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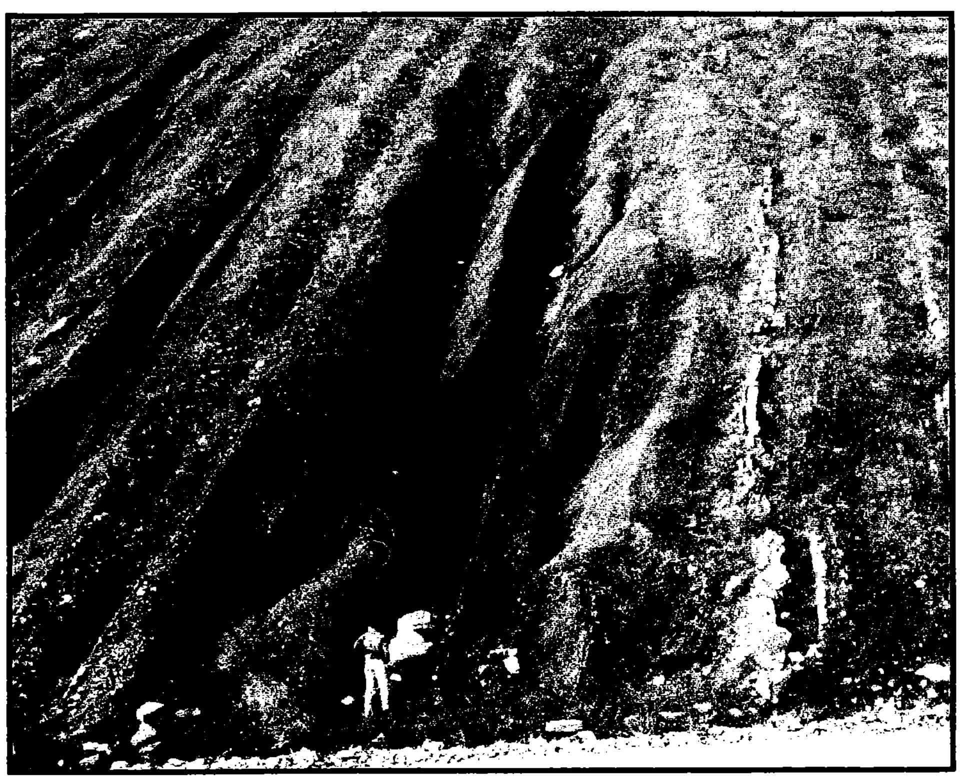
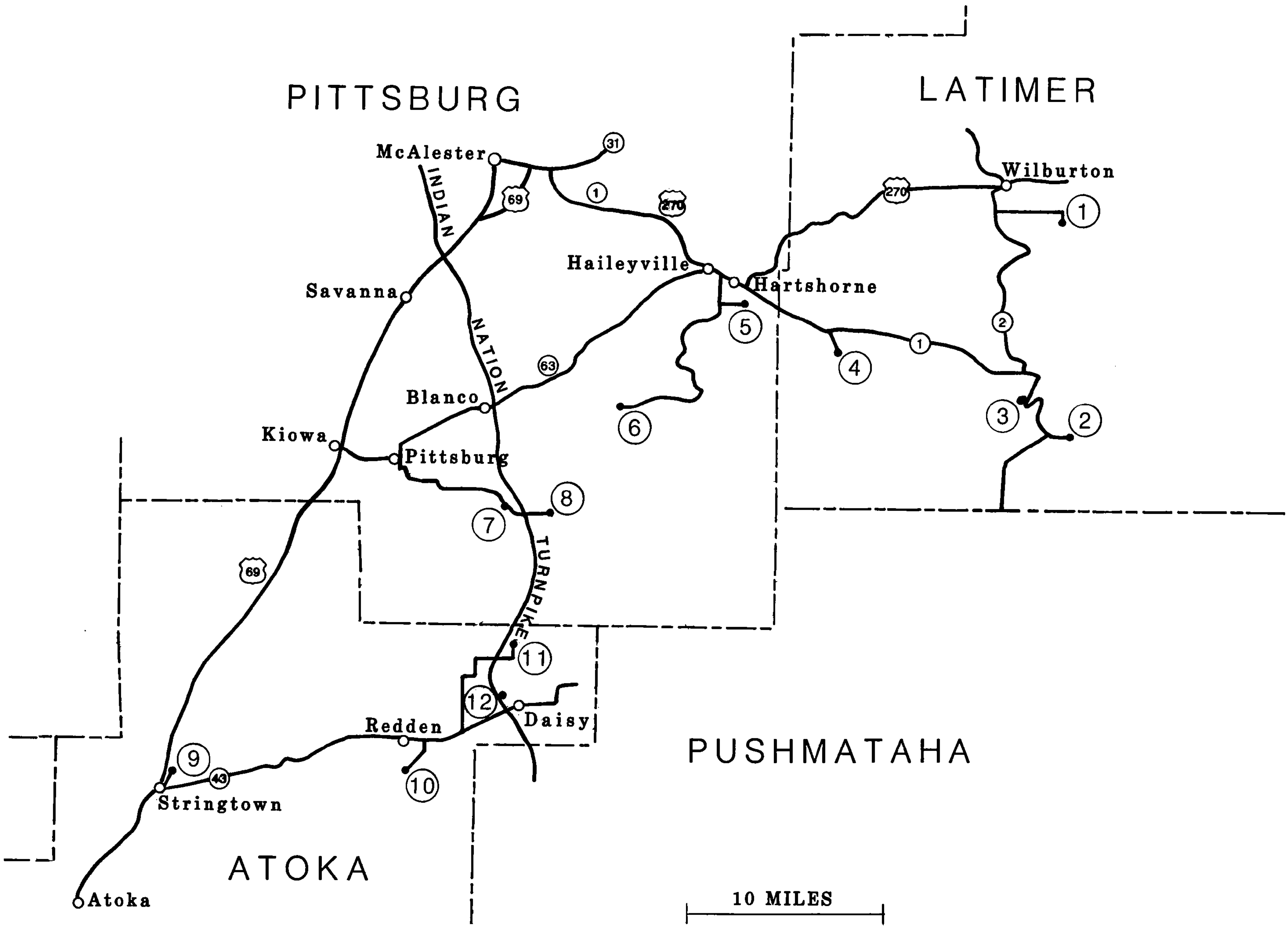
Geology and Resources of the Frontal Belt of the Western Ouachita Mountains, Oklahoma





MAP SHOWING LOCATION OF FIELD-TRIP ROUTE AND STOPS

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GEOLOGY AND RESOURCES OF THE FRONTAL BELT OF THE WESTERN OUACHITA MOUNTAINS, OKLAHOMA

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Guidebook for Field Trip No. 2, September 27–28, 1989, American Association of Petroleum Geologists, Mid-Continent Section Meeting, Oklahoma City, Oklahoma.

Oklahoma Geological Survey
Charles J. Mankin, *Director*
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Norman, Oklahoma

1990

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Front Cover

The thickest and most continuous exposure of the Atoka Formation in the Oklahoma Ouachita Mountains, Stop 7 of this guidebook, is along the Indian Nation Turnpike near Brushy Narrows. Although most of the Atoka Formation is believed to be deep-water turbidites, sedimentary structures in some sandstones in the frontal belt indicate a shallow-water environment of deposition.

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PREFACE

The first geologic map of any part of the Oklahoma Ouachita Mountains was published in 1902 by J. A. Taff. Since that time, the Ouachita Mountains have proved to be a fertile field for many lines of geologic research, both academic and energy-related. Among the most productive and insightful Ouachita geologists was T. A. Hendricks, who, with co-workers, was responsible for the first modern geologic map of the western part of the frontal belt (Hendricks and others, 1947). Day Two of this field trip is based largely on his excellent map.

Day One of this trip is mostly within the Wilburton, Damon, and Higgins 7.5′ Quadrangles; the geology of these areas has recently been mapped by Suneson and Ferguson (1989a,b) and Hemish and others (in prep.). This mapping was funded by the Oklahoma Geological Survey and the U.S. Geological Survey as part of the USGS COGEOMAP (Cooperative Geologic Mapping) program. The Ouachita project is a joint effort of the OGS, USGS, and the Arkansas Geological Commission to complete new, detailed surface geologic maps of the Ouachita Mountains in southeastern Oklahoma and western Arkansas.

Much of the well data in reports by OGS personnel is from a computerized file of oil and gas wells based on Oklahoma Corporation Commission Form 1002A. Initial funding for establishing this computerized data file was from the USGS as part of the COGEOMAP program; continued funding for the NRIS (Natural Resources Information System) activities has been through the U.S. Department of Energy, Bartlesville Project Office.

Inspiration for our interest in Ouachita hydrocarbons has come from Dr. Robert O. Fay of the Oklahoma Geological Survey. While much has been written on the Arkoma basin and frontal Ouachita gas fields, Dr. Fay is solely responsible for continually reminding the geological community that oil is produced in the Ouachitas (Fay, 1976,1984,1985). Dr. Fay is also responsible for compiling the best regional geologic map of the entire Oklahoma part of the Ouachita Mountains (Marcher and Bergman, 1983), and he is currently compiling a bibliography of Ouachita geology that will include more than 3,000 references.

Several recent studies of different aspects of frontal-belt geology are reported as field-trip stops and separate papers. This guidebook has benefited greatly from these contributions from industry, academic, and government geologists. While we have shown ourselves to be the editors of this guidebook, we are, more properly, merely facilitators and co-contributors. We decided at the outset to do as little "real" editing as possible. As a result, the ideas presented are entirely those of the author(s). Differences in stratigraphy, nomenclature, age assignments, etc. occur in places in the guidebook and reflect our view that such differences lead to discussion, which leads to testing, which leads to progress in understanding the geology of the frontal belt.

This field trip would not be possible without the permission local landowners have kindly given us to look at the rocks on their land. Mrs. JoAnne Smith has allowed us to visit the Spiro outcrop at the Slawson 1-24 Smith well site (Stop 1). Mr. Orin Harrington, Superintendent, Buffalo Valley School, gave us permission to examine the rocks at the school (Stop 2) and have lunch there. The Dolese Brothers Company has permitted us to visit their Hartshorne quarry operations in the Wapanucka Limestone near Hartshorne (Stop 5). Mr. W. A. Muse, Superintendent, Stringtown Quarry, gave us access to the Bigfork Chert there (Stop 9). Mr. L. C. Butler gave us permission to visit the tar sands and wells in the Redden oil field (Stop 10). And Mr. Earl Waldrop permitted us to visit and collect grahamite at the Waldrop deposit (Stop 11).

NEIL H. SUNESON, JOCK A. CAMPBELL,
AND MAXWELL J. TILFORD
Editors

CONTENTS

Part 2 — Contributed Papers

GEOLOGIC SETTING AND INTRODUCTION

Neil H. Suneson and Jock A. Campbell
Oklahoma Geological Survey
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The Ouachita Mountains in southeastern Oklahoma and western Arkansas are a late Paleozoic fold and thrust belt. The most common rock types in the Oklahoma Ouachita Mountains are sandstone and shale; Mississippian and Pennsylvanian turbidites dominate the stratigraphic section at the surface. Slightly metamorphosed to unmetamorphosed, mostly pre-Mississippian chert, shale, and minor limestone and sandstone crop out in the Broken Bow uplift, Potato Hills, and Black Knob Ridge areas (Fig. 1). Late Mississippian and Early Pennsylvanian shale, limestone, and sandstone crop out along the northern and western border of the mountains.

In Oklahoma, the Ouachita Mountains can be separated into three belts based on stratigraphy and structural style (Fig. 1). From north to south, these are the frontal belt, central belt, and Broken Bow uplift. The frontal belt lies between the Choctaw and Windingstair faults and consists of steeply tilted, imbricately thrusted, and tightly folded strata. Shallow-water Morrowan strata are present in the northern part of the frontal belt, and Morrowan basinal strata (turbidites and olistostromes) occur to the south. The Morrowan units in both parts of the frontal belt are overlain by Atokan turbidites. In the extreme western part of the frontal belt, Ordovician to Mississippian strata crop out near Black Knob Ridge.

The central belt is characterized by broad, open synclines, separated by tight, typically thrust-cored anticlines. Except for the tightly folded pre-Mississippian units in the Potato Hills, the only rocks exposed are Mississippian and Early Pennsylvanian turbidites. The Broken Bow uplift consists of isoclinally folded and thrusted Early Ordovician to Early Mississippian deep-water strata. The boundary between the central belt and the Broken Bow uplift is arbitrarily shown on Figure 1 as the contact between the Arkansas Novaculite and Stanley Group sediments.

The general stratigraphy of the Oklahoma Ouachita Mountains is relatively well known (Fig. 2). Prior to the compressional tectonism that resulted in the fold and thrust belt, Early Ordovician to Early Mississippian deep-water sediments ("Ouachita" facies) accumulated in a starved basin south of the southern margin of the North American craton at the same time as shallow-water clastics and carbonates ("Arbuckle" or "Foreland" facies) accumulated in a shelf environment to the north. Early and mid-Paleozoic shelf strata underlie the Arkoma basin immediately north of the Ouachita Mountains, and most, if not all, of the frontal belt. Exposed "Ouachita" facies strata in the frontal belt (Black Knob Ridge) and central belt (Potato Hills) are allochthonous; they occur in thrust sheets that overlie Morrowan strata.

Thick Carboniferous turbidites accumulated in a south-to-north migrating basin at the same time as thinner, shallow-water sediments were deposited on the shelf to the north. The facies change from deep- to shallow-water strata migrated from south to north with time, as shown by the slightly different stratigraphy in each major thrust sheet in the frontal belt (Hendricks and others, 1947).

Stratigraphic nomenclature in the frontal belt has been, and will probably continue to be, controversial. We have attempted to conform to current nomenclatural practices, realizing that, in many cases, "proper" usage conflicts with "locally accepted" usage. Units (surface and subsurface) that are formally defined in the literature are capitalized (e.g., Atoka Formation, Cromwell Sandstone). Informal but widely recognized units are shown lowercase (e.g., lower Atoka shale, Red Oak sandstone). The Spiro sandstone as used in this report conforms to petroleum-industry usage and refers to the widespread sandstone at the base of the Atoka Formation. (The Spiro Sandstone was originally defined as a member of the Desmoinesian Savanna Formation in the northern part of the Arkoma basin, but this usage is rare.) The "Springer" Formation is used throughout the road log as the shale below the Wapanucka Limestone, following Hendricks and others (1947). Geologists in the petroleum industry typically refer to the strata between the Wapanucka Formation and Cromwell sandstone as Morrow or Wapanucka shale. This unit is equivalent to the Union Valley Formation on Figure 2 and the name "Springer" is put in quotation marks because its age and correlation to its type section to the west are controversial.

The first explorers for hydrocarbons in the Ouachita Mountains of Oklahoma were probably early Native Americans who used solid hydrocarbons ("asphaltites") as adhesives to bind stone arrowheads to wooden shafts. Early white explorers in the Ouachitas referred to outcrops of "coal" (probably asphaltite) in their journals. The first development of hydrocarbon resources occurred in the late nineteenth and early twentieth centuries, when some of the asphaltite deposits were mined underground. The asphaltite from these mines was used in forges and to heat homes and was generally considered to be a very "hot-burning" form of coal. The first successful oil well in the Ouachitas was drilled in 1914 near what later became known as the Redden field. Since that time, almost 800 oil and gas wells have been drilled in the Ouachita Mountains in Oklahoma, and as of the end of 1988 parts or all of 22 oil and gas fields are within the Ouachita Mountains (Fig. 3). South of the Windingstair fault, the region remains virtually unexplored, with only about one 10,000-ft-deep well per 225 mi^2.

This field trip will focus on the structure, stratigraphy, and hydrocarbon occurrences and resources in the central and western parts of the frontal belt in the Oklahoma Ouachita Mountains. We will consider the trip a success if we raise more questions than we answer and cause geologists to pursue productive lines of research and exploration based on those questions.

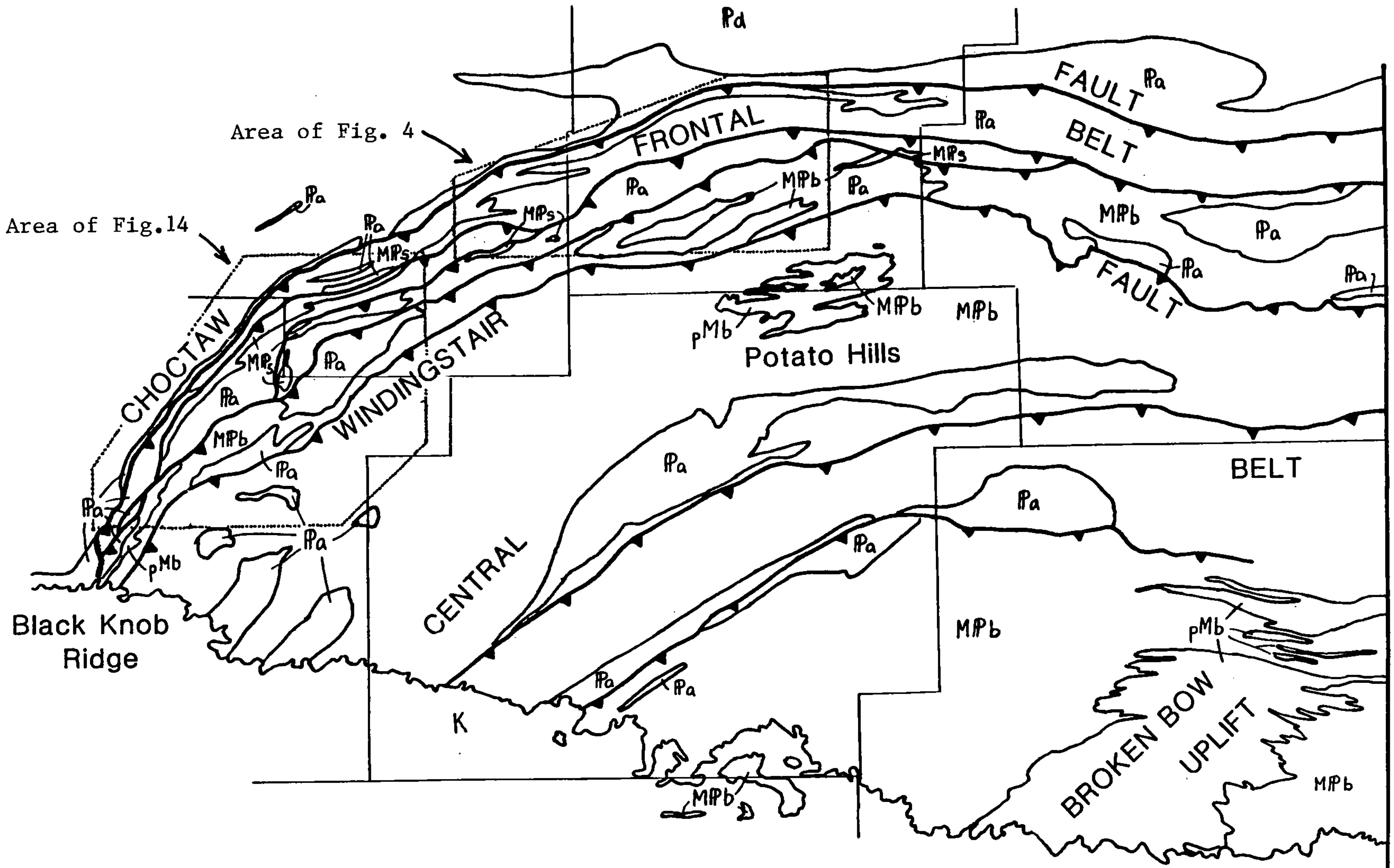


Figure 1. Generalized geologic map of Oklahoma Ouachita Mountains showing areas to be visited during field trip (dotted outlines).
Symbols: Pd = Desmoinesian clastics of Arkoma basin
Pa = Atoka Formation
MPs = Mississippian and early Pennsylvanian shelf strata
MPb = Mississippian and early Pennsylvanian turbidites
pMb = pre-Mississippian deep-water strata

	SERIES	ARKOMA BASIN			OUACHITA MOUNTAINS
PENNSYLVANIAN	Desmoinesian	Krebs Gp.	Boggy Fm.	₽bg	
			Savanna Fm.	₽sv	
			McAlester Fm.	₽ma	
			Hartshorne Fm. Upper / Lower	₽hs	
	Atokan	Atoka Fm.		₽a	Atoka Formation
	Morrowan	Wapanucka Ls.		₽m	Johns Valley Shale
		Union Valley Ls. Cromwell ss.			Jackfork Group
MISSISSIPPIAN	Chesterian	"Caney" Sh.		MD	Stanley Shale
	Meramecian				
	Osagean				Arkansas Novaculite
	Kinderhookian				
DEVONIAN	Upper	Woodford Sh.			
	Lower	Hunton Gp.	Frisco Ls. Bois d'Arc Ls. Haragan Ls.	DSOhs	Pinetop Chert
SILURIAN	Upper		Henryhouse Fm.		Missouri Mountain Shale
	Lower		Chimneyhill Subgroup		Blaylock Sandstone
ORDOVICIAN	Upper	Sylvan Sh.			Polk Creek Shale
		Viola Gp.	Welling Fm. Viola Springs Fm.	Ovs	Bigfork Chert
	Middle	Simpson Gp.	Bromide Fm. Tulip Creek Fm. McLish Fm. Oil Creek Fm. Joins Fm.		Womble Shale Blakely Sandstone
	Lower	Arbuckle Gp.	West Spring Creek Fm. Kindblade Fm. Cool Creek Fm. McKenzie Hill Fm. Butterly Dol.	OЄa	Mazarn Shale Crystal Mountain Ss. Collier Shale
CAMBRIAN	Upper		Signal Mountain Ls. Royer Dol. Fort Sill Ls.		? ?
		Timbered Hills Gp.	Honey Creek Ls. Reagan Ss.		
PRECAMBRIAN		Granite and rhyolite		pЄ	

Figure 2. Stratigraphic chart for the Ouachita Mountains in the field-trip area (from Johnson, 1988). The stratigraphy in parts of the northern frontal belt is similar to that in the Arkoma basin. Informal names (e.g., Spiro sandstone) not shown on this chart are described in text.

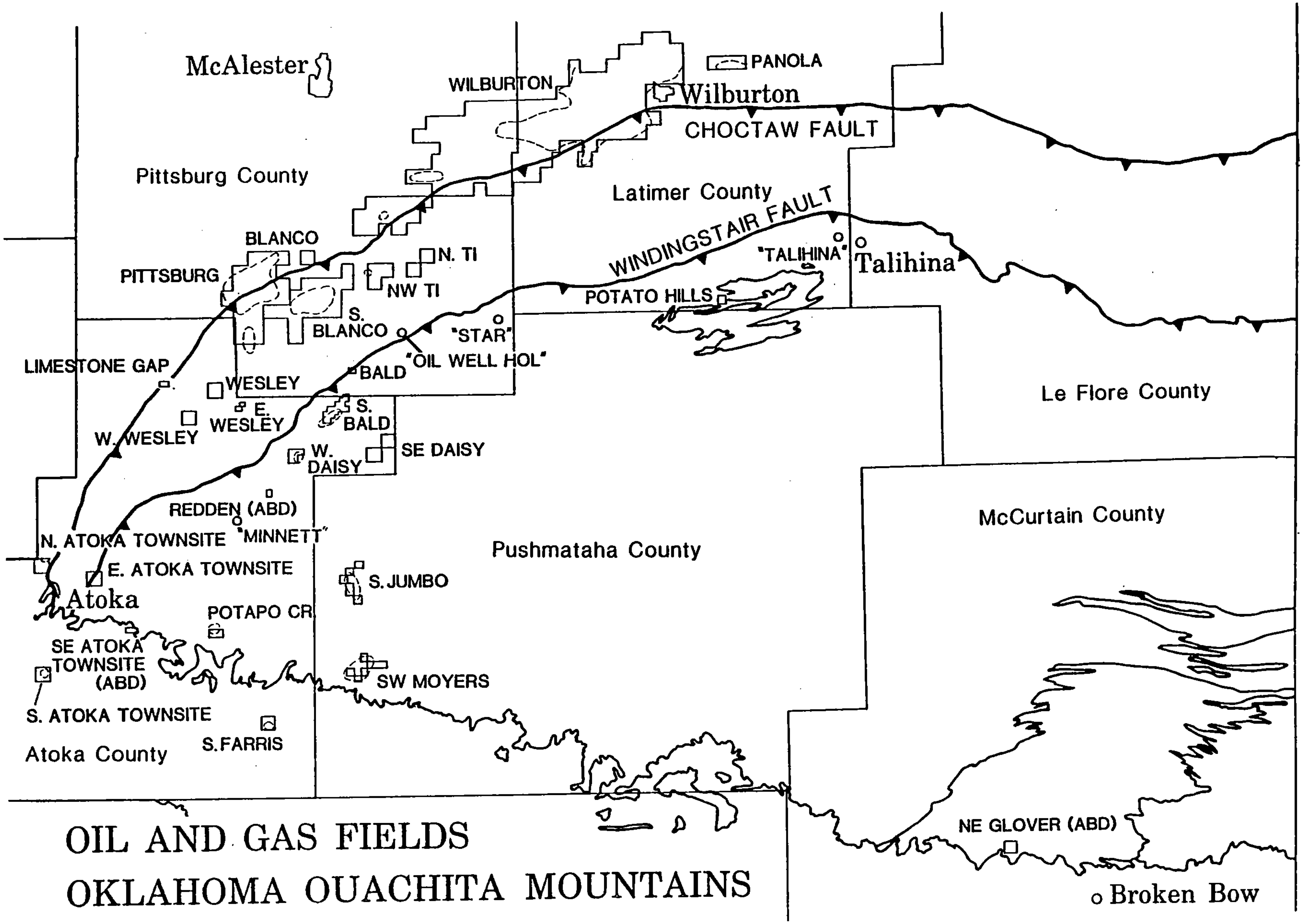


Figure 3. Map showing oil and gas fields in Oklahoma Ouachita Mountains as currently recognized by the Nomenclature Committee of the Mid-Continent Oil and Gas Association. Dashed lines are field outlines of Burchfield (1985). Names in quotation marks (" ") are informal names of small fields or single-well fields.

Part 1

Road Logs
and
Stop Descriptions

ROAD LOG—DAY ONE

Figure 4 is a generalized geologic map showing field-trip stops for Day One.

0.0 (0.0) Start field trip road log at intersection of U.S. Highway 270 and Oklahoma Highway 2, just west of downtown Wilburton. The highway intersection is located at the center of the north line of sec. 17, T. 5 N., R. 19 E.

Drive south on Oklahoma Highway 2.

WILBURTON GAS FIELD

The Wilburton gas field consists of 173 mi^2 in parts of T. 4 N., R. 16–18 E.; T. 5 N., R. 16–19 E.; and T. 6 N., R. 18–19 E. (Fig. 3). The field, as now defined by the Oklahoma Nomenclature Committee of the Mid-Continent Oil and Gas Association, includes the old Hartshorne field to the west. New drilling is extending the field east toward the Panola gas field, south into the Ouachita Mountains, and west toward the Pittsburg and South Blanco fields (Fig. 5). The principal producing formation is the Spiro sandstone, which is also known as the basal Atoka sandstone. Other producing formations in the field are sandstones higher in the Atoka Formation (especially in the eastern and western parts of the field), the Wapanucka Limestone, and the Cromwell Sandstone (basal Pennsylvanian sandstone). Total production from the Wilburton field through 1987 is 1,095 Bcfg. The best, though now dated, published summary of the Wilburton gas field is Berry and Trumbly (1968).

The first well drilled in the Wilburton field was the Limestone Oil and Gas No. 1 Nettie McCurray (SW 1/4 SW 1/4 SW 1/4 sec. 15, T. 5 N., R. 15 E., about 4.5 mi west of the county road intersection on which the trip will be turning east). It was spudded on May 12, 1927, and drilling finished on December 9, 1929, at 4,038 ft TD. The drillers log shows mostly slate (sic), shale, and sandy lime to TD, with some oil shows and gas starting at 1,075 ft. Production of 2 MMcfgd was from a gray sand at 2,518 to 2,548 ft (Hendricks, 1937).

The discovery well for the Wilburton field as recognized by the Nomenclature Committee was drilled much later and is actually a deeper pay discovery. It is the Ambassador Oil Corp. No. 1 W. M. Williams Unit. It is located in NW 1/4 NW 1/4 sec. 23, T. 5 N., R. 18 E. about 3.5 mi west of the same county-road intersection noted above. It spudded on September 21, 1960, and drilling finished on November 11, 1960, at 9,704 ft TD. It was completed on December 15, 1960, in the Spiro sandstone at 8,811 to 8,831 ft, with an open-flow potential of 8.3 MMcfgd.

The "unofficial" discovery well of the "Wilburton Deep" field is the ARCO No. 2 Yourman located in the S 1/2 S 1/2 NW 1/4 sec. 15, T. 5 N., R. 18 E., about 4.25 mi west of the intersection of highways U.S. 270 and State 2 and about 0.5 mi north of the Limestone No. 1 Nettie McCurray. It spudded on February 8, 1987, and reached a total depth of 15,391 ft on June 25, 1987. Reported perforations were in Arbuckle Group carbonates at 14,259 to 14,500 ft with an open-flow potential of 73 MMcfgd and an initial-flow potential of 9.3 MMcfgd and 128 bwpd. The well produced 275 MMcfg in January 1988. The confirmation well for the ARCO discovery was the ARCO 2 Steve Fazekas, located in the SE 1/4 NW 1/4 SE 1/4 sec. 17, T. 5 N., R. 18 E. This well had an open-flow potential of 142 MMcfgd and an initial-flow potential of 34.5 MMcfgd from Arbuckle perfs. Published reserves estimates for the "Wilburton Deep" field are 500 to 600 Bcfg, based on the first four wells (Petroleum Information, 1988). Private reserves estimates were as high as 3 Tcfg at that time.

It is generally recognized that the "Wilburton Deep" reservoir is not simply a deeper pool; it is a separate structural trap that is only indirectly related to the shallower reservoirs.

1.0 (1.0) County road intersection. Turn left (east) and drive along front of Ouachita Mountains.

INTRODUCTION TO THE OUACHITA MOUNTAINS

The leading thrust fault of the Ouachita fold and thrust belt is the Choctaw fault, the surface trace of which is about 0.75 mi north (left) of the road. Here, the Choctaw fault juxtaposes N-facing, steeply N-dipping to S-dipping (overturned) lower(?) Atoka Formation against N-facing, moderately N-dipping upper Atoka Formation. The trace of the Choctaw fault is difficult to locate precisely because outcrops are rare and it juxtaposes different parts of the same Atoka Formation, which is dominantly shale in this area.

Two fault splays from the Choctaw fault are present south (right) of the road. The southernmost splay is at the base of Limestone Ridge, which forms the skyline; the northernmost is just south of the road and juxtaposes Atoka Formation to the north against lower Atoka shale or small slices of Wapanucka Limestone and Spiro sandstone to the south. Stop 1 is at one of these small slices of Spiro sandstone.

3.8 (4.8) Stop 1, Spiro Sandstone and Structural Style of the Wilburton Area. Location: SE 1/4 NW 1/4 NW 1/4 sec. 24, T. 5 N., R. 19 E.

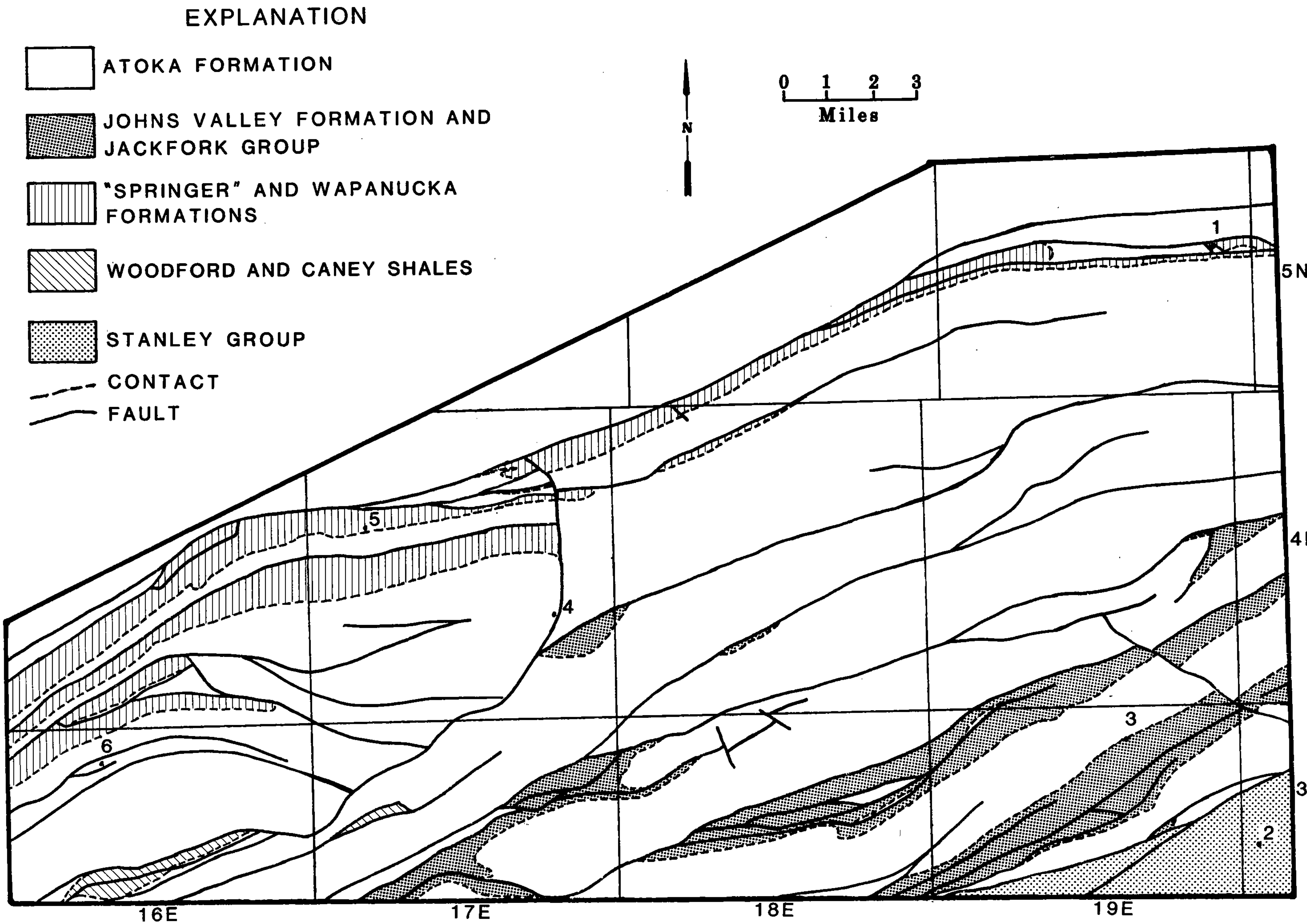


Figure 4. Generalized geologic map showing field-trip stops on Day One.

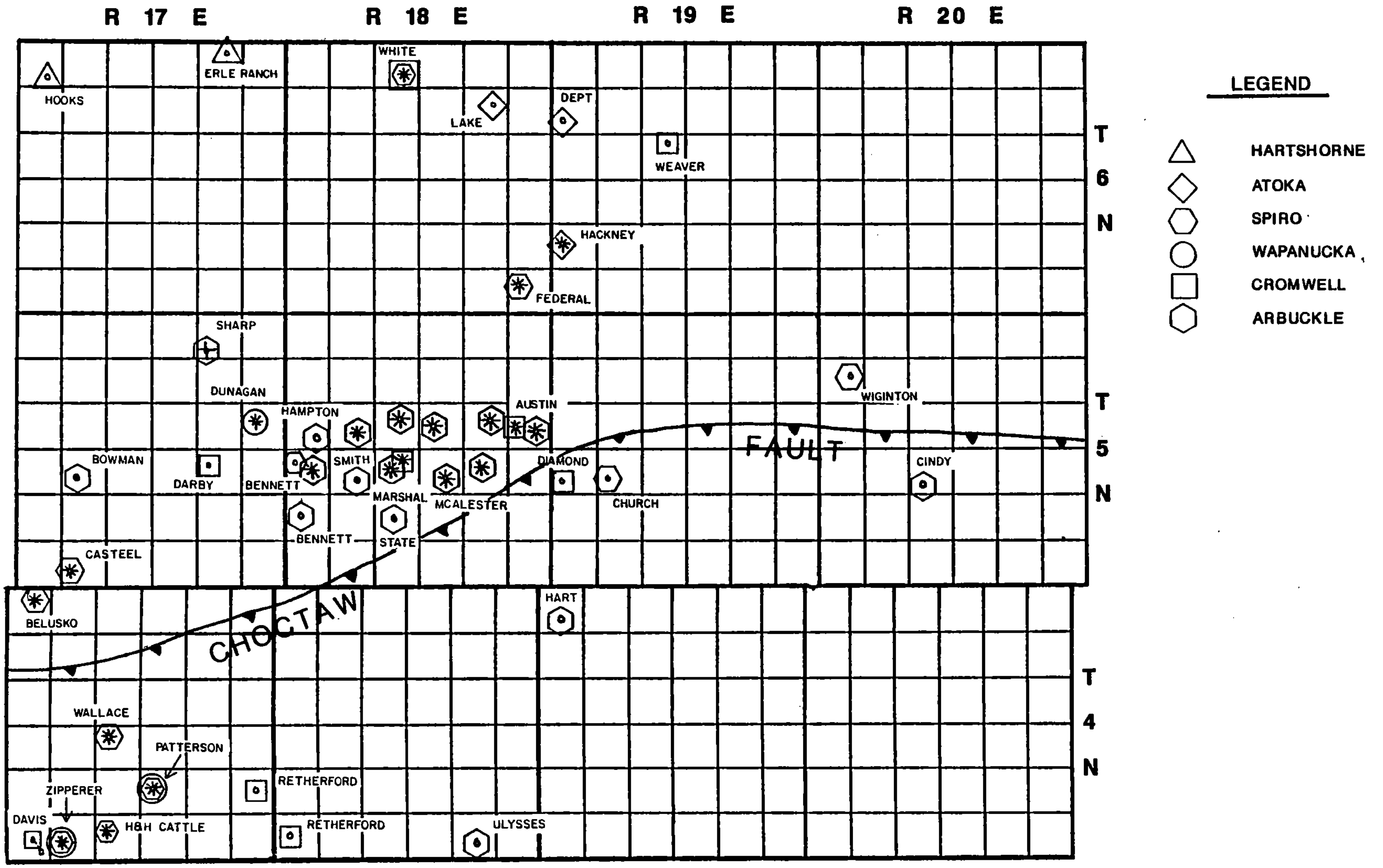


Figure 5. Map showing recent wells south of Wilburton gas field. Open circle inside symbol indicates well is permitted, drilling, testing, or no report (as of September 1, 1989).

STOP 1A
SPIRO SANDSTONE

Neil H. Suneson
Oklahoma Geological Survey

The Spiro sandstone is exposed at the drill pad of Donald C. Slawson 1-24 Smith. This well was spudded on August 26, 1984, and reached total depth on October 26, 1984, at 12,180 ft. Reported tops are Red Oak at 8,666 ft (–7,791 ft), Panola at 9,146 ft (–8,271 ft), Four-Finger at 9,989 ft (–9,114 ft), and Bullard at 11,329 ft (–10,454 ft). The well was dry and subsequently abandoned.

The Spiro sandstone at Stop 1 is exposed in a relatively thin thrust sheet south of the trace of the Choctaw fault and north of Limestone Ridge (Fig. 6). About 1 mi north of Stop 1, the Choctaw fault juxtaposes upper Atoka Formation in the footwall to the north against middle(?) Atoka Formation in the hanging wall to the south. Immediately north of Stop 1, a thrust fault that is probably a splay off the Choctaw fault juxtaposes this Spiro outcrop in the hanging wall against Atoka Formation in the footwall. Another thrust in the slope immediately to the south juxtaposes hanging-wall Spiro/Wapanucka on Limestone Ridge against footwall lower Atoka shale exposed on the south side of the drill pad. This outcrop is not the overturned limb of the Bandy Creek anticline as shown by Bowsher and Johnson (1968) and Marcher and Bergman (1983), because the Spiro here and on Limestone Ridge both face south.

Here, the Spiro sandstone is relatively quartzose, fine- to medium-grained, and poorly to well cemented with silica. Beds vary from 0.5 in. to 2 ft thick; most are parallel-planar stratified, but some are trough cross-stratified on a scale of about 0.5 to 2 ft. Stratification is marked by a variation in grain size, color, and fossil content—some beds have a very porous or "spongy" texture caused by preferential weathering of fossil fragments. Locally, molds of crinoids, brachiopods, and stems and limbs of plants are preserved. Trace fossils, especially worm burrows, are preserved on the bottoms of some of the sandstone beds.

The Spiro sandstone has been described in the Arkoma basin to the north by Lumsden and others (1971) and Houseknecht (1986,1987). They describe the Spiro sandstone as fine- to medium-grained, moderately to very well sorted, and composed of subequant to equant, rounded to well-rounded quartz grains (more than 95%). Sedimentary structures include uni- and bidirectional cross-bedding, ripple marks, and bioturbation structures. Lumsden and others (1971) separated the underlying Foster sand from the Spiro, but suggested that the NW-trending Foster channels in the central part of the Arkoma basin were eroded into the underlying Wapanucka Limestone at the same time as the Spiro sand was being deposited in a shallow marine environment in the southern part of the basin. Houseknecht (1986,1987) recognized "fluvially dominated channel deposits" within the Spiro. Both authors suggested that the Spiro was also deposited in other shallow-water environments, including beach, offshore bar, tidal flat, tidal channel, and lagoonal.

Grayson (1980) described the Spiro sandstone (his upper sandstone/limestone member of the Wapanucka Formation) from outcrop exposures in the Ouachita Mountains frontal belt. In this area, the Spiro consists of "a complex intertonguing quartz sandstone and carbonate sequence" (p. 59) and is composed of about 46% quartz sandstone, 16% spicular limestone, 16% shale (and covered intervals), 13% micritic limestone, and 9% bioclastic limestone (p. 46). The quartz sandstone and bioclastic limestone show evidence of current transport: tabular cross laminations generally dip 5–15° degrees S, tabular sets 2–4 ft thick have sharp bases, and ripple marks are locally preserved. *In situ* mold fauna in the quartz sandstone of the Spiro indicates that it was deposited in a marine environment. In outcrop, the Spiro thickens southward (basinward) from about 5 to 160 ft, mostly due to increased volume of quartz sandstone. Grayson (1980, p. 103) interpreted the tabular cross-bedded quartz sandstone to have accumulated as a system of linear offshore bars.

Based on the sedimentary structures and hand-lens petrography in this outcrop, in what environment was this Spiro deposited?

Overlying the Spiro sandstone in the exposure on the north side of the drill pad are two discontinuous outcrops of (1) coarse, crinoidal, bioclastic limestone, (2) medium-grained, bioclastic limestone, (3) calcareous siltstone, and (4) calcareous sandstone. These outcrops are similar to certain rock types in the Wapanucka Limestone. The eastern outcrop near the middle of the exposure contains slickensides. While the details of the structural relations are unclear, the limestone is probably nearly in place and shows that, in this part of the Ouachitas frontal belt, calcareous strata similar to the Wapanucka locally overlie the Spiro. This relation is clearly demonstrated at several places on Limestone Ridge.

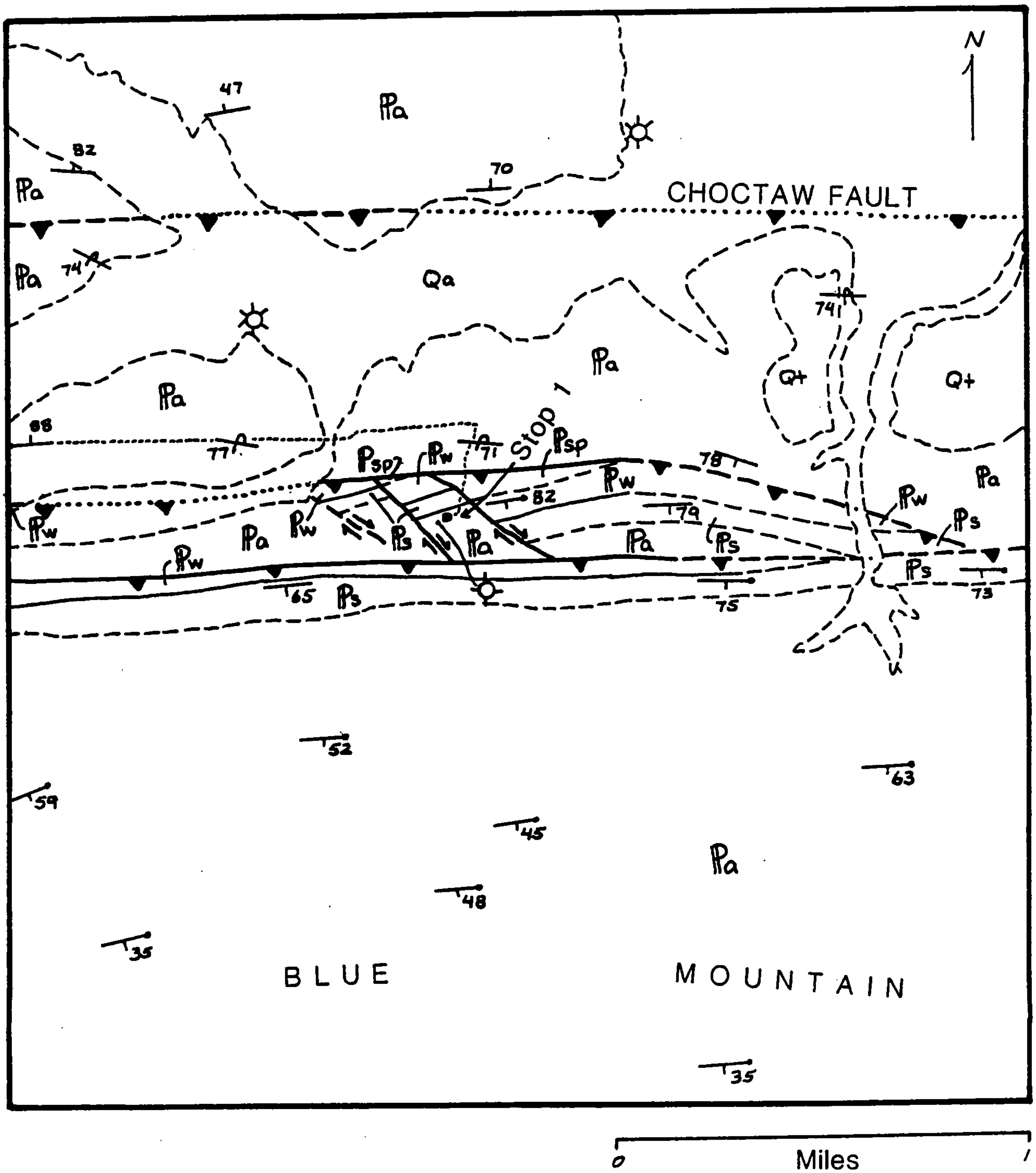


Figure 6. Geologic map of area near Stop 1. Relations described in text. Symbols: field-trip route; thrust fault; "tear" fault; formation contacts; attitude of bedding, facing direction unknown; attitude of bedding, beds upright; attitude of bedding, beds overturned; Psp = "Springer" Formation; Pw = Wapanucka Formation (dominantly limestone); Ps = Spiro sandstone; Pa = Atoka Formation; Qt = terrace gravels; Qa = alluvium.

STOP 1B
STRUCTURAL STYLE OF WILBURTON AREA

Allen J. Bertagne and Tim C. Leising
CGG American Services, Inc.

INTRODUCTION

With the recent improvements in acquisition and processing techniques, seismic data can now provide considerable insight into the geology of the Arkoma basin and Ouachita thrust belt. The objective of this paper is to describe the structural style of the Wilburton area as interpreted from recent seismic data.

SEISMIC ACQUISITION, PROCESSING, AND DATA QUALITY

Modern data are acquired with a dynamite source, a large number of recording channels, and closely spaced geophone groups. Data quality is best north of the Choctaw fault, where the structure is simpler. It is more difficult to image the complex structure south of the Choctaw fault, and care is needed to minimize aliasing (i.e., incorrect imaging of steep beds due to inadequate lateral sampling).

The most important step in the processing sequence is arguably the migration, where an attempt is made to "focus" the seismic image. Improper selection of migration velocities can change the appearance of a structure, and it is possible to make or break propects depending on the velocity selected! Bertagne and Leising (1989) discussed these topics in more detail.

STRUCTURE

Few of the published papers on the Ouachitas are based on seismic data. An important exception is the paper by Milliken (1988), which includes a balanced cross section of the Ouachitas.

Figure 7 summarizes the structural style of the Wilburton area, based on interpretation of more than 100 mi of recent seismic data. Four distinct tectonic "packages," or units, are identified and described below. Seismic data which support this interpretation were presented by Bertagne and Leising (1989).

Unit 1: Broad Synclines/Tight Anticlines

These folds are observed north of the Choctaw fault, at the surface (Marcher and Bergman, 1983), and on seismic data. The seismic events from the synclines are continuous, whereas the surface anticlines are underlain by upward-pointing triangle zones which lack coherent reflections. Although interpretation of these triangle zones is difficult, they are inferred to consist of a series of N-vergent faults overlain by a backthrust.

Unit 1 is composed of Atokan and younger sediments. The lower boundary is a décollement near the base of the Atokan. The depth to this décollement decreases toward the north.

Unit 2: Steeply Dipping Beds Above Choctaw Fault

The Choctaw fault marks the base of Unit 2 and is listric. It does not generate a seismic event as it juxtaposes rocks of similar velocities.

Seismic data from above the Choctaw fault exhibit steep, S-dipping events. The top of the Wapanucka generates a strong reflection and can be readily identified even in highly deformed areas.

The average dip of the first Wapanucka above the Choctaw fault decreases with increasing depth. It can be easily traced from the near-surface to the point where it flattens out (even if faulted).

A key to interpreting this complex area is to use the strong reflection events, the surface geology, and well data as a "skeleton" and to hang the rest of the interpretation on it.

Unit 3: Thrusted Spiro/Wapanucka/Cromwell Strata Beneath and North of the Choctaw Fault

The top of this unit is the same décollement which marks the base of Unit 1. The base of Unit 3 is a décollement near the basal Springer shale.

The top of the Wapanucka also generates a strong seismic event beneath the Choctaw fault. In a regional sense, it dips to the south, but is disrupted by N-vergent thrusts which elevate beds of the hanging wall and cause repetition of stratigraphic intervals. These thrusted structures have no direct relation to near-surface structure. They become rarer to the north.

The thrusted structures were the targets of early drilling in the Wilburton field (Berry and Trumbly, 1968) and are now being pursued farther south and west, beneath the Choctaw fault.

Unit 4: Deep Fault Blocks

Seismic data show deep structural blocks bounded by near-vertical faults. They offset lower Atokan through Precambrian units. The faults are more commonly (but not exclusively) down-to-the-south. Although the fault blocks have no direct relationship to the shallower structure, they influenced the location of later thrust ramps.

The faults are probably Atokan "growth" faults (Buchanan and Johnson, 1968) that have been modified in the later compressional phase. Long, regional seismic lines suggest that the growth faulting was active much earlier than has been documented to date, possibly as early as Arbuckle time.

PRESENT AND FUTURE EXPLORATION TARGETS

Present exploration targets in the Wilburton area consists of Spiro/Wapanucka/Cromwell thrusted structures and deep Arbuckle fault blocks. Exploration for sub-Choctaw targets is active and is moving south. Both plays require high-quality seismic data for accurate definition of the extent of structures, fault location, and crest location.

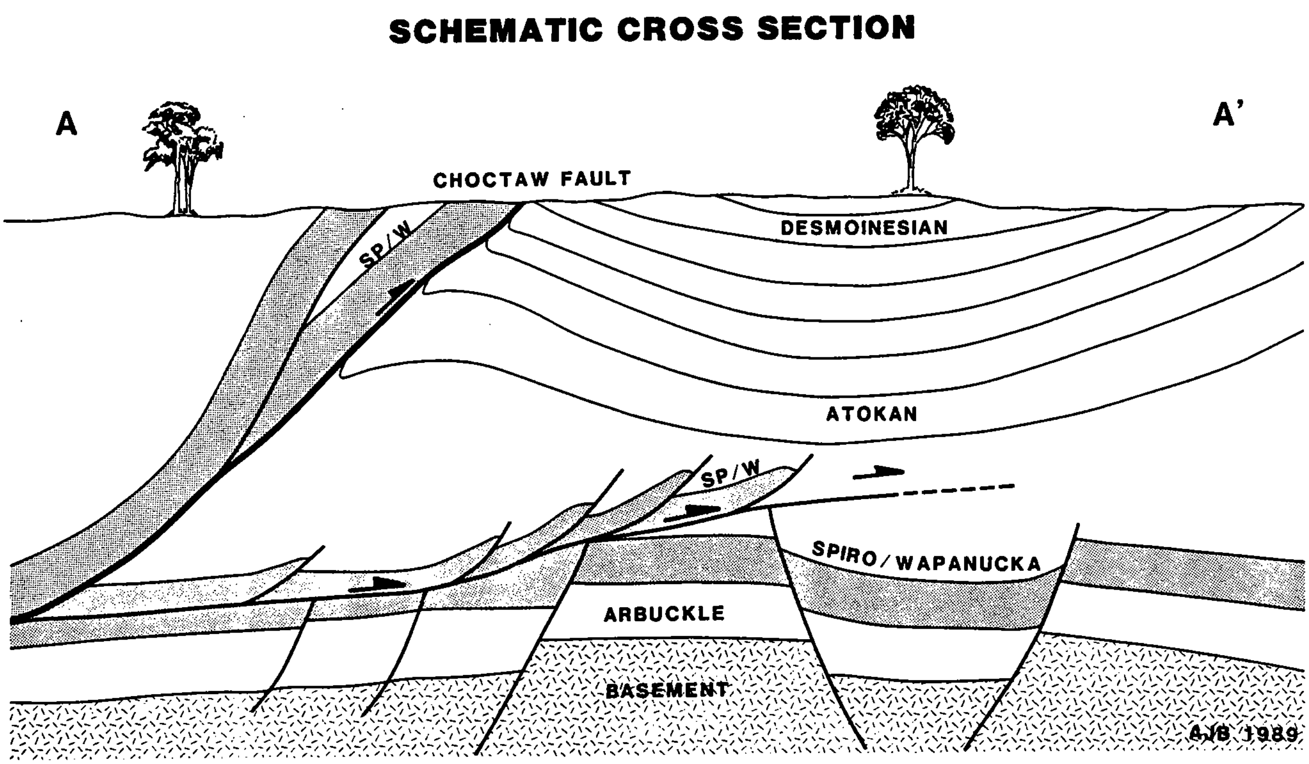


Figure 7.

Retrace route to Highway 2.

3.8 (8.6) Turn left (south) on Highway 2.

BANDY CREEK ANTICLINE

For the next 0.4 mi, we cross what has been informally been called the Bandy Creek anticline, so named because it is well exposed along the banks and in the bottom of Bandy Creek, located just east of the highway. The stratigraphy exposed in the creek has been described by Bowsher and Johnson (1968), who suggested that the sequence represented an overturned, N-directed anticline with Wapanucka Limestone exposed on the overturned north limb and upright south limb, and "Springer" Formation in the core. Recent mapping by Hemish and others (in prep.) indicates that the anticline plunges to the east and that a thrust fault in the core juxtaposes the Wapanucka Limestone to the south against the "Springer" to the north. This relation explains why the E–W-trending Spiro/Wapanucka ridge (Limestone Ridge) is nearly continuous for miles along strike. A faulted anticline also explains the dissimilar Spiro/Wapanucka stratigraphy on the "limbs" noted by Bowsher and Johnson (1968, p. 35) and Grayson (1980, p. 217–224).

0.6 (9.2) Cross Bandy Creek.

The flat, alluvium-covered valley floor immediately south of the bridge over Bandy Creek is underlain by a persistent shale unit at the base of the Atoka Formation.

0.7 (9.9) On the right, a small pit in the lower part of the Atoka Formation.

0.6 (10.5) Leave Wilburton 7.5′ Quadrangle, enter Damon 7.5′ Quadrangle.

1.1 (11.6) Top of Blue Mountain.

BLUE MOUNTAIN

Blue Mountain is underlain by a series of thick, mostly massive, poorly stratified to unstratified, fine-grained sandstones of the Atoka Formation. The sandstone beds are both amalgamated and separated by unexposed shale intervals. In outcrop, the sandstone sequence is nearly 500 ft thick and probably averages 50% sandstone, compared to a "typical" Atoka average of 10% sandstone and 90% siltstone and shale. The sandstones are about 6,500 ft stratigraphically above the Spiro 4 mi west of where Highway 2 crosses the mountain. This would place the sandstones in a stratigraphic position similar to that of the Red Oak sandstone, a prolific gas producer in the Wilburton, Panola, and Red Oak–Norris gas fields to the north. Bowsher and Johnson (1968, p. 43) correlated the sandstone on top of Blue Mountain with the Red Oak sand. Given that the Red Oak sandstone occurs in channelform bodies in the Arkoma basin (Vedros and Visher, 1978; Houseknecht, 1986,1987), and that the sandstone on Blue Mountain is separated from the Red Oak sandstone in the basin by a least three thrust faults (and was therefore probably deposited several tens of miles farther south than its present position), the two were probably never continuous.

In 1982–83, Williford Energy drilled the No. 1 Clemons in C E 1/2 E 1/2 NW 1/4 sec. 8, T. 4 N., R. 19 E., about 3 mi southwest of where Highway 2 crosses the top of the mountain. The well encountered the sandstones exposed on Blue Mountain from 8,785 to 8,953 ft. Assuming a dip of 50°, the sandstone sequence would be about 130 ft thick. The contrast in thickness between the outcrops on Blue Mountain and in the well suggests that the sandstone was deposited as a channelform body.

4.1 (15.7) Cross Gaines Creek.

1.4 (17.1) Entrance to Veterans Colony.

Just beyond the entrance to the Veterans Colony on the right (west) side of the road are some outcrops of Atoka turbidite sandstones with beautifully preserved flute casts and dish-and-pillar (dewatering) structures. This outcrop was described by Briggs and others (1975) for the Dallas Geological Society. The strata dip north and are overturned. A very important feature illustrated by this outcrop, and noted briefly by Bowsher and Johnson (1968, p. 47, mile 61.0), is that the "dip is accentuated by soil creep." Throughout the central part of the frontal belt, surface mapping has shown that dip values, and in some cases dip directions, are largely the result of soil creep, and that reliable dips can generally be found only in creek bottoms.

For the next 2.5 mi the road crosses a complex system of folds and faults in the Atoka Formation that are probably related to the Ti Valley fault (see discussion of the Ti Valley fault at Stop 4, mile 49.0).

2.7 (19.8) Intersection with Oklahoma Highways 1 and 63. Continue south on Highways 1, 2, and 63.

Near the intersection, the highway approximately follows the trace of a major NW-trending transverse fault; formation contacts, fold axes, and thrust faults show evidence for right-separation (Fig. 8). The structure, interpreted by Suneson and Ferguson (1989b) to be a strike-slip or tear fault, ends at the Ti Valley fault, indicating that thrust faults southeast of the Ti Valley fault in this area are older than the Ti Valley fault. This foreland-younging of thrust faults

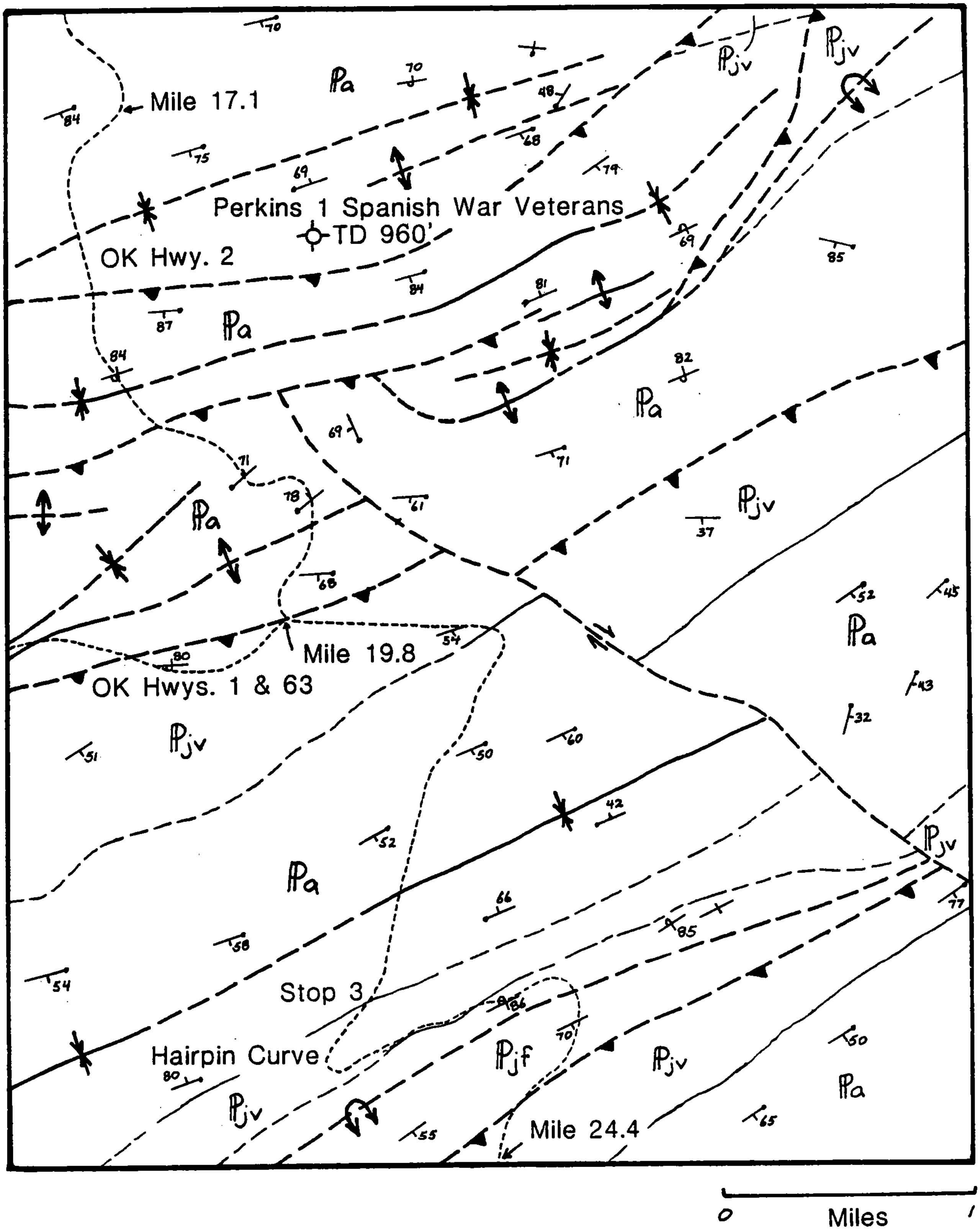


Figure 8. Geologic map of area near Stop 3. Symbols as in Figure 6, and —✱— syncline; —↕— anticline; —⤼— overturned anticline; Pjv = Johns Valley Formation; Pjf = Jackfork Group.

is typical of many other fold and thrust belts. Northwest of the Ti Valley fault, the traces of some of the major thrust faults bend along the projection of this transverse structure. The tear fault and its projection to the northwest may be related to a NW-trending basement fault that has affected the surface structure. Transverse structures in the frontal belt have not been discussed in the literature, but will be the focus of Stop 4 on this field trip.

2.5 (22.3) Hairpin curve locality and Stop 3 in this guidebook.

2.1 (24.4) Leave Damon 7.5′ Quadrangle, enter Yanush 7.5′ Quadrangle.

1.4 (25.8) Highways split. Bear left (east) and stay on Highways 1 and 63.

0.2 (26.0) Stop sign. Merge. Continue east on Oklahoma Highways 1 and 63.

Immediately north of the highway intersection, Atoka Formation to the north is juxtaposed against Stanley Group strata to the south along the Windingstair fault. The Windingstair fault is the southern boundary of the Ouachita Mountains frontal belt, and the gross structure changes from tightly folded and imbricately thrust-faulted Lower Pennsylvanian strata to broad, open synclines separated by relatively tight, thrust-cored anticlines typical of central-belt structure (Fig. 1). In this part of the mountains, Mississippian Stanley Group strata are restricted to the area south of the Windingstair fault. This contrasts with the western frontal belt, where the Stanley is exposed in the footwall of the Windingstair fault (see mile 45.1, Day Two) and the Black Knob Ridge area, where Ordovician strata are exposed in the footwall northwest of the fault.

The very irregular topography south of Oklahoma Highways 1 and 63 is the Potato Hills. These hills are underlain by Ordovician to Lower Mississippian "Ouachita"-facies, deep-water shales and cherts, including (in ascending stratigraphic order) the Womble Shale, Bigfork Chert, Polk Creek Shale, Missouri Mountain Shale, and Arkansas Novaculite. The distribution of rock types in the Potato Hills is generally agreed upon, but the structure is not. To describe the many years of controversy over the origin of the Potato Hills is beyond the scope of this brief discussion. To summarize, one group of workers (most recently, Pitt and others, 1982) suggested that the Potato Hills are essentially an autochthonous anticlinorium; another group (see Arbenz, 1968) suggested that the rocks exposed there are entirely allochthonous and in the hanging wall of the Windingstair thrust. The different interpretations of the structure are based partly on different interpretations of the (poorly exposed) surface geology, and partly on different interpretations of the logs and cuttings from the Sinclair No. 1 Reneau (sec. 32, T. 3 N., R. 20 E.) (see Stop 9). Controversy exists over whether the well bottomed in Ordovician or Pennsylvanian sediments.

1.6 (27.6) Leave Yanush 7.5′ Quadrangle, enter Kiamichi 7.5′ Quadrangle.

0.3 (27.9) Stop 2, Buffalo Valley School and Bottom Marks in Atoka Sandstone. Location: SE 1/4 SE 1/4 NW 1/4 sec. 18, T. 3 N., R. 20 E.

STOP 2
BUFFALO VALLEY SCHOOL—
BOTTOM MARKS IN ATOKA SANDSTONE

Neil H. Suneson
Oklahoma Geological Survey

The Buffalo Valley School was built in 1942 by the WPA. The sandstone facing of the school building is from the Atoka Formation; the stones were collected on the surface on the low ridge in sec. 22, T. 4 N., R. 18 E. (O. Harrington, oral communication). Locally, ranchers still gather the sandstone slabs off the surface for use as building material.

Can you identify the following bottom marks commonly found in turbidite sandstones on the blocks that make up the school? (Hint: Refer to Dzulynski and Walton, 1965.)

— Elongate-symmetrical flutes, both simple and compound
— Asymmetrical flutes
— Rills
— Longitudinal obstacle-scour marks
— Grooves, twisted grooves, and grooves with twisted ends
— Prod marks

Also, note the variety (especially in size) of burrows.

Retrace route to highway intersection; then north on Highways 1, 2, and 63 to the hairpin curve.

5.6 (33.5) Stop 3, Hairpin Curve Locality, Johns Valley Shale and Atoka Formation. Location: SE 1/4 sec. 3, T. 3 N., R. 19 E.

Buses will stop at the turnout just above the hairpin curve across from the Johns Valley Shale/Atoka Formation contact. Field-trip participants can examine the contact and the nature of the upper part of the Johns Valley below the Atoka, walk down the road to the curve, and look at the lower part of the Johns Valley there.

STOP 3
HAIRPIN CURVE LOCALITY— JOHNS VALLEY SHALE AND ATOKA FORMATION

Neil H. Suneson
Oklahoma Geological Survey

The following description of this stop is modified from Suneson (1988).

The Hairpin Curve locality is perhaps the most famous and frequently visited geologic road cut in the frontal belt of the Ouahchita Mountains. It has been described in at least eight published guidebooks of the Mountains (Tulsa Geological Society, 1947; Cline and others, 1959; Cline, 1968; Hare, 1973; Briggs and others, 1975; Decker and Black, 1976; Chamberlain, 1978; Johnson, 1988); the site undoubtedly has also been visted by many university and industry field trips. In addition to the guidebooks, several studies have focused on specific features of the strata exposed at this locality: Shideler (1968, p. 129; 1970) studied the origin of the boulder assemblage in the Johns Valley Formation; Chamberlain (1970, p. 17f; 1971) studied the trace-fossil assemblage in the sandstones; and Nooncaster (1985) studied the petrography of the sandstones. The strata exposed were measured by Hendricks and Averitt in 1939 (Tulsa Geological Society, 1947, p. 32–34) and by Cline and Laudon in 1958 (Cline and others, 1959, p. 35–37, 40–41) (Fig. 9).

