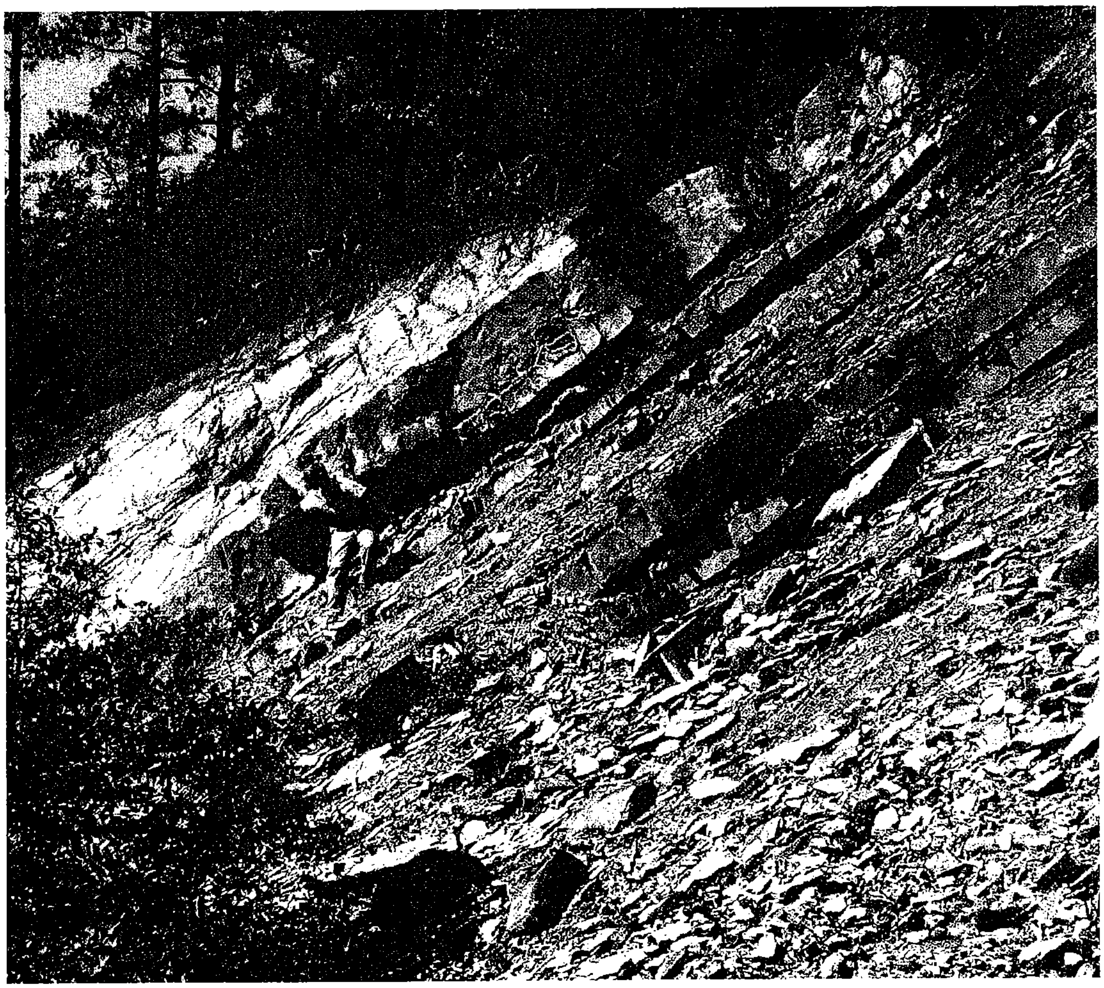
Stratigraphic and Structural Evolution of the Ouachita Mountains and Arkoma Basin, Southeastern Oklahoma and West-Central Arkansas: Applications to Petroleum Exploration



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Charles J. Mankin, *Director*

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

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Prepared for two half-day field trips and one full-day field trip to the Ouachita Mountains and Arkoma Basin of west-central Arkansas and southeastern Oklahoma. Held as part of a three-day field symposium (October 21–23, 2004) at the Kerr Conference Center, Poteau, Oklahoma.

Papers presented at the field symposium will be published in an Oklahoma Geological Survey Circular.

The University of Oklahoma
Norman, Oklahoma
2005

Front Cover

Friable and cemented sandstones in the Wildhorse Mountain Formation, Jackfork Group, exposed on the north flank of the Lynn Mountain Syncline at Stop 6A (Fig. 54 in this guidebook). The distribution, diagenesis, and origin of the two kinds of sandstone are different and have potential implications for natural gas exploration and development in these deep-water strata.

Photograph by Shuman Wu

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

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INTRODUCTION

Almost 10 years ago, the Oklahoma Geological Survey (OGS) sponsored a 3-day workshop and field trip on the geology and resources of the eastern Ouachita Mountains frontal belt and southeastern Arkoma Basin in Oklahoma. More than 60 geologists (and a few geophysicists and engineers!) from industry, government, and academia attended that meeting. To a certain extent, the purpose of the meeting was to celebrate the OGS's having completed a 7-year-long program mapping the surface geology of the eastern part of the frontal belt of the Ouachita Mountains and adjacent southern Arkoma Basin in Oklahoma. That program was called COGEOMAP (Cooperative Geologic Mapping) and was sponsored, in part, by the U.S. Geological Survey (USGS) and involved not only the OGS but the Arkansas Geological Commission (AGC). The AGC's part of the program involved mapping the Ouachita Mountains in Arkansas. COGEOMAP evolved into a similar program called STATEMAP; this program allowed the OGS to complete mapping the eastern frontal belt and Arkoma Basin as well as mapping farther to the west near McAlester.

The workshop, field trip, and guidebook (Suneson and Hemish, 1994) focused on recent advances in our knowledge of the tectonics, structure, stratigraphy, sedimentology, and paleontology of the fold-and-thrust belt and adjacent foreland basin and how that knowledge would aid in the ongoing exploration for and development of energy resources in southeastern Oklahoma. At that time (and to quote from the guidebook), "the principal energy resources of the region are coal and natural gas. Building stone and shale are relatively minor resources." Today, coal is a relatively minor resource and is being underground-mined at only one locality. Many of the old coal mines are hazardous and are identified as problem areas by the Oklahoma Conservation Commission (OCC). Coalbed methane, however, has become an actively sought-after resource, and advances in drilling and completion practices have made many formerly uneconomic deposits profitable. Between 1994 and today, drilling for natural gas in the frontal belt continued at a steady pace; as a result, gas fields such as the Talihina Northwest field, which consisted of only one well in 1994, now consists of 12 wells and has produced almost 7 Bcf of gas. Discoveries of gas in Jackfork Group sandstones in the Potato Hills have made it a viable exploration target throughout the Ouachita Mountains. A "distant"-future energy resource may be organic-rich gas shales such as the Woodford Shale. Although not an energy resource, building stone is now quarried throughout Latimer and Haskell Counties and the northern part of Le Flore County.

STRATIGRAPHY

The stratigraphy of the field-trip area is relatively well known. North of the Choctaw Fault (Oklahoma) or Ross Creek Fault (Arkansas), strata of the Arkoma Basin consist of the Atoka Formation (middle to late Atokan), overlain by the Desmoinesian Hartshorne, McAlester, Savanna, and Boggy Formations. In the subsurface, sandstones in these Middle Pennsylvanian units locally produce natural gas, and the Hartshorne (and possibly others) produces coalbed methane. South of the Choctaw and Ross Creek Faults, the stratigraphy is dominated by middle(?) Atokan and older strata; from oldest to youngest, these units include the Stanley Group (Mississippian), Jackfork Group (Morrowan), Johns Valley Formation (Morrowan), and

Atoka Formation (Atokan). In Oklahoma, equivalent units (Morrowan Springer Group and Wapanucka Limestone, basal Atokan Spiro sandstone) are present in the northernmost thrust sheets. The Stanley has a long history of minor oil and gas production in the western part of the Ouachitas, and sandstones in the Jackfork and Atoka produce gas in thrust sheets. The Wapanucka Limestone and Spiro sandstone produce gas in the thrust belt from and below thrust sheets as well as in the Arkoma Basin to the north. The oldest units in the field-trip area range from Cambrian to Devonian and are present in the Benton Uplift of Arkansas and the Potato Hills in Oklahoma. Some of these units, particularly the Ordovician Bigfork Chert and Devonian Arkansas Novaculite, have produced small quantities of gas in the past and may form deep, fractured reservoirs.

The deeper subsurface stratigraphy in the Arkoma Basin and Ouachita Mountains consists mostly of relatively shallow-water carbonates and sandstones that range in age from Cambrian to Mississippian. These formations are exposed in the Ozark Uplift to the north and the Arbuckle Mountains to the west; thus, they go by a variety of names. In structurally favorable positions, these units are prolific reservoirs (e.g., the Wilburton "Deep" gas field). An exploration well near the southernmost exposure of the Ouachitas showed that these Ozark–Arbuckle strata underlie the entire fold-and-thrust belt, with the possible exception of the easternmost Ouachitas in Arkansas. On this field trip, we will see these strata only as exotic blocks in the Morrowan Johns Valley Formation; however, they underlie everything we will see at the surface. A new play concept—unconventional gas shales—may, in the future, be tested in units such as the Woodford Shale beneath the thrust sheets.

Several lines of research are focusing on stratigraphic problems in the Ouachita Mountains; some of these problems are old ones, while others have evolved as a result of new mapping, new seismic interpretation, new drilling, and new stratigraphic concepts. Some of these issues will be addressed on this field trip and at the concurrent symposium. Others await future geologists. Some of the questions are: What is the origin of the olistostromal units in the Johns Valley Formation? What are the different facies and facies relationships in the deep-water clastic strata, and how do they affect petroleum exploration? What is the relation of the Mississippian and younger units in the Arkoma Basin to coeval units in the Ouachita Mountains, and where are those (presumed) shelf edges? How do the units in the Ouachita Mountains fit into a sequence-stratigraphic framework, and does this show us where the next undiscovered reservoir is likely to be?

STRUCTURE

A general outline of the structural geology of the Ouachita Mountains fold-and-thrust belt and its transition to the Arkoma Basin fold belt is also known. In the Oklahoma Ouachitas, the southward progression from a highly thrust-faulted and tightly folded frontal belt to a sparsely faulted and broadly open-folded central belt to the complexly deformed and slightly metamorphosed Broken Bow Uplift is commonly accepted. The Potato Hills anticlinorium interrupts this otherwise regular progress. In Arkansas, Oklahoma's central belt of broad, open folds is compressed to nothing, and the frontal belt of imbricate faults and folds is juxtaposed against the complexly deformed Benton Uplift. The southern central thrust belt (including the Athens Plateau) lies south of this uplift. These structural belts are covered by Cretaceous strata of the Gulf Coastal Plain and Tertiary strata of the Mississippi Embayment, making it difficult to decipher the structural relationship of the Ouachitas to the Arbuckle Mountains of southern Oklahoma or the southern Appalachian Mountains. To the north, north-directed thrust faults and north-vergent folds extend into the Arkoma Basin, and the triangle-zone geometry of the transition from tectonic belt to foreland basin is accepted.

Most geologists also agree that major subhorizontal detachment faults separate the Ouachita strata observed at the surface from early to middle Paleozoic, mostly platform strata that are observed far to the north in the Ozark Uplift or to the west in the Arbuckle Mountains.

Although improved seismic data, coupled with new detailed geologic mapping and modern structural concepts, have improved our understanding of the structural geometry and history of the Ouachitas, questions remain. Perhaps the most long-standing but still unanswered question is: How much displacement occurred along each of the major thrust faults in the Ouachita Mountains? An answer to this question will, of course, answer an additional question: What is the total amount of shortening represented by the Ouachita fold-and-thrust belt? More local but nonetheless critical questions follow. What is the origin of the south-vergent structures in the Benton and Broken Bow Uplifts? To what extent do duplexes explain observed surface and subsurface relations? What is the nature of the transition from one structural belt to another? Does one triangle-zone model fit the entire Ouachita Mountains–Arkoma Basin transition zone?

Since 1994 we have made impressive progress in answering some of these questions, but, as seems typical, two new questions arise for every one that is answered.

BACKGROUND SURFACE GEOLOGIC STUDIES AND PREVIOUS FIELD TRIPS

DAY ONE

The surface geology along the field-trip route in Oklahoma is based, in part, on mapping done by the OGS as part of the USGS-sponsored COGEOMAP and STATEMAP programs. Two outcrops of the Hartshorne Formation in the field-trip area were described as part of a 1998 field trip (Suneson, 1998). A large part of the surface geology in Arkansas was completed by the AGC, also as part of the COGEOMAP program. The geology of the Arkoma Basin in both states is based largely on coal-resource investigations by the USGS. In Oklahoma, the primary sources of surface geological information are, in the order in which they are relevant, Hemish and Suneson (1993), Hendricks

(1939), and Knechtel (1949). In Arkansas the primary sources of surface geological information are Hendricks and Parks (1937) and the series of 1:24,000-scale geologic maps by Haley and Stone (1995); these maps are available to the public from the AGC.

DAY TWO

Part of today's field-trip route is the same as that followed by the 1994 field trip (Suneson and Hemish, 1994); however, one of the stops (stop 17B of 1994; Stop 5 today) will have a different emphasis, and the other 1994 stops will not be revisited. The Heavener road cut (mile 17.4) was visited on the 1998 field trip mentioned under Day One (preceding page). Like Day One, the geology of the northern part of the field-trip area is also based, in part, on the OGS–USGS COGEOMAP and STATEMAP geologic maps—specifically, Hemish and Suneson (1993), Hemish and Suneson (1994), Suneson and Hemish (1993), and Mazengarb and Hemish (1993). To the south, the surface geology was mapped by Hart (1963), Seely (1963), and Briggs (1973).

DAY THREE

The first part of today's route follows the 1994 route (Suneson and Hemish, 1994). However, only one stop (stop 10 of 1994; Stop 8 today) will be a repeat; none of the other 1994 stops will be visited this year. Eight outcrops of the Hartshorne Formation in the field-trip area, most just south of U.S. Highway 270, are described in the guidebook for the 1998 field trip (Suneson, 1998). Stops 10A and 10B in that guidebook were also described by Hemish and Suneson (1997) in a guidebook on the Krebs Group. The geology along parts of State Highway 1 between Hartshorne and Buffalo Valley was briefly described by Suneson and others (1990) for a field trip run in 1989.

Like Days One and Two, modern, detailed 1:24,000-scale geologic maps have been published for most of the field-trip route. The order in which these maps are crossed is as follows: Hemish and Suneson (1993), Hemish and Mazengarb (1992), Hemish (1991), Hemish and others (1990a), Suneson and Ferguson (1990), Suneson and Ferguson (1989b), Suneson and Ferguson (1989a), Suneson (1996), Hemish (1992), Hemish and others (1990c), and Hemish and others (1990b). The surface geology of the Potato Hills area is based on Pitt and others (1982), which is a compilation of others' mapping (cited in Pitt and others, 1982), and on Miller and Smart (2001). Where the field trip crosses the Arkoma Basin, the coal-resource studies by the USGS (Hendricks, 1937, 1939) are also useful.

ACKNOWLEDGMENTS

Our work in the Ouachita Mountains and Arkoma Basin started many years ago and is continuing. Many individuals and organizations have contributed to our efforts.

Neil Suneson is grateful for having been able to work with two excellent geologists—Charles Ferguson (now with the Arizona Geological Survey) and LeRoy Hemish (retired from the OGS). Their energy in mapping and intellect in unraveling the complex structure and stratigraphy of the Ouachita frontal belt and southern Arkoma Basin cannot be overappreciated. Suneson also acknowledges the support of the U.S. Geological Survey through their COGEOMAP and STATEMAP programs. Without that financial support, the mapping may never have been completed. Field-production data were provided by Petroleum Information/Dwights LLC dba IHS Energy Group. The efforts of the OGS editorial staff, particularly Christie Cooper, Manager, and Bill Rose, technical editor, and the OGS cartographic staff, including Jim Anderson, Manager, and Laurie Lollis, are gratefully acknowledged. Virginia Rose is thanked for the page layout. Finally, Suneson acknowledges the support of his wife, Judy Reynolds, and sons, Peter and Ryan, who had to endure long periods of an absent husband/father while he traipsed through the woods looking at rocks.

Ibrahim Çemen would like to thank the mappers at the OGS and the late Zuhair Al-Shaieb for introducing him to the exciting geology of the Ouachita Mountains. Without the surface maps, much of OSU's structural work could not have been accomplished. And without Dr. Al-Shaieb's ideas on the chamosite facies of the Spiro sandstone, the structural work would not have had major applications to gas exploration in the Ouachitas. Çemen also would like to acknowledge the support he received from the Oklahoma Center for the Advancement of Science and Technology (OCAST) between 1992 and 1995 (OCAST Project No. AR2-025:4391). He also would like to thank ExxonMobil and Amoco (now BPAmoco) for donating 2-D seismic lines for the structural interpretations. Finally, Çemen would like to thank his wife, Pam, and son, Rahmi, for supporting his field trips to the Ouachitas with his graduate students and colleagues, and for enduring his frustration over the interesting and challenging structural problems they encountered.

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Mike Roberts and Charlie Stone wish to acknowledge the gracious assistance of many people, including the Fort Smith Geological Society, and in particular Phillip Shelby, Kim Butler, and Clay Norton with SEECO and Scott Bruner and Debbie Fritsche with the Arkansas Oil and Gas Commission.They also would like to thank several aggregate companies active in the region—John McCullen and Todd Wheeler with Martin Marietta, Lynn Burton with Granite Mountain Quarries, and Michael Bailey with Arkhola. Data from several geophysical companies—Floyd Wilson with Wilson Geophysical, Roger Forsythe with

GEOMAP, and others—are gratefully acknowledged. Ed Ratchford's (Arkansas Geological Commission) knowledge of Arkansas coal and coal-seam natural gas was especially helpful. Several property owners have been very kind in allowing us access to key outcrops, including Bill Shaddon and John and Patricia Heinen of Boles, Arkansas, and others. Boyd Haley (retired, U.S. Geological Survey), J. K. Arbenz (retired, Shell), and Neil Suneson (OGS) provided numerous comments on our part of the guidebook.

Roger Slatt and his students would like particularly to thank Lou and Myra Ward of Ward Petroleum for providing initial inspiration for their work during a local field trip and for subsequently releasing proprietary data. Slatt would also like to thank GHK Company for providing logs of some of their Potato Hills wells, Jan Dodson for providing assistance with computing issues, and ChevronTexaco, Inc., and the Gene and Astrid VanDyke Fellowship Fund for providing graduate student fellowships. The Ardmore Geological Society (through Bob Allen) also provided data for the subsurface studies. The American Chemical Society, Petroleum Research Fund Grant No. 125-5017, to Smart and Slatt, titled "Surface Characterization of Fractures—An Integrated Structural and Stratigraphic Analysis of the Pennsylvanian Jackfork Group, Oklahoma," is also gratefully acknowledged.

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Galen Miller's work on the Potato Hills is the subject of his M.S. thesis at the University of Oklahoma, and Miller would like to thank Kevin Smart, Shankar Mitra, and Doug Elmore for being on his thesis committee. Miller thanks Charles Mankin, Neil Suneson, Michelle Summers, Stan Krukowski, and the Oklahoma Geological Survey for advice and financial support. Miller also acknowledges Gregg Cook, Paul Denny, and GHK LLC for providing well logs and financial assistance, and the U.S. Geological Survey's EDMAP program for providing partial funding. Special thanks are due his wife, Kathy, and son, Daniel, who endured his frequent trips to the field.

DAY ONE

Arkoma Basin, Frontal Ouachita Mountains, and Benton Uplift of Western Arkansas: Structure, Stratigraphy, and Economic Geology

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Charles G. Stone
Arkansas Geological Commission

with road log in Oklahoma by
Neil H. Suneson
Oklahoma Geological Survey

INTRODUCTION

Today's field trip will cross through part of the southern Arkoma Basin near the Oklahoma–Arkansas state line, then cross into the Ouachita Mountains fold-and-thrust belt in western Arkansas (Fig. 1).

The Arkoma Basin near the Oklahoma–Arkansas state line is an area rich in natural-gas wells, active aggregate and dimension-stone quarries, and mostly old coal mines. At the surface, the basin consists of a series of anticlines and broad synclines in Pennsylvanian (Atokan and Desmoinesian) sedimentary rocks, many of which contain gas fields and former coal mines. The first commercial gas production in Arkansas began in 1902 with the drilling of two gas wells in an anticline in the Atoka Formation near Mansfield. The Washburn Anticline south of Greenwood contains several large gas fields and is the site of much current development drilling. The topography in the Arkoma Basin is the result of differential erosion, with thick Desmoinesian and Atokan sandstones forming ridges and hills.

The Ouachita Mountains province is south of Waldron. Here, several large thrust faults have been mapped at the surface that offset deep-water lower Atokan and older Carboniferous sedimentary rocks. The frontal hills of the Ouachita Mountains are mostly sandstone-rich sequences in the lower part of the Atoka Formation and thick quartzose sandstones of the Jackfork Group. Little exploration for natural gas has taken place in this area, but potential plays are indicated by surface and subsurface (seismic-reflection data) information. Potential development of dimension-stone and aggregate quarries also exists. A region of lower relief, underlain by complexly deformed Mississippian Stanley Group strata, with structurally intercalated ridges of Mississippian–Devonian Arkansas Novaculite and older strata, is south of Mena. These older rocks constitute the Benton–Broken Bow Uplift of the Ouachita Mountains.

Today's field trip will stop in each of three major tectonic provinces of western Arkansas—one in the Arkoma

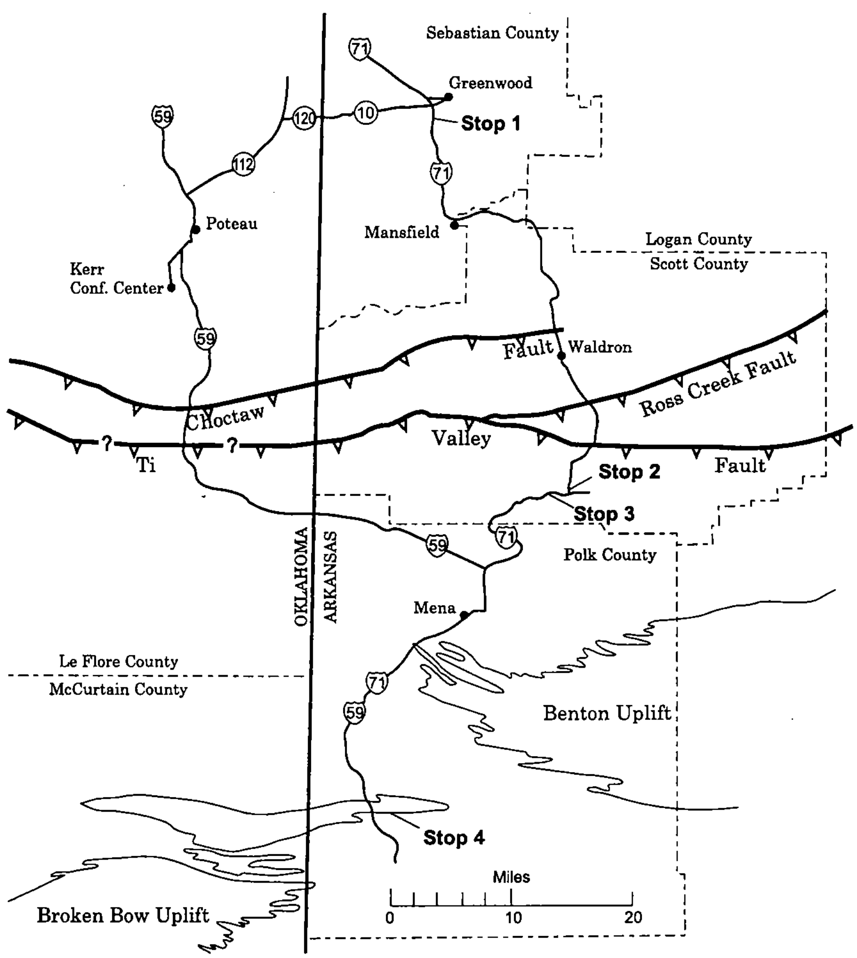

Figure 1. Map showing field-trip route for Day One, major towns, locations of stops, and some geologic features.

Basin, two in the frontal Ouachitas, and one in the Benton–Broken Bow Uplift (Fig. 1). The route crosses much complex geology. The region contains not only dramatic structural geology and shallow- to deep-water stratigraphic and sedimentologic features, but also economically important reserves of natural gas, coal, aggregates, and minerals. In some places the geology is still incompletely understood despite detailed surface-mapping efforts, and problems in interpreting the structure and stratigraphy remain. Future exploration for hydrocarbons or minerals in the Arkoma Basin and Ouachita Mountains will require imagination, additional acquisition and interpretation of geophysical data, correct structural and stratigraphic models, and dedicated budgets!

STRATIGRAPHY

The strata exposed along today's field-trip route range in age from Silurian to Pennsylvanian (Desmoinesian) (Fig. 2). Ordovician strata, which we will see on Day Three,

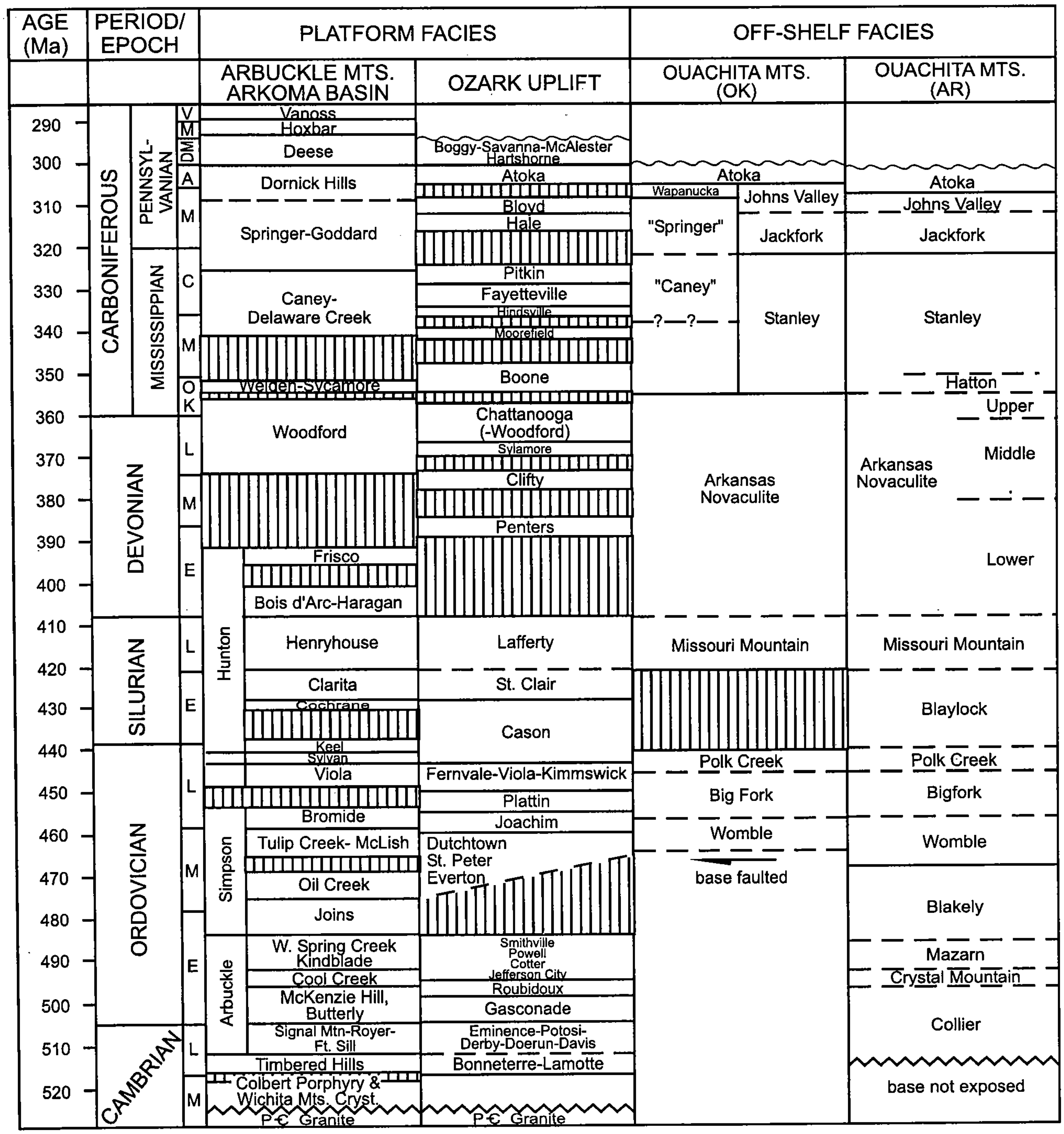

Figure 2. Generalized surface and subsurface stratigraphy in field-trip area (modified from Arbenz, 1989a).

are exposed just east of Mena. The Arkoma Basin is underlain by Cambrian to Early Mississippian shelfal, mostly carbonate strata. This early to middle Paleozoic platform was broken by normal faults and began to subside in the Mississippian. It was buried by later Mississippian and Pennsylvanian clastic strata, which mostly were deposited in shallow-water to fluvial environments throughout the northern and central parts of the basin. However, to the south, deeper-water sediments started to accumulate in the early Atokan. Lower Pennsylvanian syndepositional, listric normal faults formed and flattened above the platform strata.

