticlinoria, and possibly exposed in the Collier limestone quarry southwest of Mt. Ida, Arkansas; about 8,000 to 10,000 feet below much of the folded Carboniferous; and even more beneath the major synclines containing a thick Jackfork section.

Moreover, there are large faults in the suprastructure which are mechanically unrelated to the folding pattern and are best interpreted as surface expressions of large block movements in the infrastructure. Several of the extensive cross-fault zones (cf. Pattern V discussion) are rather definite in this respect. The same may be true of some of the major strike faults, although the field relations are not conclusive. If the infrastructure broke into blocks along cross faults, it is difficult to see how it could escape fracturing parallel to the regional trend. Such strike faults in the infrastructure would be compressive and the only means by which the rigid infrastructure could have responded to stress. The infrastructure certainly was not capable of tight folding. If it had been, the older rocks should be exposed in the anticlinoria, and there would be no disharmonic shearing-off. Any folding that occurs in the infrastructure must be gentle. If block faulting occurs in the infrastructure many of its reverse faults might not extend above the shearing-off horizon (Plates IX, XIII).

There is also a possibility that faults in the infrastructure occur along trends not represented among the surface faults. There could be block faults which trend diagonally, falling into the northeast quadrant between the strike and the cross faults. It also appears probable that some of the northwest-southeast trending faults of the eastern Arbuckle region (geologic map of Oklahoma, 2) continue into the Ouachitas beneath the Cretaceous cover south of Atoka. They might form horst-like prolongations of the Arbuckles. A well[7] recently drilled south of the Ouachitas near a hypothetical southeastward prolongation of the Reagan-Mill Creek fault zones drilled out of Cretaceous rocks at 700 feet and then drilled in granite and associated igneous rocks to a total depth of 12,510 feet. This apparently supports an eastern extension of the Tishomingo granite (2) beneath the Cretaceous; i.e., a horst-like prolongation of the Arbuckle area.

It is probable that shortening is present in the infrastructure. If this shortening is considerably less than that of the suprastructure, a northward push from now concealed thrust masses to the south would be required. If no such push was exerted, shortening in infrastructure and suprastructure must have been about equal, requiring intense block-slicing in the infrastructure to match the strong shortening of the exposed suprastructure.

OIL POSSIBILITIES

Known Indications of Oil and/or Gas

Gilsonite and allied asphaltic compounds have been reported from numerous localities in the Ouachitas. Those localities visited by the writers are indicated on the accompanying geologic maps. A laboratory report on a sample from the Jumbo area is in Appendix B.

The geologic map (Plate I) of the Oklahoma Ouachitas shows the location of all wells known to the writers which have been drilled in this area. A list of these wells, keyed to the map locations, is in Appendix B.

Shallow wells, rarely in excess of 700 feet deep, produce minor quantities of oil from upper Stanley sandstones south of Redden (T. 1 S., R. 14 E.), west and southwest of Bald Mountain (T. 1 and 2 N., R. 15 E.), and on Potapo Mountain anticline (T. 2 S., R. 13 E.). Driller's logs, electric logs, and oil analyses from some of these wells are in Appendix B. It is significant that both wells and asphaltite deposits are generally associated with faults.

A well[8] was drilled just off the axis of the main syncline in Round Prairie, Potato Hills (Plate II). Various shows of carbonaceous material and gas were encountered. The well, currently flowing water and minor quantities of gas, may be ignited at the well head. This well was drilled entirely within the Stanley shale.

These scattered indications of petroleum have been interpreted in terms of the overthrust hypothesis. It is generally believed (3) that the oil came up from the Arbuckle "facies" underlying the overthrust Ouachita "facies." Moreover, it has been the consensus that the rocks of the Ouachita "facies" are incapable of producing oil.

There is no compelling reason for these assumptions. The results of this project indicate the Ouachitas are an autochthonous folded system. Thus, the oil must have come from rocks of the Ouachita section.