The aforementioned studies of the Hairpin Curve strata can be summarized as follows: Most authors agree that the Atoka/Johns Valley contact is exposed here and is depositional, although the exact position of the contact is debatable, and it is probably gradational (Fig. 9). There is a siliceous (spicular) shale zone about 160 ft above the top of the Johns Valley that was useful to Hendricks in mapping the base of the Atoka. Cline correlated this spiculite zone with "some part of the upper Wapanucka" and suggested that the base of the Atoka Formation here may be Morrowan. In addition, Ferguson and Suneson have observed a very sparse fauna from the base of the Atoka at the sharp bend in the road about 1.8 mi to the north, vaguely reminiscent of the fauna that is so profuse in the Spiro sandstone.

Historically, the Johns Valley Formation at the Hairpin Curve has been separated into two units: Hendricks called these the "upper boulder bed" and "lower boulder bed" (predominantly Caney Shale) of the Johns Valley, and Cline called them the "upper Johns Valley" and "lower Johns Valley" (Caney facies). This outcrop, among others, undoubtedly served as the focal point for the long-lasting Caney–Johns Valley controversy. The argument was based on interpretations of the depositional environment of the Caney part of the Johns Valley and can be summarized as follows: Cline (and others) felt that the Mississippian Caney Shale was stratigraphically autochthonous, that is, it had been deposited on Jackfork strata south of the Ti Valley fault; that the Jackfork was therefore Mississippian, and that the exotic-boulder-bearing Morrowan Johns Valley was deposited on it. Hendricks (e.g., Hendricks and others, 1947) believed that the Caney part of the Johns Valley was stratigraphically allochthonous, that Mississippian (as well as older) strata were enclosed in a Pennsylvanian matrix, and that the Jackfork was Pennsylvanian. Later, Gordon and Stone (1977) showed that the Jackfork and Johns Valley are Morrowan. However, questions remain as to the mode of deposition of the Caney Shale near the base of the Johns Valley.

Perhaps the best description of the "upper" Johns Valley at the Hairpin Curve is that of Cline and others (1959), because the outcrops were fresh due to road-widening:

> "The shales containing the limestone erratics are of special interest. The most conspicuous boulder bed . . . has been interpreted by some as a friction carpet at the base of an advancing thrust sheet. This boulder-bearing clay-shale rests in a channel which cuts out a least 11 1/2 feet of (the underlying strata). There is a noticeable decrease in the size of the erratics upward in this deposit, the overall effect being not unlike that of graded bedding, but it is of course on a somewhat larger scale than the usual examples. The erratics in the lower part of the channel fill include well rounded boulders with diameters in excess of a foot, slightly rounded blocks of similar dimensions, the whole being embedded in a clay-shale matrix. Upward the boulders give way to cobbles and they in turn give way to pebbles which are widely separated in the shale and give a plum pudding effect. Throughout this deposit there are rounded masses of hard, brown, quartzitic sandstone. We interpet this particular boulder bed as the product of a single turbidity flow or submarine slide. The flow initally attained a high velocity during which phase it was able to transport boulders and scour previously deposited muds and sands. As the peak of the flow was reached and the velocity trailed off, pebbles began to drop out and were deposited with the muds of the flow and the muds obtained from the reworked bottom. The rolled sandstone masses represent lenses of sand torn from the bottom and rolled along the flow. The convolute bedding and the flute casts on the undersurfaces of some of the sandstones support the general view that turbidity currents were operative during this time."

Shideler (1968,1970) recognized boulders and cobbles from the following formations (oldest to youngest) in the Johns Valley on the north side of the Hairpin Curve (i.e., "upper" Johns Valley): Fort Sill, Kindblade, West Spring Creek, Oil Creek, McLish, Bromide, Fite, Viola, Chimneyhill, Henryhouse, Pinetop, Boone, and Sycamore.

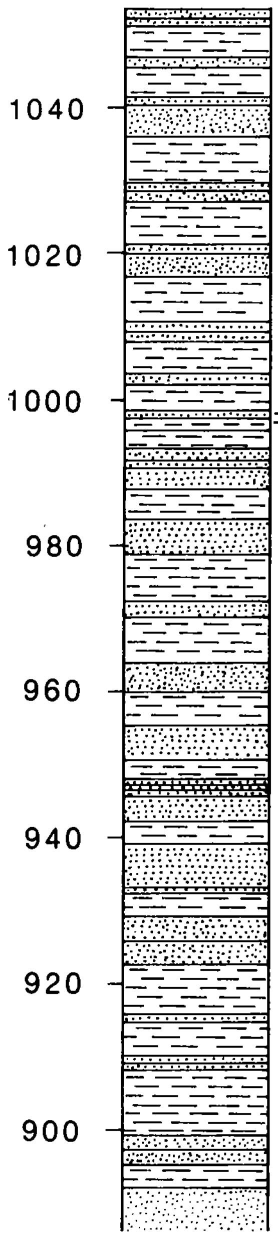
To the south, the "lower" Johns Valley or "Caney facies" of the Johns Valley is exposed in now deeply weathered road cuts. Hendricks measured 100 ft of lower Johns Valley that contained a 550 × 30 ft coherent Caney Shale block. Cline measured 117 ft of lower Johns Valley, in which 27 ft were "typical Mississippian Caney Shale." In general, stratification in the Caney is parallel to that in the Johns Valley, but the Caney is typically harder, more fissile, and blacker than the Johns Valley. In many places in the frontal Ouachitas, the Caney contains limestone boulders that are best described as concretions, with stratification parallel to that of the enclosing shale. This contrasts with the Johns Valley, in which exotic limestone boulders are clearly foreign to the enclosing shale. On the south side of the Hairpin Curve ("lower Johns Valley"), Shideler (1968,1970) found boulders and cobbles of the following units (oldest to youngest): West Spring Creek, Joins, Tyner, Fite, Viola, Fernvale, Bigfork, Bois d'Arc, Sycamore, Wapanucka.

In contrast to the attention that has been paid to the Atoka and Johns Valley Formations, the Jackfork at this locality is virtually unstudied, perhaps because it is even more poorly exposed that the Johns Valley, is less interesting than the Johns Valley, and is nearly a mile northeast of the convenient turnout at the curve. Most authors agree that the sandstones that immediately underlie the Johns Valley are part of the Game Refuge Formation, the uppermost formation in the Jackfork Group. Underlying the Game Refuge is the Wesley Formation, a unit that many authors called the Wesley siliceous shale member of the Jackfork Formation.

At the Hairpin Curve locality, the Game Refuge Sandstone consists of interbedded sandstone, siltstone, and shale (the siltstone and shale are largely covered and therefore inferred). The sandstone beds range from a few inches to possibly as much as 70 ft thick, but average about 2 to 5 ft thick. Bouma sequences are well developed in the thinner sandstones; the thicker sandstones tend to be unstratified and massive. The sandstones are similar to Atoka sandstones, except that locally they are distinctly bimodal (1- to 2-mm grains in a fine-grained matrix), contain fossil fragments (brachiopods, crinoids), and are interbedded with granule conglomerates. The Wesley Shale consists of brownish, fissile mudstone with rare 1-in. to 1-ft sandstone beds exhibiting a typical T(b)cd Bouma sequence.

Although the stratigraphy of the units exposed at the Hairpin Curve is relatively well understood, the geology is not. Five geologic maps of the hairpin curve have been published (Hendricks and others, 1947; Misch and Oles, 1957; Fellows, 1964; Bowsher and Johnson, 1968; Suneson and Ferguson, 1989b). Suneson and Ferguson (1989b) mapped a relatively simple overturned (to the northwest) anticline with a thrust fault in the core juxtaposing Johns Valley against Jackfork (Fig. 8).

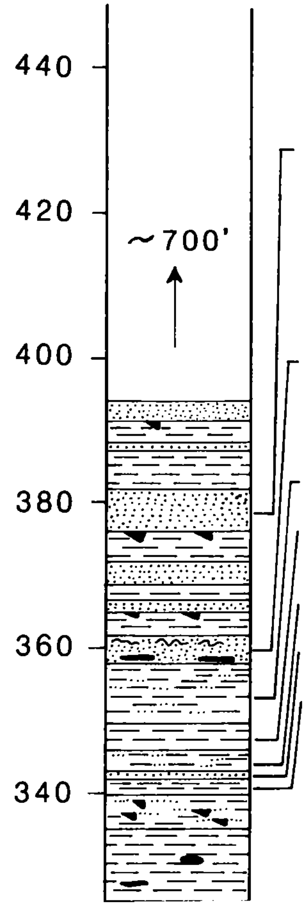
HENDRICKS AND AVERITT (1939)



1. Alternating sandstone and shale. The shale is gray and fissile; the sandstone is gray, fine- to medium-grained, and well bedded and makes up about 40% of the section 625
2. Sandstone, fine-grained, with some greenish gray siliceous shale laminae........ 1
3. Shale, siliceous, black, well laminated, weathers to large blocks and small angular fragments........ 1 1/2
4. Alternating sandstone and shale, similar to unit 1 150

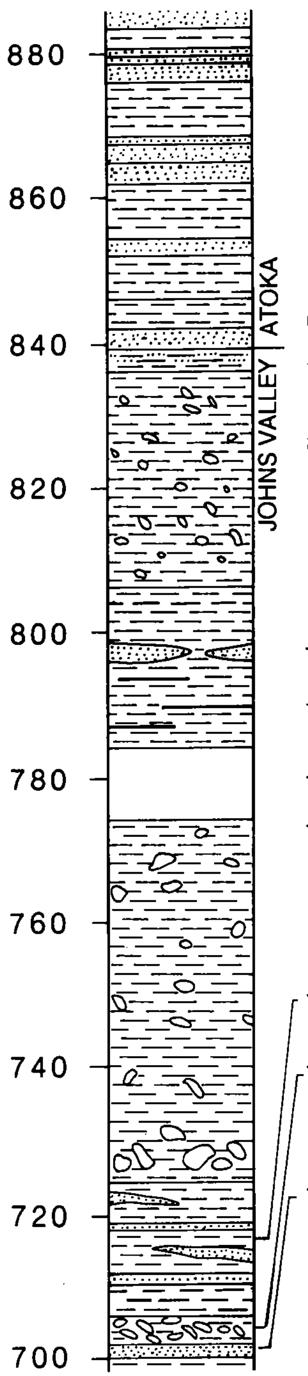
Figure 9 (p. 21–30). **Comparison of Atoka Formation–Johns Valley Shale measured sections by Hendricks and Averitt (1939; published in Tulsa Geological Society, 1947) and Cline and Laudon (1958; published in Cline and others, 1959) and measured section of Johns Valley Shale–top Jackfork Group by Suneson. The Atoka–Johns Valley sections are matched at the contact between the two formations; note that Cline and Laudon placed the contact about 100 ft above the highest occurrence of limestone olistoliths. The Johns Valley–Jackfork section starts at the westernmost exposures at the Hairpin Curve (about 2,000 ft west of the east line and 1,000 ft north of the south line of sec. 3, T. 3 N., R. 19 E.) and extends east–northeast on the south side of the highway to near the center of sec. 2, T. 3 N., R. 19 E.**

CLINE AND LAUDON (1958)

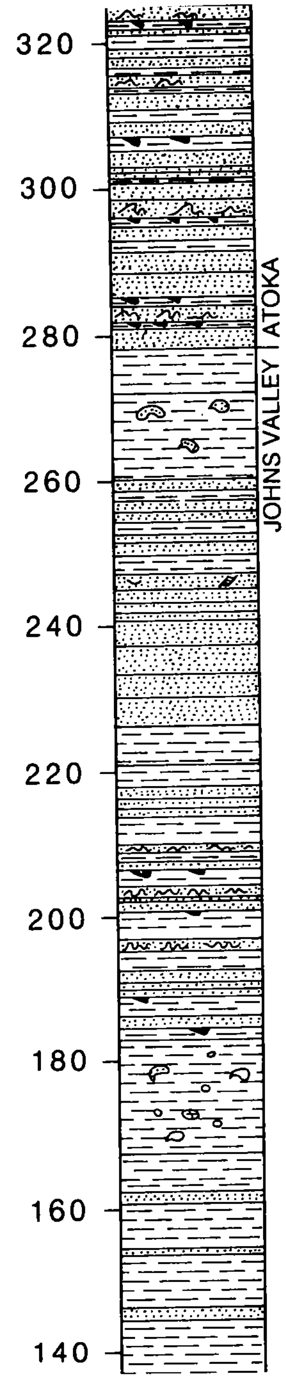


23. Shale and sandstone; dark blue-gray laminated shale comprising 60 to 65% of the interval; interbedded sandstone in beds as thick as 6 feet. Flute casts abundant on lower surfaces of sandstones. Shale units as thick as 20 feet. Exposed below culvert... 335

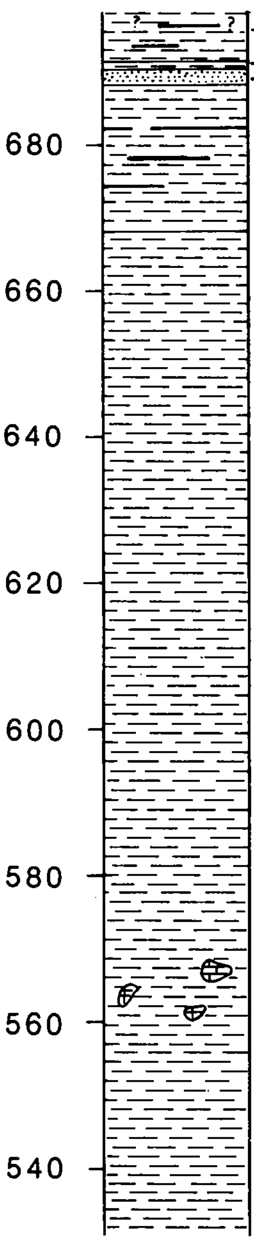
    About the same thickness of Atoka is exposed above culvert.
22. Sandstone; hard, convolute bedding near top; casts of reed-like plants on base of bed, one being nearly 5 feet long, of uniform thickness, and with longitudinal ribs........ 3 1/2
21. Shale; medium gray, laminated, silty 8 1/2
20. Shale; gray, lower 2 feet dark gray to black, may be siliceous........ 3 1/2
19. Shale; medium gray, laminated silty 3
18. Sandstone; hard, laminated but weathers massive 0.8
17. Shale with thin beds of sandstone; dark gray, almost black, upper 2 feet siliceous; four sandstone beds in interval, each averaging only 3 inches but with prominent load and flute casts on under surfaces; beds slightly overturned........ 7
16. Shale; dark gray to black, thinly bedded, some clay-ironstone concretions 10



5. Shale, gray 4
6. Sandstone, greenish gray, fine- to medium-grained, massive 3
7. Sandstone and shale interbedded in beds 2 to 4 inches thick 3
8. Mudstone, gray to tan, weathers to some shaly structure, contains fairly abundant erratic boulders up to 1 foot in diameter 30
9. Shale, gray, clayey, weathers tan 8
10. Sandstone, gray to brown, fine-grained, lenticular......... 2
11. Shale, dark gray to black, well bedded, flaky, contains limonite bands, weathers gray to tan 12
12. Covered 10
13. Mudstone, with some irregular shaly bedding, gray, weathers tan to mustard colored. Contains abundant erratic boulders up to 5 feet in diameter in the lower part and smaller ones in the upper part. Elongate boulders lie at random angles to the general bedding 50
14. Sandstone and shale interbedded. Shale is gray to black and clayey; sandstone is fine-grained and light gray. 18
15. Mudstone, with some shaly structure where weathered, tan to gray, contains abundant small erratic boulders (1/4 inch to 6 inches in diameter). Elongate boulders lie at random angles to the general bedding 4 1/2
16. Sandstone, chocolate-colored, massive, fine-grained 1 1/2



15. Sandstone; beds as thick as 3 feet; cut by small fault on north; convolute bedding and bottom markings abundant 47
14. Shale; dark gray, fissile 6
13. Shale; poorly bedded, includes rolled sandstone masses; poorly exposed 12
12. Sandstone; includes beds as thick as 3 feet; some shale 10 1/2
11. Shale; gray 2 1/2
10. Sandstone; massive contains a sandstone mold and cast fauna of marine invertebrates; stained brown............ 2
9. Sandstone; in beds 4 to 5 feet thick 19
8. Shale; gray, thinly bedded, weathers buff 5
7. Sandstone and shale; sandstone predominating, weathers light gray, in massive beds the thickest of which is about 2 feet; shale dark blue-gray finely laminated. Some sandstone beds have flute casts and intricate convolute bedding 38
6. Clay shale; with pebbles and cobbles of limestone erratics and masses of rolled sandstone; may be a repetition of upper part of zone 4 16
5. Infolded sandstone and shale in small drag fold; in fault contact with underlying shale; probably belongs higher stratigraphically 32



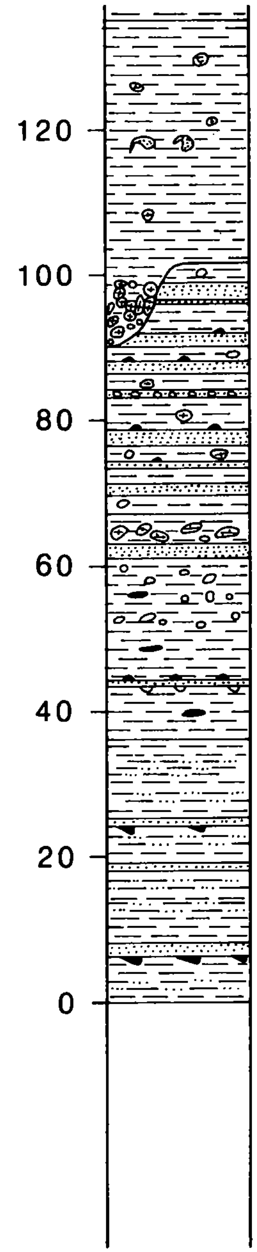
17. Shale, gray, clayey, contains 1-inch limonite bands, weathers gray to olive .... ?

18. Shale, black, soft, clayey, blocky where fresh, weathers flaky gray to tan 1

19. Sandstone, greenish gray, fine-grained, hard, irregularly laminated 2

20. Shale, gray, clayey, well bedded, nonfissile, contains limonite bands, weathers gray-green and tan and more deeply to a mustard color 20

21. Shale, weathered to tan clay and poorly exposed, small limestone boulders noted in place in one exposure. Forms landslide area on west side of road 150



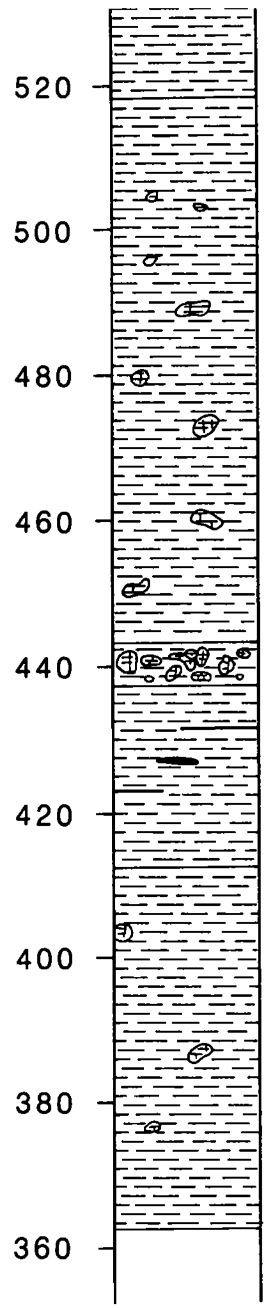
FAULT. SOME SECTION MISSING

4. Clay shale with included limestone boulders; the lower 11 1/2 feet occupies a channel cut into the underlying zone 3; limestone erratics are so thick that it resembles a coarse conglomerate; some of the boulders have diameters up to 2 feet. The upper half of the zone is a drab-weathering claystone which includes large masses of rolled sandstone of depositional origin; it also contains smaller limestone erratics 45

3. Sandstone and sandy shale; sandstone predominating, in beds as thick as 3 feet but averaging only 4 inches in upper portion; interbedded and laminated shale contains occasional limestone erratics. Abundant animal trails on upper surfaces of sandstone; a thin conglomerate 6 feet below the top 23

2. Shale; dark blue-gray, laminated, weathers into small plates and chips; beginning 17 feet above the base numerous limestone erratics averaging 3 to 4 inches in diameter (but up to 1 foot) occur; they appear to have undergone some weathering prior to deposition in the shale. Some thin beds of fine-grained sandstone show numerous animal trails on upper surfaces and irregular load casts on under surfaces. One massive sandstone bed 4 feet below top. Some clay-ironstone concretions in shales. Upper 4 feet of shale contains abundant erratics and is well bedded 31

1. Gray silty shale; weathers drab; about 35% of interval composed of thin-bedded siltstone with sandstone beds up to 2 feet thick. Sandstone beds show convolute bedding and flute casts 36

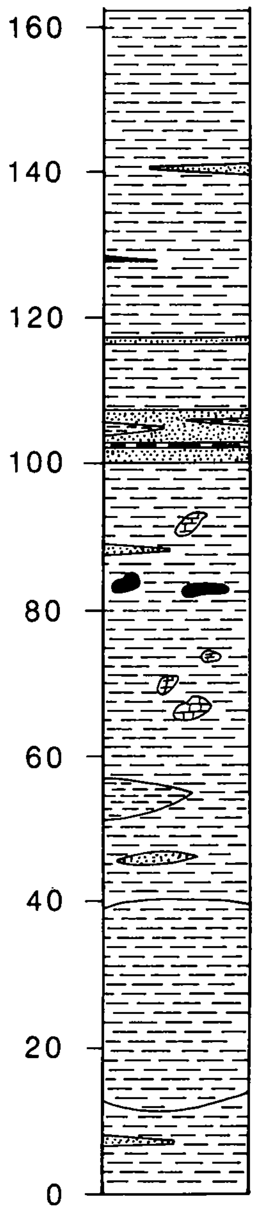


22. Shale, intermittently exposed, gray, weathers tan, contains scattered limestone, chert, and shale boulders and some limonitic concretions 75

23. Shale, weathered to tan clay contains very abundant limestone boulders less than 1 inch to more than 3 feet in diameter. Some boulders are cemented together by sandy, clayey, limonitic material. The boulders are rounded to subrounded 6

24. Shale, dark gray, clayey, flaky, contains limonite bands and concretions, weathers tan to mustard-colored. 25

25. Shale, deeply weathered to mustard-colored clay, appears to contain small erratic limestone boulders. 50



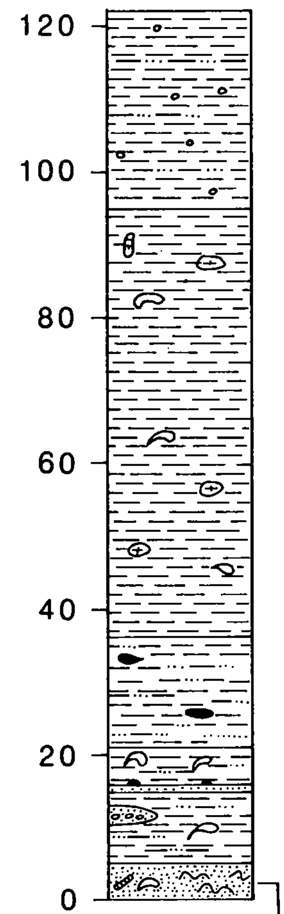
26. Covered in fill at sharp bend in the road 200

27. Shale, dark gray with greenish tinge, evenly banded, very flaky, clayey, contains thin beds of limonite and sandstone similar to those below 65

28. Sandstone, gray, micaceous, fine-grained, alternating with dark gray clay shale containing limonite bands.. 7

29. Shale, dark gray, very clayey, weathers tan to mustard-colored. This zone contains scattered limestone boulders up to 4 feet in diameter, numerous limonitic concretions up to 3 feet in diameter, large erratic masses of Caney shale, and lenses of fine-grained, gray micaceous sandstone.

The largest mass of Caney shale measured 550 x 30 feet in continuous exposure. The bedding of the Caney shale is parallel to that of the Johns Valley shale and is undistorted, whereas, that of the Johns Valley shale is highly contorted 100



5. Shale; typical Mississippian Caney shale; black, laminated, includes several zones of siltstone that weather light gray; many rounded phosphatic concretions the size and shape of marbles, some contain goniatites including Lyrogoniatites. Exposed to road level.. 27

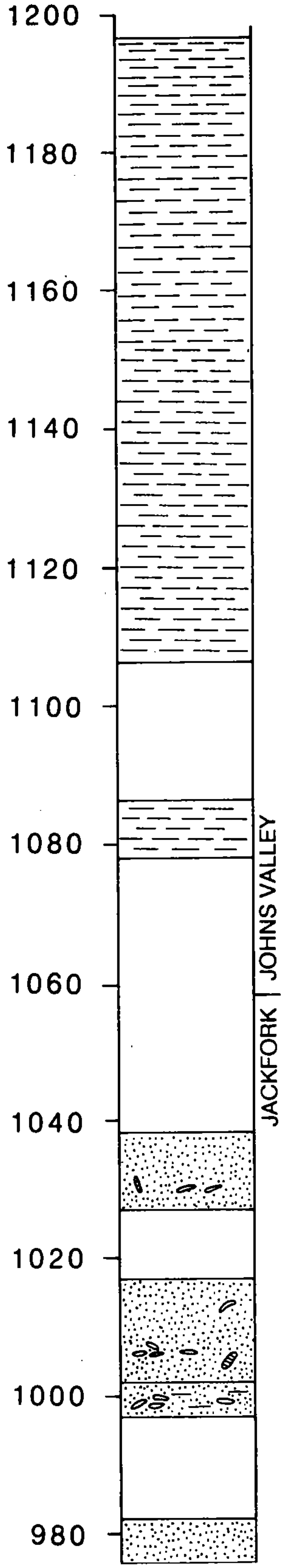
4. Shale; dark blue-gray, platy, with some zones of lighter colored clay shale; includes some lenticular beds of clay-ironstone and rolled masses of hard, fine-grained sandstone which shows convolute bedding. Limestone erratics are embedded in some of the gray clay-shale. Some small drag folds 59

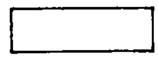
3. Shale and siltstone; interlaminated dark gray shale and brown-weathering siltstone with shale predominating; contains some clay-ironstone concretions 15

2. Shale; jumbled appearance; alternating gray shale and brown silty shale including some beds of hard fine-grained sandstone as thick as 6 inches. Upper surfaces of sandstones have meandering animal trails, the lower surfaces have prominent load casts. Lenses of conglomeratic sandstone. Rolled sandstone masses prominent. Many features of turbidity flow deposition. Beds dip 34 degrees southeastward into the hill; note that dips become successively lower higher in the cut; actually, the lowest dips have the greatest structural disturbance because the entire section is overturned.. 16

1. Sandstone; only the top 5 feet described. In beds from 2 inches to 3 feet thick; medium-grained to fine-grained, weathers light gray with iron-stained surfaces; contains crinoid columnals and other fragmentary fossils. Sandstone has well developed convolute bedding; torose load casts on under surfaces. Beds are overturned but nearly flat.................................... 5

SUNESON





Shale. Olive black (5Y2/1). Extremely fissile, soft laminated shale with 1- to 3-inch flattened non-calcareous concretions. Locally slightly harder, more platy.

Shale. Olive black (5Y2/1). Platy and hard to soft and extremely fissile.

Shale. Hard platy shale, locally paper-thin. Locally weathers to rusty or slightly yellowish stain.

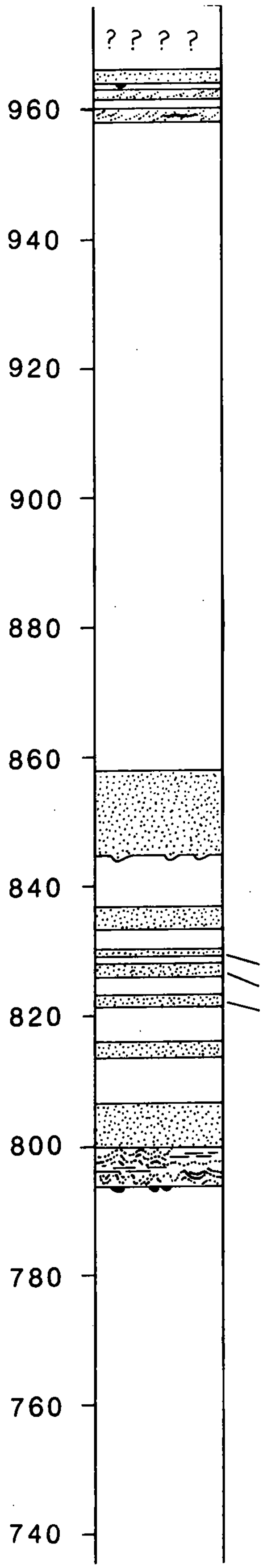
Shale. Olive black (5Y2/1). Slightly blocky shale interbedded with extremely fissile shale. Stratification 1/4 to 1 inch thick.

Sandstone. Fine-grained. Quartzose, trace iron oxide coating on grains. Rare mud rip-ups, one crinoid stem mold observed. Dark yellowish orange (10YR6/6). Unstratified to very faintly stratified. Locally with elongate vugs, possible fossil molds.

Sandstone. Unstratified. Locally with abundant mud chips. One crinoid stem mold observed. Fine-grained.

Sandstone. Dark yellowish orange (10YR6/6). Amalgamated. Locally with abundant mud chips. Locally extremely vuggy (up to 50%) with eroded mud chips. Fine-grained.

Sandstone. Quartzose, possible trace glauconite. Very light gray (N8). Unstratified. Brownish-orange weathering rind typical.



Sandstone. Unstratified. Rare, poorly exposed trace fossils.

Sandstone. Parallel- and cross-laminated.

Sandstone. Very fine-grained. Quartzose. Light olive gray (5Y6/1). Cross-laminated. Ripples at top.

Sandstone. Fine-grained. Slightly porous. Trace brachiopod fragments. Grayish orange (10YR7/4). Unstratified. Flutes at base indicate N77E to S77W paleocurrent direction. Very weathered.

Sandstone. Fine-grained. Unstratified. Dusky yellow (5Y6/4). Conspicuous mica.

Sandstone.

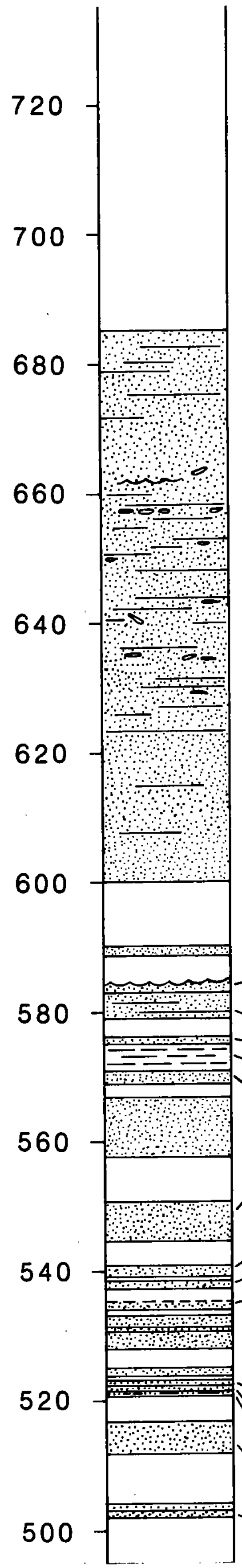
Sandstone.

Sandstone.

Sandstone.

Sandstone.

Sandstone. Outcrop about 75% sandstone. 25% covered, probably clayey mudstone. Sandstone very fine-grained. Dusky yellow (5Y6/4). Parallel- and cross-laminated, locally contorted into dish and pillar structures. Bottom of beds with trace fossils and bottom marks.



Sandstone. Fine- to rarely medium-grained. Quartzose. Trace granule conglomerate in float, rare brachiopod fragments. Locally with abundant mud rip-ups that parallel bedding. Locally with relatively abundant plant debris and trace organic material. Yellowish gray (5Y7/2). Mostly unstratified, amalgamated beds 2 to 5 feet thick. Locally with faint stratification. Locally with poorly developed ripples. Fractures both planar and at high angles. Weathers to large, angular blocks.

Sandstone. Faintly stratified.

Sandstone. Rippled top indicates current direction about N14E/S14W.

Sandstone. Amalgamated.

Sandstone.

Mudstone. Poorly exposed.

Sandstone.

Sandstone. Fine-grained. Dusky yellow (5Y6/4). Unstratified.

Sandstone. Fine-grained. Conspicuous 1 mm mica. Dusky yellow (5Y6/4). Unstratified. Slightly fractured. Flat base.

Sandstone.

Sandstone.

Sandstone. Grades up to laminated siltstone.

Sandstone. Amalgamated.

Sandstone.

Sandstone. Fine-grained. Yellowish gray (5Y7/2). Fractured perpendicular to bedding.

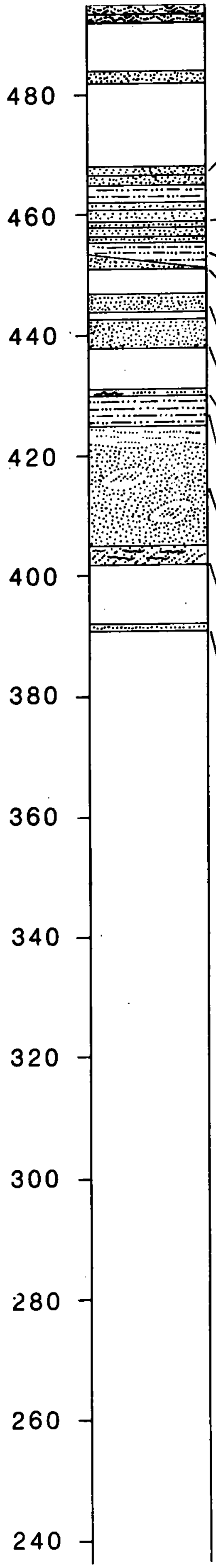
Sandstone.

Siltstone. Laminated.

Sandstone.

Sandstone.

Sandstone. Cross-laminated.



Sandstone. Amalgamated. Wavy laminations.

Sandstone.

Sandstone. Yellowish gray (5Y7/2). Faintly laminated, possibly two 1 1/2 feet amalgamated beds. Trace glauconite.

Siltstone. Laminated.

Sandstone. Consists of 1- to 2-foot amalgamated sandstone beds. Unstratified. Bases locally with abundant plant and stem molds.

Siltstone and Mudstone. Possibly fills channel in underlying sandstone.

Sandstone. 10% to 15% feldspar, trace 2 mm mica and trace organic material. Grayish orange (10YR7/4). Unstratified. Flat base. Contains mineralized slickensides indicating dip-slip movement. Thickness varies.

Sandstone.

Sandstone. Unstratified.

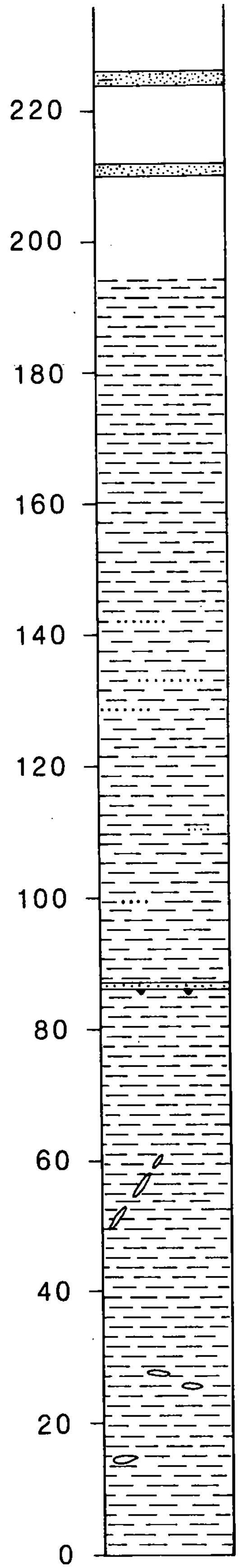
Sandstone. Fine- to medium-grained. Approximately 15% feldspar. Yellowish gray (5Y7/2). Faint parallel laminations within, possible inclined laminations at top. Small (1 inch) dish and pillar structures, load casts at base.

Siltstone. Possibly with some thin sandstone and shale.

Sandstone. Trace glauconite. Mostly unstratified, but faintly cross-laminated in interior and parallel-laminated at top.

Sandstone. Fine-grained. Quartzose with conspicuous mica, glauconite. Very light gray (N8). Consists of amalgamated 1- to 3-inch cross-laminated sandstone beds with rippled tops.

Sandstone.



Sandstone. Fine-grained. Abundant matrix material surrounds quartz grains. Yellowish gray (5Y7/2). Unstratified. Possible slight mineralization on fractures.

Sandstone. Fine-grained. Abundant oxidized mafic minerals. Light olive gray (5Y5/2). Unstratified. Weathers to angular blocks. Probably mostly mudstone.

Mudstone.

Mudstone.

Mudstone. Well-stratified. Relatively hard. Contains rare 1 inch cross-laminated sandstones. Sandstones are fine-grained, quartzose, slightly lenticular. Medium gray (N5).

Mudstone. Very slightly silty. Light olive gray to olive gray (5Y5/2 to 5Y3/2). Brown sheen on fractures.

Sandstone. Fine-grained, quartzose, mica on laminations. Medium gray to olive gray (N5 to 5Y4/1). Consists of amalgamated 1/4- to 2-inch poorly exposed cross-laminated layers. Locally with abundant trace fossils on bottom, irregular top.

Mudstone. Very fissile. Locally weathers to "pencil" structure.

Mudstone. Slightly silty. Cut by resistant siltstone "dike" or series of aligned pods oblique to bedding. Olive black (5Y2/1).

Mudstone. Includes small pods of siltstone. Moderate brown (5YR4/4). Siltstone stratified, discontinuous. Mudstone weathers to "pencil" structure.

Mudstone. Light olive brown to olive gray (5Y5/6 to 5Y3/2). Sheen on weathered fractures.

Continue north on Highways 1, 2, and 63.

2.5 (36.0) Turn left (west) on Oklahoma Highways 1 and 63.

For the next three miles, the road crosses the same complex of folds and faults associated with the Ti Valley fault as was noted at mile 17.1.

3.3 (39.3) Cross Pine Creek.

1.8 (41.1) Leave Damon 7.5′ Quadrangle, enter Higgins 7.5′ Quadrangle.

1.6 (42.7) Cross ridge underlain by Atoka sandstones used to build Buffalo Valley School.

1.4 (44.1) Cross Gaines Creek.

The trace of a major thrust fault, possibly the Pine Mountain thrust of Hendricks and others (1947), approximately follows Gaines Creek in this area. The thrust mostly juxtaposes Atoka Formation against Atoka Formation. However, near Stop 4 a channel(?) of Johns Valley Shale is in the hanging wall to the south, and Atoka Formation is in the footwall to the north (see Stop 4). The imbricate nature of the thrust faults in the Higgins and Damon Quadrangles (Suneson and Ferguson, 1989a,b) suggests that attempting to relate (and name) faults over long distances is difficult, if not impossible. Suneson (1988, p. 44) similarly concluded that the name "Ti Valley" fault could not be extended from Ti Valley to the east.

0.4 (44.5) "Village" of Higgins.

On the right (to north) is a county road to Wilburton. Several wells (including the recently drilled Exxon 1 Mabry Trust), some dry and others productive, have been drilled along this road on and just over Blue Mountain (ridge on skyline).

2.9 (47.4) Re-cross Gaines Creek.

A major N–S transverse structure (Stop 4), buried beneath the alluvium of Gaines Creek, crosses the road here.

0.2 (47.6) Turn left (south) on county road.

Immediately cross eastern end of fourth Spiro/Wapanucka ridge (N 1/2 SE 1/4 sec. 14, T. 4 N., R. 17 E.) (see Hendricks and others, 1947; Suneson and Ferguson, 1989a).

1.4 (49.0) Stop 4, Transverse Structures in the Frontal Belt. Location: S 1/2 SE 1/4 SE 1/4 sec. 23, T. 4 N., R. 17 E.

STOP 4
TRANSVERSE STRUCTURES IN THE FRONTAL BELT

Neil H. Suneson
Oklahoma Geological Survey

The trace of a major transverse structure (tear fault? thrust ramp?) underlies the alluvium of Buffalo and Gaines Creeks immediately east of here. The evidence for the structure is shown on Figure 10 and can be summarized as follows:

1) East of the structure, the doubly repeated sequence (oldest to youngest) "Springer", Spiro/Wapanucka, lower Atoka shale, Atoka turbidites strikes into a repeated (fourfold) Spiro/Wapanucka, lower Atoka shale sequence to the west.

2) Strata east of the structure uniformally strike about N. 70° E. and face south. Strata west of the structure progressively change strike from N. 70° E. (S-facing), to E–W (S-facing), to N–S (W-facing), to N. 40° E. (NW-facing) as the structure is approached.

The exact nature of this structure is unknown; however, it is possible that the surface geology is reflecting an approximately N–S-striking basement fault or monocline with the west side up relative to the east side. This might explain the juxtaposition of older units to the west against younger units to the east at the surface.

Surface evidence for a basement fault or monocline does not extend north of the Choctaw fault where the NE-trending ridge of Desmoinesian Hartshorne Sandstone is not offset. Similarly, the surface structure does not extend more than 2 mi to the south, where sandstone marker beds in the Atoka Formation strike uninterruptedly N. 55° E. across the projected position of the structure.

Several other basement structures may be reflected in the surface geology in the frontal belt. One has already been described at mile 19.8. Another may be about 7.5 mi west of here (secs. 27 and 35, T. 4 N., R. 16 E.) at mile 61.9, where Atoka Formation turbidites underlying Blue Mountain strike into a doubly repeated "Springer," Wapanucka, lower Atoka shale sequence (mapping by Hendricks and others, 1947). The surface geology at the west end of Blue Mountain suggests an up-to-the-west basement structure, as at Stop 4. These and other structures farther southwest await confirmation or rejection by strike-parallel seismic work.

About 1 mi southwest of Stop 4 is a large, relatively well-exposed outcrop of an olistostrome similar to the Johns Valley Shale. The significance of this outcrop and another about 3 mi to the east with respect to the Ti Valley fault has been discussed by Suneson (1988). To summarize: Hendricks (1959) suggested that the Ti Valley fault had more displacement across it than any other single thrust fault in the Ouachitas, based partly on his observation that basinal Morrowan Johns Valley Shale to the south was juxtaposed against shelf Morrowan Wapanucka Limestone–Chicachoc Chert to the north across the fault. However, the rocks exposed here, and some noted by Cline (1960, p. 63) to the southwest in secs. 31 and 32, T. 2 N., R. 14 E., indicate that the Johns Valley Shale crops out north of the Ti Valley fault of Hendricks and others (1947). This suggests that the Ti Valley fault as identified and mapped by Hendricks and others (1947) may not be the single largest thrust fault in the Ouachita Mountains; in fact, in much of the frontal belt, it may be only one of many complexly imbricated thrust faults.

The very limited outcrop areas of the two Johns Valley Shale exposures here suggest that they may be filled channels originally located on the slope between the shelf (site of Wapanucka Limestone deposition) and basin (site of most Johns Valley Shale deposition).

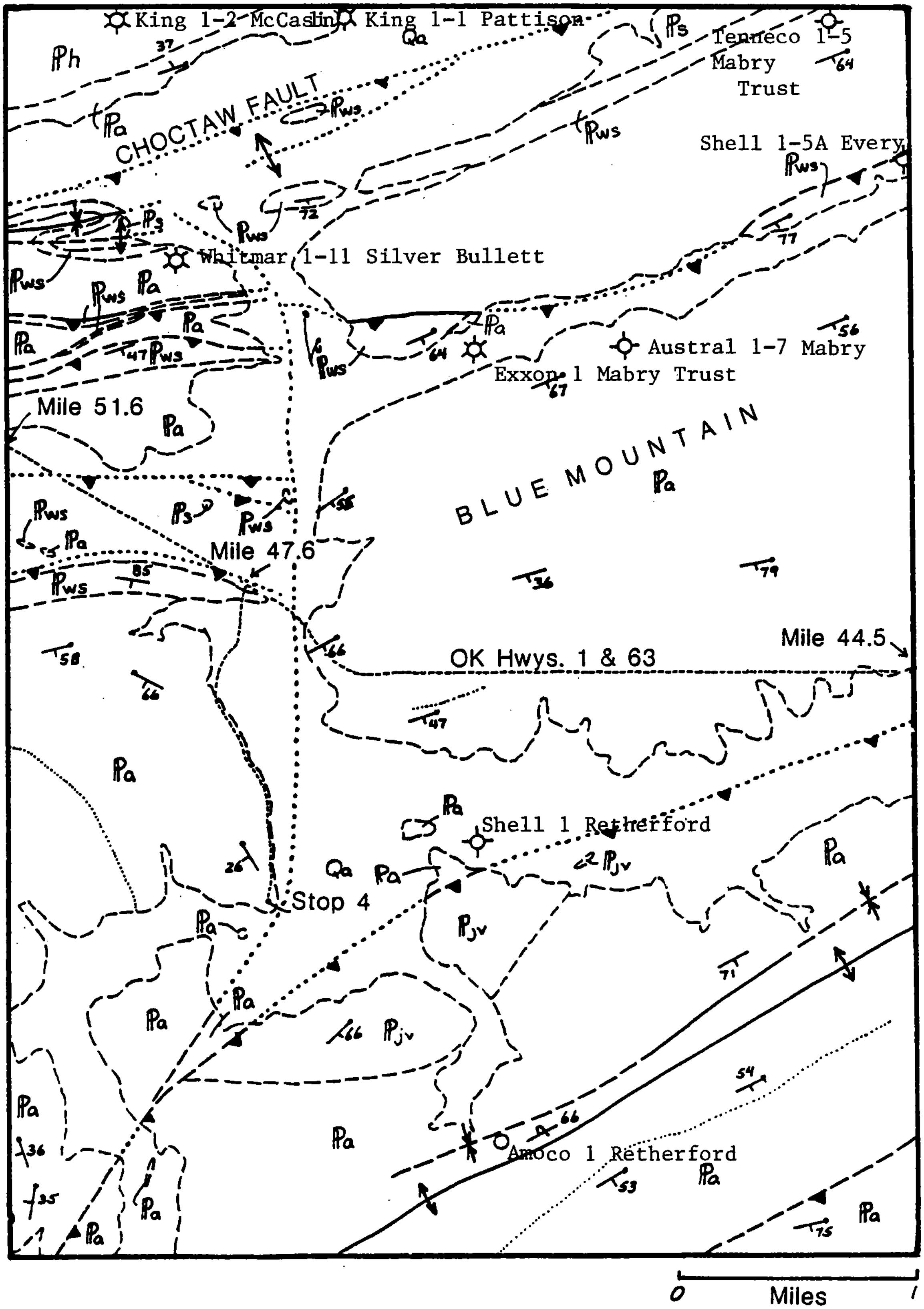


Figure 10. Geologic map of area near Stop 4. Symbols as in Figures 6 and 8, and .... marker bed in Atoka Formation; Ph = Hartshorne Sandstone; Pws = Wapanucka Formation and Spiro sandstone.

Retrace route to Oklahoma Highways 1 and 63.

1.4 (50.4) Turn left (west) on Oklahoma Highways 1 and 63.

1.2 (51.6) Leave Higgins 7.5′ Quadrangle, enter Hartshorne 7.5′ Quadrangle.

0.4 (52.0) Limestone Ridge.

This outcrop of Wapanucka Limestone was measured and studied by Grayson (1979, p. 69). He described the following rock types and environments of deposition: spicular limestone (low-energy, well-circulated lagoon); micritic limestone (low-energy, poorly circulated lagoon); calcarenites, including oolite, bioclastic calcarenite, limestone-pebble conglomerate (transition from subaerial through intertidal to shallow, agitated subtidal environments).

0.5 (52.5) Leave Latimer County, enter Pittsburg County.

0.3 (52.8) Cross surface trace of Choctaw fault as mapped by Hendricks and others (1947) and enter Arkoma basin. The low rise immediately northwest of here is underlain by very deformed Atoka Formation; the trace of the Choctaw fault may, in fact, be on the northwest side of this low rise.

0.7 (53.5) Ridge of Desmoinesian Hartshorne Sandstone.

0.6 (54.1) Intersection of Oklahoma Highways 1 and 63 and U.S. Highway 270 to Wilburton. Continue west on Highways 1, 63, and 270 toward Hartshorne and McAlester.

HARTSHORNE GAS FIELD

The Hartshorne gas field was discovered in 1941 by the Public Service Co. No.1 Craig (NE 1/4 SE 1/4 NE 1/4 sec. 9, T. 4 N., R. 16 E.). Scout tickets show the well as the Public Service Co. No. 1 Tribal Land, and Corporation Commission Form 1002A lists the well as the C. W. McIlhenny No. 1 Tribal Choc-Chic. The well spudded on November 29, 1941, and drilling finished on November 29, 1941, at 1,655 ft TD. The well was plugged back to 1,280 ft and completed in the Hartshorne sand from 1,204 to 1,280 ft. Initial production was 2 MMcfgd. In 1987, the field name was discontinued and the area was included within the Wilburton field.

0.7 (54.8) Hartshorne City Hall.

0.5 (55.3) Turn left (south) on 7th Street (at Sonic Drive-In).

0.8 (56.1) Cross very low ridge of Hartshorne Sandstone overlying Atoka Formation.

0.5 (56.6) Cross trace of Choctaw fault as mapped by Hendricks and others (1947).

0.2 (56.8) Turn left (east) to enter Dolese quarry.

0.9 (57.7) Entrance to Dolese limestone quarry. Please wear sturdy boots, hardhats, and safety glasses at all times while in the quarry. This is a federal regulation. Our hosts, Dolese Brothers, have an excellent safety record and want it to continue.

Stop 5, Wapanucka Limestone at Dolese Quarry. Location: N 1/2 N 1/2 sec. 17, T. 4 N., R. 17 E.

STOP 5
WAPANUCKA LIMESTONE AT DOLESE QUARRY

Neil H. Suneson
Oklahoma Geological Survey

The Wapanucka Limestone is a prolific gas producer to the southwest in the Pittsburg and South Blanco fields (see Day Two, miles 1.0 and 6.3); in the South Blanco field, it produces from multiply thrust-faulted and repeated Wapanucka reservoirs above the Choctaw fault. In the Pittsburg field and locally in the Wilburton field, Wapanucka production is from strata beneath the Choctaw fault. Sub-thrust Wapanucka is about 12,500 ft deep beneath the quarry, based on tops from the TXO No. 1 Wright (NW 1/4 sec. 18, T. 4 N., R. 17 E.) drilled in 1985 on Limestone Ridge about 1 mi west of the quarry.

The stratigraphy of the limestone in the Dolese quarry has not been studied in detail; however, Grayson (1980) measured the Wapanucka in the old Hartshorne quarry in the NW 1/4 NW 1/4 sec. 18, T. 4 N., R. 17 E., about 1 mi west of the Dolese quarry, and in Carlton's quarry in the SE 1/4 SE 1/4 sec. 9, T. 4 N., R. 17 E., about 1.5 mi east of the Dolese quarry. The dominant rock type exposed at the Hartshorne quarry is micritic limestone; Grayson (1980) suggested that the Wapanucka micritic-limestone facies accumulated in a mostly subtidal, lagoonal environment, characterized by low-energy deposition and poor marine water circulation. Other important rock types exposed at the Hartshorne quarry are bioclastic limestone, spicular limestone, and spicular chert. In contrast, the dominant rock type at Carlton's quarry is spicular limestone. Grayson (1980, p. 85) interpreted the spicular limestones on Limestone Ridge to have been deposited in "near shore settings proximal to marshes through relatively deeper, stagnant water, and lagoons," based on his observation that they intertongue with and grade into shallow-water, micritic limestones. Other important rock types in Carlton's quarry are micritic limestone and shale.

In addition to examining the different rock types that constitute the Wapanucka at the Dolese quarry, we will be able to collect coaly material interbedded in the limestone. In most places, this material is parallel to laminations in the limestone, but locally it is oblique to bedding and may fill fractures, suggesting that it was once mobile. Is this material more properly called "dead oil" or asphaltite?

Overlying the Wapanucka Limestone we will observe the Spiro sandstone and a shale that separates the Spiro and Wapanucka. The base of the Spiro is locally a channel that clearly eroded into the underlying shale. Grayson (1980, p. 69) recognized that the Spiro generally conformably overlies a shale (his middle shale member) that separates the Spiro and Wapanucka, but that locally (as in this area) the Spiro is in erosional contact with the shale.

Return to quarry entrance.

Retrace route to 7th Street.

0.9 (58.6) Turn left (south).

0.1 (58.7) Road forks. Bear right (west).

0.2 (58.9) Hartshorne Lake on left.

0.5 (59.4) Dipslope of Spiro sandstone on right (north), on south side of Limestone Ridge.

1.7 (61.1) Bear left (south) on paved road.

0.7 (61.8) Cross low ridge of Wapanucka Limestone. This is the same ridge as at mile 47.6.

0.1 (61.9) Cross Blue Creek.

For the next 2 mi, the road passes around the west end of Blue Mountain. ENE-striking Atoka turbidites on Blue Mountain to the east strike into a doubly repeated "Springer" Formation, Spiro/Wapanucka, and lower Atoka shale sequence to the west. The surface geology is similar to that described at Stop 4 and could be interpreted as a similar transverse structure (thrust ramp?) that reflects basement structures.

3.8 (65.7) Top of New State Mountain (Blue Mountain to local residents). Turn right (west) on drill road.

2.4 (68.1) Leave Hartshorne 7.5′ Quadrangle, enter Hartshorne SW 7.5′ Quadrangle.

0.8 (68.9) Stop 6, New State Mountain (Amoco 1-5 Rosso Unit). Location: SE 1/4 NE 1/4 SE 1/4 sec. 5, T. 3 N., R. 16 E.

STOP 6
NEW STATE MOUNTAIN
(AMOCO 1-5 ROSSO UNIT)

Dave L. Reeves, W. Phil Schreiner, T. Mike Sheffield
Texaco USA

SURFACE

A panoramic view of the Ouachita frontal zone of the Arkoma basin is available from the Amoco Rosso Unit on New State Mountain (Fig. 11). Looking to the north, the closely spaced ridges are the surface expression of a complex series of imbricate fan thrusts. These thrusts, involving primarily the Spiro (Atokan) and Wapanucka (Morrowan), mark the boundary between the Ouachitas to the south and the Arkoma basin proper to the north. Measured surface dips along these thrusts range from 30 to 80°, generally decreasing with depth. The northernmost ridge, Limestone Ridge, is the surface expression of the Choctaw thrust. To the north of Limestone Ridge are the Haileyville syncline and Craig anticline, the surface expressions of a zone of complex folding and faulting near the front edge of the Choctaw thrust. Still farther to the north, entering the heart of the Arkoma basin, is the Kiowa syncline. Desmoinesian shales and sands are exposed throughout the area north of the Choctaw thrust (Limestone Ridge).

SUBSURFACE

Subsurface structure is not normally directly relatable to the surface or near-surface structure. Complex structures involving Desmoinesian through Morrowan sediments are separated from the overlying Haileyville and Craig surface structures by a series of thrusts. Example lines 1 and 2 (Figs. 11–13) are migrated dynamite seismic lines that show the extensive thrusting of the Spiro/Wapanucka section which underlies virtually all of the area. Underlying these structures is a normally faulted Paleozoic section where an Arbuckle Group play is currently being made.

SEISMIC

Line 1 (Fig. 12) shows the southwestern subsurface extension of the Craig anticline near the center of the section, and the Kiowa syncline on the northwestern end of the section. Spiro/Wapanucka imbricate thrusts are shown in the southeastern to central parts of the section. Normally faulted Paleozoic strata can be seen throughout the section. The general trend of these faults is down to the south/southeast. Notably, there are indications of a Paleozoic low/syncline below the Craig anticline.

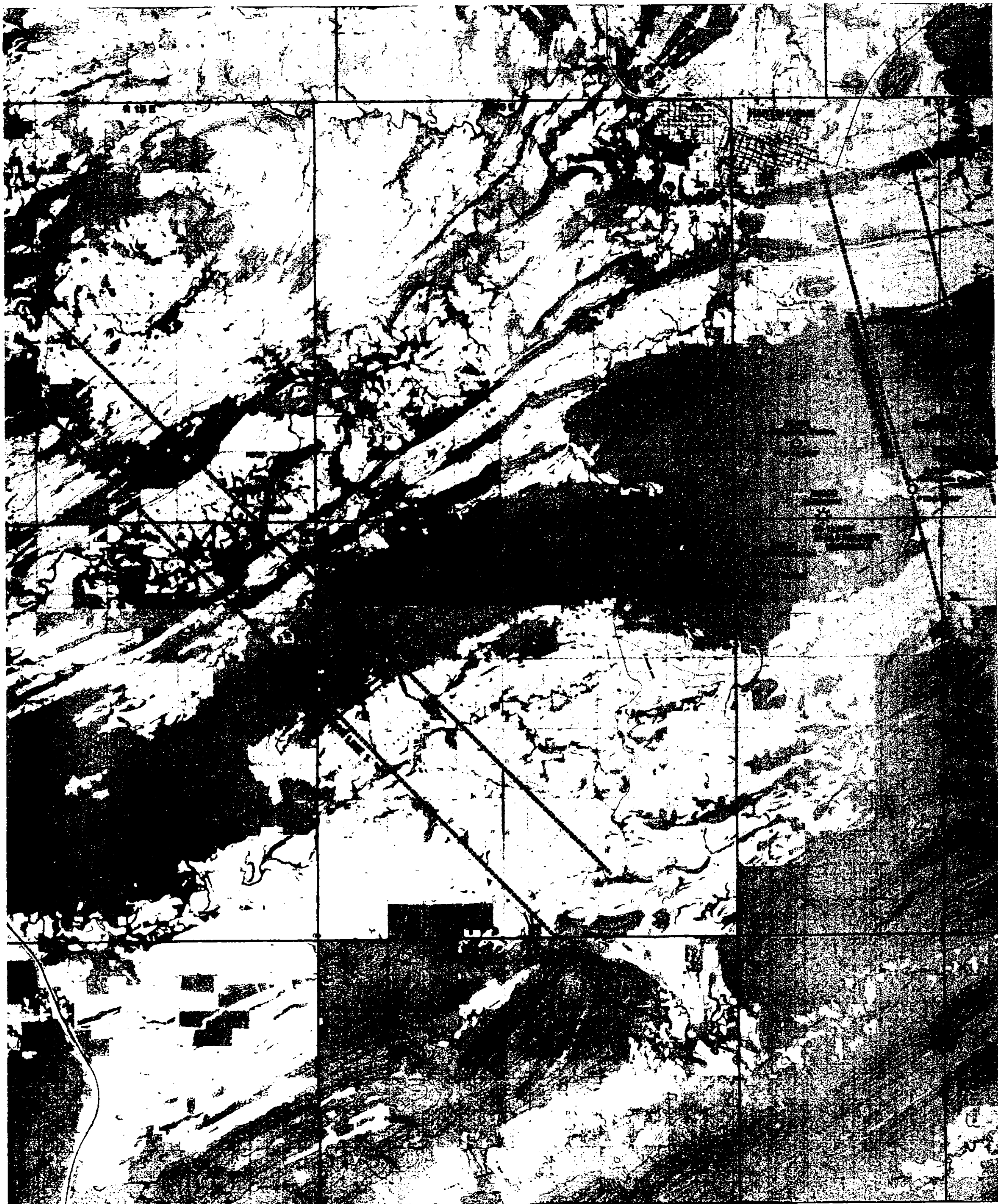
Highlighted on Line 2 (Fig. 13) are a succession of fairly small, deep thrust plates involving the Spiro/Wapanucka; these thrusts have undergone relatively little movement compared to the Choctaw thrust above them, which has experienced significant movement and has significant areal extent.

ACTIVITY

To the west of the Rosso Unit, the Texaco J. A. Goddard Unit has discovered significant middle Atokan reservoirs. Amoco's Scott Unit has confirmed and enhanced this play, and this area will see continued activity. East of the Rosso Unit, numerous wells have been drilled to a variety of deep, thrusted structures. Significant discoveries include the Amoco Garrett (Spiro/Cromwell), Amoco Zipperer (Spiro/Wapanucka), and Texaco Wallace (Spiro/Wapanucka).

End of road log for Day One.

RECENT ACTIVITY & EXAMPLE LINE LOCATIONS



NOTE: ALL LOCATIONS ARE APPROXIMATE SURFACE LOCATIONS.

FIGURE 11

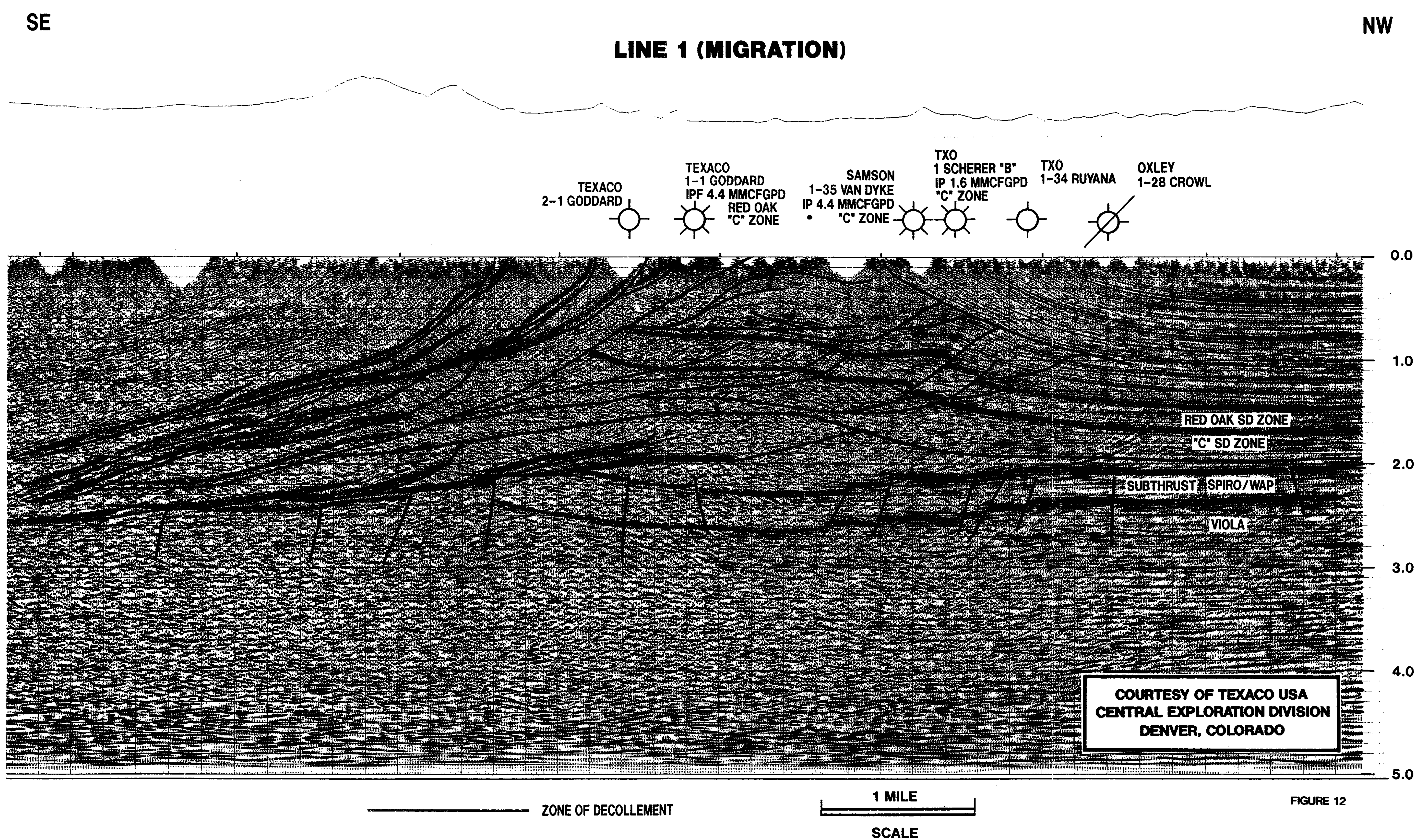

SE
NW
LINE 1 (MIGRATION)
TEXACO 2-1 GODDARD
TEXACO 1-1 GODDARD IPF 4.4 MMCFGPD RED OAK "C" ZONE
SAMSON 1-35 VAN DYKE IP 4.4 MMCFGPD "C" ZONE
TXO 1 SCHERER "B" IP 1.6 MMCFGPD "C" ZONE
TXO 1-34 RUYANA
OXLEY 1-28 CROWL
0.0
1.0
2.0
3.0
4.0
5.0
RED OAK SD ZONE
"C" SD ZONE
SUBTHRUST
SPIRO/WAP
VIOLA
COURTESY OF TEXACO USA
CENTRAL EXPLORATION DIVISION
DENVER, COLORADO
ZONE OF DECOLLEMENT
1 MILE
SCALE

FIGURE 12

LINE 2 (MIGRATION)

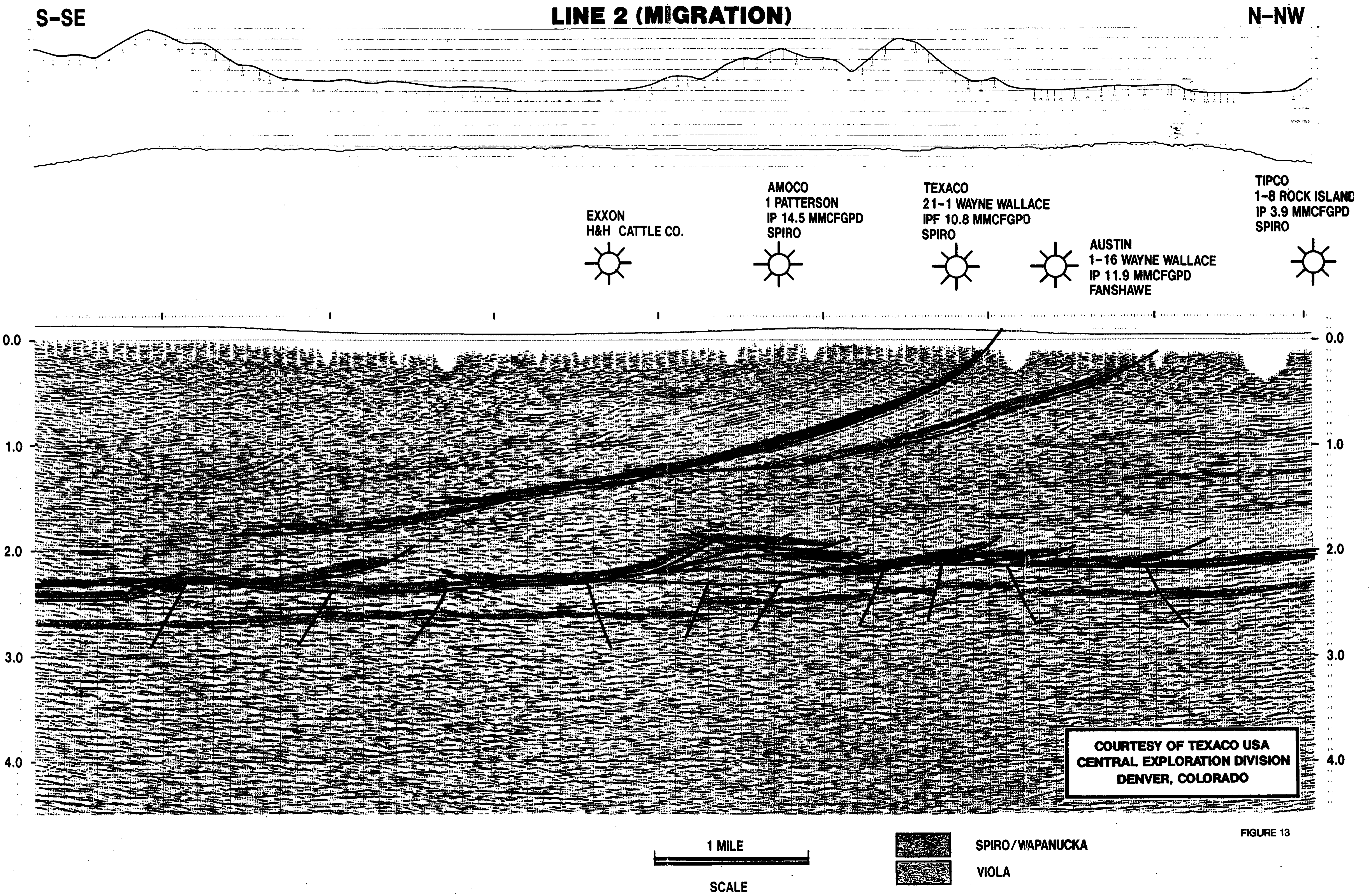


FIGURE 13

ROAD LOG—DAY TWO

Figure 14 is a generalized geologic map showing field-trip stops for Day Two.