The first part of today's field trip will cross the upper and middle parts of the Atoka Formation (Atokan) and the Desmoinesian Hartshorne, McAlester, and Savanna Formations. Our first stop will examine a fluvial facies of the Hartshorne Sandstone south of Greenwood. The Hartshorne is quarried for aggregate and building stone and produces gas in Oklahoma. We will then cross lower Atoka deep-water clastic strata in the frontal thrust sheets of the Ouachita Mountains.

The Ouachita frontal belt also contains Morrowan "Ouachita facies" strata—deep-water, tectonically far-traveled facies coeval with the shallow-water facies of the Ozarks and Arkoma Basin. The Ti Valley Thrust, crossed by U.S. Highway 71 just north of Y City, carries the Ouachita facies (Johns Valley Formation and Jackfork Group) northward. Stops 2 and 3 will examine these Morrowan units. The Jackfork Group is a deep-water deposit that is quarried for aggregate in Arkansas and Oklahoma and is explored for as a gas reservoir in Oklahoma (Day Two, this field trip). South and east of Mena, the Benton–Broken Bow Uplift is underlain by the thick Mississippian Stanley Group, the Mississippian–Devonian Arkansas Novaculite, and Silurian–Ordovician deep-water clastic and carbonate strata that are equivalent to the platform-facies strata under the Arkoma Basin and that crop out in the Ozark Uplift (Fig. 2). The relationship of the Ouachita facies to their coeval facies in the Arkoma Basin is still debated, but the Ouachita facies clearly were thrust to the north many miles from a site south of the shelf edge of the northern platform facies. Stop 4 will examine the Arkansas Novaculite and Hatton Tuff, a lentil in the lower part of the Stanley Group, in the Benton–Broken Bow Uplift. These units are quarried for aggregate; elsewhere, some grades of Arkansas Novaculite also are made into whetstones.

ROAD LOG

Cumulative mileage *Interval*

0.0 0.0 Start field trip at Kerr Conference Center near Poteau, Oklahoma, which is located on the basal sandstone of the Savanna Formation immediately above the Spaniard Limestone (Fig. 1). Drive due north along section-line road.

Enter west part of Poteau Southeast coalbed-methane field.

Poteau Southeast Coalbed-Methane Field

The Poteau Southeast coalbed-methane field was discovered by the Bear Productions No. 1 Turner well in the W½NE¼SW¼ sec. 22, T. 6 N., R. 26 E. The well was spudded on August 2, 1997, finished drilling on August 3, 1997, and was open-hole completed on September 10, 1997, from 838 to 1,025 ft. The initial potential from the Hartshorne coal (Fig. 3) was 44 Mcf gas per day with no water.

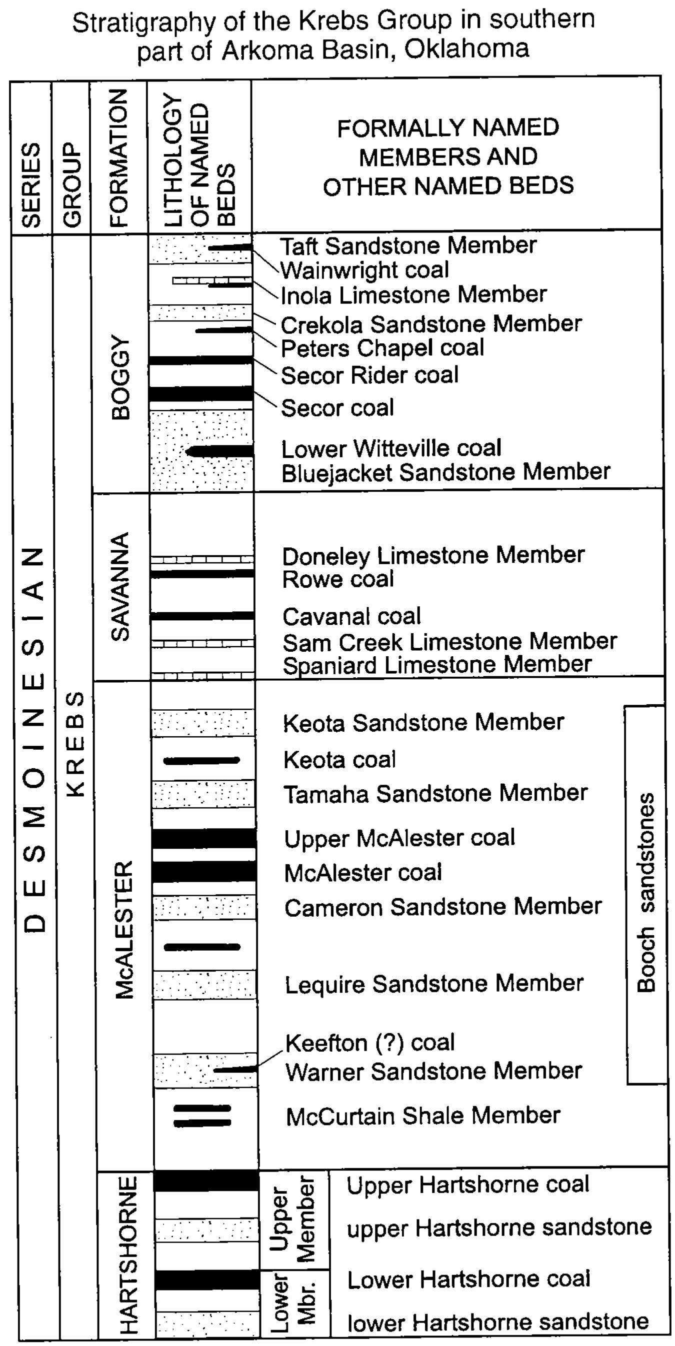

Figure 3. Stratigraphy of Krebs Group in the Oklahoma part of the field-trip area, emphasizing named coal beds (modified from Hemish and Suneson, 1997). The Lower Hartshorne coal is the principal target for coalbed methane in this part of the Arkoma Basin.

The field extends from here ~10 mi east and includes most of the township immediately to the east (T. 6 N., R. 26 E.) (Boyd, 2002). The southern part of the field lies on the crest of the Hartford Anticline, but most of the field is on the north flank of the anticline. At the end of 2003, there were 75 coalbed-methane wells in the field (Brian Cardott, personal communication, 2004). All wells were completed in the Hartshorne, Lower Hartshorne, or Upper Hartshorne coal. The completion depth in the field ranges from 421 to 1,921 ft; initial production ranges from 2 to 240 Mcf gas per day with 0–175 bbl water per day. There are nine horizontal coalbed-methane wells in the field.

1.0 1.0 Leave Wister 7.5′ quadrangle; enter Poteau West 7.5′ quadrangle. Leave Poteau Southeast coalbed-methane field.

1.9 0.9 Intersection with county road immediately south of Burlington Northern railroad. Turn right (northeast) on county road.

3.5 1.6 Intersection with U.S. Highway 59. Turn left (north).

3.9 0.4 Intersection with U.S. 271. Turn right (northeast) on U.S. 59/271.

Several old strip mines in the Cavanal coal are present near the base of the low ridge immediately northwest of U.S. 271 (Fig. 4). The ridge is underlain by Savanna sandstones nos. 6 and 7 of Hemish and Suneson (1993). Some of the mines initially operated as underground mines as shown by Hendricks (1939) and therefore were active in 1931. The strip mines, however, are not shown by Hendricks (1939) but do appear on the 1968 topographic map. Oklahoma Conservation Commission (OCC) files show the strip mines to have been active in 1940.

The now-closed underground and strip mines just northwest of U.S. 271 are within the OCC's Turnipseed Problem Area, because open pits (including one filled with water), vertical openings (air shafts), and open portals were present. The area was reclaimed between 1997 and 2002 under the Abandoned Mine Land Reclamation Program.

4.8 0.9 Enter Poteau, Oklahoma. Flagstone sales yard on left.

In the last 10–15 years, Le Flore and Haskell Counties have become the center of a growing building-stone industry. About 30 properties in each county are permitted to quarry building stones (data from Oklahoma Department of Mines). Most of the operations are relatively small (employing <10 people) but are efficient. A thin soil overburden is removed, and the sandstone flagstones are exposed and quarried, using bulldozers, front-end loaders, and forklifts. Some operations split the thicker slabs into blocks; others simply stack the naturally broken flagstones onto pallets. Much of the stone is sold in the rapidly expanding Dallas–Fort Worth area, but some is sold as far away as Pennsylvania and Oregon.

The primary units that are being quarried are sandstones in the McAlester, Savanna, and Boggy Formations (including the Bluejacket Sandstone). A few quarries produce sandstone from the Hartshorne and Atoka Formations.

5.7 0.9 Leave Poteau West 7.5′ quadrangle; enter Poteau East 7.5′ quadrangle.

6.9 1.2 Leave Poteau East 7.5′ quadrangle; reenter Poteau West 7.5′ quadrangle.

7.4 0.5 Road to left (west) leads to the top of Cavanal Mountain.

Cavanal Mountain

Cavanal Mountain is advertised by Le Flore County boosters as the "World's Highest Hill." Exactly how the mountain earned its reputation is unknown, but Fugate and Fugate (1991, p. 76) suggest the following:

> Before World War II, members of an English class in a Le Flore County high school exchanged letters with students in a similar class in England. The British class discovered from a Boy Scout manual that Cavanal Hill, near Poteau, was "The World's Highest Hill." Subsequent investigation revealed that the British Geological Society defined a hill as less than 2,000 feet above the surrounding terrain, and a mountain as 2,000 or more. Cavanal Hill measured 1,999 feet above the local area.

(Note: The *Glossary of Geology* (Jackson, 1997) defines a hill as having less than 1,000 ft of relief.)

The highest point on Cavanal Mountain is 2,385 ft above sea level (1968 topographic map of the Poteau West 7.5′ quadrangle). If a "hill" has 1,999 ft of relief, but no more, the "base" of Cavanal Mountain should be 386 ft above sea level. As one drives west from Poteau toward the top of Cavanal Mountain, the "base" of the mountain would seem to be the base of the slope capped by the Bluejacket Sandstone Member of the Boggy Formation. The Bluejacket separates the rugged topography of Cavanal Mountain from the surrounding countryside on at least three sides of the mountain. The base of the slope capped by the Bluejacket is between 600 and 700 ft in elevation. The elevation of the Poteau River just east of Poteau is about 410 ft above sea level. The closest 386-ft elevation to Cavanal Mountain cannot be determined exactly from existing topographic maps, but probably is close to where the Poteau River empties into the Arkansas River on the west side of Fort Smith, Arkansas. In hindsight, this may be a logical "base" of Cavanal Mountain.

8.9 1.5 Intersection with State Highway 112. Turn right (northeast) on S.H. 112.

Several old, small strip mines in a local coal immediately below the Cavanal coal cross S.H. 112 near the intersection with U.S. 59/271 (Fig. 5). Knechtel (1949) shows several slope mines along the outcrop belt; these mines must have been present in 1943 when Knechtel did his field work. The strip mines are shown on the 1968 topo-

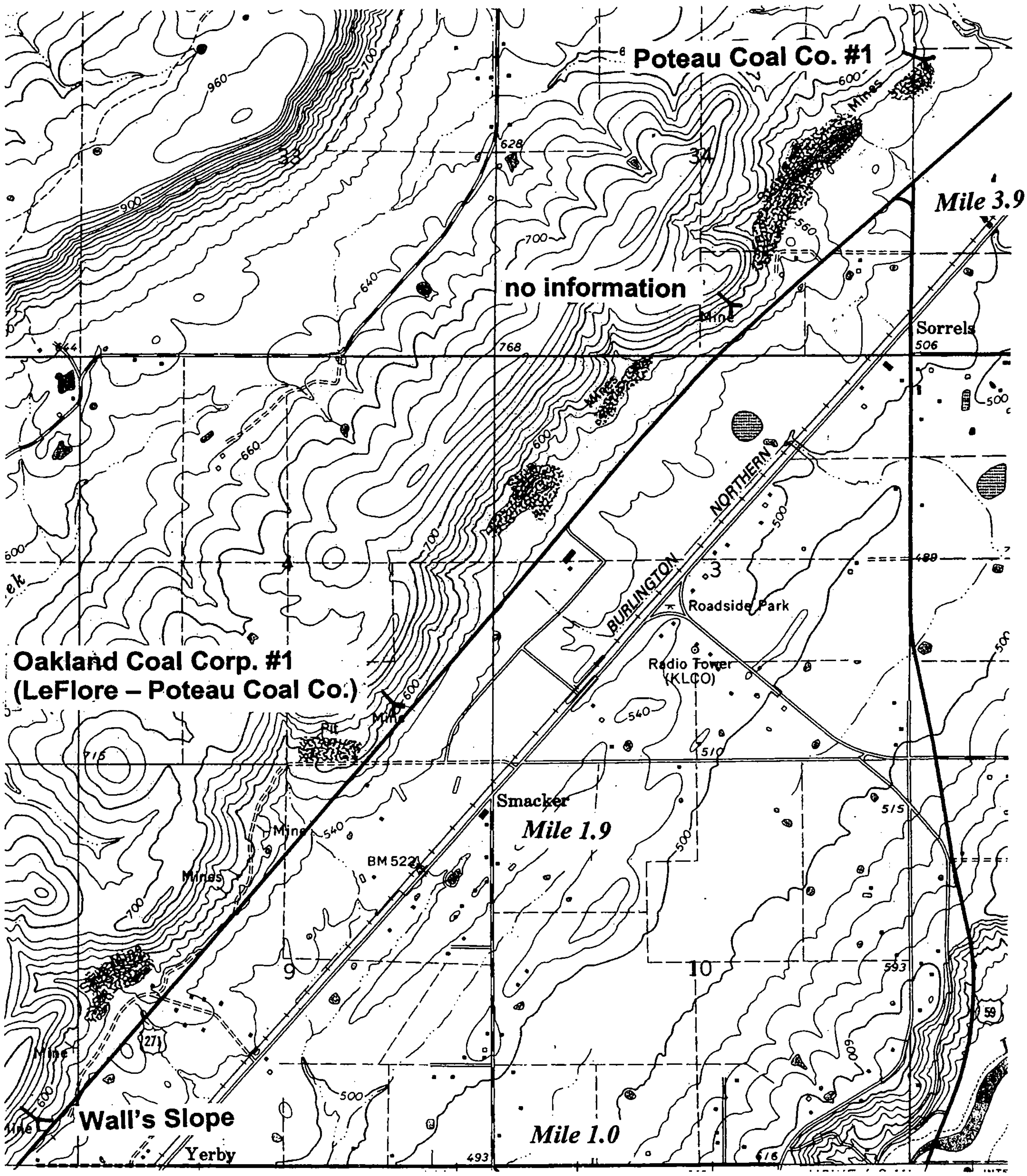

Figure 4. Part of topographic map of Poteau West 7.5′ quadrangle (photorevised 1982 edition) showing mines in Cavanal coal. Bold adit symbols (labeled) are mines shown by Hendricks (1939), which were present in 1931. Origin of other adits is unknown. Strip pit immediately southwest of the Oakland Coal no. 1 mine was developed between 1965 and 1980; the other strip pits were developed before 1965.

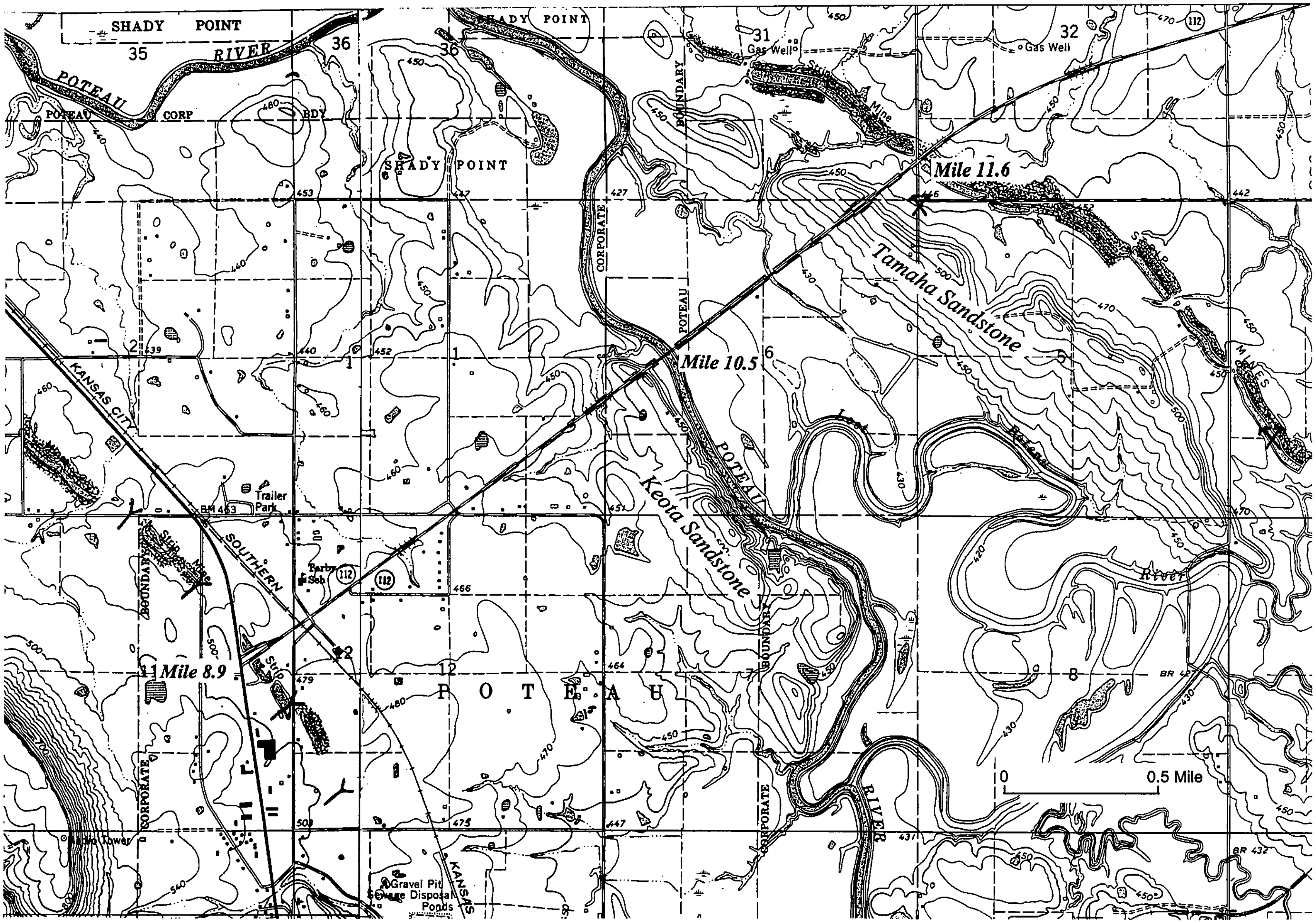

Figure 5. Parts of Poteau West and Poteau East 7.5′ topographic-quadrangle maps (photorevised 1982 editions) showing strip mines. The adit symbols near mile 8.9 show slope mines mapped by Knechtel (1949) in a local coal immediately below the Cavanal coal. The Cavanal coal probably is near the base of the slope in the southwest corner of the map. The strip pits have been reclaimed. The strip pits near mile 11.6 were developed in the Stigler coal. Knechtel (1949) shows two coal prospects in the area; the northern one (northwest corner sec. 5, T. 7 N., R. 26 E.) is in a coal (Stigler Rider?) (Upper McAlester?) above the main Stigler (McAlester) coal. Both sets of strip pits were developed before 1965.

graphic map of the Poteau West 7.5′ quadrangle. OCC files show that the strip mines were active from 1946 to 1948.

These strip mines were part of the OCC's Monks Development Problem Area because hazardous water bodies were present. The mines west of U.S. 59/271 were reclaimed in 1994. One of the strip mines (now occupied by a Wal-Mart store) was reclaimed in 1987 at a cost of ~$71,000.

9.3 0.4 Leave Poteau West 7.5′ quadrangle; reenter Poteau East 7.5′ quadrangle.

9.7 0.4 Enter Cameron gas field and Cameron A coalbed-methane field.

Cameron Gas Field

The Cameron gas field extends from ~2 mi west of here to the Arkansas state line (Boyd, 2002); it is ~12 mi long and ~5 mi wide at its widest point. The Cameron A coalbed-methane field overlaps the west end of the Cameron field, and the Cameron B coalbed-methane field overlaps the east end of the field (Boyd, 2002) (Fig. 6).

The Cameron gas field was discovered in 1911 by the Le Flore County Gas and Electric Company No. 9 Tucker (NE¼NW¼ sec. 3, T. 7 N., R. 26 E.) (Knechtel, 1949). The producing formation (1,526 ft deep) was either the Hartshorne sandstone or a sandstone in the lower part of the McAlester Formation; the open-flow capacity was 500,000 cf gas per day. Further development of the field did not occur until 1923 (Knechtel, 1949).

The principal reservoirs in the Cameron field are Atoka sandstones, including the Atoka Middle (indefinite), Red Oak, Gose (indefinite), and Morris. The "indefinite" sandstones are poorly defined and vary in stratigraphic position throughout the field. As of July 2004, the Cameron gas field had produced ~65 Bcf gas (data courtesy IHS Energy).

Cameron A and B Coalbed-Methane Fields

The Cameron A and B coalbed-methane fields cover relatively small areas on either end of the Cameron gas field (Fig. 6). Based on data compiled by Brian Cardott (Oklahoma Geological Survey), all the wells in the fields are completed in the Hartshorne or Lower Hartshorne coal. The first coalbed-methane well in the area was the Jolen Operating Company No. 1 Lynch in the NW¼NW¼ SE¼NW¼ sec. 28, T. 8 N., R. 26 E. The well spudded on July 16, 1991, reached total depth at 1,014 ft, and was completed in the Lower Hartshorne coal at 942–947 ft on December 20, 1991.

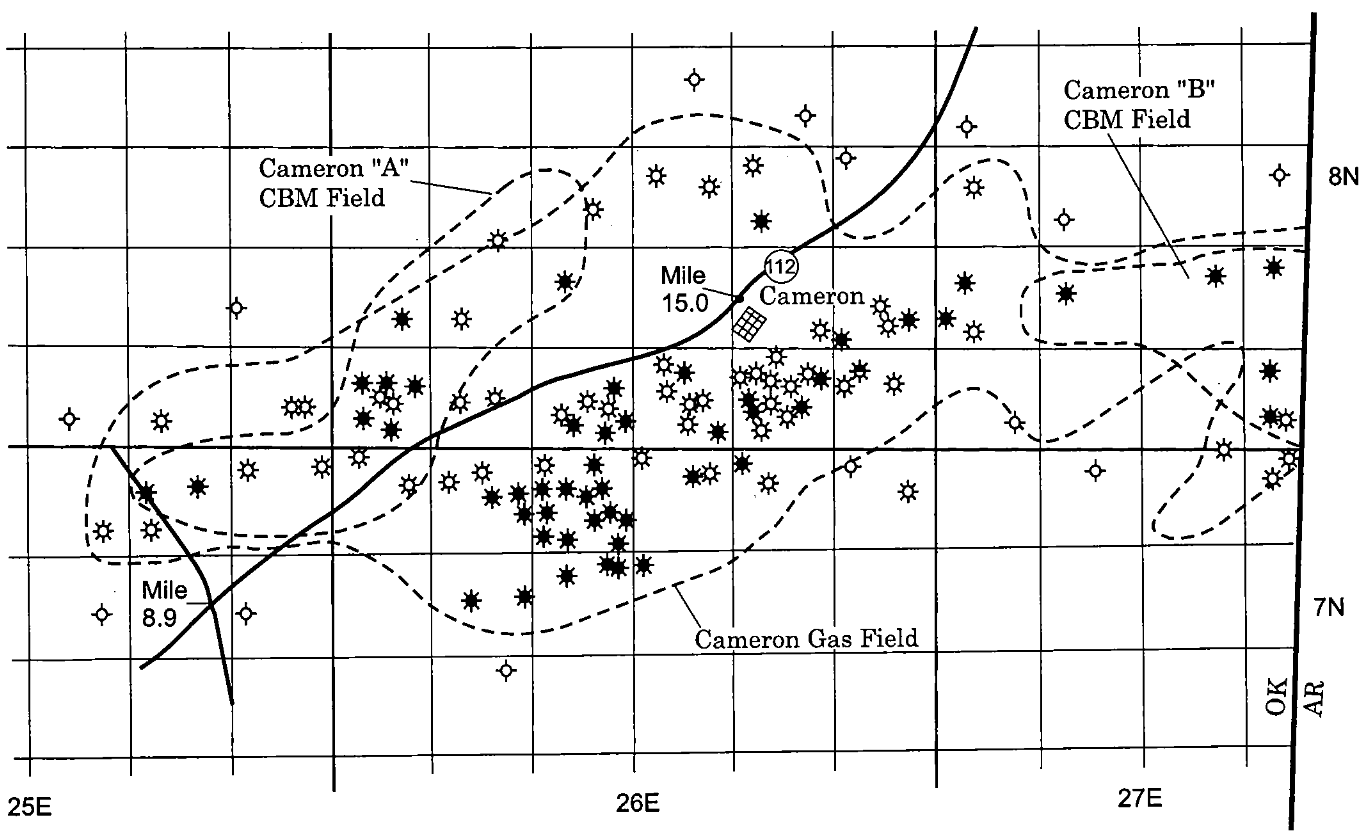

Figure 6. Production map of Cameron gas field, Cameron "A" coalbed-methane field, and Cameron "B" coalbed-methane field (from Boyd, 2002). Open gas-well symbols are those with Atoka sandstone reservoirs. Filled gas-well symbols are wells completed in the Hartshorne coal and/or sandstone. Note that a large number of coalbed-methane wells have been completed since Boyd (2002) compiled his map of Oklahoma's oil and gas fields.

10.4 0.7 Highway cuts through ridge underlain by the Keota Sandstone Member of the McAlester Formation. This is one of the upper Booch sandstones (subsurface nomenclature) (Fig. 3).