The question then is not whether there is oil in the Ouachita rocks, but whether oil can be produced in commerical quantities. Stratigraphic and structural conditions indicate that there is a fair chance to find oil in commercial quantities. Only after a number of deep wells have been drilled, each of which must be located on the basis of adequate and detailed structural work, will it be possible to say that a conclusive test has been made.

Source Rocks in the Ouachita Section

The most likely potential source rocks are the thick, dark shales of the Ordovician section, most of which are of the same age as the Simpson Group of the Arbuckles (Table II). One of these formations, the late Ordovician Polk Creek shale, is particularly rich in bituminous matter. At several places a true petroleum odor has been noted emanating from the finely textured brownish-black mudstones.

The Bigfork (Ordovician) limestones, mudstones, shales, and cherts are black or brownish-black, in part highly bituminous, and certain horizons are fossiliferous. Beds exposed in 1939 during operations at the Stringtown quarry on Black Knob Ridge were saturated with oil (3).

Most of the Womble shale (Ordovician) is dark or black and contains organic matter. As in the Polk Creek shale, graptolites and other marine organisms are plentiful.

Dark shales also occur lower in the Ordovician section. The Mazarn and Collier shales cannot be ruled out as source beds, though where they are exposed in the Arkansas and Choctaw anticlinoria they generally have been altered to slaty or phyllitic rocks. The Collier shale, on the basis of the disharmonic shearing-off hypothesis, lies very close to—perhaps immediately above—the shearing-off plane. Thus it would have been intensely sheared everywhere in the Ouachitas, as it has in the exposed culminations of the anticlinoria.

[7]Phillips Petroleum Co. #1 Matoy, Sec. 24, T. 5 S., R. 11 E.

[8]Ringling & Brooks (1915?), abandoned at about 3,100 feet in Stanley shale.

It is probable that the known Ouachita section is underlain by a massive limestone comparable to the Arbuckle limestone or parts of it. If this be true, this limestone should not be excluded as a possible source. Recent shows[9], apparently not connected with faulting, have been found in the Arbuckle limestones, and Dr. Ham of the Oklahoma Geological Survey believes (personal communication) that the organic content of the Arbuckle group is sufficiently high to make them source beds.

The Mississippian Stanley shale may be a source, though it appears to be less favorable than the Ordovician shales. The Stanley contains quantities of dark and black shales, these being most prominent in the lower or Caney part of the sequence.

In the westernmost belt of the Oklahoma Ouachitas the Wapanucka and Chickachoc limestones (early Pennsylvanian) in some places emit an odor of petroleum, and zones are occasionally rich in blebs of gilsonite. The fact that these formations are exposed through erosion, as well as a consideration of the features of Belt I, makes them unfavorable.

Reservoir Rocks

Sandstones

There are a number of sandstones in the Ouachita section, the possibilities of which are discussed in ascending order.

Crystal Mountain sandstone (Ordovician): Provided a lower source is present, such as the Collier formation (Ordovician), and there is porosity, especially in the conglomeratic parts of this formation, this formation may provide a reservoir;

Blakely sandstone (Ordovician): This formation, higher in the section, is stratigraphically more favorably located. However, its areal distribution is limited, and it may not be present in a section as far west, for example, as Jumbo Valley;

Blaylock sandstone (Silurian): The comments on the Blakely equally apply here;

Stanley group (Mississippian): There are many sandstone members intercalated in this section. Individually rather thin, their aggregate thickness is considerable. Many of these sandstones appear very low in permeability and porosity inasmuch as they have an argillaceous admixture. In parts of the southern Ouachitas (e.g., south of the Potato Hills in the Kiamichi Valley) there is a thick and massive sandstone member in the lower part of the formation. This might be a favorable reservoir;

Jackfork group (early Pennsylvanian): This group contains great masses of sandstone. Some members are argillaceous and silty; others are rather pure. Although this group contains some potential reservoir rocks, these rocks must be ruled out in those structurally favorable areas where erosion has exposed the Stanley. Only in the smaller anticlines in Pattern IV and V areas would the Jackfork be a potential reservoir.