0.0 (0.0) Start road log at intersection of U.S. Highway 69 and Oklahoma Highway 63 in Kiowa.

Drive east on Highway 63 through Kiowa.

1.0 (1.0) Cross north-south section-line road. Enter sec. 19, T. 3 N., R. 14 E. and Pittsburg gas field.

PITTSBURG GAS FIELD

The Pittsburg gas field was discovered by the Hamilton Brothers No. 1 Chitty-Scott (N1/4 SW1/4 NE 1/4 sec. 30, T. 3 N., R. 14 E.), which spudded on September 27, 1978, and finished drilling on November 27, 1978, at 10,440 ft TD. Formation tops as reported to the Corporation Commission are Hartshorne at 517 ft (+266 ft), Atoka middle sand at 4,930 ft (–4,147 ft), Atoka lower at 8,784 ft (–8,001 ft), Wapanucka at 9,358 ft (–8,575 ft), Cromwell upper at 10,250 ft (–9,467 ft), Cromwell lower at 10,320 ft (–9,537 ft). The Cromwell tested 2.2 MMcfgd from perforations at 10,279 to 10,284 ft and 10,330 to 10,349 ft, and the Wapanucka tested 4.65 MMcfgd from perforations at 9,381 to 9,525 ft.

The South Pittsburg field is now included with the Pittsburg field, which contains the following sections: secs. 5–8, 17, and 18, T. 2 N., R. 14 E.; sec. 25, T. 3 N., R. 13 E.; and sec. 8–10, 16–22, and 27–32, T. 3 N., R. 14 E. (Fig. 15). Within this 23-mi^2 area, there are 28 producing wells and 5 dry holes. There are 27 completions in the Wapanucka Limestone and 10 in the Cromwell Sandstone. Three of the dry holes, including two early attempts in 1967 and 1968, did not penetrate the Wapanucka. As of the end of 1987, the field had produced 26.4 Bcfg. Richardson (1986) stated that, of the 23 producing wells in the field at that time, 9 contained more than 3 Bcfg reserves per well, 3 wells had 1–3 Bcfg, and 11 had less than 1 Bcfg.

Recently, exploration efforts by Texaco, Inc. and Amoco Production Co. have extended the one-well Wesley field (sec. 35, T. 2 N., R. 13 E.) to the northeast toward the Pittsburg field. The Texaco 25-1 Chastain in sec. 25, T. 2 N., R. 13 E. tested 2.8 MMcfgd from Wapanucka perforations at 11,062 ft to 11,240 ft. The 25-1 Chastain is about 2 mi southwest of the Pittsburg field.

0.4 (1.4) Leave Kiowa 7.5′ Quadrangle, enter Pittsburg 7.5′ Quadrangle.

1.6 (3.0) Highway 63 turns left (north) on the east side of the small town of Pittsburg. Field-trip route turns right (south) on county road.

0.3 (3.3) Hendricks and others (1947) mapped the trace of the Choctaw fault through the town of Pittsburg.

0.2 (3.5) Turn left (east).

0.2 (3.7) Cross Chun Creek. Road turns right (south).

0.4 (4.1) Turn left (east). Road cuts through Limestone Ridge.

Road parallels and is immediately south of E-W-striking, steeply S-dipping (40–60°) Spiro/Wapanucka on Limestone Ridge. This is the first major exposure of the Spiro/Wapanucka south of the Choctaw fault.

1.1 (5.2) Turn right (south).

Hendricks and others (1947) mapped two thrust faults in this valley; the southern fault juxtaposes "Springer" Formation in the hanging wall to the south against lower Atoka shale in the footwall to the

0.6 (5.8) Turn left (east).

0.5 (6.3) Cross section line into secs. 26 and 35, T. 3 N., R. 14 E. Leave Pittsburg gas field, enter South Blanco gas field.

SOUTH BLANCO GAS FIELD

The South Blanco field, encompassing secs. 2 and 11, T. 2 N., R. 14 E.; secs. 24–26 and 33–36, T. 3 N., R. 14 E.; secs. 16, 19–21, and 29–32, T. 3 N., R. 15 E., (Fig. 15) is unique among the major frontal-belt gas fields because it produces mostly from multiply thrust-faulted Wapanucka Limestone, in contrast to the Pittsburg field immediately to the south, where the principal reservoir is below most of the major thrusts. The South Blanco field was discovered in 1982 by the Hamilton Brothers 1-30 Indian Nation. The well spudded on October 2, 1981, and drilling finished on March 10, 1982, at 10,293 ft TD. The well was tested at 2.65 MMcfgd from lower Wapanucka perforations at 8,965 to 8,750 ft, and 2.5 MMcfgd from upper Wapanucka perforations at 6,018 to 5,970 ft. Petzet (1982, p. 48) reported 3.5 and 1.7 MMcfgd, respectively, from the two intervals. Hardie (1988, p. 237, cross section C–C′) interpreted both producing zones to be above a basal detachment fault that underlies the Choctaw fault.

As of December 31, 1988, the South Blanco field consisted of 18 wells. As of the end of 1987, the field had produced just over 21 Bcfg.

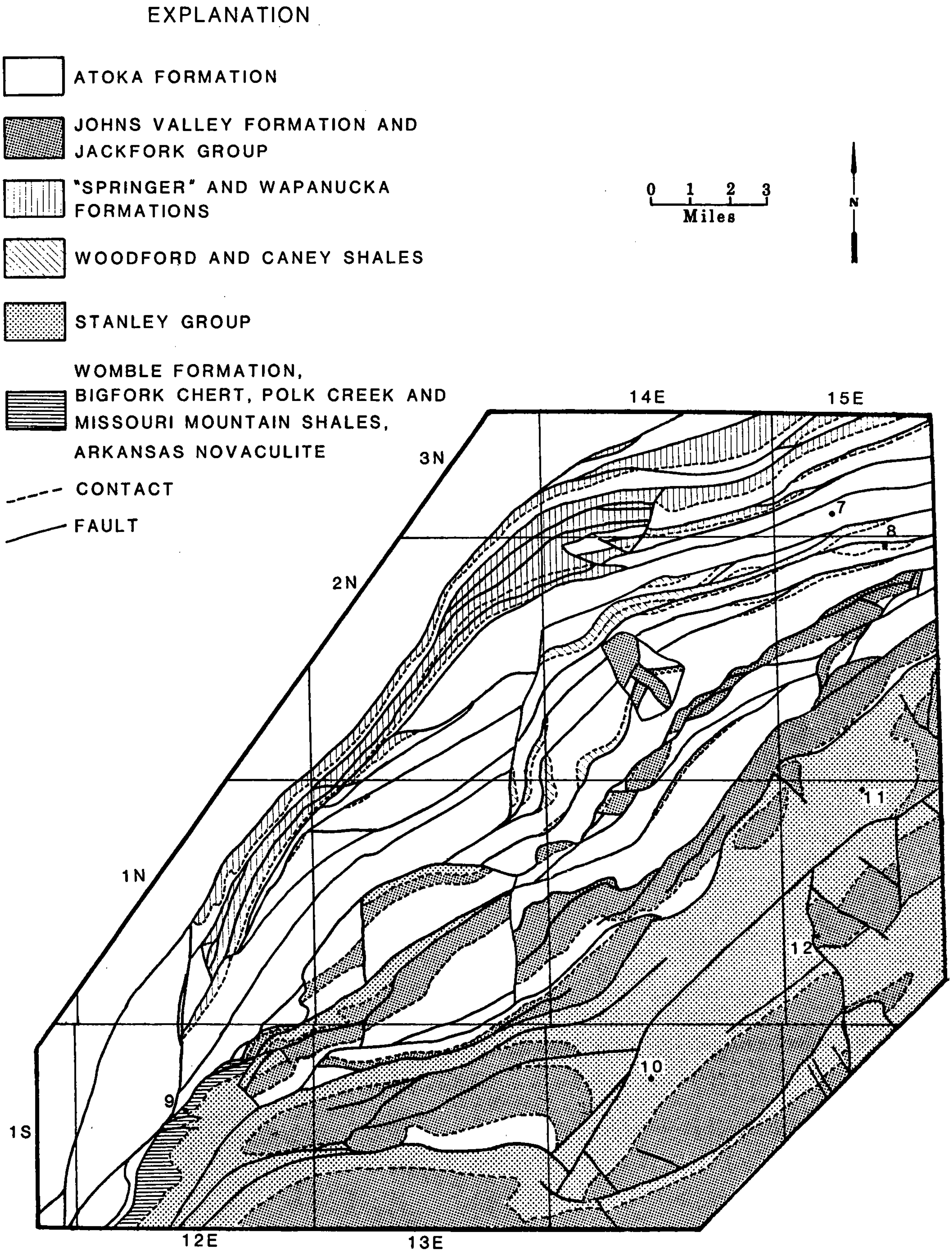


Figure 14. Generalized geologic map showing field-trip stops on Day Two.

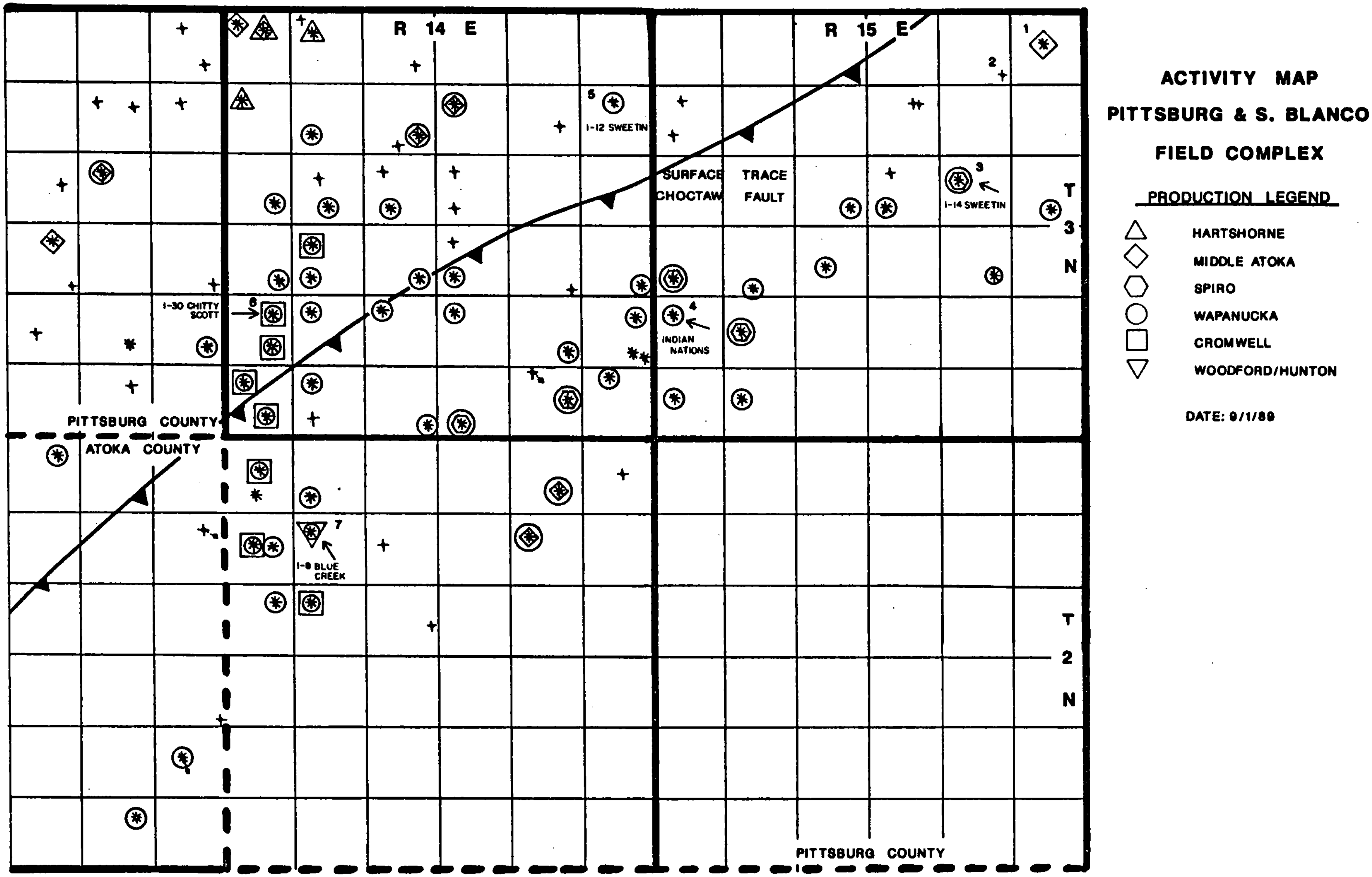


Figure 15. Map showing wells drilled near Pittsburg, South Blanco, and adjacent gas fields. Wells drilled for objectives shallower than the Hartshorne Sandstone are not shown.

1.7 (8.0) County road intersection. Road to left (north) goes to small town of Blanco. Continue straight ahead (east).

0.7 (8.7) Road curves gently to left. The low ridge immediately to the north is underlain by Chicachoc Chert, the basinward equivalent of the lower part of the Wapanucka Limestone.

0.2 (8.9) Road swings right and parallels the Indian Nation Turnpike.

0.9 (9.8) Stop 7, Atoka Formation, Brushy Narrows Section, Indian Nations Turnpike. Location: C E 1/2 W 1/2 sec. 32, T. 3 N., R. 15 E.

STOP 7
ATOKA FORMATION, BRUSHY NARROWS SECTION, INDIAN NATIONS TURNPIKE

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BRUSHY NARROWS SECTION

The measured thickness of this section, corrected for a 75° S dip, is 222 m (Fig. 16). The section starts 220 m south of the bridge on the west side of the frontage road on the west side of the Indian Nations Turnpike, SW 1/4 SE 1/4 NW 1/4 sec. 32, T. 3 N., R. 15 E., and continues south. The lower part of the section (to the north) at this outcrop was not measured, because of poor exposure. The unmeasured part of the outcrop consists predominantly of shale, some of which may be slumped, perhaps containing displaced blocks of sandstone. The top of the Atoka Formation is not exposed and is probably cut by the Pine Mountain fault, which is just south of the section. The section is probably 600–1,000 m above the Wapanucka Formation (Ferguson and Suneson, 1988). We have identified 7 facies at this section, described below.

F1) Faintly horizontally bedded to massive, fine-grained sandstone; base typically contains sole marks, including horizontal burrows, load casts, and scour and tool marks.

F2) Well to faintly laminated sandstone with undulose to swaley bedding.

F3) Highly contorted sandstone with some apparently truncated tops.

F4) Thin, planar-bedded sandstone.

F5) Rippled sandstone, commonly containing shale flasers, shale clasts, and plant debris. Some ripples have linguoid morphologies. F5 occurs with other sandstone facies, as well as in isolated beds.

F6) Dark-gray, marine shale which is silty in some intervals and contains bioturbated zones.

F7) Thin, isolated, undulose sandstone beds.

Using sand/shale ratios, bed thicknesses, and facies associations, we divide this section into 6 sequences (Fig. 16). The facies associations and sandstone characteristics for each of the six sequences are described below.

Sequence 1 contains 14 sandstones that are up to a meter thick. Other, thinner sandstones occur within thicker (6-m) shale intervals. There is an overall up-sequence decrease in the sand/shale ratio. Many individual sandstone packages have a vertical facies succession of F1 through F5. Tool and scour marks on bed bases have various azimuths, but the predominant current sense is N–S. Minor, slickensided, syndepositional faults suggest a south-facing paleoslope. In marked contrast to the bottom markings, rippled tops suggest west-to-east paleocurrents.

Sequence 2 fines upward and has thinner sandstones than Sequence 1. F2 and F4 make up the lower part of some sandstones. Some bases are burrowed and some have scour and tool marks which are oriented E–W, perpendicular to the prevalent sense of tool marks in Sequence 1. The upper part of most sandstones has ripples (F5) that indicate west-to-east paleocurrents, like the ripples in Sequence 1. Contorted bedding (F3) is uncommon. The uppermost sandstone in Sequence 2 contains swaley bedding (F2), which is similar to hummocky cross-stratification.

Sequence 3 is a shaly interval having more than 20 thin (<30 cm) sandstones, which commonly cap coarsening-upward subsequences about 1.5 m thick. Individual sandstones tend to be either massive (F1) or rippled (F5), and many beds pinch and swell along strike. In some beds, massive sandstones grade up into rippled sandstones. The ripples indicate west-to-east paleocurrents, as do rare tool marks.

Sequence 4 is predominantly dark marine shale (F6) with a few thin (8–10 cm), rippled sandstone interbeds in the lower part of the sequence. The number of thin sandstones increases in the middle part of the sequence.

These sandstones have climbing ripples and beds that pinch and swell (F7).

Bottom markings are common. The upper part of the sequence is composed of massive (F1) to flaser-bedded (F5) sandstone 2–25 cm thick. Some beds are rippled from base to top. In places these upper sandstones have channeled bases.

Sequence 5 consists of five (approximately 0.6 m) massive sandstones separated by poorly exposed, thinly interbedded sandstones and shales. Some of the massive sandstones cut steeply into the underlying shale. Woody debris is abundant. Sole marks are common, and tops are generally rippled and contain abundant shale clasts. One bed appears to be a series of disrupted blocks.

Sequence 6, the uppermost unit, is a poorly exposed shaley sequence with widely spaced, thin (2–3 cm), massive to rippled sandstones that may occur in coarsening-upward packages.

DISCUSSION

Some of the sandstone beds at the Brushy Narrows section resemble turbidites. Although turbidites may be present at this locality, we believe that most of the sandstones were deposited by storm processes.

The sandstones in Sequence 1 have vertical facies successions (F1 through F6) which resemble Tabcd Bouma sequences, but they are also similar to certain storm deposits (Fruit and others, this volume). Features seen at this section which are not commonly associated with turbidites include

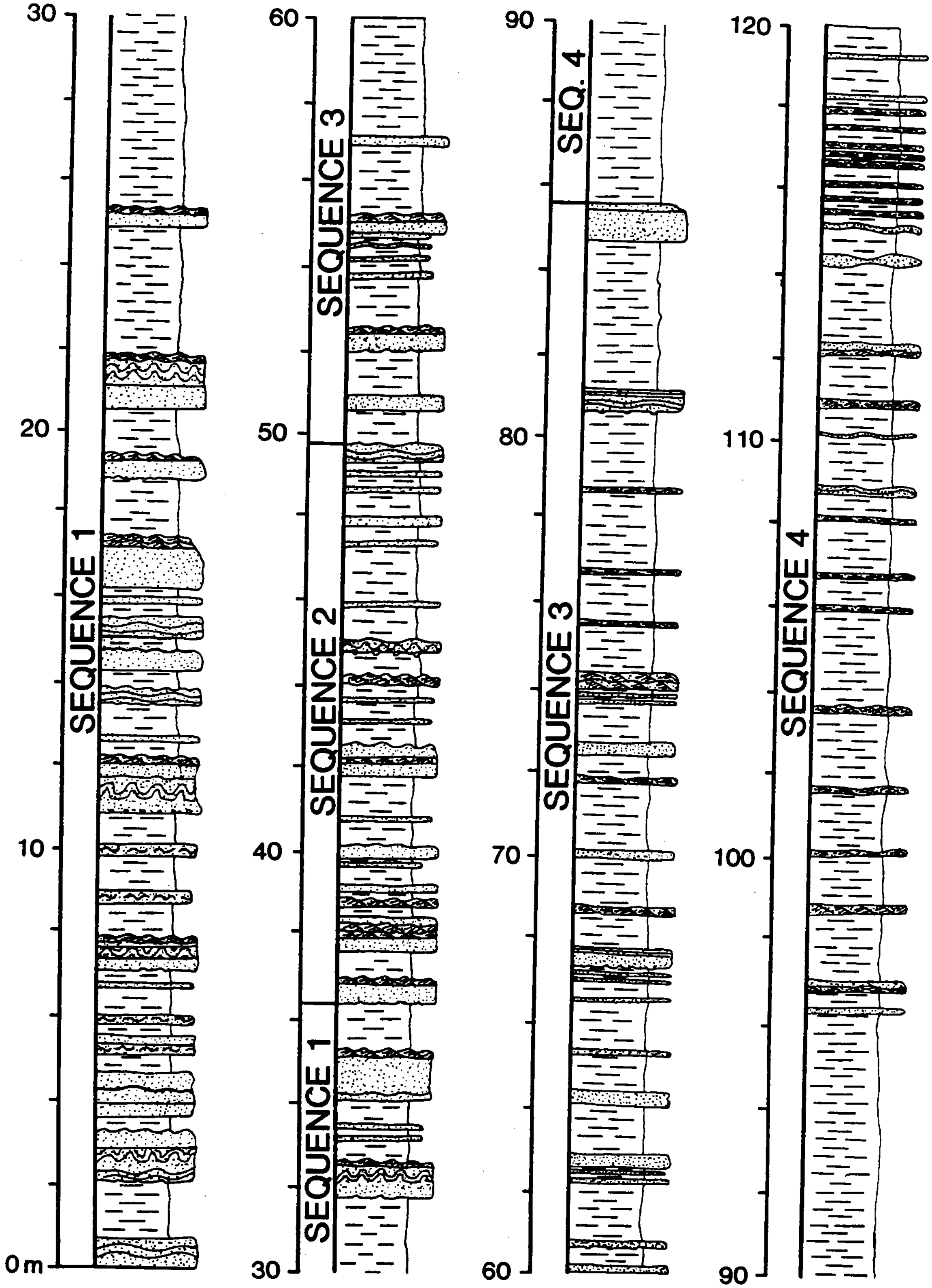

Figure 16. Graphic columnar section for Stop 7, Brushy Narrows Section.

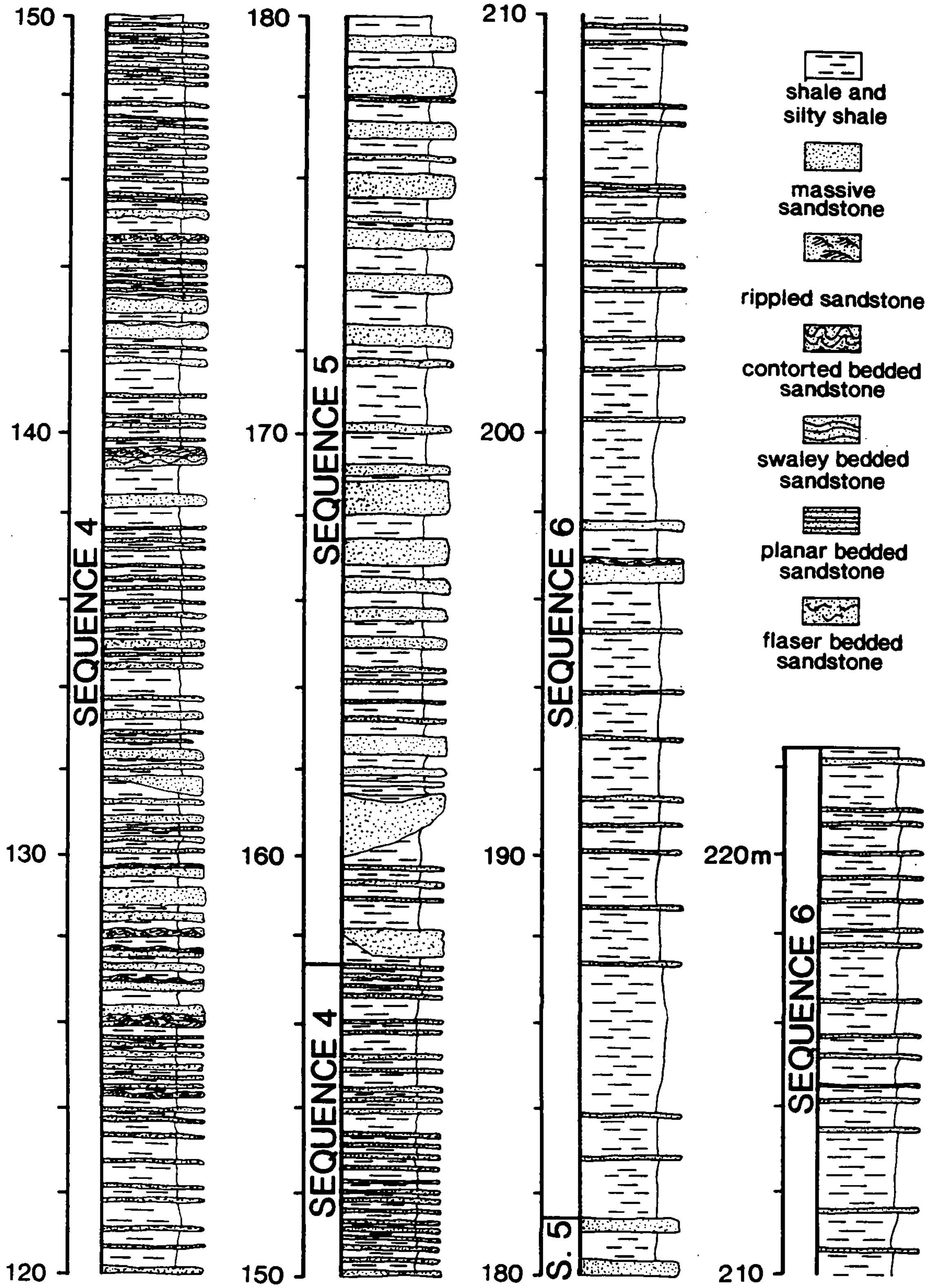

Figure 16. *Continued.*

flaser-bedded sandstones (F5), beds composed of multiple stacks of climbing ripples, thin beds that pinch and swell, and the swaley bedding (F2), which is similar to hummocky cross-stratification. There are also a few true flute casts.

Evidence supporting a storm interpretation includes multi-directional sole marks, the variability of facies sequences with individual sandstones, shale partings with sandstones, and the lenticular pinch and swell of some beds (Fruit and others, this volume). Notable features of this section include the apparent truncation of the contorted sandstones (F3) by thin, plane-bedded sandstones (F4). Most bed tops are rippled (F5). It is also interesting that the bottom markings and soft-sediment faults in Sequence 1 indicate flow down a south-facing slope, whereas rippled tops indicate west-to-east flow directions. Plant debris is abundant in some beds, some pieces being more than a foot long.

While many well-documented sections of Atokan turbidites are found in the literature, alternative explanations should be considered for sections such as the Brushy Narrows outcrop, which contains many features difficult to explain using a turbidite model.

Continue south parallel to Indian Nation Turnpike.

0.2 (10.0) Cross Brushy Creek.

0.5 (10.5) Leave Pittsburg 7.5′ Quadrangle, enter Ti 7.5′ Quadrangle.

0.5 (11.0) Road intersection with bridge over turnpike. Turn left (east) and go over turnpike.

0.7 (11.7) Stop 8, Pinetop Section. Location: C NW 1/4 NE 1/4 sec. 4, T. 2 N., R. 15 E., along and south of county road immediately east of hill at 742 ft.

STOP 8
PINETOP SECTION

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These exposures were visited as part of the Tulsa Geological Society's 1947 field trip, led by Tom Hendricks. (This publication is the single best guidebook to the western Ouachita Mountains frontal belt.) The exposed section consists predominantly of three units: the Pinetop Chert (equivalent to part of the Devonian Hunton Group in the Arkoma basin, and to the Arkansas Novaculite of the "Ouachita"-facies strata to the south), the Devonian Woodford Shale, and the Mississippian Caney Shale. The Woodford and Caney are part of the "Foreland"-facies sequence found in the Arkoma basin and Arbuckle Mountains. The exposed section was measured by Hendricks and Gardner (Tulsa Geological Society, 1947, p. 23–24) and is shown on Figure 17, with additional observations by Campbell and Suneson. This outcrop affords an excellent opportunity to examine some key formations rarely exposed in the Ouachitas. More questions than answers are raised by these exposures; they focus on (1) the nature of the transition from lower to mid-Paleozoic "Foreland"-facies carbonates and clastics in the Arkoma basin to the north to deeper-water cherts and shales ("Ouachita" facies) to the south, and (2) the nature of the various olistoliths (exotic boulders and blocks) in the Morrowan Johns Valley Shale.

PINETOP CHERT

The Pinetop Chert was named by Miser (1934, p. 974) for exposures near Pinetop School in sec. 5, T. 2 N., R. 15 E. Amsden (1983) also described the biostratigraphy of the Pinetop at this locality and correlated it with the Helderbergian (lowermost Devonian) Haragan and Bois d'Arc Limestones of the Hunton Group. In addition, Amsden (1983, p. 1249) noted that the environment of deposition of the Pinetop ("restricted environment, probably offshore, moderately deep water") was significantly different from "typical" (our quotation marks) Haragan–Bois d'Arc carbonates ("warm, shallow-water, shelf environment"). The Pinetop also differs lithologically from the correlative lower division of the Arkansas Novaculite exposed in the Potato Hills and at Black Knob Ridge.

This outcrop of Pinetop Chert may be critical for addressing the following: Does the Pinetop Chert represent the transition from "Foreland"- to "Ouachita"-facies strata for the Lower Devonian? If so, in what environment was it deposited relative to the shelf to the northwest and the basin to the southeast?

JOHNS VALLEY FORMATION

Hendricks (1959), in addition to many earlier workers, suggested that the Johns Valley Formation was restricted to the area south of the Ti Valley fault. However, Cline (1960, p. 63) and Suneson and Ferguson (1989a) (see also Stop 4, this guidebook) noted boulders similar to those typically found in the Johns Valley north of the Ti Valley fault as mapped by Hendricks and others (1947). Suneson and Ferguson (in prep.) interpreted the large outcrop of Woodford Chert–Caney Shale near Bengal, Oklahoma (C NW 1/4 SW 1/4 sec. 11, T. 4 N., R. 21 E.) (Kramer, 1933; Fellows, 1964), as a large olistolith in the Johns Valley Formation. This contrasts with the interpretation of Hendricks and others (1947), who believed that these large outcrops of Devonian and Mississippian cherts and shales marked the base of the hanging walls of major thrust faults, and who mapped some thrusts accordingly. Is it possible that the many large outcrops of (Pinetop)–Woodford–Caney–"Springer" in the frontal belt north of the Ti Valley fault are stratigraphically allochthonous, that is, are large, stratigraphically coherent landslide or debris-flow blocks that are part of the Lower Pennsylvanian section (Johns Valley?) below the Atoka Formation? Are these outcrop belts derived from the north as debris flows (and later moved to the north as parts of thrust sheets), or are they derived entirely from the south as parts of thrust sheets? Do the smaller fragments of Woodford Chert and Caney Shale that are common in the more "classic" Johns Valley to the south merely represent the more broken, basinward equivalent of the large, coherent blocks similar to that at this stop?

HYDROCARBONS

Production

In 1983, Martingale Resources drilled the 2W Lambert (NW 1/4 NE 1/4 SW 1/4 sec. 6, T. 1 N., R. 14 E.) downdip from an outcrop of Woodford Chert–Caney Shale. Based on mapping by Hendricks and others (1947) and surface dips (which are variable and difficult to accurately determine due to poor exposures), the expected wellbore geology would be: spud in Atoka, top "Springer" at 800 ft, top Caney at 1,050 ft, top Woodford at 1,600 ft, fault and top Atoka at 2,100 ft. The drilled geology was interpreted as Atoka at 300 to 650 ft, "Springer" at 733 to 1,100 ft, Woodford at 1,100 to 1,648 ft, and Misener at 1,648 to 1,682 ft, TD 2,992 ft (Oklahoma Corporation Commission Form 1002A). The drilled geology was remarkably similar to the expected geology, with the exception of the Misener. The well tested 32 bopd, 43.5 API gravity, from Misener(?) perforations at 1,649 to 1,682 ft; it is the discovery well for the East Wesley field.

The Misener sandstone is a widespread post-Hunton, pre-Woodford sandstone in northern and central Oklahoma. However, it does not crop out anywhere in the Ouachita Mountains, nor is it present in the subsurface in the Arkoma basin. Three alternatives to the "Misener" producing interval seem possible: (1) fractured Woodford Chert; (2) a sandstone

Pinetop chert. Section exposed in small stream, NW¼ NE¼ sec. 3, T. 2 N., R. 15 E., Pittsburg County. Base of section on north side of road. Measured by T. A. Hendricks and L. S. Gardner.

Springer formation

	Feet
1. Shale, poorly exposed, pale gray, clayey, contains limonitic concretions	20

Caney shale

2. Shale, black, soft	85
3. Shale, black, cherty, blocky but weathers to plates	2
4. Shale, black, fairly soft with a few one-inch bands of hard shale. Weathers into small flakes and finally to red and gray mottled clay. Contains some phosphatic nodules	184
5. Shale and siltstone, black, hard, in layers 1/16 to one inch thick. Much harder than beds above and below and forms small ridge	8
6. Shale, black, hard, platy in layers 1/16 to ⅛ inch thick, weathers into plates and small flakes. Some layers are harder and stand as small ridges	100
7. Shale, black, hard, platy, weathers to small flakes, contains septarian concretions	50
8. Shale, greenish gray, hard, breaks into small angular fragments	6
9. Shale, similar to that above but contains large septarian concretions	10
10. Shale, black, hard, gritty, platy to fissile, contains some layers of calcareous siltstone one to two feet thick, weathers gray	70
11. Shale, greenish gray, breaks into small angular fragments, contains conodonts, and has abundant phosphate nodules and glauconite in a six-inch zone at the base	9

Woodford chert

12. Shale, black, hard, flaky, weathers gray, contains abundant phosphate nodules and conodonts	2½
13. Chert, black, in beds one to four inches thick, gritty. Contains partings of black paper shale, abundant round phosphatic nodules and flattened discoidal phosphatic nodules	32
14. Shale, hard, black, platy, cherty, in layers 1/16 to ¼ inch thick, which contains some beds of blocky black chert about four inches thick. Weathers gray to white	25
15. Chert breccia or conglomerate, white with some lenses of very fine-grained crystalline limestone	7

Pinetop chert

16. Chert, mostly white, or light gray with some lenses of very fine-grained gray limestone, and thin beds of blue-gray earthy limestone. Some of the chert weathers brown and porous. Sparingly fossiliferous (Middle Devonian)	40
17. Limestone, blue-gray, very fine-grained, irregularly bedded, and slightly cherty, weathers buff with dendritic markings, sparingly fossiliferous (Middle Devonian)	20

Figure 17. Measured section of strata exposed near Pinetop (Tulsa Geological Society, 1947, p. 23–24). (Note that originally published location is incorrectly given as sec. 3; correct location is sec. 4.) In addition to the observations by Hendricks and Gardner, field-trip participants should also note that the Pinetop Chert contains sparse pyrite in limestone, and that the Woodford Chert has a petroliferous odor, pyrite on bedding planes, and concentration of phosphate-nodule residuum at the base near the breccia.

in the Atoka beneath the thrust-faulted Woodford; or (3) a chert conglomerate at the base of the Woodford, similar to that noted near Pinetop by Hendricks (Tulsa Geological Society, 1947) and Fay (1985, p. 65).

Petroleum-Source-Rock Potential

The Woodford Shale (Upper Devonian) and its equivalent units are long-recognized petroleum source rocks in the Midcontinent region. Its significance as a source of hydrocarbons in the Anadarko basin have been reported on by Cardott and Lambert (1985) and by Sullivan (1985). The petroleum source potential and maturity of the equivalent Chattanooga Shale of the Ozark uplift and adjacent Arkoma basin have been studied by Carr (1987). The Woodford has yet to be reported on in terms of its source potential and maturity in the Ouachita uplift. However, it has been sampled at two localities in the western Ouachita Mountains, and study is underway at the Oklahoma Geological Survey.

The Woodford has excellent source potential in the section exposed in a road cut on the west side of the Indian Nation Turnpike (Table 1), with a mean of 3.3% total organic carbon (TOC). The sampled rocks also contain relatively abundant hydrocarbons, which is also indicative of good source potential (Table 1). However, the maturity of the Woodford at the two localities is low, about 0.53% R_o (vitrinite reflectance in oil), near the threshold of significant generation of hydrocarbons (Hunt, 1979, p. 331). Inasmuch as other studies (Curiale, 1983; Houseknecht and Matthews, 1985) have found generally higher R_o values, this part of the Ouachita uplift, or of the Pine Mountain thrust sheet, may not have been buried as deeply as other parts of the Ouachitas.

As part of a more comprehensive study, Curiale (1983) reported on the source potential and maturity of the Arkansas Novaculite, the middle part of which is equivalent to the Woodford Shale (Fig. 2). His investigation included the study of drill cuttings from the Southwest Exploration Co. No. 1 Denton-Perrin well in sec. 9, T. 2 S., R. 15 E. Twenty-seven samples were composited through 100-ft intervals between 6,500 and 9,200 ft, which was interpreted to be the Novaculite interval. These samples yielded a range of TOC from 0.33 to 1.42% (mean, 0.77%). A single outcrop sample from the Potato Hills yielded 14.6% TOC (Curiale, 1983, p. 26). Vitrinite-reflectance values for part of the same section averaged about 0.98% R_o (Curiale, 1983, p. 42), substantially higher than the Woodford at the Pinetop locality.

The most comprehensive study of hydrocarbons in the Ouachita region to date is that of Curiale (1983). A major part of that report was the examination of 126 samples (11 outcrop and 115 subsurface) of 6 stratigraphic units for petroleum-source-rock potential. Source-rock quality was estimated through analyses for total organic carbon (TOC) and extractable organic matter (EOM). The six units ranked as "good" and "fair" source rocks according to the EOM criteria established by Philippi (1957), and all contain more than 0.5% TOC (Table 2). Thermal maturity of the rocks was investigated by vitrinite reflectance and by several geochemical methods. All six of the stratigraphic units were found to occur in the lower range of the oil window (Curiale, 1983, p. 53); however, it is important to recognize that the Stanley Shale and Arkansas Novaculite contain primarily woody plant material (type III kerogen), and are therefore gas-prone source rocks. The two best petroleum source rocks are the Womble Shale (Middle Ordovician) and the Stanley Shale (Middle Mississippian), according to Curiale (1983, p. 43).

Table 1.—Hydrocarbon Source Potential and Maturity of the Woodford Shale, Southern Pittsburg County, Oklahoma[a]

Sample number[b]	Location	Organic Carbon TOC[c]	Hydrocarbons EOM (ppm)[d]	Vitritinite reflectance % R_o[e] Range	Mean
638A	Sec. 5, T. 2 N., R. 15 E.	2.05	1,370	0.32-0.76	0.52
638B	W. side of Turnpike	4.56	936	(86 data points)	
914A	Sec. 4, T. 2. N., R. 15 E.	n.a.	n.a.	0.41-0.68	0.54
914B	Pinetop section	n.a.	n.a.	(75 data points)	

[a]Unpublished data, courtesy Brian J. Cardott and Jane Weber, Oklahoma Geological Survey.
[b]A, near base of unit; B, near top of unit.
[c]Total organic carbon, weight percent.
[d]Extractable organic matter, parts hydrocarbon per million parts rock.
[e]Percent reflectance in oil.

Table 2.—Hydrocarbon-Source-Rock Quality in the Ouachita Mountains, Southeastern Oklahoma
(after Curiale, 1983, table 11)

	Hydrocarbons EOM (ppm)[b]	Organic Carbon TOC[c]	n[d]	Stratigraphic Unit
Good Source Rocks[a] (500-1,500 ppm)	332-4,086 mean: 1093	0.25-1.89 mean: 1.05	8	Stanley Shale
	60-1,830 mean: 660	0.47-6.51 mean: 2.54	3	Polk Creek Shale
	179-1,578 mean: 1,055	0.76-3.35 mean: 1.94	6	Womble Shale
Fair Source Rocks[a] (150-500 ppm)	99-151 mean: 128	0.51-1.05 mean: 0.83	3	Arkansas Novaculite
	310-464 mean: 371	0.68-1.42 mean: 1.05	3	Missouri Mountain Shale
	102-216 mean: 177	0.87-1.48 mean: 1.09	3	Bigfork Chert

[a]Criteria of Philippi, 1957.
[b]Extractable organic matter, parts hydrocarbon per million parts rock.
[c]Total organic carbon, weight percent.
[d]Number of samples.

Retrace route to Kiowa.

11.7 (23.4) Junction Oklahoma Highway 63 and U.S. Highway 69. Turn left (south) on U.S. Highway 69.

For the next 5 mi, the road generally parallels low ridges underlain by NE-striking, NW-dipping (15–25°) sandstones in the Boggy and Savanna Formations on the southeast flank of the Kiowa syncline.

3.4 (26.8) Highway 69 crosses railroad tracks. Leave Pittsburg County, enter Atoka County.

The low ridge that the highway is built on is the Bluejacket Sandstone (Marcher and Bergman, 1983), the lowest member of the Boggy Formation.

3.9 (30.7) Cross very low ridge of steeply-dipping Hartshorne Sandstone and continue down-section into upper Atoka Formation.

0.3 (31.0) Cross Buck Creek.

0.1 (31.1) Leave Kiowa 7.5′ Quadrangle, enter Limestone Gap 7.5′ Quadrangle.

1.5 (32.6) Cross trace of Choctaw fault. Here, the Choctaw fault juxtaposes "Springer" Formation in the hanging wall to the southeast against Atoka Formation in the footwall to the northwest.

0.3 (32.9) Cross Limestone Creek.

About 1 mi to the north is the one-well Limestone Gap oil field, discovered in 1962 by the Aubrey Price No. 1 Martin. Initial production was 8–12 bpd of 49-API-gravity oil from open hole in Atoka Formation at 754 to 816 ft (TD).

1.3 (34.2) Highway cuts through Limestone Ridge.

0.9 (35.1) Leave Limestone Gap 7.5′ Quadrangle, enter Coalgate SE 7.5′ Quadrangle.

3.1 (38.2) Junction with Oklahoma Highway 43 to west. Continue south on Highway 69.

1.1 (39.3) Oklahoma State Penitentiary. Continue south on Highway 69.

1.8 (41.1) Leave Coalgate SE 7.5′ Quadrangle, enter Stringtown 7.5′ Quadrangle.

2.1 (43.2) Intersection with Oklahoma Highway 43 to east. Turn left (east) into Stringtown.

0.1 (43.3) Cross railroad tracks and immediately turn left into Stringtown Quarry.

Stop 9, Bigfork Chert at Stringtown Quarry. Please wear hardhats, safety glasses, and sturdy boots at all times while in the Amis Materials Co. Stringtown Quarry. Location: N 1/2 sec. 16, T. 1 S., R. 12 E.

STOP 9
BIGFORK CHERT AT STRINGTOWN QUARRY

Neil H. Suneson
Oklahoma Geological Survey

The Bigfork Chert was named by Purdue (1909) for exposures near the Bigfork Post Office, Polk County, Arkansas. In Oklahoma, the Bigfork Chert crops out in the Broken Bow uplift area (Honess, 1923), the Potato Hills, (Pitt and others, 1982, and references cited therein), and along Black Knob Ridge (discussed below) (Fig. 1). It is a gas reservoir in three wells in the Potato Hills and South Jumbo fields (Fig. 3).

Hendricks and others (1937) and Goldstein and Hendricks (1953) divided the Bigfork Chert exposed along Black Knob Ridge into two parts based on lithology: a lower part, 410–510 ft thick, composed of bedded cherty shales, siliceous limestone and limestone-replacement chert, and nodular and concentric cherts; and an upper part, 100–190 ft thick, composed of bedded chert and black shale. Much of the lower part of the Bigfork Chert was originally calcareous and subsequently silicified; evidence includes carbonate rhombs in the cherty shales, the lateral transition from siliceous limestone to chert, a porous or vuggy texture resulting from preferential leaching of limestone over replacement chert, and calcareous fossils (crinoids, brachiopods, trilobites). Goldstein and Hendricks (1953, p. 437) estimated that only 10–20% of the silica in the lower limestones was syngenetic, and the remainder epigenetic. By contrast, the chert and shale in the upper part were deposited entirely as siliceous sediments.

More recently, Kasulis (1988) studied the Bigfork Chert at Scratch Hill, located immediately southeast of Atoka, Oklahoma, and at the Stringtown Quarry (Fig. 18). Based on field relations and petrographic analyses, Kasulis (1988) recognized four facies in the Bigfork Chert that are consistent with the carbonate base-of-slope apron depositional model of Mullins and Cook (1986): (1) clast-supported, channelized conglomerates and pebbly calcarenites (2% of formation), interpreted as debris-flow deposits that grade laterally into turbidites; (2) allochthonous, bioclastic packstones, grainstones, and wackestones (18%), characterized by the Bouma sequence (but Tc commonly absent), and interpreted to be classic carbonate turbidites; (3) subequal proportions of allochthonous bioclastic packstones/wackestones and mudstones (57%), interpreted as dilute, distal turbidites; and (4) siliciclastic mudstones and rare bioclastic mudstones (23%), interpreted as hemipelagic and pelagic suspension deposits. Except for the basal 30 ft, the Bigfork sediments accumulated in an anoxic, below-storm-wave-base, base-of-slope environment; this contrasts with the turbidite-fan model proposed for Bigfork sedimentation by Sediqi (1985). Kasulis (1988) suggested that three coarsening- and thinning-upwards cycles could be recognized in the lower Bigfork Chert, and that these were caused by glacio-eustatic lowering of sea level.

Most of the calcareous rocks of the Bigfork Chert have been replaced by silica. Kasulis (1988, p. 123) recognized ten diagenetic events and related them to four diagenetic phases, including shallow burial (original deposition to Late Ordovician), exposure (Early Silurian), deeper burial (Early Silurian to Early Pennsylvanian), and tectonism (Middle Pennsylvanian). Dissolution of siliceous bioclasts, especially sponge spicules, silicification of carbonate clasts and matrix, and silica cementation occurred during the first three diagentic phases.

In the subsurface, the Bigfork Chert is generally similar to that exposed on Black Knob Ridge. The lower part consists of gray, brown, or black chert; calcareous chert; cherty shale; siliceous limestone; and thin black shale (Arkoma Basin Study Group, 1961). Petrographically, the rocks range from limestone-replacement chert to very siliceous limestone to noncherty, fossiliferous, clastic limestone. Fractures are commonly filled with calcite or calcite plus quartz. The upper part of the Bigfork Chert consists of black to dark-brown, massive, pyritic, spicular chert and siliceous shale and minor cherty limestone and oolitic and cherty dolomite.

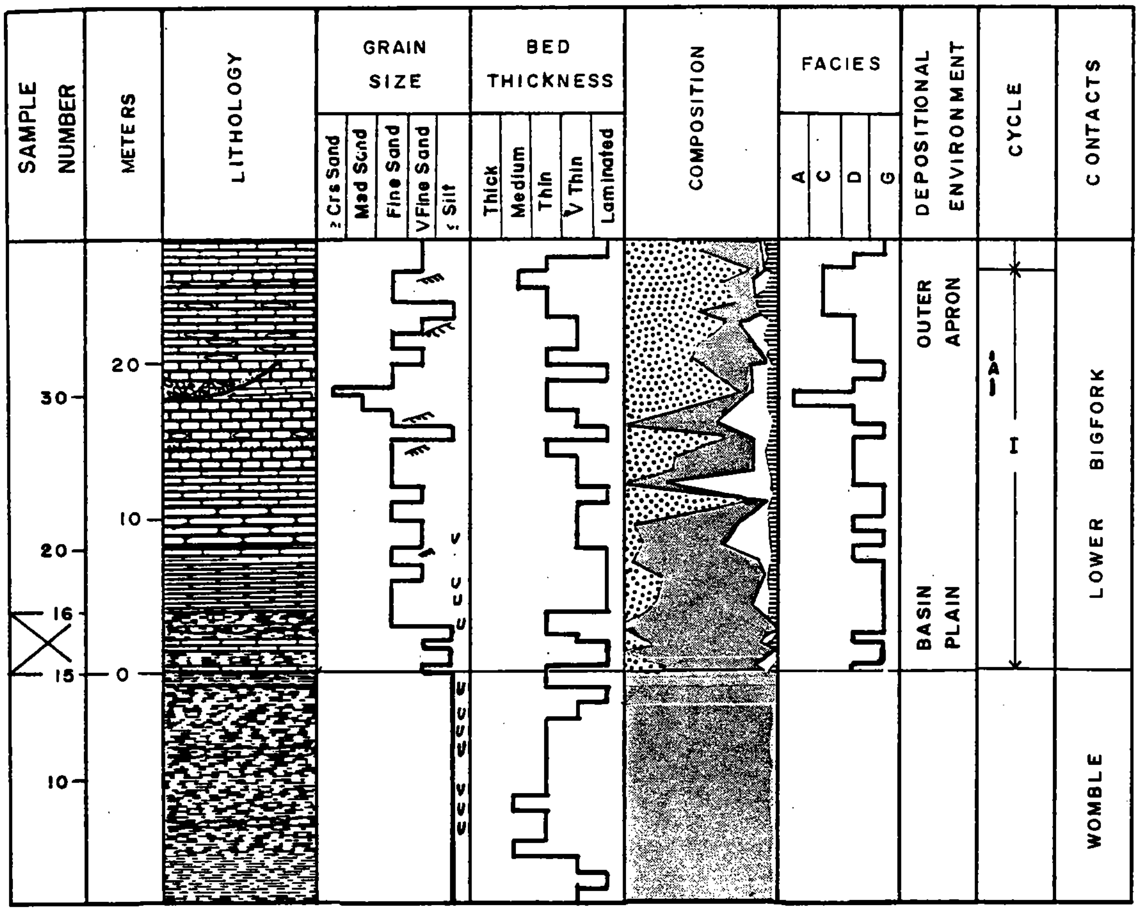
The Bigfork Chert on Black Knob Ridge is highly fractured. Most of the fractures are filled with calcite, or more rarely quartz or asphaltite. (Pitt and others [1982, p. 14] reported asphalt in vugs in the Bigfork Chert in the Potato Hills.) Leonhardt (1983, p. 39) concluded that fracture development was complex and involved reactivation of previously formed structures. He determined that the following microfabric development history could be deciphered:

1) Quartz veins develop parallel to bedding.
2) Initial folding and fracturing. Quartz veins develop perpendicular to bedding.
3) Continued folding and fracturing.
4) Calcite veins develop.
5) Minor fracturing.

Kasulis (1988, p. 143) concluded that 99% of all fractures were tectonically induced and that hydrocarbon generation(?) and migration(?) accompanied Middle Pennsylvanian tectonism (p. 123).

The Bigfork Chert is a gas reservoir in three wells in the central belt of the Ouachita Mountains. The northernmost is the Sinclair No. 1 Reneau (SE 1/4 SE 1/4 NW 1/4 sec. 32, T. 3 N., R. 20 E.) in the Potato Hills (see mile 26.0, Day One). The well spudded on May 9, 1959, and drilling finished on February 9, 1960, at 7,097 ft TD. The open-flow potential of the well was 1.8 MMcfgd from the Bigfork Chert at 2,340 to 2,410 ft. The Arkoma Basin Study Group (1961, p. 77) indicated that production was from "small vugs and fractures, most of which do not appear to be connected."

The well spudded in the Stanley Group, drilled a relatively thin Arkansas Novaculite–Missouri Mountain–Polk Creek section, and entered a complex, multiply-repeated Bigfork–Womble section (Fig. 19). Unruh (1963, p. 44) suggested that



Structures	Symbol
Burrow	U
Cross-stratification	

Lithology	Symbol
Siliceous Claystone	
Siliceous Clastic Mudstone ...	
Bedded Chert	
Conglomerate	
Siliceous Limestone	
Limestone	
Pebbly Calcarenite	

Composition	Symbol
Allochems	
Matrix	
Dolomite	
Cement	

Figure 18. Stratigraphic section of the Bigfork Chert at Stringtown Quarry (from Kasulis, 1988, p. 167–170).

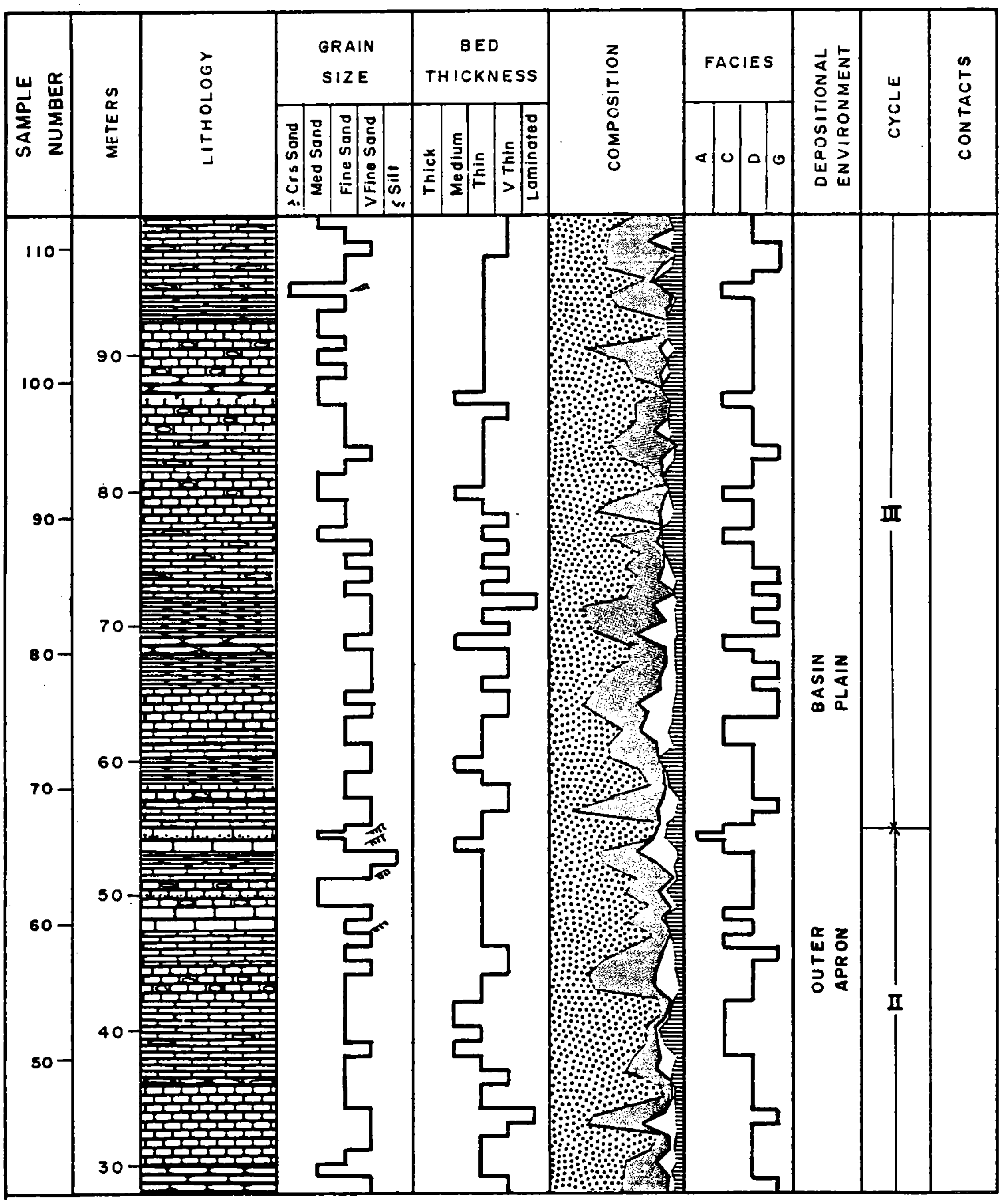


Figure 18. *Continued.*

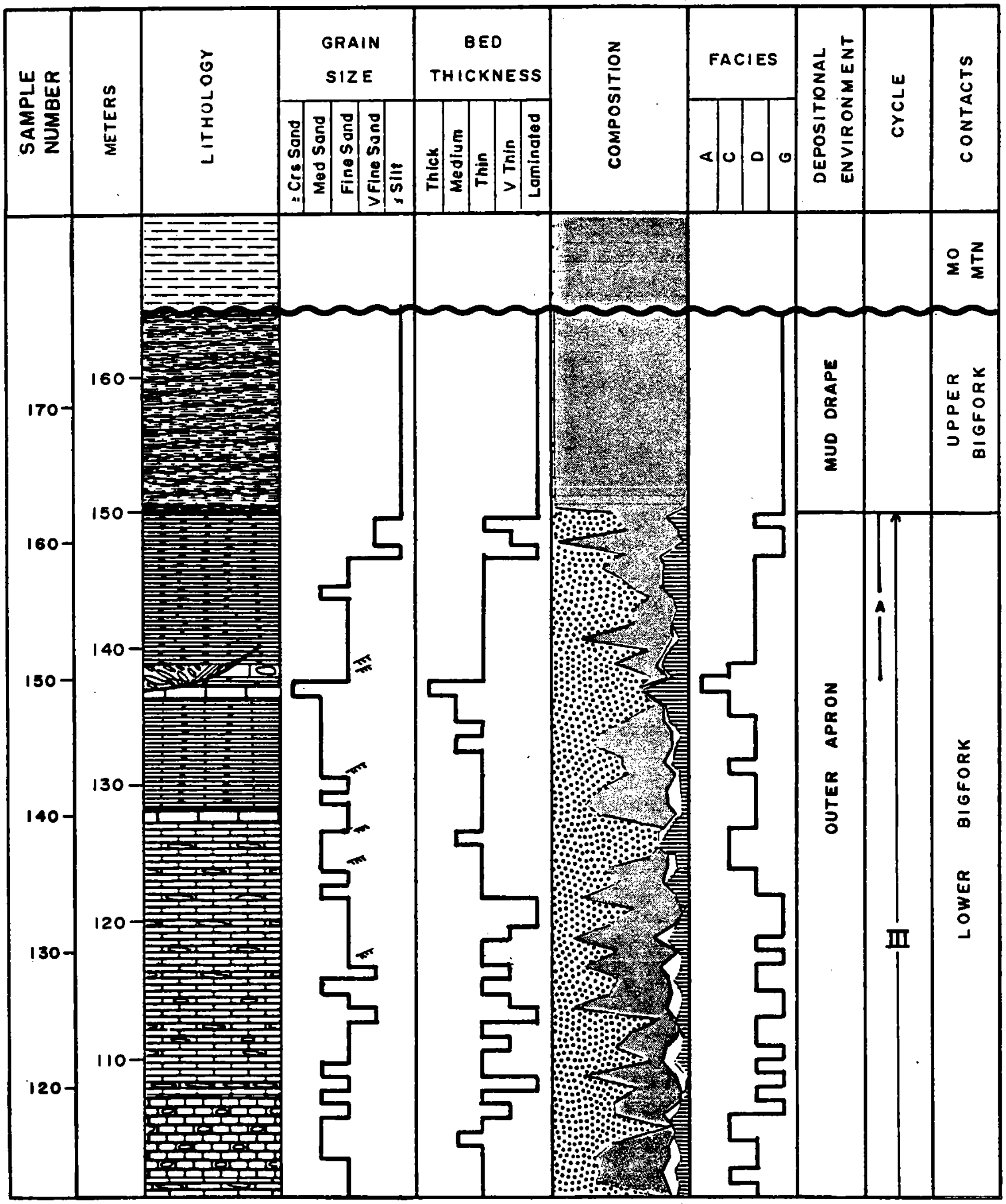


Figure 18. *Continued.*

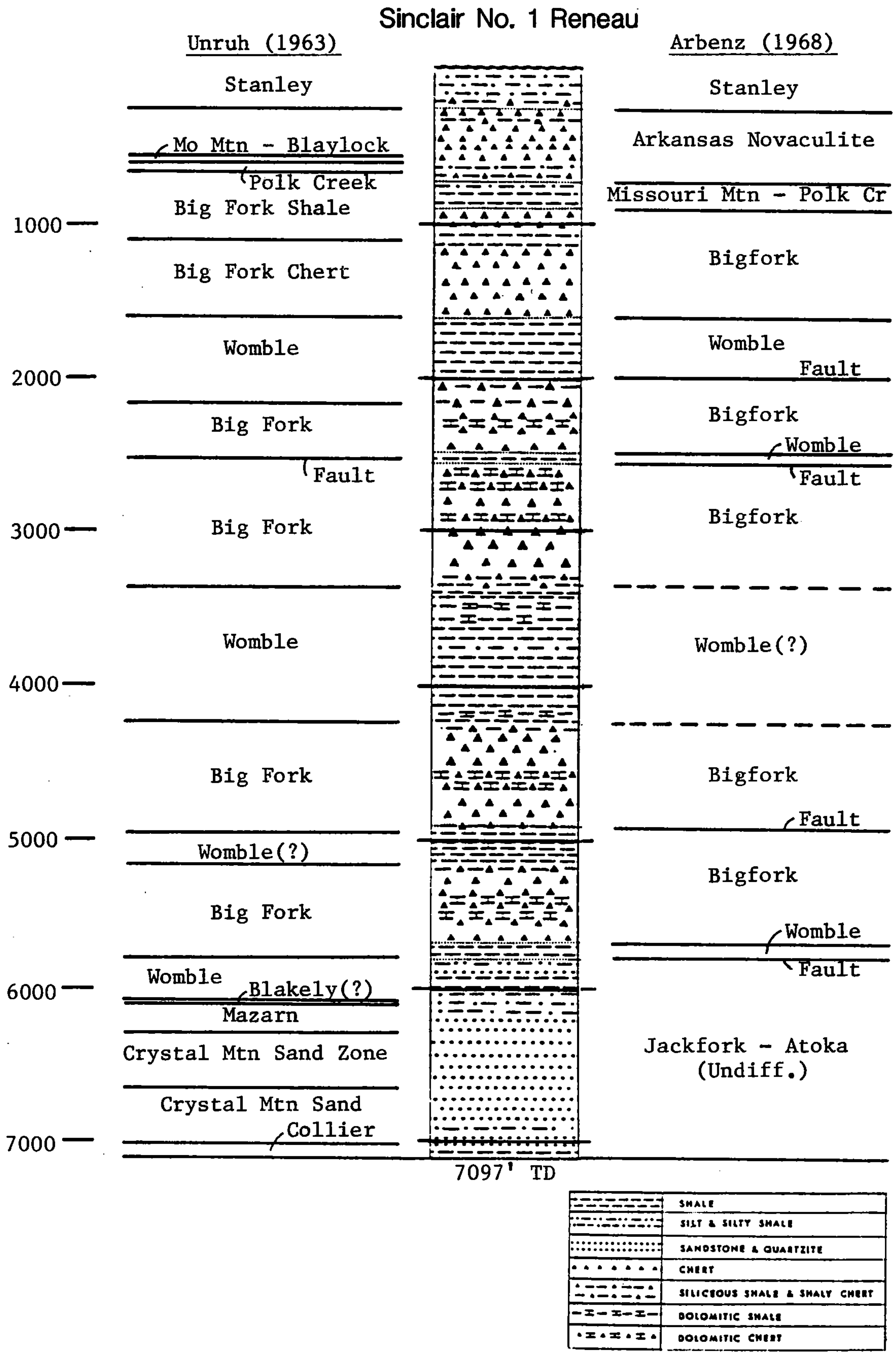


Figure 19. Comparison of drilled strata, Sinclair No. 1 Reneau, Potato Hills gas field.

the well drilled an essentially autochthonous, though repeated, sequence of units, and that graptolites from the lower part of the well indicated that it reached total depth in Ordovician strata. Pitt and others (1982, p. 41) agreed that the strata in the Potato Hills were essentially in place, despite their evidence that fossil wood in cores from 6,360 to 6,376 ft indicated Mississippian Stanley Group at that depth. Based on the presence of Carboniferous palynomorphs in samples from 6,655 to 6,675 ft and 7,077 to 7,095 ft, Arbenz (1968, p. 116) concluded that the lower and middle Paleozoic rocks of the Potato Hills had been thrust over upper Paleozoic rocks. The principal difference in interpretations is that Arbenz (1968) states that the well penetrated a major thrust at 5,780 ft that he correlates with the Windingstair fault. This fault juxtaposes Ordovician strata in the hanging wall against Pennsylvanian strata in the footwall.

A second well in the Potato Hills field in which the Bigfork Chert is also reported to be a reservoir is the Wyoming No. 1 Allen (NE 1/4 sec. 31, T. 3 N., R. 20 E.), about 0.5 mi west of the No. 1 Reneau. That well tested 2.2 MMcfgd from the Bigfork Chert at 2,787 to 3,195 ft (Pitt and others, 1982, p. 45).

The Bigfork Chert also produces gas in the U.S. Mineral and Royalty No. 1 Perrin Estate (C SE 1/4 SW 1/4 sec. 9, T. 2 S., R. 15 E.), the discovery well of the South Jumbo field. The well was originally drilled as the Southwest Exploration No. 1 Denton-Perrin from April 16, 1956, to January 1, 1957, to 11,328 ft TD. The well tested 20 Mcfgd from perforations in the Stanley at 2,770 to 2,786 ft. In 1980, the well was reworked as the U.S. Mineral and Royalty No. 1 Perrin Estate. The Arkansas Novaculite from 6,588 to 6,958 ft tested 1 MMcfgd, and the Bigfork Chert from 7,517 to 8,307 ft tested 2.5 MMcfgd.

However, like the No. 1 Reneau, the Perrin Estate well is not without controversy. Formation tops given by Corporation Commission Form 1002A for the Southwest Exploration No. 1 Denton-Perrin and U.S. Mineral and Royalty No. 1 Denton-Perrin, scout tickets for the U.S. Mineral and Royalty No. 1 Denton-Perrin, Arkoma Basin Study Group (1961), Flawn and others (1961), and Morrison (1980) are virtually identical: Arkansas Novaculite, 6,458 ft; Missouri Mountain/Polk Creek, 6,955 ft; Bigfork, 7,456 ft; Womble, 9,020 ft; fault and Stanley, 9,020 ft; Arkansas Novaculite, 10,972 ft. In contrast, Chenoweth (1959) published the following tops: Arkansas Novaculite, 6,400 ft; Missouri Mountain, 9,200 ft; Polk Creek, 9,550 ft; Bigfork, 9,820 ft; fault and Bigfork, 10,780 ft. Curiale (1981) favored Chenoweth's (1959) interpretation.

Petzet (1982, p. 48) suggested that the U.S. Mineral and Royalty 1-16 Brame in sec. 16, T. 2 S., R. 15 E. (South Jumbo field) produced gas from the Bigfork Chert, but Corporation Commission Form 1002A for that well indicates that it reached total depth in Polk Creek Shale above the Bigfork.

In the West Daisy field, the Max Pray No. 1 Wyrick (see mile 60.4, Day Two) spudded on July 6, 1957, and drilled to 12,088 ft (TD) on August 9, 1958. It drilled an intact(?) lower and middle Paleozoic section; formation tops are Arkansas Novaculite, 8,114 ft; Polk Creek, 8,404 ft; Bigfork, 8,426 ft; Womble, 9,098 ft (Fay, 1976, p. 94). A DST from 8,431 to 9,852 ft estimated 0.3 MMcfgd (Howell and Lyons, 1959, p. 60).

In addition to the scattered Bigfork producers in the Ouachitas, the Bigfork Chert also produces oil in the Isom Springs field, located in southern Marshall County, about 55 mi southwest of Stringtown. Most production at Isom Springs is from the Arkansas Novaculite (estimated reserves 8 MMbo; Voight and Sullivan, 1982), but some wells also produce from the Bigfork (Morrison, 1985, p. 77).

Return to quarry entrance.

Turn left (east) on Oklahoma Highway 43 and drive through Stringtown.

0.6 (43.9) Road forks. Stay left on Highway 43.

1.2 (45.1) Cross Rocky Creek.

WINDINGSTAIR FAULT

Here, Hendricks and others (1947) showed the Windingstair fault with Stanley Group strata in the hanging wall and footwall. This contrasts with the Windingstair fault in the central part of the frontal belt, in which the Stanley is restricted to the hanging wall (see mile 26.0, Day One). Similarly, the frontal belt in this part of the Ouachita Mountains is about 3 mi wide, in contrast to the central part, where it is almost 12 mi wide. These observations and the presence of lower to middle Paleozoic rocks on Black Knob Ridge in the footwall of the Windingstair fault suggest that (1) in the western frontal belt, major displacements occurred on the Choctaw(?), Pine Mountain, and Ti Valley faults (as mapped by Hendricks and others, 1947) and that (2) major displacement was transferred to the Windingstair fault eastward. Is it possible that the thrust faults between the Pine Mountain/Ti Valley fault in the extreme western part of the frontal belt and the Windingstair fault in the central part of frontal belt act as connecting splays within a transfer zone in the sense of Boyer and Elliot (1982)?