10.5 0.1 Cross Poteau River.

11.3 0.8 Highway cuts through ridge underlain by the Tamaha Sandstone Member of the McAlester Formation. This also is a Booch sandstone (Fig. 3).

11.6 0.3 County road to left (north) and right (south). Continue straight on S.H. 112.

A belt of strip mines in the Stigler (McAlester) coal oriented northwest–southeast was present here (Fig. 5). Another coal ~80 ft stratigraphically above the Stigler (McAlester) (Knechtel, 1949, p. 49) is present at the base of the Tamaha Ridge, noted at mile 11.3. In 1943 both coals were marked by a series of prospect pits (Knechtel, 1949, pl. I), and by 1968 parts of the lower coal (Stigler) (McAlester) had been strip mined. Records on file at the OCC show the strip mining to have occurred in 1947.

The strip-mined area is shown on OCC maps as the Bud French Strip Mines and Lafevers Mines Problem Areas south and north, respectively, of S.H. 112. Both have hazardous water bodies and are used for unauthorized recreation; dangerous highwalls are present in the Bud French area. Small areas have been reclaimed where county roads cross the old mines.

12.0 0.4 Leave Cameron A coalbed-methane field.

12.9 0.9 Leave Poteau East 7.5′ quadrangle; enter Spiro 7.5′ quadrangle.

15.0 2.1 Small town of Cameron on right (southeast) side of road. Cameron Mountain, the high hill immediately on the other side of the town, is capped by the Tamaha Sandstone. The Cameron Sandstone is poorly exposed on the low ridge to the left (northwest).

16.2 1.2 County road to left (north) and south (right). Continue straight on S.H. 112. Leave Cameron gas field.

17.3 1.1 Low ridge is underlain by the Lequire Sandstone Member of the McAlester Formation. This is a lower or middle Booch sandstone, using subsurface nomenclature (Fig. 3).

Enter Rock Island gas field.

Rock Island Gas Field

The Rock Island gas field extends from near here ~8 mi west–southwest (Boyd, 2002) (Fig. 7). It is about 1–2 mi wide. The discovery well for the field is the Le Flore County Gas and Electric No. 25 Littman (SW¼NW¼NW¼ sec. 18, T. 8 N., R. 27 E.), which spudded on July 22, 1922, reached total depth at 1,607 ft, and probably was completed in an Atoka sandstone.

All the wells in the Rock Island field produce from sandstones in the Atoka Formation; these are shown on Oklahoma Corporation Commission forms as Atoka (nonspecific), Morris (Fig. 8), or Brazil. (It is possible that the Morris and Brazil are equivalent.) As of July 2004, the field had produced ~6.3 Bcf gas (data courtesy IHS Energy).

17.5 0.2 Cross James Fork.

18.3 0.8 Leave Spiro 7.5′ quadrangle; enter Hackett 7.5′ quadrangle.

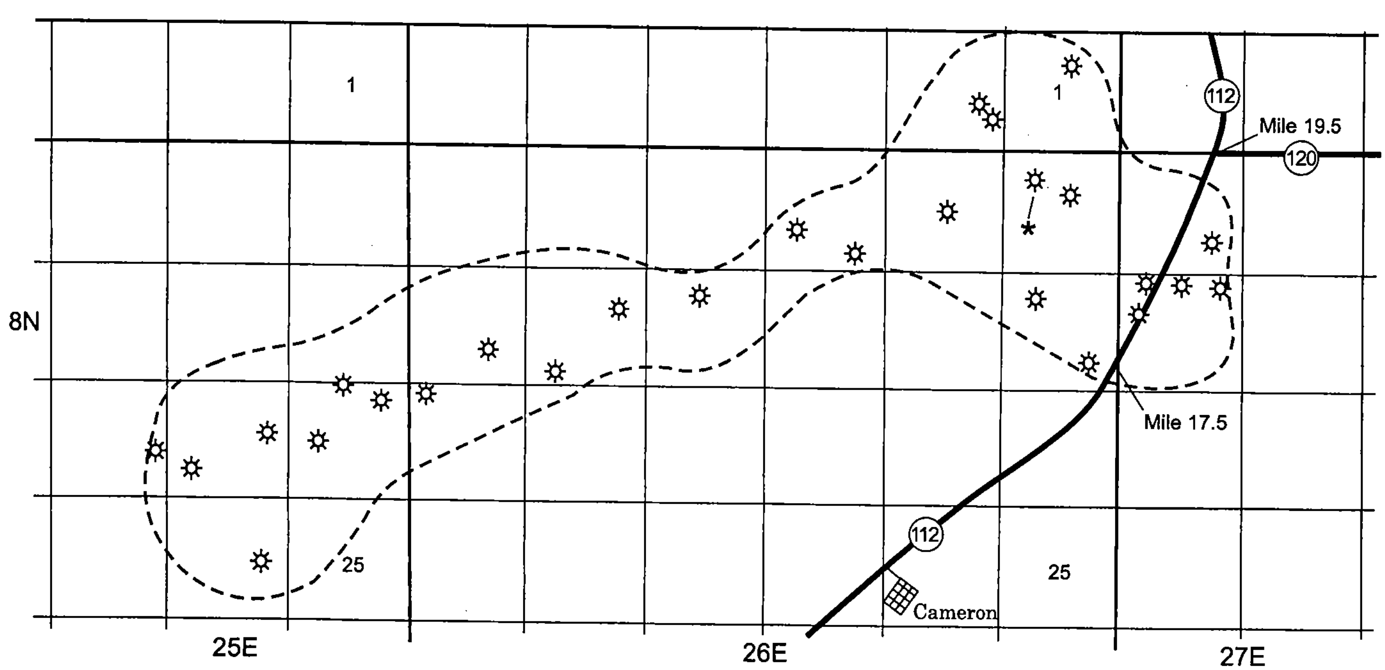

Figure 7. Production map of Rock Island gas field. Asterisk (*) denotes the Oxley No. 1 Johnnie (see Fig. 8).

18.7 0.4 Cross old railroad grade. This railroad served the many coal mines in the Hartshorne coal immediately east of here. OCC records show the mines (underground and surface), about 0.5–2 mi east of here, to have been active in 1952.

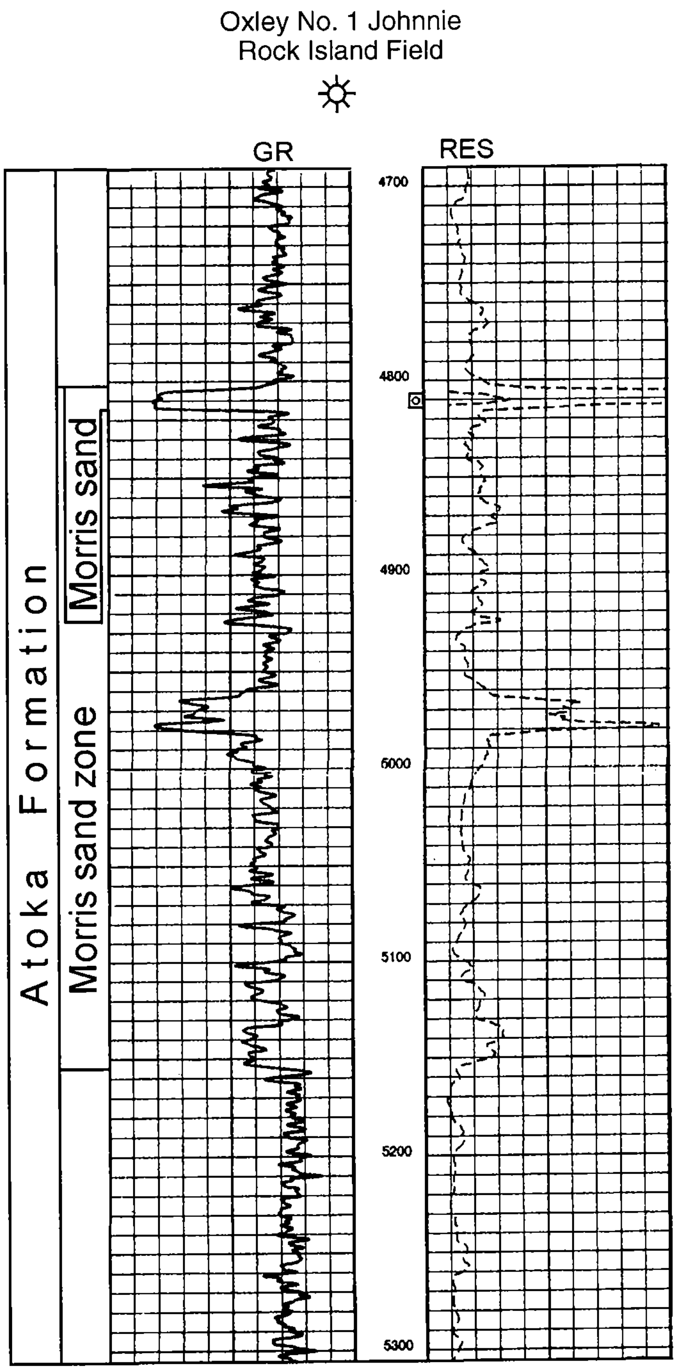

Figure 8. Part of electric log from the Oxley No. 1 Johnnie (NW¼NW¼SE¼NW¼ sec. 12, T. 8 N., R. 26 E.) (Rock Island gas field), showing productive interval in the Morris sand. The interval production-tested 1,139 Mcf gas per day. Note that the Morris sand "zone" (4,803–5,155 ft) extends well beyond the productive unit(s). *GR* = gamma ray; *RES* = resistivity.

About 65 acres is shown by the OCC as the Rock Island Problem Area; problems include a dangerous highwall, a hazardous water body, and two sites with unauthorized residential waste. In addition, the water bodies are used for unauthorized fishing and swimming.

19.3 0.6 Leave Rock Island gas field.

19.5 0.2 Intersection of S.H. 112 and State Highway 120 to right (east). Turn right (east) on S.H. 120.

20.0 0.5 Enter Pocola South gas field.

Pocola South Gas Field

The Pocola South gas field was discovered by the Monsanto No. 1 Hardin (SE¼NW¼SE¼ sec. 32, T. 9 N., R. 27 E.), which spudded on May 20, 1966, reached total depth at 8,220 ft, and was completed in the Morris (4,728–4,855 ft) and Spiro (7,546–7,585 ft) sandstones. Most of the wells in the field also produce from the Morris and Spiro sandstones (Figs. 9, 10A,B), although Oklahoma Corporation Commission forms also show the Hartshorne, Carpenter B, Red Oak, Cromwell, and a variety of nonspecific Atoka sandstones (e.g., Atoka B, Atoka M, Atoka) also to be productive.

As of July 2004, the Pocola South gas field had produced ~37 Bcf gas (data courtesy IHS Energy).

20.3 0.3 Small town of Rock Island on low ridge underlain by Hartshorne sandstone to right (south).

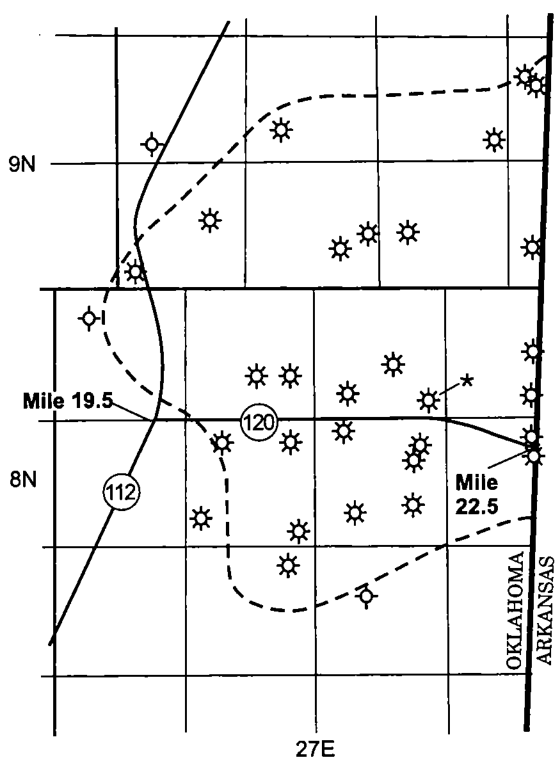

Figure 9. Production map of Pocola South gas field. Asterisk (*) denotes the Oxley No. 2 Basinger (see Fig. 10).

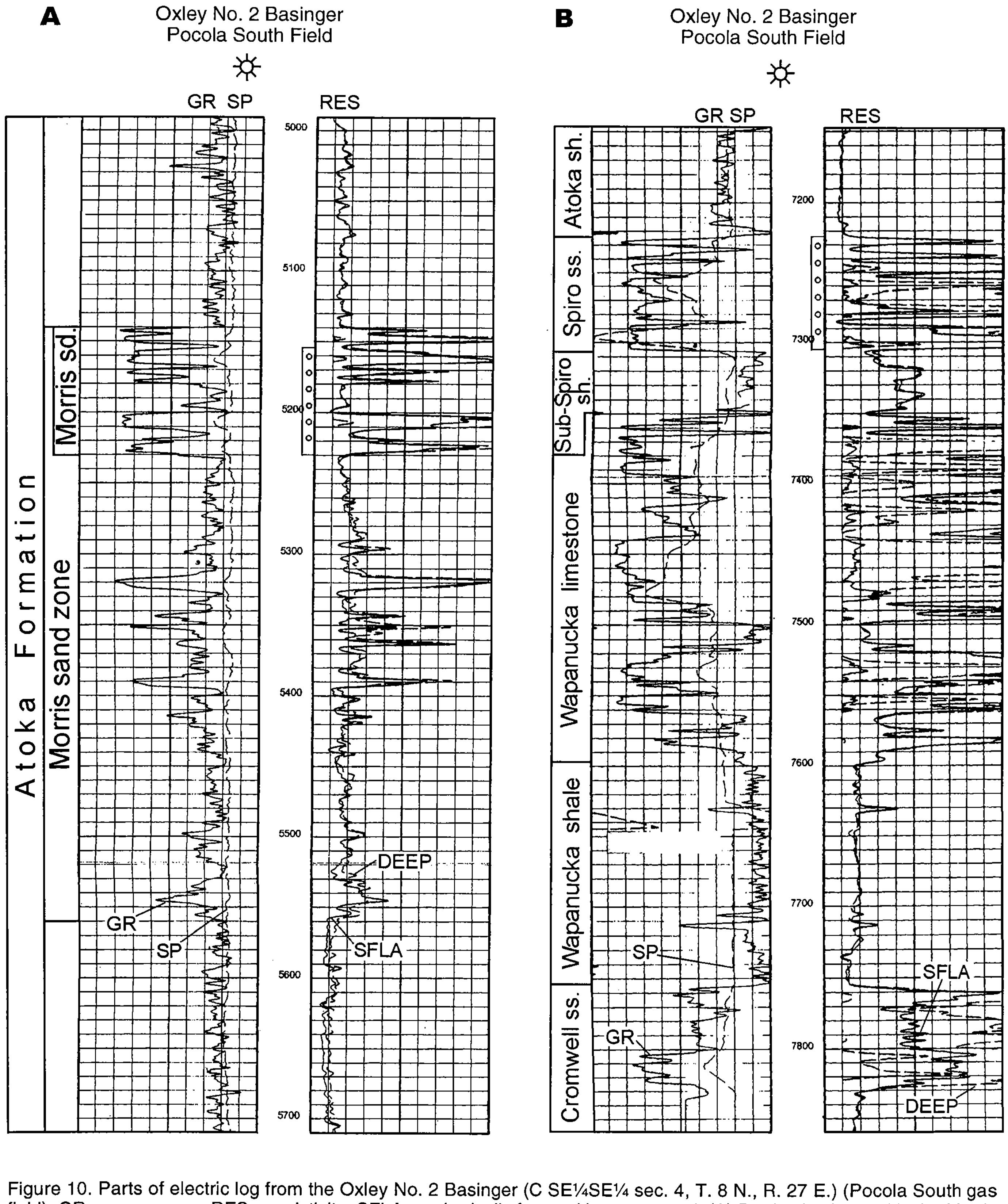

Figure 10. Parts of electric log from the Oxley No. 2 Basinger (C SE¼SE¼ sec. 4, T. 8 N., R. 27 E.) (Pocola South gas field). GR = gamma ray; RES = resistivity; SFLA = spherically focused log, averaged. (A) Productive interval is the Morris sand, which production-tested 1,565 Mcf gas per day. Note that the Morris sand in this well, like that in the Oxley No. 1 Johnnie (Fig. 8), is a zone rather than a single interval. (B) Productive interval is the Spiro sandstone, which production-tested 859 Mcf gas per day. The top of the Wapanucka is at 7,352 ft, and the top of the Cromwell sandstone is at 7,755 ft.

21.7 1.4 Highway ascends ridge underlain by Hartshorne sandstone.

22.0 0.3 Entrance to Green Country Stone Quarry. This quarry in the Hartshorne sandstone was stop 17 on the 1998 field trip (Suneson, 1998). The following description of the Hartshorne in the quarry is from Suneson (1998, p. 64):

> Most of the exposures in the Green Country Stone quarry are upper-distributary-mouth-bar deposits. Equally, if not more impressive, are two distributary channels that eroded into the bars [see Fig. 11]. Sandstone fills most of the channels and occurs as a series of nested, highly cross-stratified deposits. The azimuth of the channels is about N. 20° E.–S. 20° W. The dip of large foreset beds within the channels suggests that the current direction was toward the north.

22.5 0.5 Oklahoma–Arkansas state line. End of Oklahoma State Highway 120 in Le Flore County, Oklahoma; start of Arkansas S.H. 10 in Sebastian County, Arkansas. Continue straight (east).

22.7 0.2 Ibison Stone Supply headquarters to left (north). Large volumes of high-quality quarried sandstone used for residential landscaping and other such uses obtained from thin layers of Hartshorne Sandstone here. Building-stone business is a major industry in Arkansas, and the two other most notable districts are near Poteau, Oklahoma, and near Midway, Arkansas.

22.9 0.2 More stockpiles of dimension stone to the north. Numerous spoil piles from abandoned underground coal mines in the Excelsior–Greenwood district occur on the south side of the road and extend eastward for ~12 mi. These mines targeted the lower Hartshorne coal bed in the basal part of the McAlester Formation (Arkansas nomenclature). The coal ranged in thickness from 2 to >5 ft.

ARKANSAS VALLEY COAL FIELD

Michael Ed Ratchford
Arkansas Geological Commission

Acknowledgments

The coal fields of Arkansas have been extensively studied by several state and federal agencies, and the geologic description in this report is a brief synopsis of the previous investigations. This report makes special recognition of the excellent pioneering work of Boyd R. Haley, Thomas A. Hendricks, Brian Parks, and Arthur J. Collier of the U.S. Geological Survey. Their work was also partially supported by the Arkansas Geological Commission.

Coal-Field Location and Nomenclature

The coal fields of west-central Arkansas are confined to the Arkansas Valley province and a portion of the central Arkoma Basin. The area of the Arkansas coal fields is ~33 mi wide at the Oklahoma border and continues eastward for ~92 mi, where the field tapers to a narrow point southeast of Russellville, Arkansas (Fig. 12). The field trends in an east–west direction and is bounded on the north by the Boston Mountains of the Ozark Plateau and to the south by the frontal segment of the Ouachita Mountains. The historically accepted definition of the Arkansas coal field includes all areas within the eastern Arkoma Basin that are underlain by the McAlester and younger formations. In common practice with earlier definitions of the coal field (Collier, 1907; Hendricks and Parks, 1937; Haley, 1954), scattered coal beds within the underlying Atoka Formation are excluded from the field.

History, Production, and Reserves

Coal was first mined in 1840 from surface exposures (Table 1); however, all significant production up to 1918 was from underground mines. By 1918, the development of mechanized power equipment stimulated the production of coal by surface-mining methods. However, under-

Figure 11. Upper-distributary-mouth-bar deposits (horizontally bedded strata at base of exposure), overlain and eroded into by distributary channel. Erosive base of channel is near geologist's head (from Suneson, 1998, fig. 68).

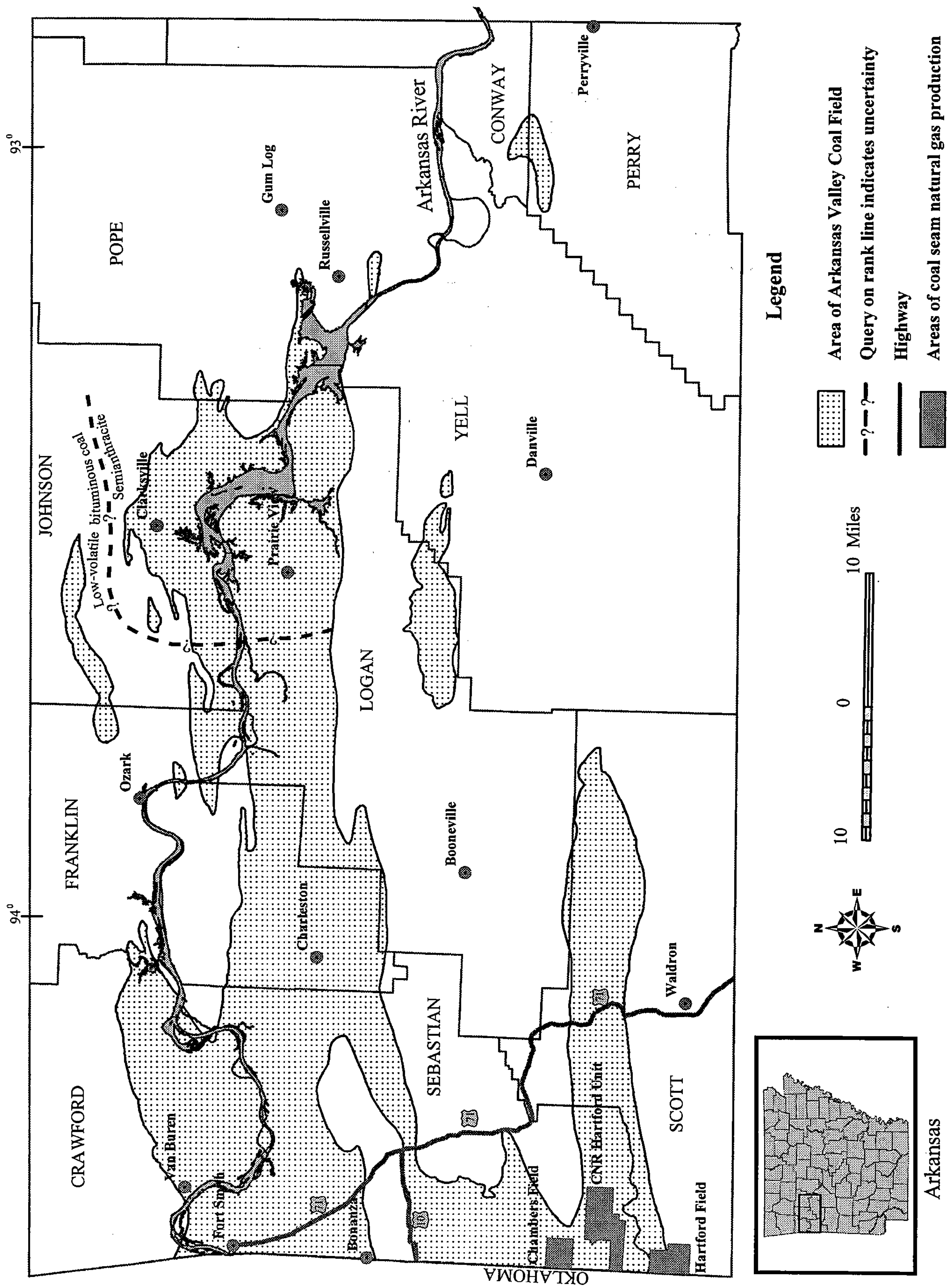

Figure 12. Arkansas Valley coal field as depicted at the base of the McAlester Formation (modified from Bush and Colton, 1983; Haley, 1987).

Table 1. — Annual Coal Production,[a] Arkansas Valley Coal Field, Arkansas

Year	Surface	Underground	Total
1840–1927	988.7[b]	58,272.1	59,260.8
1928–1966	8,926.9	32,025.0	40,951.9
1967	144.0	45.0	189.0
1968	152.0	59.0	211.0
1969	167.0	61.0	228.0
1970	217.0	51.0	268.0
1971	236.0	40.0	276.0
1972	420.0	8.0	428.0
1973	431.0	3.0	434.0
1974	455.0	—	455.0
1975	488.0	—	488.0
1976	481.7	24.0	505.7
1977	442.7	24.0	466.7
1978	319.3	—	319.3
1979	224.7	—	224.7
1980	203.0	—	203.0
1981	220.0	—	220.0
1982	100.1	—	100.1
1983	88.0	—	88.0
1984	74.6	—	74.6
1985	49.3	—	49.3
1986	105.3	—	105.3
1987	137.3	—	137.3
1988[c]	66.4	—	66.4
1989	107.0	—	107.0
1990	69.1	—	69.1
1991	46.9	—	46.9
1992	63.2	—	63.2
1993	63.8	0.029	63.8
1994	45.5	—	45.5
1995	44.3	—	44.3
1996	19.4	—	19.4
1997	18.4	—	18.4
1998	36.3	—	36.3
1999	34.1	—	34.1
2000	16.3	—	16.3
2001	15.5	1.0	16.5
2002	14.8	1.7	16.5

[a]In thousands of short tons.
[b]First recorded production in 1918.
[c]In 1988, >221,799 tons of lignite was mined.
(Table modified from Bush, 2003.)

ground production continued to exceed surface production until 1958. Since 1958, large- to small-scale surface mines have accounted for most of the production. The peak year of coal production was 1907, when 2,670,000 short tons was produced. Total estimated original reserves were 455.8 million tons of semianthracite and 1,769.9 million tons of low-volatile bituminous coal (Haley, 1954). A total recoverable reserve of 1 billion tons remains today (Bush, 2003). Arkansas coal production has dwindled in recent years because of a national trend toward cleaner burning fuels, such as natural gas, and strong competition from low-sulfur coals from the Powder River Basin in Wyoming.

Stratigraphy

Bedrock exposed in the coal field is entirely Pennsylvanian in age and belongs to the Atoka, Hartshorne, McAlester, Savanna, and Boggy Formations. The lithology, thickness, and distribution of the coals are summarized in Figure 13. With the exception of the Hartshorne Sandstone, the other formations consist principally of carbonaceous dark shale, shaly siltstone, and lesser amounts of light-colored shaly to silty sandstone. Owing to variability in the resistance to weathering, a disproportionate amount of the outcrops are sandstone, and sandstone underlies most of the ridges within the coal field.

Structure

The Pennsylvanian strata of the Arkansas Valley coal field are complexly deformed by folding and faulting. Most of the folds and faults trend approximately east–west, parallel to the long axis of the field. Haley (1987) divides the coal field into two structural domains by denoting a generalized transect that extends eastward from Bonanza through Charleston, Prairie View, and Gum Log (Fig. 12).

South of this transect the strata are folded into long, asymmetrical anticlines that are separated by broader synclines and broken locally by thrust faults. The dip of the bedding typically ranges from 10° to vertical, and beds are locally overturned on the north limbs of some anticlines.

North of this transect the area is characterized by open anticlines and synclines. South- and north-dipping normal faults are prevalent throughout the area, and they are particularly abundant along the northern border with the Boston Mountains. The strata typically dip between 3° and 35°.

Bituminous and Semianthracite Deposits

Twenty coal beds in the Arkansas Valley coal field have been studied by state and federal agencies, and four of these beds are considered to be economically important: the Lower Hartshorne and Upper Hartshorne coal beds of the McAlester Formation, and the Charleston and Paris coal beds of the Savanna Formation (Fig. 13).