Fracture Reservoirs

The Bigfork chert (Ordovician) and the Arkansas novaculite (Devonian-Mississippian) are generally intensely fractured and intricately jointed, especially in anticlines. Numerous cross faults, caused by local secondary tensional stresses, have been produced along plunging anticlines. These minor faults probably enhance the reservoir properties of these rocks.

Of the two formations the Arkansas novaculite seems to be the more favorable. Its fracturing is generally more intense than that of the Bigfork chert, because of its larger proportion of brittle, pure cherts. Moreover, the novaculite occupies a more favorable structural position, being above the Polk Creek shale (Ordovician) which may be considered as one of the best potential source beds. The Bigfork chert could be a fracture reservoir only for hydrocarbons derived from middle and lower Ordovician shales and/or limestones.

Evaluation of Structural Patterns for Exploration

Pattern I: The Belt of Imbricate Faulting (Figure 2 and Plate I)

This structural pattern is not favorable for exploration. Fault traps might exist, but their presence cannot be affirmed. Some anticlines occur (Plate I), though they are subordinate to the tilted steep faults slices. Most of the anticlines plunge in one direction, the other direction usually being faulted. Such faulted, plunging anticlines might form fault traps. Only one doubly-plunging anticline with apparently satisfactory closure has been observed. This structure lies southwest of Hartshorne (Secs. 3, 4, and 9, T. 4 N., R. 17 E.). However, as with all of the other folds of this belt, it is small.

The Wapanucka-Chickachoc rocks of this belt are locally petroliferous. However, these rocks have been truncated by erosion, both in the faulted south and southeast dipping homoclines and in the tight folds. Thus, these formations are not promising.

Pattern II: The Belt of Tight Folding (Figure 2 and Plate I)

This pattern is represented in the broad belt of Pennsylvanian rocks of the northwestern Ouachitas. Comparable structural patterns, involving a large proportion of Mississippian rocks, probably occur in some parts of the southern Ouachitas, especially west of the Choctaw anticlinorium, and in Arkansas.

The tight folds of this area with their generally low plunges are complicated by tight minor folding. This makes difficult

[9]Frankfort #2 Williams, Sec. 12, T. 5 S., R. 2 W. (Oklahoma)

the location of axial highs with satisfactory closure. In some places faulting adds to the structural complexity.

The most favorable aspect of this belt in the northwestern Ouachitas is that erosion has not been as deep as in the other parts of the mountains. The major part of this area is underlain by Pennsylvanian sandstones of Jackfork and, in part, Atoka age. Mississippian rocks are exposed only in subordinate zones, usually along the large strike faults (Plate I). The great majority of the major anticlines, even in their structurally highest positions, are underlain by Jackfork. Thus, in these anticlines the entire pre-Pennsylvanian section would be preserved. The Jackfork might be considered as potential reservoir rock in areas of this pattern. However, the intense folding which is complicated by faulting, and the relatively small size of the structures make this pattern less desirable than others.

Pattern III: The Ouachita Anticlinoria (Figure 2 and Plate I)

All of the Choctaw anticlinorium and most of the Arkansas anticlinorium must be ruled out because of the dynamic metamorphism of the pre-Carboniferous argillaceous rocks. In the event the Jumbo well should encounter oil in the pre-Bigfork section, certain anticlines (e.g., the Albion anticline, Plate II) within the Potato Hills anticlinorium should be investigated.

Pattern IV: The Open Synclines and More Tightly Folded Anticlines (Figure 2 and Plate I)

The Pattern IV areas offer the best structural conditions for exploration in the Ouachitas. This is particularly true of that part of the Pattern IV area in the southwestern Oklahoma Ouachitas which extends from the Kiamichi Mountains to east of Atoka and Stringtown.

The major structures to be considered are the larger anticlines. Though most are relatively strongly compressed and have steep flanks, they display rather regular patterns. Complications by minor folds or faulting may not detract from, and may actually enhance, the closure of these folds (cf. the fault closure of the Jumbo anticline, Plates V, VI).