1.4 (46.5) Leave Stringtown 7.5′ Quadrangle, enter Lane NW 7.5′ Quadrangle.

1.1 (47.6) Cross Breadtown Creek.

4.3 (51.9) Leave Lane NW 7.5′ Quadrangle, enter Limestone Gap 7.5′ Quadrangle.

2.0 (53.9) Leave Limestone Gap 7.5′ Quadrangle, enter Redden 7.5′ Quadrangle.

1.7 (55.6) Road to right (south) to McGee Creek reservoir.

About 5 mi south is the small, "unofficial" Minnett oil field (sec. 19, T. 1 S., R. 14 E. and sec. 24, T. 1 S., R. 13 E.) (Fay, 1976), the southernmost of the McGee Valley oil fields. Chenoweth (1959, p. 205) suggested that the oil is from shallow (100–300 ft) Atoka Formation, but Hendricks and others (1947) mapped Stanley Formation at the surface.

0.1 (55.7) Redden Cemetery.

0.7 (56.4) Cross McGee Creek.

0.2 (56.6) Turn right (south) onto county road.

0.5 (57.1) Leave Redden 7.5′ Quadrangle, enter Lane NE 7.5′ Quadrangle.

1.0 (58.1) Stop 10, Redden Oil Field. Location: NE 1/4 sec. 9, T. 1 S., R. 14 E.

STOP 10
REDDEN OIL FIELD

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The Redden oil field, located in the NE 1/4 sec. 9, T. 1 S., R. 14 E., appears to be a classic example of petroleum liquids trapped downdip of a tar seal (Chenoweth, 1959). However, a search of well records has determined that only two of the 13 producible wells of record are in a position that would corroborate that trapping mechanism. Those two wells (index nos. 3 and 5, Table 3, Fig. 20) are located southeast of the SE-dipping oil-impregnated sandstone in the NE 1/4 SE 1/4 NW 1/4 NE 1/4 sec. 9. The historically producible wells occur along a SW–NE trend that is more than 1 mi long and about 0.5 mi wide, but within that area there have been many more dry holes than producers (Fig. 20). Although parts of the reservoir may have been depleted prior to 1930, the evidence is that the entrapment of oil in the Redden field area is much more varied and complex than previously thought.

No complete and accurate historical record of field development is available; even the location of the earliest production in the Redden area is in question. However, the discovery of the field can be confined to either late 1913, or about the first half of 1914. Whitney (1913) referred to exploratory drilling near the town of Redden, which was located about 1.25 mi north–northwest of the field, adjacent to the present position of Oklahoma Highway 43. The discovery of the second reservoir sand at Redden was reported by the Oklahoma Oil and Gas News on July 9, 1914 (Skelton and Skelton, 1942, p. 163). The year 1914 is generally accepted for the discovery of the Redden oil field.

Little more is known of the early history of the field, but numerous wells may have been drilled, because the value of crude oil in Oklahoma increased steadily from 1914 to 1920, during which time it more than quadrupled (Jordan, 1958, p. 28). There is no record of any well known to have been drilled prior to 1930 (Table 3). According to Rea (1947, p. 16), who had access to records of the Croxson (Croxton?) Oil Company, in "about" 1929, there were 9 producible wells that averaged about 2.5 bopd. By 1936, only 4 wells averaged 3–3.7 bopd. Those wells were drilled to depths ranging from 90 to 350 ft, and produced from one or more sandstone units in the Stanley Shale (Late Mississippian). The sandstones are commonly known as the "Miller sands," having been named for an early property owner, Edgar P. Miller. At least one of the wells, evidently the Croxton Oil Co. No. 5 Miller (index no. 20, Table 3) is reported to have produced as much as 6–9 bopd (Fay, 1976, p. 93). In 1954, the field was producing an average of 3 bopd from each of 3 wells (Ardmore Geological Society, 1954, p. 8); however, there is no knowledge of production having been continuous or episodic during the intervening years. Although a cable-tool rig was on site drilling a development well as recently as 1984 (Fay, 1985), no commercial quantities of oil have been produced from the field since 1972 (L. C. Butler, personal communication, 1989). The cumulative production of record is 490 bo. That is probably only a fraction of the actual production from the field, and may represent as little as a few percent of the total. However, much of the total production probably occurred prior to about 1935, at which time record-keeping efforts in Oklahoma improved markedly with the formation of Vance Rowe Reports of Tulsa.

At a time when the field was being produced regularly, the oil was reported to have an API gravity of 36° and to contain 0.24% sulfur (Rea, 1947). More recently, Curiale (1983) reported an API gravity of 31.8° and 0.34% sulfur. Sulfur-isotope and other geochemical evidence suggests that the source (or sources) of the Redden oil is organic shales of Silurian and/or Ordovician age, i.e., Womble, Polk Creek, and/or Missouri Mountain (Curiale, 1983, p. 53). Furthermore, the Stanley Shale and Arkansas Novaculite were shown to contain an abundance of gas-prone organic mqtter, or type III kerogen (Curiale, 1983, p. 24), a further indication that the most likely source of petroleum liquids lies below these strata.

In general, the wells are cased, open-hole completions. According to Rea (1947), the wells could be pumped only intermittently for several hours at a time, after which it was necessary for them to be idle while oil seeped into the wellbore. This behavior indicates a low-permeability reservoir under gravity-drainage conditions. It was also reported (Rea, 1947) that virtually all of the wells drilled circa 1929 were stimulated with as much as 90 quarts of nitroglycerine, and that this practice decreased, rather than increased, the amount of recoverable oil.

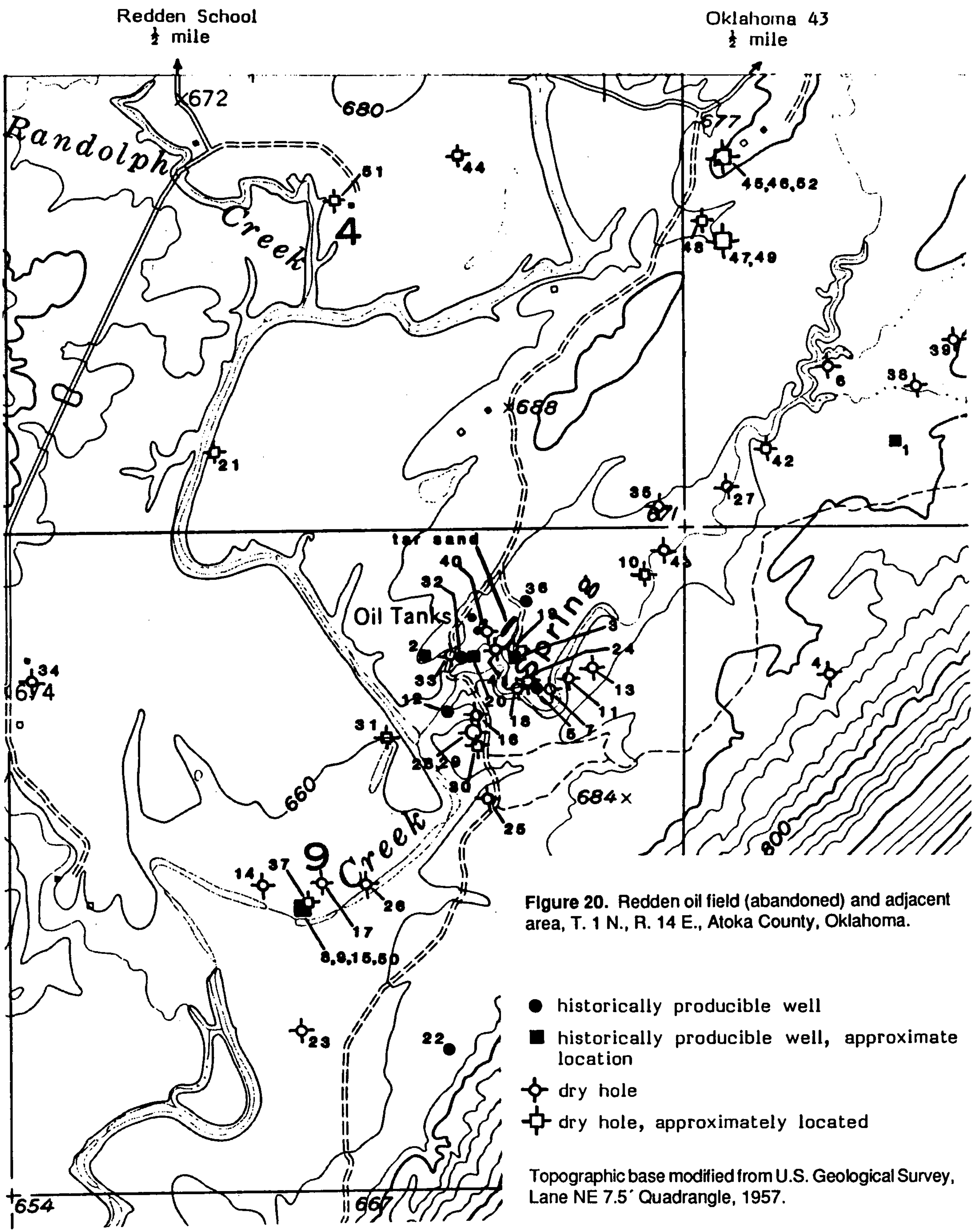

Figure 20. Redden oil field (abandoned) and adjacent area, T. 1 N., R. 14 E., Atoka County, Oklahoma.

- ● historically producible well
- ■ historically producible well, approximate location
- dry hole
- dry hole, approximately located

Topographic base modified from U.S. Geological Survey, Lane NE 7.5′ Quadrangle, 1957.

Table 3.—Wells of Record Drilled for Oil in the Redden Field and Vicinity, Atoka County, Oklahoma

Index numbers refer to Figure 20

	Operator	Well number	Lease	Completion date	Total depth (ft)
			A. Chronologically, by completion date		
1.	E. V. Croxton	1	Schumaker	12-?-1930	908
2.	E. V. Croxton	1	Miller	1930	192
3.	E. V. Croxton	2	Miller	1930	556
4.	Bryant et al.	1	Southern Trust	1-28-1931	900
5.	Bryant et al.	2	Miller	3-7-1931	189
6.	E. V. Croxton et al.	1-A	Southern Trust	5-6-1931	300
7.	E. V. Croxton et al.	3	Miller	7-21-1931	415
8.	Croxton & Norton	3	Miller	8-9-1932	90
9.	Croxton & Norton	5	Miller	8-9-1932	280
10.	Indiana Oil Co.	1	Miller	8-23-1932	1,400
11.	Norton et al.	1	Miller	10-18-1932	275
12.	Sam Miller	1	Miller	10-18-1932	304
13.	Sam Miller	2	Miller	10-18-1932	310
14.	Tucker et al.	1	Littlejohn	11-8-1932	165
15.	Croxton & Norton	2	Miller	1932	880
16.	Sam Miller	3	Miller	1-3-1933	310
17.	Bufford et al.	1	Cook	1-17-1933	185
18.	Croxton Oil Co.	6	Miller	5-25-1933	170
19.	Croxton Oil Co.	3-A	E. P. Miller	5-31-1933	265
20.	Croxton Oil Co.	5	Miller	1933	175
21.	J. W. Lekenbauer	1	Spring et al.	1933	65
22.	Stemick et al.	4	Alene Miller	5-23-1934	270
23.	Whitney & Phillips	1	I. L. Cook	11-14-1934	210
24.	Paul Doran	1	Mason	11-28-1934	603
25.	Clare et al.	1	Bass	6-11-1935	1,250
26.	Clare Oil Co.	1	Fain	11-19-1935	50
27.	Lewis et al.	1	Southern Trust	11-19-1935	675
28.	Boukens & Joels	3	Miller	4-12-1938	80
29.	O. T. Meyers	1	A. P. Miller	3-11-1942	300
30.	O. T. Meyers	3	A. Miller	1942	246
31.	O. T. Meyers	4	A. Miller	1942	230
32.	O. T. Meyers	3	E. P. Miller	4-11-1944	147
33.	C. B. Meyer	1	Miller	6-20-1944	235
34.	J. J. Madden	1	Joe Winter	4-15-1953	1,000
35.	Buck Drilling Co.	1	Melton	1953	1,120
36.	C. R. Fenstermacher	4	Mattie Vaughn	5-20-1954	185
37.	David Bliss	4	Mattie Vaughn	5-31-1966	212
38.	Bobcat Drilling Co.	5-3	Merle	1-27-1982	750
39.	Bobcat Drilling Co.	5-3	Leslie/Welch-Gamble	3-17-1982	1,150
40.	Doyle E. Glazner	1	Mattie Vaughn	10-10-1982	500
41.	Doyle E. Glazner	1	B & G	6-3-1983	120

Table 3.—*Continued*

	Operator	Well number	Lease	Completion date	Total depth (ft)
			B. Completion date unknown		
42.	Bryant et al.	1	Southern Trust	Abd. 8-9-1932	900
43.	Croxton & Norton	4	Miller	Abd. 8-9-1932	280
44.	Croxton & Norton	1	Spring	Abd. 8-23-1932	400
45.	Kelly Spring	1	Spring	Abd. 1-24-1933	297
46.	Kelly Spring	1	Fee	Abd. 5-23-1933	145
47.	Kelly Spring	2	Southern Trust	Comp. before 1945	275
48.	Kelly Spring	4	Southern Trust	Comp. before 1945	208
49.	Wylie	1	Southern Trust	Comp. before 1945	200
50.	Unnamed well (?)			Comp. before 1945	315
51.	Newman & Garrett		unknown	Unknown	205
52.	Zellars et al.		unknown	Unknown	255

Author stands by small, electrically powered pump jack in the central part of Redden oil field. Well is probably the Croxton no. 2 Miller, from which ~50 bbl of 41 gravity oil was produced in early 1986. Reservoir is in Stanley Group, ~72 ft below the surface. Oil storage tank in right distance. Ticks everywhere.
(Photo by Neil Suneson, June 1989.)

Retrace route to Highway 43.

1.5 (59.6) Intersection with Highway 43. Turn right (east).

0.8 (60.4) Section line road to left (north). The West Daisy field is located about 1.5 mi north of here (Fig. 3).

WEST DAISY FIELD

The West Daisy field encompasses the N 1/2 NE 1/4 and W 1/2 sec. 26, T. 1 N., R. 14 E. It was discovered in 1953 by the Hal H. Vaughn School Land (N 1/2 S 1/2 N 1/2 NW 1/4 sec. 26, T. 1 N., R. 14 E.). Thirteen wells have been drilled in sec. 26; four are shallow oil producers from Stanley sandstones, six are shallow dry holes, two produce deep gas from Stanley Group strata and the Arkansas Novaculite, and one deep well (Max Pray No. 1 Wyrick; see Stop 9) was dry. Reported total production to the end of 1987 is 164 bo and about 50 MMcfg. Unassigned production from sec. 25 immediately to the east is about 1,200 bo and 400 MMcfg.

2.3 (62.7) Turn left (north) on county and section-line road.

3.2 (65.9) Turn right (east) on section line road between sec. 7 and 18, T. 1 N., R. 15 E.

0.5 (66.4) Turn left (north) through middle of sec. 7, T. 1 N., R. 15 E. The small pump jacks to the east (right) are within the South Bald oil field (Fig. 3).

SOUTH BALD OIL FIELD

The South Bald oil field presently encompasses NW 1/4 NW 1/4 and SW 1/4 SW 1/4 sec. 4; SE 1/4 NE 1/4 and S 1/2 SE 1/4 and NW 1/4 SE 1/4 and E 1/2 SW 1/4 sec. 5; SE 1/4 NE 1/4 and E 1/2 SE 1/4 sec. 7; and N 1/2 NW 1/4 and SW 1/4 NW 1/4 sec. 8; all in T. 1 N., R. 15 E. It was discovered in 1932 by the H. M. Hicks et al. No. 2 Stiles (NE 1/4 NE 1/4 SE 1/4 sec. 5, T. 1 N., R. 15 E.). Chenoweth (1959) reported that production is from shallow (about 200 ft) Stanley sandstone and consists of 42°-API-gravity oil. Reported cumulative production through the end of 1987 is about 7,000 bo; unassigned production from sec. 8, T. 1 N., R. 15 E. is about 800 bo. Total production from the field is undoubtedly much greater. The South Bald field is currently active: Many wells can be pumped intermittently for 2–5 bopd.

1.0 (67.4) Turn right (east) on section line road between secs. 6 and 7, T. 1 N., R. 15 E.

0.5 (67.9) Bridge over Indian Nation Turnpike.

0.5 (68.4) Leave Redden 7.5′ Quadrangle, enter Daisy 7.5′ Quadrangle.

0.2 (68.6) Cross Buck Creek.

0.3 (68.9) Turn left (north) on section-line road between sec. 4 and 5, T. 1 N., R. 15 E.

0.7 (69.6) Stop 11, Waldrop Ranch Grahamite Deposit. Location: NW 1/4 SW 1/4 NW1/4 sec. 4, T. 1 N., R. 15 E.

STOP 11
WALDROP RANCH GRAHAMITE DEPOSIT

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Grahamite is one of a family of solid bitumens, also including gilsonite, albertite, impsonite, and others. Grahamite is among the more soluble and more fusible of the solid bitumens, commonly called asphaltites. The infusible and insoluble varieties are known as pyrobitumens and include impsonite, which also occurs in the Ouachita Mountains. Compared chemically to impsonite, grahamite has a higher H/C ratio, much greater asphaltine content, and much lower content of saturated and aromatic hydrocarbons (Table 4). Grahamite is known from at least 16 localities in the Ouachita Mountains (Ham, 1956; Jordan, 1964). Bodies of grahamite that crosscut the host rock structure, and commonly referred to as "veins," occur primarily in the Stanley Shale (Mississippian). However, there are documented occurrences in the Missouri Mountain Shale (Silurian), and Bigfork Chert (Ordovician) as well. Geochemical evidence indicates a Silurian–Ordovician (i.e., Womble, Polk Creek, and/or Missouri Mountain) origin of the solid bitumens (Curiale, 1983, p. 53). Further investigation of this subject has been made by Curiale (1986).

Grahamite was mined in the Ouachita Mountains from as early as 1891, and the deposits were worked extensively during the period 1903 to 1924 (Honess, 1927; Ham, 1956). Three of eight known deposits hosted active mines in the early part of this century, according to Taff (1909). The principal uses of grahamite were in the preparation of roofing compounds, and in the manufacture of paints and varnishes. Other uses included insulation, chemical tank linings, a component of candles and ointments, as well as other applications (Shannon, 1914). These applications have been supplanted by other materials, which offer superior, less expensive, or otherwise more desirable products.

The first publication to document the existence of a grahamite deposit at this location was by Ham (1956, p. 11). The Waldrop deposit was subsequently named by Fay (1985), but a typographical error resulted in the spelling "Waldrip," which has also reached print in subsequent publications. The Waldrop Ranch grahamite deposit is located in the Stanley Shale on or near the southwest end of a NE-trending anticline, as mapped by Hendricks and others (1947) (Fig. 21). The grahamite body apparently strikes about perpendicular to the axis of the fold. The grahamite "vein" was observed to strike NW and to dip approximately 45° NE by Marsh (1936) (Fig. 22). Although mining of grahamite in the western Ouachitas was in progress as early as 1892 (Taff, 1899) at what was to become the Jumbo mine about 9 mi south of the Waldrop Ranch, there is no known record of grahamite at this location prior to 1936. On October 17, 1936, W.A. Furr and Ed Blackburn were granted a coal and asphalt lease by C. E. Rowland, on a grahamite body in the NW 1/4 sec. 4, T. 1 N., R. 15 E. According to Marsh (1936), the digging of a shaft was in progress in early November of that year. By November 18, the shaft was over 50 ft deep and intersected a grahamite body about 5 ft thick (Fig. 22). The grahamite body was later reported by Railey (1938) to be 7 ft thick. The extent of that body is unknown, as is the extent of the mine workings. There is no know record of production from the mine. At present, the only evidence of the deposit is the fragments of grahamite that occur on the surface at the site. A pond constructed to provide water for livestock on a minor tributary to Buck Creek presently occupies the approximate site of the mine. It is apparent that material from the mine dump was used to build the small earthen dam, and it seems probable that the available earth made it particulary convenient to locate the pond here.

Table 4.—Physical and Chemical Properties of Bitumen and Pyrobitumen
(after Curiale, 1983, tables 6, 7, and 13)

A - PHYSICAL PROPERTIES OF BITUMEN AND PYROBITUMEN

Sample Number	Type	Specific Gravity	API Gravity	Luster	Solubility in Methylene Chloride (%)
6[a]	grahamite	1.20	-13.6	dull	33.9
21[b]	grahamite	1.08	-0.5	vitreous	34.5
44[c]	impsonite	1.30	-22.7	variable	1.3
[d]	gilsonite	1.02	+7.2	vitreous	99.9+

B - CHEMICAL DATA FOR BITUMEN AND PYROBITUMEN

Sample Number	Elemental Analysis								
	Percentage[e]					Atomic Ratios			
	C	H	O	N	S	H/C	O/C	N/C	S/C
6[a]	69.56	7.79	2.52	1.552	1.78	1.33	0.0272	0.0191	0.0096
21[b]	85.42	8.24	1.20	1.396	2.93	1.15	0.0105	0.0140	0.0129
44[c]	88.10	5.38	2.09	1.881	1.40	0.73	0.0178	0.0183	0.0060
d	85.36	10.36	1.53	2.800	0.03	1.45	0.0135	0.0281	0.0001

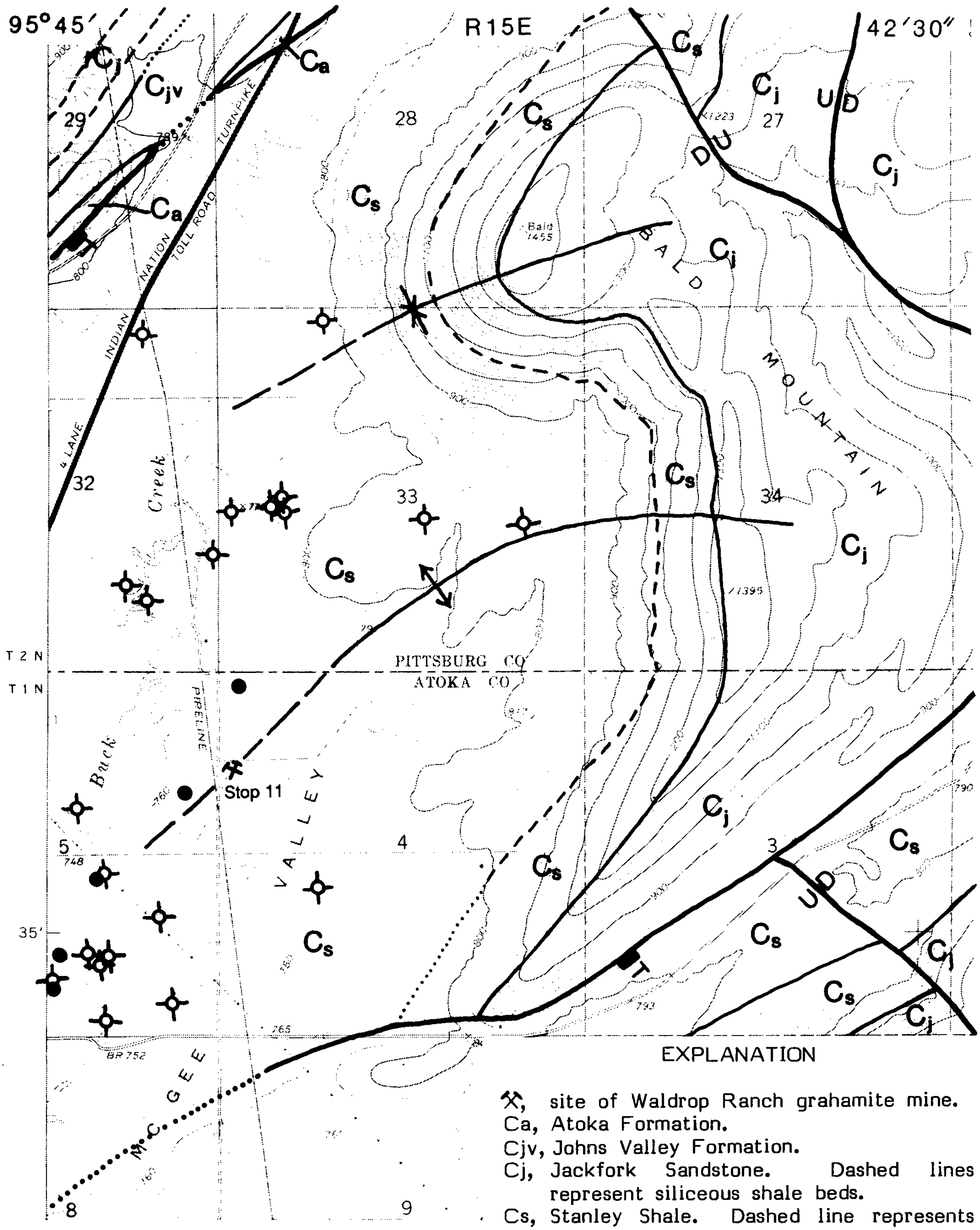
[a]Jumbo deposit: Sec. 28, T. 1 S., R. 15 E., Pushmataha Co. (Stanley Group).

[b]Waldrop Ranch deposit: Sec. 4, T. 1 N., R. 15 E., Atoka Co. (Stanley Group)

[c]Page deposit: Sec. 23, T. 3 N., R. 26 E., Le Flore Co. (Jackfork Group)

[d]Uinta Basin, Uintah Co., Utah (Eocene)

[e]Raw weight percentage.



EXPLANATION

⚒, site of Waldrop Ranch grahamite mine.
Ca, Atoka Formation.
Cjv, Johns Valley Formation.
Cj, Jackfork Sandstone. Dashed lines represent siliceous shale beds.
Cs, Stanley Shale. Dashed line represents siliceous shale bed.
T, hanging wall of overthrust fault.
D, downthrown, and U, upthrown blocks of high-angle faults.
South Bald oil field (in part) at left.
Solid circles indicate wells that are producible, or have produced historically.

Figure 21. Geologic map of the vicinity of Bald Mountain, Atoka and Pittsburg Counties, Oklahoma. Base, U.S. Geological Survey, Daisy 7.5′ Quadrangle, 1973 (1:24,000). Geology after Hendricks and others, 1947.

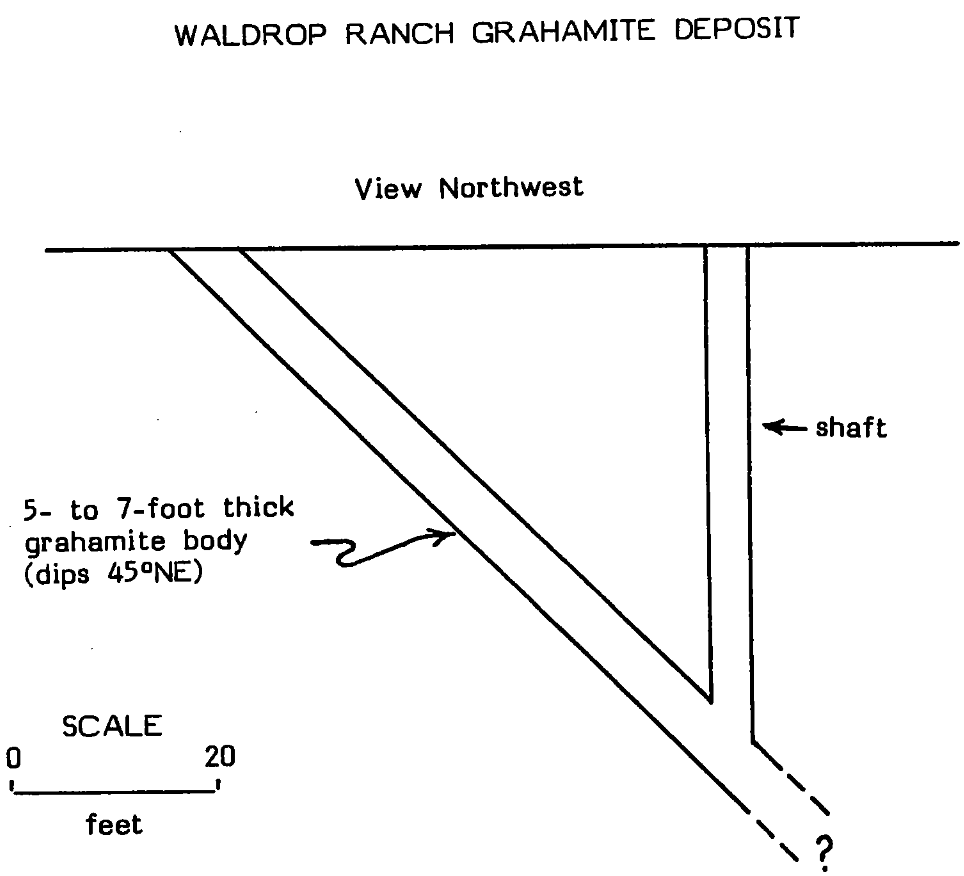


Figure 22. Geologic section of grahamite body on the Waldrop Ranch, NW 1/4 SW 1/4 NW 1/4 sec. 4, T. 1 N., R. 15 E., Atoka County, Oklahoma. Sketch based on observations by Marsh, 1936.

Retrace route to Oklahoma Highway 43.

6.9 (76.5) Intersection with Oklahoma Highway 43. Turn left (east).

1.5 (78.0) Junction with Indian Nation Turnpike. Go under bridge and turn left (north) onto Indian Nation Turnpike toward McAlester.

0.8 (78.8) Stop 12, Jackfork Group Type Section. The field trip will stop along the Indian Nation Turnpike and examine Jackfork Group strata on the east side of the highway. The best exposures are in the bottom part of the upper half of the Jackfork Sandstone as mapped by Hendricks and others (1947). Location: S1/2 S1/4 sec. 19, T. 1 N., R. 15 E.

STOP 12
JACKFORK GROUP TYPE SECTION

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The Jackfork Sandstone was named by Taff (1902) for exposures above the "Standley" Shale on Jackfork Mountain, considered by him to be Silurian. Taff (1902) never exactly located a type section for the Jackfork Sandstone; Pitt and others (1982, p. 23), presumably based on Taff's vague reference to Jackfork Mountain, suggested that the type section be along the Indian Nation Turnpike in sec. 19, T. 1 N., R. 15 E. (Fig. 23).

Harlton (1938, 1959) elevated the Jackfork Sandstone to group status and divided it into five formations; in ascending order, these are the Wildhorse Mountain, Prairie Mountain, Markham Mill, Wesley, and Game Refuge. Some workers recognize the Prairie Hollow Shale between the Wildhorse Mountain and Prairie Mountain Formations, and some include the Chickasaw Creek Siliceous Shale at the base of the group with the Jackfork; others include it in the underlying Stanley Group.

Hendricks and others (1947) did not map Harlton's (1938) Jackfork formations. They did recognize a laterally persistent "maroon and green shale and buff siltstone near the top of the lower third of the formation" and four siliceous-shale beds in the upper half of the formation. Similarly, Pitt and others (1982) were not abie to map the formations defined by Harlton (1938, 1959) throughout Pushmataha and southern Latimer Counties; they were able to separate the Jackfork Group into upper and lower parts, based on their stratigraphic positions relative to the mappable Prairie Hollow Shale. On the east end of Jackfork Mountain, the maroon shale of Hendricks and others (1947) correlates with the Prairie Hollow Shale of Pitt and others (1982).

The Jackfork Group varies in thickness from about 1,500 ft at its northwesternmost exposure (C T. 1 N., R. 13 E.) to about 7,000 ft in the central part of the Oklahoma Ouachita Mountains (Hendricks and others, 1947; Pitt and others, 1982). At its "type section" on the west end of Jackfork Mountain, it is 3,620 ft thick (Fig. 23). Cline (1960) was the first to recognize that sandstones in the Jackfork were deposited by turbidity currents; paleocurrent indicators in the Jackfork Group in Oklahoma suggest an approximately east-to-west flow direction down the axis of the Ouachita trough (Briggs and Cline, 1967). The ultimate source of Jackfork sediments remains controversial, and northern and southern source terranes have been suggested (see review by Briggs and Roeder, 1975, p. 7).

The most recent detailed study of the Jackfork strata exposed at the "type section" along the Indian Nation Turnpike is by Evoy (1989). He used the turbidite-lithofacies classification of Mutti and Ricci Lucchi (1972, 1975) which is based on bed geometry and thickness, texture, internal structure, and sandstone/shale ratio. The seven lithofacies (A to G) reflect depositional energy, rather than position on the submarine fan. For example, a low-energy facies (F or G) sequence may have been deposited in a subenvironment on a "proximal" part of the fan. Despite 10 to 15% exposure, Evoy (1989) documented that the upper part of the Jackfork here records a fining-upward megacycle consisting of, in ascending stratigraphic position, facies B (high-concentration turbidity currents), C ("classical" turbidity currents), D (dilute, low-density turbidity currents), and G (pelagic and hemipelagic mudrocks).

End of field trip and road log.

JACKFORK GROUP TYPE SECTION

Section measured by R. O. Fay and W. D. Pitt along east side of Indian Nation Turnpike and on Jackfork Mountain, beginning at approximate contact of Johns Valley Shale at the SW 1/4 SE 1/4 SE 1/4 sec. 19, T. 1 N., R. 16 E., and proceeding northward, ending at base of section in the NW 1/4 NW 1/4 NE 1/4 sec. 19, Atoka County, Oklahoma.

	Feet
Jackfork Group (total measured thickness 3,620 feet):	
Covered interval; probably shale	300.0
Sandstone, gray to tan, quartzose, ferruginous, fine- to medium-grained, weakly- to well-indurated, locally laminated, in 1- to 3-foot beds, alternating with tan to gray, silty, sandy, platy shale	42.0
Sandstone, dark-gray to dark-brown, alternating with light-gray to tan sandstones and gray to tan shales; quartzitic, mostly covered	28.0
Shale, black, brown, blue-gray, thin-bedded, fissile, with some siliceous shale (**Wesley?**) and 1- to 3-inch gray to tan, weakly-indurated sandstones; partly covered	50.0
Shale and sandstone, gray, fine-grained, weakly-indurated, thin-bedded	55.0
Sandstone, dark-gray, quartzose, fine- to medium-grained, well-sorted, well-indurated, massive	25.0
Sandstone and shale, gray to tan, fine- to medium-grained, thin-bedded, weakly-indurated	105.0
Sandstone, gray, tan, maroon, quartzose, micaceous, ferruginous, fine- to medium-grained, well-indurated, thick-bedded, alternating with some gray shale	54.0
Shale, gray to tan, black, platy, limonitic, weakly-indurated, with 1- to 3-inch sandstone beds, with many fossil plants	22.0
Sandstone, gray, tan, red-brown, quartzose, ferruginous, thin- to medium-bedded, fine-grained, eroding into an escarpment	52.0
Shale and sandstone, gray, fine-grained, weakly-indurated, thin-bedded	35.0
Sandstone, dark- to olive-gray, quartzitic, tuffaceous, vuggy, fine- to coarse-grained, resistant, in 0.5- to 1-foot beds, conglomeratic, alternating with dark-gray shale, weathering olive green, eroding into prominent ledges; **Calamites** and plant fragments present	16.0
Shale, maroon to gray, weakly-indurated, platy, with much ironstone, with some thin- to medium-bedded sandstones, and plant fossils	23.0
Sandstone, olive-gray to orange-brown, quartzose, fine- to medium-grained, well-indurated, thin- to thick-bedded, eroding into a ledge	7.0
Shale, gray to olive-gray, weakly-indurated, and dark-gray to black siliceous shale (**Markham Mill?**), with many thin- to medium-bedded gray quartzitic sandstone beds	90.0
Sandstone, gray to tan, quartzose, micaceous, fine- to medium-grained, well-indurated, massive, eroding into a ledge	16.0
Shale, dark-gray to tan, platy, weakly-indurated	13.0
Sandstone, maroon, quartzose, micaceous, moderately-indurated, medium-bedded, with thin ironstone layers, alternating with maroon to gray shales	13.0
Shale, gray, platy, weakly-indurated, with some maroon ironstone beds, with some medium-bedded quartzitic sandstones	18.0
Sandstone, light-gray, micaceous, quartzose, fine- to medium-grained, conglomeratic, with very coarse quartz grains, well-indurated, thick-bedded	28.0
Shale, gray, tan, maroon, platy, weakly-indurated, with thin gray sandstone beds	31.0
Sandstone, gray, tan, maroon, quartzose, medium-grained, well-indurated, thick-bedded, alternating with some gray shales	27.0
Shale, gray, black, maroon, greenish-gray in lower 10 feet, platy, weakly-indurated, with thin sandstone and gray chert beds	105.0
Sandstone, gray to tan, quartzose, micaceous, fine- to medium-grained, well-indurated, massive, eroding into a ledge	15.0
Shale, green, platy, with lenticular olive-green, fine-grained, weakly-indurated sandstones several feet thick	75.0
Covered interval; probably shale with some sandstone, tan to red-brown, quartzose, ferruginous, fine- to medium-grained, well-indurated, thick-bedded, massive	100.0
Sandstone, gray, massive, eroding into a ledge	40.0
Covered interval; mostly sandstone and shale	360.0
Sandstone, brown to gray, massive, mostly covered	400.0
Covered interval; mostly shale (may be **Prairie Hollow Shale**)	100.0
Sandstone, brown to gray, massive; mostly covered	1100.0
Chickasaw Creek Formation (total thickness 275 feet):	
Chert, black, speckled white, interbedded with bluish-gray shale and chert, with some sandstones	275.0
Total thickness of Jackfork Group, type section	3,620.0

Figure 23. Measured section of Jackfork Group type section (from Pitt and others, 1982, p. 80).

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Part 2

Contributed Papers

LITHOFACIES ASSOCIATIONS AND DEPOSITIONAL ENVIRONMENTS OF THE JACKFORK GROUP, OKLAHOMA AND ARKANSAS

Richard W. Evoy
Derry, Michener, Booth and Wahl

INTRODUCTION

Plate tectonic modeling suggests that the Ouachita Mountains in Oklahoma and Arkansas represent the largest exposed part of a a late Paleozoic suture formed during collision via south-dipping subduction of North America under a southern island arc or continent (Briggs and Roeder, 1975; Viele, 1979; Nelson and others, 1982). During closure of the Paleozoic ocean basin prior to collision, a deep trench and remnant ocean basin served as a major accumulation site for deep marine clastic sediments. An estimated 12,000 m of sediment (Lillie and others, 1983) were deposited through Mississippian and earliest Pennsylvanian time (Meramecian -Morrowan), and this sediment underwent syndepositional deformation as the basin closed.

Ultimately, as all oceanic crust was consumed and the outbuilding subduction complex encountered more bouyant transitional to continental crust, the deep marine sequence was thrust over the southern margin of North America (Viele, 1973; Lillie, 1985; Thomas, 1985). At that time (Atokan through Desmoinesian) the local depocenter shifted north, and sediment accumulation occurred primarily within the Arkoma foreland basin (Houseknecht and Kacena, 1983). Prior to final closure of the Ouachita basin, sediment accumulation was primarily in the form of sediment-gravity flows and interbedded hemipelagic muds from suspension settling (Morris, 1974; Graham and others, 1975; Moiola and Shanmugam, 1984).

OUACHITA STRATIGRAPHY

The Ouachita stratigraphic succession is readily divisible into two distinct sequences. The lower Paleozoic section, composed of Late Cambrian to Early Mississippian graptolitic shale, limestone, sandstone and chert, forms the core of the Ouachita Mountains and reflects a typical passive-margin facies association.

The Carboniferous section is a flysch sequence 6,500 m (Owen, 1984) to 7,600 m (Cline, 1970) thick. Sedimentation was primarily from turbidity currents and hemipelagic suspension resulting in a sequence of interbedded sandstone and shale. This sequence accumulated in a series of submarine fans within an active-margin setting; however, considerable controversy has developed over the precise location and orientation of the subduction front, the locations of the active sediment source(s), and the timing of collision resulting in the Ouachita orogeny.

The Carboniferous sequence has been subdivided into four lithostratigraphic units: the Stanley Group, Jackfork Group, Johns Valley Shale, and Atoka Formation. The Atoka Formation has locally been further subdivided; in Oklahoma, Marcher and Bergman (1983) have redesignated deep-water marine sediments of the lower Atoka the Lynn Mountain Formation.

JACKFORK GROUP STRATIGRAPHY

The Jackfork Group is the major ridge-forming unit in the Ouachitas, and these strata provide the focus of this study. The Jackfork Group conformably overlies the characteristic "shaley flysch" of the Stanley Group (Cline, 1960; Luttrell, 1965) and is uniquely situated to record both sedimentologic and structural changes resulting from the transition between subduction during Stanley time and collision during Atokan time.

Jackfork Group sandstones are predominantly fine- to very fine-grained, quartzose, and contain little matrix (Owen, 1984; Owen and Carozzi, 1986); primary depositional features are generally well preserved and include sole marks, flute casts, parting lineations, and base-cut-out Bouma sequences.

The type section for the Jackfork Group lies along the west face of Jackfork Mountain in the western Ouachitas (Taff, 1902; Pitt and others, 1982). The group has been subdivided into five formations based on the presence and recognition of several thin, siliceous shales and chert beds; these formations were subsequently extended throughout most of Oklahoma (Cline and Morretti, 1956; Shelburne, 1960; Seely, 1963). Lack of siliceous shales in Arkansas led to the subdivision of the Jackfork into only two formations (Morris, 1971, 1974).

The use of multiple formation designations - compounded with the difficulty of recognizing and correlating thin siliceous shale beds over significant geographic distances - has given rise to unneccessary difficulty in geologic interpretation. Furthermore, such attempted correlations require an "a priori" assumption of uniform, geosynchronous sedimentation within a single depositional setting. A brief survey of modern turbidite systems reinforces the fact that such uniformity is atypical, and the usage of the more generic Jackfork "Group" by recent workers appears to be a tacit acceptance of this principle of non-uniformity.

METHODOLOGY

Lithofacies data were collected at all Jackfork locations visited without consideration of the thickness of the exposed section. This produces a first approximation of blanket coverage in all accessible regions of the study area (Fig. 1). The resulting lithofacies data are presented regardless of their relative stratigraphic position within the Jackfork Group, thus giving distribution in space and time. Acceptance of this technique rests on the recognition that turbidite systems evolve through time by the progradation and lateral migration of lithofacies units over their predecessors. Basin-wide correlations of individual strata in a dynamic turbidite system are dubious, given the extreme degree of morphologic variation observed in analogous modern marine environments.

Where thicknesses greater than 20 m are preserved, complete measured sections were made to look for evidence of vertical cyclicity. As far as exposure permitted, sections were measured on a bed-by-bed basis; both contact geometries and internal structures were noted, in addition to standard lithologic features. Internal structures were described and, where possible, placed within the standard Bouma sequence.

Nine composite sections through the entire Jackfork Group were completed (Fig. 1). Most of these were compiled along paced

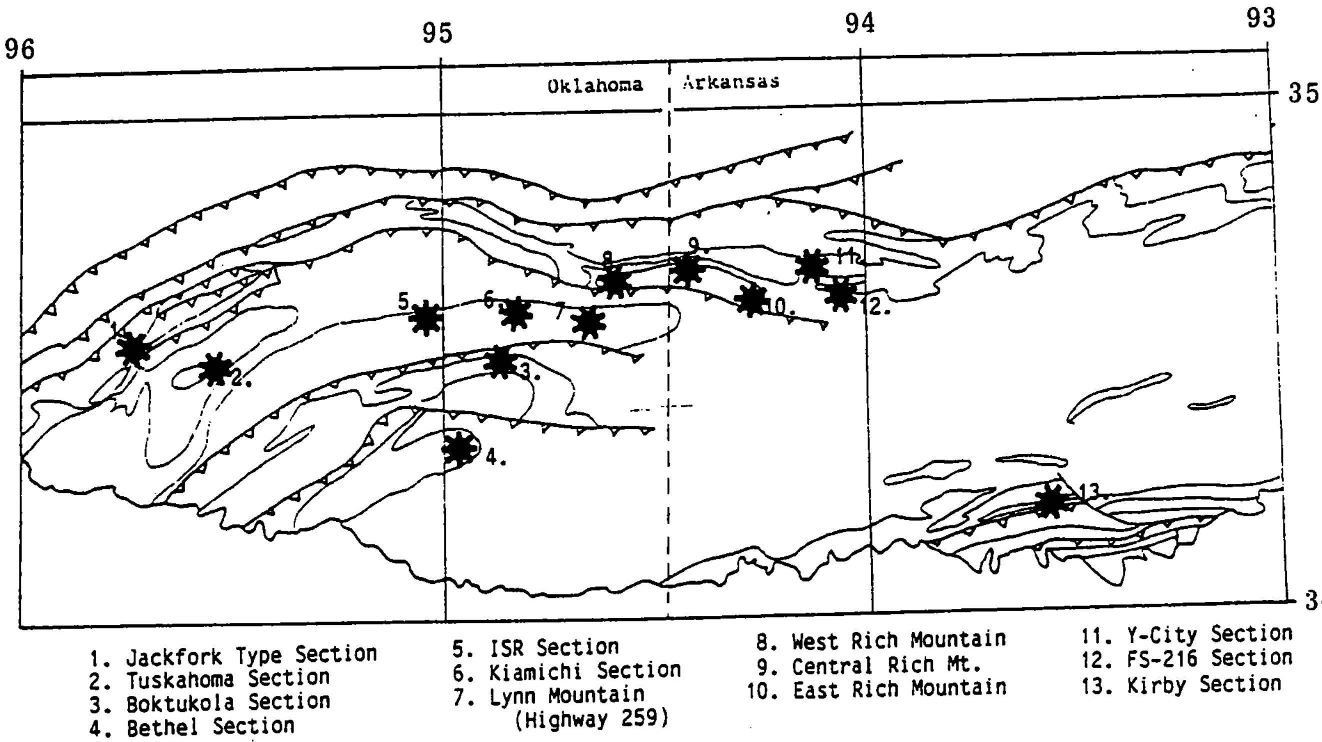


Figure 1. Study area and location map for major measured sections.

traverses with variable intervals of section covered and only minor amounts of section well exposed. The establishment of widely distributed, composite sections through the Jackfork affords the opportunity to compare vertical changes in lithofacies distribution on a regional scale. By thus constraining depositional geometry, it is possible to evaluate critically the possibility of multiple basins during Jackfork sedimentation.

The degree of variation in Jackfork lithofacies is greater than that implied by previous workers; however, this variability is in complete accord with the results of recent studies of deep-water marine depositional patterns in all types of tectonic settings (Piper and others, 1973; Schweller and Kulm, 1978; Stoffers and Ross, 1979; von Huene and others, 1980; McMillen and others, 1982; Moore and others, 1982a; von Huene and Arthur, 1982; Barnes and Normark, 1983/84; Stow and others, 1983/84).

LITHOFACIES CLASSIFICATION SCHEME

Classification schemes and models for the accumulation of deep-water marine sediments are abundant in the recent literature; the turbidite lithofacies classification used in this study is that established by Mutti and Ricci Lucchi (1972, 1975). Following this method, turbidites and other genetically related deep-water marine deposits are assigned to one of seven lithofacies based on bed geometry and thickness, texture, internal structure, and sandstone-to-shale ratio. Slight modifications in the relative importance of individual characteristics have been made to reflect the specific nature of exposures in the Ouachitas, the extreme degree of weathering encountered, and the limited lateral extent of most outcrops (Table 1). These problems are best accommodated by stressing the bed thicknesses and sandstone-to-shale ratios, as these features are independant of weathering or diagenetic overprinting, and applicable even where lateral extent of exposures is limited.

The seven lithofacies thus defined crudely reflect waning depositional energies of the individual depositional event, independant of the general depositional environment. The uniformity in grain size of most Jackfork sandstones makes the development and preservation of basal Bouma beds rare; thus, the presence of base-cut-out sequences is not definitive of facies D turbidites in the study area.

DEPOSITIONAL MODELS

Radial fans are supplied sediment via a single point source, typically a submarine canyon cutting across the continental shelf. Rapid deposition occurs, resulting in a classic tripartite fan morphology and possible suprafan bulge, where the inner fan consists of a single leveed valley (Normark, 1970, 1978). The middle fan is typified by shallow, bifurcating distributary channels; the outer fan generally lacks any channelized flow and is dominated by thin-bedded turbidites and hemipelagic muds (Fig. 2).

Development of radial fans is favored by the presence of a sediment point source with medium sediment input rates. Sandy sediment is frequently greater than or equal to the amount of mud- and clay-sized material. Modern examples include the Navy

TABLE 1 - MODIFIED LITHOFACIES CLASSIFICATION SCHEME FOR JACKFORK GROUP SEDIMENTS

FACIES	CHARACTERISTICS
A	Thick-bedded conglomerate; not present in the study area.
B	Thick-bedded (>1 m) sandstones; frequently exhibit amalgamation surfaces; may show lateral thickness changes on an outcrop scale;dish-and-pillar structures common where internal laminae are visible; rip-up clasts, plant fragments; SS:Sh ratio >10.
C	Medium-bedded (30-100 cm) fine-grained sandstone; Ta rarely recognized but common plant fragments, slurried bases; shallow channels common; SS:Sh >1.
D	Very fine to fine-grained, thin-bedded sandstone; tabular bedding geometry most common; abundant trace fossils; ripple cross-lamination frequently poorly developed; SS:Sh ratio <1.
E	Fine-grained, thin-bedded sandstone; pinch and swell laterally; SS:Sh >1; not significant in study area.
F	"Chaotic beds", all units having undergone non-brittle deformation; slumps, and debris flows.
G	SS:SH <1:9.

Modified from: Mutti and Ricci Lucchi, 1972, 1975.

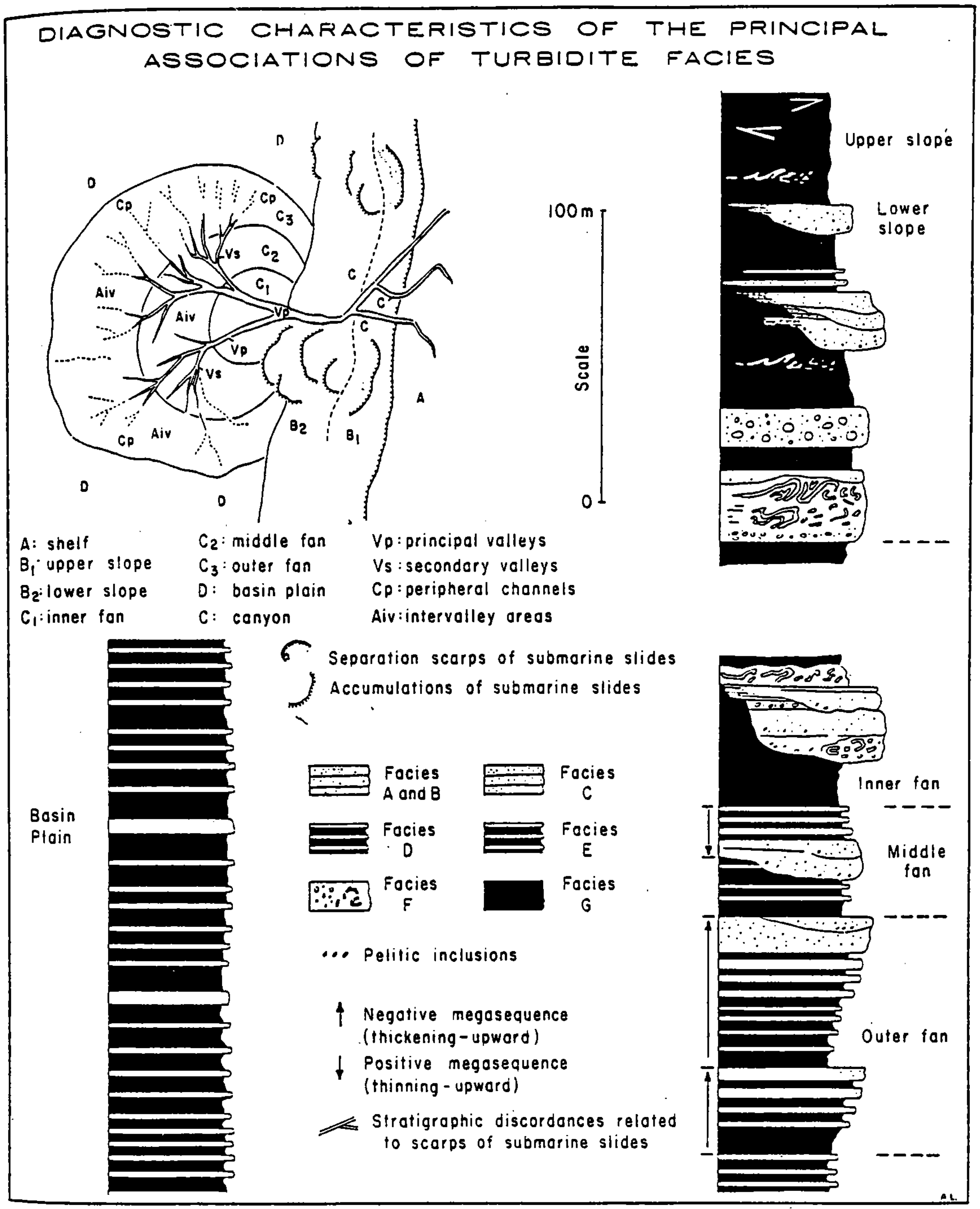


Figure 2. Environmental model and idealized stratigraphic sections of the principle turbidite lithofacies associations, (Mutti and Ricchi-Lucchi 1972).

Fan (Normark and Piper, 1972) and the La Jolla Fan (Shepard and von Rad, 1969).

Elongate fans also have a single primary source area, but differ from radial fans in that sediment input is greater in both rate and volume. The dominant grain size generally falls between clay and fine sand, and their elongate shapes reflect the funnelling of the sand sized fraction to the outer fan. This sediment bypassing of the inner and middle fans is aided by the abundance of fine-grained sediment as the resultant mud-rich turbidity currents transport sand more efficiently than other sediment-gravity flows.

The inner part of an elongate fan typically has a single active channel, plus one or more abandoned channels. Because much of the sand-sized sediment reaches the outer fan, the textural distinction between the middle and outer fan is less specific than in a radial fan. Examples of modern elongate fans include the Bengal Fan (Emmel and Curray, 1983) and the Amazon Fan (Damuth and Kumar, 1975).

Slope-apron systems are not considered true submarine fans because of the absence of channels (Stow and others, 1983/84). They are fed by a number of closely spaced point sources, or a linear source; sediment input rate is low, and sediment type is mixed. In profile, slope-aprons are wedge-shaped, with bed thickness, sand-to-mud ratio, and mean grain size decreasing basinward. Slope basins are the most numerous modern slope-apron systems, and on active margins trench-slope basins are the most significant depositional sites for slope-apron turbidite systems (Moore and Karig, 1976; Stevens and Moore, 1985).

Recognition of ancient trench fill is difficult strictly from a sedimentologic perspective. In modern trenches, most paleocurrent indicators are oriented parallel to the trench margin, due to axial transport of sediment (Piper and others, 1973; Schweller and Kulm, 1978); however, small fans with radial paleocurrent indicators may form where submarine canyons debouch into trenches (Underwood and Bachman, 1982). Further complications exist where the scale of observation and incomplete nature of the rock record may hamper recognition of the degree of structural rotation of paleocurrent indicators, the shape of the basin margin during deposition, and the depositional continuity of individual features.

The gradation of fine-grained pelagic sediment to coarser terrigenous clastics in trench-floor environs, and the lateral continuity of individual turbidites in trenches, are well documented; however, neither is unique to any specific turbidite system. Coarsening-upward sequences reflecting movement of a subducting plate toward the trench may provide the strongest single indication of a paleo-trench environment (Moore and Karig, 1976), but at any single location this type of cycle could equally represent growth of a submarine fan.

LITHOFACIES ASSOCIATIONS

Inner-fan facies associations may include all lithofacies categories, but thick accumulations of conglomerate and sandstone are generally characteristic of the inner-fan channel. Sedimentary structures include basal Bouma sequences, dish structures, and mud rip-up clasts. Levees of variable prominence flank the channel, and interchannel areas are dominated by thin sandstones and hemipelagic shales. Large facies F slumps may be incorporated into the channel as a result of failure and/or undercutting of the channel walls, and smaller slumps can be generated along the edges of the interchannel region, producing small synsedimentary folds. Facies changes are abrupt, both laterally and vertically. Cyclicity is generally marked by thinning- and fining-upward sequences and is frequently stacked; however, thinning- and thickening-upward cycles are possible.

Middle-fan facies associations are dominated by facies C in the distributary channels, grading up to facies D and G in the interchannel areas. Slumping is rare and limited to small-scale synsedimentary folding along the levee flanks. Sedimentary structures in the channel commonly include complete Bouma sequences, well-developed sole marks, and channeled basal contacts. Channel migration in the middle fan produces well defined thinning- and fining-upward cycles. Fan progradation may also produce coarsening-upward megasequences and a gradational transition to inner-fan facies associations.

Depositional lobes in the outer-fan environment are deposited from unconfined turbidity currents to form large unchannelized bodies composed of fine sands, silts, and mud. Individual beds become progressively thinner and finer in a down-fan direction. On an outcrop scale, bed thicknesses are remarkably consistent, and bed contacts are typically planar; sedimentary structures are dominated by base-cut-out Bouma sequences. Facies association is facies D and G, with occasional facies C sandstones.

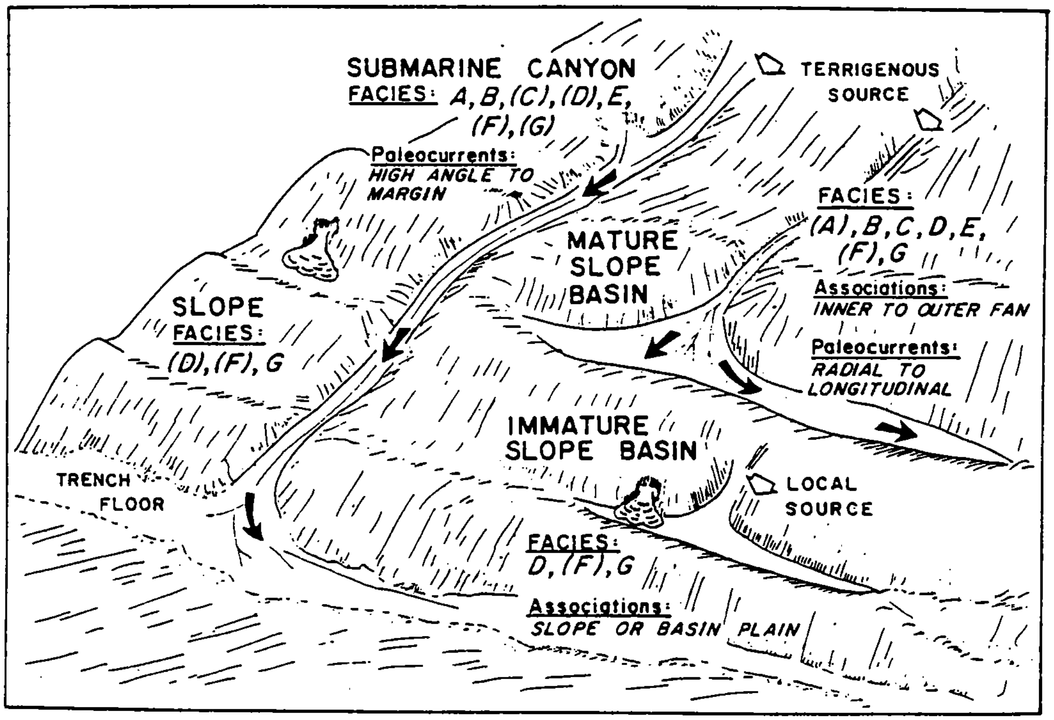
The fan fringe represents the transition from outer fan to basin plain. Grain sizes and bed thicknesses continue to decrease from the outer fan through the fan fringe to the basin plain. Sandstone bed thicknesses rarely exceed 15 to 20 cm in this environment, and plane-parallel laminations are the most common sedimentary structure.

Vertical cyclicity in the outer fan-fan fringe region is composed of small (2-5 m) thickening- and coarsening-upward sequences stacked into large thickening- and coarsening-upward megacycles which reflect progradation of the fan and lobe migration.

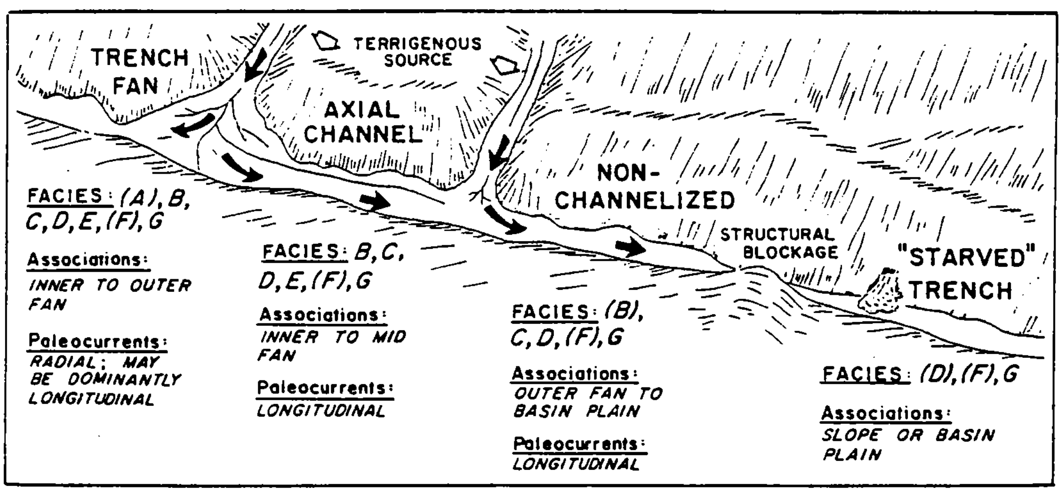
Sedimentary facies in trench and trench-slope settings can be compared to facies associations in submarine fans (Fig. 3). Where a submarine canyon or other major sediment source debouches into a trench environment, a trench fan may develop; the size and shape of the fan will reflect a multitude of variables, including trench geometry, rate of sediment input, and strength of axial currents. Facies associations range from inner fan through outer fan-fan fringe.

Trench-floor sedimentation can be divided into channelized and unchannelized sequences. Where large axial channels are present, thick packages of facies B and facies C sandstones are expected. Where axial channels are not prominent, sediment transport is accomplished via unconfined sheet flow; facies D turbidites and facies G shales would predominate, with secondary facies C sandstones. Facies associations for the channelized trench floor would reflect inner- and middle-fan assemblages. Outer fan-fan fringe associations would develop in the absence of active axial channels, or if the frequency of turbidity currents is low, basin-plain associations can accumulate.

Trenches formed in conjunction with subduction zones may develop structural blockages to lateral sediment transport as a result of irregularities in the subducting oceanic crust. Where this occurs, parts of the trench may be cut off from appreciable terrigenous sediment input. The resultant starved trench will



(a.)



(b.)

Figure 3. Lithofacies distribution patterns for:
(a.) trench-slope, and
(b.) trench floor environments.
From Underwood and Bachman (1982).

accumulate hemipelagic muds (facies G) and dilute unconfined turbidity currents (facies D). Similar lithofacies should also accumulate in trench-slope basins lacking a direct terrigenous source to supply coarse sediment via by-passing of the continental shelf. Facies association would resemble basin- plain or slope sediments, but would be laterally restricted by the scale of their depositional environments.

Southeastern Oklahoma

Exposures in southeastern Oklahoma are dominated by facies D, C, and G. Interfacies contacts are rarely observed; they are usually marked by gradual changes in sandstone-to-shale ratios and/or individual bed thicknesses. Sharp interfacies contacts appear limited to facies B exposures in the Tuskahoma syncline. Vertical cyclicity is poorly preserved, but both thinning- and fining-upward and thickening- and coarsening-upward megacycles can be recognized. Thinning- and fining-upward cycles can also be resolved at an outcrop scale.

Thick sequences of shale and randomly interbedded, thin, facies D and C sandstones accumulate as a result of deposition of hemipelagic sediment from suspension, combined with periodic influxes of coarser sediment from weak, unconfined turbidity currents. Probable depositional environments for sections in southeastern Oklahoma are outer fan-lobe fringe in a submarine fan (Mutti and Ricci Lucchi, 1972; van Vliet, 1978), or restricted intraslope basins (Moore and Karig, 1976; Hein, 1985; Stevens and Moore, 1985).

Lynn Mountain Syncline

Sedimentation in the Lynn Mountain syncline is marked by significant accumulations of predominantly thin-bedded (<1 m thick), fine- to very fine-grained sandstones. Along the crest of Kiamichi Mountain, longitudinal variation over a distance of 35 km can be seen primarily as decreases in percent amalgamations preserved in facies B sandstones, and a corresponding increase in the amount of visible matrix or silt content in the thicker, more massive facies B and C sandstones.

Facies associations along Highway 259 are typically B and C with D and G; some facies F is present locally. Westward toward the Indian Services Road, facies C and D become more significant, and facies B decreases in importance. Along strike, variation in grain size is negligible; fine- to very fine-grained sandstones, siltstones and shales are equally common at all three locales. The bases of many sandstone beds, especially facies C sandstones, are formed of slurried beds of fine-grained sandstones with 30 to 50% silt- and mud-sized matrix material. Fine-grained and mud-rich turbidity currents are also more efficient at long-distance sediment transport. Bases of sandstone beds are strongly loaded as a result of rapid sedimentation.

Thickening-upward cycles from 10 to 60 m thick consist of facies C sandstones grading up into facies B sandstones. These cycles reflect growth and/or lateral migration of large depositional lobes or channels. Fining- and thinning-upward cycles are more common, but rarely exceed a few meters in thickness. These fining-upward sequences are interpreted as the product of migration and abandonment of small channels.

Facies contacts are sharply defined between facies B, C, and G, reflecting rapid changes in depositional processes. Contacts between facies C and D, and D and G, are less well defined. The transitional nature of these contacts reflects a gradual waning of flow strength, likely in interchannel areas fed by overbank flows, sheet flow, and dilute, unconfined turbidity currents. Possible depositional environments are a large depositional lobe in a middle- to outer-fan setting, a large trench-slope basin, or unchannelized trench-floor sedimentation (Underwood and Karig, 1980; Underwood and Bachman, 1982).

Frontal Ouachitas and Athens Plateau

Lithofacies associations in the frontal Ouachitas in Arkansas and the Athens Plateau include all seven turbidite facies. However, facies A was only encountered in the vicinity of the DeGray Dam, and is not within the main area discussed. Interfacies contacts are exceptionally sharp, with thick sandstones overlain by shales, followed by additional thick sandstone units. Such rapid switching of channel and inter-channel environments is most common near the margins of channelized deposition in the suprafan lobe (Normark, 1970, 1978) where distributary channels begin to bifurcate.

Amalgamation surfaces and shale rip-up clasts are common throughout these sections, most notably at Y-City, and attest to high erosive power in some flows. Cyclicity is encountered at two scales. Thinning- and fining-upward cycles are generally <5 m thick, although some cycles up to 25 m are found. These cycles represent channel-fill sediments. Coarsening- and thickening-upward sequences are usually >20 m thick, and reflect lobe migration and progradation. The probable depositional environment within a classic fan model is a channelized middle fan characterized by rapid channel switching and sand accumulation, with cyclicity reflecting channel and lobe migration (Nelson and Kulm, 1973; Mutti and Ricci Lucchi, 1975). Similar lithofacies associations can develop in a trench floor or a large trench-slope basin setting (Underwood and Bachman, 1982). Paleocurrents in the Jackfork Group are dominantly east-to-west with only minimal scatter (Briggs and Cline, 1967), and do not constrain either model.

SUMMARY AND DISCUSSION

In Oklahoma, a slight north-to-south decrease in both sandstone thickness and sandstone-to-shale ratio is found throughout the study area, with a dramatic reduction in sandstone across the Octavia fault. Sediments south of the Octavia fault are predominantly thin, base-cut-out turbidites and hemipelagic shales; very little evidence for either depositional channels or erosive flow is present. North of the Octavia fault, both thick, amalgamated sandstones and channelized sandstones are present. Overall longitudinal variations in lithofacies types are more pronounced, with marginally channelized and channel/inter-channel associations dominant in the eastern field area, giving way to lobe-fringe/interlobe/basin-plain associations in the western field area.