The Lower Hartshorne coal is the most extensive and productive coal bed in Arkansas and underlies a region of 1,360 mi^2. It is >14 in. thick over a 740-mi^2 area and attains a maximum thickness of 8 ft in Sebastian County. The thickness of the coal is inversely related to the thickness of the underlying Hartshorne Sandstone. The rank of the Lower Hartshorne coal ranges from low-volatile bituminous in the western part of the Arkansas Valley coal field to semianthracite in the eastern part.

The Upper Hartshorne coal underlies ~28 mi^2 of the southwestern Arkansas Valley. It is ~14 in. thick over an

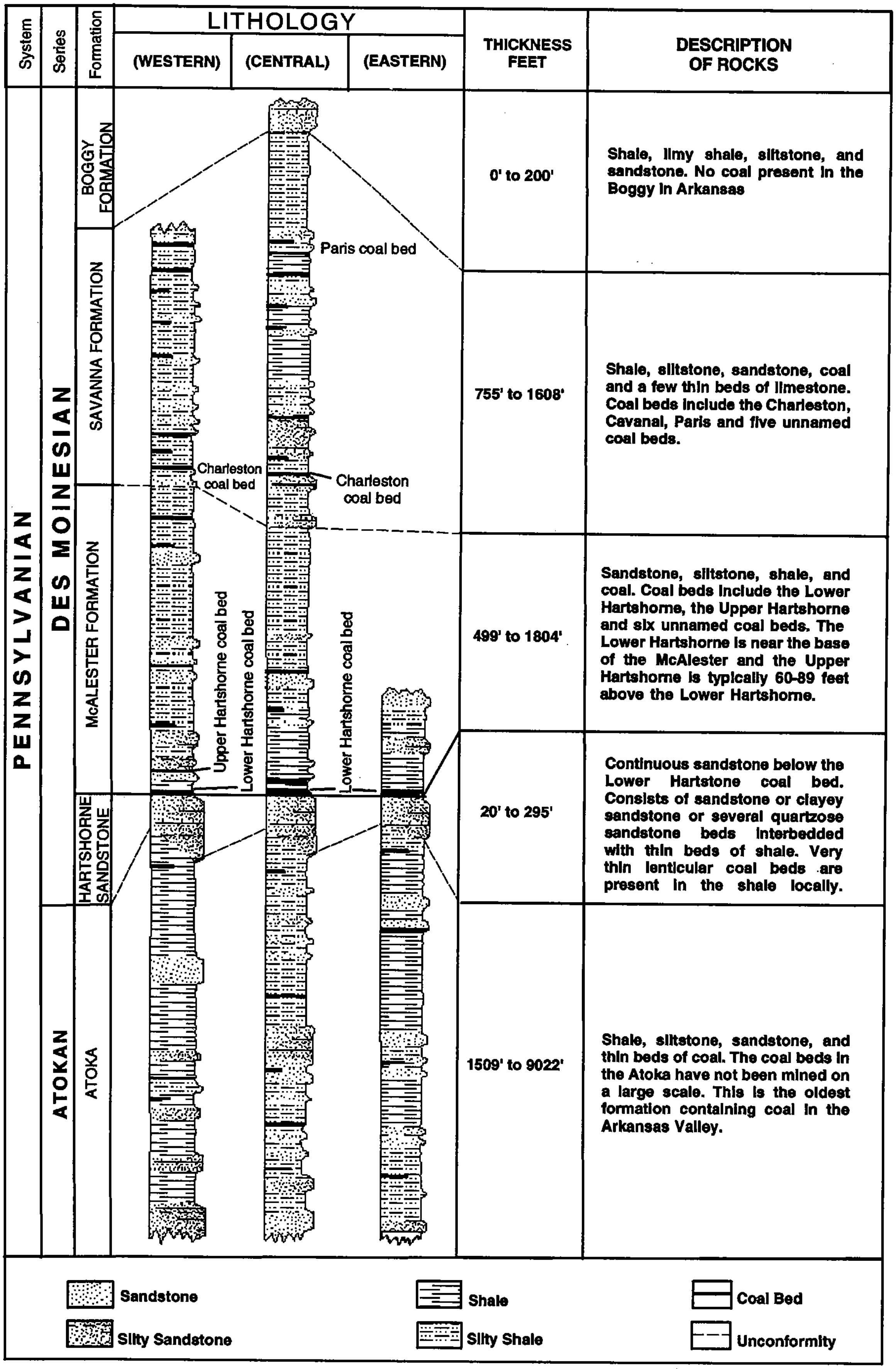

Figure 13. Generalized stratigraphic section in the Arkansas Valley coal field (modified from Bush and Colton, 1983).

Table 2. — Average Analyses of Arkansas Valley Coals[a]

Coal bed	No. of samples	Counties	Moisture (%)	Volatile matter (%)	Fixed carbon (%)	Ash (%)	Sulfur (%)	Btu/lb
Charleston	5	Franklin, Sebastian	2.4	18.2	74.0	5.5	2.6	14,363
Paris	43	Franklin, Logan	1.8	17.9	70.6	9.8	2.4	13,765
Atoka	3	Johnson, Pope	1.4	13.8	77.2	7.6	3.4	14,070
Lower Hartshorne	125	Scott, Sebastian	2.9	17.4	72.1	7.7	1.3	13,771
Lower Hartshorne	68	Franklin, Johnson	3.0	13.5	75.9	7.6	1.8	13,854
Lower Hartshorne	14	Logan, Pope	2.8	12.0	75.7	9.6	1.7	13,499

[a]As-received basis.
(Reproduced from Bush and Gilbreath, 1978.)

area of ~16 mi^2, with a maximum thickness of 34 in. It has been mined in one surface operation between Hartford and Huntington.

The Charleston coal has been mined by many surface operations in both the eastern and western districts. The coal underlies an area of ~120 mi^2, reaches a maximum thickness of 23 in., and attains a thickness of 14 in. or more over an area of 52 mi^2. In the western part of the Arkansas Valley the coal is low-volatile bituminous in rank, whereas in the eastern part it is semianthracite.

The Paris coal underlies three small areas that total 18 mi^2 and ranges in thickness from 14 to 32 in. The rank of the Paris coal is low-volatile bituminous (Bush, 2003).

Coal Quality

Low-volatile bituminous and semianthracite coals have been commercially developed in Arkansas (Fig. 12). These coals are well suited as feed material for electrical power plants owing to their high heat value and relatively low ash content (Table 2). Arkansas low-volatile coal is also blended with high-volatile coal for the manufacture of metallurgical coke. The blend contains 10–20% low-volatile bituminous coal and 80–90% high-volatile coal. Arkansas bituminous coal is also used as a source of carbon and for the manufacture of charcoal briquettes (Bush, 2003).

COAL-SEAM NATURAL GAS, ARKOMA BASIN, ARKANSAS

Michael Ed Ratchford
Arkansas Geological Commission

Arkansas's first development of coal-seam natural gas (CSNG) began in 2001 with the permitting and development work of CDX Gas LLC, a Dallas-based independent energy company. Prior to the exploitation of CSNG, the Arkansas Oil & Gas Commission established field rules and regulations specific to the exploration and production of this commodity. Mr. Rick Johnson, Project Manager with CDX, provided most of the information on CSNG, which is discussed as follows.

Initially, CDX drilled and evaluated cores from wells within several leased-acreage positions. Development drilling commenced with 14 vertical wells and 1 converted vertical core well. These 15 vertical wells were all within the Chambers field. Four horizontal wells were drilled later, utilizing the patented Z-Pinnate Technology that was developed by CDX's wholly-owned subsidiary, CDX-DART Drilling & Technology LLC.

The Hartford field, a second CSNG field, was established in 2002 along the crest of the Hartford Anticline. The Hartford field consists entirely of horizontal wells. Development drilling continues in the field with several additional wells planned. Currently, production from 13 horizontal wells averages 4.9 MMcf gas and 230 bbl water per day.

Horizontal drilling has started in a third development area. CDX sought and was granted approval for a field-wide unit to continue horizontal-drilling development of

CSNG reserves near Hartford. The new unit will provide >7,600 acres to drill and test for CSNG.

CDX Gas has produced 3.47 Bcf gas and 225,000 bbl water since production began in 2001. Current production volumes are increasing, owing to continuous drilling operations. CDX has drilled >400,000 ft of horizontal laterals to date. Daily production rates average 6.9 MMcf gas and 450 bbl water.

23.4	0.5	Stockpiles of dimension sandstone to north.
23.9	0.5	Hackett, Arkansas. Junction of S.H. 45 and 10; turn left (north) on S.H. 10/45.
24.3	0.4	Junction of S.H. 45 and 10; turn right (east) on S.H. 10.

Road cuts expose thick sequences of steeply south-dipping upper and middle Atoka deltaic sandstones and ma-

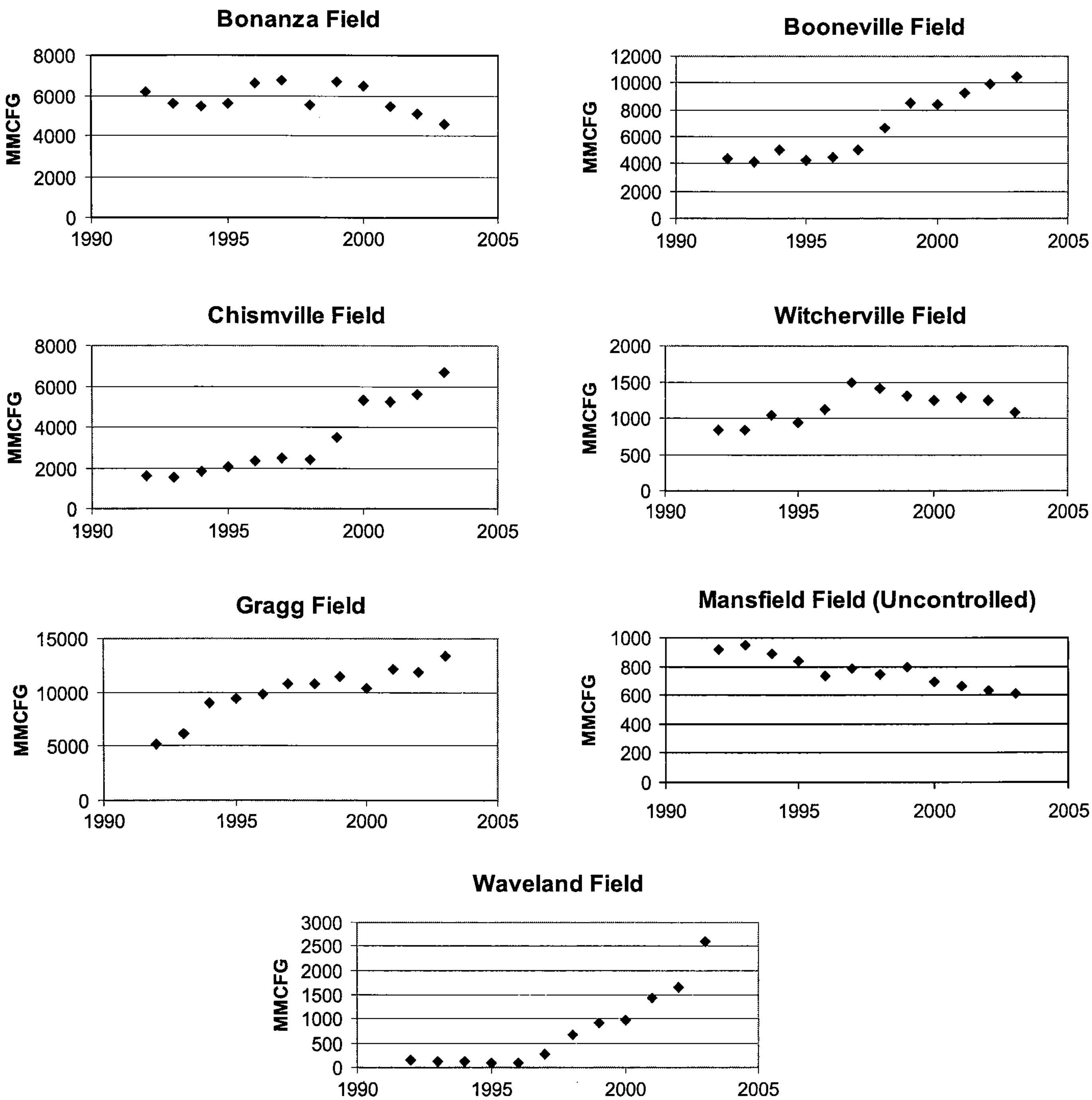

Figure 14. Production from gas fields in Arkoma Basin, Arkansas (data from Scott Bruner, Arkansas Oil and Gas Commission).

rine shales along the south flank of Backbone Anticline. Numerous gas wells have been drilled along this structure. Production has been reported from Atokan and Morrowan sandstones and from strata as old as the Ordovician–Devonian Hunton Group. The thrust fault in the core of the structure may have utilized preexisting listric normal faults localized by deeper block faulting in the basement and platform strata (e.g., Roberts, 1994). The Bonanza gas field in the area has produced between 5.0 and almost 7.0 Bcf gas per year since 1992 (Fig. 14 [on facing page]).

25.2	0.9	Note steep south dip slope of the Hartshorne Sandstone.
26.4	1.2	Producing gas well to north. Old coal-mine dumps and spoil piles to south. Griffith Mountain, visible 1 mi to the south, is capped by sandstone in the McAlester Formation. The axis of the Greenwood Syncline trends west–southwest across this mountain.
26.6	0.2	Leave Hackett 7.5′ quadrangle; enter Greenwood 7.5′ quadrangle.
27.1	0.5	Old coal-mine workings to south.
29.8	2.7	Junction of S.H. 253 and 10, continue straight ahead (east) on S.H. 10. Former Excelsior community and coal mines to southeast ~0.25 mi. The old railroad grades are still visible.
30.3	0.5	Auto junkyard to north lies on top of Hartshorne Sandstone.
31.4	1.1	Junction of S.H. 10 and U.S. Highway 71; turn right (south) onto U.S. 71. Small aggregate quarry in the Hartshorne to north. A large aggregate quarry in the Hartshorne operated by the Arkhola Sand and Gravel Company is ~3 mi farther north at Jenny Lind.
32.1	0.7	McAlester Formation shale and sandstone exposed on ridge to east along the Greenwood Syncline.
32.5	0.4	Park at north end of outcrop along shoulder of highway. This is a very busy four-lane highway, so please pay attention to the traffic.

STOP 1

HARTSHORNE SANDSTONE, DEVILS BACKBONE RIDGE

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Location: Devils Backbone Ridge; road cut along U.S. 71 ~2.5 mi southwest of Greenwood, SE¼NW¼NE¼ sec. 22, T. 6 N., R. 31 W., Sebastian County, Arkansas

Structural Setting

This outcrop is on the steep south flank of the Greenwood Syncline/north flank of the Washburn Anticline, Arkoma Basin (Figs. 15, 16). About 4 mi to the north the Backbone Thrust zone, consisting of several imbricate slices, has been mapped at the surface. This fault zone is seen on seismic data to merge into a sole fault, which passes beneath the Greenwood Syncline in the Atoka and detaches the Atokan–Desmoinesian section from the underlying block-faulted, older Paleozoic platform section and basement rocks. A few miles to the west, seismic data indicate that this sole fault is 9,000–13,000 ft deep and skims the tops of the basement/platform fault blocks. This basal detachment continues to the south, where in places it is arched by subthrust duplexes and appears to merge with the same sole fault that the Choctaw Fault flattens into at depth. A similar thrust cores the Washburn Anticline south of this stop (Fig. 17). Seismic data also indicate that the basement-involved faults merge into an intrabasement detachment fault that is at about −45,000 ft below the Backbone Anticline and rises to about −10,000 ft ~21 mi to the north (Roberts, 1994). It is this basement detachment that is hypothesized to have been reactivated during the Ouachita orogeny to form the basement duplexes under the Benton–Broken Bow Uplift.

Age

The Hartshorne Sandstone is the basal Desmoinesian unit in the region. It overlies with erosional contact the upper part of the Atoka Formation (Fig. 18) and is overlain conformably by the Desmoinesian McAlester Formation (Fig. 19).

Lithology

At this site the Hartshorne Sandstone (lower Hartshorne sandstone of Oklahoma) is ~215 ft thick and is composed dominantly of ripple-bedded and cross-bedded sandstone with many scour surfaces (Fig. 20). Paleocurrent directions are toward the west. The base of the sandstone is eroded into marine silty shales of the upper part of the Atoka Formation. The top of the sandstone package

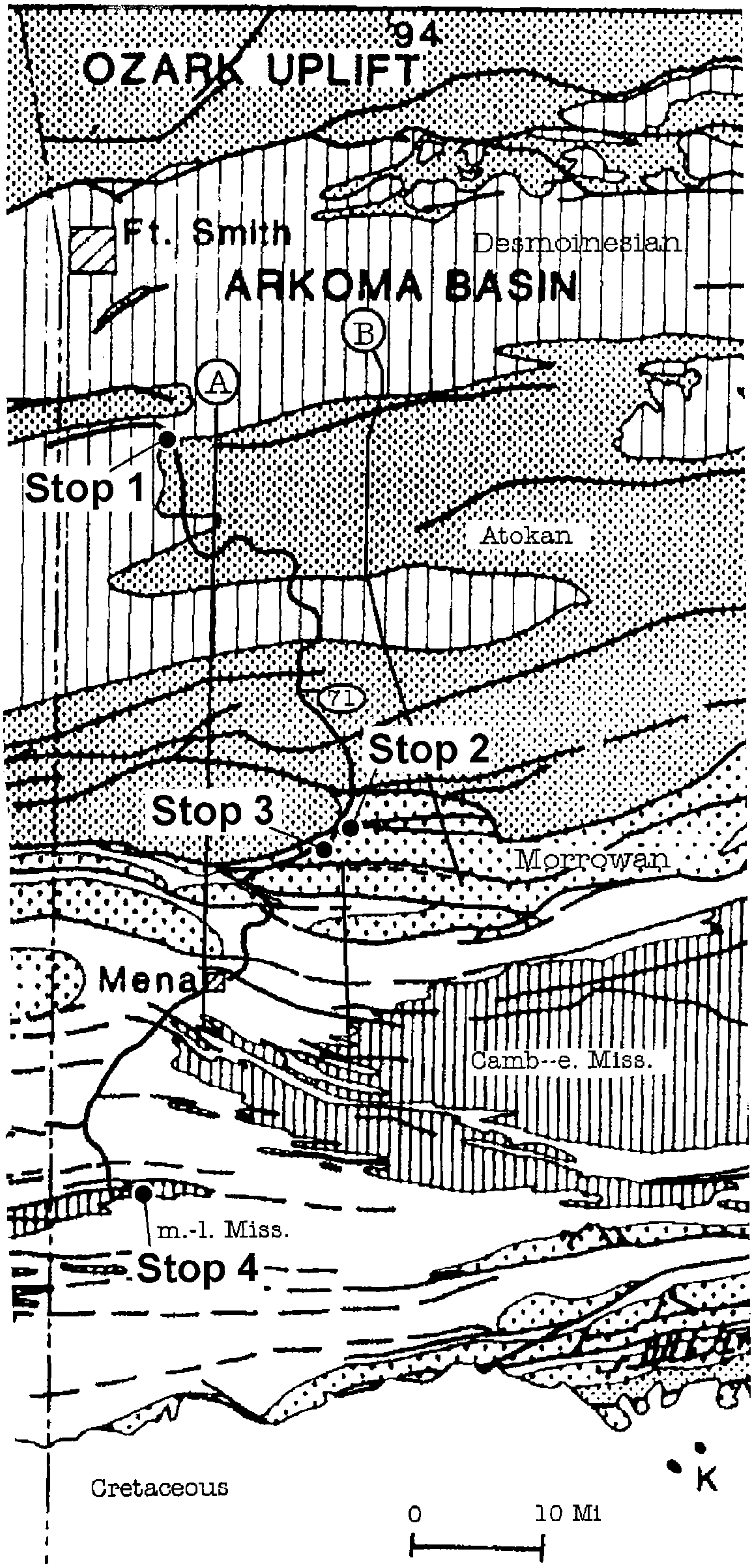

Figure 15. Simplifed geologic map of west-central Arkansas, showing U.S. 71, field-trip stops for Day One, and location of seismic lines used in cross sections (*A* and *B*). From Arbenz (1989a).

fines upward into coal-bearing shales of the McAlester Formation. The Hartshorne ranges from 10 to 300 ft thick across the area.

Depositional Environments

Rufus LeBlanc and Lloyd Yeakel (unpublished Shell Oil Company reports) interpret the Hartshorne Sandstone here (and in the excellent Jenny Lind Quarry exposures to the north) as a point-bar sequence of a major west-flowing meandering river. It may be amalgamated point-bar sequences with minor amounts of other channel deposits. It is eroded into prodelta deposits of the Atoka Formation and is overlain by delta-plain deposits of the McAlester. Throughout the Arkansas part of the Arkoma Basin the Hartshorne is dominantly a fluvial deposit with associated overbank sediments. However, delta-distributary and delta-front deposits occur in Oklahoma. Houseknecht (1983), on the other hand, has interpreted this Greenwood exposure of Hartshorne as a sequence of delta-front and distributary-channel deposits. No marine fossils have been found here in the Hartshorne, however. A thin marine shale that locally occurs on top of the Hartshorne may represent a minor highstand transgression. The Hartshorne represents part of the late-stage fill of the Arkoma Basin after the foredeep basin had been nearly filled with thick Atoka clastics and the sea had retreated into Oklahoma. The north-to-south deposition of the Atoka Formation (paleocurrents turning to the west in the deeper parts of the basin) was replaced by east-to-west-flowing streams, with a scatter of paleocurrent directions representing the meandering nature of the Hartshorne fluvial system. The Hartshorne Sandstone was deposited in a relatively narrow meander belt across central Arkansas.

Historical Note

A Civil War battle was fought at Devils Backbone in 1863. Union forces under General Blunt captured Fort Smith, and Colonel Cloud pushed southward through Jenny Lind with a force of Kansans, Missourians, and Indianans. A Confederate force under General Cabell stopped them at Devils Backbone and fought a delaying action. The battle raged for several hours and included artillery, cavalry, and infantry actions. Cabell withdrew his forces to Waldron after the battle. The Union forces withdrew to Fort Smith with Confederate prisoners.

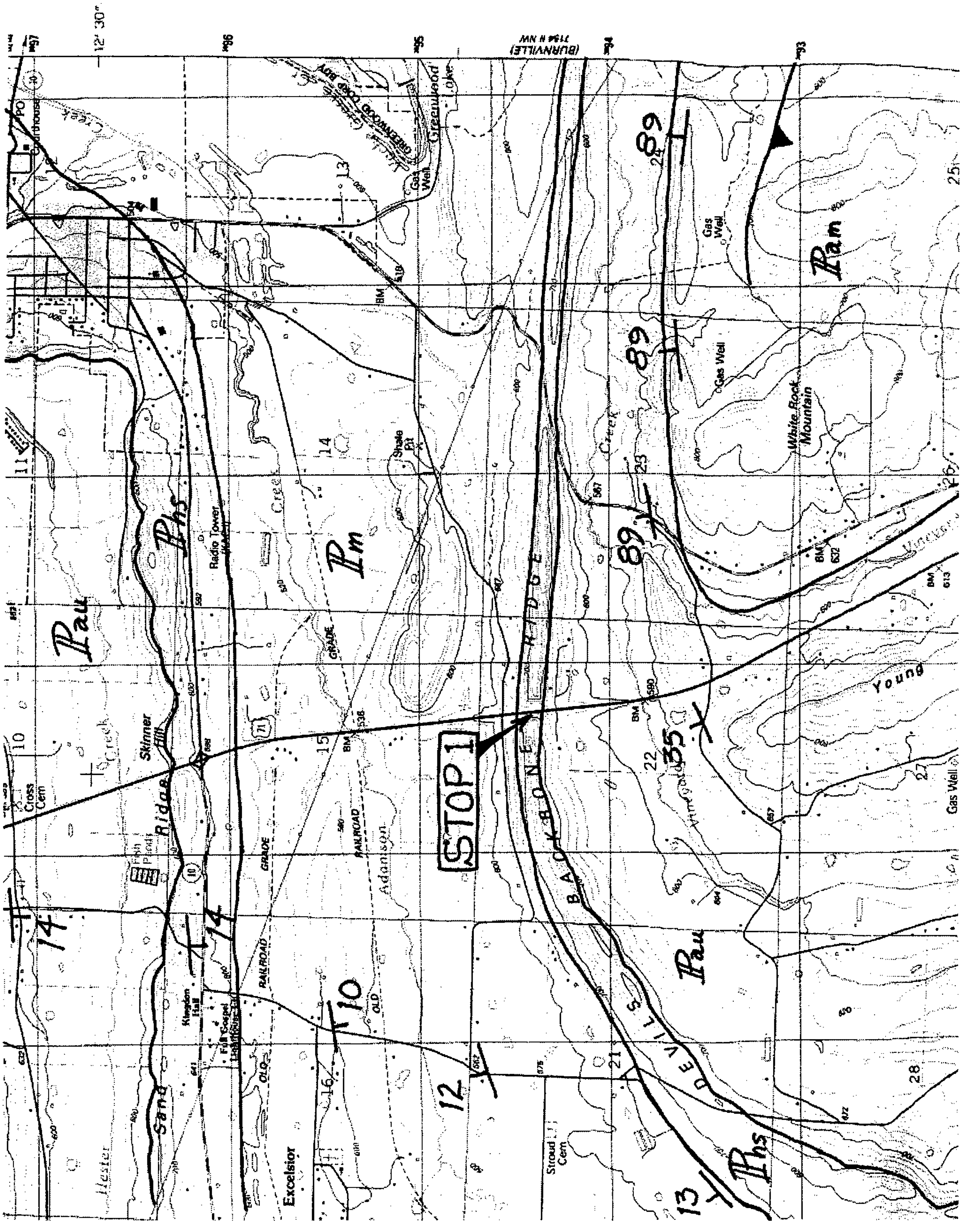

Figure 16. Geologic map of the area of Stop 1 (from Haley and Stone, 1995). Pam = middle Atoka Formation; Pau = upper Atoka Formation; Phs = Hartshorne Sandstone; Pm = McAlester Formation.