The widespread axial plunge of the Pattern IV folds and reversals of plunge along the strike produce axial culminations favorable to the accumulation of oil. These are best found by determining the position of the axial culminations and depressions in the broad synclines, and then determining whether these axial highs and lows continue into the adjacent anticlines. The lows usually do, but the highs often do not, owing to the complications arising from the diverging trends of the many anticlines which wrap around the oval-shaped synclines. However, these complications do not occur where major synclines contain secondary axial culminations within their middle portions. These centrally located culminations generally continue into the adjacent anticlines. It was on this basis that the axial high in the Jumbo anticline (Plates I, V, VI) was located. The method used at Jumbo and applied to other Pattern IV areas consists of photo-interpretation, elimination of those anticlinal areas which obviously do not contain highs with satisfactory closure, and then detailed field work in those areas which appear favorable.

A point of interest which applies to the Jumbo structure, as well as to all of the Pattern IV areas, is the probable structural pattern at depth. The complexity expected at depth beneath the anticlines is not expected beneath the broad open synclines. This means that the simple synclinal limbs probably maintain their homoclinal pattern at depth. This would permit an uninterrupted up-dip rise into the anticlines of possible hydrocarbons from vast areas of the adjacent synclines.

Locations made on the basis of axial highs on the anticlines will depend for potential production on the fracture and sandstone reservoirs previously discussed. Faults might not detract materially from the favorable character of axial highs. Part of the closure on the Jumbo anticline is suggested as being formed by a major strike fault (Plate VI).

A second type of structure found within the Pattern IV areas appears less promising than the major anticlines. This type is represented by the smaller anticlines in Jackfork rocks which occur at those few localities where the Jackfork rocks have been more tightly folded (Plate I). These anticlines are small, relatively narrow, and often are bordered by narrow and strongly compressed synclines of Jackfork rocks. Thus these anticlines would not be associated with the rather gently dipping homoclinal limbs of synclines up which hydrocarbons might have migrated from large areas. The one advantage of these smaller anticlines would be the presence of a fully-preserved Stanley section beneath the Jackfork rocks. Exploration based on the assumption that the Stanley group might include source beds should look for locations on these smaller anticlines. The Potapo Mountain anticline (Plate IV), lying between the Lane and Pine Springs synclines, is in large part underlain by Jackfork rocks. Though the Jackfork has been breached at the axial culmination, all but a few hundred feet of the Stanley section is preserved.

Pattern V: The Faulted Belt North of the Pattern IV Area (Figure 2 and Plate I)

The main difference between this belt and the Pattern IV areas is the complication caused by a large number of steep, reverse, strike faults.

This belt is less favorable structurally than the typical Pattern IV areas south of it. However, complete folds occur in addition to tilted fault blocks, and anticlinal highs might be found (e.g., Bald Mountain anticline, Plate III). This applies in particular to parts of the western half of this belt. In the eastern part there is apparently a rather uniform plunge away from the Potato Hills anticlinorium which lessens the possibility that axial highs with closure exist.

Fault traps might occur in this belt. They would most likely occur where homoclines of Stanley rocks run into steep strike faults, the downthrown side being on the north. If there are potential reservoir rocks beneath the Stanley rocks of the anticlines of Pattern IV, these should occur also beneath these homoclines. However, the degree of fracturing of the Arkansas novaculite and Bigfork chert in these homoclines is not known. Some fracturing is undoubtedly present, but it is questionable whether the fracturing of these two cherty formations within homoclinal sequences would be as intense as that displayed in plunging anticlines. The secondary local tensional stress caused by plunging in the anticlinal folds, which may have improved the reservoir properties of these two formations, has certainly not occurred in uniformly dipping homoclines. The possible source rocks should be the same as those beneath the Stanley rocks of the anticlines of Pattern IV. There also would be broad areas from which hydrocarbons might have migrated up-dip toward the faults which terminated these homoclines on the north. At Redden oil field this up-dip migration of oil has been checked by an asphalt seal of the outcropping heavy sandstones.