The general trend of decreasing number and thickness of sandstones from east to west through the Jackfork Group reflects a gradual decrease in depositional energy and increasing distance from the primary sediment source. This is compatible with paleocurrent data indicative of east-to-west paleoflow conditions. The depositional environment can therefore be approximated as an elongate turbidite system fed from the east and building to the west through Jackfork time. Further definition of the paleogeography of the Ouachita subduction zone during this period is possible, based on the facies distribution patterns mapped during field work.

If interpretations of the Jackfork facies data follow accepted lithofacies association classification schemes for submarine fans (Mutti and Ricci Lucchi, 1975; van Vliet, 1978; Walker, 1979), then the gradation from middle-fan to basin-plain associations is compatible with a large, elongate fan, prograding from east to west in the Jackfork basin (Fig. 4). Alternative criteria based on trench/trench-slope facies models (Underwood and Bachman, 1982; Lash, 1985; MacDonald, 1986) result in the recognition of possible trench, slope, and slope-basin facies distributions (Fig. 5).

The presence of generally unidirectional flow, as opposed to radial paleocurrent patterns, appears to favor a trench environment, but this is not a definitive interpretation, for two reasons. First, the scale of the study area in comparison to large modern submarine fans is small enough that the entire area may have been dominated by a single channel within a depositional lobe. Second, the number of variables governing fan geometry are complexly inter related, resulting in a variety of hybrid fans containing elements of radial, elongate, and trench/slope geometries (Stow and others, 1983/84).

Sedimentation in the Ouachita basin during Jackfork time consisted of a large turbidite system fed from an eastern and/or southern source, and prograding in a westerly direction. Grain sizes, individual bed thicknesses, and total sandstone content all decrease gradually from east to west up to the Octavia fault, where a sudden and dramatic decrease in sandstone content and thickness is encountered. Lithofacies associations in the northern part of the study area are compatible with deposition from a high-energy, channelized turbidite system (facies B, C, D, and G).

Degree of channelization also decreases from east to west, reflecting gradually waning depositional energies down-flow. Lithofacies associations in the southwestern field area are virtually unchannelized, and accumulated in a significantly different environment characterized by much lower depositional energies. Paleocurrent data throughout the field area are consistent with westward-flowing turbidity currents.

Regional correlation, if possible, will reflect large-scale extra-basinal sea-level fluctuations (Vail and others, 1977; Stow and others, 1983), whether due to tectonic processes, Carboniferous glaciation in the southern hemisphere, or other processes. The presence of increased sand accumulations one third of the way up-section in all of the composite measured sections other than I.S.R. and the type section may represent one such global lowstand in sea level. More-detailed sedimentologic data are necessary before these possibilities can be adequately assessed.

Turbidity currents and related sediment-gravity flows fall within a continuum of traction/deposition regimes (Carter, 1975; Middleton and Hampton, 1973; Lowe, 1979, 1982). This results in the deposition of blanket-like temporal sequences; internal character at any given point in the resulting sediment accumulation will therefore be a complex of such variables as depositional slope, fluid density, flow velocity, viscosity, internal flow turbulence, etc., all at the time of deposition. However, while correlation of specific lithologies is improbable,

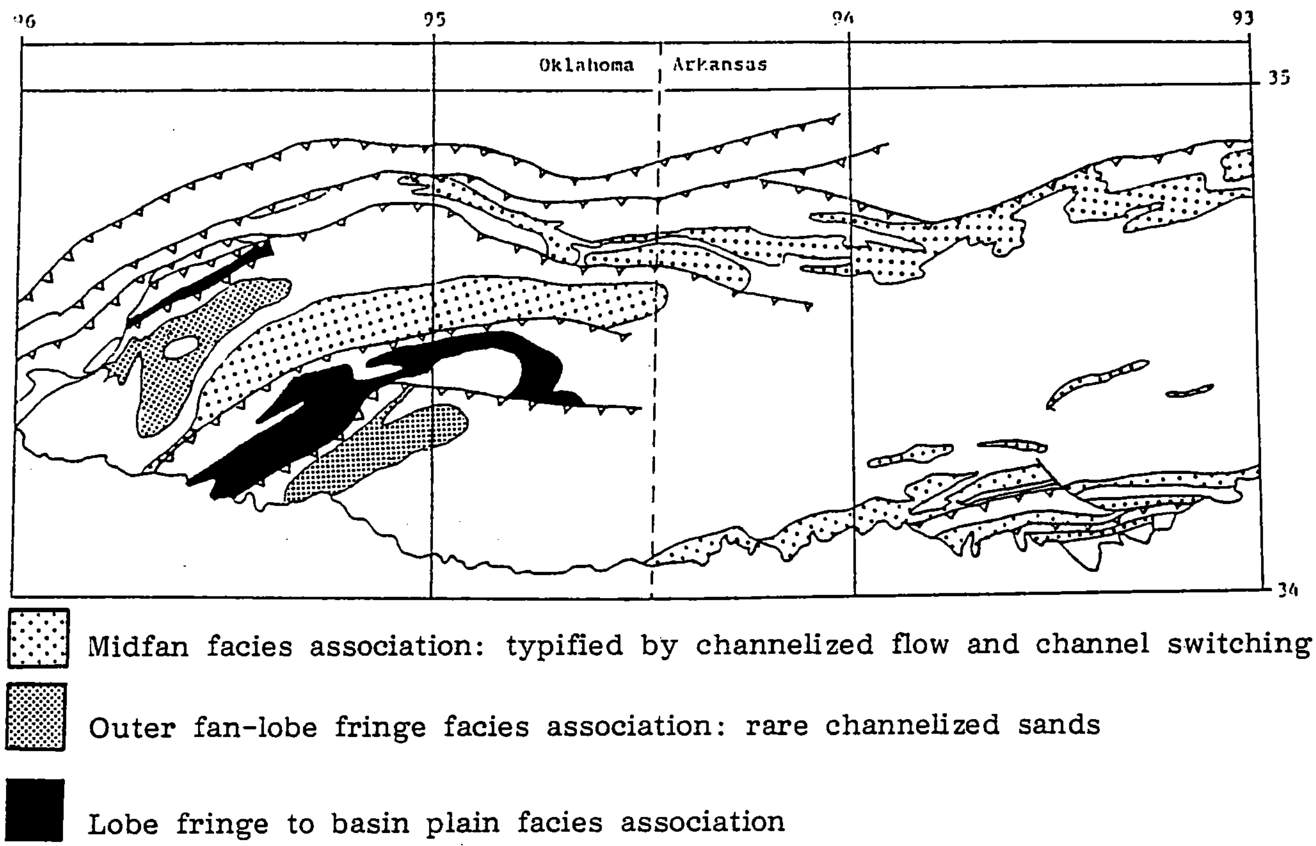


Figure 4. Lithofacies associations and interpreted depositional environment of Jackfork Group sediments, based on the assumption of a submarine fan geometry.

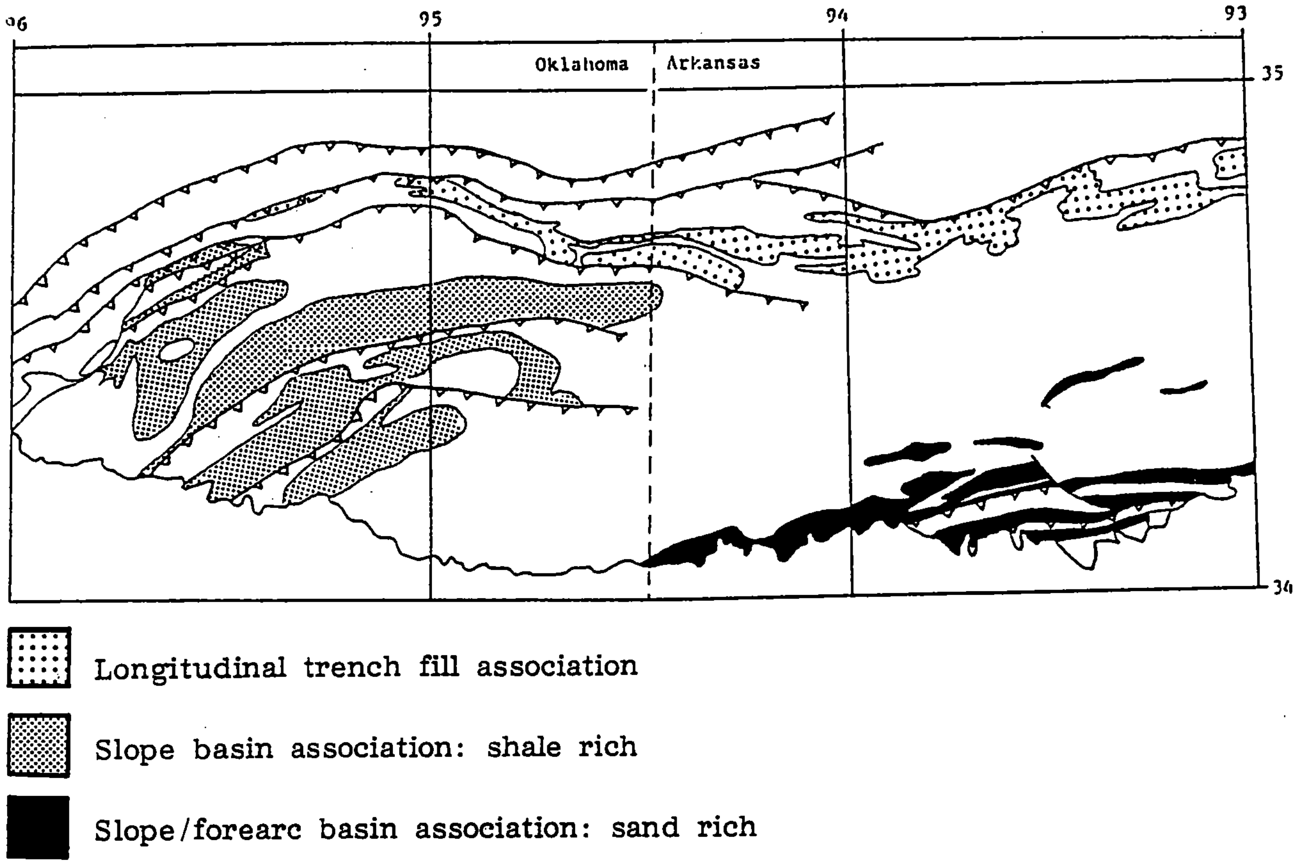


Figure 5. Interpretted depositional environment of Jackfork Group sediments assuming deposition in a trench/ trench-slope setting.

detailed sedimentology and facies analysis may allow for correlation of "depositional events".

CONCLUSIONS

Two different depositional models for the Jackfork Group sediments are possible. The first, following fan models, is development of a large, elongate submarine fan with channelized and interchannel associations (middle fan) in the east, giving way to depositional lobes, outer-fan, and fan-fringe associations in the west. Alternatively, based on a trench/trench-slope model, the Jackfork Group may represent trench-slope basin sediments and accreted trench-floor deposits.

Based on analysis of structural fabrics in the Jackfork Group strata, including fabrics indicative of early deformation under high confining and pore-fluid pressures (Evoy, 1989), a trench-slope model is envisioned for the depositional environment of the Jackfork Group.

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COMPARATIVE STUDY OF CRUDE-OIL COMPOSITIONS IN THE FRONTAL AND CENTRAL OUACHITA MOUNTAINS

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INTRODUCTION

The Ouachita Mountains fold and thrust belt in southeastern Oklahoma is a complexly deformed area which yields small but commercial quantities of liquid petroleum, mostly from shallow wells. These wells, which appear to tap small pools, lie along a SW-trending line that generally follows the Windingstair fault. A question of major geologic interest over the years has been the source of this oil. Was it generated from rocks within (1) the Ouachita facies, (2) the southern Oklahoma aulacogen, or (3) the foreland beneath the thrust belt (Curiale, 1983; Chenoweth, 1985)? An additional possible source for shallow oil accumulations in the area immediately south of the outcrop area of Ouachita strata is sediments within the Cretaceous overlap. Another facet of the same question is whether the oil derives from a single source or multiple sources. By studying geochemical characteristics of an oil, it is possible to distinguish subtle chemical differences which indicate, among other things, the nature of the original organic matter from which that oil was derived. By differentiating oils in this manner, one can type them, i.e., assign them to a particular family or group. Those with similar or matching characteristics are said to correlate. However, it should be noted that whereas evidence indicative of a correlation can happen by chance, evidence incompatible with correlation is always due to a definite cause. Thus, determining that oils cannot be related to one another is as important as determining that they might be related.

Previous published work on the correlation of liquid crude oils from the Ouachitas is limited to four oils studied by Curiale (1983). He examined one oil from Bald field, two from S Bald, and one from Redden -- all located in McGee Valley. He concluded that those oils have a common source, probably rocks of the Ouachita facies.

As part of an overall review of the regional geology, and aware of industry's continuing interest in the oil potential of the Ouachita fold and thrust belt, the Oklahoma Geological Survey (OGS) is collecting oil samples from all producing fields in the area, as well as any isolated wells known to contain oil. Although this work focuses on oils of the thrust belt, several samples from the W Idabel field, located near the southern edge of the Broken Bow uplift, have also been collected and will be reported on here. By contrast, they will serve to emphasize any similarities among oils of the frontal and central belts.

Data presented in this paper are preliminary and cover results obtained to date. Geochemical analyses conducted during this first phase of the study concentrate on whole-oil characterization. It is anticipated that subsequent work will involve examination of oil fractions at the molecular level.

COLLECTION OF OILS

Crude oils representing eight named fields and two isolated wells were collected specifically for this study. For convenience of discussion, the sampled oils have been placed into two groups: the Thrust Belt group, referring to oils obtained from wells located in the fold and thrust belt, and the Broken Bow Uplift group, referring to oils from W Idabel field; this terminology relates only to geographic location and has no geologic connotation. In most cases, well names used here are those listed on signs at the well sites or supplied by current owners/operators; these names do not necessarily reflect the names given to the wells at the time they were drilled. Unfortunately, documentation bearing on well histories is frequently incomplete. The data presented in this paper cover all oils collected thus far (excluding three late acquisitions), plus two samples collected earlier by Curiale (1983) and included here for comparison.

TABLE 1. OUACHITA CRUDE OILS USED IN STUDY

Sample Number	Well Name	Location	Field	Well Type	Sampling Method	Sampling Date	Comment
	Thrust Belt						
1	Warren 1	2-3N-21E	"Talihina"	Oil	Wellhead; OGS personnel	12-88	Well inactive
2	Jim 1	5-2N-17E	"Star"	Oil	Stock tank; OGS personnel	6-88	
3	Dallas James 1	28-2N-15E	Bald	Oil	Flowline; OGS personnel	12-88	
4	Dallas James 2	28-2N-15E	Bald	Oil	Flowline; OGS personnel	12-88	
5	"S Bald Field"	5-1N-15E	S Bald	Oil	Stock tank; J. Curiale	8-78	Well not identified
6	Crockett 2	5-1N-15E	S Bald	Oil	Supplied by pumper	9-88	
7	Crockett D	5-1N-15E	S Bald	Oil	Supplied by pumper	9-88	
8	Smith 1	5-1N-15E	S Bald	Oil	Supplied by pumper	9-88	
9	Rowland Bledsoe 1	7-1N-15E	S Bald	Oil	Stock tank; OGS personnel	6-88	
10	Foster B-2	7-1N-15E	S Bald	Oil	Stock tank; OGS personnel	6-88	Tank appears to be fed by two (inactive? unidentified?) wells
11	Frazier 1 + Loman 1	8-1N-15E	S Bald	Oil	Supplied by pumper	9-88	Two wells; oil commingled
12	Foster 1	8-1N-15E	S Bald	Oil	Stock tank; OGS personnel	6-88	
13	Four North 1-1 + 1-2	8-1N-15E	S Bald	Oil	Stock tank; OGS personnel	6-88	Two wells; oil commingled
14	Lambert 2W	6-1N-14E	E Wesley	Oil	Obtained from bottle kept by owner	6-88	Well inactive since 1984
15	Wyrick 2-26	26-1N-14E	W Daisy	Gas	Stock tank; OGS personnel	12-88	
16	School Land 2	26-1N-14E	W Daisy	Oil	Stock tank; OGS personnel	12-88	Well inactive
17	Isom 4	24-1N-15E	SE Daisy	Oil	Supplied by owner	6-88	Well under pressure
18	Williams 1-26	26-1N-15E	SE Daisy	Gas	Stock tank; OGS personnel	6-88	
19	"Redden Field"	9-1S-14E	Redden	Oil	Stock tank; J. Curiale	1978	Well not identified
20	E. Miller 2	9-1S-14E	Redden	Oil	Supplied by owner	3-86	
21	Lee Cole 1	19-1S-14E	Minnett	Oil	Bailed from open pipe hole; OGS personnel	9-88	Well inactive
	Broken Bow Uplift/Cretaceous Overlap						
22	Harvey Harmon 2('88)	33-7S-23E	W Idabel	Oil	Stock tank, bottom valve; OGS personnel	6-88	
23	Harvey Harmon 2('86)	33-7S-23E	W Idabel	Oil	Supplied by owner	1-86	
24	"Harvey Harmon #?"	33-7S-23E	W Idabel	Oil	Bailed from open pipe hole; OGS personnel	6-88	Well inactive
25	Smith	5-8S-23E	W Idabel	Oil	Stock tank; OGS personnel	6-88	Well inactive; visible tar mat in tank

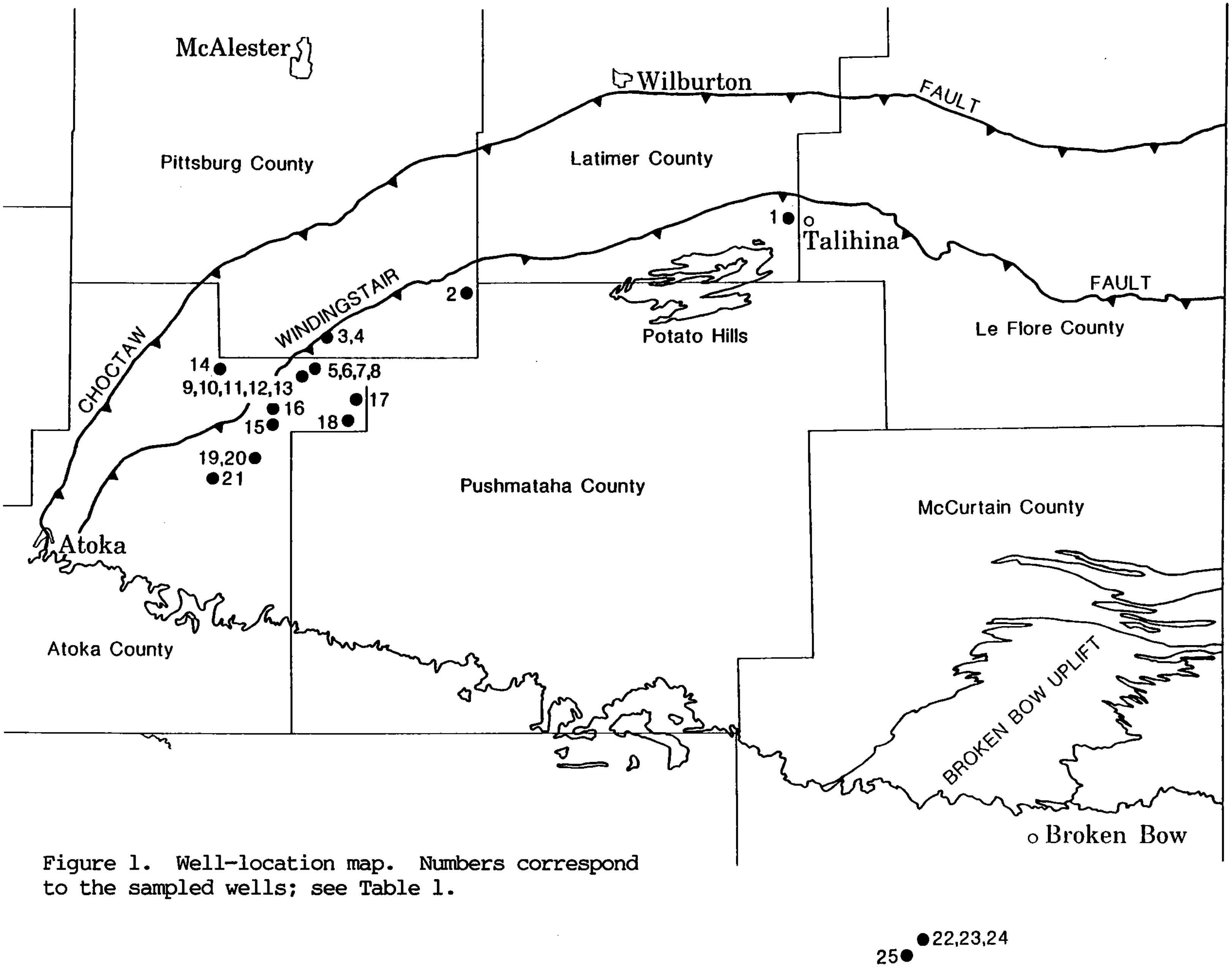

Figure 1. Well-location map. Numbers correspond to the sampled wells; see Table 1.

Two oil samples from the Harvey Harmon 2 well were used; one was supplied by the owner in 1986, and the other was obtained by OGS personnel from the stock tank in 1988. From an analytical viewpoint, these samples are not true duplicates; but their fundamental chemical characteristics should be essentially the same. The other sample from the Harvey Harmon property (Number 24 on Table 1) has been arbitrarily referred to as "Harvey Harmon #?", although there is reason to believe it was drilled as one of the Bennie Street series of wells.

In terms of production, most of the wells (locations shown in Fig. 1) fall in the stripper-well category, although several of them are not currently equipped to produce any oil (pumps have been removed or are inoperative, ownership of well is in litigation, etc.). Stripper wells (10 barrels or less per day) are pumped at intervals, the frequency depending in part on the amount of oil available and the profitability of the operation, which at the present time is barely economic to subeconomic. In two cases, the sampled wells coproduce oil and gas, gas being the primary product.

Due to the disparate nature and condition of the wells, it was not possible to employ a consistent sampling procedure. While freshly pumped oil constitutes the ideal sample, the samples used in this study were obtained in whatever way proved feasible. Sampling methods are listed in Table 1 and should be kept in mind when evaluating data.

Oils sampled from stock tanks by OGS personnel were scooped from beneath the surface of the liquid in the tank. The stock tank at Harvey Harmon 2 (1988 sample) was sampled by opening a valve near the bottom of the tank and catching the effluent. "Harvey Harmon #?" and Lee Cole 1 are open-pipe holes. Both were sampled by a bailing technique: A styrofoam coffee cup on a rope was used for the former, whereas a metal bailer fashioned from plumber's pipe was lowered by rope into the latter.

It is not known if owner- or operator-supplied samples were taken at the wellhead, from flow lines, or from stock tanks. According to its owner, Isom 4 has not produced oil for about three years, due to a gas-pressure problem. For that reason, he insisted on sampling the well himself. The Lambert 2W last produced oil in 1984. OGS personnel obtained a sample of that oil from a glass bottle kept by the well owner. Samples listed here as "S Bald Field" and "Redden Field" have been stored in glass bottles at OGS since 1978. They were originally collected by Curiale (Curiale and Harrison, 1981) from stock tanks; he did not identify individual wells.

All samples were placed in clean, dry screw-cap containers made of glass, polyethylene, or aluminum, and stored at room temperature.

ANALYSIS OF OILS

The analytical procedures described below are commonly used in geochemical studies and are compatible with the equipment available at OGS laboratories.

API gravities were measured at room temperature with a hydrometer and then corrected to 60°F.

Loss on evaporation (topping) was achieved by heating approximately 50 mg of crude oil to 43°C in an oven for 18 hr. The Smith sample was not topped because it contained no low-boiling fraction.

Asphaltenes were removed by suspending topped oil (whole oil in the case of Smith) in a 50-fold excess of n-pentane, refrigerating overnight, and filtering off precipitated asphaltenes onto two stacked 20-µm polyethylene frits. After removal of solvent from the filtrate by evaporation, the asphaltene-free residue was chromatographed on a column of activated silica gel overlain with alumina. Stepwise elution with n-pentane, benzene, and chloroform–methanol (1:1) yielded saturate, aromatic, and NSO (nitrogen-, sulfur-, and oxygen-containing) fractions, respectively. A final column wash with methylene chloride to remove any remaining material was added to the NSO fraction. Separated asphaltenes were recovered by rinsing the filters with methylene chloride. Individual fraction weights were determined after solvent evaporation, and then their relative distributions were calculated.

Whole, untopped oils were analyzed on a Hewlett Packard 5840 gas chromatograph equipped with a flame-ionization detector and a 30 m x 0.25 mm i.d. fused-silica capillary column coated with a bonded dimethylpolysiloxane phase (0.25 μm film thickness). The carrier gas was helium; injector and detector temperatures were 300°C and 310°C, respectively. For complete-range oil profiles, the oven was programmed at 8°C/min from 60° to 290°, with a final hold of 15 min. To elucidate components in the C_6–C_{11} range, oven programming was 4°/min from 40° to 80°, 8°C/min from 80° to 120°, and 20°C/min from 120° to 290°, with a final hold of 12 min to elute remaining compounds from the column. Peak areas were integrated electronically, but, due to overlapping small peaks, some peak areas were visibly erroneous. Consequently, peak-height measurements were used for most calculations. Peak assignments were made by comparison of retention times with published chromatograms and an in-house standard solution containing C_9 through C_{26} n-alkanes, pristane, phytane, and even-numbered n-alkanes from C_{28} to C_{34}.

RESULTS AND DISCUSSION

Crude oil is a complex mixture of varying amounts of hydrocarbons and other closely related organic compounds trapped in a porous reservoir rock. Generally similar in chemical composition, crude oils differ only in their relative distributions of certain components or homologous series. An homologous series is a family of organic compounds in which successive members differ regularly in composition, frequently by one carbon atom and two hydrogen atoms (CH_2). The concept that crude oil originates from and therefore can be associated with organic matter in a fine-grained sedimentary "source" rock is widely accepted in the literature. The nature of this organic matter and conditions prevailing at the time of deposition are thought to be the dominant factors influencing which compounds are present in a crude oil and their relative amounts (Koons and others, 1974; Kinghorn, 1983). (Absolute amounts of the thousands of individual constituents of a crude oil are seldom determined.) It follows that oils generated by the same or similar source rocks should have the same or similar types and relative amounts of compounds; their chemical characteristics should bear a close resemblance to each other. However, minor facies variations within a source unit plus the fact that a source rock is part of a dynamic system can result in minor differences within an oil generated from that single source. Of greater importance are alterations caused by migration or temperature effects, bacterial action, water washing, or deasphalting. Water washing involves removal of water-soluble compounds at the oil/water interface. Most affected are light hydrocarbons, particularly aromatics (e.g., benzene, toluene), and small polar compounds (e.g., fatty acids, phenols). Natural deasphalting, the precipitation of asphaltenes in a reservoir, is caused by their low solubility in light hydrocarbons. This phenomenon occurs when reservoir pressure is great enough to keep generated hydrocarbon gases in solution. For the most part, chemical changes attributable to these processes are fairly well known and can frequently be recognized in a set of oils.

Information obtained from both bulk properties and specific chemical compounds is discussed below.

BULK CHARACTERIZATION OF OILS

Oils are commonly fractionated (separated) into four chemical-compound types: saturates (alkanes), aromatics, NSOs, and asphaltenes. Table 2 lists API gravities and fractionation data for Ouachita oils analyzed in this study. API gravities for Thrust Belt samples fall between 32° and 48°. If the two oils coproduced from gas wells are excluded, the range narrows to 32° to 41° API. None of these oils can be termed heavy, although most are from shallow reservoirs. Noticeably lower values of 20° to 23° API for samples from the Broken Bow Uplift group are attributed to biodegradation (the destructive alteration of crude oil by bacteria), discussed below.

Evaporation loss measures the amount of C_1 through approximately C_{14} compounds, i.e., those boiling below 270°C, the boiling point of n-pentadecane (C_{15}). Losses on the order of 15% or less can indicate prior removal of some light-boiling components by biodegradation (Powell and McKirdy, 1975) or volatilization. The latter is a distinct possibility for oils sampled from undisturbed stock tanks at inactive wells. Gas-chromatography data presented below suggest that

TABLE 2. ANALYTICAL DATA FOR OUACHITA CRUDE OILS

	°API[a]	Topping Loss[b] (%)	Weight Percent[c] Sat	Arom	NSO	Asph	Recovery[d] (%)	Sat/Arom	Pr^e/Ph	Pr^e/C_{17}	Ph^e/C_{18}	$(Pr + C_{17})^e/(Ph + C_{18})$	OEP $(C_{14} - C_{18})$
Thrust Belt													
Warren 1	37	15.5	73	20	6	1	85	3.6	1.44	.48	.46	1.41	1.18
Jim 1	33	17.2	61	26	12	1	89	2.3	1.50	.37	.41	1.63	1.24
Dallas James 1	34	17.7	60	28	11	1	88	2.1	1.46	.58	.50	1.33	1.08
Dallas James 2	34	16.9	60	27	12	1	91	2.1	1.43	.56	.48	1.28	1.11
"S Bald Field"	36	15.6	69	20	9	1	80	3.4	1.44	.35	.33	1.36	1.11
Crockett 2	37	17.8	71	22	7	0	86	3.2	1.44	.34	.31	1.35	1.10
Crockett D	38	20.3	71	21	8	0	87	3.4	1.39	.36	.34	1.34	1.13
Smith 1	40	22.5	70	21	8	1	84	3.3	1.34	.37	.36	1.32	1.12
Rowland Bledsoe 1	36	14.7	70	22	8	0	87	3.2	1.50	.27	.22	1.24	1.07
Foster B-2	32	10.3	62	25	12	1	85	2.5	1.55	.48	.40	1.38	1.13
Frazier 1 + Loman 1	39	22.3	69	23	8	0	88	3.0	1.40	.36	.34	1.36	1.12
Foster 1	36	17.9	69	21	7	3	86	3.3	1.50	.28	.23	1.28	1.10
Four North 1-1 + 1-2	37	17.8	71	21	8	0	86	3.4	1.36	.38	.39	1.40	1.15
Lambert 2W	39	23.0	74	16	10	1	87	4.6	1.72	.84	.58	1.38	1.06
Wyrick 2-26	47	26.3	-	-	-	-	(12)	4.1	1.89	.29	.26	1.71	1.08
School Land 2	35	7.8	74	19	6	1	86	3.9	1.36	.31	.29	1.30	1.09
Isom 4	39	26.8	73	20	7	0	86	3.6	2.00	1.19	.73	1.56	1.08
Williams 1-26	48	45.9	-	-	-	-	(7)	-	2.00	.51	.46	1.85	1.15[f]
"Redden Field"	34	12.8	72	19	8	1	86	3.8	1.51	.31	.28	1.38	1.12
E. Miller 2	41	26.5	78	16	6	0	82	4.9	1.50	.24	.20	1.28	1.07
Lee Cole 1	34	18.6	58	25	10	7	89	2.3	1.26	.42	.44	1.30	1.15
Broken Bow Uplift/Cretaceous Overlap													
Harvey Harmon 2 ('88)	21	3.7	49	29	11	11	89	1.7	.54	.55	1.14	.82	1.02
Harvey Harmon 2 ('86)	23	13.2	51	34	7	8	89	1.5	.55	.50	1.06	.86	-
"Harvey Harmon#?"	23	6.9	48	35	9	8	91	1.4	.57	.70	1.43	.82	1.07
Smith	20	-	51	32	7	9	95	1.6	.60	3.10	8.35	.68	-

[a]Corrected to 60°F.
[b]18 hrs @ 43°C.
[c]Normalized to 100%.
[d]Topping, deasphalting, and fractionating steps combined.
[e]Calculated from peak-height measurements on gas chromatograms.
[f]C_{11}-C_{15} range.

biodegradation is primarily responsible for the low loss values of the W Idabel samples, whereas volatilization seems to be the major cause for the low values obtained for School Land 2 (known to be inactive) and Foster B-2 (possibly inactive).

Lowered API gravities and evaporation losses brought about by biodegradation of the W Idabel oils clearly separate them from the main cluster of Thrust Belt oils on the plot in Figure 2. Also easily distinguished are the two oils coproduced from gas wells; they plot in the upper right sector of the diagram, indicating that they have experienced a higher level of thermal cracking. With increasing temperature, crude-oil hydrocarbons break down (crack) into smaller, lighter components.

It is widely accepted that biodegradation of crude oil is characterized by preferential removal of n-alkanes, followed by branched alkanes and then some aromatics and cyclic alkanes. Knowledge of the sequential nature of this process permits researchers to not only detect but also estimate the extent of bacterial activity in an oil. A decreased level of the saturate (alkane) fraction or a lowered saturate/aromatic ratio may signal that bacterial degradation has occurred. Thrust Belt oils have saturate contents ranging from 58% to 78%, with distributions of 58–62% and 69–78%; their saturate/aromatic ratios are 2.1 to 4.9, with three distribution ranges: 2.1–2.5, 3.0–3.9, and 4.6–4.9. It is interesting that the same five oils (Jim 1, Dallas James 1 and 2, Foster B-2, and Lee Cole 1) constitute the low-level subgroup in both cases. Evidence for biodegradation of the W Idabel oils includes their relatively low levels of saturates (48–51%), increased amounts of asphaltenes, and low saturate/aromatic ratios (1.4–1.7).

Material recoveries for the combined topping–deasphalting–column–chromatography procedures averaged 87%. Recovery values for the Wyrick 2-26 (12%) and Williams 1-26 (7%) were not included, because their fraction weights were less than 1 mg, a level at which weighing errors become significant. Given the nature of these samples as shown by their gas chromatograms, volatilization is the probable explanation for loss of components during the deasphalting and column-chromatography steps. If so, then evaporation losses listed for these oils in Table 2 (26.3% and 45.9%) are erroneously low.

GAS CHROMATOGRAPHY OF WHOLE OIL

Although lacking structural specificity at the molecular level, high-resolution gas chromatography is particularly well suited for characterizing and correlating oils; it provides a quick and easy method for profiling compounds over the entire molecular-weight range. Relative proportions of individual compounds can be readily determined by measuring peak areas or peak heights on a chromatogram.

In this study, whole-oil samples were chromatographed using two sets of conditions: (1) to profile the whole oil, and (2) to separate and enlarge minor peaks in the C_6–C_{11} region.

With only one major exception, Thrust Belt oils exhibit classic "ski-slope" profiles (Fig. 3), typifying mature to supermature oils with a marine origin (Koons and others, 1974; Bockmeulen and others, 1983; Kinghorn, 1983). The largest number of compounds are low-molecular-weight and low-boiling, with only a small percentage above C_{25}. A barely perceptible odd-carbon predominance is visible between C_{11} and C_{19}.

Apparent exceptions to the foregoing include a group of six samples which show reduced concentrations or a loss of compounds below C_9 or C_{11}. In five of these oils (School Land 2, "S Bald Field", Rowland Bledsoe 1, Foster B-2, and "Redden Field") this effect is attributed to volatilization, since all classes of compounds have been affected, and compound concentrations increase as the higher boiling temperatures of C_9 to C_{11} are approached. Low-boiling components that seem to be missing from the sixth sample, Wyrick 2-26, would be found as part of the gas coproduced from that well. The fact that the other coproduced oil, Williams 1-26, has a full complement of low-boilers may merely reflect differences in the way companion oil-gas pairs are separated at the respective wells. The "dip" in the "S Bald Field" profile is anomalous. After accounting for their loss of light-boilers, the chromatograms of these six samples are seen to closely resemble others from the Thrust Belt group.

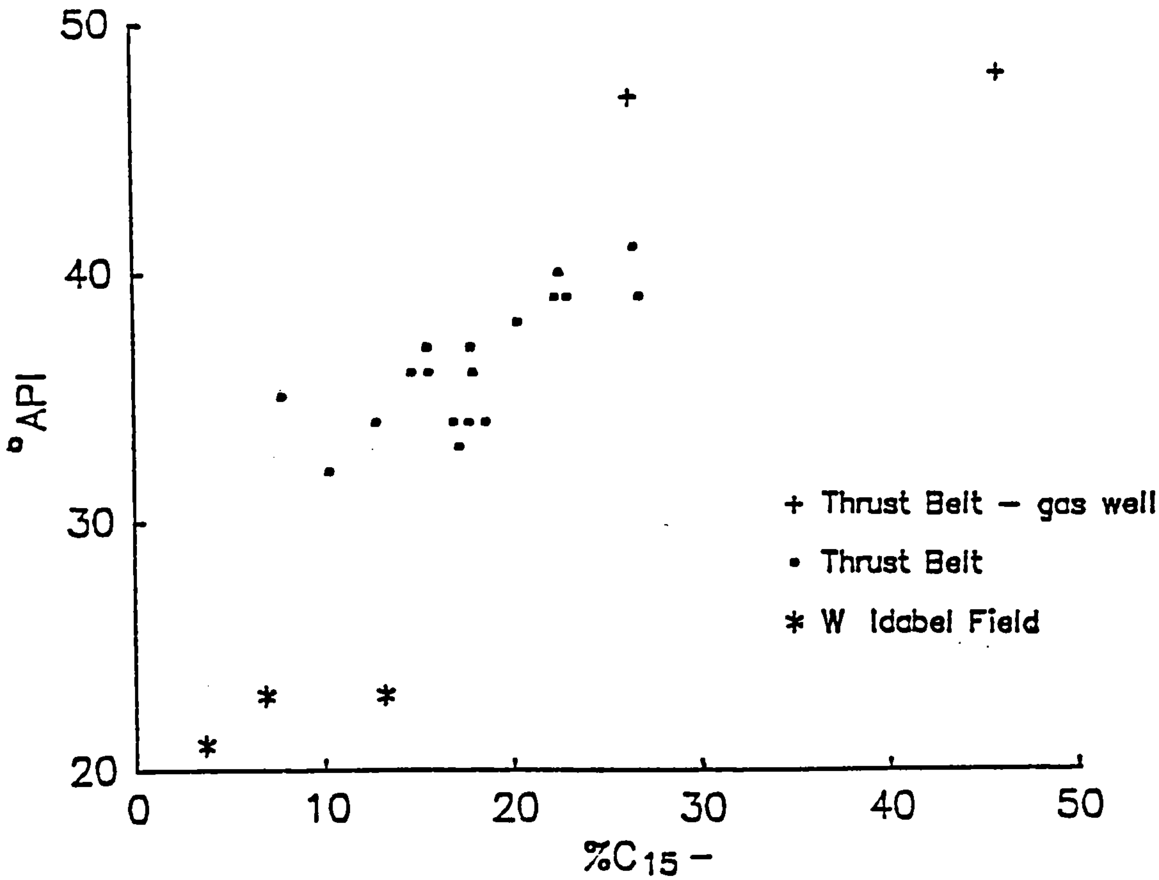

Figure 2. API gravity vs. loss on evaporation for Ouachita Mountains oils.

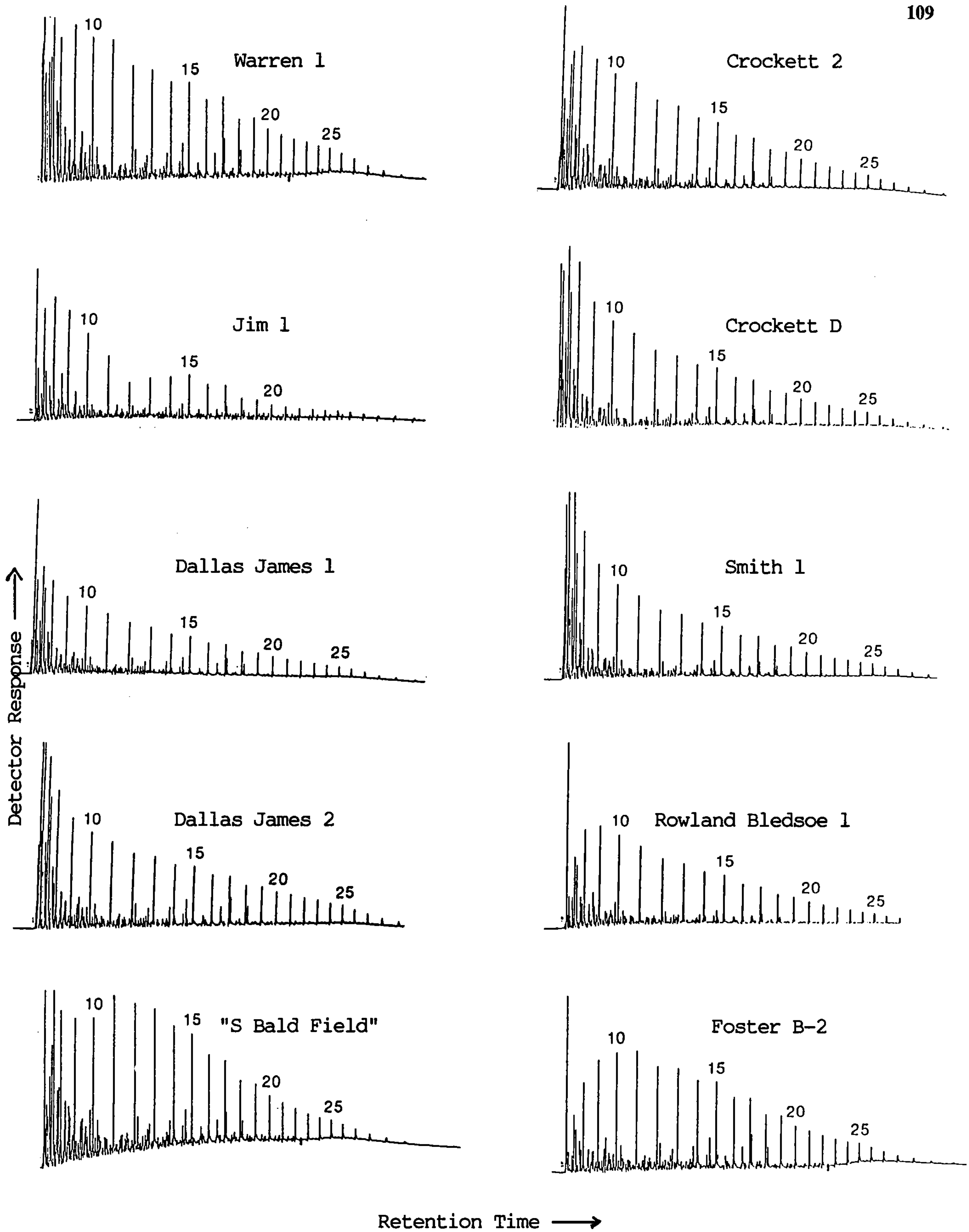

Figure 3. Whole-oil gas chromatograms of oils from the Ouachita Mountains region.

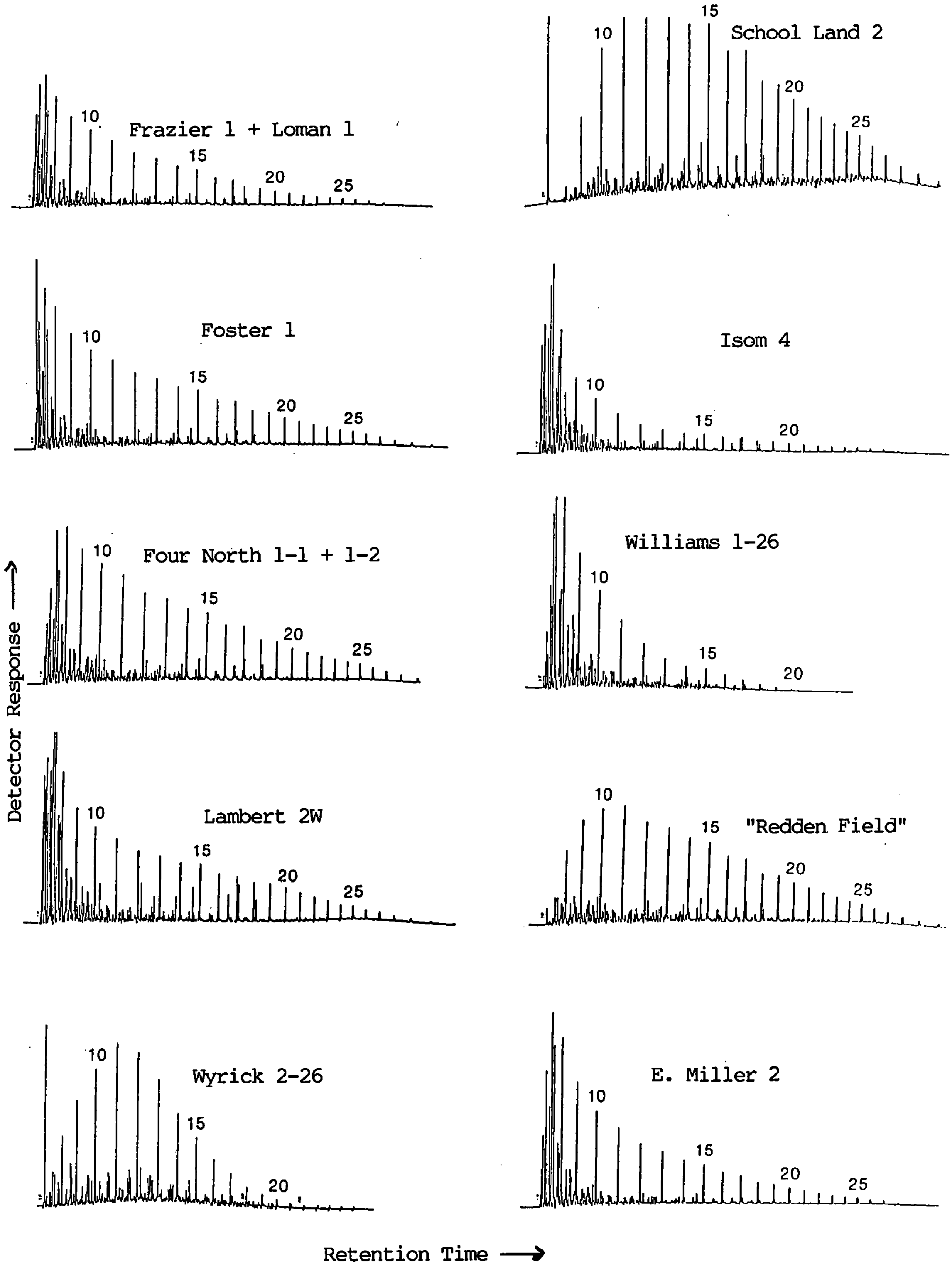

Figure 3 (continued).

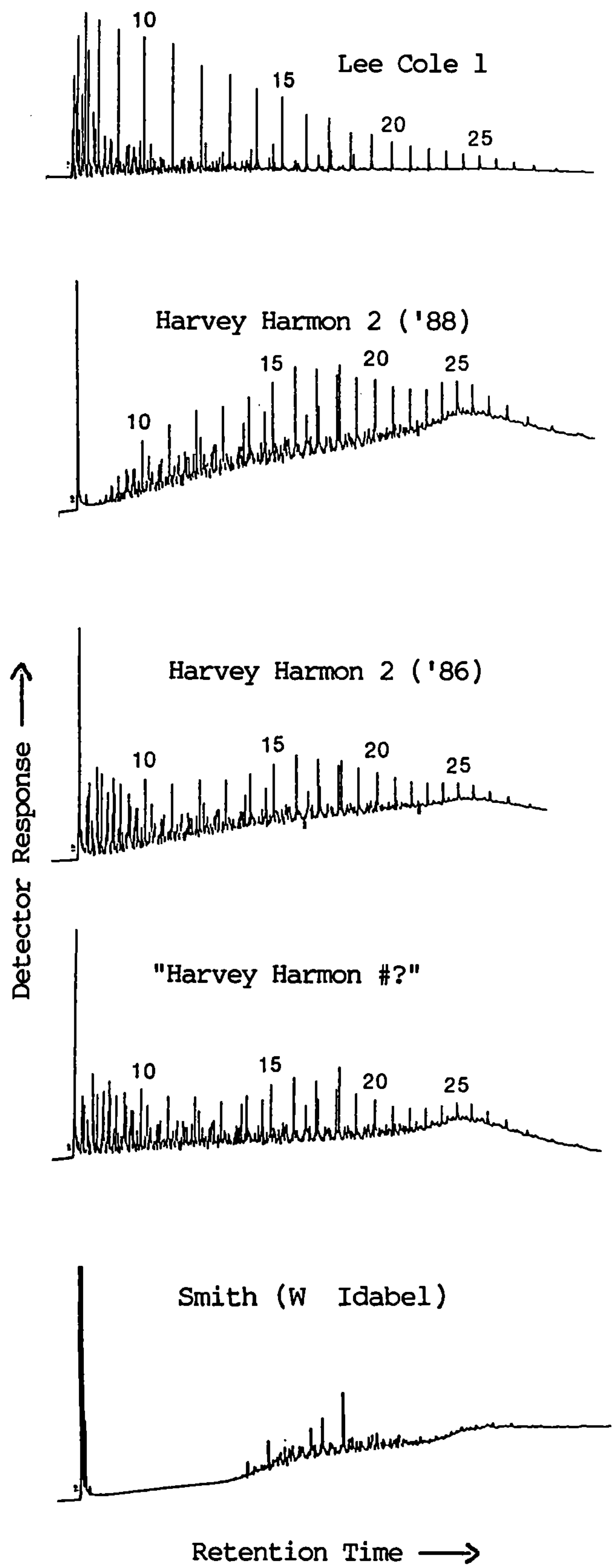

Figure 3 (continued).

The one different profile is that of the Jim 1 oil; it is characterized by depressed peak heights for C_{12} through C_{14} n-alkanes, giving the chromatogram a bimodal appearance. Since only the n-alkanes are affected, a maturation- or source-induced effect seems less likely than some type of restricted bacterial attack, but neither possibility can be ruled out at this point. The same chromatographic profile has been found in a sample from the Isom Springs field in Marshall County (J. Weber, unpublished data).

The degree of correspondence of Thrust Belt oils is exhibited further by their normalized percentage distributions of C_{11} through C_{25} n-alkanes, as shown in Figure 4. Not represented in this comparison diagram are the Jim 1, Wyrick 2-26, and Williams 1-26 oils.

In contrast to Thrust Belt oils, oils from the Broken Bow Uplift group (Fig. 3) are good examples of mildly to moderately biodegraded oils. The mildly degraded samples are characterized by a depletion of n-alkanes (n-alkane peaks do not dominate the Harvey Harmon chromatograms) and a hump of unresolvable material under the baseline. The moderately biodegraded Smith sample is devoid of n-alkanes; the prominent peaks on the chromatogram are acyclic isoprenoids. Volatilization has also undoubtedly contributed to the absence of peaks at the beginning of the Smith chromatogram. As noted in Table 1, Smith is not an active well. This sample was taken from beneath a tar mat in the stock tank. Oil in the ground at the Smith well is probably not degraded to this same extent.

Several commonly cited correlation parameters involving isoprenoids and obtainable from gas chromatograms are listed in Table 2. All were calculated from peak-height measurements. Acyclic isoprenoids are branched alkanes composed of a series of five-carbon isoprene units, which consist of a methyl group attached to every fourth carbon atom. Pristane and phytane, normally the two most abundant isoprenoids in crude oil, are believed to be remnants of the phytol side chain of chlorophyll, although additional precursors have been recognized; they are frequently used to infer redox conditions of the environment during deposition, oxic systems favoring the formation of pristane, and reducing environments preferentially forming phytane. However, because the isoprenoid composition of a crude oil can be affected by several factors--original organic input, depositional conditions, temperature history of the source rock, and biodegradation--ratios involving isoprenoids are not considered absolute evidence for an oil–oil correlation, but they can serve as confirmatory data.

The majority of oils in the Thrust Belt group show good agreement where isoprenoid ratios are concerned. Notable exceptions are the SE Daisy field samples, particularly Isom 4, along with the Wyrick 2-26 and Lambert 2W oils. These oils have slightly elevated values for at least two of four calculated parameters. Plots of the normalized percentage distributions of isoprenoids vs. carbon number emphasize the uniformity of all but the SE Daisy and Wyrick 2-26 oils (Fig. 5). It is not clear whether the irregular isoprenoid patterns of these three samples are depth-related (Williams and Wyrick produce from >7,400 ft; Isom from 1,350 ft) or are due to minor changes in the source organic matter.

Isoprenoid ratios (Table 2) and distribution patterns (Fig. 5) of W Idabel oils clearly place them in a different genetic family from the Thrust Belt group. Their pristane/phytane ratios of 0.6 indicate a reducing-type environment, whereas the comparable value of 1.5 for Thrust Belt oils suggests that oxidizing conditions prevailed when their source material was deposited. Also, the amounts of farnesane (iC_{15}), pristane (iC_{19}), and phytane (iC_{20}) relative to the other isoprenoids are quite different between the two sets of oils. An identical isoprenoid profile has been found for a sample from Talco Field, located in northwestern Titus County, Texas, about 45 mi SSW of Idabel, Oklahoma (J. Weber, unpublished data). The Smith sample is skewed toward higher-molecular-weight isoprenoids because biodegradation and volatilization have removed its lower-molecular-weight members.

The final parameter calculated from the whole-range gas chromatogram is odd-even preference (OEP). Applicable to any five consecutively numbered n-alkanes, this value denotes deviation from an unbiased distribution of odd and even carbon numbers. For mature oils, the value approaches unity and therefore loses its usefulness as a correlation tool. The OEP values shown in Table 2 fall between 1.02 and 1.24, suggesting that all samples in this study are mature.

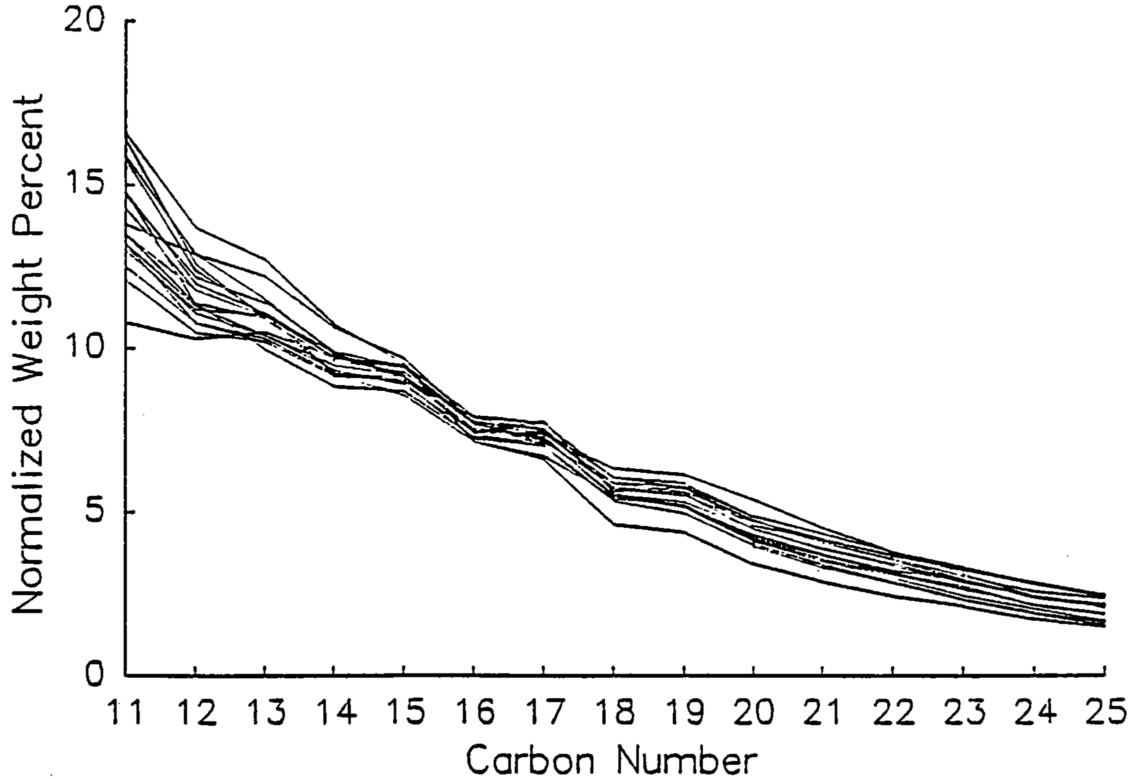

Figure 4. Distribution of C_{11} through C_{25} n-alkanes for Ouachita thrust-belt oils.

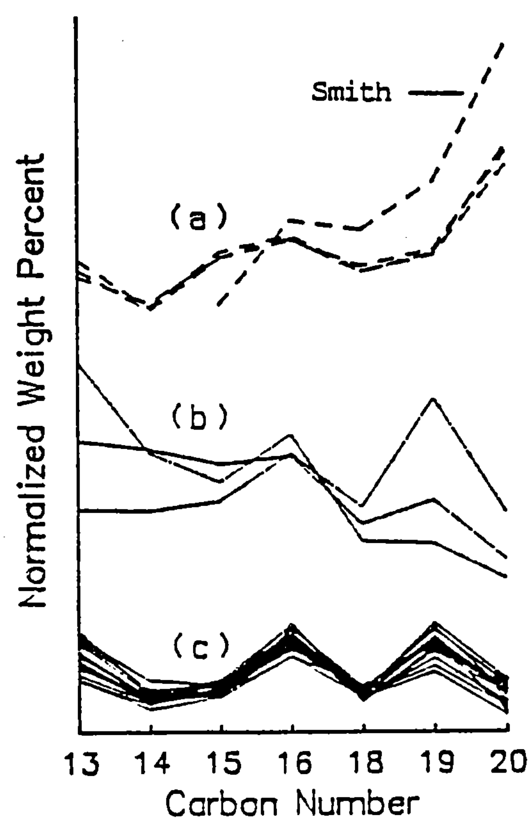

Figure 5. Isoprenoid distributions in Ouachita Mountains oils: (a) W Idabel field; (b) Wyrick 2-26, Williams 1-26, Isom 4; (c) all others. Note: iC_{17} usually is not present in crude oils.

The second temperature program used to chromatograph oils was designed to more clearly show minor peaks in the C_6–C_{11} region. The order of factors controlling the presence of low-molecular-weight compounds in a crude oil is biodegradation (if present) > maturation effects > source input (Koons and others, 1974). Despite these factors which could lead to changes in oil composition, close inspection of partial chromatograms representative of all sampled Thrust Belt fields shows highly reproducible peak patterns between C_8 and C_{11} (Fig. 6). Individual component peak heights may vary among samples, reflecting either different component concentrations or use of different instrument attenuations.

Another way to characterize low-molecular-weight compounds is with a triangular plot of the relative abundance of straight-chain, branched, and cyclic alkanes. In Figure 7, isomeric compounds have been chosen to minimize effects due to secondary alteration processes, such as sample handling or migration, which might produce a boiling-point-dependent fractionation. Normalized amounts of n-heptane, the sum of 2-methylhexane plus 3-methylhexane, and methylcyclohexane are used to represent straight-chain, branched, and cyclic alkanes, respectively. When compared in this manner, Thrust Belt oils show a moderately narrow range of composition, plotting within a 28% band on all three axes. Some variation may result from measurement errors caused by co-eluting small peaks contributing to apparent peak heights and/or peak areas.

SUMMARY

Several common geochemical analyses have been applied to a series of oils collected from the Ouachita Mountains region. Data generated from bulk characterization and whole-oil gas chromatography of oils from the frontal and central Ouachitas are sufficiently consistent to classify these oils in the same family. Furthermore, no evidence incompatible with such an assignment was found. However, more-detailed analysis at the molecular level is needed before suggesting that all these oils originated from the same source rock.

In contrast, a distinction can be drawn between thrust-belt oils and those from the area south of the Broken Bow uplift. Superficial differences noted in API gravities and fractionation data can be ascribed mostly to bacterial alteration of the latter group of samples. But fundamental differences exist in isoprenoid profiles and parameters obtained from gas chromatograms. In particular, the predominance of phytane over pristane in the Broken Bow Uplift/Cretaceous-overlap samples signifies that they represent a different environment of deposition (one lacking in oxygen), or that they were derived from entirely different organic precursors.

ACKNOWLEDGMENTS

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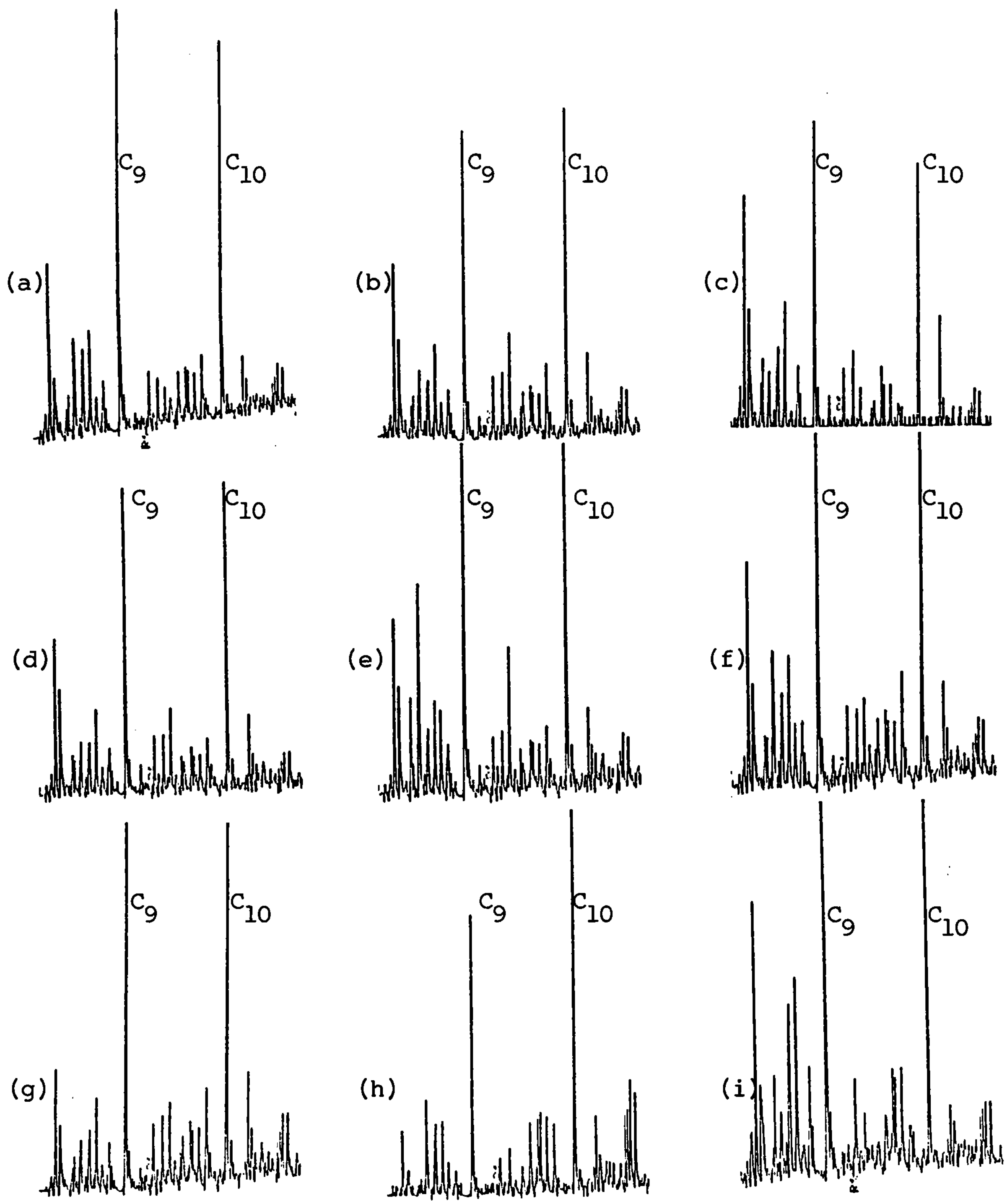

Figure 6. Details of gas chromatograms from $>C_8$ to $<C_{11}$ region for representative oils of all sampled thrust-belt fields: (a) Redden; (b) "Talihina"; (c) E Wesley; (d) Bald; (e) "Star"; (f) S Bald; (g) Minnett; (h) W Daisy; (i) SE Daisy.

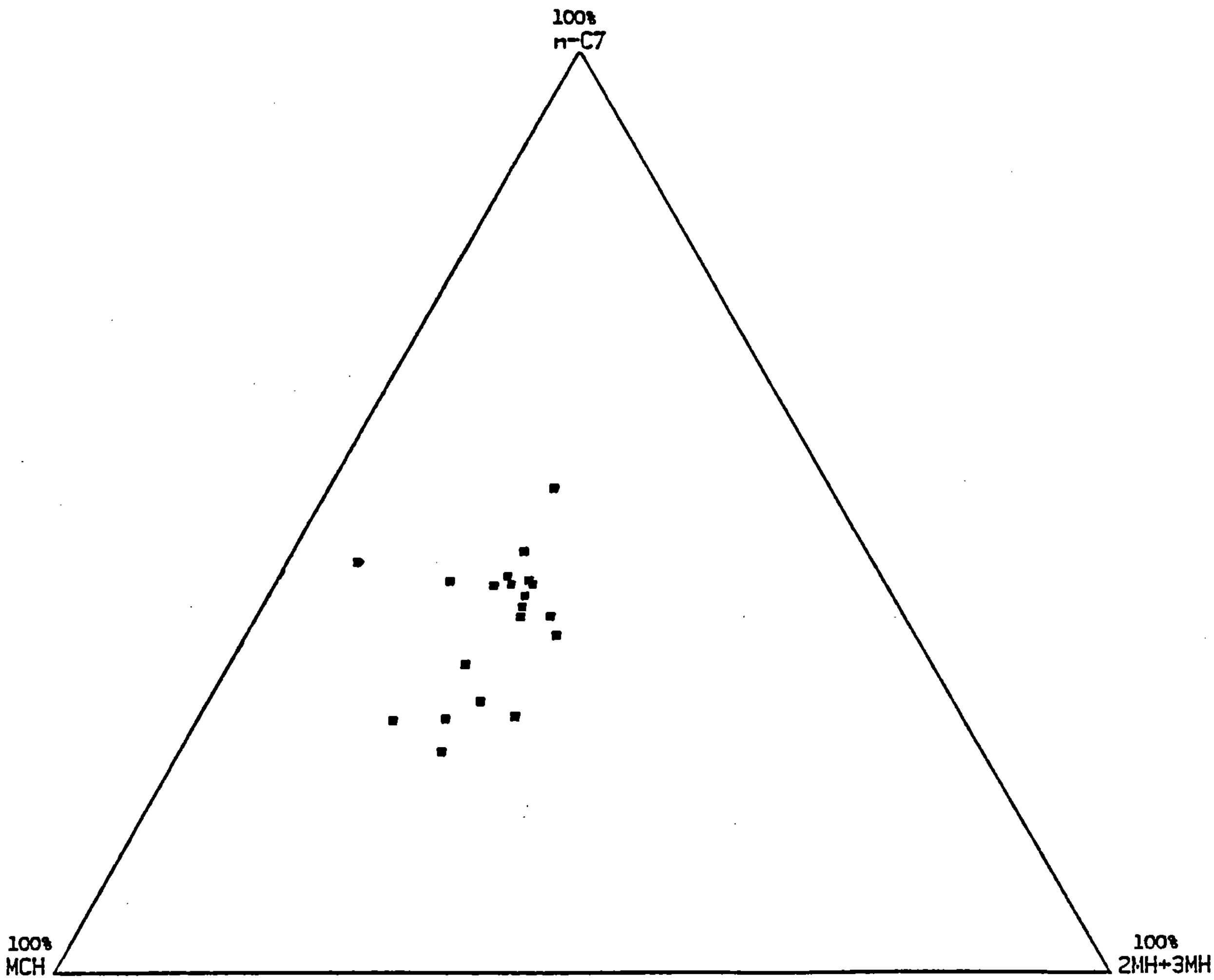

Figure 7. Relative abundance of straight-chain, branched, and cyclic C_7 alkanes in thrust-belt oils. Abbreviations: $n-C_7$, n-heptane; MCH, methylcyclohexane; 2MH + 3MH, sum of 2-methylhexane and 3-methylhexane.

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<u>SANDY TEMPESTITES IN THE LOWER-MIDDLE ATOKA FORMATION, SOUTHEASTERN OKLAHOMA</u>

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ABSTRACT.- A well-exposed outcrop of the Atoka Formation at Brushy Narrows lies in the western end of the Choctaw fault block, the first thrust of the frontal Ouachitas (southeastern Oklahoma). The sandstones and shales at this outcrop are interpreted as recording deposition on a storm-dominated shelf. Evidence supporting this interpretation includes stratification types indicative of oscillatory flow, internal variability in facies organization within sand beds, mud partings within sandstones, and variable tool-mark vectors. While previous authors have implied a transitional position for this area between shallow-water deposits in the Arkoma basin and the deep Ouachita flysch deposits, the nature of these rocks and the processes involved in their deposition have not been emphasized.