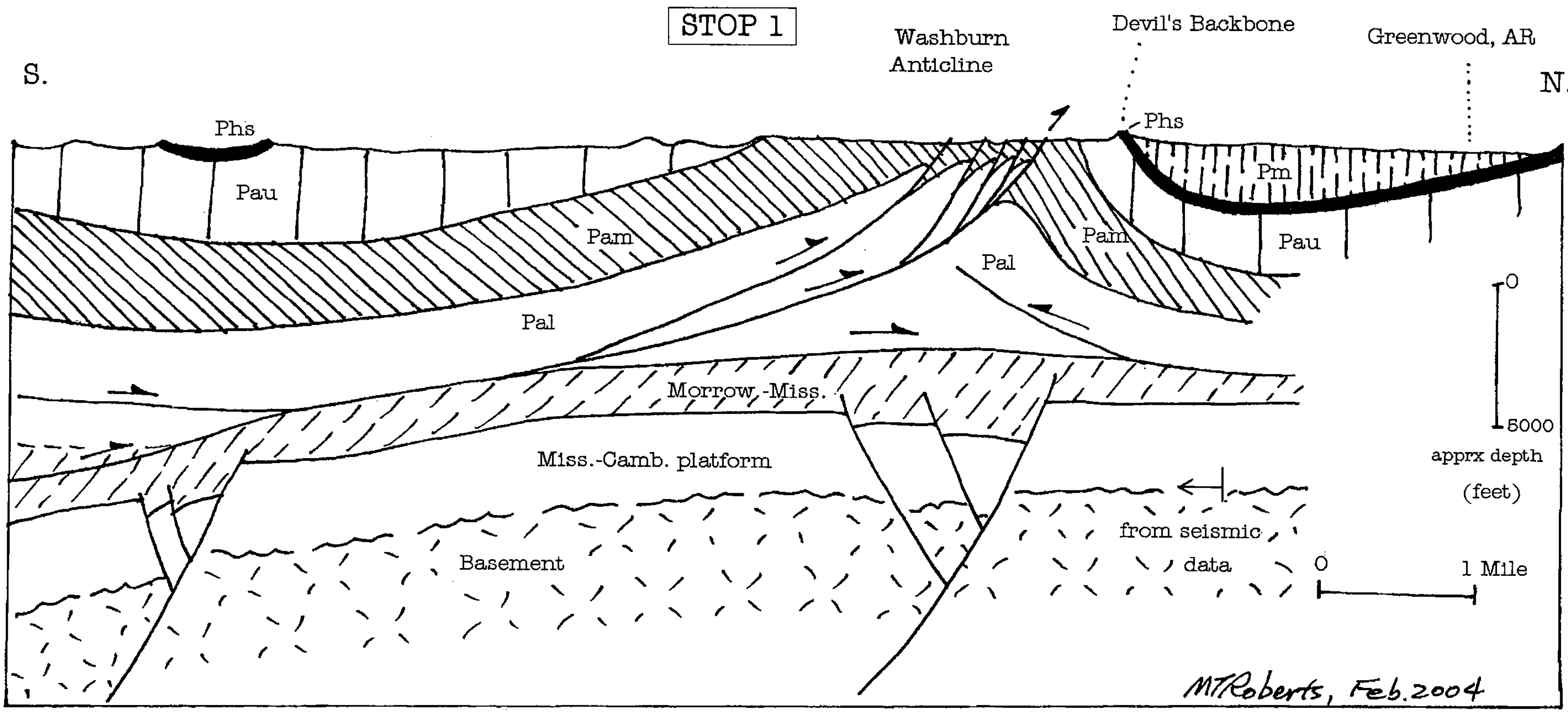

Figure 17. North–south cross section showing subsurface relations at Washburn Anticline–Devils Backbone (Stop 1), based on CGG seismic line 606 (~3 mi east of stop). Pal = lower Atoka Formation; Pam = middle Atoka Formation; Pau = upper Atoka Formation; Phs = Hartshorne Sandstone; Pm = McAlester Formation.

Figure 18. Stop 1: Hartshorne Sandstone, Devils Backbone Ridge south of Greenwood, Arkansas, U.S. 71 road cut. Photograph shows steeply north-dipping fluvial sandstones and their contact with prodelta siltstones and shales in the upper part of the Atoka Formation on the right (south). Pictured here is ~170 ft of Hartshorne (Ph) and 70 ft of Atoka (Pa) strata. The top of the Hartshorne is ~45 ft stratigraphically to the left (north) of photograph, where it grades into fine-grained clastic strata of the McAlester Formation.

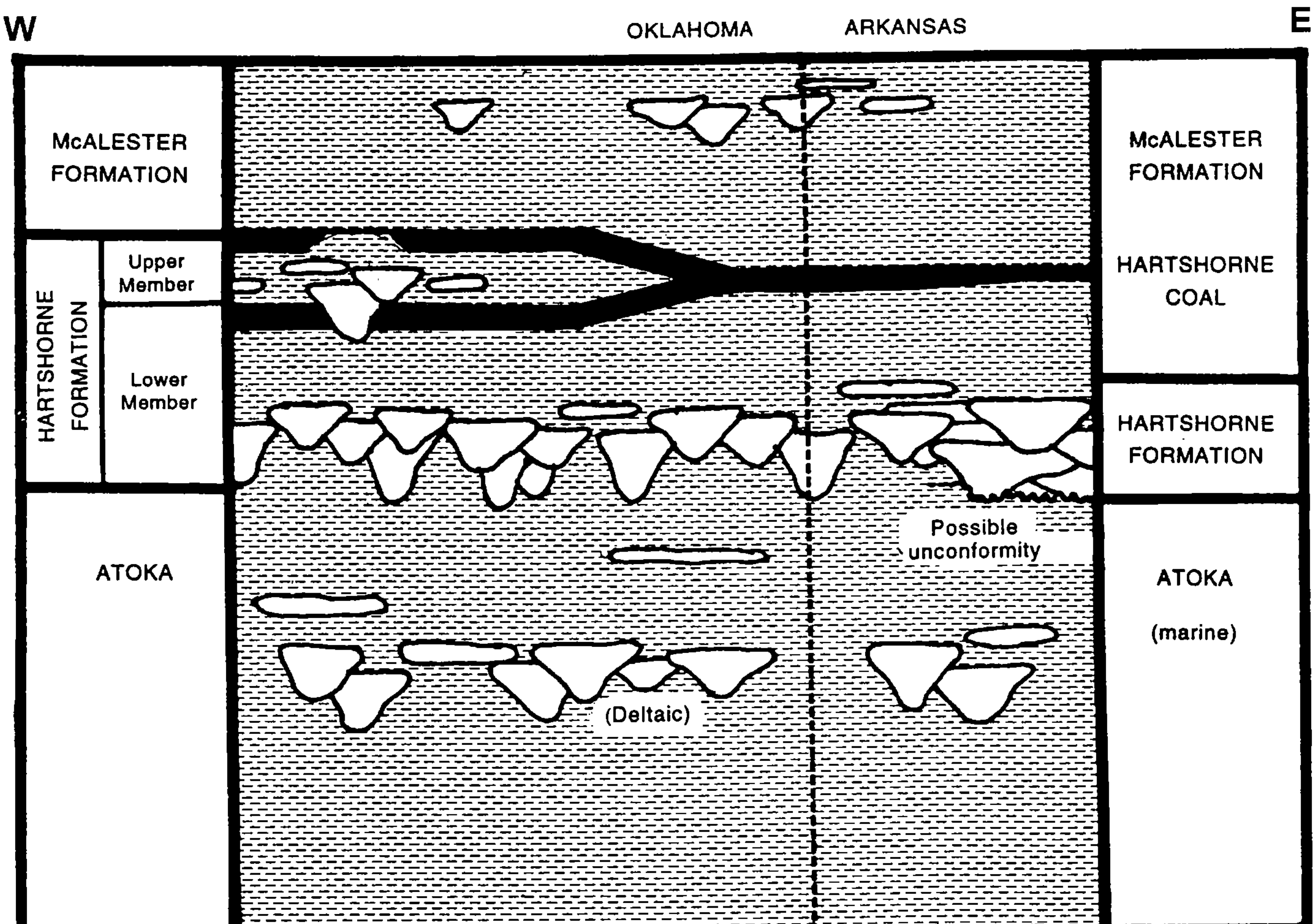

Figure 19. Stratigraphic relations of the Hartshorne Formation in Arkansas and Oklahoma (from Storm, 1998).

Figure 20. Close-up of cross-bedding in the Hartshorne Sandstone at Stop 1 (pencil for scale, about mid-photograph).

Discussion

Variations exist both in interpretation of the Hartshorne depositional environments and in the relationship between the Hartshorne Sandstone and underlying Atoka Formation. Some favor a point-bar origin of the sandstones around Greenwood, and others interpret the unit as more deltaic, with distributary channels and delta-front sands. Some think the basal contact of the Hartshorne is an unconformity, and others think it is a locally erosive conformable contact. More than 250 ft of the upper Atoka sequence may be missing at this contact in some places. The formation clearly was deposited during a period when the accommodation space of the basin had been nearly filled and slight changes in sea level could have had major paleogeographic consequences. Unlike the sections we will view at subsequent stops, the section here has not been tectonically transported far from its original site of deposition. It was simply "rumpled" up by late-stage deformation of the foredeep basin, possibly related to the emplacement of the basement duplex under the Benton–Broken Bow Uplift in the Late Pennsylvanian/Early Permian.

Continue south on U.S. 71.

SUBSURFACE GEOLOGY ALONG ROUTE OF DAY ONE

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Figure 21A,B shows cross sections interpreted from CGG seismic data in western Arkansas, and extended using the surface geology of Haley and Stone (1995) (Fig. 15). Cross section A (Fig. 21A) is along CGG line 606, and cross section B (Fig. 21B) is along CGG lines 1 and 6. These sections are included as a regional overview of the geology along most of the route of Day One. The depth values of the cross sections are shown in seconds of traveltime, but a general idea of depth can be obtained by using average velocities of 12,000–13,500 ft/sec. Note the differences between these two cross sections, especially in the vicinity of the Ross Creek Fault, despite the fact that they are only 11 to 18 mi apart. Stop 1 is on the north flank of the Washburn Anticline at the north end of these sections. Stops 2 and 3 are in the frontal Ouachita Mountains south of the Y City Fault. Stop 4 is in the Benton Uplift south of the two cross sections, but in a geologic setting similar to that seen at the south ends of the cross sections.

33.0 0.5 Small thrust faults in north-dipping thin sandstones and shales of the upper part of the Atoka Formation.

33.3 0.3 Axis of the west-plunging Washburn Anticline; minor exposures of upper Atoka Formation; natural-gas wells are visible nearby.

Several major gas fields lie along this anticline. The Booneville field has increased its annual production from ~4.0 Bcf gas in 1992 to ~10.5 Bcf gas in 2003 (Fig. 14). The nearby Gragg field has increased its annual production from ~5.0 Bcf gas in 1992 to ~13.5 Bcf gas in 2003 (Fig. 14). Likewise, the Chismville field has increased annual production from ~1.6 Bcf gas in 1992 to ~6.6 Bcf gas in 2003 (Fig. 14). Production is from Atokan sandstones.

35.2 1.9 Gently southwest-dipping upper Atoka sandstones in road cut to west.

36.5 1.3 Witcherville, Arkansas; location of Witcherville gas field, which produced ~1.5 Bcf gas in 2003 (Fig. 14).

37.2 0.7 Leave Greenwood 7.5′ quadrangle; enter Huntington 7.5′ quadrangle.

38.3 1.1 Junction with S.H. 252. Continue straight (south) on U.S. 71. Dip slope on upper Atoka strata inclined to south; axis of Midland Anticline begins ~0.5 mi to the west.

39.9 1.6 Reclaimed open-pit mine in Lower Hartshorne coal in the Huntington–Hartford coal district to the west. Cross axis of the west-plunging Cavanal Syncline.

A

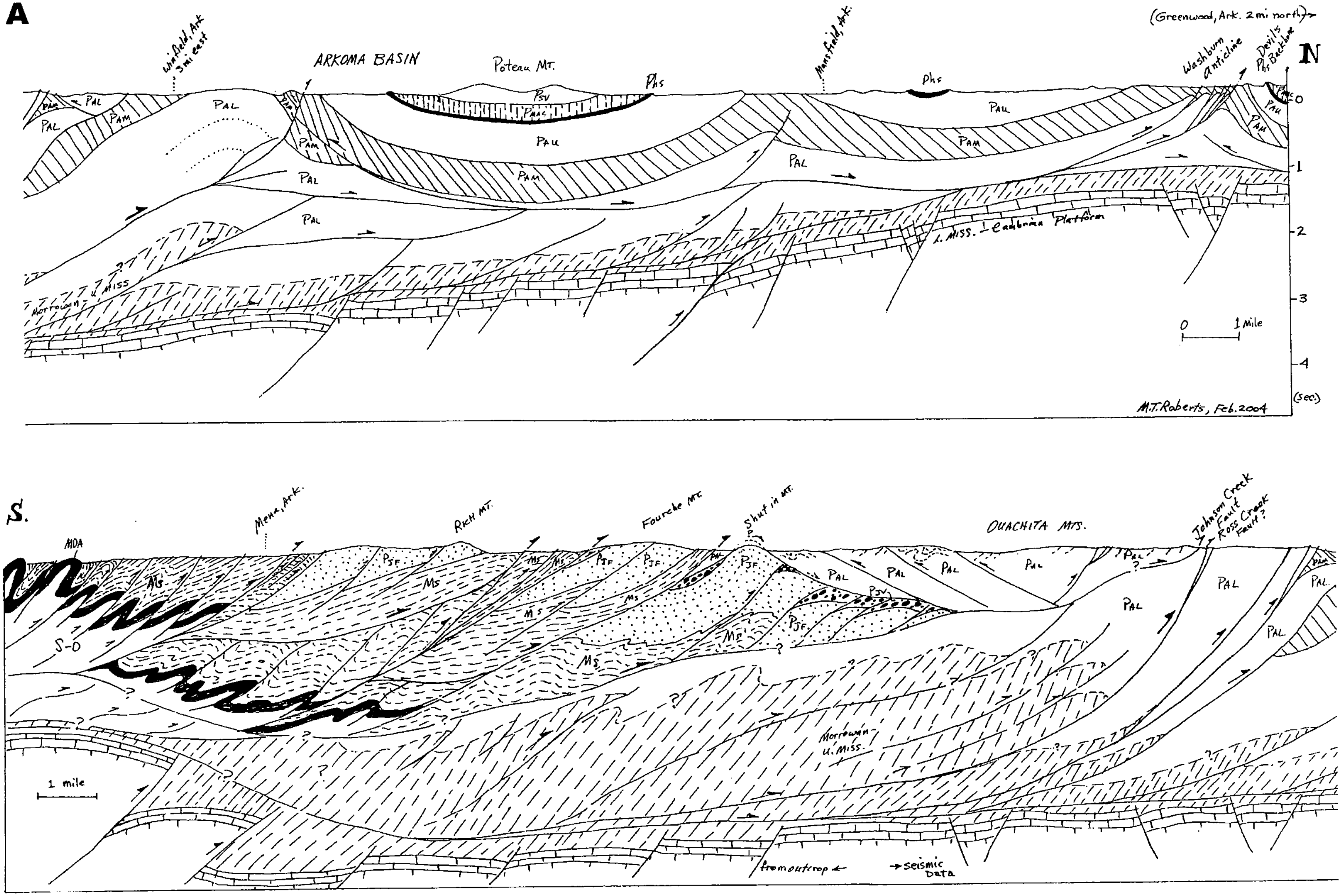

Figure 21. (A) Cross section A along CGG seismic line 606 in western Arkansas, with extension south of Mena, Arkansas, using surface geology of Haley and Stone (1995). S–O = Silurian and Ordovician units; MDa = Arkansas Novaculite; Ms = Stanley Group; Pjf = Jackfork Group; Pjv = Johns Valley Formation; Pal = lower Atoka Formation; Pam = middle Atoka Formation; Pau = upper Atoka Formation; Phs = Hartshorne Sandstone; Pmac = McAlester Formation; Psv = Savanna Formation. *(Part B of this figure is shown on next page.)*

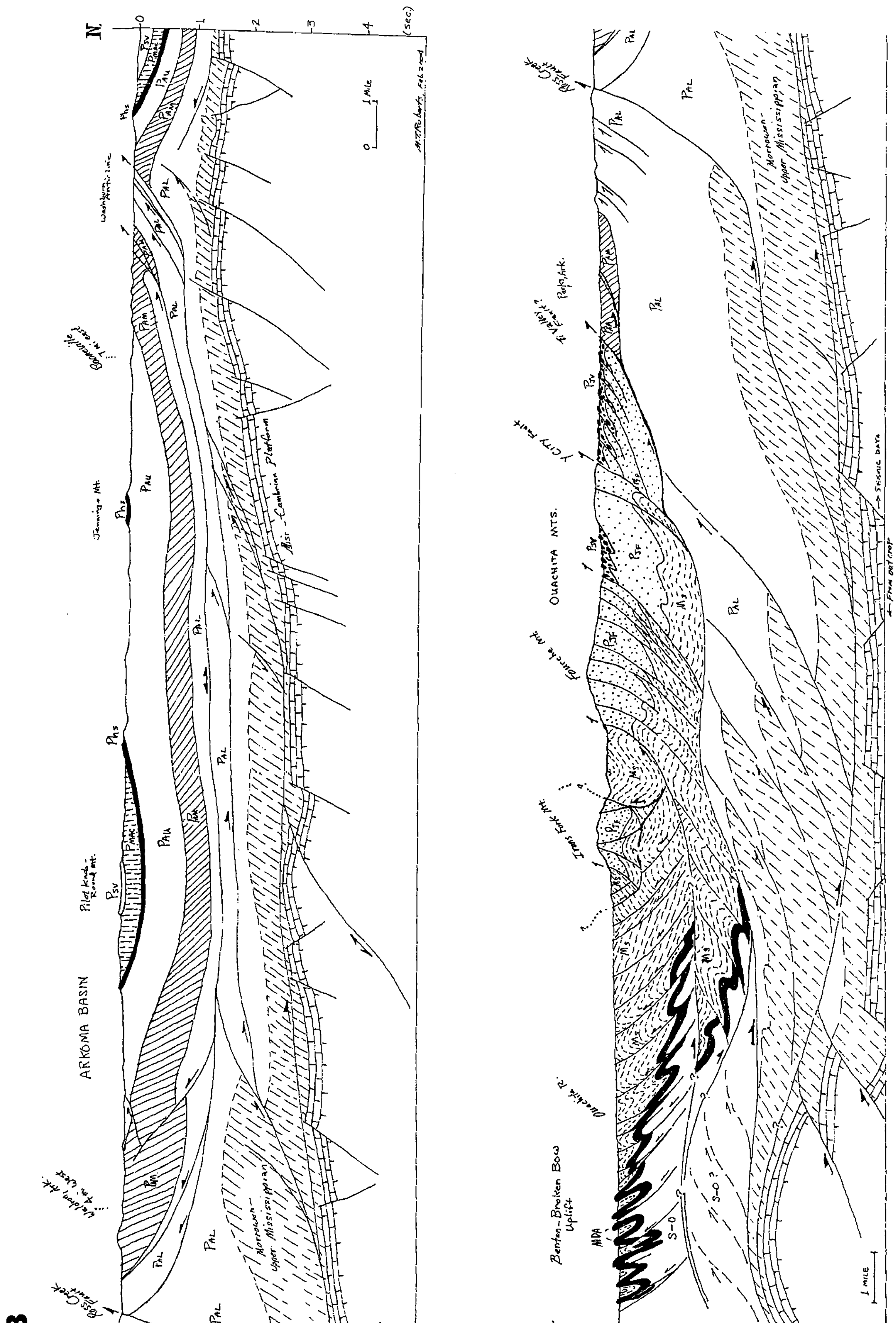

Figure 21. (B) Cross section B along CGG seismic lines 1 and 6 in western Arkansas, with extension south of Y City, Arkansas, using surface geology of Haley and Stone (1995). S–O = Silurian and Ordovician units; MDa = Arkansas Novaculite; Ms = Stanley Group; Pjf = Jackfork Group; Pjv = Johns Valley Formation; Pal = lower Atoka Formation; Pam = middle Atoka Formation; Pau = upper Atoka Formation; Phs = Hartshorne Sandstone; Pmac = McAlester Formation; Psv = Savanna Formation. *(Part A of this figure is shown on page 27.)*

40.2 0.3 Huntington, Arkansas; junction with S.H. 252 to right (west). Continue straight (south) on U.S. 71.

40.5 0.3 North-dipping Hartshorne Sandstone and erosional contact with upper Atoka shale and siltstone.

41.1 0.6 Leave Sebastian County and enter Scott County, Arkansas. Leave Huntington 7.5′ quadrangle; enter Abbott 7.5′ quadrangle. Gently north-dipping upper Atoka sandstone and shale in road cuts.

41.2 0.1 Junction with State Highway 96. Continue straight (south) on U.S. 71. Exposure of upper Atoka on north flank of Hartford Anticline.

41.5 0.3 Mansfield, Arkansas; site of the Mansfield gas field, which includes the oldest commercial gas production in Arkansas (1902). The field produces from sandstones in the middle part of the Atoka Formation; beds of the upper Atoka are seen at the surface around Mansfield, and middle Atoka units are exposed in the core of the Hartford Anticline 1–2 mi south of town. The Mansfield field produced ~2.8 Bcf gas in 2003 (Fig. 14) (data courtesy Scott Bruner and Debbie Fritsche, Arkansas Oil and Gas Commission).

The first producing natural-gas well in Arkansas was the Choctaw Oil and Gas Company No. 2 Duncan, ~1 mi south of Mansfield in sec. 1, T. 4 N., R. 31 W. The well was drilled to a total depth of 1,125 ft, completed in March 1902, and had a reported initial production of 550 Mcf gas per day. The well was still flowing in January 1934. At present there are no records for this individual well after 1934. In the early 1950s, ~13 shallow Mansfield field gas wells were commingled for production purposes, and likely it was included.

44.6 3.1 Abbott, Arkansas. The highway follows the north flank of the Hartford Anticline from Mansfield to Abbott across gently dipping upper Atoka strata.

45.6 1.0 Approximate axis of Hartford Anticline. Gas wellheads are visible here.

45.9 0.3 Gas wells along highway.

47.8 1.9 Leave Scott County; enter Logan County, Arkansas.

48.2 0.4 Bridge over upper Petit Jean River.

48.4 0.2 Upper Atoka Formation deltaic sandstones and marine shales with low south dips.

48.8 0.4 Leave Logan County; enter Scott County, Arkansas.

49.1 0.3 Leave Abbott 7.5′ quadrangle; enter Ione 7.5′ quadrangle.

49.8 0.7 Boothe, Arkansas. Upper Atoka strata dip gently south.

50.8 1.0 Junction with State Highway 23. Continue straight (south) on U.S. 71.

51.0 0.2 Rest area on east side of road. Stop for brief break and discussion of Waveland field by Kim Butler.

RESTORATION OF THRUSTED MIDDLE ATOKA RESERVOIR TRENDS, WAVELAND FIELD, YELL COUNTY, ARKANSAS

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The Waveland field is a gas-development project along the crest of the Ranger Anticline (Fig. 22; Fig. 14). The field, which produces from middle Atoka turbidites at depths of 1,800–7,400 ft, is being developed on 80-acre spacing without tight seismic control, because existing seismic data on the anticlinal crest exhibit indecipherable noise owing to the extreme dips and structural complexity. This drill spacing is regulated on the basis of the structural complexities and limited drainage of gas from the middle Atoka reservoirs. At present, the field produces from 31 wells, with a combined cumulative production of 9.6 Bcf gas.

The Ranger Anticline is in the southern Arkoma Basin between the Poteau and Mount Magazine Synclines. It is an east–west-trending, asymmetric, north-vergent anticline cored by antiformal stacked duplex thrust sheets that repeat middle Atoka clastic reservoirs (Fig. 23). These faults have individual offsets of a few hundred to >7,000 ft, but they do not offset the upper Atoka Alma sandstone ridges surrounding the field. The thrusts flatten in upper Atoka shales below these ridges.

The permeability of the middle Atoka reservoirs ranges from <0.001 to 2.13 md, and porosity ranges from 3% to 17%. The sandstones are fine to very fine grained, poorly sorted sublitharenites with >7% clay matrix. Every well is hydraulically fractured to enhance the natural fracture system, because the effective permeability is not sufficient for economic production.

The Upper Borum sandstone (middle Atoka) is >600 ft thick; sandstones in the Upper Borum are quartzarenites to sublitharenites. Reservoir units have gamma-ray values <70 API units (Fig. 24). Porosity ranges from 3% to 17% (>8% filled), but permeability ranges from <0.001 to 1.09 md (Fig. 25). Cementation is dominantly clays (chlorite–illite–smectite) with quartz overgrowths and dolomite/calcite. The formation has been subdivided into three fining-upward parasequences (A, B, and C sandstones) that are interpreted to be deep-water clastic strata. The main sandstones in these parasequences range from a few feet to >100 ft of net sand. The sandstones have sharp basal contacts above marine shales and appear to have filled a middle Atoka paleotopographic low. The shale below sandstone C is regional; shales below sandstones A and B are more local.

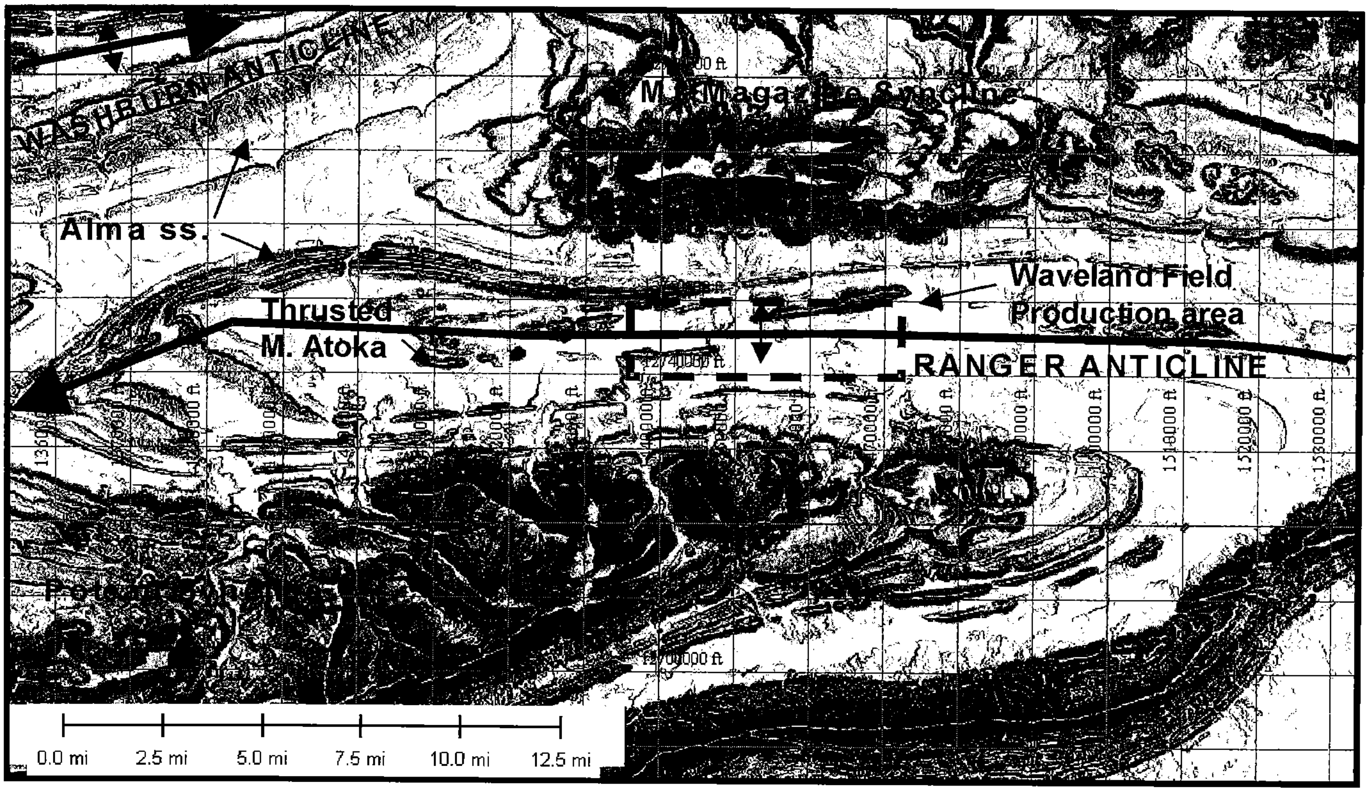


Figure 22. Digital elevation model of the Ranger Anticline (from National Elevation Dataset, http://seamless.usgs.gov/).

Balanced cross sections were utilized to restore the thrust offsets and trend maps for the parasequences (Fig. 26). The pre-thrust trend maps indicate that each parasequence is a channelized turbidite fan. The restoration of the porosity trends has been a key factor in determining the areal extent of the reservoirs and in successfully predicting the offset locations for development of this field.

51.2	0.2	Hartshorne Sandstone on gently south-dipping north flank of Poteau Syncline. Thin Lower Hartshorne coal is present at top of sequence. One to two miles to the west, the coal was thick enough to mine.
51.5	0.3	Lower McAlester Formation sandstone with low south dips. This sandstone may be equivalent to the upper Hartshorne Formation of Oklahoma. Two coal seams occur in the lower McAlester. Upper Petit Jean River to east.
51.6	0.1	Elm Park, Arkansas. Junction with State Highway 378. Continue straight (south) on U.S. 71. Granite Mountain Quarries is currently testing the Hartshorne Sandstone near here for a future large aggregate quarry.
52.5	0.9	McAlester sandstones and shales dipping 14° south.
53.0	0.5	McAlester shale exposure.
53.1	0.1	Leave Ione 7.5′ quadrangle; enter Waldron 7.5′ quadrangle.
54.3	1.2	Approximate axis of Poteau Syncline; small exposures of flat-lying lower Savanna sandstone and shale. Enter Ouachita National Forest.
55.9	1.6	Square Rock Lake to south, used as auxiliary water supply for Waldron, Arkansas. North-dipping lower McAlester shale on south flank of Poteau Syncline. Thin Lower Hartshorne coal here thickens westward to >4 ft near Bates, Arkansas, where it is mined, and extends to Forester, Oklahoma, where it is also mined.
56.2	0.3	Thin, north-dipping (37°) Hartshorne Sandstone.
56.6	0.4	Upper Atoka deltaic to marine sandstone and shale dipping 45° north.
57.0	0.4	Steep (50° N.) north flank of the Hon Anticline, with exposures of the contact between upper Atoka shale and the middle Atoka "traceable three" deltaic sandstones.
57.4	0.4	Junction with State Highway 28. Continue straight (south) on U.S. 71.
58.1	0.7	Junction with U.S. Highway 71B. Continue straight (south) on U.S. 71. Waldron, Arkansas, and Poteau River nearby. The concealed trace of the Choctaw Fault, regarded as the leading-edge fault of the Ouachita Mountains in Oklahoma, is near here along the axis of the Hon Anticline.

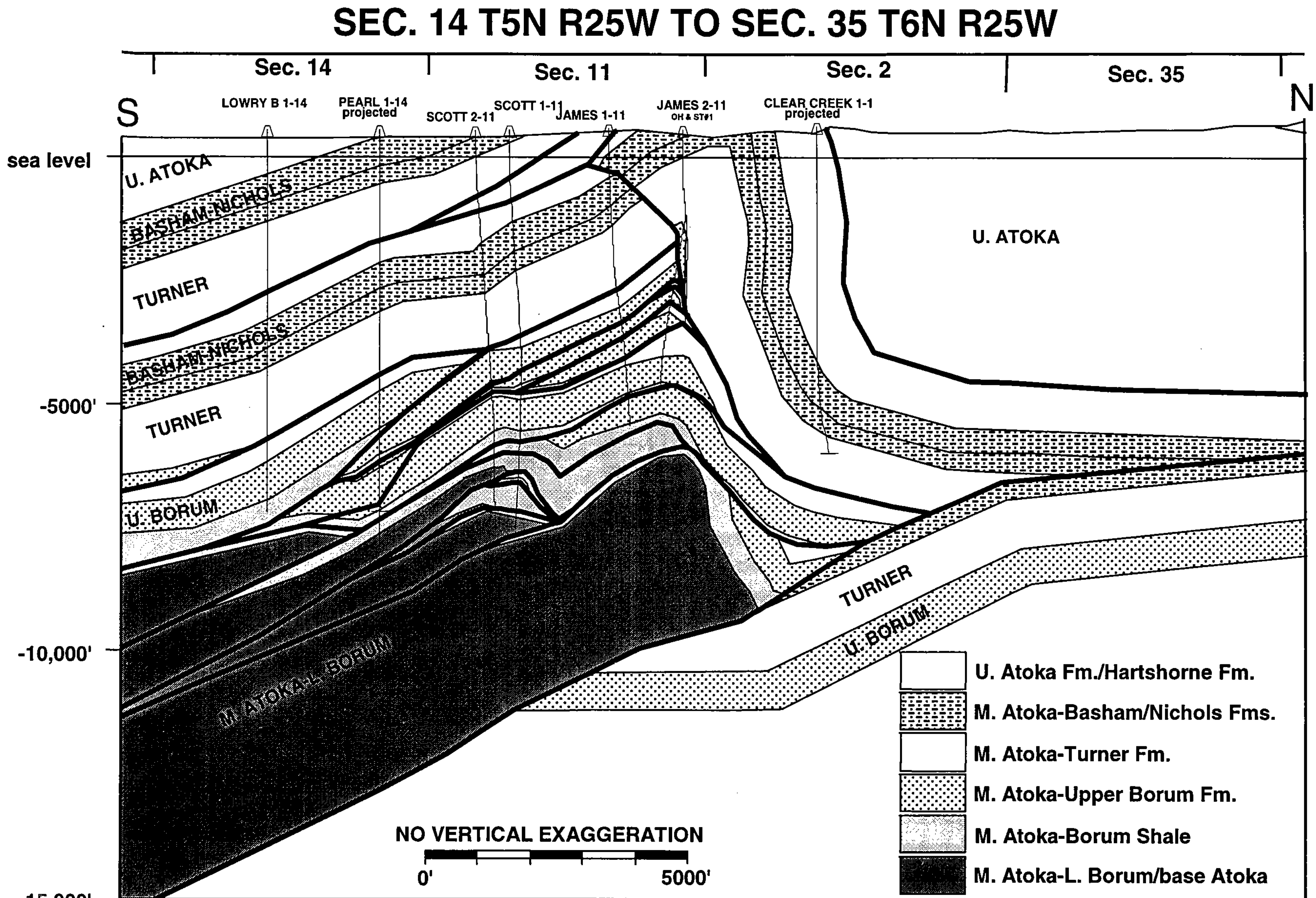


Figure 23. North–south cross section through the Waveland gas field. Productive units are the middle Atoka Basham/Nichols, Upper Borum, and Lower Borum sandstones.

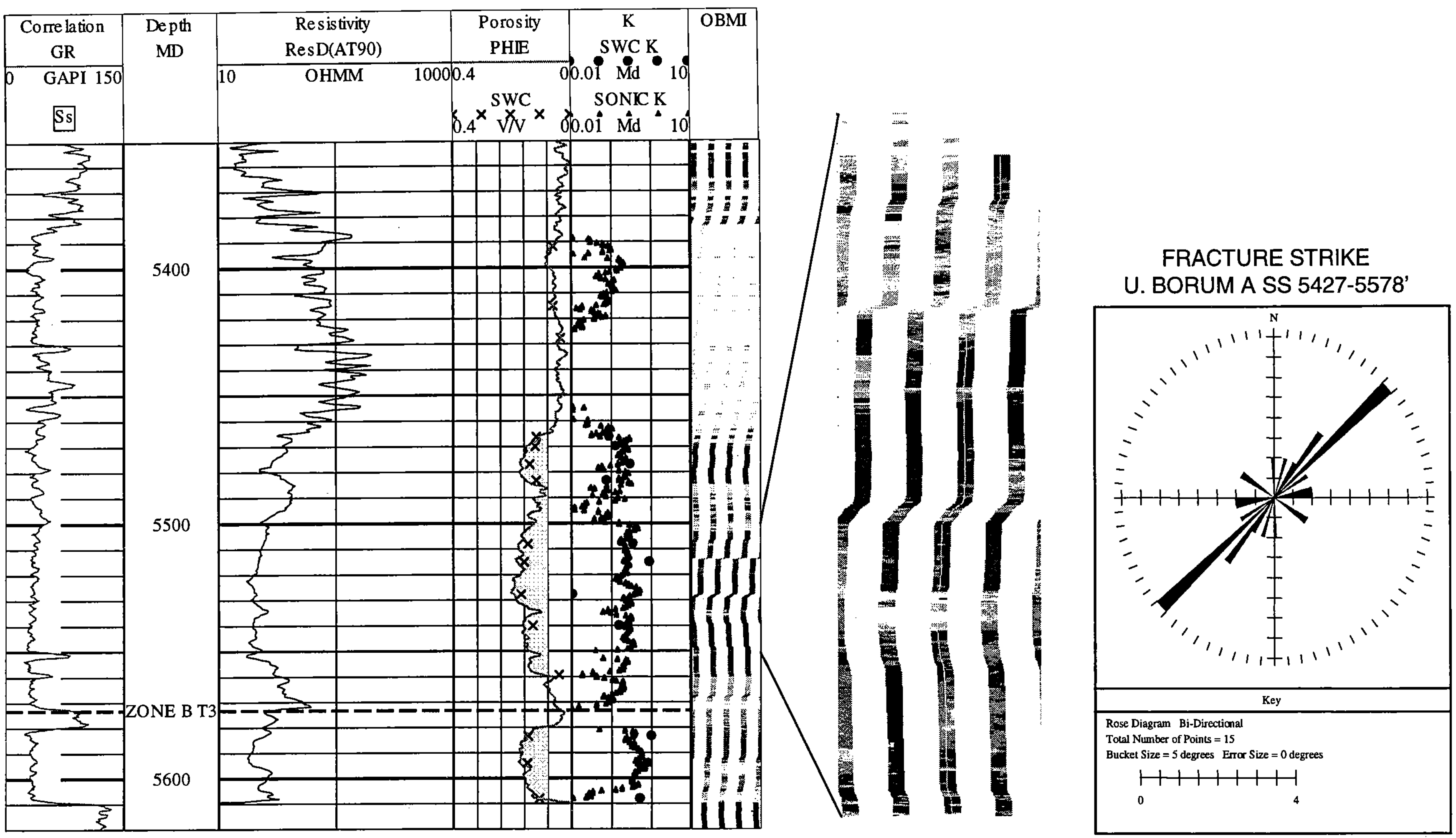


Figure 24. Type log of the Upper Borum sandstone. The perforated interval is shown by the box in the depth track. The log has been correlated to sidewall cores shown by the Xs (percent porosity) and the solid circles (permeability, *k*, in md). Estimated permeabilities from the dipole sonic are shown by the solid triangles. A Schlumberger oil-based-mud imaging log shows the details of bedding across a thick porous zone. The dark color on this image is related to the resistivity, not to thick interbedded shales. Fracture strikes from the imaging log are shown in the rose diagram.

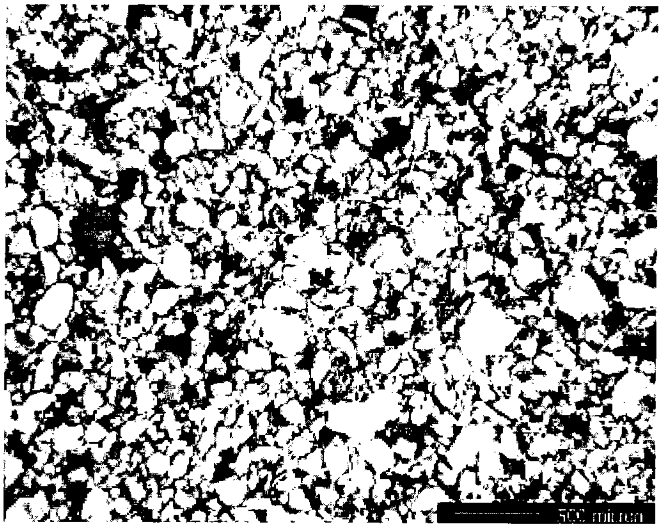


Figure 25. Thin section of rotary sidewall core representative of high-porosity zones in the Upper Borum sandstone. Measured porosity in this sample is 13.4%. Air permeability is 0.929 md. Porosity is dominated by intergranular porosity but includes lesser amounts of microporosity associated with the clay matrix and some intragranular porosity within partially dissolved grains. (Analysis by PTS Labs & Geosystems, Houston, Texas.)

58.6	0.5	South-dipping middle Atoka sandstones, south flank of Hon Anticline.
59.6	1.0	Contact of middle and upper Atoka units.
59.8	0.2	Kansas City Southern Railroad track crossing.
60.2	0.4	Junction with State Highway 80. Continue straight (south) on U.S. 71. Axis of Waldron Syncline here in upper Atoka shale.
60.8	0.6	Junction with State Highway 248. Continue straight (south) on U.S. 71.
60.9	0.1	Contact of upper and middle Atoka on south flank of Waldron Syncline. Strata dip 10° N.
61.1	0.2	Junction with State Highway 272. Continue straight (south) on U.S. 71. North-dipping middle Atoka deltaic sandstones.
62.0	0.9	Leave Waldron 7.5′ quadrangle; enter Boles 7.5′ quadrangle.
62.4	0.4	Exposures of north-dipping middle Atoka sandstones.
63.0	0.6	Poorly exposed minor thrust fault in middle Atoka.
63.2	0.2	Truman Baker Park fishing lake to west in middle Atoka deltaic strata that dip 40° N. Junction with U.S. 71B. Continue straight (south) on U.S. 71.
64.2	1.0	Middle Atoka proximal deep-water strata with 60° dip to N.
64.7	0.5	Broad valley underlain by thick interval of middle Atoka shale (Washburn Shale). This unit is 3,200 ft thick near Waldron.
64.9	0.2	Bridge over Ross Creek and the concealed, major Ross Creek Fault. Several other thrusts are also present and form a triangle zone.

Lower Atoka strata were thrust many thousands of feet north over middle Atoka shale along the Ross Creek Fault. The lower Atoka sediments were deposited as deep-water turbidites generally transported east to west along the axis of the developing Arkoma Basin foredeep.

65.6	0.7	A branch of Ross Creek Fault zone trends east–west along this valley in lower Atoka strata. Ouachita National Forest next 20 mi.
67.8	2.2	Exposures of south-dipping lower Atoka deep-water facies.
68.1	0.3	Needmore, Arkansas, and junction with S.H. 28. Continue straight (south) on U.S. 71. Valley to south underlain by Washburn Shale (middle Atoka). A mostly concealed north-directed thrust fault occurs here.
69.4	1.3	Steeply south-dipping lower Atoka sandstones and shales form ridge to west.
69.7	0.3	Concealed trace of the fault correlated with the Ti Valley Fault of Oklahoma.

Ouachita deep-marine-facies strata, exposed south of the fault trace, were thrust-faulted many miles to the north over Arkoma Basin–facies strata, which are not far from their original sites of deposition. Lower and middle Atoka strata are present to the north, and the Morrowan Johns Valley Formation is present to the south, of the fault trace.

70.4	0.7	Boles, Arkansas. Exposures of Johns Valley Formation with erratic blocks of shelf limestones, dolostones, and other rocks occur ~0.5 mi east–northeast of Boles, along the northwest bank of the Fourche La Fave River.

Potential Exploration Targets in the Frontal Belt

Natural-gas accumulations and aggregate-quarry sites may exist near Boles, but are as yet undeveloped. Their evaluation is difficult because of complex thrust faulting and uncertain correlations with the economically important units of the region. A possible aggregate site lies 12–14 mi west of Boles on Horseshoe Mountain, where ~600 ft of mostly clean, medium-grained quartzarenites occur at the top of the lower part of the Atoka Formation. These strata probably are deep-water sheet sandstones. They are likely the downdip equivalent of deltaic sequences mapped as zones 58–62 in subsurface-correlation well-log charts of the Atoka in the Arkoma Basin by Haley (1982) and Gilbreath and Haley (1982).

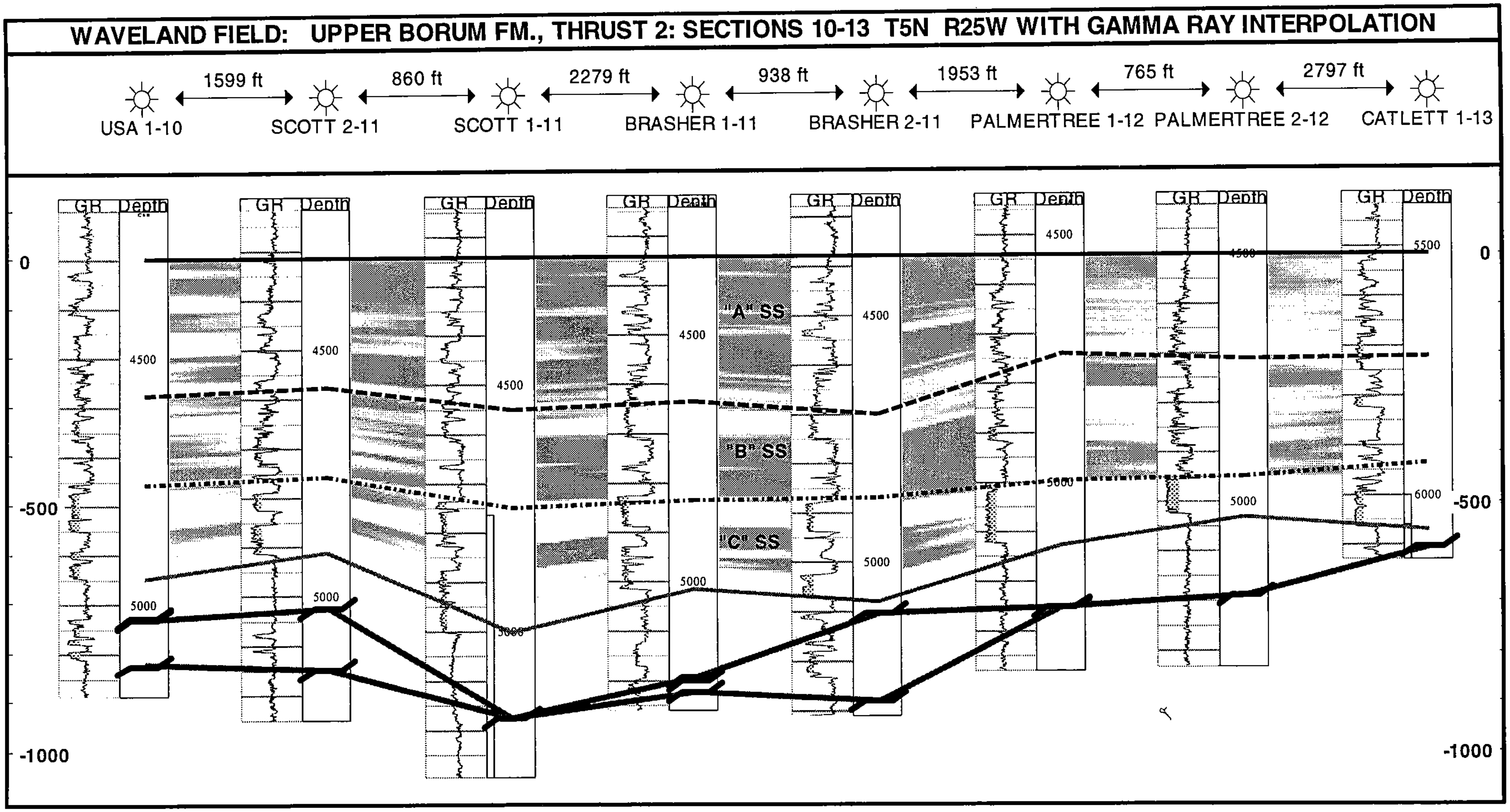


Figure 26. Upper Borum sandstone in these wells is believed to be unfaulted. The datum of the profile is the top of the Upper Borum. Relative distances are shown between wells. The gray-scale colors denote clay-matrix-rich sandstones, siltstones, or shale with gamma-ray values >70 API units. Net sand is based on gamma-ray values <70 API units, shown as white in this cross section.

A second locality of interest is ~1.5 mi south of the Horseshoe Mountain site, north of Eagleton, Arkansas. Here, ~400 ft of quartzarenite, with some calcareous fossiliferous sandstone beds, is present in the lowermost Atoka Formation. These deposits probably are deep-water equivalents of the shallow-marine Spiro sandstones (zones 108 and 109 of Haley, 1982; Gilbreath and Haley, 1982), which are prolific gas producers to the north and west. (See also Stops 9, 10, and 12 by Dennis Kerr, this guidebook.) These units may have been deposited as deep-water channelized sheets that are several miles wide. We agree with Longden and others (2000) that the Spiro strata represent a time of lowstand deposition that immediately followed a highstand near the end of Bloyd Shale time (late Morrowan). Cross sections across the frontal belt drawn from seismic-reflection data indicate that the Spiro-equivalent sandstones could be present in the subsurface in duplex thrust structures beneath the Johnson Creek and Ti Valley thrust sheets. These deeper structures may also involve older Morrowan and Chesterian clastic strata equivalent to the Jackfork and Stanley Groups.

72.6 2.2 Bridge over Fourche La Fave River.

The Johns Valley Formation, containing olistoliths of exotics, is exposed in river and creek banks to the west. At the base of the mountain to the west the low-angle Johnson Creek Fault separates overlying lower Atoka strata in the hanging wall from the thrust-faulted Johns Valley Formation in the footwall. More than 15,000 ft of Atoka deep-water sandstones and shales apparently were carried east and north many miles. The relationships are not clear, however, and the structure is an unusual "younger over older" thrust or "roof fault" over a duplex structure. Kaspar Arbenz (in preparation) interprets the structures as parts of a partially exhumed triangle zone. The synformal lower Atoka above the Johnson Creek Fault contains sandstones correlated with the Oklahoma Spiro sandstone.

Granite Mountain Quarries is planning to begin operations on a large aggregate quarry at this site.

73.5 0.9 Leave Boles 7.5′ quadrangle; enter Y City 7.5′ quadrangle.

73.7 0.2 Old aggregate quarry to west, which used alluvial cobbles and gravel from Mill Creek terraces for local road building. Exposures of Johns Valley Formation ~2 mi east–northeast contain many limestone and shale exotic masses and lenses.

73.9 0.2 Y City Thrust Fault, separating Johns Valley Formation in the footwall to the north from tightly folded middle Jackfork Group strata in the hanging wall to the south. These two Morrowan units lie stratigraphically below the Atoka in a normal sequence, with the Johns Valley being the uppermost Morrowan formation.

74.2 0.3 Thrust-faulted axis of the Mill Creek Anticline in middle Jackfork strata.

74.4 0.2 Park on right (west) side of highway in front of the "Y" City Mountain Inn, where Mr. John Heinen has granted access to the site. Heavy traffic, be careful!

Permission to park on the properties of the "Y" City Mountain Inn and also to access other unique exposures in Mill Creek (west) has been kindly granted by John and Patricia Heinen. If you wish to further investigate the strata at this site, please contact Mr. and Mrs. Heinen well in advance

STOP 2

MIDDLE JACKFORK SANDSTONE, Y CITY

Michael T. Roberts
Palmer Petroleum, Inc.

Charles G. Stone
Arkansas Geological Commission

Location: Road cuts on U.S. 71 just north of Mill Creek bridge and intersection of U.S. 71 and U.S. 270, Y City, SE¼SE¼SE¼ sec. 16, T. 1 N., R. 29 W., Scott County, Arkansas

Structural Setting

Stop 2 is located in the Ouachita frontal thrust belt ~0.5 mi south of the Y City Fault (Fig. 27) and is within the northern belt of exposures of the Jackfork Group in Arkansas. Sandstone and shale here strike N. 85° E. and dip 70–90° south–southeast. The Mill Creek Anticline is part of the Y City and Ti Valley thrust sheets and was thrust northward over deformed lower Atoka and older units. These sheets are, in turn, overlain by north-directed thrust sheets that consist of the Jackfork and Stanley Groups and probably older strata at depth (Fig. 28). Seismic data to the west of this area indicate that these north-directed thrusts, with Ordovician(?) to Lower Pennsylvanian deep-water facies in their hanging walls, merge into a low-angle detachment zone at about –15,000 ft. These data also are suggestive that block-faulted Mississippian(?) to Cambrian shallow-water shelf units, overlying cratonic Precambrian basement, lie at about –25,000 ft or more. Duplexes of Mississippian–Pennsylvanian clastic strata may be present between the block faults and the detachment. Here, the Jackfork strata may have been tectonically transported >40 mi north of their original site of deposition, on the basis of cross-section reconstructions.

Age

The Jackfork Group was once considered to be Chesterian but is now known to contain early Morrowan am-

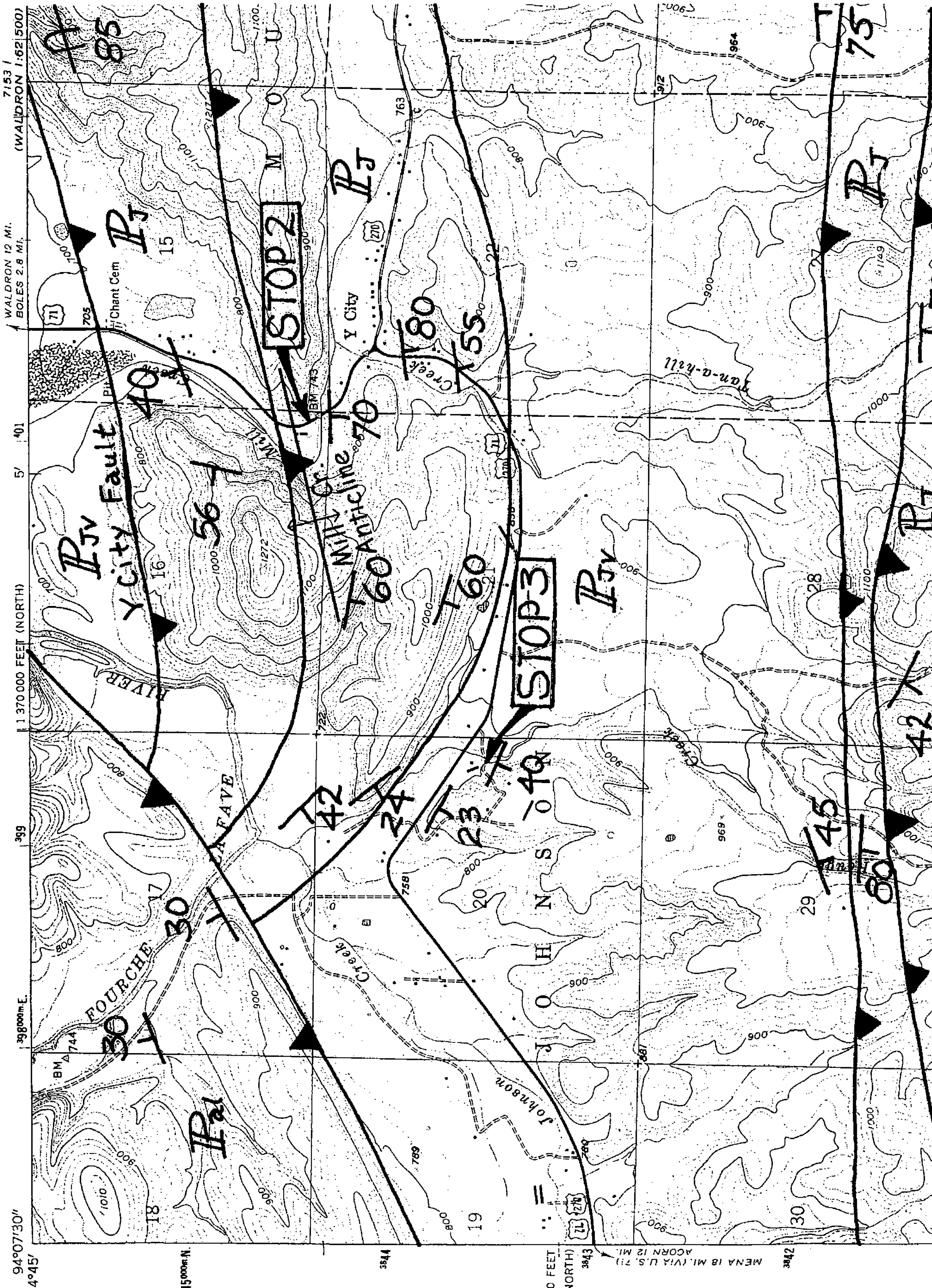


Figure 27. Geologic map of the Y City area (Stops 2 and 3) (from Haley and Stone, 1995). Pal = lower Atoka Formation; Pjv = Johns Valley Formation; Pj = Jackfork Group.