The Brushy Narrows section is divided into six sequences representing fluctuations of proximal and distal environments across a storm-dominated shelf over time. Proximal sequences contain thick (>1 m) sand beds with complex internal structures, whereas distal sequences are less sand-prone and have thin sand beds, some occurring in coarsening-upward cycles. Paleocurrents in general are west-to-east with the exception of sole marks in the lowest sequence, which have a N-S sense. Shelf paleocurrents are not paleoslope indicators. Soft-sediment faults in the lowest sequence indicate a south-dipping paleoslope.

Storm deposits may superficially resemble turbidites. In a case such as the Atoka Formation where turbidites are common, identification of storm deposits can aid in paleocurrent and paleoslope analysis and may also influence paleogeographic reconstructions.

INTRODUCTION

Some types of sandy storm deposits (tempestites) can superficially resemble turbidites (e.g., Aigner and Reineck, 1982; Johnson and Baldwin, 1986; Kreisa, 1981; Brenchley, 1985). A considerable body of work on both types of deposits in the last decade has provided criteria for distinguishing between them. Correct environmental interpretations have important implications for paleocurrent analysis and paleobathymetric, paleoenvironmental, and paleogeographic reconstructions.

The lower to middle Atoka Formation in southeastern Oklahoma is generally thought of as recording deposition in deep water by turbidity currents on submarine fans (e.g., Ferguson and Suneson, 1988; Houseknecht and Kacena, 1983). In this paper we report the results of a study of one section (Brushy Narrows) in the lower to middle Atoka Formation, where, in contrast to most previous regional studies, the rocks are interpreted to record deposition by storm processes.

GEOLOGIC SETTING

The late Paleozoic Stanley-Jackfork-Atoka sequence (Fig. 1) records the evolution of a depositional basin from a rifted continental margin to a peripheral foreland basin in the Arkoma-Ouachita system (Houseknecht and Kacena, 1983). The 13 km of sandstones and shales of this sequence were folded and thrust northward in Desmoinesian time as the depocenter shifted northward into the present-day Arkoma basin (Sutherland, 1988).

Flysch facies are well documented in the Stanley and Jackfork formations (e.g., Neim, 1976) and the Atoka Formation (e.g., Morris, 1974; Houseknecht and Kacena, 1983; Briggs and Cline, 1967). While several authors (e.g., Briggs and Cline, 1967; Chamberlain, 1971a; and Sutherland, 1988) have noted or implied the transitional nature of sediments in the frontal Ouachitas between the deep Ouachita flysch deposits and the shallow-water deposits of the central and northern Arkoma basin, the nature of these rocks and the processes involved in their deposition have not been documented. The Brushy Narrows section lies in the western portion of the Choctaw fault block, the northernmost thrust in the frontal Ouachitas (Fig. 2). The Atoka Formation is a maximum of 3.5 km thick in the Choctaw fault block (Ferguson and Suneson 1988).

BRUSHY NARROWS SECTION, INDIAN NATIONS TURNPIKE

The Lower Pennsylvanian Atoka Formation crops out along a frontage road of the Indian Nations Turnpike in Pittsburg County, Oklahoma, about 15 mi south of McAlester by the Brushy Narrows Bridge (SW1/4SE1/4NW1/4 sec. 32 T. 3 N., R. 15 E.). A section was measured and described in detail on the southern ridge which has a well-exposed, continuous sequence (Cullen and others, this volume). The measured thickness of this section, corrected for a 75°S dip, is 222 m. The top of the Atoka Formation is not exposed and is probably cut by the Pine Mountain fault, which is just south of the section. The section is probably 600-1,000 m above the Wapanucka Formation (Ferguson and Suneson, 1988). Seven facies identified at this section were used to divide the section into six sequences. For a description of the facies and sequences as interpreted below, see Cullen and others (this volume).

INTERPRETATION OF THE BRUSHY NARROWS SECTION

The Brushy Narrows section is interpreted as recording storm-dominated shelf deposition. Although sandy tempestites in a shelf setting may superficially resemble turbidites (e.g. Aigner and Reineck, 1982; Reading, 1986; Kreisa, 1981; Brenchley, 1985), the following features found at this section have been reported elsewhere in the literature as characteristic of tempestites:

1) Few flute casts, but abundant tool and impact marks (Seilacher, 1982);

2) Discontinuous grain-size distribution, storm sand to mud blanket (Seilacher, 1982);

3) Hummocky cross-stratification (Hamblin and Walker, 1979; Dott and Bourgeois, 1982);

4) Wave ripple lamination and oscillation ripples at the tops of sandstones (Aigner and Reineck, 1982; see Fig. 3);

5) Association with mudstones containing a benthic shelf fauna;

6) A sequence of internal structures less well organized than that of

TIME		FAULT BLOCKS: CHOCTAW	FAULT BLOCKS: PINE MOUNTAIN	FAULT BLOCKS: TI VALLEY
PENNSYLVANIAN	DESMOINESIAN	Krebs Group: fluvial molasse, sandstone and shale	?	?
PENNSYLVANIAN	ATOKAN	Atoka Formation: marine flysch, shale, and sandstone		
PENNSYLVANIAN	MORROWAN	Wapanucka Formation: shelf-facies limestone, sandstone, and minor shale	Johns Valley Shale: marine shale-rich flysch with olistostromes	
PENNSYLVANIAN	MORROWAN	Springer shale: outer-shelf-facies calcareous shale and sandstone		Jackfork Group: marine sand-rich flysch with olistostromes
MISSISSIPPIAN	CHESTERIAN	Caney shale: outer-shelf-facies calcareous shale and pelagic limestone		Stanley Group: marine volcaniclastic shale-rich flysch with tuff beds
CAMBRIAN through EARLY MISSISSIPPIAN		Shelf-facies rocks: Arbuckle Group – Woodford Shale		Marine deep-basin-facies rocks: Arkansas Novaculite and older strata

Figure 1. Stratigraphic column for the Ouachita Mountains, Oklahoma (from Ferguson and Suneson, 1988).

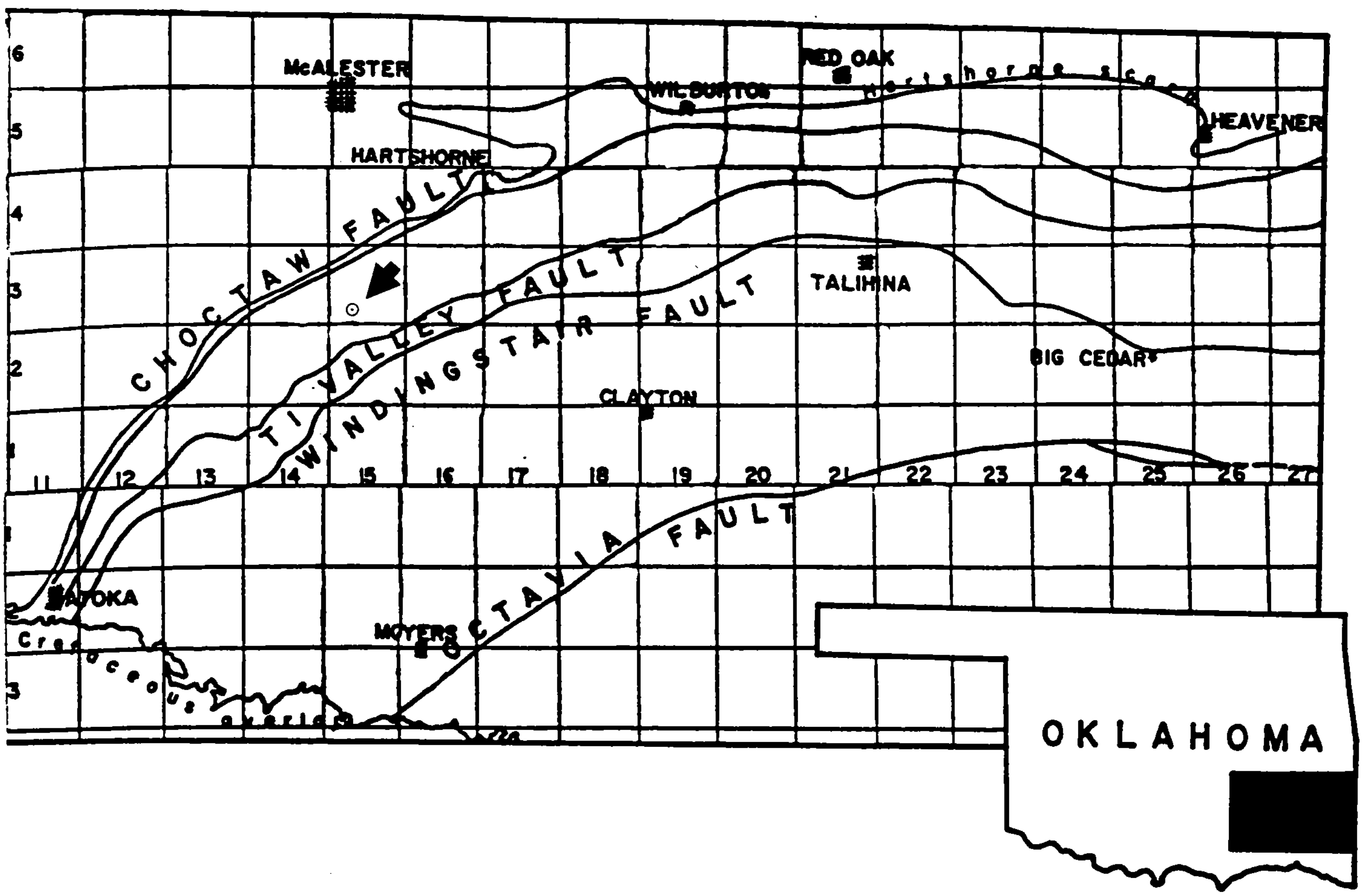

Figure 2. Location map for the Brushy Narrows section (denoted by arrow) in the western part of the Choctaw fault block. Six-mile by six-mile township/range grid for scale. Modified from Briggs and Cline (1967).

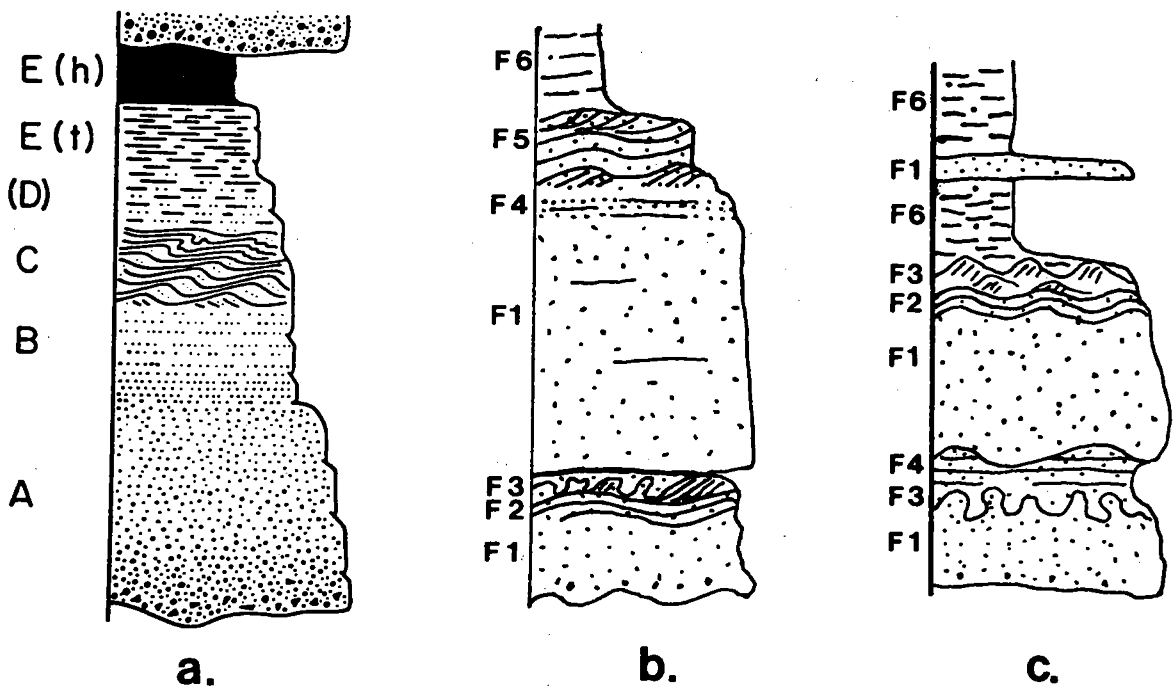

Figure 3. Comparison of two of the sandstone beds from sequence one with a diagram of a classic Bouma sequence from Walker (1967). (a) Classic Bouma sequence: A, massive to graded sand; B, parallel-laminated sand; C, cross-laminated and convolute sand; D, parallel-laminated, fine silt and sand; Et, turbidite mud; Eh, hemipelagic mud. (b) Second sandtone from base (second major sandstone from bottom of sequence 1); irregularly loaded base, massive to faintly horizontally laminated sandstone, swaley-bedded sandstone, rippled and contorted sandstone, shale parting, massive to faintly horizontally laminated sandstone, plane-bedded sandstone, symmetrically rippled sandstone, asymmetrically rippled sandstone, silty shale. Numbers refer to facies in text. (c) Fifth sandstone from base (fifth major sandstone from bottom of sequence); massive to faintly horizontally laminated sandstone, contorted sandstone, plane-bedded sandstone, undulose contact with massive to faintly horizontally laminated sandstone, swaley-bedded sandstone, rippled sandstone, silty shale, thin and massive to faintly horizontally laminated sandstone. Numbers refer to facies in text.

turbidites (Brenchley, 1985; see Fig. 3);

7) Internal mud partings indicative of more discontinuous deposition than is commonly associated with turbidites (Brenchley, 1985; see Fig. 3);

8) Variable tool-mark vectors (Seilacher, 1982);

9) Oscillation ripples in the form of reticulate interference ripples, "tadpole nests" (Seilacher, 1982);

10) A high quantity of starved ripples (Nelson, 1982).

The vertical succession of sedimentary structures in sequence 1, while generally progressing vertically from facies 1 to 5, is highly variable and can be partially repeated within one bed (Figs. 3, 4). This is presumably due to fluctuation of flow conditions during a storm, as in the passing of the eye of a hurricane. If turbidity currents were responsible, deposition within a bed should record evidence of a consistently waning flow. Tool-mark vectors in this sequence also have significant variability, and true flute casts are rare. Facies 2 (well- to faintly laminated sandstone with parallel, undulose to swaley bedding), which is common in sequence 1, is generally not reported in turbidites and is probably a wave-induced bedform similar to climbing wave-ripple lamination.

A number of sandstones interpreted to record deposition by storms in the literature share characteristics with the sandstone packages in Sequence 1. For example, Kreisa (1981) studied the Ordovician Martinsburg Formation in southwestern Virginia and interpreted it as recording deposition on a storm-influenced marine carbonate platform. He observed vertical transitions from plane lamination and/or hummocky stratification at the bases of beds to climbing wave-ripple lamination (analogous to our facies 2), followed by matrix-rich plane lamination or wave-ripple cross-lamination. Tucker (1982) found normally graded sandstone beds containing parallel lamination and single sets of cross-lamination with some wavy, undulating lamination in the Precambrian Biri Formation and interpreted them as storm deposits. Contorted lamination was also present, and many sandstones showed ripples on their upper surfaces. The "proximal storm sands" (North Sea) described by Aigner and Reineck (1982) are a modern example sharing many characteristics with the sandstones in sequence 1.

Sequence 2 is interpreted as recording deposition in a more-distal, storm-influenced shelf setting than sequence 1. Energy conditions were lower, there was less clastic input, and water depth was greater. Sequence 2 sandstones contain many F4 to F5 transitions and have rippled tops. The beds of sequence 2 are generally thinner and show less complex facies transitions than those in sequence 1. In other shelf sequences the influence of water depth and distance from shore has been well documented. Brenchley (1985) and Aigner and Reineck (1982) described decreases in thickness and grading and changes in internal sedimentary structures in modern and ancient storm sands related to the waning strength of depositional currents from proximal to distal areas.

Sequence 3 is interpreted as deposition in an increasingly distal, sand-poor shelf with sand transported in thin localized sand sheets by storm-augmented currents. The thickening- and coarsening-upward cycles are somewhat analogous to the coarsening-upward cycles in the North American Cretaceous Seaway (e.g., Brenner, 1978; Spearing, 1976), although they are relatively poorly developed and resemble only the bases of those much-thicker deposits. The pinch and swell of beds in this sequence supports a shelf setting. Kreisa (1981), for example, reported that Martinsburg tempestites are laterally variable in thickness. The isolated undulose bedded sandstone (F7) may indicate lowering of wave base during storms of unusual intensity.

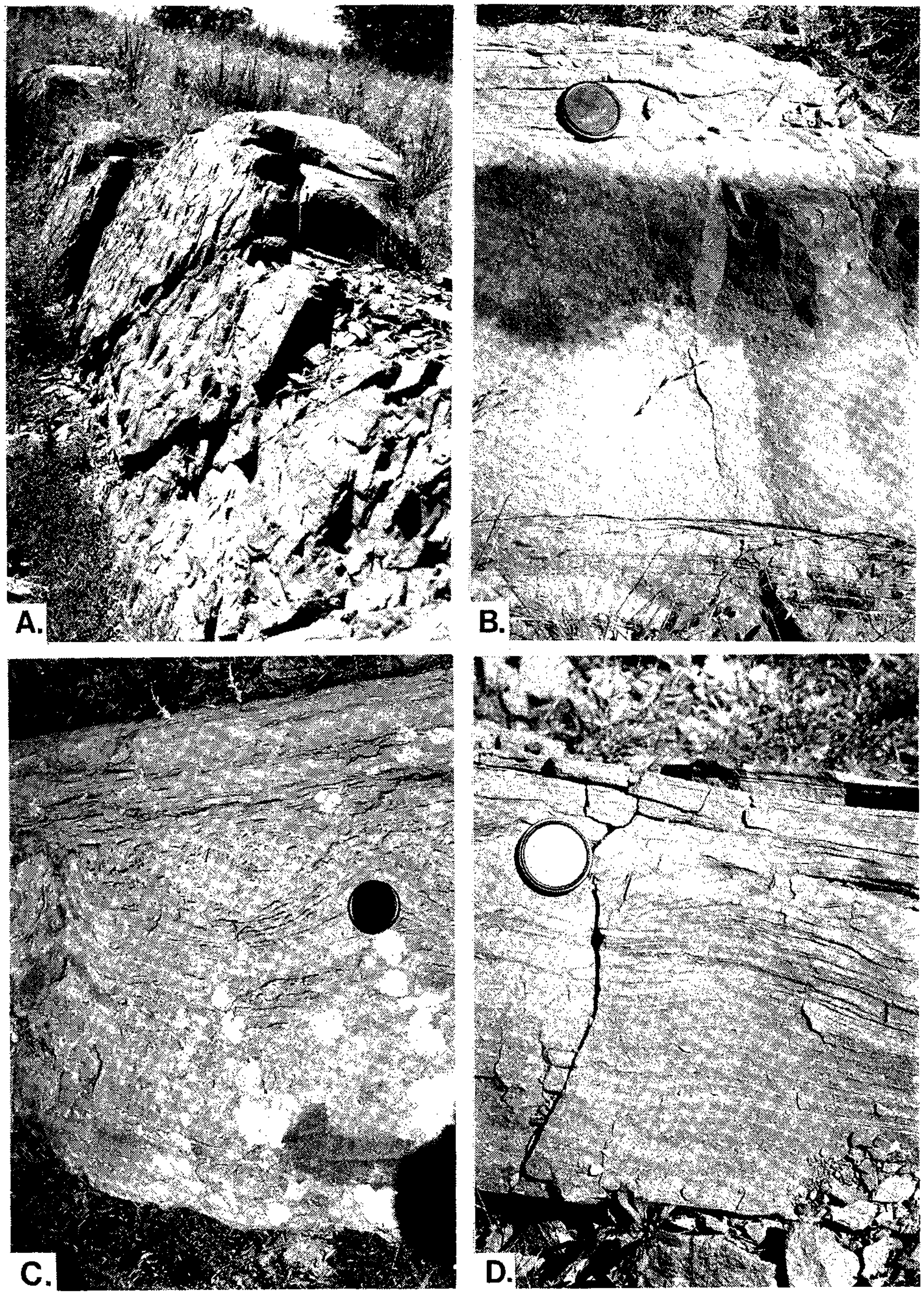

Figure 4. Photographs of sandstones, Brushy Narrows section. (a) This picture shows the angle of dip (~70°) and the characteristic rippled bed tops. This is the top of sandstone of sequence 1. (b) Sandstone (from base) with irregularly loaded base, massive to faintly horizontally laminated sandstone, swaley-bedded sandstone, rippled and contorted sandstone, shale parting, massive to faintly horizontally laminated sandstone (dark area is due to weathering), thin plane-bedded sandstone, symmetrical rippled sandstone, asymmetrically rippled sandstone. This is sandstone 2 (second from base of sequence 1, also shown in Figure 3b). (c) Sandstone with massive to faintly horizontally laminated sandstone at base, followed by contorted sandstone truncated by thin, plane-bedded sandstone. Bed is capped by multiple stacked ripples with plant debris, shale partings. This is the seventh sandstone from base of sequence 1. Note truncated contorted bedding. (d) Sandstone showing swaley bedding and ripples from sequence 2.

A possible modern analog to this sequence are the sand ribbons of Stanley and Swift (1974) in the North Sea.

Sequences 4 and 6 are shaley, distal-shelf intervals with many small interbedded sandstone and siltstone beds. Some sandstones occur as part of coarsening-upward packages much like those of sequence 3. Sequence 5 records a resumption of deposition of thicker sands with many of the features seen in sequence 1, although the sedimentary structures are less well defined than in sequence 1.

DISCUSSION

The facies and facies relationships within the Atoka Formation at the Brushy Narrows section can be explained by the fluctuation of relatively proximal and distal environments across a storm-dominated shelf over time. Sequences 1 and 5, with relatively thick sand beds and complex facies transitions within beds, are most proximal. Sequences 3, 4, and 6 have lower sand/shale ratios, show less-frequent indications of oscillatory flow, and record deposition by more-distal processes. Sequence 2 is transitional. The apparent fluctuation of energy level recorded in the different sequences could be explained by eustatic changes in sea level, tectonic influence on source areas or bathymetry, or a combination of factors.

As previously stated, several workers have implied a shelf setting for part of the Atoka Formation in the study area. Briggs and Cline (1967), for example, noted that the frontal Ouachitas have rocks of an intermediate character between the Ouachita flysch and the Atoka of the northern and central parts of the Arkoma basin, which is of shallow-water origin. A shelf setting is also consistent with the Chondrites trace-fossil assemblage reported by Chamberlain (1971a,b) for the Atoka Formation in the study area and the lower to middle Atokan paleogeography suggested by Sutherland (1988).

Delivery of sand onto the shelf may be recorded by the down-slope paleocurrent indicators in sequence 1. One possible mechanism, storm-induced geostrophic flows, would be consistent with the evidence for oscillatory currents. The easterly paleocurrent directions recorded by the ripples at the tops of the beds in sequence 1 are also common in sequences 2 and 3 (Fig. 4). These currents were probably too weak to transport much sand except when enhanced by storm currents and/or oscilatory flow. Finally, in sequence 3, the more-distal shelf is mud-dominated, with isolated sand sheets and only localized transport of sand.

The cause of the change in current sense from N-S on sole marks in sequence 1 to predominantly E-W in the rest of the section is difficult to interpret. One potential problem with interpreting paleocurrents is the relationship between paleocurrent and paleoslope. In certain environments currents are slope-controlled, but in others they are not. Turbidite environments, for example, are strongly slope-controlled, whereas shelf paleocurrents are variable (e.g., Selley, 1988). In shelf deposits, paleoslope indicators should be sought to complement the paleocurrent indicators. For example, early slump-related faults tend to parallel paleoslope (isobaths) and are useful for providing current directions for sole markings, which normally give only orientation (Thompson, 1973).

Soft-sediment faults in sequence 1 suggest a south-facing paleoslope. These faults only cut one bed. In contrast, faults in the other sequences that apparently cut several beds may be tectonic. Therefore, only the faults in the lowest sequence (sequence 1) are clearly early and can be used as paleoslope indicators. Because there are no valid paleoslope indicators above sequence 1, the paleoslope is difficult to determine.

The divergence of sole markings (N-S sense) and current-modified wave ripples on bed tops (easterly vector) in sequence 1 is similar to the situation on the modern Oregon-Washington coast, which is storm-dominated. Symmetrical wave ripples out to depths of 204 m parallel the shoreline, in contrast to northwesterly transportation by currents (Johnson and Baldwin, 1986).

With indications of northerly and easterly directed paleocurrents at the Brushy Narrows section, sources both to the west and the east for Atokan sediments in the Ouachitas as proposed by Ferguson and Suneson (1988) must be considered. The southerly paleocurrent directions in sequence 1 are possibly in accordance with southerly paleocurrents north of the Choctaw fault reported by Briggs and Cline (1967).

Storm-dominated deposition should be considered and watched for in the lower and middle Atoka, since storm deposits may superficially resemble turbidites. A correct environmental assessment is important in evaluating paleocurrents and paleoslope. The distinction between turbidites and storm deposits may also influence paleogeographic reconstructions.

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EXPLORATION CASE STUDY: ATOKA AND JACKFORK SECTION, LYNN MOUNTAIN SYNCLINE, LE FLORE AND PUSHMATAHA COUNTIES, OKLAHOMA

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ABSTRACT. - Standard Oil Production Company, now BP Exploration, concluded an exploration program along the Lynn Mountain syncline during 1987 with the drilling of the #1-7 Weyerhaeuser. The objective of the well was to test several stratigraphic traps in the Carboniferous flysch sequence. The well spudded in Atoka and reached TD at 8,014 ft in the lower Wildhorse Mountain Formation (lower Jackfork Group). We estimate the total Jackfork thickness to be 4,400 ft., which is less than the 5,700—6,000 ft reported from outcrop. High-resolution seismic was of sufficient quality to identify and map seismic sequences and anomalies with a high level of confidence and to tie these anomalies to surface outcrops. Seismic and outcrop data demonstrate that the post-Johns Valley (lowermost Atoka) succession is significantly different from the underlying Jackfork. This distinction of the lower Atoka is most evident in the development of N-trending channel and slump morphology. While the SOPC #1-7 Weyerhaeuser well was nonproductive, it did demonstrate the ability of the section to stratigraphically entrap hydrocarbons, and offers the potential for future exploration on trend.

INTRODUCTION

Standard Oil Production Company, now BP Exploration Inc., conducted an extensive exploration program from 1980 through 1987 in the Ouachita fold and thrust belt. The vast majority of this work was located on properties owned by Weyerhaeuser Company. A part of this varied exploration program included evaluation of the hydrocarbon potential of the Carboniferous turbidite flysch sequence.

From regional geochemical and petrologic data, it was determined that the most prospective area to encounter liquid hydrocarbons and reservoir-quality sandstones in the flysch sequence is in the northern part of the central fold belt. We further postulated that stratigraphic traps could be developed within the Jackfork on the simple north limbs of the large dominant synclines. Our Weyerhaeuser Oklahoma exploration program was centered within the Lynn Mountain syncline.

In 1986, Standard Oil Production Co. acquired 200 mi of high-resolution Vibroseis seismic data in order to define stratigraphic traps in the Lynn Mountain syncline. The data were acquired along existing logging roads, using GSI Party 1207 equipped with DFS VII instrumentation. The data were processed by TLC Processing in Dallas, applying a rigorous treatment of the crooked-line geometry, utilizing azimuth-oriented binning and cross-line dip correction. This approach yielded large improvements in static solutions and velocity definition over more-conventional techniques. Interpretation of these data resulted in identification of multiple stratigraphic-trap geometries.

Due to its simple structure and our favorable land position, this broad, gently dipping thrust sheet offered an excellent exploration opportunity to correlate nearby surface outcrop data with the high-resolution seismic data. Regionally continuous, high-amplitude seismic events were correlated to outcrops, where they were identified as major shale boundaries and were mapped throughout the syncline. These data showed the Jackfork geometry to be remarkably tabular . While local, relatively minor variations in thickness were noted for individual formations, the total Jackfork thickness varied little. At the well, the Jackfork thickness was estimated to be 4,400 ft Published outcrop measurements for the Jackfork are 5,700 to 6,000 ft (Cline and Moretti, 1956). A simple cross section reconstruction along Highway 259, honoring dips, elevations, and contacts, suggests a Jackfork thickness of 5,000 ft This variance between the outcrop and subsurface data may be attributed to the difficulties associated with Jacob's-staff measurements of extremely oblique and discontinuous outcrop segments.

The SOPC #1-7 Weyerhaeuser well (1,049 ft FSL and 1,453 ft FEL, sec. 7, T. 1 N., R. 23 E.) was drilled to test several vertically stacked potential stratigraphic traps. Although nonproductive, the well encountered numerous shows and validated the subsurface predictions based upon surface geology and facies predicted from seismic sequence analysis.

GEOLOGIC AND SEISMIC STRATIGRAPHY

The Lynn Mountain syncline is 60 mi long and 8 mi wide. The structure, shown in Figure 1, is actually a half syncline with the south limb truncated by the Octavia fault. The rocks exposed at the surface on the north flank of the syncline comprise a thick Carboniferous flysch section consisting of the Stanley Group, Jackfork Group, Johns Valley Formation, and Atoka Formation (Fig. 2). We focused our exploration interests on the Jackfork Group and Atoka Formation, which we believed offered the best chance for adequate reservoir development within the flysch sequence.

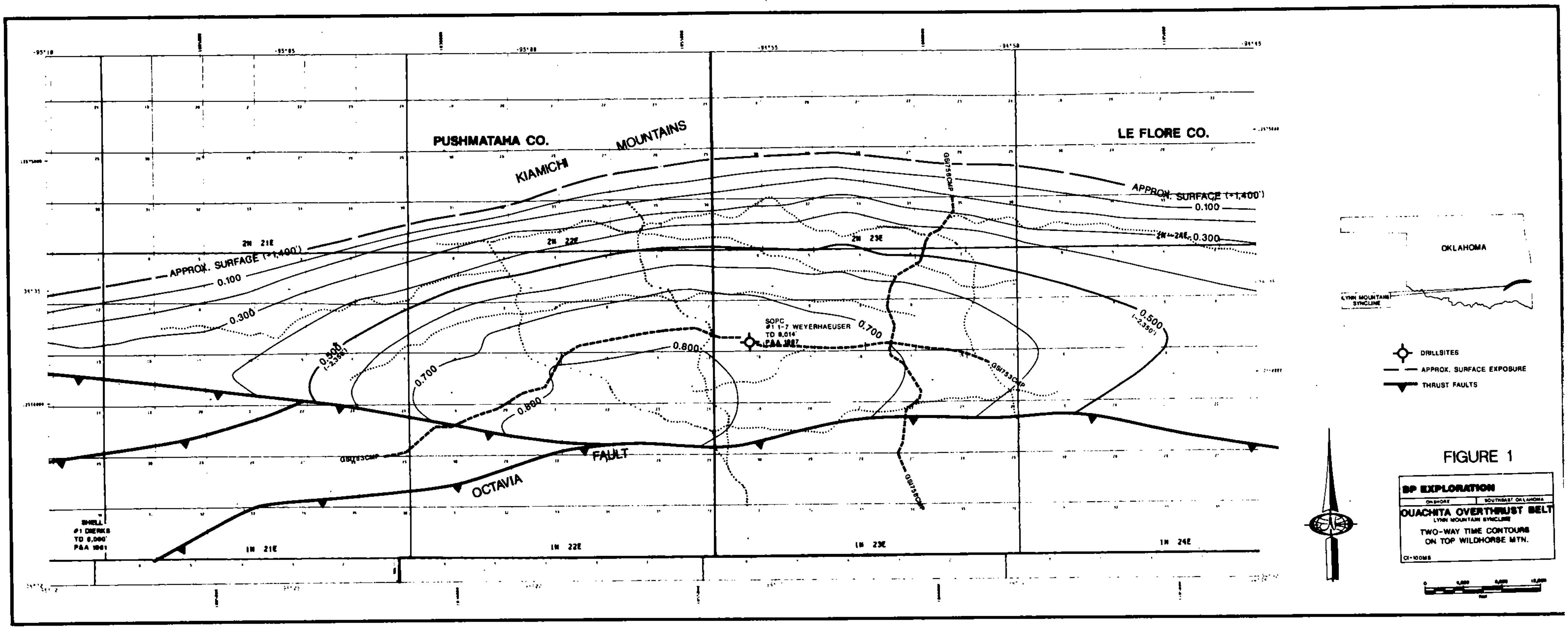

Figure 1. Time-structure map on top Wildhorse Mountain Formation, Lynn Mountain syncline.

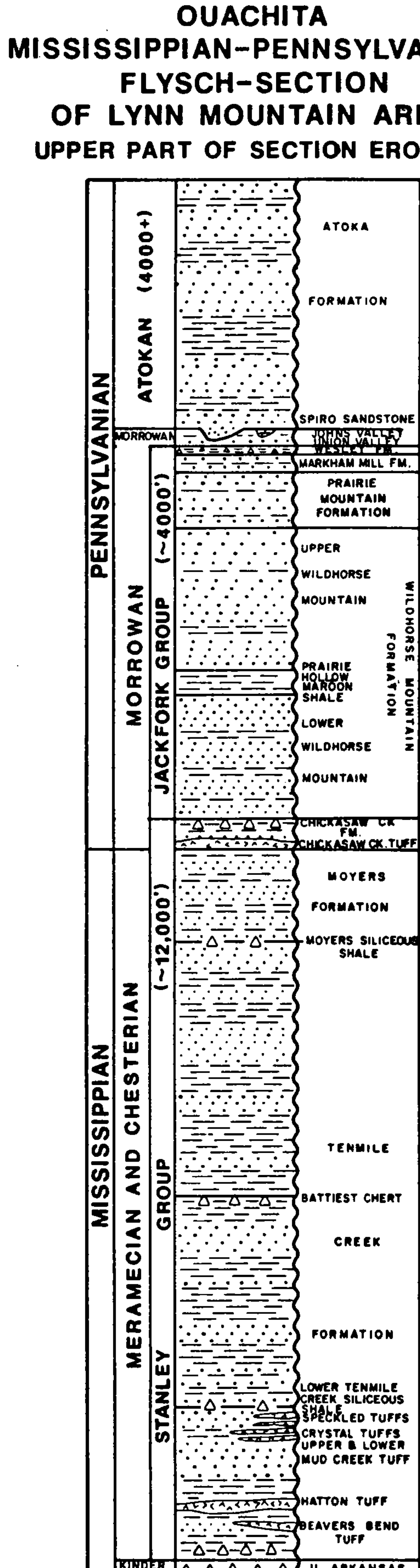

FIGURE 2

Figure 2. Stratigraphic column for Carboniferous units in the Lynn Mountain syncline area.

Cline and Moretti (1956) described two complete stratigraphic sections of the Jackfork and lower Atoka on the north flank of the Lynn Mountain syncline. These sections were described on the then newly exposed road cuts along the Indian Service Road and Highway 259, which are 22 mi apart. In the past 30 years, these sections have been weathered and overgrown, but still afford the best continuous surface exposures of the section. While classic outcrops of the Jackfork—Atoka, they speak little to the section's lateral continuity and uniformity of thickness. Due to their separation, little could be concluded regarding the lateral variability and distribution of turbidite facies on more than outcrop scale.

The Jackfork is divided into four formations. In ascending order, they are the Wildhorse Mountain, Prairie Mountain, Markham Mill, and Wesley Formations. We believe that the Game Refuge Formation, which has been called the uppermost formation of the Jackfork Group, is actually a channel facies of the basal Atoka. This will be discussed later. The Jackfork Group is the major ridge-former and consists of interbedded sands and shales typical of flysch. The individual sandstone beds are generally less than 3 ft thick, but are commonly amalgamated into sand bodies 20—200 ft thick. Sandstones are fine- to medium-grained, and moderately well sorted.

The Jackfork has many characteristics of sediments deposited on a deep-sea fan. Morris (1974) referred to the Jackfork sandstones as proximal turbidites and postulated that they were deposited in lower fan channels or channel-mouth bars. The turbidite-submarine fan regime, under which the Jackfork was deposited, lends itself to the development of many types of stratigraphic traps. Fig. 3 illustrates the typical sand geometries found in the #1-7 well. Fig. 3a shows a typical flysch sequence from the Wildhorse Mountain: Note the combination of both coarsening- and fining-upward sequences typical of turbidite lobe and channel deposition. Fig. 3b is from the "Spiro" channel section and typifies the isolated channel sands within the larger, mud-dominated, incised valley.

<u>The Wildhorse Mountain Formation</u> consists of interbedded gray shales and gray to white sandstones. The sandstone exceeds 60% of the section. Amalgamated sandstone beds may exceed 100 ft in thickness. The shales are very silty, unlike the clay shales of the Stanley. The total thickness of the Wildhorse Mountain Formation is about 2,700 ft in the #1-7 Weyerhaeuser well and up to 3,200 ft as measured in outcrop (Cline and Moretti, 1956). The Prairie Hollow Shale divides the Wildhorse Mountain into upper and lower members. It consists of maroon and green shales and is 330 ft thick in southwestern Pushmataha County (Pitt, 1982).

Seismically (Figs. 4, 5), the Wildhorse Mountain is characterized by continuous, moderate-amplitude reflections which display a concordant and parallel relationship with bounding sequences. Locally, downlapping terminations were identified, which are interpreted to represent the limits of individual fan lobes. These are vertically interrupted by regionally continuous, higher-amplitude reflections indicative of interbedded shale, most notably the Prairie Hollow shale. The lateral continuity displayed on seismic supports the interpretation that the Wildhorse Mountain was largely deposited as a series of laterally continuous, amalgamated fan-lobe sands, interbedded with passively deposited basinal silts and shales.

<u>The Prairie Mountain Formation</u> has lithologies similar to the Wildhorse Mountain Formation, although the sandstones may be slightly coarser-grained. A 2-ft-thick siliceous shale separates the two formations. Where the shale is not present, it is difficult to separate them. In the 1-7 Weyerhaeuser well, the Prairie Mountain was estimated to be 1,080 ft thick. In measured sections its thickness has ranged from 1,300 to 3,000 ft, probably due to the difficulty of picking the base.

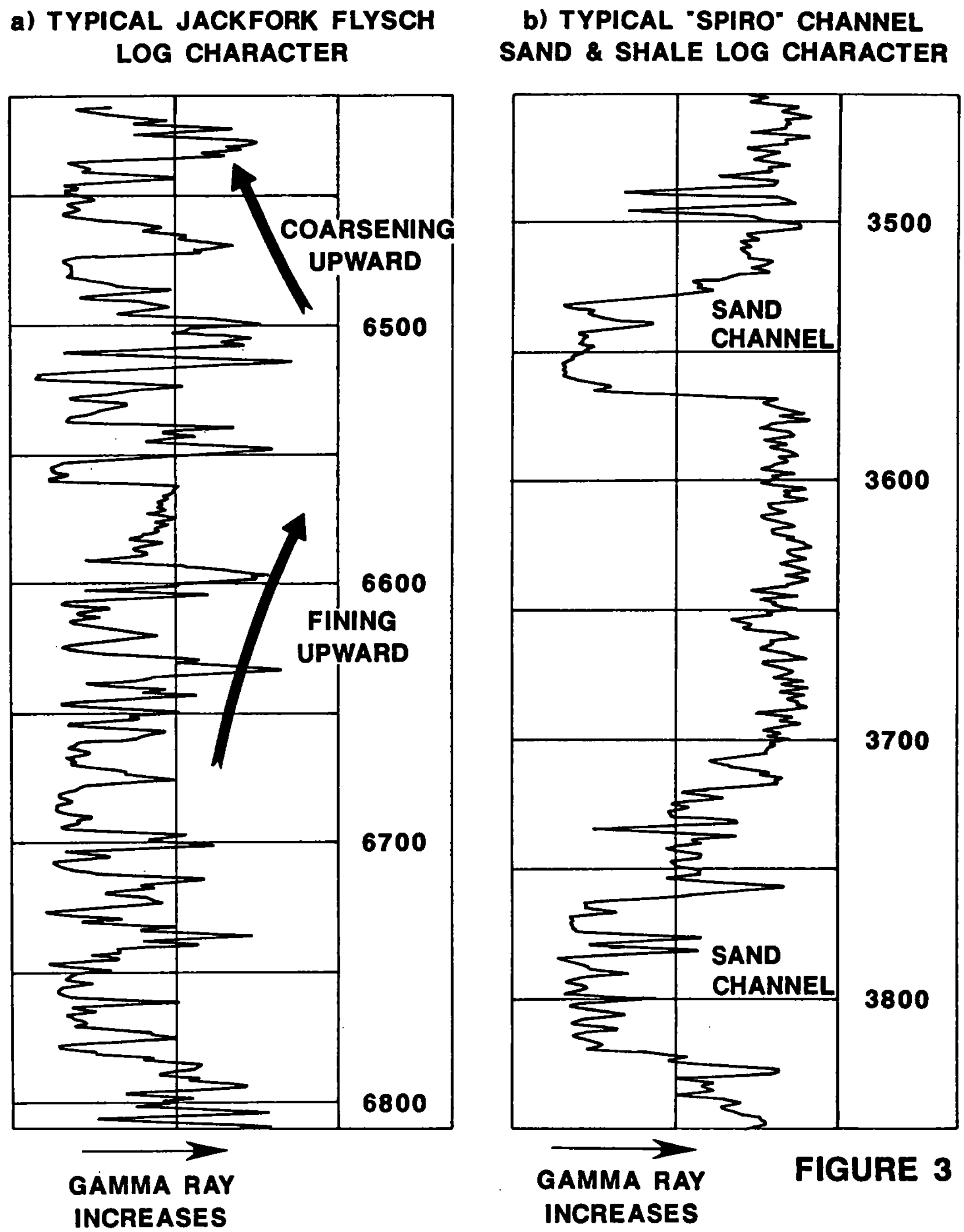

Figure 3. Gamma ray log facies character.

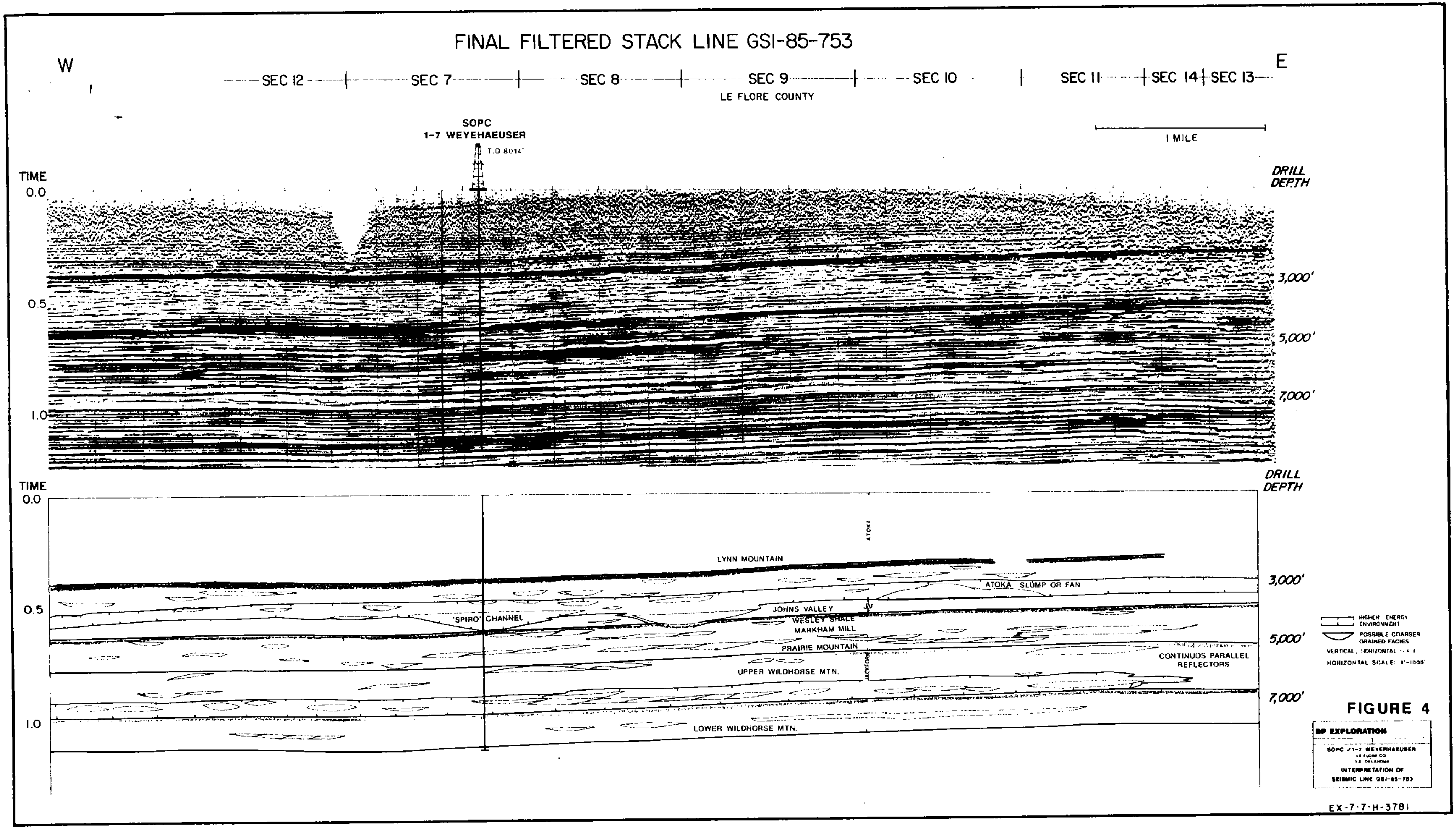

Figure 4. Interpretation of seismic line GSI-85-753.

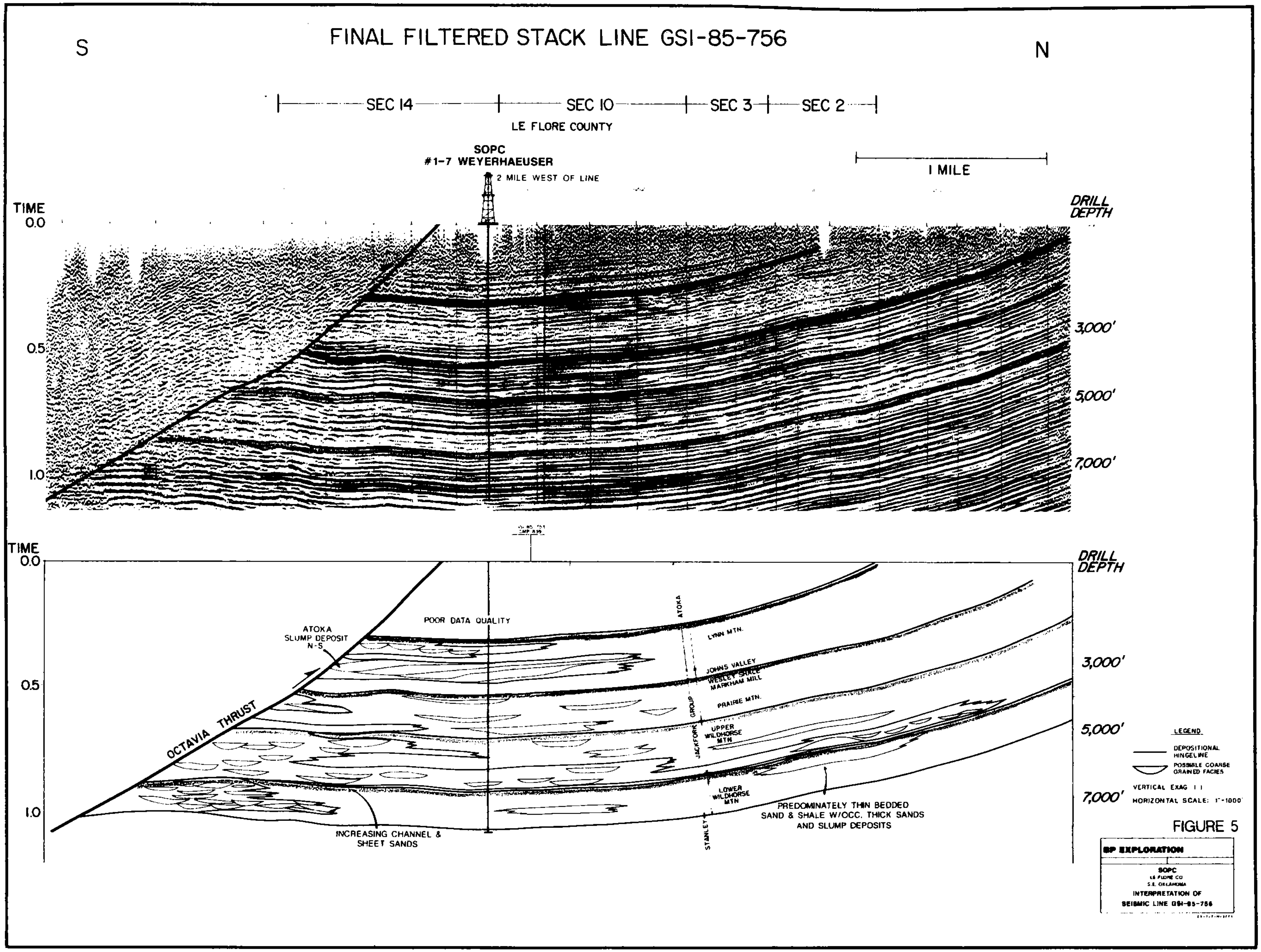

Figure 5. Interpretation of seismic line GSI-85-756.

The Markham Mill Formation consists of thick-bedded sandstones interbedded with shales. The exposure along Highway 259 contains exotic boulders. The formation is 380 ft thick in the #1-7 Weyerhaeuser well and ranges from 320 to 450 ft in Pushmataha County (Pitt, 1982).

The Wesley Formation consists of blue-gray shale, with some very thin beds of chert and silty sandstone. The unit ranges from 150 to 400 ft thick in outcrop and is 265 ft thick in the #1-7 Weyerhaeuser well. This starved-basin shale unit suggests the beginning of a marine transgression prior to the start of Johns Valley deposition.

Seismically, the Prairie Mountain, Markham Mill and Wesley are interpreted as a single sequence. The lower Prairie Mountain Formation is characterized seismically by low- to moderate-amplitude reflections displaying a wavy to discontinuous geometry. This grades vertically to include more laterally continuous, high-amplitude reflections. This corresponds to the increase in shale seen in the #1-7 well as the Prairie Mountain grades into the shalier Markham Mill Formation, ultimately culminating in the laterally continuous Wesley Shale.

The Johns Valley Shale consists of 600 to 850 ft of gray shale and is characterized on the surface as a distinct, wide valley. In thrust sheets north and west of the Lynn Mountain syncline, the Johns Valley Shale is boulder-bearing, but boulders have not been observed in Lynn Mountain. The Johns Valley has been cut by numerous channels that have been filled by sands and shales containing rework Morrowan fossils. These channels are probably equivalent to the Spiro sandstone, which is the basal Atoka sandstone in the Arkoma basin to the north. Such a channel was cored in the #1-7 Weyerhaeuser well, and sandstones in the core contained crinoid columnals.

The locally mapped Game Refuge Sandstone and the Union Valley Sandstone are associated with the Johns Valley. They consist of limonitic sandstone and contain impressions of plants and molds of marine invertebrates such as crinoid columnals, brachiopods, and bryozoans. We believe that the Game Refuge and Union Valley sandstones are the basal Atokan channel fill incised into the Johns Valley. We have opted to call these channel sands "Spiro"-equivalent rather than use the confusing Game Refuge and Union Valley nomenclature.

The Johns Valley Formation appears seismically as a sequence of laterally continuous, low- to moderate-amplitude reflectors. These are locally incised by younger Spiro-equivalent channels (Fig. 4) that appear seismically as a package of moderately discontinuous, low-amplitude events onlapping the channel margins. The channels are separated by more continuous, moderate-amplitude events representing the Johns Valley Shale. At the #1-7 well, the Johns Valley has been completely removed and replaced by the targeted channel sequence.

The Atoka Formation consists of about 60% gray shale and 40% greenish-gray, fine-grained sandstone. It is at least 3,500 ft thick as measured in the Standard Oil #1-7 Weyerhaeuser well, but an undetermined amount has been eroded. The sandstone beds are generally much thinner than in the Jackfork. In the well, these sands exhibit primarily a fining-upward log and sample character, although several examples of coarsening-upward sandstones were noted. Sandstone character ranges from very fine- to medium-grained, moderately sorted, and generally tight.

The lower Atoka Formation appears seismically to consist of laterally continuous, moderate-amplitude reflections separated by higher-amplitude continuous reflections. The basal Atoka section is characterized by numerous channel (Fig. 4) and slump or mound (Fig. 5) features. The slump features generally postdate the Johns Valley. Their seismic definition is impaired by the relatively low signal-to-noise ratio exhibited by the shallow (<500 milliseconds) section. In outcrop, this section is characterized by interbedded shales and silts interrupted by massive sands.

These observations are corroborated by the results of the #1-7 well and suggest deep-water, low-energy deposition in the distal portion of the turbidite fan.

DRILLING SUMMARY

SOPC spudded the #1-7 Weyerhaeuser, sec. 7, T. 1 N., R. 23 E. in Le Flore County, Oklahoma, on April 23, 1987. The objective of the well was to test stratigraphic traps identified on seismic (Fig. 4) within the Atoka—Johns Valley and Jackfork sections. The well reached a total depth of 8,016 ft in the lower Wildhorse Mountain Formation on May 23, 1987, with no significant drilling problems. Figure 6 compares the seismic section to the well log. The drilling contractor was Alexander Drilling, Inc. The well employed air drilling techniques to TD.

The well spudded in the Atoka Formation. The section is composed of intercalated shales and sandstones. Cements were primarily quartz and clay. Porosity ranges from 0 to 6%, consisting predominantly of microporosity and secondary moldic porosity. Insignificant gas shows were encountered through much of the section.

The basal Atoka section is composed of a thick shale sequence, with only minor sand beds from 2,715 to 3,501 ft X-ray diffraction of the Atoka shale samples was conducted to predict the effects of drilling mud on the shales. Analysis indicated a composition of 60—76% quartz, 8—10% feldspar, 4—14% chlorite, 3—12% illite, 3—5% kaolinite, and 2—3% siderite. These results suggest little danger of swelling-clay problems in the local Atoka section, which is remarkably different from experience in parts of the Arkoma basin to the north.

A basal Atoka "Spiro"-equivalent channel sequence was encountered at 3,501 to 4,302 ft. The section is composed of thickly bedded units of sandstone and shale. Large channel-sand bodies show a predominantly fining-upward character. A conventional core was attempted using air at 3,780 to 3,784 ft in a major channel sandstone, using an experimental air coring bit. Coring was attempted in this interval to better understand the channel facies and cause of a significant gas show encountered at 3,760 ft. This show resulted in a 10-ft flare lasting three minutes; the flare recurred on trips thereafter. The Atokan channel sandstones are very similar to the overlying Atoka, with the exception that the grain size ranged up to coarse. Bed thickness was very different from the overlying section with massive sandstone channels 30-50 ft thick being interspersed with shales 50-250 ft thick. Log porosities ranged up to 10%, but overall averaged less than 5%. Of importance is the fact that the entire Johns Valley section appears to be absent in the well. Seismic (Fig. 6) suggests that the "Spiro" channel has completely incised the Johns Valley section at the well location.

The base of the Atokan channel sequence in the well is marked by the Wesley Shale. This regional event is quite evident when the units are correlated to the seismic, which displays a significant regional, high-amplitude event in this interval (Fig. 6). The base of the massive shale at 4,566 ft marks the top of the Markham Mill Formation of the Jackfork Group. At this location the top of the Markham Mill is located at the base of the Wesley Shale and is a clean channel sandstone. This boundary is visually apparent on the log as the occurrence of the first massive sandstone below the Wesley Shale. The top of the Markham Mill is coincident with the first occurrence of Morrowan *Spelaeotriletes triangulus* spores in well cuttings.

The Markham Mill sandstones are predominantly fine-grained, with significant siltstone layers. Overall lithologic composition resembles the overlying sections. The base of the Markham Mill occurs at 4,956 ft with the change from the predominantly sandstone and siltstone depositional patterns to the more normal sand and shale packages of the Prairie Mountain Formation. As with the overlying sections, gas was noted from the major sandstone units. The base of the Prairie Mountain Formation is picked at the top of a massive shale bed which occurs at 6,026 ft, or effectively at the end of major sand deposition associated with the Wildhorse Mountain Formation.

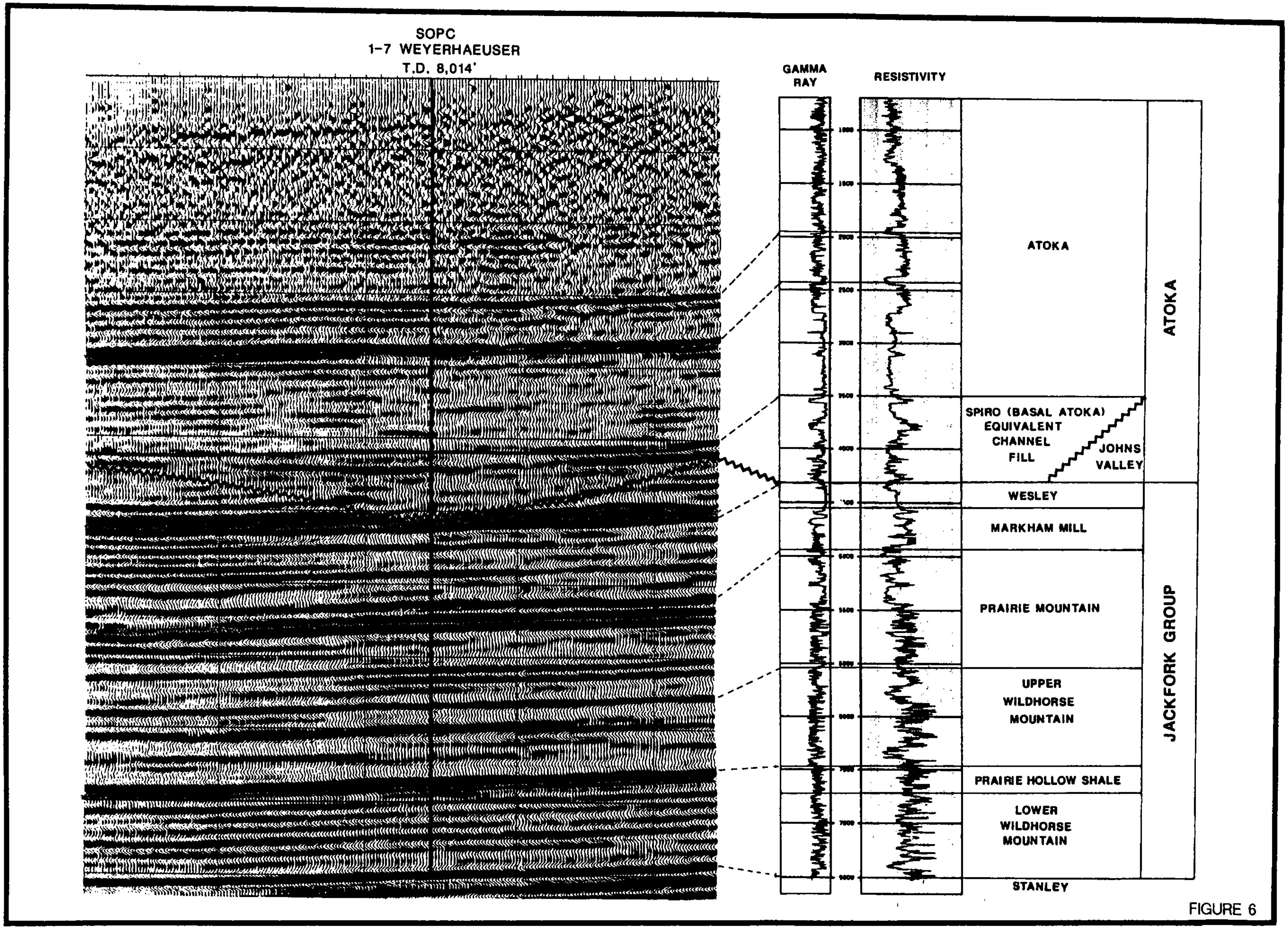

Figure 6. Correlation of seismic line GSI-85-753 to the SOPC 1-7 Weyerhaeuser well log.

Increased sandstone occurrence was accompanied by increased gas, noted while drilling, and a larger gas flare during trips. While logs indicated porosities in excess of 5%, standard analysis of rotary sidewall cores suggests porosities no greater than 3%.

The well was within the Lower Wildhorse Mountain Formation at the programmed total depth of 8,014 ft. By directly tying continuous seismic reflections to the outcropping Stanley contact to the north, we estimate that top of Stanley would have been encountered at 8,700 ft.

ORGANIC GEOCHEMISTRY

Organic geochemistry was an essential component of our program. Samples from both cuttings and the rotary cores were analyzed for maturity and source potential. Produced hydrocarbons were sampled for typing and maturity analysis. In summary, the drilled section spudded in rocks with a vitrinite maturity of 0.8% R_0. A normal maturity-versus-depth relation was noted to the TD, where maturities of 1.66% R_0 were encountered. As expected, the hydrocarbon content mimicked the maturity profile, wet gas being recorded to approximately 6,200 ft and dry gas to TD. The shallower samples contained 90—93% methane with 4—8% ethane and trace quantities of C3—C5. The deepest sample at 7,932 ft contained 99.3% methane with trace ethane.

The source quality of the section was disappointing. Total organic carbon averaged only 0.27% and ranged from 0.04 to 0.88%. Typing of the kerogen within the flysch sequence suggests that it is capable of generating only minor amounts of gas. These results are typical of the Mississippian and Pennsylvanian flysch sequence in general. Our regional analysis suggests that the Stanley shales are the most likely source for Carboniferous-reservoired gases encountered.

PETROGRAPHY

The encountered sandstones could be subdivided into two lithic types. Lithic type I has relatively high (10—15%) clay content and poor to moderate sorting of the sand fraction. Clays are predominantly chlorite. Lithic type I contains relatively low amounts of silica cement. Lithic type II has lower clay content (<10%) and has better sorting (moderate to well sorted). It also has a moderate amount (>15%) of silica cement in the form of quartz overgrowths.

All sandstone samples from the well exhibit negligible to very low porosity (<5%). Porosity destruction is due to compaction, coupled with either detrital and/or authigenic clay (lithic type I) or quartz cement (lithic type II). Most visible porosity is secondary, resulting from dissolution of feldspar grains and fine rock fragments. Secondary pores are commonly partially infilled by late-stage quartz cement. It is likely that these two lithic types will weather differently in outcrop and that the more-friable units noted in outcrop are related to the clay-rich lithic type I sandstone.

CONCLUSIONS

This well is one of the few wells to test the potential of the Carboniferous flysch sequence within the Ouachita fold belt. It is only the second well within the central fold belt of Oklahoma to evaluate the potential of the Atoka—Jackfork section, the first being the Shell #1 Dierks.

The well has proven the ability to use seismic-sequence techniques within the flysch sequence. When correlated to nearby outcrops, the seismic offered a high degree of predictability with respect to subsurface facies and stratigraphy. The well and seismic demonstrate that the Jackfork section displays a relatively uniform thickness throughout much of the syncline. The Jackfork thickness encountered in the well is less than outcrop measurements, on the order of 4,400 ft versus 5,700—6,000 ft.

Well, seismic, and outcrop data demonstrate the presence of significant post-Johns Valley channel and slump/mound development. In places this involves complete incision of the Johns Valley, which is absent at the #1-7 well location. The cause of incision is not clearly understood, but we believe it must be related to local tectonic uplift.

Although the "Spiro" channels are exposed in nearby updip outcrops, no fresh-water flows were noted, and gas was encountered. This suggests a significant amount of reservoir heterogeneity and offers the distinct possibility for viable stratigraphic traps if better reservoir rocks are encountered. Observed porosities were significantly lower than those reported from surface samples by Morris and others (1979). This difference is no doubt created by surface weathering. We believe there is a relationship between increasing geochemical maturity and reservoir destruction through silica cementation. Future tests of the Jackfork section in areas with lower geochemical maturity may find reservoir-quality rocks.

ACKNOWLEDGMENTS

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PRELIMINARY INTERPRETATION OF A SEISMIC PROFILE ACROSS THE OUACHITA FRONTAL ZONE NEAR HARTSHORNE, OKLAHOMA

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INTRODUCTION

Significant recent hydrocarbon exploration is taking place in southeastern Oklahoma in an area termed the Ouachita "frontal fairway" by Bertagne and Leising (1989). These authors outline the importance of seismic-reflection data and interpretations in this structurally complex region.

A north-south proprietary seismic-reflection profile (Fig. 1) across the frontal zone of the Ouachita thrust belt in this region, near Hartshorne, Oklahoma, illustrates a style of deformation: the triangle zone (Jones, 1983), known or suspected to be present wherever thrust belts advance into foreland basins such as the Arkoma basin. The triangle zone is a wedge-shaped structure, floored by a foreland-directed thrust, at the foreland tip of which a complementary foreland-dipping, hinterland-directed thrust of equal and opposing slip occurs shallower in the section. These opposing thrusts form the front of the triangle zone. Within the triangle zone a number of hinterland-dipping, foreland-directed, imbricate thrusts are usually present (Jones, 1983). The Choctaw thrust (Fig. 1) is interpreted to be such an imbricate, i. e., the frontal imbricate within the triangle zone at the exposed thrust front of the Ouachita thrust belt in Oklahoma.

Arbenz (1984) was the first to illustrate this style of deformation in the frontal Ouachita thrust belt, in a schematic section across the thrust belt in Arkansas. Hardie (1988) has recently remapped the Pittsburg Quadrangle in southwestern Pittsburg County, Oklahoma. He carefully interpreted the structure of the frontal zone in that area using available well data and modern structural concepts, and was the first to recognize the presence of a triangle zone in the frontal Ouachita thrust belt of Oklahoma. Recent high-quality seismic-reflection profiles (Fig. 1) portray the geometry of such features.

Two aspects of Ouachita surface geology suggest that triangle zones may characterize thrust geometry throughout the entire frontal belt in Oklahoma. Immediately west and north of the Choctaw fault, the Hartshorne Sandstone dips away from the fault, forming an anticlinal structure similar to the "front fold" in the Alberta foothills (Jones, 1983). Between the towns of Atoka and Pittsburg, in the western part of the frontal belt, dips are steep to vertical to southeast-dipping and overturned (Hendricks and others, 1947, sheet 1). In addition, cross sections across the southern part of the Arkoma basin and Ouachita frontal belt (e.g., Hendricks and others, 1947, sheet 3, A-A′) show an overthickened section of Atoka Formation beneath the Choctaw fault (compare Jones, 1983, fig. 22). Both features may be the result of imbricate stacking of thrust sheets between blind floor and roof thrusts. New seismic-reflection data may show the presence of imbricate stacks, and surface geology may show evidence of hinterland-directed thrusting.

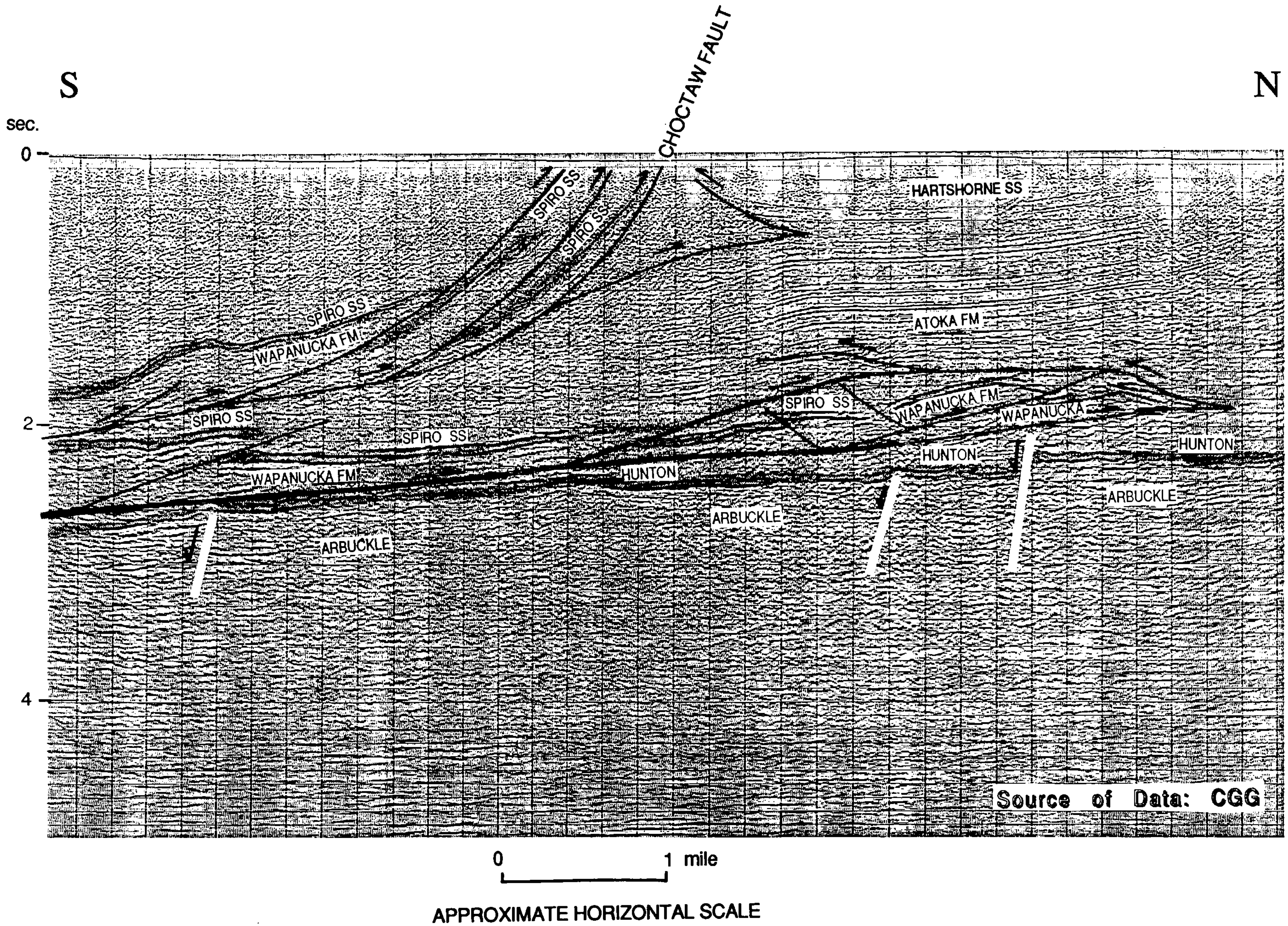

Figure 1. Seismic-reflection profile across the frontal zone of the Ouachita thrust belt near Hartshorne, Oklahoma.

DISCUSSION

In our interpretation (Fig. 1), the Choctaw thrust is simply the frontal imbricate of a complex, partially eroded, upper triangle zone which represents approximately six miles of shortening. The Middle Pennsylvanian Hartshorne Sandstone appears to be merely peeled upward along the northern margin of this triangle zone and is not significantly displaced with respect to the Arkoma basin to the north.

The Hartshorne Sandstone and underlying Middle Pennsylvanian Atoka Formation are interpreted to form the roof of a deeper triangle zone near the northern end of the profile (Fig. 1). This zone is interpreted to be a passive-roof duplex in the sense of Banks and Warburton (1986), i.e., an imbricate zone bounded by floor and roof thrusts, the roof sequence of which remains relatively stationary during thrust propagation within the underlying imbricate zone. The passive-roof duplex interpreted on Figure 1 is unusual because it contains two foreland-dipping backthrusts between the floor and roof thrusts. This represents a reinterpretation of the complex structure within the basal Pennsylvanian sequence (Wapanucka Formation and Spiro Sandstone) on strike with the Wilburton gas field mapped by Berry and Trumbly (1968). The floor thrust of this deeper zone appears to be a décollement or flat for a distance of more than seven miles north-south within the Upper Devonian and Mississippian shale sequence (Woodford Shale, not shown on Fig. 1). The Carbon fault of Berry and Trumbly (1968), which probably splays upward and to the north from near the tip of this duplex zone, also is not shown on our preliminary interpretation (Fig. 1). Although the roof sequence has probably moved northward a short distance as part of the hanging wall of the Carbon thrust, it appears to have remained relatively passive with respect to shortening within the underlying duplex zone.

Beneath the floor thrust of this deeper imbricate zone, the Hunton through Arbuckle (Devonian to Cambrian) sequence is cut by steeply dipping extension faults, in which the sense of displacement appears generally down-to-the-south. These illustrate the style of structural traps involved in the subthrust Arbuckle gas play near Wilburton. Similar down-to-basin faults are described by Houseknecht (1986). Those imaged in Figure 1 do not appear to displace the floor thrust of the deeper triangle zone, and are therefore older than this thrust. However, the floor thrust does appear to rise to the north where it crosses the extension faults, suggesting that the position and dip of the thrusts was influenced by underlying structures.

In summary, typical triangle-zone features, suspected by earlier workers, are imaged by a high-quality seismic-reflection profile across the frontal zone of the Ouachita thrust belt near Hartshorne, Oklahoma. Down-to-the-south extension preceded thrusting. Frontal thrusting is younger than the Hartshorne Sandstone of late Middle Pennsylvanian (Desmoinesian) age, the youngest Paleozoic stratigraphic unit preserved along the seismic profile.

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CARBONIFEROUS CONODONT FAUNAS, NORTHERN OUACHITA MOUNTAINS, OKLAHOMA

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Abstract. Carboniferous conodont faunas from the northwestern Ouachita Mountains represent six assemblages: two Mississippian (Meramecian(?)-Chesterian) and four Pennsylvanian (Morrowan-Atokan). The distribution of these assemblages suggests tentative modifications of previous biostratigraphic estimates for ages of stratigraphic units. Usage of the terms Caney and "Springer" Formations as equivalent to the chronostratigraphic subdivisions Mississippian and Pennsylvanian is unwarranted, on account of the Caney being partly Pennsylvanian. The lower Johns Valley Formation is Pennsylvanian, but can now be shown to include rocks slightly older than previously estimated. Although preliminary, Carboniferous stratigraphic units are demonstrably diachronous. Thus, the Mississippian/Pennsylvanian and Morrowan/Atokan boundaries cross lithostratigraphic boundaries. Future work will further refine the present contribution and more precisely locate chronostratigraphic boundaries.

INTRODUCTION

This preliminary report is concerned with Upper Mississippian through lower Middle Pennsylvanian conodont faunas obtained in conjunction with the COGEOMAP project in the northern Ouachita Mountains of Oklahoma. It was envisioned that conodonts might serve as a tool for identification of stratigraphic units either in complexly deformed areas or where the stratigraphy was uncertain. Some stratigraphic uncertainties stem from the fact that similar facies occur in the various stratigraphic units. This is not unexpected, considering the limited number of depositional settings developed at the mid-Carboniferous transition from continental margin to basin. Some examples are: the Caney, "Springer," and Johns Valley Formations include black shale facies; the "Springer" and Johns Valley Formations contain olistostromes; and the Jackfork and Atoka Formations represent lithologically similar successions of sandy turbidites and shale. The present data are not sufficiently complete to unequivocally establish stratigraphy simply on the basis of conodont faunas. Nor is it considered a necessity. Continued study will more thoroughly establish lateral facies, as well as provide a more precise temporal framework for scenarios regarding basin evolution.

Conodont samples were collected primarily from stratigraphically incomplete localities that had been described by earlier authors or from localities recently discovered by Oklahoma Geological Survey workers. However, three localities (sampled at about 15-m intervals) represent essentially continuously exposed and apparently unfaulted stratigraphic sections. These include the exposures of Caney and "Springer" Formations at the well known Pinetop locality, the Caney(?) and "Springer" Formations at the Boggy Creek locality, and the Johns Valley and Atoka Formations at the famous Hairpin Curve locality. The geographic distribution of sampled localities and sections is shown in a general way on the index map (Fig. 1); more precise locations can be obtained from Whiteside (in prep.).

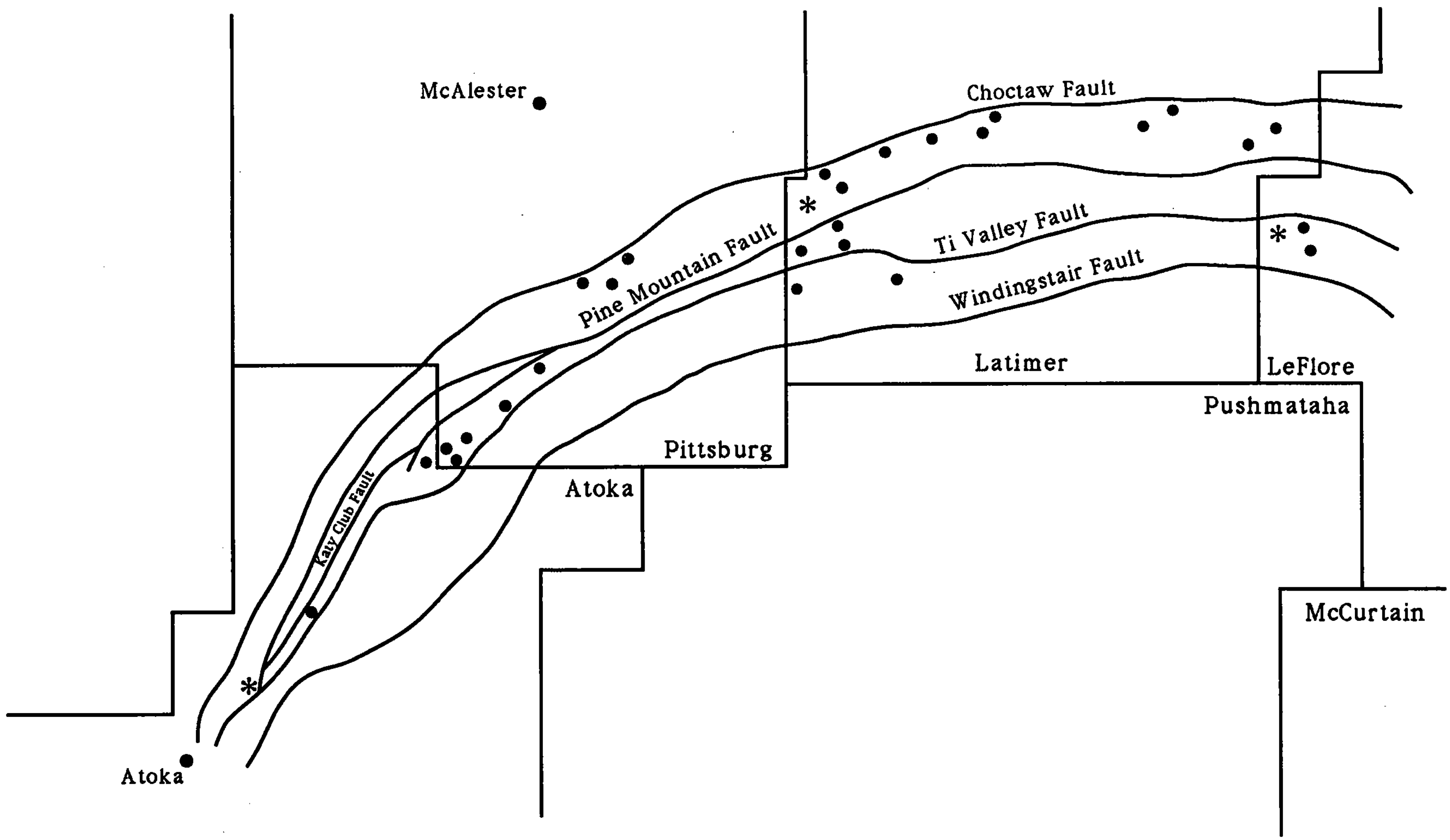

Figure 1. Generalized location map showing geographic distribution of samples. Asterisks indicate locations of measured sections.

STRATIGRAPHY

In the northwestern Ouachita Mountains the major reverse faults, from south to north, include the Ti Valley, Pine Mountain, Katy Club, and Choctaw faults (Fig. 1). There is a relationship between these faults and stratigraphic terminology (Fig. 2). Carboniferous stratigraphic units exposed southeast of the Ti Valley thrust include the Stanley, Jackfork, Johns Valley, and Atoka Formations. North of the Ti Valley fault, the Caney, "Springer," and Atoka Formations are recognized. Between the Pine Mountain and Choctaw faults the Wapanucka, Chickachoc Chert, middle shale, and "Spiro" separate and distinguish "Springer" shales from shales of the lower Atoka Formation.

For the most part, the present conodont samples come from shale units within the Caney, "Springer," Johns Valley, and Atoka Formations. We have also sampled, with good results, limestone concretions from the Caney and "Springer" Formations, and calcareous turbidites of the Atoka Formation. The character of the units and the significance of their conodont faunas are discussed in the following sections.

CANEY SHALE

Taff (1902) named the Caney for outcrops in Johns Valley at the settlement of Caney. He considered his Caney to be equivalent with similar black shales in the Arbuckle Mountains region, which Taff (1904) later also referred to as Caney. Taff's original concept of the Caney was substantially altered when workers discovered two facts: (1) his "type" Caney is actually exotic masses within Pennsylvanian shale, and (2) the Caney as subsequently recognized was partly Pennsylvanian age. In the central Ouachita Mountains, the Pennsylvanian shales containing "Caney" olistostromes became the Johns Valley Formation. In the frontal Ouachitas, presumed Pennsylvanian shales became the Springer Formation. A presumably complete section of the Caney is exposed in Ti Valley (NW 1/4, NE 1/4, sec. 3, T. 2 N., R. 15 E.), where the formation attains a thickness of 140 m (Hass and Huddle, 1965) and conformably overlies the Woodford Chert. Above the thin basal glauconitic and phosphatic shale, the formation is characterized by black to bluish-gray, hard, platy, phosphatic and siliceous shales. These are overlain by soft, flaky, black shales in the upper part of the formation. Phosphate nodules attain a diameter of 2.5 cm, and limestone concretions, which are common in the lower part of the formation, are as much as 3 m in diameter. The concretions locally contain pyritized ammonoid cephalopods and exquisitely preserved conodonts, including nearly complete apparatuses of the Mississippian *Gnathodus bilineatus*, *Idioprioniodus*, *Kladognathus tenuis*, and *Lochriea commutata*. The shales associated with the concretions often contain a prolific pelecypod fauna, including *Caneyella*, as well as other forms described by Girty (1909). This lithology, particularly when siliceous, has been difficult to successfully process, and when processed generally yields few, if any, conodonts.

Our Caney samples yield conodonts characteristic of the *Gnathodus texanus-Kladognathus tenuis*, *Gnathodus bilineatus-Lochriea commutata*, and *Neognathodus symmetricus* assemblages. The former two assemblages are consistent with the Meremecian and Chesterian age established by ammonoid cephalopod occurrences (Gordon and Stone, 1977). The latter assemblage is indicative of the Morrowan, and confirms the inadequacy of using geologic age as a lithostratigraphic criterion.

"SPRINGER" FORMATION

The predominantly shale, presumably Pennsylvanian interval overlying the Caney Formation in the Choctaw, Katy Club, and Pine Mountain thrust sheets is assigned by many workers to the Springer Formation. The term Springer is derived from the Ardmore basin, where a sequence of shale, sandstone, and limestone spans

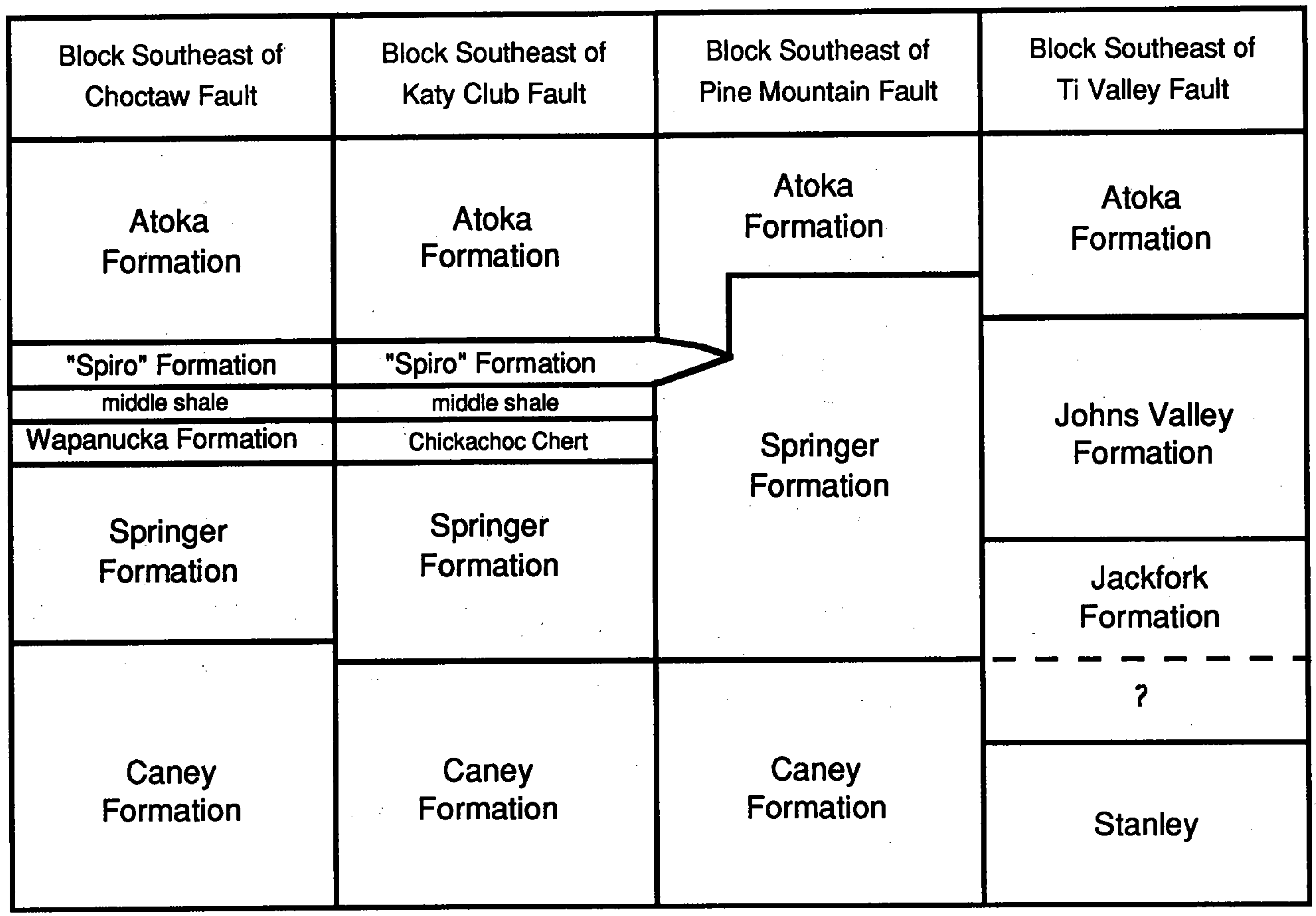

Figure 2. Carboniferous stratigraphic units in the northern Ouachita Mountains, Oklahoma.

the Mississippian/Pennsylvanian boundary (Goldston, 1922). Harlton (1938) applied the term to rocks of the Ouachita Mountains because he thought they occupied the same time-stratigraphic interval. Hendricks and others (1947) used the term Springer for lighter-colored, supposedly Pennsylvanian rocks overlying inferred Mississippian, black Caney shales. As recognized by them, the formation can be succeeded by either the Wapanucka or Atoka Formation. Hart (1974), in a recent geologic map of the western Ouachitas, referred the Springer of Hendricks and others' to the Goddard Shale, borrowing the term from the Ardmore basin stratigraphy. Extension of Ardmore basin terms into the Ouachita Mountains is unwarranted and inappropriate. Furthermore, the chronostratigraphic implications of the terms applied to the shales containing the Mississippian/Pennsylvanian boundary are not acceptable. If the Springer is equated with the Pennsylvanian and the Caney with the Mississippian, there is apparently no consistent lithologic basis for their separation.

We do not have sufficient information to warrant proposing any modification of the existing nomenclature, but we use the term "Springer" with considerable distress. A further complication is introduced by occurrences of olistostromes within the "Springer" (Cline, 1960), which suggests that the "Springer" does not differ substantially from the olistostrome-bearing Johns Valley Formation.

Lithologically, the "Springer" varies with its position within the frontal province. In the Choctaw sheet, characteristic lithologies include dark-gray, micaceous shales and siltstones that weather into small flakes with a variegated yellow, red, and blue appearance (Goldstein and Hendricks, 1953, p. 403). To the south, "Springer" shales become more gray or tan in color and contain siderite concretions, phosphate nodules, thin silty limestones, and occasional olistostromes.

"Springer" conodonts include both indigenous and obviously reworked forms. The latter forms, found associated with olistostromes, have not been specifically identified, but include types characteristic of Ordovician, Devonian, and Mississippian faunas. The former represent a restricted shelf assemblage that generally consists of *Idiognathoides sinuatus*, *Cavusgnathus lautus*, and *Ellisonia* sp. In rare instances, the diagnostic taxon of the *Idiognathodus klapperi* assemblage occurs in the upper part of the formation. Gordon and Stone (1977), using occurrences of ammonoid cephalopods, showed the "Springer" to represent a substantial part of the Lower Morrowan. However, occurrences of *I. klapperi* indicate that the upper "Springer" may be slightly younger than they supposed.

WAPANUCKA AND "SPIRO" FORMATIONS

The units overlying the "Springer" Formation and underlying shales of the Atoka Formation (north of the Katy Club fault) were referred to as Wapanucka Formation by Grayson (1979). Grayson's usage of the term Wapanucka has been restricted to his lower limestone member, and his upper sandstone-limestone member is now tentatively assigned to the "Spiro" Formation.

Taff (1901) named the Wapanucka Formation for exposures near the town of Wapanucka in the eastern Arbuckle Mountains. In the Ouachita Mountains, the formation consists of two units, the Wapanucka and Chickachoc Chert members. The latter is composed of dark-gray shale, spicular limestone, and spiculite that range from 0 to 100 m in thickness. The former unit, up to 40 m thick, consists of algal, micritic, spicular, oolitic, and bioclastic limestone; shale; calcareous sandstone; and limestone boulder and pebble conglomerate. For the most part, the Chickachoc Chert is the basinward (ramp slope) equivalent of the shelf (platform) Wapanucka. Where both are developed, Wapanucka facies have prograded over Chickachoc facies. Succeeding either the Wapanucka or Chickachoc is a 20- to 80-m-thick, gray clay shale informally referred to as the middle shale. The middle shale is overlain by the "Spiro" Formation, which ranges in thickness from 20 to 60 m; in the southwestern outcrops it consists of carbonate facies similar to those found in the Wapanucka. These carbonate facies grade eastward into predominantly sandstone facies.

Although the Wapanucka conodont faunas have yet to be treated in detail, their general significance is known (Grayson, 1979; Grayson and Sutherland, 1988). The major parts of both the Wapanucka and Chickachoc produce a generalized latest Morrowan conodont assemblage. In the upper part of both units, a distinctive conodont assemblage is present that could be (depending on the criteria employed to define the boundary) either Morrowan or Atokan. The conodont assemblage from the "Spiro" Formation includes occurrences of the conodont *Diplognathodus coloradoensis* and the foraminifer *Eoschubertella* (Groves and Grayson, 1984). These taxa are generally regarded as index fossils for the early Atokan (Lane and others., 1972; Dunn, 1976; Sutherland and Manger, 1983).

We did not attempt to duplicate any of Grayson's samples. However, we did discover that a Chickachoc Chert-like facies in the Pine Mountain thrust, which was assigned by Cline (1960) to the basal Atoka Formation, is a lateral facies equivalent of the "Spiro." Whether these spiculites and shales should be assigned to the Atoka Formation, "Spiro" Formation, or a Chickachoc Chert needs to be more fully considered.

JOHNS VALLEY

The Johns Valley consists of gray or tan clay shale; thin, gray sandstone beds; and occasional erratic boulders that form lenticular olistostromes (Cline, 1960; Shelburne, 1960). The boulder beds occur at several horizons within the formation, but the Caney exotic masses are usually found in the lower parts of the formation (Cline, 1960). Occurrences of the exotics diminish to the south, and are entirely absent south of Kiamichi Mountain.

Reworked forms recognized in Johns Valley olistostromes are similar to those from "Springer" olistostromes, with the possible exception of admixed Pennsylvanian taxa. The olistostromes are indicative of many of the formations Shideler (1970) established as the source of the allochthonous clasts. Three Pennsylvanian conodont assemblages are recognized: the *Neognathodus symmetricus*, the *Idiognathodus sinuosus-Neognathodus bassleri*, and the *Idiognathodus klapperi* assemblages. At the Hairpin Curve locality, these assemblages occur in a succession that is difficult to unequivocally interpret. A single sample from the basal exposure contains the *I. sinuosus-N. bassleri* assemblage. This is succeeded by the *N. symmetricus* assemblage, the *I. sinuosus-N. bassleri*, and *I. klapperi* assemblages in apparent superposition. Thus, there are at least two possibilities: 1) there is an unrecognized reverse fault in the lower part of the section; or, 2) the *N. symmetricus* assemblage represents reworked Pennsylvanian taxa within a non-diagnostic part of the *I. sinuosus-N. bassleri* assemblage. If the *N. symmetricus* assemblage is indigenous to the lower Johns Valley, it would indicate proximity to the base of the Pennsylvanian, and an age older than that estimated by Gordon and Stone (1977). The middle and upper Johns Valley, which produces the *I. sinuosus-N. bassleri* and *I. klapperi* assemblages, is middle to late Morrowan. The latter assemblage might also indicate that the uppermost part of the formation becomes as young as early Atokan. This would be a somewhat younger age for the upper Johns Valley than previously supposed.

ATOKA FORMATION

The Atoka Formation was named by Taff and Adams (1900) for discontinuous exposures of sandstone and shale along the southern margin of the eastern Choctaw coalfield. This area would now be considered part of the Arkoma basin. Since then, the usage of the term Atoka has been broadened to include rocks of widely different character and stratigraphic relations. Ouachita rocks called Atoka Formation obviously represent distinctly different facies than those called Atoka in the Arkoma basin and Ozark Mountains regions. We have not exhaustively examined this problem. However, application of the term Atoka for either the "Spiro" or turbidites and shale traditionally assigned to the Atoka should eventually be discontinued.

As applied to the frontal Ouachita Mountains, the Atoka Formation characteristically consists of resedimented shales and sandy turbidites, submarine-fan facies, and pelagic shales above the "Spiro" formation or its spicular basinward equivalent. Three general lithologic subdivisions are recognizable in this region: a lower, predominantly shale succession; a middle, sandy turbidite-and-shale association; and an upper, predominantly shale interval. The thickness of the generalized units is indeterminable, as is their relationship to rocks assigned to the middle and upper Atoka Formation in the Arkoma basin. Conodonts have not yet been obtained from the basal part of the lower shale interval, or from the upper shale interval. Those from the upper part of the lower shale and from the middle, sandy, turbidite-bearing interval represent the late Atokan *Idiognathodus incurvus* assemblage. In more southern areas, where the "Spiro" was not deposited, the Atoka Formation is distinguished from the underlying "Springer" or Johns Valley by the appearance of sandy turbidites. These basal Atoka rocks overlying the "Springer" yield the late Atokan *I. incurvus* assemblage. However, this assemblage can not be demonstrated to occur in basal Atoka sandstones and shale succeeding the upper Johns Valley, which contain the *I. klapperi* assemblage. The lowest occurrence of *I. incurvus* is about 115 m above the base of the Atoka Formation. Consequently, basal Atoka Formation in the central Ouachita Mountains might be older than the base of the formation in areas north of the Ti Valley fault.

CONODONT ASSEMBLAGES

The conodont biostratigraphic data needed to conclusively establish correlations of Ouachita Carboniferous stratigraphic units have not yet been assembled. Our data add to the available information, and suggest that some modifications of the correlations previously established by Gordon and Stone may be necessary (1977).

Hass (1950,1956) and Hass and Huddle (1965) described Lower Mississippian conodonts from the Stanley and upper Woodford Formations. Elias (1959) and Branson and Mehl (1941) reported Mississippian conodonts from the Stanley and Caney Formations. Harlton (1933) figured some Pennsylvanian conodonts from the Johns Valley Formation, and Grayson (1979) and Grayson and Sutherland (1988) using conodonts, suggested a late Morrowan to early Atokan age for the Wapanucka and "Spiro" (their upper sandstone-limestone) Formations, respectively. In addition to the conodonts, ammonoid cephalopods (Gordon and Stone, 1977), foraminifers (Groves and Grayson, 1984), and palynomorphs (Wilson, 1973) have been important in attempts to better understand age relationships of Ouachita rocks.

Six conodont assemblages are recognized from the middle Carboniferous succession in the frontal Ouachita Mountains: two are considered Mississippian, and four are characteristic of the Pennsylvanian (Fig. 3). The conodonts characteristic of these assemblages are illustrated in Plates 1 and 2. Figure 4 presents a tentative regional interpretation of the present biostratigraphic and lithostratigraphic data. Conodont recovery varies from one unit to another, but about 50% of samples yield identifiable conodonts. This fact, combined with a proven biostratigraphic record, probably makes conodonts one of the most important groups for correlating and dating Ouachita rocks.

GNATHODUS TEXANUS-KLADOGNATHUS TENUIS ASSEMBLAGE

This assemblage, which occurs in the lower Caney and in some of the Caney exotics in the Johns Valley Formation, is distinguished by occurrences of *Gnathodus*

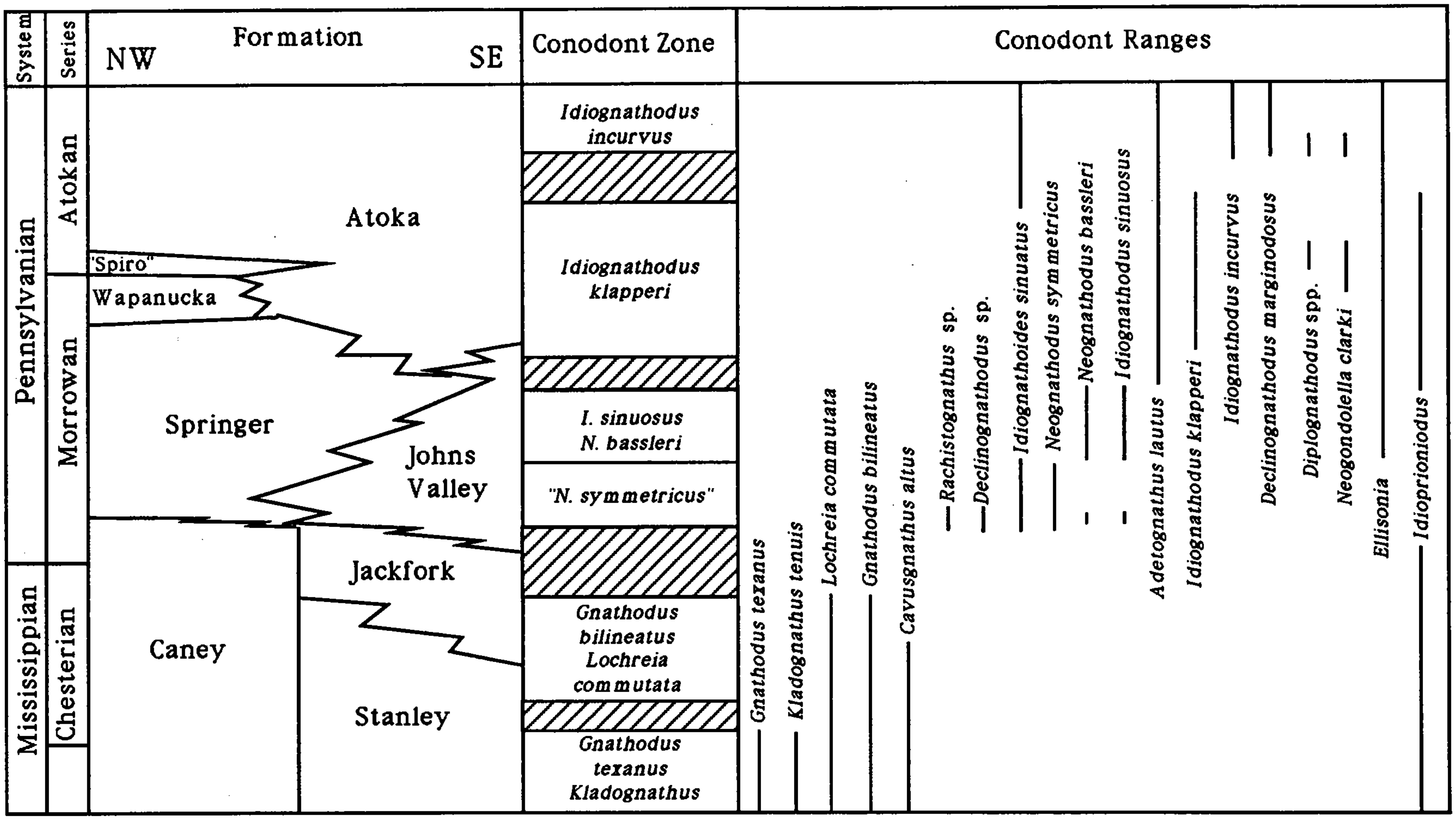

Figure 3. Distribution of Carboniferous conodont assemblages and ranges of characteristic taxa.

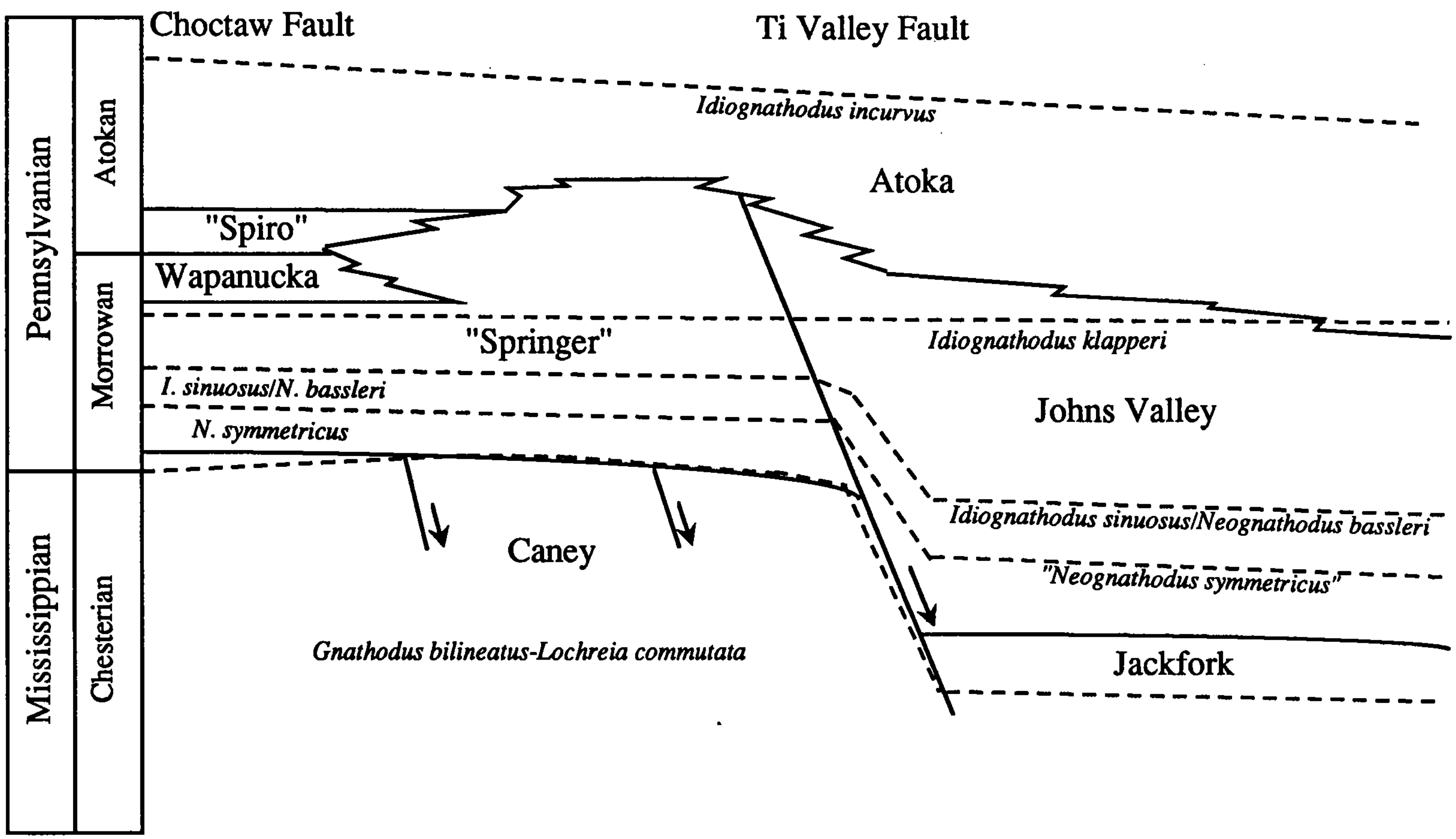

Figure 4. Generalized cross section showing tentative relationships of lithostratigraphic and biostratigraphic data.

texanus, Kladognathus tenuis, Gnathodus bilineatus, Lochreia commutata, Cavusgnathus altus, and *Idioprioniodus.* The overlap of *G. texanus* with *G. bilineatus* suggests a Meramecian age for the lower Caney. This is consistent with previous conodont (Huddle, in Gordon and Stone, 1977) and ammonoid cephalopod (Gordon and Stone, 1977) interpretations. However, an early to middle Chesterian age for at least part of the assemblage can not be ruled out because *G. texanus* is known to range into rocks of middle Chesterian age (Thompson, 1972). It is probable that the general equivalent of this assemblage is present in the lower Barnett Formation of Texas, based on Merrill's (1980) data.

GNATHODUS BILINEATUS-LOCHREIA COMMUTATA ASSEMBLAGE

Occurrences of *Gnathodus bilineatus* and *Lochreia commutata* without *Gnathodus texanus* are characteristic of this assemblage. The assemblage is present in the upper Caney, and suggests a Chesterian age. Whether the assemblage is indicative of part or all of the Chesterian can not be established with the present data. Both *G. bilineatus* and *L. commutata* range through the Chesterian, but in many cases they occur with more temporally significant taxa. For example, in the southwestern Arkoma basin, the assemblage is present in the Rhoda Creek Formation, where it represents a biofacies that interfingers with an *"Adetognathus" unicornis* biofacies. The latter taxon is generally considered an index for the late Chesterian, and in the Rhoda Creek this biofacies relationship occurs below the Mississippian/ Pennsylvanian boundary. A similar assemblage (without *"A." unicornis*) in the upper Barnett Formation of Texas is considered to indicate a Late Mississippian (Chesterian) age. In both the Rhoda Creek and Barnett Formations, occurrences of *G. bilineatus* and *L. commutata* are succeeded by the Lower Pennsylvanian *Declinognathodus noduliferus-Gnathodus higginsi* assemblage. This latter assemblage has not yet been discovered in the Ouachita Mountains region.

NEOGNATHODUS SYMMETRICUS ASSEMBLAGE

At present, this represents the lowest Pennsylvanian conodont assemblage discovered in the Ouachita Mountains region. It has been recovered from the uppermost sample of Caney shale at the North Boggy Creek section near Stringtown. At that locality, *N. symmetricus,* interfingers with occurrences of *Declinognathodus* sp. and *Rhachistognathus* sp. The assemblage has also been identified in the lower Johns Valley at the Hairpin Curve locality, where *Neognathodus symmetricus* occurs with *Idiognathoides sinuatus* and rare *Ellisonia* sp. In central Texas, this assemblage occurs in the upper Barnett and lower Marble Falls Formations (Grayson and others, 1987). In the southwestern Arkoma basin, it has been found in the lower "Union Valley" Formation (Grayson, in press).

IDIOGNATHODUS SINUOSUS-NEOGNATHODUS BASSLERI ASSEMBLAGE

This assemblage is characterized by occurrences of *Idiognathodus sinuosus, Neognathodus bassleri,* and *Idiognathoides sinuatus.* In some regions, such as the type Morrow area, occurrences of *N. bassleri* alone distinguish a zone below that of *N. bassleri* with *I. sinuosus.* This development of two distinct assemblages is not recognizable in the Ouachitas, central Texas (Grayson and others, 1987), or the southwestern Arkoma basin (Grayson, in press). Thus, the two taxa must have somewhat differing paleoenvironmental requirements, which completely overlap in at least some paleoenvironmental settings. Consequently, occurrences of either species have essentially the same biostratigraphic significance. In the Ouachita Mountains, the assemblage has been found in the lower "Springer" and middle Johns Valley Formations. This assemblage occurs in the the Brentwood Member in

Arkansas, the Bloyd Formation of northeastern Oklahoma, and the upper Primrose Member of the Golf Course Formation (Lane and Straka, 1974). In central Texas, it occurs in the highest Barnett and lower Marble Falls Formations (Grayson and others, 1987). It is also present in the upper "Union Valley" Formation in the southwestern Arkoma basin (Grayson, in press).

IDIOGNATHODUS KLAPPERI ASSEMBLAGE

This assemblage is distinguished by the appearance of *I. klapperi*, which evolved from *I. sinuosus* through morphologic changes in the rostral ridges and anterior part of the platform element. In addition to *I. klapperi*, the assemblage contains *Idiognathoides sinuatus, Cavusgnathus lautus, Ellisonia*, and *Idioprioniodus*. *Diplognathodus coloradoensis, D. orphanus*, and *Neogondolella clarki* occur with *I. klapperi* in the "Spiro" Formation, based on Grayson's (1979) data. We have also found *D. coloradoensis* in the basinward spiculite-and-shale equivalent of the "Spiro" that Cline (1960) considered basal Atoka Formation. The assemblage, based on occurrences of *I. klapperi*, is present in the upper part of the "Springer" through the "Spiro" in the Choctaw thrust sheet, in the middle part of the"Springer" in the Pine Mountain sheet, and in the upper part of the Johns Valley Formation in the Ti Valley sheet. The upper limit of the assemblage has not been found, but probably occurs in the lower Atoka Formation. At Hairpin curve, the highest Johns Valley sample that produced conodonts is near the upper limit of the assemblage, based on the "advanced" traits exhibited by some specimens. *Idiognathodus klapperi* ranges from the Dye Shale through the Trace Creek Members of the Bloyd Formation in northwestern Arkansas, from the upper Marble Falls Formation into the lower Smithwick Formation of central Texas (Grayson and others, 1987), and from the base of the Wapanucka through the "Spiro" in Oklahoma. In the central Ouachita Mountains of Arkansas, the ammonoid cephalopod *Axinolobus modulus*, which partly correlates with this assemblage, occurs in the middle Johns Valley Shale (Gordon and Stone, 1977).

IDIOGNATHODUS INCURVUS ASSEMBLAGE

This, the youngest conodont assemblage recognized in the Ouachita Mountains region, occurs in the middle Atoka Formation. It is distinguished by occurrences of *Idiognathodus incurvus*. This taxon evolved from *Idiognathodus klapperi* by extension of the rostral ridges anteriorly down along the free blade. *I. incurvus* occurs commonly with *Idiognathoides sinuatus* and *Declinognathodus marginodosus*, and less commonly with *Cavusgnathus lautus, Ellisonia*, and *Diplognathodus*. The assemblage has been recognized in the upper Marble Falls and Smithwick Formations of central Texas (Grayson and others, 1987), and in the Atoka Formation in the southwestern Arkoma basin of Oklahoma (Grayson, 1984; Grayson, in press). The assemblage is more or less the general equivalent of the fusulinid zone of *Fusulinella*, and is indicative of a late Atokan age.

CHRONOSTRATIGRAPHY

MISSISSIPPIAN (MERAMECIAN AND CHESTERIAN)

The Caney Formation ranges from Meramecian to (at least at one locality) earliest Morrowan in age. The Stanley and Caney Formations, which contain similar conodont assemblages (Hass and Huddle, in Gordon and Stone, 1977) and ammonoid cephalopods (Gordon and Stone, 1977), partly accumulated as lateral facies. It also seems probable that accumulation of the lower Jackfork Formation overlapped with that of the upper Caney.

MISSISSIPPIAN/PENNSYLVANIAN BOUNDARY

The Mississippian/Pennsylvanian boundary is probably located within the upper Caney, the lower "Springer," and either the lower Johns Valley or upper Jackfork. A paucity of continuous exposures of the predominantly mudrock successions has complicated precise location of the boundary. Additional work may lead to more conclusive evidence for locating the boundary, and two of the present localities seem to be potentially significant. At the Hairpin curve locality, our sample distribution has been extended to include material from exposures of the lowest Johns Valley and highest Jackfork. These samples will (hopefully) either span the boundary or direct our search to a stratigraphic position lower in the Jackfork. At the Boggy Creek locality, the boundary can be biostratigraphically located approximately in a 15 m interval within the Caney Formation, above occurrences of the *Gnathodus bilineatus-Lochriea commutata* assemblage and below occurrences of the *Neognathodus symmetricus* assemblage. This interval has been re-collected and the samples are being processed. Even though these two localities fail to provide evidence for more closely locating the boundary, they already demonstrate the dangers of equating lithostratigraphic and chronostratigraphic units. In southern Oklahoma and central Texas, all attempts with which we are familiar have consistently failed to establish a stratigraphic datum that distinguishes Mississippian lithologies from those of Pennsylvanian age. This presumably indicates the transitional and gradational nature of the changes from the Mississippian to the Pennsylvanian.

PENNSYLVANIAN (MORROWAN)

Earliest Morrowan rocks include the upper Caney, the lowermost "Springer," the lower Johns Valley, and possibly the upper part of the Jackfork. Middle Morrowan rocks are represented by the middle "Springer" and the middle Johns Valley. Most of the upper "Springer," the upper Johns Valley, and the Wapanucka and Chickachoc Chert are late Morrowan.

MORROWAN/ATOKAN BOUNDARY

In the northern frontal Ouachita Mountains, the Morrowan/Atokan boundary occurs either in the largely unfossiliferous middle shale or within the "Spiro." An early Atokan age for the "Spiro" is indicated by occurrences of the index fossils *Diplognathodus coloradoensis* and *Eoschubertella*. Because these taxa apparently could not live under the paleoenvironmental conditions represented by presumed equivalents to the south, the boundary must be established using differing criteria. One possibility is to arbitrarily place the boundary within the middle part of the range of *Idiognathodus klapperi*. This results in the boundary falling within the "Springer," Atoka, and Johns Valley Formations.

ATOKAN AND DESMOINESIAN(?)

Atokan rocks are represented by the middle shale, "Spiro," the lower and middle Atoka, and upper "Springer" (southward from the "Spiro" pinchout) Formations. Desmoinesian rocks have never been recognized in the Ouachita Mountains region, nor do we have any evidence to refute this general conclusion. However, it should be pointed out that the upper Atoka Formation has not been biostratigraphically dated, and could prove to be partly of Desmoinesian age.

CONCLUSIONS

Establishment of the relationship of Ouachita Carboniferous strata to their equivalents in the Arkoma basin and basin-edge areas such as the Ozark Mountains region are imprecise owing to an insufficiency of common biostratigraphic data.

This study documents the potential applicability of conodonts to resolution of this problem. Within the Ouachita Mountains, faulting has juxtaposed units that may have originally accumulated tens of miles apart. Clearly, conodonts will be useful in unraveling these structural complications and reconstructing the nature of the change from shelf to basin. Furthermore, the conodonts could potentially provide a more precise temporal framework for tracing the evolution of the basin than might otherwise be available.

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PLATE 1

All figures represent upper view of Pa element. Numbers in parentheses are sample numbers and localities. All specimens held in the Invertebrate Paleontology Repository at the University of Oklahoma.

Figs. 1,2. *Lochreia commutata.* All 30X (47C).

Fig. 3. *Rachistognathus* sp. 50X (32).

Figs. 4,32,35,36. *Idiognathodus klapperi.* 4, 50X (102); 32, 30X (6); 35 and 36, 50X (48C).

Figs. 5,13. *Gnathodus bilineatus.* All 30X (47C-2).

Fig. 6. *Diplognathodus orphanus.* 50X (44).

Fig. 7. *Diplognathodus coloradoensis.* 50X (95).

Figs. 8,25-27. *Idiognathoides sinuatus.* All 50X (13).

Figs. 9,24. *Cavusgnathus altus.* All 30X (47C-2).

Figs. 10,19. *Gnathodus texanus.* All 30X (47C-2).

Fig. 11. *Neognathodus symmetricus.* 50X (32B).

Figs. 12,28,29. *Declinognathodus marginodosus.* 12, 50X (39B); 28 and 29, 50X (95).

Figs. 14,33. *Neogondolella clarki.* All 30X (44).

Figs. 15,20-23,34. *Idiognathodus incurvus.* 15 and 20, 50X (37); 20, 50X (53); 22, 30X (39B); 23 and 34, 30X (48F).

Figs. 16,17,30,31. *Cavusgnathus lautus.* All 30X (2).

Fig. 18. *Neognathodus bassleri.* 50X (48J).

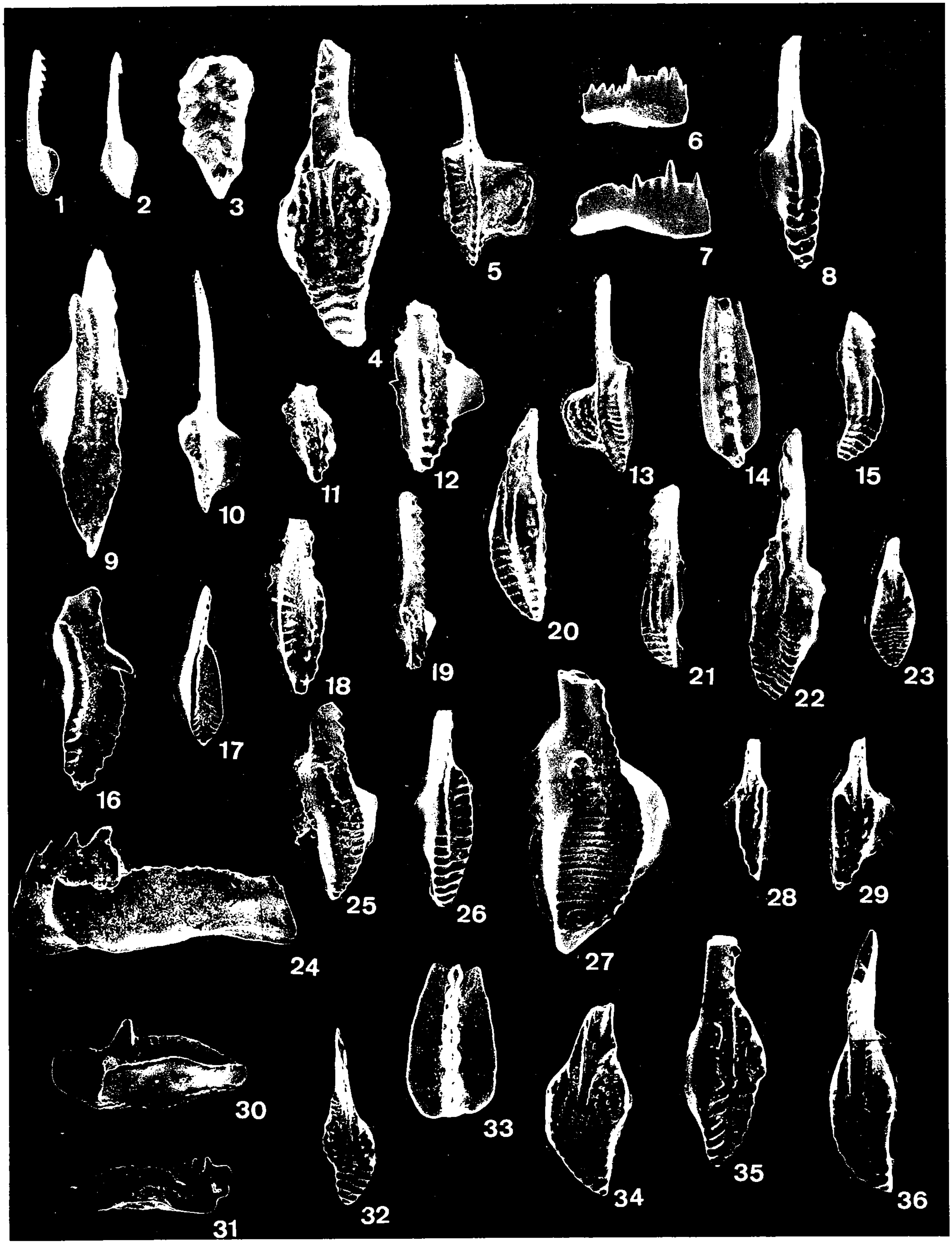
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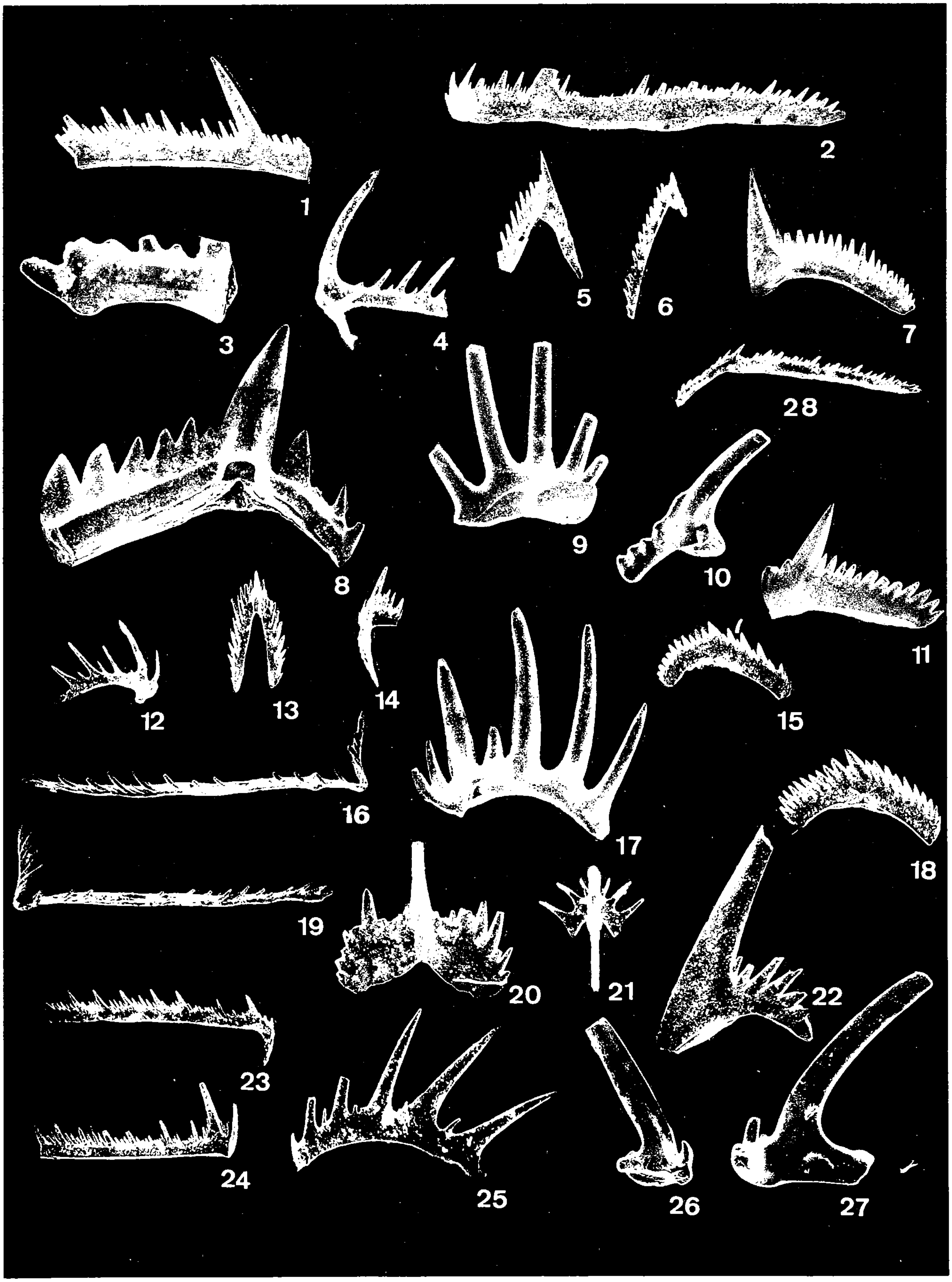
PLATE 2

Numbers in parentheses are sample numbers and localities. All specimens held in the Invertebrate Paleontology Repository at the University of Oklahoma.

Figs.12,7,11,20.	Vicarious cavusgnathoid elements. Lateral views of Sb, Sb, M, M, and Sa elements, respectively. All 30X (47C2).
Figs. 3,9,27.	*Ellisonia* sp. Lateral views of ?Pb, ?Sa, and Sc elements. All 50X (2).
Figs. 4,12,21, 22,25.	*Kladognathus tenuis*. 4 and 12, Sc element; 21, Sa element; 22, M element. All 50X (47B). 25, Sb element, 50X (47C2).
Figs. 5,6,13-16, 18,19,23,24	*Gnathodus bilineatus* ramiform elements. 5 and 6, lateral view of M element, 30X; 13 and 14, posterior and side views of Sa elements, respectively, 30X; 15 and 18, lateral views of Pb elements, 30X; 16 and 19, upper views of Sd elements, 30X; 23 and 24, lateral views of Sc elements, 30X. All specimens are from 47C2.
Figs. 8,10,17,26.	*Idioprioniodus* sp. 8, ponderosiform element; 17, bidentatiform element, and 26, Sc element. All 30X (47C2); 10, clarkiform element, 30X (2).
Fig. 28.	Unassigned Pb element. 30X (47C2).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GEOLOGICAL REVIEW OF THE OUACHITA MOUNTAINS THRUST BELT PLAY WESTERN ARKOMA BASIN, OKLAHOMA

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INTRODUCTION

Discovery of major gas reserves from detached thrust sheets in the wedge zone beneath the Ouachita overthrust block in the western Arkoma basin has created a burgeoning lease and drilling play in Atoka, Pittsburg, Latimer, and Le Flore Counties, Oklahoma (Fig. 1). The recent major gas discoveries are primarily from Spiro sandstone, Wapanucka limestone, and Cromwell sandstone, south of the Wilburton field area and east of Stringtown in northeastern Atoka County.

Until the late 1970s, few attempts had been made to drill for deep gas reserves south of the surface trace of the Choctaw fault. Due to increases in natural gas prices and improved technology, new attention was given to the obvious seismic anomalies that extended south from the foreland Arkoma basin beneath the Ouachita Mountains overthrust block in Atoka, Pittsburg, Latimer, and Le Flore Counties, Oklahoma.

Early attempts to drill near the Choctaw fault and extend Spiro sandstone production in the Wilburton gas field to the south, beneath the frontal edge of the Ouachita overthrust block, were unsuccessful due to lack of sufficient reservoir quality. Later, near the towns of Pittsburg and Kiowa, in Pittsburg County, drilling was undertaken for reserves in low-porosity, fractured Wapanucka limestone, primarily in the in situ, basin-flooring rocks. The play then progressed into the relatively shallow, imbricate fold and thrust sheets south of the trace of the Choctaw fault (frontal edge of the Ouachita Mountains). Most recently, drilling has led to the discovery of detached, highly productive thrust sheets in the wedge zone, the area between the base of the Ouachita overthrust block and the in situ basin-flooring rocks.

The completion of the Amoco #1 Zipperer in 1988 from porous, fractured Wapanucka limestone -- and additional perforations in Wilburton-quality Spiro sandstone in 1989 -- from one of these detached thrust sheets in the wedge zone

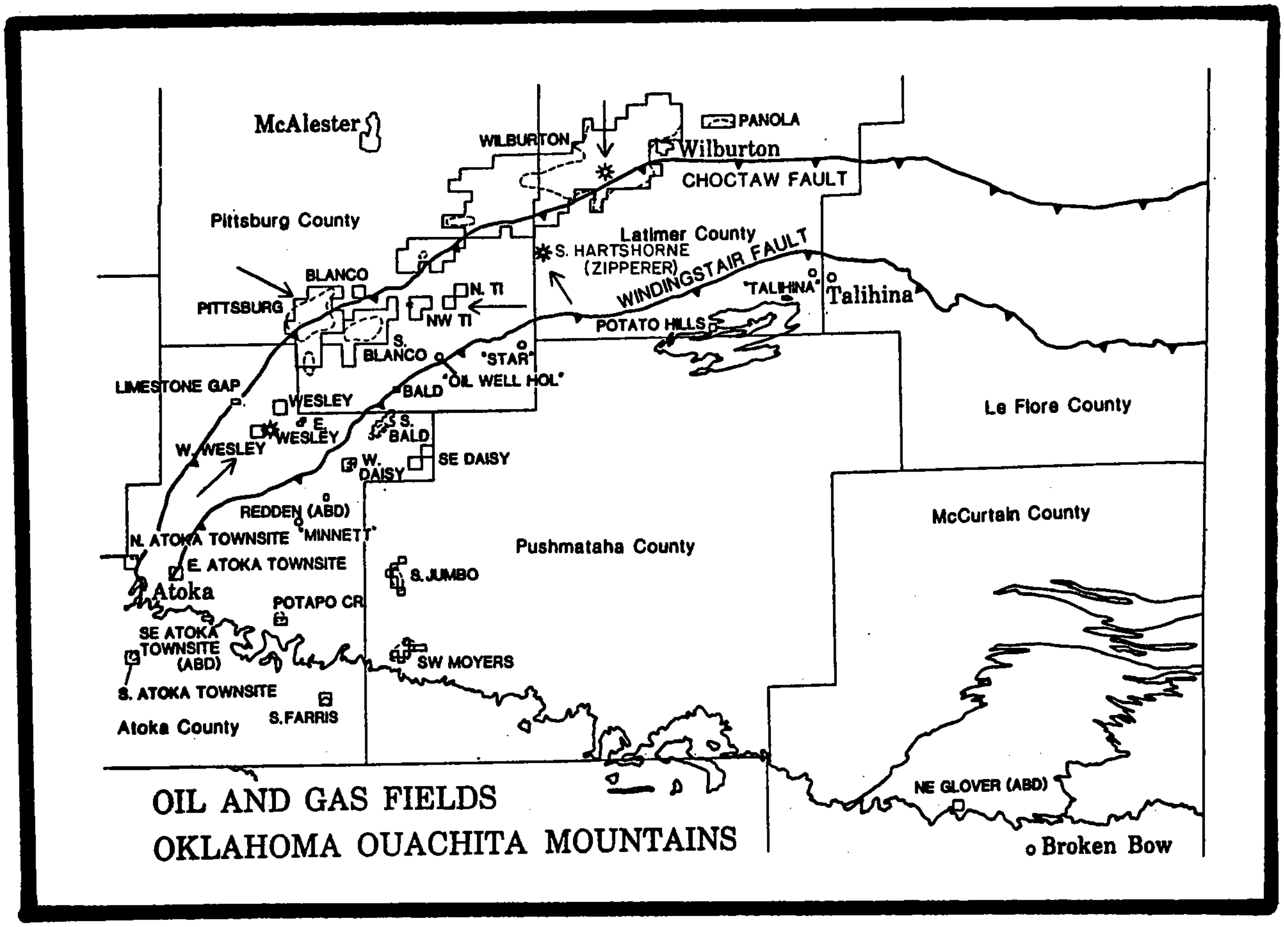


Figure 1. Map showing oil and gas fields in the Ouachita Mountains and nearby foreland Arkoma basin areas. Arrows point to field areas discussed in the text.

proved that the depositional trend of porous and productive Spiro sandstone extended farther south and west than previously known, and kicked off an extensive lease and drilling play. Coupled with the Arbuckle discoveries at Wilburton, the resulting activity has made the western Arkoma basin the hottest exploration play in the contiguous United States during 1989.

STRUCTURAL DEFINITIONS

From the standpoint of both convenience and structural analysis, the petroleum geology of this region can be divided into four principal structural domains (Fig. 2):

1) The Ouachita Mountains overthrust block, separated from the foreland Arkoma basin on the surface and at depth by the Choctaw fault;

2) Autocthonous, Wapanucka-to-basement rock units flooring the Arkoma basin, occurring without break depositionally from the shelf areas for tens of miles (at least) south of the trace of the Choctaw fault;

3) Allocthonous, often detached, sometimes overturned thrust sheets of Spiro and Wapanucka- to Cromwell-age rocks, bounded by Atokan or Morrowan shales. Some thrust sheets may be the result of axial plane thrusting of nearly isoclinal folds. The units of domain 3 occur in the interval between the overlying rocks of the Ouachita overthrust (domain 1) and the underlying, autocthonous units flooring the Arkoma basin (domain 2); this interval is herein called the " wedge zone". The base of the wedge zone may be a decollement surface, extending from the plane of intersection of the Ouachita overthrust with the base of the Wapanucka limestone in the apex of the wedge zone, and terminating at the frontal edge of the Wilburton anticline (Carbon thrust fault);

4) In situ sediments filling the Arkoma basin, principally Atokan shales with intermittent sands, sometimes severely deformed.

The Atokan and younger rocks of domain 4 are separated from the older, basin-flooring units (domain 2) because of their difference in response to deformational stress. The basin-flooring units are structurally much more competent than the Atokan rocks, and include the thick Arbuckle carbonates. The autocthonous rocks of domain 2 (below any decollement surface) are dominated by high-angle normal and reverse faulting, whereas Atokan shales and overlying units

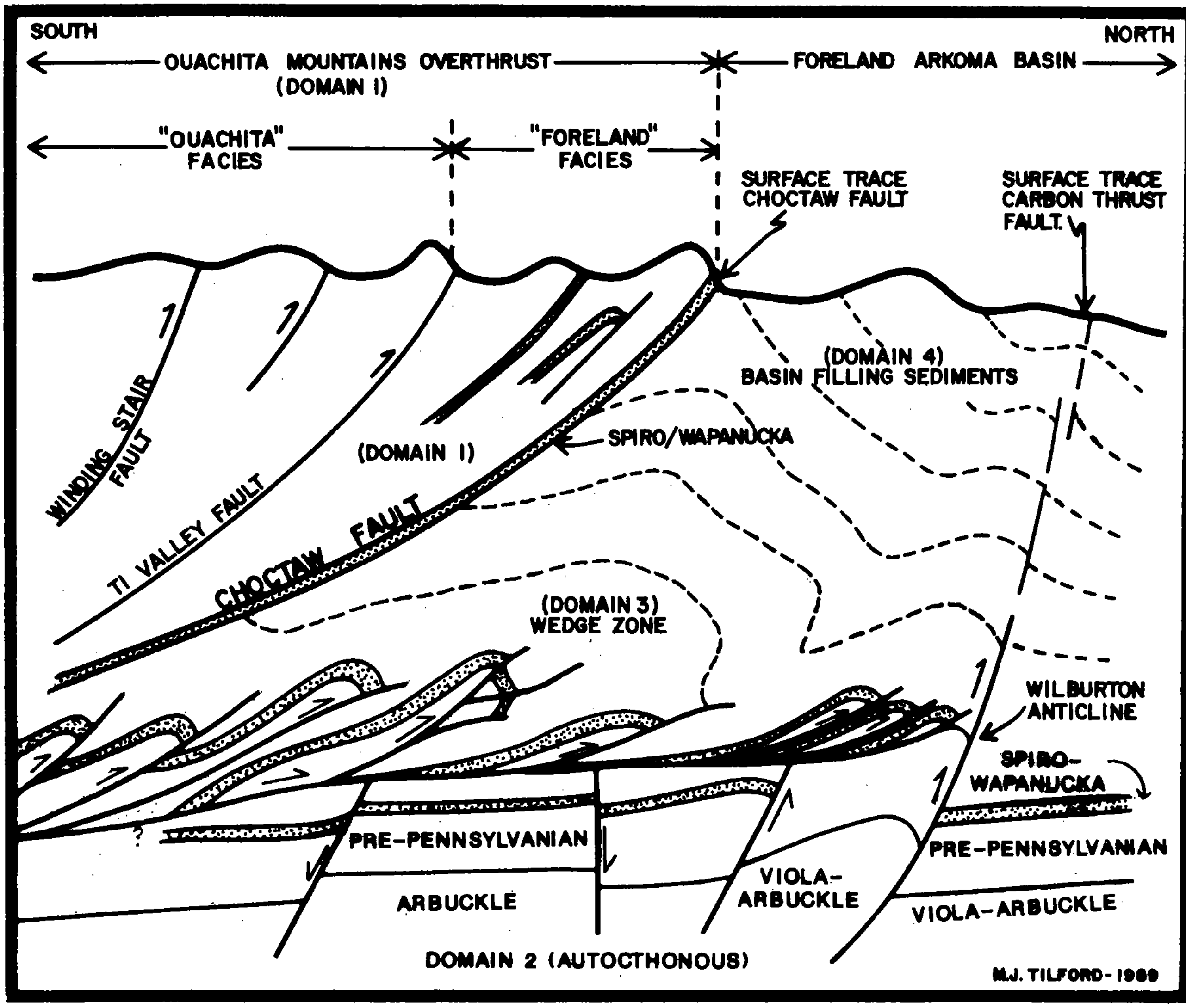


Figure 2. Schematic diagram showing domains and structural relationships developed in the western Arkoma basin, Oklahoma. Dashed lines in domain 4 (basin-filling sediments) represent form-line structural contours necessary to fulfill volume requirements in the area between the wedge zone (domain 3) and domain 4.

are much more susceptible to folding, low-angle thrust faulting, and syndepositional growth faults.