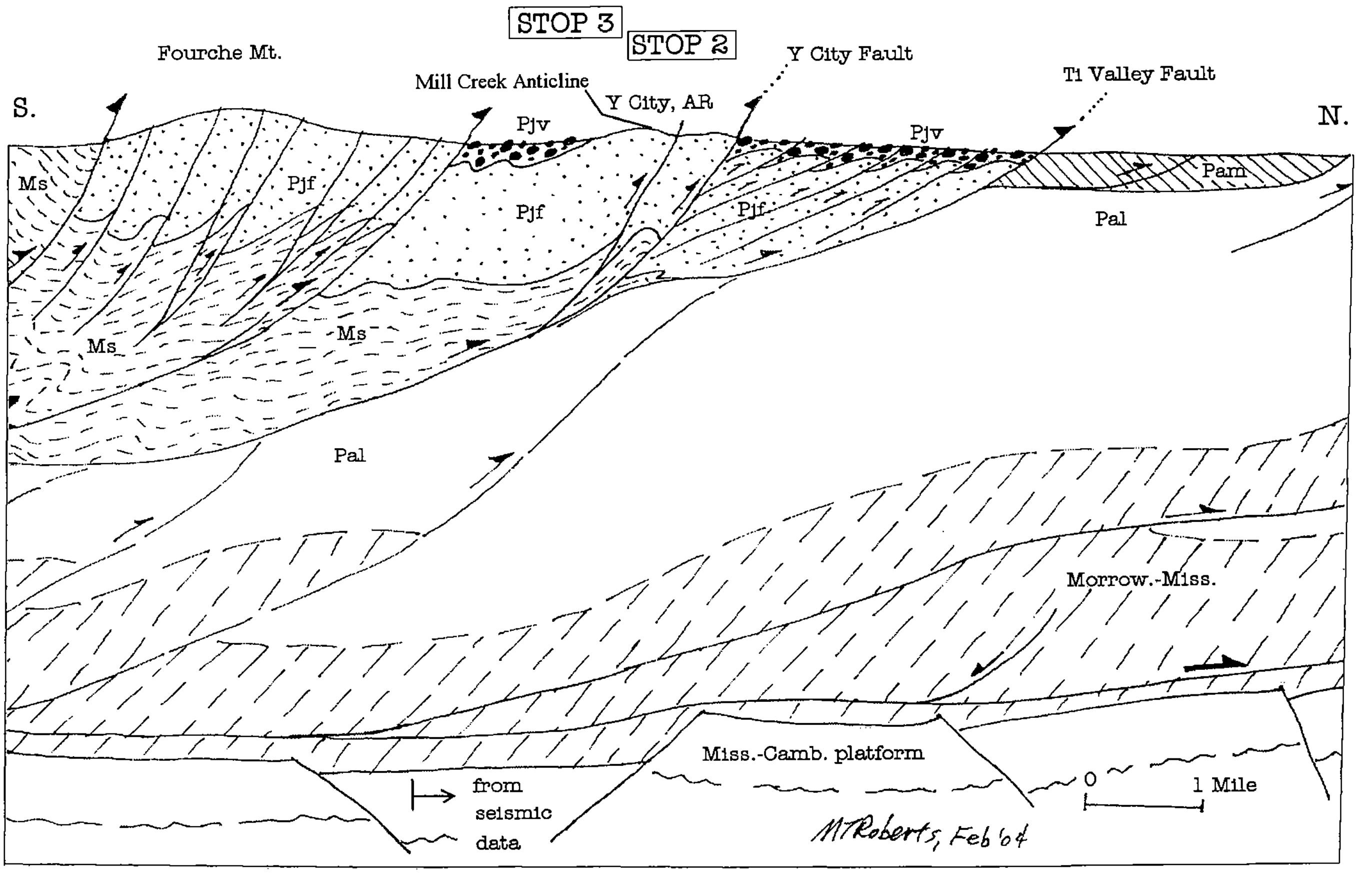


Figure 28. Cross section showing subsurface relations in the Y City area (Stops 2 and 3), based on CGG seismic line 1 and suface mapping by Boyd Haley and Charles Stone. Line 1 crosses the Y City Fault ~8 mi east of Stop 2. Ms = Stanley Group; Pjf = Jackfork Group; Pjv = Johns Valley Formation; Pal = lower Atoka Formation; Pam = middle Atoka Formation.

monoids (Gordon and Stone, 1969). It sits conformably on Chesterian units of the Stanley Group and is conformably overlain by the upper Morrowan Johns Valley Formation. A significant (and worldwide) hiatus is present in shelf and cratonic areas to the north between the Morrowan and Chesterian units that is probably represented by deep-water sediments in the Ouachita Basin. A sequence boundary—a worldwide sea-level drop—occurred at 320 ± 10 m.y. ago (Ross and Ross, 1988), separating the Morrowan and Chesterian. The influx of the quartzitic Jackfork sand on top of the Stanley shales may have resulted from that sea-level drop (Roberts, 1994). Palynomorphs that indicate deposition within the hiatus period on the shelf have been recovered from the Jackfork.

Lithology

The Jackfork Group consists of 5,000–6,000 ft of quartzitic sandstones and dark shales with a sand/shale ratio estimated from several sections at ~60/40. The Jackfork sequence is typified by intercalated layered sheet sandstones, amalgamated sheet sandstones, siltstones, shale, and disturbed beds of contorted shale and sandstone beds (Fig. 29). Siliceous and sideritic organic-rich mudstones that commonly have abundant deep-water trace fossils and give positive gamma-ray-log readings are present. They are considered to be highstand deposits and may represent 4th-order condensed zones. Additional facies include conglomeratic beds, coaly layers, and some probable channel-like bodies of sandstone and shale. Sandy facies include both low sand/shale thin-bed and high sand/shale thick-bed packages. Thicker sand beds typically are nearly structureless, but Bouma sequences occur in the thin-bed facies. Amalgamated sandstones commonly show scour and fill, and some are lensoid at outcrop scale. Layered sheet sandstones show both thinning- and thickening-upward bed sequences and compensation bedding. The mainly internally structureless thick beds in places have water-escape features and dish structures, and commonly have bottom marks such as flutes and load casts. Paleocurrent directions are dominantly east to west with some northeast to southwest (Morris, 1985). These units are interpreted as parts of major deep-water submarine-fan complexes that were fed mainly from eastern (Appalachian) and northern (cratonic) sources and were deposited from east to west along the axis of the basin. The Y City area is, paleogeographically, about mid-fan in the system, but coalescing, north-derived, proximal-channel, and slurry-bed sequences may have contributed to this fan system.

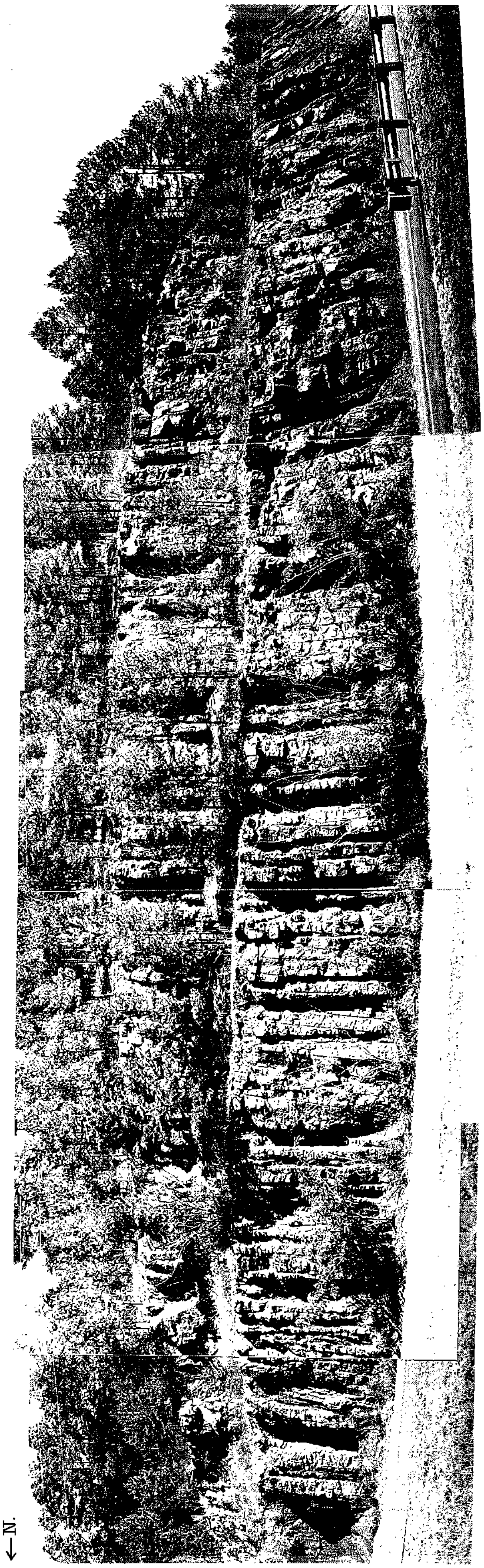


Figure 29. Stop 2: Y City, Arkansas. Panoramic photograph of nearly vertical sandstone beds in middle part of Jackfork Group in road cut along U.S. 71. Y City Fault is ~3,000 ft to the north (left) and juxtaposes the Jackfork over the Johns Valley Formation. This outcrop is on the south limb of the faulted Mill Creek Anticline. The depositional contact with the overlying Johns Valley Formation is ~3,300 ft to the south. Photograph shows a thick interval of layered sheet sandstones and amalgamated sandstones between shalier intervals.

Outcrops along U.S. 71 and a nearby Mill Creek stream bed at Y City expose ~3,000 ft of the middle and upper Jackfork Group and its contact with the Johns Valley Formation (Stop 4). The dominant bedding type here is disturbed beds (Morris, 1977), including disrupted mudstones, disrupted mixtures of mudstones and sandstones, and slurry beds of muddy sandstones. About 20% of the exposed strata are typical turbidite facies such as layered and amalgamated sheet sandstones (Fig. 30).

The top of the Jackfork Group is exposed in a stream bed and road cut ~0.25 mi south of the Y City cut. Not far below the Johns Valley contact, the Jackfork section contains ~120 ft of sheet sandstones exhibiting scour-and-fill features that are part of a thickening- and coarsening-upward bed sequence. The sequence is capped by a slumped shaly unit with deformed blocks of sandstone (Fig. 31). Below the sequence, the upper Jackfork also is dominated by shaly disturbed bedding with deformed sandstone layers. Slurry-flow sandstones occur near the base of the exposure. These latter sandstone beds are mainly structureless but show an increase in the amount of matrix upward and contain shale clasts in their upper parts. The sandstones at the top of the Jackfork here have a greater abundance of feldspar grains and metaquartz granules than the slurry-bed sandstones and are interpreted to have a different source (Morris, 1985). A rare invertebrate mold fauna is found in these beds as well.

In general the Jackfork Group is thought to have been derived mostly from eastern sources, with minor northern sources. The slumps (disturbed beds) and slurry beds have been interpreted as coming from northern sources. Large submarine leveed-channel systems, however, may be typified by local slumps on levee slopes both away from and into the channels. One set of flutes in the sandstone package indicates west–southwest flow.

Depositional Environments

The Jackfork Group contains classic turbidite sequences, many disturbed beds, and some deep-water trace fossils. Physical processes represented in the unit include turbidity flows, debris flows, grain flows, slurry flows, slumps/slides, and pelagic deposition. Locally, bottom currents moved sand waves. The Jackfork is interpreted as deposits of deep-water submarine fans and associated slumps, perhaps including slumps derived externally from basin-rimming slopes and slumps derived internally from channel–levee slopes.

The Jackfork in outcrop is structurally allochthonous and may have been deposited 70 mi or more south of the northern shelf–slope break of the Morrowan Ouachita Basin. The northern outcrop belt of the Jackfork is part of a major north-directed imbricate-thrust system, which was separated later from

Figure 30. Steeply south-dipping (to right), layered and amalgamated sheet sandstones in the middle part of the Jackfork Group at Stop 2.

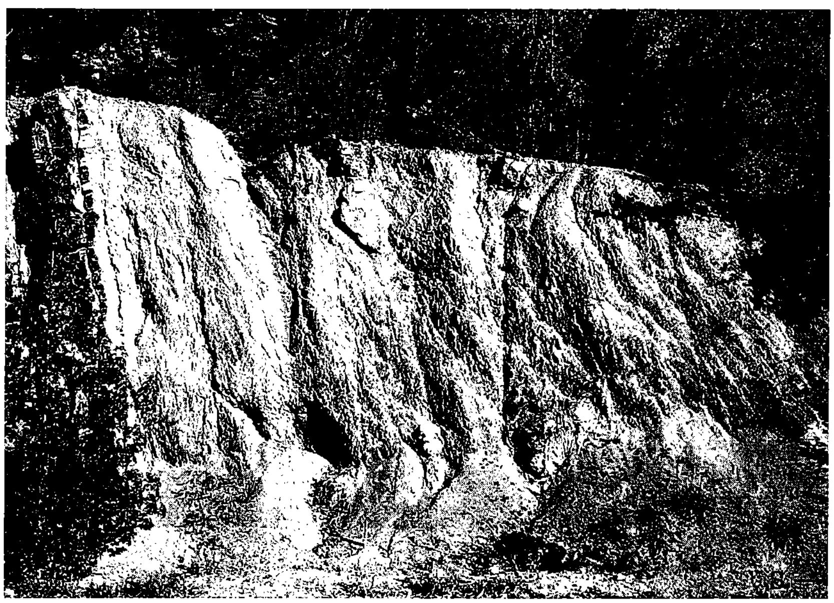


Figure 31. Deformed shale interval at top of road-cut exposure, Stop 2, in the middle part of the Jackfork Group. "Rolled" or "balled" sandstone beds (soft-sediment deformation) occur within the shale interval. Such intervals are common here and in the upper Jackfork but are dissimilar from those in the Johns Valley Formation seen at Stop 3, which contains exotic clasts.

the southern outcrop belt by the Benton Uplift and subsequent erosion. At Y City the thrust sheets containing the Jackfork probably merge into a sole fault that has moved the strata >45 mi northward. Subsurface studies, including seismic data, indicate that the shelf–slope break in the Morrowan lay 20 to 25 mi north of Y City (Roberts, 1994, fig. 29). Therefore, the Jackfork fans may have been deposited at least 70 mi south of the equivalent shelf section.

The early Morrowan slope may have been long and broken by fault scarps, which later contributed older platform debris into the Johns Valley Formation. It has been suggested that the disturbed beds in the Jackfork represent slumps from the northern basin slope, and, indeed, rare exotic platform-sequence clasts have been found in them. However, several Jackfork exposures have been interpreted as large leveed-channel sequences, and such sequences may contain slumps derived locally from levee slopes. Our early models for the Jackfork were at too small a scale and relied on incomplete knowledge of modern deep-water systems. Large-scale leveed channels would have contained thick levee, splay, channel, and slump units that would have aggraded (stacked) and prograded and built thick sequences like those we see in the Jackfork. Outcrops of Jackfork from Little Rock west into southeastern Oklahoma show evidence of major west-building submarine-fan complexes. A major feeder-channel complex is exposed in North Little Rock at the Big Rock Quarry. Channel complexes also are seen near Arkadelphia, at De Gray Dam, Hollywood Quarry, and elsewhere. Overall, many Jackfork exposures show prograding vertical sequences. Down-fan facies into Oklahoma seem to have a greater abundance of layered sheet sandstones and thin-bed facies. The Jackfork Group may be a mixture of classic submarine fans (Type II of Mutti, 1985) and channel–levee complexes (Type III fan of Mutti, 1985). Both types were deposited axially in the east–west basin confined on the south by advancing submarine thrust sheets that apparently did not contribute sediment to the fans, although some interpret the metaquartz granules as having originated from southeastern sources.

The middle Jackfork Group sequence at the Y City road cut opposite the Mountain Inn is the main focus of this stop, and here the origin of the Jackfork is controversial. Are we seeing contributions from a northern source? Are we seeing the midfan facies of a large axial submarine fan derived from the east? What is (are) the origin(s) of the slumped and slurried beds that are volumetrically important here? The section includes amalgamated and layered sheet sandstones bounded by mud-rich facies. Is this the product of a large-scale, migrating, aggrading, leveed-channel system, or a coalescing of axial and basin-margin-derived fans? Are the slumps internally derived from levee failures or externally derived from failures on the northern slope of the basin?

At the base of the >150-ft-thick sand-rich package is a deformed siliceous-shale unit that may be a highstand condensed zone. The abruptly overlying sandstones may represent a lowstand sequence. These are overlain by the enigmatic slumped shales containing soft-sediment-deformed sandstone blocks.

Discussion

The Jackfork Group has been the subject of many industry and academic field trips and studies, and several models have been put forth to explain its deposition. It is a target for hydrocarbon exploration, especially in Oklahoma. Many diverse environments of deposition and paleogeographic settings are represented in the Morrowan strata of the Ozark–Arkoma Basin–Ouachita Mountains region. These have been juxtaposed by north-vergent thrusting. Many field trips purport to look at shelf-to-basin transitions, but most transitions are hidden from view beneath foredeep fill or thrust sheets. Coeval with the thick, deep-water Jackfork deposits are thin, shallow-water carbonate-shelf deposits in northeastern Oklahoma and fluvial-deltaic clastic strata in northern Arkansas. The northern shelf–slope break of the Morrowan basin lay 20–30 mi north of Little Rock and trends about east–west into Oklahoma. It is buried mostly by Atokan and younger clastic strata of the Arkoma Basin; in the Ouachitas it is overridden by thrust sheets. Some exposures of the shelf–slope break area may be present near Searcy and Bald Knob. Seismic data indicate that the slope deposits were laid down over a long block-faulted ramp composed of earlier platform-sequence strata.

The transition from slope facies to basinal fans also is mostly buried, and its position is essentially unknown. The thrust-faulted Bayou Meto Anticline near Cabot contains exposures of dark sideritic shale with some sandstone lenses. A drill hole indicates that >2,500 ft of this facies is present. The shale is mapped as Johns Valley and is considered to be an upper Morrowan slope facies. The slope may have been >70 mi wide (dip direction). Slope facies may be present in the thrusted Maumelle Zone west of Little Rock, where mélange-like tectonized shale and sandstone units crop out. Gordon and Stone (1977) report exotic early Morrowan fossiliferous platform clasts in some of these intervals, which may indicate periods of active growth faulting along the shelf–slope margin or of slope channels. Seismic data also indicate the presence of growth faults (Roberts, 1994). Large blocks of sandstone sequences incorporated in the zone in the Pinnacle Mountain area may be dismembered slope–canyon fill. Nearby Big Rock Quarry in North Little Rock exposes a major feeder-channel complex cut into contorted black shales. (The base is best seen in road cuts on Interstate Highway 430 just south of the Arkansas River.) These exposures are far traveled on thrusts. Whether the Jackfork Group was deposited entirely on subsided and attenuated cratonic crust or partly (or all) on some now-subducted oceanic crust is unknown. Epizonal granite clasts and other exotics in Ordovician strata in the core of the Ouachita Uplift are suggestive of the former model, as is the extreme rarity of ultramafic rocks involved in the thrust sheets. The interactions, if any, between Jackfork sedimentation and the advancing submarine thrust sheets on the south side of the Ouachita Basin are also unresolved.

Continue south on U.S. 71.

74.5	0.1	Bridge over Mill Creek. Large lenticular, channel-like body of Jackfork sandstone beneath northern side of bridge.
74.7	0.2	Junction of U.S. Highway 270 and U.S. 71. Continue straight (south) on U.S. 71/270. Road cut on west side exposes Jackfork shales with lenticular sandstone beds and deformed, balled beds of sandstone ("glumps" and "gloops" of C. Stone). Thick Jackfork sandstones crop out in the bed of Tan-a-hill Creek here. Strata dip steeply to the south and contain small faults.
75.1	0.4	Massive uppermost Jackfork sandstone and Johns Valley shales and siltstones in Tan-a-hill Creek to the south and in road cut to the west. An interval of granule conglomerate with some chert clasts occurs here in the uppermost Jackfork. Six miles to the east an invertebrate mold fauna is present in this massive sandstone.
76.2	1.1	Turn onto dirt road to left (southwest) to small quarry.
76.3	0.1	Quarry exposing Johns Valley Formation. Permission to visit this quarry has been kindly granted to us by Mr. Bill Shaddon of Boles, Arkansas. If you would like to visit this exposure in the future, please contact Mr. Shaddon well in advance.

STOP 3

JOHNS VALLEY FORMATION

Michael T. Roberts
Palmer Petroleum, Inc.

Charles G. Stone
Arkansas Geological Commission

Location: shale pit just south of U.S. 71 ~1.6 mi west–southwest of Y City; nearby highway exposures along U.S. 71, C E½E½ sec. 20, T. 1 N., R. 29 W., Scott County, Arkansas

Structural Setting

Stop 3 is in the Ouachita frontal belt ~1 mi south of the Y City Fault on the south flank of Mill Creek Anticline, which is cored at the surface by the Jackfork Group (Fig. 27). The upper Morrowan Johns Valley Formation appears to overlie the Morrowan Jackfork Group conformably, and both may have been tectonically transported >40 mi north of their original site of deposition on the basis of nearby cross-section reconstructions (see discussion under Stop 2; Fig. 28). Coherent turbidite strata within the shale dip moderately to the south. Steep to moderate dips in the Johns Valley Formation along strike, and the width of the outcrop belt here, indicate either an unusually thick deposit of the unit or unmapped structural repetitions.

Age

Middle and some upper Morrowan fossils, especially ammonoids, have been recovered from the Johns Valley Formation. Furthermore, the presence of clasts and large lenses of the Wapanucka Formation indicates a late Morrowan age for the middle and upper parts of the Johns Valley. Kerr (2003) suggests that the age of the Johns Valley may range into the earliest Atokan. He noted a Spiro-equivalent marker bed in upper Johns Valley lithofacies near Bengal, Oklahoma. The Johns Valley Formation lies with apparent conformity between the Morrowan Jackfork Group and the Atokan Atoka Formation. It appears to be a stratigraphic layer and not a tectonic unit related to the major regional thrust faults. The unit appears to interfinger with both Atoka and Jackfork strata. But in places Johns Valley channels are incised into the Jackfork (e.g., Murray Quarry, De Gray Lake, and Sohio seismic lines in the Lynn Mountain area).

Lithology

The Johns Valley Formation is dominantly a dark-gray clay shale with interspersed chaotic boulder beds, some thin turbidite sandstone beds, and minor siliceous shale and chert beds. It is ~1,500 ft thick in the frontal Ouachita Mountains. The boulder beds (Fig. 32) attract the most attention, and the "boulders" range in size from pebbles to at least one block of Caney Shale 3,000 ft long in Oklahoma. Reinemund and Danilchik (1957) report that near Boles, ~4 mi northeast of this borrow pit, a very large exotic dolostone mass in the Johns Valley briefly was quarried for aggregate. Another large, pure quartzite block in the area was prospected for use as a glass-sand resource. Large clasts are all extrabasinal and were derived from the older platform-facies strata exposed to the north (Ozark facies) and west (Arbuckle facies). Clasts include limestone, dolomite, sandstone, chert, and shale derived from formations ranging in age from Cambrian to Morrowan (Shideler, 1970). The boulders typically are encased in clay shale in a diamictite fashion, but some formed conglomerate beds that may be disrupted slope–channel bodies. In most fresh exposures the clay matrix is sheared, and the unit probably behaved as a ductile body during orogenic events. Interbedded (in situ) sandstone beds exhibit Bouma sequences and bottom markings, such as flute casts, and are rarely amalgamated.

Just south of Y City the Johns Valley Formation is exposed along road and stream cuts and in a small quarry (borrow pit) nearby. The pit exposes the classic scaly shale with exotic boulders and siderite concretions as well as a few beds of normal turbidite sandstones that strike east–west.

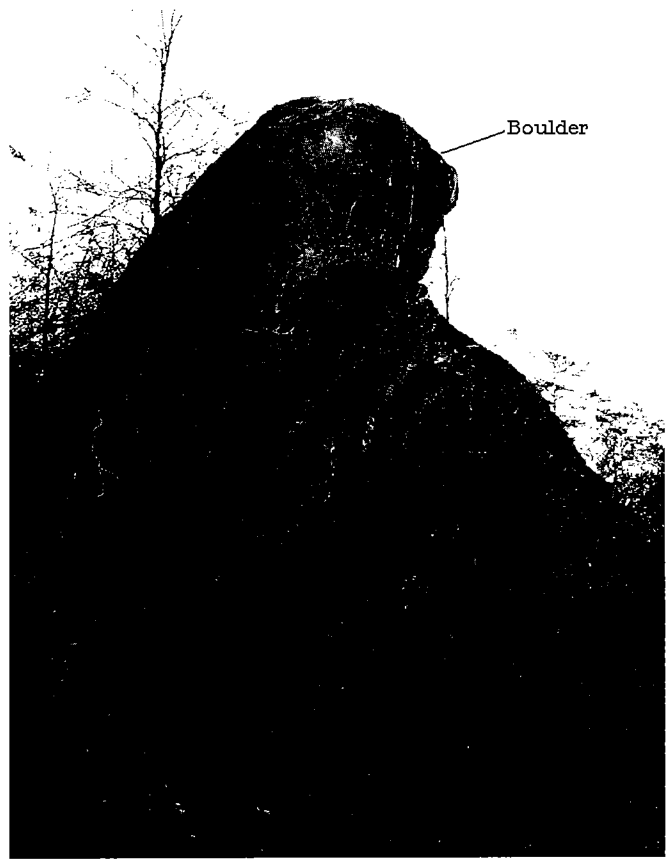


Figure 32. Stop 3: Johns Valley Formation exposed in shale pit south of U.S. 71, southwest of Y City (see Figs. 27 and 28 for map and cross-section relations). Photograph shows large exotic block embedded in sheared shale. The Johns Valley does not lend itself to good exposures but can be viewed in stream channels near this old borrow pit.

Depositional Environments

The stratigraphic setting (conformable between submarine-fan facies of the Jackfork Group and Atoka Formation) and the presence of turbidite beds with *Nereites*-facies trace fossils indicate a deep-water site of deposition for the Johns Valley Formation. The boulder-bearing facies extends for 140 mi along the northern exposures of the frontal Ouachita Mountains. Much of the unit is clay and fine-grained turbidite beds indicative of distal (or starved) basinal settings or slope deposits. Disrupted conglomerate beds may be resedimented, penecontemporaneous slope–channel fills. The exotic boulders are interpreted to be the deposits of slumps, slides, debris flows, and lags from turbidity flows (olistostromes; Fig. 33). Stone and Haley (1978) suggested that normal-fault scarps developed in the Chesterian through early Atokan north of the deposition site and shed coarse debris into the basin. Industry seismic data in the region support this hypothesis and show extensive basement block faulting at depth under the Arkoma Basin and Ouachita frontal zones. This faulting represents a Late Mississippian to Early Pennsylvanian extensional episode that affected the basement and platform strata, and offsets of ~5,000 ft have been observed. The Morrowan Wapanucka Formation was deposited in southeastern Oklahoma over the block-faulted platform units near sea level. More than 5,000 ft of section must have been available to erosion/mass wasting to obtain the lithologies (including the Wapanucka) in the Johns Valley. A simplistic reconstruction suggests that the Johns Valley Formation was deposited in water ~5,000 ft deep. The actual source terrains are buried under the thrust sheets and are unknown. Directional data in Reinemund and Danilchik (1957) from Johns Valley strata indicate a dominantly southwestward flow in the area of this trip.