This report is primarily concerned with the geology of those wells penetrating and producing from units classified as domains 2 and 3, the focus of the ongoing thrust-belt play. The study area covered in this report extends from the south edge of the Wilburton gas field in Pittsburg and Latimer Counties to east of Stringtown, in northeastern Atoka County.

An additional definition needs to be presented to prevent confusion in nomenclature of the various fault blocks in the frontal belt of the Ouachitas. Historically, a distinction is drawn between the rocks occurring on the surface north and south of the Ti Valley fault: Units on the north belong to the foreland or "Arbuckle" facies, while those on the south belong to the basinal or "Ouachita" facies. The foreland facies rocks are found in the shelf and foreland basin areas, and correlate easily with the same units occurring in the frontal fold and thrust belt of the Ouachita Mountains. The basinal or Ouachita facies rocks are thrusted from the south and are generally considered to be deeper water, basinal equivalents to those found in the shelfal areas. The Ouachita facies rocks extend on the surface approximately from the Ti Valley fault south to burial by Cretaceous overlap.

In the remainder of this report, those rocks classically known as foreland facies (including the Spiro-Wapanucka) and occurring in the frontal fold and thrust belt of the Ouachita Mountains are designated as belonging to the Choctaw fault block or Choctaw thrust block. The rocks that classically are known as Ouachita facies belong to the Ti Valley fault or thrust block. The entire overthrusted sheet known as the Ouachita Mountains on the surface (everything south of the Choctaw fault trace) is referred to as the Ouachita overthrust. The interval between the Choctaw fault (base of Ouachita overthrust) and the autocthonous rocks is defined as the "wedge zone". These relations are schematically shown in figure 2.

WILBURTON GAS FIELD

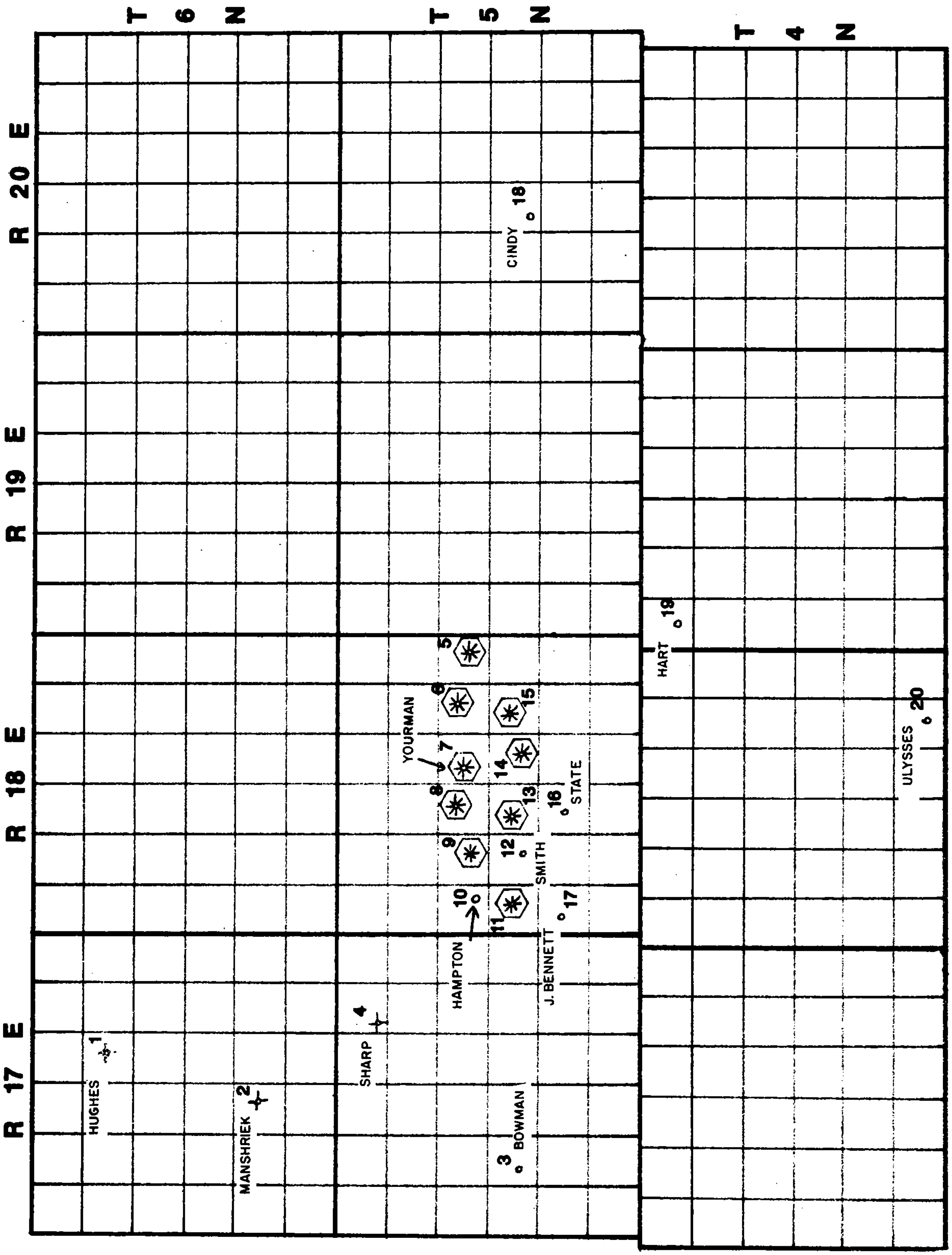
Credit for the discovery of the Wilburton gas field was given in 1960 to the Ambassador Oil #1 W.M. Williams Unit, sec. 25, T. 5 N., R. 18 E., Latimer County, completed in the Spiro sandstone at 8811-8831 ft, with an open flow potential of 8300 MCFGPD, although the true discovery was a shallow gas well drilled in 1929. Subsequent development drilling in the Wilburton area has officially expanded the field to more than

175 miles, with south and east limits as yet undefined. Current drilling will cause the official limit to be extended farther south, where the field will connect with the area surrounding the Amoco #1 Zipperer. Since 1960, Wilburton field has produced in excess of 1.1 TCF gas, principally from the Spiro sandstone. Berry and Trumbly (1968) wrote an excellent description of the Wilburton field, although it is now out of date.

The discovery in late 1987 of Arbuckle production at the ARCO #2 Yourman, sec. 15, T. 5 N., R. 18 E., initiated an intense "drill deeper" play in the Wilburton field. The Arbuckle reservoir is an extensively fractured, low matrix-porosity limestone and dolomite. Tremendous reservoir enhancement has occurred through extensive karst development. Formation (salt) water is produced from every well due to the excellent permeability developed by the fracture systems. Figure 3 is an activity map in the vicinity of the Wilburton field, showing completed, drilling, and proposed Arbuckle penetrations through September 1989. Wells completed in or targeted to other zones are not shown.

Petroleum Information (8/31/89) reports that the discovery well, the ARCO #2 Yourman, has produced more than 8.1 BCF gas since late 1987 from the Arbuckle. Other Arbuckle field wells are commingled with up-hole zones, making production from the Arbuckle alone difficult to determine. A total of 43.9 BCF has been produced from seven of the nine Arbuckle wells through May 1989. Other published reports have indicated that the initial Arbuckle wells announced as completed in 1987 and 1988 have reserves in excess of 600 BCF; the same sources are reported to have said privately that production from the Arbuckle alone on the Wilburton anticline may well exceed the amount previously produced from the Spiro (greater than 1 TCF). Although there is scattered Arbuckle production elsewhere in the Oklahoma portion of the Arkoma basin, none (to date) begins to approach the magnitude of the Wilburton discoveries.

The only successful Arbuckle wells to date have been located in the eastern part of the field, on the Wilburton anticline. The Wilburton structure at the Arbuckle level is a fault-bounded, doubly plunging anticline, elongated parallel to the Ouachita thrust front. Two, and possibly three fault blocks have been found productive in the eastern part of the structure. The Nicor test in sec. 20, T. 5 N., R 18 E (Fig. 3) is located on the untested western extension of the Wilburton anticline, five miles west of the nearest announced Arbuckle producer (sec 19, T. 5 N., R. 18 E). Another Arbuckle well is currently drilling east of the



ARBUCKLE PRODUCTION

DATE: 9/1/89

Figure 3. Activity map of the Wilburton field area, showing existing and proposed Arbuckle penetrations only. Wells which did not penetrate the Arbuckle, or not proposed as deep enough, are not spotted. Arrows refer to key wells discussed in the text. Numbers refer to wells listed in Table 1a.

Table 1a. List of wells numbered in Figure 3, activity map showing completed and proposed Arbuckle wells in the area near the Wilburton field.

Well No.	Location	Operator and Lease Name	TD or (PTD)	Formation	Perforations	Formation	IPF	Status	Compl. Date
1	10-6N-17E	Steve Gose 1-Hughes	11,675	Arbuckle	-	-	-	P&A	1964
2	28-6N-17E	Magnolia 1-Manshrick	12,915	Arbuckle	-	-	-	P&A	1954
3	20-5N-17E	Nicor 4-Bowman	(15,400)	Arbuckle				Drilling	1989
4	2-5N-17E	ARCO 1-Sharp	15,508	Arbuckle	-	-	-	P&A	1988
5	13-5N-18E	ARCO 1-Austin	14,350	Arbuckle	13,258-13,867	Arbuckle	IPF 10444 MCF	Gas	1989
6	14-5N-18E	ARCO 3-Costilow	14,200	Arbuckle	13,113-13,594	Arbuckle	IPF 14338 MCF+ 72 BW	Gas	1988
7	15-5N-18E	ARCO 2-Yourman	15,391	Arbuckle	14,259-14,500	Arbuckle	IPF 17489 MCF+ 40 BW	Gas	1987
8	16-5N-18E	ARCO 2-Kilpatrick	13,964	Arbuckle	12,853-12,540	Arbuckle	IPF 10587 MCF+ 24 BW	Gas	1988
9	17-5N-18E	ARCO 2-Fazekas	10,440	Arbuckle	13,002-13,624	Arbuckle	IPF 34526 MCF+107 BW	Gas	1988
10	18-5N-18E	ARCO 2-Hampton	(14,650)	Arbuckle				Drilling	1989
11	19-5N-18E	ARCO 2-Bennett-State	14,500	Arbuckle	13,444-13,985	Arbuckle	IPF 22339 MCF	Gas	1989
12	20-5N-18E	ARCO 3-Smith	(14,500)	Arbuckle				Testing	1989
13	21-5N-18E	ARCO 2-Paschall	14,278	Arbuckle	13,228-13,653	Arbuckle	IPF 12140 MCF+ 40 W	Gas	1988
14	22-5N-18E	ARCO 3-McAlester	14,400	Arbuckle	13,568-14,196	Arbuckle	IPF 36685 MCF	Gas	1989
15	23-5N-18E	Anadarko 3A-Williams	15,000	Arbuckle	13,538-13,980	Arbuckle	IPF 31370 MCF	Gas	1989
16	28-5N-18E	ARCO 2-State-C	(14,500)	Arbuckle				Drilling	1989
17	30-5N-18E	ARCO 2-Jessie Bennett	(14,100)	Arbuckle				Drilling	1989
18	21-5N-20E	An-Son 1-21 Cindy	(16,500)	Reagan				Drilling	1989
19	6-4N-19E	ARCO 1-Hart	18,085	Arbuckle	unknown			SI	1989
20	35-4N-18E	ARCO 1-Ulysses	(20,000)	Reagan				Location	1989

Table 1b. List of wells numbered in Figure 2, activity map of the South Hartshorne field area.

Well No.	Location	Operator and Lease Name	TD or (PTD)	Formation	Perforations	Formation	IPF	Status	Compl. Date
1	25-4N-17E	Amoco 1-Retherford	(15,000)	Cromwell				Drilling	1989
2	27-4N-17E	Amoco 1-Patterson	14,380	Cromwell	11,840-11,895	Spiro	IPF 5300 MCF	Gas	1989
					11,944-12,124	Wapanucka	IPF 14,500 MCF	Gas	1989
3	30-4N-17E	Exxon 1-Ellis Rudy Trust	(14,600)	Cromwell				Location	1989
4	31-4N-17E	Exxon 1-Elliot Davis	(14,300)	Cromwell				Drilling	1989
5	32-4N-17E	Amoco 1-Zipperer	12,600	Atoka	12,148-12,296	Wapanucka	IPF 10,000 MCF	Gas	1989
					12,240-12,286	Wapanucka	IPF 48,000 MCF		
					12,014-12,060	Spiro	IPF 35,000 MCF		
6	33-4N-17E	Exxon 1-H&H Cattle Co-A	14,518	Cromwell	5,030-5,201	Wapanucka	IPF 320 MCF	SIGW	1989
7	6-3N-17E	Exxon 1-H&H Cattle Co-C	(15,000)	Cromwell				Location	1989
8	1-3N-16E	Exxon 1-Szenasy Unit	15,000	Cromwell				SI	1989
9	2-3N-16E	Amoco 1- Garrett Unit-A	15,047	Cromwell	13,194-13,266	Spiro	IPF 6040 MCF	Gas	1989
					13,882-13,912	Cromwell	IPF 9154 MCF		
10	3-3N-16E	Amoco 1-A Tschappat Unit	14,497	Cromwell				WOCT	1989
11	4-3N-16E	TXO 1-Dromgold	(14,500)	Cromwell				Drilling	1989
12	5-3N-16E	Amoco 1-Rosso Unit	(13,700)	Wapanucka				Drilling	1989
13	6-3N-16E	Amoco 1-6 Collins	11,670	Wapanucka				Testing	1989
14	7-3N-16E	Samson 1-16 Trosper	4,432	Atoka ?				J&A	1984
15	8-3N-16E	TXO 1-Henley-F	11,045	Wapanucka				P&A	1984
16	9-3N-16E	Samson 1-Eugene	12,560	Wapanucka	8,939-8,942	Atoka	IPF 1600 MCF	Gas	1984
					11,247-11,290	Wapanucka			
17	17-3N-16E	TXO 1-Sweetin-A	12,850	Wapanucka	10,074-10,300	Wapanucka	IPF 145 MCF	Gas	1984

Table 1c. List of wells numbered in Figure 5, activity map of the Pittsburg and South Blanco field area.

Well No.	Location	Operator and Lease Name	TD or (PTD)	Formation	Perforations	Formation	IPF	Status	Compl. Date
1	1-3N-15E	Texaco 1-J.A. Goddard	7,485	Atoka	4,339-4,440	Atoka	IPF 1700 MCF	Gas	1989
					6,080-6,144	Atoka	IPF 4500 MCF		
2	2-3N-15E	Texaco 2-1 Goddard Unit	12,140	Atoka	-	-	-	P&A	1988
3	14-3N-15E	Getty 1-14 Sweetin	13,873	Spiro	11,091-12,010	Spiro	IPF 596 MCF + 12 BLW	Gas	1983
4	20-3N-15E	Samson 1-20 Iverson	10,925	Atoka	4,798-10,814	Wapanucka	IPF 817 MCF	Gas	1984
5	30-3N-15E	Hamilton 1-30 Indian Nat.	10,923	Atoka	5,950-6,048	Wapanucka	IPF 2500 MCF	Gas	1983
					8,740-8,972	Wapanucka	IPF 2650 MCF		
6	12-3N-14E	Hamilton 1-12 Sweetin	12,000	Cromwell	10,915-11,055	Wapanucka	IPF 4000 MCF	Gas	1982
7	30-3N-14E	Hamilton 1-30 Chitty Scott	10,440	Cromwell	9,381-9,520	Wapanucka	IPF 4650 MCF	Gas	1979
					10,279-10,349	Cromwell	IPF 2200 MCF		
8	8-2N-14E	Hamilton 1-8 Blue Creek	15,000	Arbuckle	12,618-12,776	Wdfd/Hntn	IPF 986 MCF + 48 LW	Gas	1980
					10,679-10,680	Wapanucka	IPF 2482 MCF + 75 LW		

Table 1d. List of wells numbered in Figure 4, activity map of the West Wesley area.

Well No.	Location	Operator and Lease Name	TD or (PTD)	Formation	Perforations	Formation	IPF	Status	Compl. Date
1	24-2N-13E	Slawson 1-24 Trapp	12,208	Wapanucka	-	-	-	P&A	1984
2	25-2N-13E	Texaco 1-25 Chastain	12,321	Wapanucka	11,062-11,240	Wapanucka		Gas	1989
3	35-2N-13E	Hamilton 1-35 Pine Mtn.	15,225	Arbuckle	11,800-11,864	Wapanucka	IPF 80 MCF + 15 W	Gas	1982
4	2-1N-13E	Texaco 2-1 Smith	(14,000)	Cromwell	unknown			Testing	1989
5	3-1N-13E	Amoco 1-McEntire	(8,700)	Wapanucka				Location	1989
6	9-1N-13E	Amoco 2-Jenkins	10,930	Wapanucka	unknown			Testing	1989
7	9-1N-13E	Amoco 1-A Jenkins	13,468	Atoka	8,578-8,822	Spiro	IPF 1134 MCF	Gas	1987
					8,926-9,096	Wapanucka			
8	9-1N-13E	Amoco 1-Jenkins	10,376	Atoka	unknown	Wapanucka		P&A	1987
9	10-1N-13E	Texaco 1-LaFevers	12,850	Cromwell	12,250-12,283	Wapanucka	IPF 8070 MCF	Gas	1988
10	11-1N-13E	Texaco 11-1 Smith-B	13,517		unknown			Testing	1989
11	16-1N-13E	D-Pex 1-16 Jenkins Unit	13,500		unknown			Testing	1989
12	19-1N-13E	ARCO 1-19 Ingersoll	15,000	Cromwell	-	-	-	P&A	1987

Wilburton field on a separate structure, the An-Son 1-21 Cindy, sec. 21, T. 5 N., R. 20 E., projected to 16,500 ft in the Reagan sandstone. In early September 1989, ARCO announced another Arbuckle wildcat to be drilled east of the Wilburton anticline at the #1 Ulysses, in sec. 35, T. 4 N., R. 18 E., Latimer County. If drilled to the projected total depth of 20,000 ft, this well would be the deepest well in the Oklahoma portion of the Arkoma basin (Fig. 3).

Deeper drilling on the Wilburton anticline has also led to the discovery of new reserves in lower thrust sheets than originally produced by initial wells in the field. Enhancement of original reserves in the Wapanucka limestone, and middle Atoka, Spiro, and Cromwell sandstones has resulted from increased density drilling for known pays. Good gas shows have also been reported from the Simpson sandstones in some of the Arbuckle wells, although no wells have yet been announced as completed from the Simpson.

SOUTH HARTSHORNE GAS FIELD

The Amoco #1 Zipperer, sec. 32, T. 4 N., R. 17 E., on the east edge of Pittsburg County, is destined to become one of the most famous discovery wells in the Arkoma basin. Not only was this well the first to find major reserves in the wedge zone thrust sheets south of the trace of the Choctaw fault, it also extended the fairway of porous Spiro sandstone farther south and west by several miles than previously known. The two sets of perforations initially announced for the Zipperer were in the Wapanucka limestone 12,240-12,286 ft, IPF 48,800 MCF, 48/64" ck, FCP 3400#; and 12,148-12,286 ft, IPF 10,000 MCF, 48/64" ck, FTP 4200#. Additional perforations were announced in August 1989 from the Spiro sandstone 12,014-12,066 ft, with an IPF 35,000 MCFGPD. The Zipperer sold more than 20,000 MCF gas per day from Wapanucka perforations since hook-up during the spring of 1989; during September, 1989 the well reportedly sold in excess of 70,000 MCFGPD from all perforations.

The significance of the Zipperer discovery is twofold: the well discovered the most porous section of Wapanucka limestone yet seen in the Arkoma basin; and the detachment of the productive thrust sheet from both the basement and overlying rocks suggests it was moved by drag some unknown distance from the south to its present position--indicating that the lands originally blanketed with porous Wapanucka and Spiro deposition may be much greater than currently known, and may be of significant extent.

Several wells have been completed, and others are drilling or completing as offsets to the #1 Zipperer. Figure 4 is a plat of the Zipperer area showing the activity status as of September 1, 1989. Another important discovery in this area was made by the Amoco #1-A Garrett, sec. 2, T. 3 N., R. 16 E., a dual completion from the Spiro and Cromwell. Cromwell pay is uncommon in the Wilburton area due to lack of reservoir. Along with the Morrowan shales, the zone was reported to be overpressured in the Garrett well, requiring a drilling liner to be set below the Wapanucka limestone. Cromwell was perforated in the interval 13,854-13,910 ft, and reported IPF 8900 MCF on a 24/64" ck at 2610# FTP.

Two other wells near the Zipperer are also significant. The Amoco #1 Patterson, sec. 27, T 4 N., R. 17 E., on the western edge of Latimer County, was completed from a separate thrust sheet than the Zipperer. Perforations were in the Spiro 11,840-11,895 ft for an IPF 5300 MCF, 4100# FTP; and in the Wapanucka from 11,944-12,124 ft for an IPF 14,500 MCF, 24/64" ck, 3925# FTP, and SITP 4200#. North of the Patterson, Texaco completed the #1 Wallace, sec. 21, T. 4 N., R. 17 E., on the easetern edge of Pittsburg County, in yet another thrust sheet, from Spiro sand in the interval 13,258- 13,308 ft for an IPF 10,800 MCFGPD, 34/64" ck, FTP 1700#.

At the time of this writing, there are several wells permitted or drilling with thrusted Spiro- Wapanucka as an objective in the Zipperer area. Many of the sections not yet permitted for drilling have been included in spacing applications at the Oklahoma Corporation Commission, with the implication that additional productive thrust sheets will be discovered. Ultimately, the areas encompassed by the South Hartshone field and the Wilburton field will be recognized as a district rather than individual fields.

PITTSBURG, SOUTH BLANCO, NORTH TI, AND NORTHWEST TI GAS FIELDS

This complex of fields straddles the surface trace of the Choctaw fault near the junction of Atoka and Pittsburg Counties. Production occurs from units of all four structural domains defined in the western Arkoma basin, and from stratigraphic, structural, and combination traps.

Gas production in the area of the Pittsburg field complex was discovered by the Hamilton Brothers 1-30 Chitty Scott, sec. 30, T. 3 N., R. 14 E., completed as a dual producer from Wapanucka limestone and Cromwell sandstone in 1979, and designated as the discovery well for the Pittsburg field.

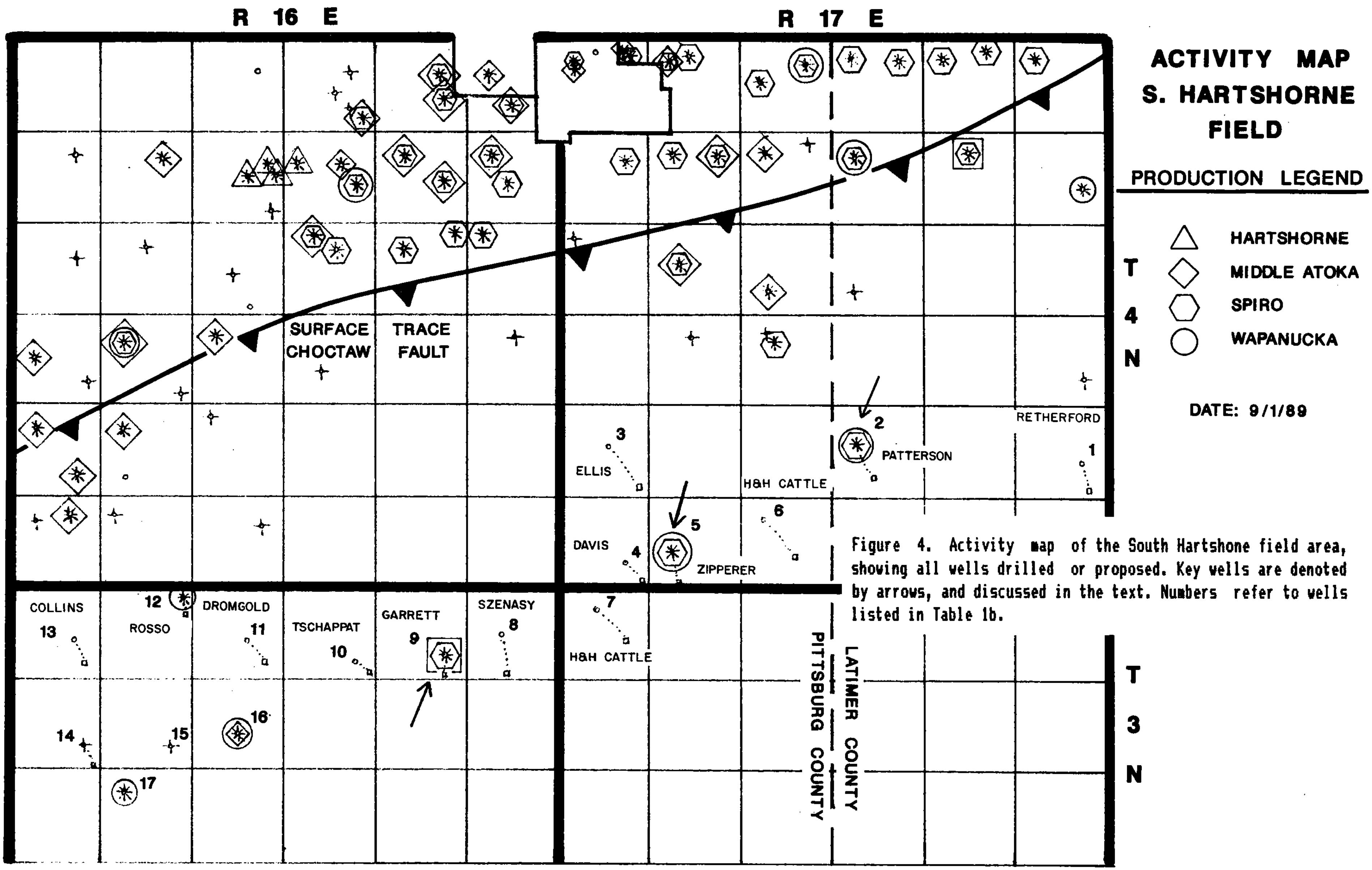


Figure 4. Activity map of the South Hartshone field area, showing all wells drilled or proposed. Key wells are denoted by arrows, and discussed in the text. Numbers refer to wells listed in Table 1b.

The Cromwell was perforated at 10,279- 10,349 ft, and reported an IPF 2400 MCF + 4 BWPD; the Wapanucka was perforated at 9381- 9520 ft, and reported an IPF 5073 MCF + 7 BWPD (both zones after treatment). This well was spudded less than one mile in front of the surface trace of the Choctaw fault, and completed from the in situ rocks of domain 2. The prospect was drilled on the basis of a seismically controlled, structurally high basement fault block.

The South Pittsburg field, now part of the Pittsburg field, was discovered by the Hamilton Brothers #1-8 Blue Creek, sec. 8, T. 2 N., R. 14 E., in Atoka County. The well was drilled to a total depth of 15,000 ft in Arbuckle. It was completed in the Woodford and Hunton, at 12,618-12,776 ft overall, with an IPF 986 MCF + 48 BLWPD, in 1980. The well was recompleted as a dual producer in the Woodford-Hunton and Wapanucka (perf 10,679- 10,680 ft, IPF 2482 MCF + 75 BLWPD) in 1984. As in the Chitty-Scott well, the prospect was drilled on a seismic basement high, about two miles south of the trace of the Choctaw fault. This is the only well in the western Arkoma basin known to have been completed in rocks older than Cromwell underneath the Ouachita overthrust block.

Production from autocthonous Wapanucka (domain 2) in the area of the Pittsburg and South Blanco fields covers approximately 40 mi^2, although not every section has been drilled or is productive (Fig. 5). The Cromwell sandstone has been found productive over a much smaller area, about nine mi^2; however, many of the wells that found Wapanucka production were not drilled deep enough to test the Cromwell section.

In addition to wells completed from the in situ, autocthonous Wapanucka, at least 17 wells to date within these field boundaries have been completed in one or more of the folded and imbricately thrust-faulted sheets comprising the frontal belt of the Ouachita Mountains overthrust (domain 1). The first well to complete from Wapanucka in this domain was the discovery well for the South Blanco field, the Hamilton Brothers 1-30 Indian Nations, sec. 30, T. 3 N., R. 15 E., in March 1982. Two thrust sheets of Wapanucka were perforated, stimulated, and commingled in this well, at 5950-6048 ft (IPF 2500 MCF, no water) and 8740- 8972 ft (IPF 2650 MCF, no water).

The proven, productive area of imbricately thrusted Wapanucka from the Choctaw thrust block in the Ouachita frontal belt currently extends from T. 2 N., R. 14 E. to T. 3 N., R. 16 E. As with the autocthonous Wapanucka in the Pittsburg field area, many sections included in the stated

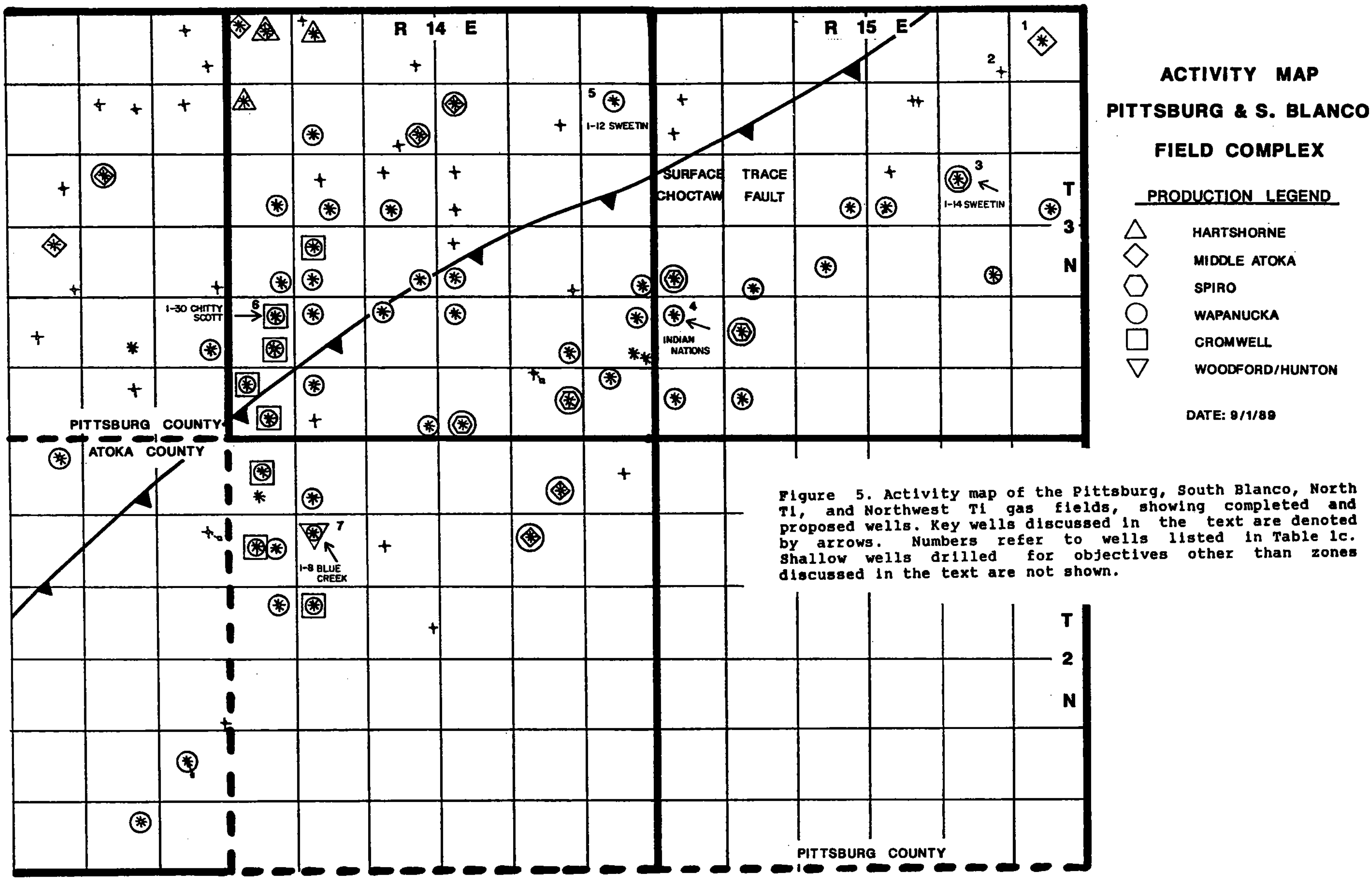


Figure 5. Activity map of the Pittsburg, South Blanco, North Ti, and Northwest Ti gas fields, showing completed and proposed wells. Key wells discussed in the text are denoted by arrows. Numbers refer to wells listed in Table 1c. Shallow wells drilled for objectives other than zones discussed in the text are not shown.

acreage have not been drilled; most that were found nonproductive were the result of noncommercial flow rates rather than no shows.

The limits of production from the thrusted Wapanucka in the frontal belt at this time are totally undefined. The only boundary to the play is the Choctaw fault. Wapanucka can be seismically mapped considerably south of the Ti Valley fault in the deeper part of the Choctaw block (Fig. 2). Outcrop traces of Wapanucka limestone parallel to and between the Choctaw and Ti Valley faults extend from T. 1 S., R. 12 E (Katy Club fault) to at least as far east as T. 5 N., R. 22 E. Seismic data indicates that Spiro-Wapanucka exists in the subsurface along much of the Choctaw fault trend even where it is not exposed in surface outcrop. Spiro-Wapanucka is thus prospective along almost all of the map trace of the Choctaw fault in Oklahoma, an areal extent greater than 100 miles.

The first well to clearly establish production from rocks in the wedge zone between the autocthonous basement rocks and the overthrusted Ouachita block was the discovery well for the Northwest Ti field, the Getty 1-14 Sweetin, sec. 14, T. 3 N., R. 15 E. The well was completed in Spiro-Wapanucka from perfs 11,091- 12,010 ft, for FARO 596 MCF + 12 BWPD, after stimulation. This well to date (September 1989) has not been connected to a pipeline, and is a shut-in gas well.

WEST WESLEY GAS FIELD

The deep discovery well for the West Wesley field was the Amoco #1-A L.R. Jenkins. The well was drilled to a total depth sec 9, T. 1 N., R. 13 E., Atoka County. The well was drilled to a total depth of 13,468 ft, completed with perfs in Spiro-Wapanucka at 8758- 9096 ft, and tested for 1134 MCFGPD. Production was established from an upper thrust sheet in the wedge zone. A more prolific offset was drilled at the Texaco #1 LaFevers, sec. 10, T. 1 N., R. 13 E., in a different thrust sheet, which tested an IPF 8077 MCF from perforations in a sandy Wapanucka facies at 12,258-12,285 ft. Some industry analysts have given the LaFevers well reserves in excess of 20 BCF. Several additional wells are now drilling or completing (Fig. 6).

The productive thrust sheets penetrated by the Jenkins and LaFevers wells appear similar in genesis to those farther east. The leading edge of the subthrust wedge zone sheets also occurs closer to the surface trace of the Choctaw fault, which in this area has a more northerly component than to the

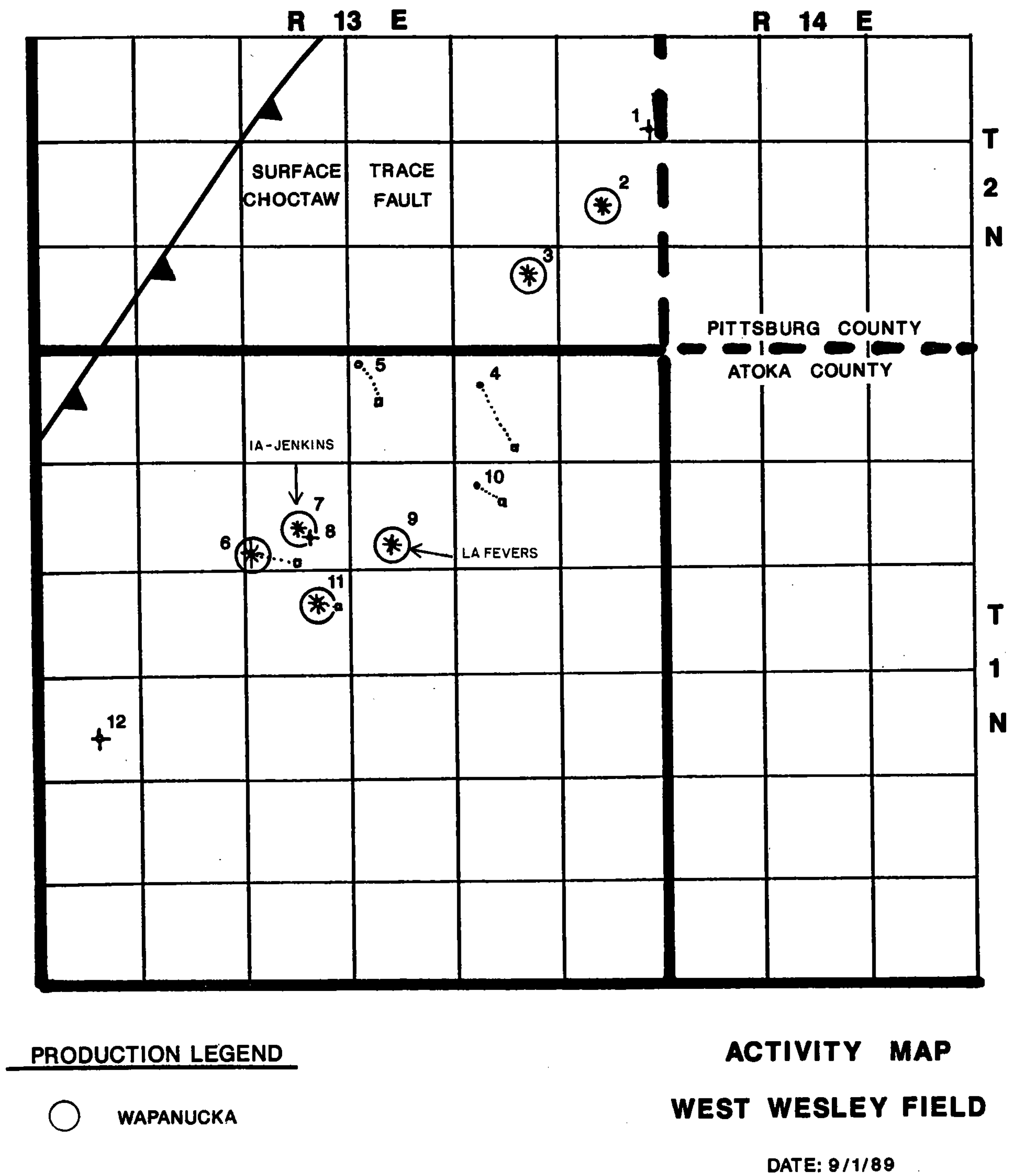


Figure 6. Activity map of the West Wesley field area, showing completed and proposed wells. Shallow wells drilled for objectives not discussed in the text are not shown. Arrows refer to key wells. Numbers refer to wells listed in Table 1d.

east. The first pipeline connections in this area are to be made in August 1989; thus, there is no production history at this time.

STRUCTURAL ANALYSIS OF DOMAIN 3: ZIPPERER-TYPE THRUST SHEETS

The detached thrust sheets of the wedge zone comprising domain 3 are the focus of the ongoing drilling play south of the surface trace and underneath the Choctaw fault block in the western Arkoma basin. Obviously, the economic incentive of large reserves has spurred the drilling of a geologic style of deformation that previously was considered to be of little importance in the western Arkoma basin.

Several wells in the early 1980s had penetrated the subthrust wedge zone between the Choctaw fault and the autocthonous units flooring the Arkoma basin. While shows were recorded, and marginal production established, there were no actual gas sales from the wells and little incentive for further development. With the discovery of the #1 Zipperer and the realization the area could harbor major reserves, acreage prices skyrocketed and lease availablity became severely limited during the months of January and February, 1989.

Figure 7 is a diagrammatic north-south cross-section depicitng the type of deformation encountered in the wedge zone in the vicinity of the #1 Zipperer. It is a composite cross-section, similar to Figure 2, based on geologic interpretation of seismic data from several locales along the thrust front. The faults shown in the wedge zone are primarily imbricate, forward-directed sole thrust faults. Additional styles may be interpreted, including southward-directed backthrusts and antithetic, relaxation faults. In Figure 7 the Amoco #1 Zipperer is depicted as at least partially trapped against a backthrust on top of a tight, thrust-cored fold, with the north limb overturned. The seismic data used to construct this diagram may also be interpreted in a more conventional manner, as shown in Figure 2, where no backthrusts are utilized. The majority of productive wells drilled to date are believed to be trapped against forward-directed faults rather than backthrusts. The base of the wedge zone sole thrusts is probably a decollement surface, extending northwards to the Wilburton anticline.

In the first version of this paper, written for the original guidebook, the statement was made that there are fundamental differences between thrust sheets found in the Zipperer area and in the West Wesley area. Subsequent

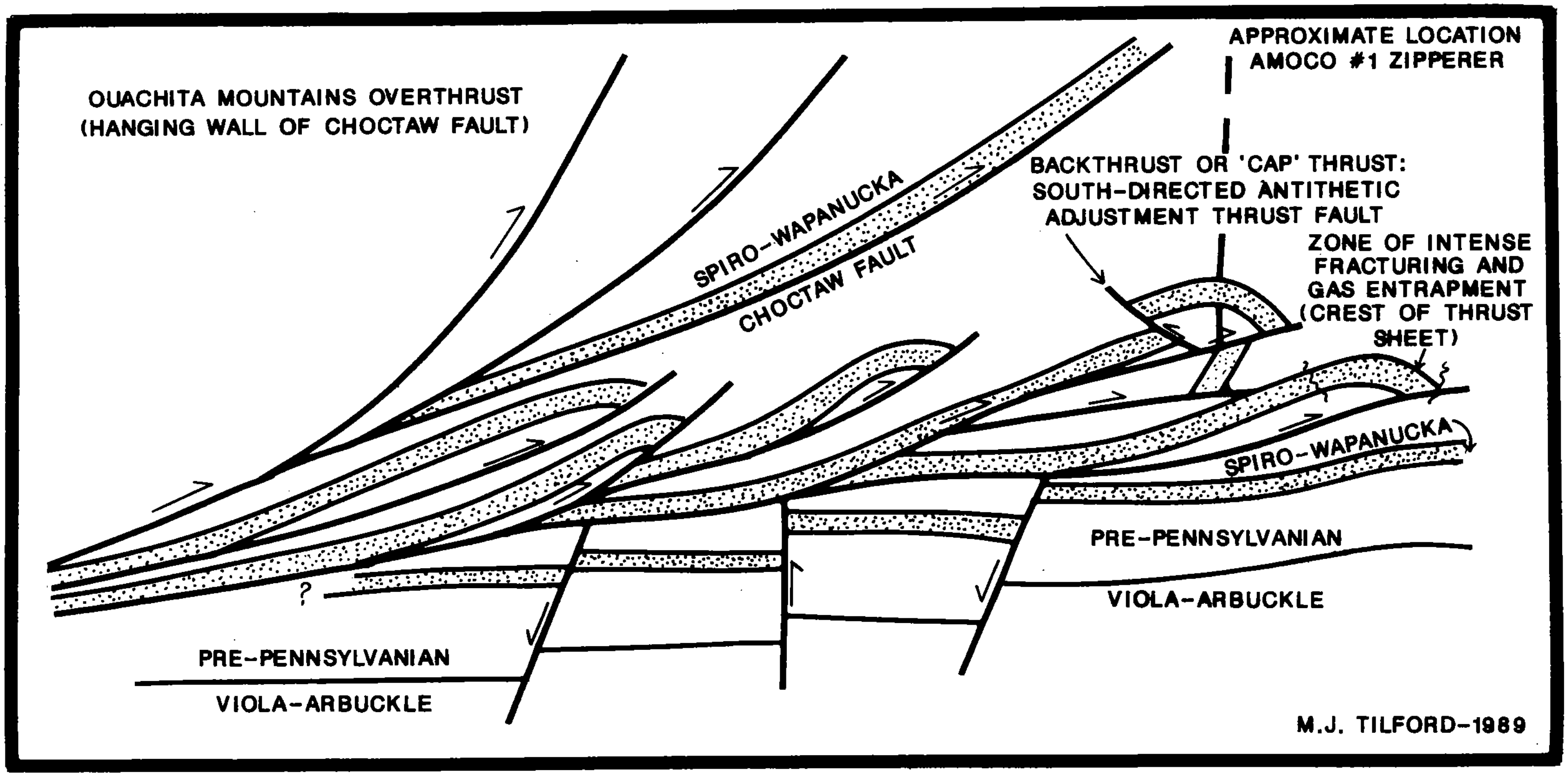


Figure 7. Diagrammitc sketch of the deformational style encountered in the wedge zone (domain 3). The folded, imbricate thrust sheets in the wedge zone are completely detached from both the underlying, autocthonous, basin-flooring rocks (domain 2), and the overlying Ouachita Mountains overthrust sheet (domain 1). The #1 Zipperer is shown to be at least partially trapped by a backthrust fault (nicknamed a "cap thrust") in this diagram. Contrast this interpretation with that shown in Figure 2.

investigation has determined that this is unlikely. Thrust sheets in both areas exhibit similar geometries, although their orientation is different, dependent on location along the Ouachita thrust front.

Thrust sheets in both areas tend to reach maximum length of three to four miles long (parallel to the Choctaw fault trace), and about two miles wide (perpendicular to the Choctaw fault trace). The resulting ratio of length: width is thus between 3:2 and 2:1. This size relationship appears to be valid in both areas studied. In the more densely thrusted areas, such as south of the Wilburton field, the frontal edges of each respective sheet may be as close as three-fourths mile apart, and imbricately stacked in subparallel trends. Some of the underthrusted sheets can be mapped seismically, and may be valid exploration targets. Current understanding of the thrust sheets is limited by available seismic data and well control. The more dense seismic control is in a given area, the more complicated the resulting interpretation becomes. Seismic data quality is generally much poorer in the West Wesley area than to the east, and may be extremely difficult to interpret.

The imbricate nature of the wedge zone thrusting yields complicated map patterns, schematically shown in Fig. 8. Inherent to this model is the assumption that principal tectonic stress was primarily directed perpendicular to the northward moving Ouachita thrust front. The difference in orientation of thrust sheets in the West Wesley and Zipperer areas is caused by the change in azimuth of the trace of the Choctaw fault, the leading edge of the Ouachita overthrust, which becomes more southerly west of the Pittsburg field.

Many more thrust sheets appear to be developed south of Wilburton field than in the West Wesley area. One explanation may be that the primary stress direction in the West Wesley area was tangential to the Choctaw fault trace, thus causing fewer thrust sheets to develop than in the Zipperer area, and to occur in a much narrower band relative to the Zipperer area.

Some wells in the wedge zone exhibit overturned bedding, recognized by inversion of the Spiro-Wapanucka units. The significance of overturned Spiro-Wapanucka found in the Zipperer and a few other wells in the wedge zone should not be overlooked. The overturned beds are bounded on both top and bottom by flat or low-angle thrust faults, with glide planes in Atoka or Morrow shale. The thrusted beds are detached from the underlying, autocthonous rocks. In the Zipperer, there is approximately 700 ft of Atoka shale

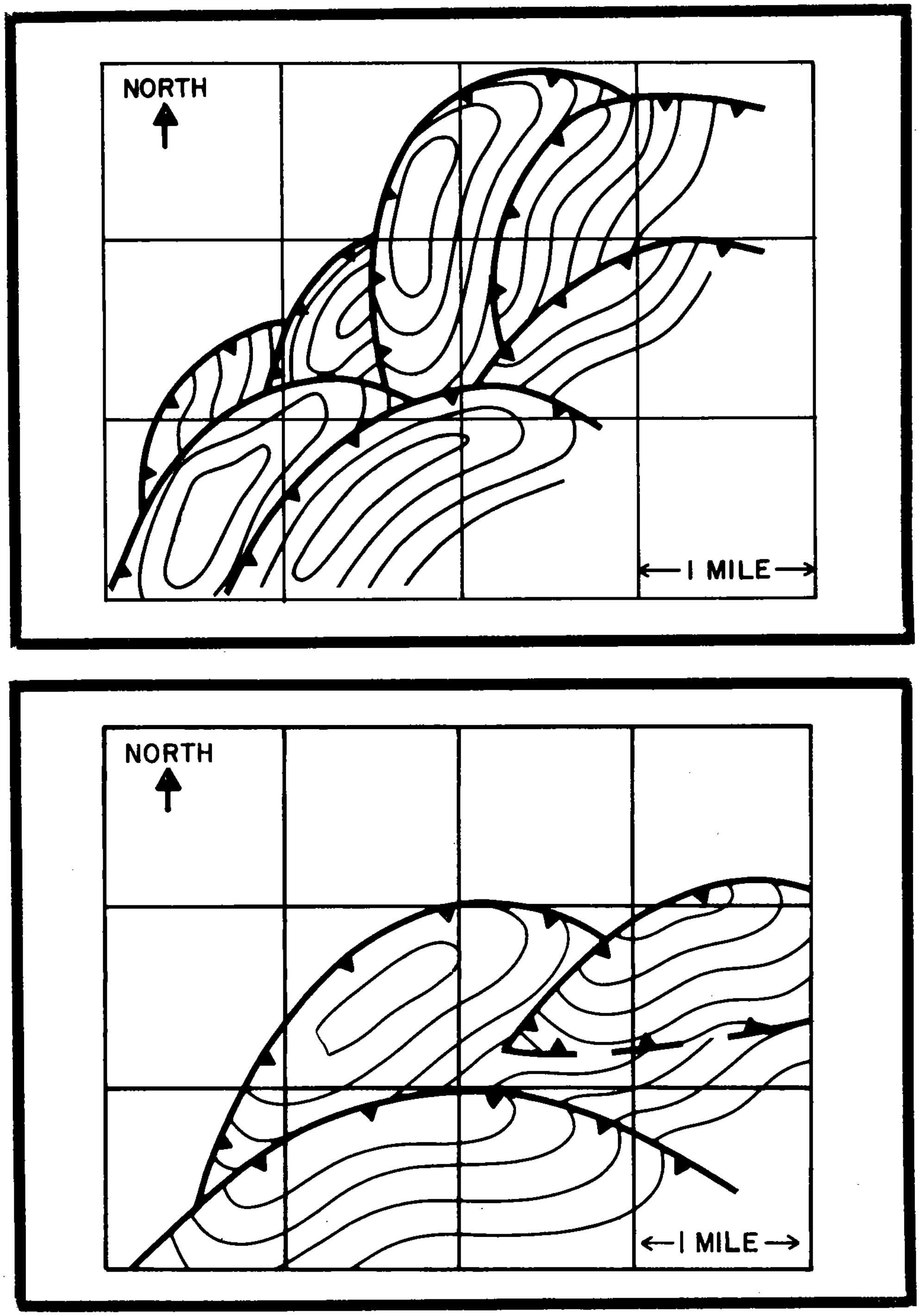


Figure 8. Comparison of map patterns of the wedge zone thrust sheets in the areas studied. Figure 8a is representative of the patterns found in the West Wesley area. Orientation of the thrust sheets is parallel to the surface trace of the Choctaw fault, in this area about N 40 E. Figure 8b shows a very similar style developed in the area south of Wilburton, where the orientation is N 60 E to N 70 E, parallel to the surface trace of the Choctaw fault. In both the West Wesley and Wilburton areas, the thrust sheets become more closely spaced as the intersection of the Choctaw fault and the in situ beds is approached. Both maps show hypothetical form-line structural contours.

between the porous and productive right-side up beds and the overturned beds at 12,000+ ft. This distance is indicative of the size of the fold that faulted along its axial plane, and created these two particular thrust sheets. Overturned sections in other wells, for example the Samson 1-20 Iverson, sec. 20, T. 3 N., R. 15 E., has no intervening section between normal and overturned Spiro-Wapanucka. In this instance, the wellbore either penetrated the forwardmost lip of a thrust sheet, or the fold was very tight and is probably separated by only a minor axial plane thrust fault. The scarcity of recognizable overturned beds in the wells drilled so far demonstrates they are probably a rare occurrence in comparison to the number of imbricate thrust sheets developed.

STRUCTURAL ANALYSIS OF DOMAIN 2: BASIN-FLOORING ROCK UNITS

The autocthonous rocks of domain 2 are the floor of the Arkoma basin. In the description used here, the Spiro and Wapanucka form the uppermost units, in areas away from the wedge zone thrusting; the massive Arbuckle carbonate and underlying crystalline basement form the lower part. Where the wedge zone (domain 3) is present, rocks of domain 2 begin under the thrust glide planes. The rocks belonging to domain 2 are differentiated from those of domain 4 (predominantly Atokan basin-filling shales) because of their difference in response to deformational stress.

Throughout most of the Arkoma basin, the rock units of domain 2 deform as a unit, dominated by gentle folds, tilting, and deep-seated, high-angle reverse and normal faults. Imbricate thusting of the Spiro-Wapanucka is indicative of the wedge zone tectonics that is described in domain 3. Wedge zone deformation does not occur north of the Wilburton area.

Richardson (1986) presented a geologic map and cross section of the Pittsburg-South Blanco field area. While this data may be interpreted differently, the maps overall depict the style of structuring common to rock units of domain 2. The Pittsburg-South Blanco area is one of the few that has enough geologic control to establish map patterns and structural trends in the basin-flooring rocks of domain 2. This area is dominated by deep-seated, high-angle faulting that dies out in the overlying Atokan shales, forming gently deformed fault blocks in the Wapanucka to basement units. Repeated Wapanucka sections are common in the northern part of the area; however, the magnitude of throw and amount of overall shortening is minor compared to that exhibited on the

Wilburton anticline or in the Zipperer area. The entire area of the Pittsburg- South Blanco fields is part of a large, NW-trending anticlinorium, with the apparent updip limit beneath the surface expression of the Savanna anticline and bounded by an extension of the Carbon thrust fault. Another area recommended for the study of deformation common to domain 2 is the South Ashland field area, in T. 3 N., R. 11 E. and R. 12 E.

In Figure 9 (drawn by Gary Hart, personal communication), a model is presented to explain the anomalous situation found on some basement structures in the western Arkoma basin. In the neighborhood of the Wilburton and Savanna anticlines, and along some of the larger basin-paralleling basement faults, post-Hunton truncation is observed on fault blocks which may or may not be present-day structural highs. The mechanism proposed in Figure 9 postulates that rotational, down-to-the-basin normal faults were tilted and truncated during post-Hunton time, then reactivated in the early Atokan during the period of primary basin growth. Throw on the faults was then reversed during the period of Ouachita Mountains overthrusting, creating basement fault blocks with only minor relief apparent at the base of the Woodford, but potentially structurally high at the deeper levels of the Ordovician and Cambrian units.

In general, however, most of the basement faults of the western Arkoma basin appear to have been normal faults throughout time. North of the Choctaw fault, the majority of fault blocks have retained their down-to-the-basin profile. They are gently tilted to the south, and bounded by south dipping, down-to-the-basin normal faults. There is not enough data to postulate the attitude of the majority of basement faults overridden by the Ouachita overthrust. Trapping conditions are formed when blocks are bounded by reverse faults with the south side upthrown, or by preservation of porosity in the original updip portions of the south-dipping blocks bounded by normal faults.

COMPARISON OF DOMAINS TWO AND THREE

The Spiro-Wapanucka rocks exhibit dramatic differences in deformational style, depending on where they were situated in the basin during the period of Ouachita overthrusting. The contrast in deformational style of the Spiro-Wapanucka as weakly deformed rocks of domain 2 with the highly folded and thrusted Spiro-Wapanucka units of the wedge zone (domain 3) is strictly determined by the geographic location of the particular bed in question relative to the northward-

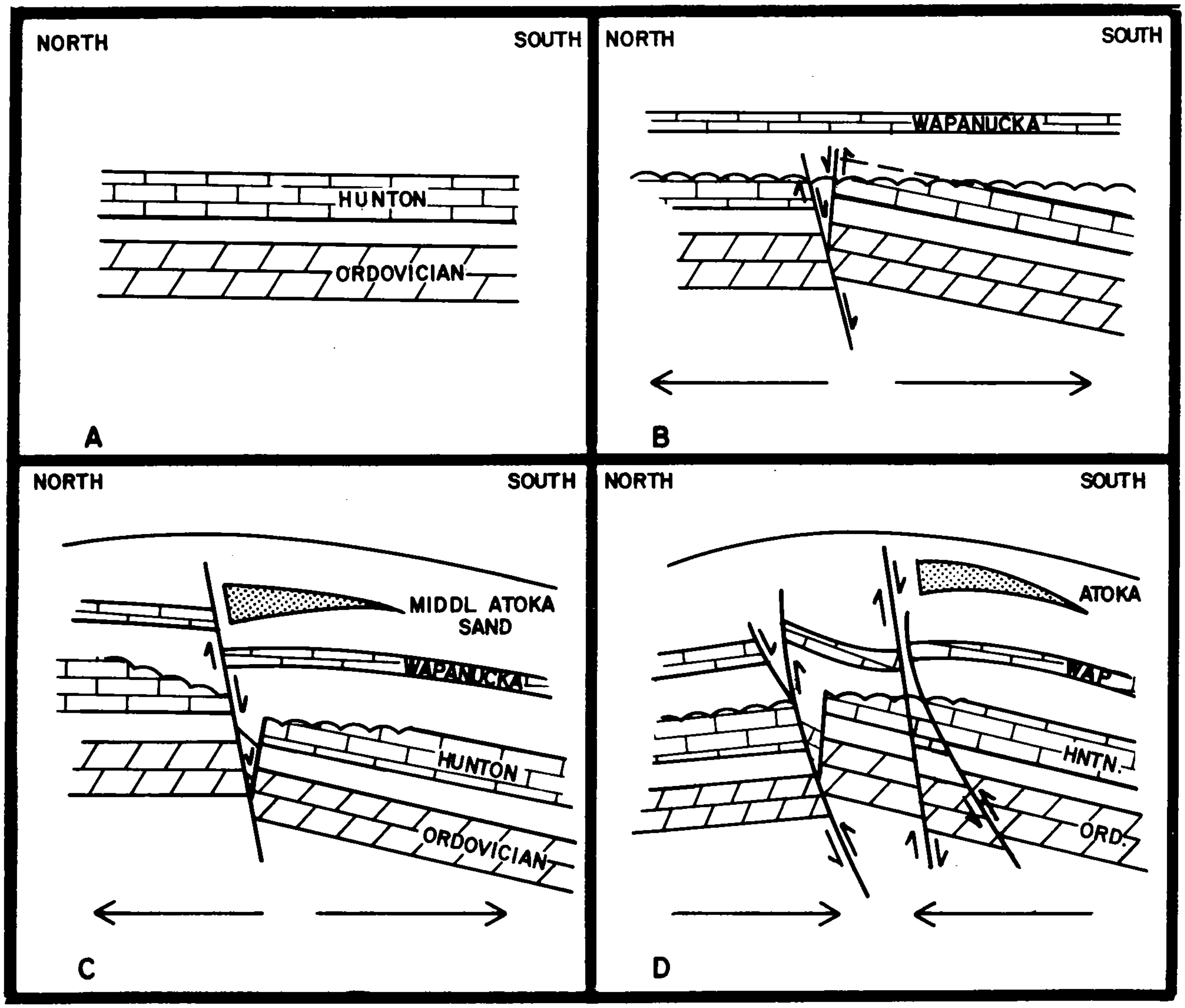


Figure 9. Proposed mechanism for formation of structurally high basement fault blocks found in the area of the Wilburton and Savanna anticlines in the western Arkoma basin. In Figure 9a, stable shelf deposition is present to the end of Hunton time. In Figure 9b, rotational flexure faulting is followed by erosional truncation during post-Hunton time. In Figure 9c, growth of the Arkoma basin occurs during the Atoka, after deposition of the Wapanucka limestone. The dominant stress field to this time is tensional. Ouachita overthrsuting and compression in the late Pennsylvanian causes reversal of throw on the older normal faults in Figure 9d, creating apparent low-relief structures at the base Woodford, but structurally high in the Ordovician and Cambrian units. This figure is modified from one drawn by Gary Hart (personal communication).

propagating stress field of the Ouachita overthrust.

Incipient zones of weakness in the shale units above the Spiro sandstone (Atokan), below the Wapanucka limestone (Morrowan), and, to a much lesser extent, below the Cromwell sandstone (lower Pennsylvanian or Mississippian shale) caused glide planes to develop as the Ouachita overthrust moved over them. The dramatic ductility contrast between the Atokan and Morrowan shales and the Spiro sandstone and Wapanucka limestone resulted in the tremendous differences in deformational style between domains 2 and 3, in the presence of the compressional Ouachita Mountians overthrust stress field. Where the impinging stress of the Ouachita overthrust was strong enough to cause glide planes to develop in the bounding shales, the intervening Spiro and Wapanucka were literally sheared off and rolled up into tight thrust-cored folds and imbricate thrust sheets undereneath the massive Ouachita Mountians overthrust block, and moved to the north by drag as the Ouachita overthrust passed over them.

The basement rocks, underneath the glide planes, were and are relatively undeformed by the movement of the Ouachita terrain over them. At some point along the deeper part of the Choctaw fault, obviously, the Wapanucka and Spiro are completely removed from the basement section, and moved to the north by drag (probably along a decollement surface) to form the sheared and thrusted units occurring in the wedge zone. As seismic proceessing techniques improve and drilling continues, accurate palinspastic reconstruction of the basin will be possible, allowing the transition between foreland and basinal facies to be understood.

HYDROCARBON OCCURRENCE

Gas is usually associated with porosity in the Atokan and Morrowan rocks of the western Arkoma basin, away from surface outcrop. Almost never is porosity developed that is wet with connate water. The assumption may be made, therefore, that the presence of hydrocarbons has played a major role in the preservation of original porosity. In many areas a case may be strongly presented for the early entrapment of hydrocarbons prior to deformation, hence the preservation of primary porosity in the Atokan and Spiro sandstones. As a result, the occurrence of porosity may or may not be associated with present day structure in the basin foreland fields such as Kiowa, Wilburton and Red Oak.

The occurrence of porosity and major reserves on the crestal portions of the wedge zone thrust sheets, however, is probably not just a simple coincidence. It is obviously the intent of the major drillers in the play to stay on the structurally highest part of each respective thrust sheet. Assuming that the Spiro sandstone shared essentially the same depositional environment in the area of origin of the wedge zone thrust sheets as in the more northerly autocthonous basinal rocks, then either early porostiy has been destroyed on the downdip portions, or it has yet to be discovered. Knowing that open fractures play a significant role in Wapanucka production, it is likely that as a thrust sheet was being deformed, early entrapped gas migrated through open fractures to the crestal part of the fold. The downdip fractures were then sealed or closed by crystallization or changes in tectonic stress, greatly reducing porosity and permeability in the lower structural elevations of a particular thrust sheet. Seals would have been formed by the much more ductile overlying and underlying Atokan or Wapanucka shale, which does not fracture as easily as the more competent sandstone and limestone units.

FUTURE EXPLORATION

Exploration in the western Arkoma basin south of the Choctaw fault is in its infancy. Only in 1989 has the potential of this province been proven in terms of produceable reserves. The productive trend of Spiro and Middle Atokan sandstones in the Arkoma basin plunges underneath the Ouachita overthrust in the areas south and west of the Wilburton field; extent of the trend is unknown. At the present time, only structural anomalies can be considered as viable drilling targets; as time and drilling progress, stratigraphic fairways in the Atokan and Cromwell sandstones and Wapanucka limestone probably will be delineated.

Good seismic control is extremely critical, not only to understand the structural deformation that has occurred, but in order to determine the most suitable drill sites. At this stage of the play, the only commercially viable wells are those on the structurally highest portions of a given thrust sheet. There is not enough well data to map these sheets geologically; it is imperative that seismic be utilized to choose drill sites.

The area of the Arkoma basin explored thus far is very small in relation to the size of the entire basin. It is conceivable that more than one major Atokan sand trend was deposited in the basin, possibly with more than one source area. The potential of the overpressured Cromwell can not yet even be estimated. Arbuckle production in the Wilburton field is outstanding; equally attractive structures undoubtedly exist in the vast, undrilled areas underneath the Ouachita overthrust. Traditional exploration targets in the Arkoma will retain the majority of exploration emphasis in the near future; however, in drilling new plays, new zones and structural and stratigraphic styles will likely be discovered that are not producing today.

The extent of the complex of fields stretching from Wilburton to West Wesley can only be proven by the drill bit. Ultimately, these lands will be found productive in nearly every section. Amounts of gas in excess of 1 TCF have already been produced from this area, even though many of the major wells and fields are only in their infancy. It is reasonable to expect that several multiples of the gas already produced will be discovered by additional drilling.

Recent spacing and pooling applications filed at the Oklahoma Corporation Commission indicate that the thrust-belt play will be extended into eastern Latimer and Le Flore Counties during the latter part of 1989. Additional drilling activity is rumored southwest of the West Wesley field, with commencement in early 1990.

Exploration in the Ouachita-facies rocks south of the Ti Valley fault zone has occurred sporadically since the early 1900s. Initial drilling occurred near oil and tar seeps, with some reasonable production established. Future reserves will undoubtedly be discovered as operators drill through the Ouachita overthrust in search of deeper targets.

CONCLUSIONS

1. Structural domains are established in the western Arkoma basin, separating rock units based on their deformational style. The term "wedge zone" is introduced to define the area in which imbricate thrust sheets occur, detached from both the basin-flooring basement rocks and the overlying Ouachita overthrust.

2. Discovery of the Amoco #1 Zipperer initiated a burgeoning exploration play in the western Arkoma basin during 1989 for Spiro sandstone and Wapanucka limestone in detached thrust sheets of the wedge zone, underneath the Ouachita Mountains overthrust sheet. Continued success in drilling for Arbuckle on the Wilburton anticline has forced the reassessment of other large structures in the Arkoma

basin for deeper producing zones.

3. Structural analysis of the western Arkoma basin indicates that deformation of the Spiro-Wapanucka is dependent on the geographic location of the segment under study at the time of deformation, which governs its response to the impinging stress field of the Ouachita Mountains overthrust.

4. The thrust sheets that are the focus of the current thrust belt drilling play appear similar in all areas of the western Arkoma basin. Length-to-width ratios of individual thrust sheets seem to fall between 3:2 and 2:1 in the areas studied. Individual thrust sheets occur in subparallel trends that coincide with the surface trace of the Choctaw fault. Many more thrust sheets are developed in the area south of Wilburton field than in the West Wesley area. This difference is probably due to the contrasting strength and direction of the stress field generated by movement of the Ouachita overthrust block in the Wilburton area compared to the West Wesley area.

5. Rock units forming the floor of the western Arkoma basin are most often only gently deformed, and primarily consist of south-dipping, block-faulted structures dominated by high-angle, deep-seated normal and reverse faults.

6. In the foreland portion of the Arkoma basin, porosity and gas production often occur independent of structure. However, in the wedge zone thrust play, drilling results indicate gas and porosity occurrence has been limited to the structurally highest parts of individual thrust sheets.

7. Seismic control is necessary in order to understand the deformation involved in the thrust belt play, and absolutely imperative in order to locate drill sites and obtain bottom hole locations.

8. Boundaries of existing fields in the western Arkoma basin already are becoming indistinct. The merger of the West Wesley, South Pittsburg-Blanco area, South Hartshorne, and Wilburton fields will assure the western Arkoma basin remains a major gas producing province. Ultimately, production will probably be found both in the frontal fold and thrust belt of the Ouachita Mountains and the underlying wedge zone along the entire trace of the Choctaw fault in the Oklahoma Arkoma basin, if not into central Arkansas. Additional structural and probably stratigraphic trends in the basin-flooring units will also be discovered.

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