Discussion

There has been a long-standing argument over the origin of the Johns Valley Formation. Some geologists have considered the deposit to be a tectonic unit, with the exotics tectonically "plucked" and sheared from units along fault zones. However, the preponderance of evidence points to a sedimentary origin for the Johns Valley. The boulder beds are evidence that the formation may be related to an extensional episode that affected the cratonic side of the collision zone during its subduction under the approaching southern landmass ("Yucatan"). During later compressional tectonism, the Johns Valley Formation acted as a ductile zone sandwiched between the more competent, sandstone-rich Jackfork Group and Atoka Formation.

76.4	0.1	Return to U.S. 71; turn left, and continue south.
77.1	0.7	Prolific invertebrate-fossil site with indigenous and exotic fossils in Johns Valley Formation.

Road cuts made in the early 1970s revealed ammonoids and other fossils having lower Bloyd Shale (upper Morrow) correlations (Gordon and Stone, 1977). Most indigenous cephalopods are found in clay–ironstone concretions in the lower Johns Valley. They are of the *Branneroceras branneri* ammonoid zone, found on the Ozark Shelf in the Brentwood Limestone Member of the Bloyd Formation. A higher Johns Valley fauna has been found at nearby sites, including the *Axinolobus modulus* zone and *Axinolobus quinni* McCaleb and Furnish, which are found in the Dye Shale Member of the Bloyd in the Ozarks and in the middle part of the Wapanucka Limestone in Oklahoma.

78.1	1.0	Leave Y City 7.5′ quadrangle; enter Acorn 7.5′ quadrangle. Large sandstone olistolith in the Johns Valley Formation to south.
80.5	2.4	Thick beds of Jackfork sandstone and thin shale dip 65° S. on east side of road.

A large thrust fault lies just north of this exposure that juxtaposes the Fourche Mountain complex of faulted Jackfork Group northward over the Johns Valley Formation. Complex patterns of thrust faults occur to the west and east of this area, involving, at the surface, the lower Atoka, Johns Valley, Jackfork, and Stanley. Vergence generally is to the north. The area may be underlain at depth by duplex structures of the lower Atoka Formation and older Carboniferous units.

82.9	2.4	Exposures of massive, amalgamated, clean Jackfork sandstones, dipping 80° S. and overturned.
83.0	0.1	Leave Scott County; enter Polk County, Arkansas.
83.2	0.2	Beds of overturned Jackfork sandstone, dipping 65° S.
83.7	0.5	Severely faulted, highly fractured beds of Jackfork sandstone dip 70° S.
84.0	0.3	Foran Gap; highly faulted beds of Jackfork dip 45° S.
86.2	2.2	Moyers Formation (upper Stanley Group) poorly exposed here, thrust northward over the Jackfork.
87.5	1.3	Junction with road to Irons Fork Lake to left (east), a water supply for Mena and nearby communities.

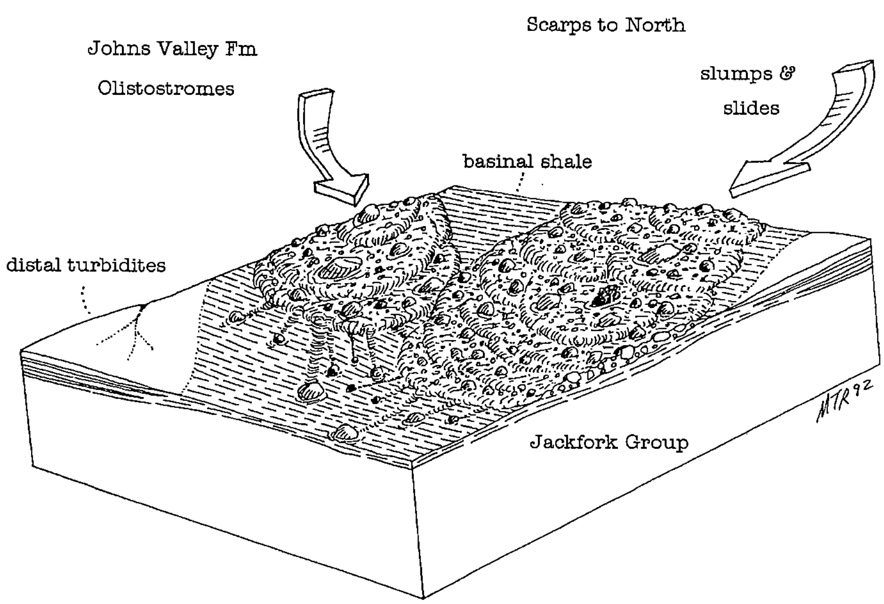


Figure 33. Depositional model, Johns Valley Formation. Fine-grained basinal facies with slumps, slides, and flows of unsorted boulder-rich masses derived from fault scarps that exposed northern platform–facies strata.

88.9 1.4 Weathered upper Stanley Group (Moyers Formation) sandstones and shale. A small, fossiliferous, cherty, oolitic limestone erratic was found in the road cut here.

90.1 1.2 Major fault zone in highly faulted, sheared middle Stanley Group. This zone has been correlated by some to the Briery Fault.

90.3 0.2 Bridge over Ouachita River.

90.4 0.1 Acorn, Arkansas; junction with U.S. 59/270. Continue straight (south) on U.S. 59/71.

91.7 1.3 Leave Acorn 7.5′ quadrangle; enter Mena 7.5′ quadrangle.

92.6 0.9 Dark chert and siliceous shale in middle part of Stanley Group, tightly folded and repeated by thrust faults. This unit may correlate with the Battiest Chert in the upper part of the Tenmile Creek Formation of Oklahoma. About 1 mi west, the Tenmile Creek is truncated by a low-angle fault with gently dipping upper Stanley and Jackfork beds of the Rich Mountain Syncline in the hanging wall.

94.5 1.9 Junction with State Highway 88 to the left (east). Continue straight (south) on U.S. 59/71. The trace of the major Windingstair Thrust is nearby; the poorly exposed Stanley Group is extremely complex structurally in the Mena area.

96.1 1.6 Mena, Arkansas. Junction with S.H. 88 to right (north). Continue straight (south) on U.S. 59/71.

The scenic Talimena Drive begins in west Mena on S.H. 88 and continues west along the crest of Rich Mountain (north flank of the Rich Mountain Syncline) to Queen Wilhelmina State Park and Lodge, then into Oklahoma on Oklahoma State Highway 1 to near Talihina. Good exposures of lower Jackfork deep-water sandstones and shales occur at several sites along this road.

97.4 1.3 Junction with State Highway 8W. Continue straight (south) on U.S. 59/71. Leave Mena 7.5′ quadrangle; enter Potter 7.5′ quadrangle.

To the south are views of the Caddo and Cossatot Mountains (northern part of Benton Uplift), which are formed mainly of resistant units of the Devonian–Mississippian Arkansas Novaculite. These are underlain by Ordovician and Silurian shales, sandstones, cherts, and limestones. The novaculite in the northern Benton Uplift is composed of thin-bedded chert, siliceous shale, novaculite, and conglomerate. It plunges westward beneath sequences of the Stanley Group in eastern Polk County (12 mi east). Major thrust faults such as the Octavia Fault have transported the southern and central novaculite facies northward to within ~5 mi of the frontal Ouachita belt near Mena.

98.4 1.0 Intensely deformed and thrust-repeated sequences of lower Stanley Group. The area west of Mena is a complex of steeply dipping thrust-faulted Stanley Group strata and intersecting low-angle thrusts with gently dipping Stanley Group and Jackfork Group strata in the hanging walls (Figs. 34, 35).

100.6 2.2 Potter Junction, Arkansas. Lowermost Stanley Group exposed. Ridges to east are part of Caddo Mountains; ridge to south is part of Cossatot Mountains.

101.1 0.5 Massive, thick Arkansas Novaculite of the lower division; tight box and chevron folds present in middle-division thin cherts and siliceous shales. Small, cold springs issue from the Arkansas Novaculite in places here.

102.4 1.3 Thick interval of lower Stanley sandstone, Hatton Tuff, and shale dipping 89° N.

102.6 0.2 West-plunging anticlinal nose of upper Arkansas Novaculite and Hot Springs Sandstone Member of the Stanley Group. This sandstone contains beds of chert–novaculite–sandstone conglomerate and siliceous shale.

106.8 4.2 Exposure of thrust-faulted lower Stanley Group.

107.0 0.2 Leave Potter 7.5′ quadrangle; enter Cove 7.5′ quadrangle.

107.2 0.2 Hatfield, Arkansas. Junction with State Highway 246 to right (west). Kansas City Southern Railroad cuts expose steeply dipping lower Stanley Group sandstones and shales. Manganese and slate have been mined from the Missouri Mountain Shale, Arkansas Novaculite, and Stanley Group in eastern Polk County, and copper, silver, gold, zinc, lead, barite, and other minerals have been prospected for.

108.6 1.4 Sheared and crenulated lower Stanley in shale pit to east.

111.3 2.7 Lower Stanley sandstone with ~80° N. dip.

111.7 0.4 Cove, Arkansas; junction with State Highway 4W to right (west). Continue straight (south) on U.S. 59/71. On our return trip we will take this road west into Oklahoma. Numerous exposures of thrust-faulted and folded lower Stanley Group strata are in the area. Late Paleozoic milky-quartz veins of hydrothermal origin fill some joints and fault planes.

115.8 4.1 Vandervoort, Arkansas; junction with State Highway 246 to left (east). Continue straight (south) on U.S. 59/71. S.H. 246 leads east ~8 mi to the scenic Cossatot River State Park, which, in addition to fine camping, hiking, canoeing, and fishing, has excellent exposures of Stanley Group strata along the river bed.

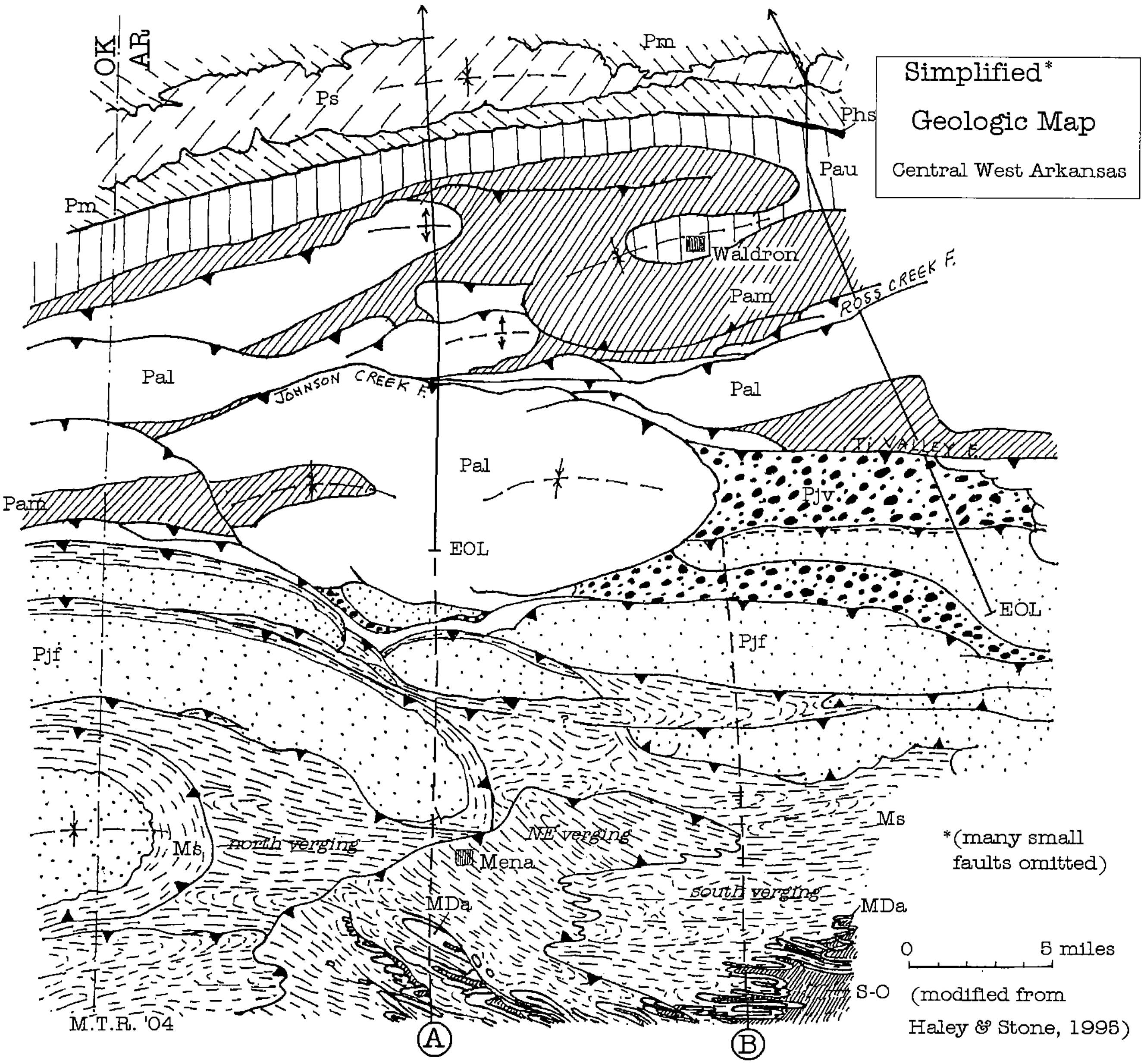


Figure 34. Simplified geologic map of central western Arkansas, showing south end of seismic lines used in cross sections A and B (Fig. 21A,B). Dashed lines are extensions of cross sections based on surface geology (Haley and Stone, 1995). Numerous small faults have been left off the map for simplicity. A cross section (Fig. 35) was constructed along the Oklahoma–Arkansas state line (southwestern part of map). S–O = Silurian and Ordovician units; MDa = Arkansas Novaculite; Ms = Stanley Group; Pjf = Jackfork Group; Pjv = Johns Valley Formation; Pal = lower Atoka Formation; Pam = middle Atoka Formation; Pau = upper Atoka Formation; Phs = Hartshorne Sandstone; Pm = McAlester Formation; Ps = Savanna Formation.

116.2	0.4	Leave Cove 7.5′ quadrangle; enter Bog Springs 7.5′ quadrangle.
117.4	1.2	Hatton, Arkansas. Turn left (east) onto County Road 482.
117.5	0.1	Leave Bog Springs 7.5′ quadrangle; enter Wickett 7.5′ quadrangle.
117.7	0.2	Cross Kansas City Southern Railroad tracks. Turn right on County Road 482 and 15.
117.9	0.2	Bear left on County Road 15.
118.4	0.5	Continue left.
119.0	0.6	Cross Kansas City Southern spur track and continue to headquarters of Martin Marietta Aggregate and Hatton Quarry. Park at designated (company) sites. The field-trip leaders extend their sincere appreciation to Mr. Todd Wheeler and Mr. John McCullen and other representatives of Martin Marietta for granting us permission to visit this site.

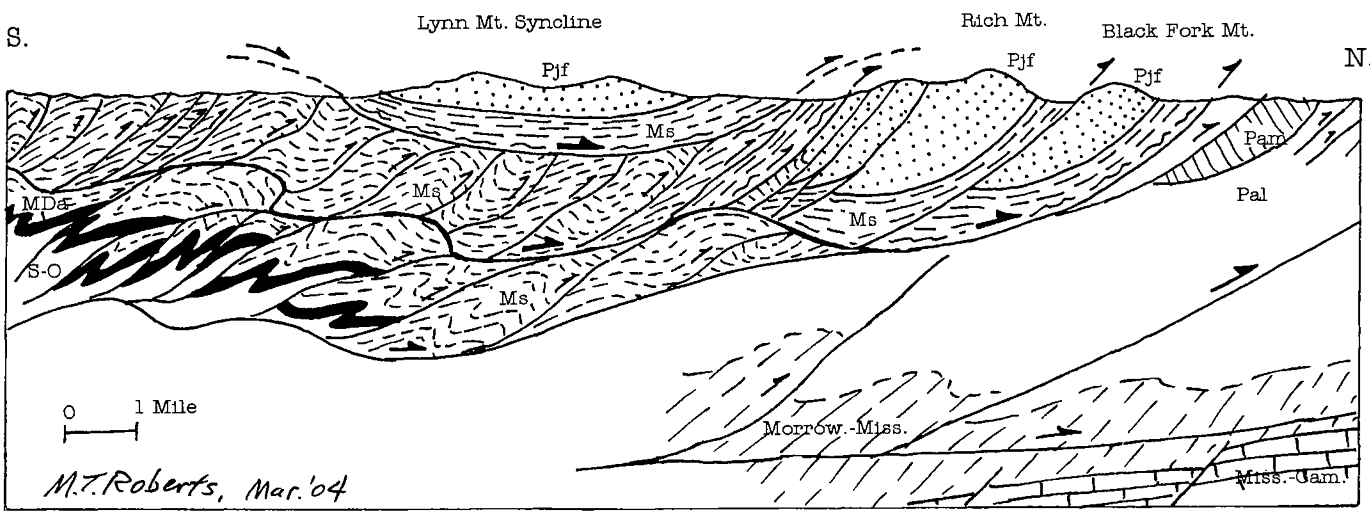


Figure 35. Speculative cross section, illustrating one interpretation of structural relations west of Mena, Arkansas, along the Oklahoma–Arkansas state line. The Lynn Mountain Syncline may be a roof structure over deeper duplexes of Stanley and older units (exposed in the Mena area). S–O = Silurian and Ordovician units; MDa = Arkansas Novaculite; Ms = Stanley Group; Pjf = Jackfork Group; Pal = lower Atoka Formation; Pam = middle Atoka Formation.

STOP 4

LOWER STANLEY GROUP, ARKANSAS NOVACULITE

Michael T. Roberts
Palmer Petroleum, Inc.

Charles G. Stone
Arkansas Geological Commission

Location: Martin Marietta Aggregate Quarries
2 mi east of Hatton, sec. 6, T. 5 S., R. 31 W.,
Polk County, Arkansas

Structural Setting

This outcrop of the lower Stanley Group and Arkansas Novaculite is in the Cross Mountains of the Benton–Broken Bow Uplift or core zone of the Ouachita Thrust Belt (Fig. 36). The uplift occurred in the late Paleozoic, probably involved basement, and was accompanied by low-grade metamorphism and the introduction of hydrothermal fluids that created quartz veins throughout the region. Numerous thrust faults and tight folds are present, including south-vergent thrusted subsidiary folds (Fig. 37) contained in north-vergent thrust sheets and probable folded thrusts (Fig. 38). Seismic data indicate that the area is underlain by late-stage, basement-involved duplex structures. The surface strata show cleavage, jointing, quartz veins, and some mineralization, including local films of turquoise and variscite in the Arkansas Novaculite.

This stop is in the axis of the Cross Mountain Anticline, where quarrying has exposed the Missouri Mountain Shale (Fig. 39) in the core of the anticline as well as the entire Arkansas Novaculite and the lower part of the Stanley Group, including the actively mined Hatton Tuff lentil.

Age

The Arkansas Novaculite is Devonian to Early Mississippian, and the Stanley Group is Mississippian. The lowermost Stanley has a Meramecian fauna. The top of the Stanley is as young as Chesterian. The Missouri Mountain Shale is Silurian.

Lithology

The Arkansas Novaculite is as thick as 900 ft in the Cossatot and Caddo Mountains to the north and consists of nearly pure SiO_2 novaculite, bedded chert and interbedded siliceous shales, and sandy cherts. Here, the formation is ~350 ft thick. It consists of three parts: a lower white, massive-bedded novaculite with interbedded shale toward its basal contact with the Missouri Mountain Shale; a middle division of dark shale interbedded with thin beds of dark novaculite; and an upper division of thick-bedded white, rarely calcareous novaculite. Some very thin silty to sandy cherts of turbidite origin occur in the middle division. High gamma-ray-log readings are reported from parts of the middle division. South of a line along the north edge of the Caddo and Cossatot Mountains (north of Stop 4), the thick, massive lower division novaculite intervals form sharp-crested ridges.

The Stanley Group is a very thick (11,000 ft) accumulation of shale, siltstone, and turbidite sandstones and rela-

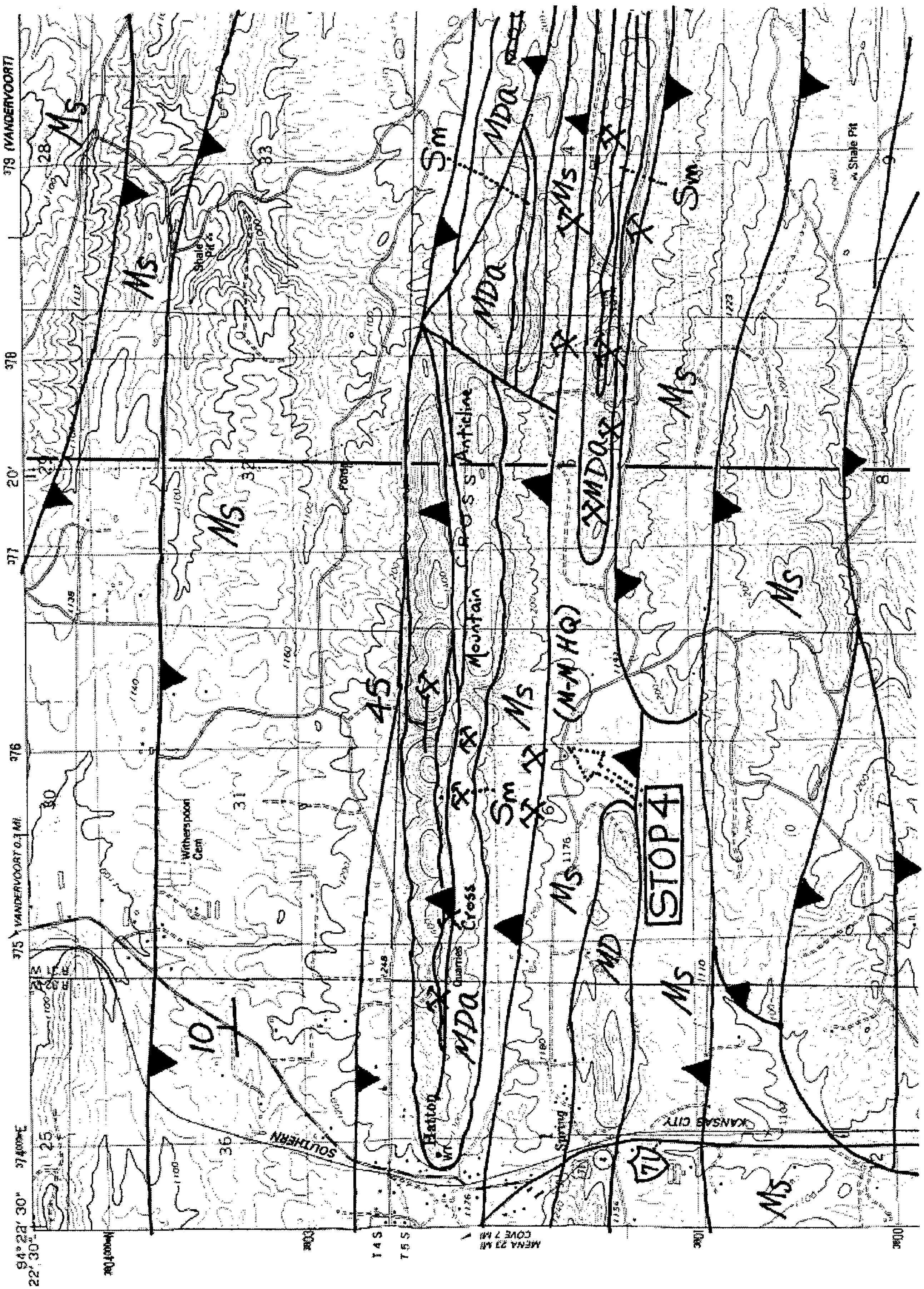


Figure 36. Geologic map of area near Stop 4, Hatton Quarry (Martin Marietta Aggregates) in the Hatton Tuff (lower Stanley Group) and Arkansas Novaculite (from Haley and Stone, 1995). Sm = Missouri Mountain Shale; MDa = Arkansas Novaculite; Ms = Stanley Group.

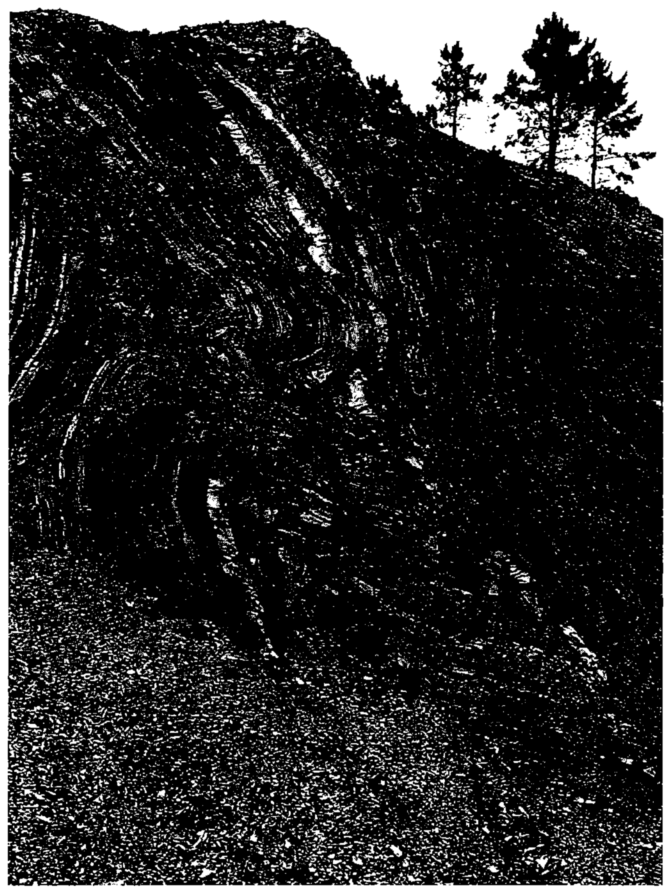


Figure 37. Small-scale (subsidiary) folds in thin-bedded unit of the Devonian–Mississippian Arkansas Novaculite (Stop 4). These folds are on the south limb of the Cross Mountain Anticline in the old part of the Hatton Quarry.

tively thin tuff beds (e.g., Hatton and Beavers Bend Tuffs) near its base (Fig. 40). The lower and upper Mud Creek Tuffs are as much as 1,500 ft above the base of the Stanley. Bedded barite, siliceous shales or chert beds, and rare conglomerates also occur in the Stanley. The lower part of the Stanley exposed at the Hatton Quarry is being mined for the Hatton Tuff bed (Fig. 40), which is ~90 ft thick here and is ~140 ft above the Arkansas Novaculite. The tuff has a lower, coarse-grained crystal-rich zone and an upper, fine-grained vitric zone. Graded bedding has been noted in the crystal tuff, which is a volcanic arenite composed of euhedral plagioclase crystals in an ash matrix. The vitric zone is ash with fragments (shards) of glass-bubble walls and small amounts of silt-sized quartz and plagioclase.

Depositional Environments

The Arkansas Novaculite is somewhat of an enigma. Deep- and shallow-water depositional environments have been proposed for the formation. The origins of chert, in general, are controversial. We favor a deep-water, starved-basin origin for the novaculite. The Stanley Group is a complex of deep-water distal shales—but with a high accumulation rate—interbedded with turbidite sandstones,

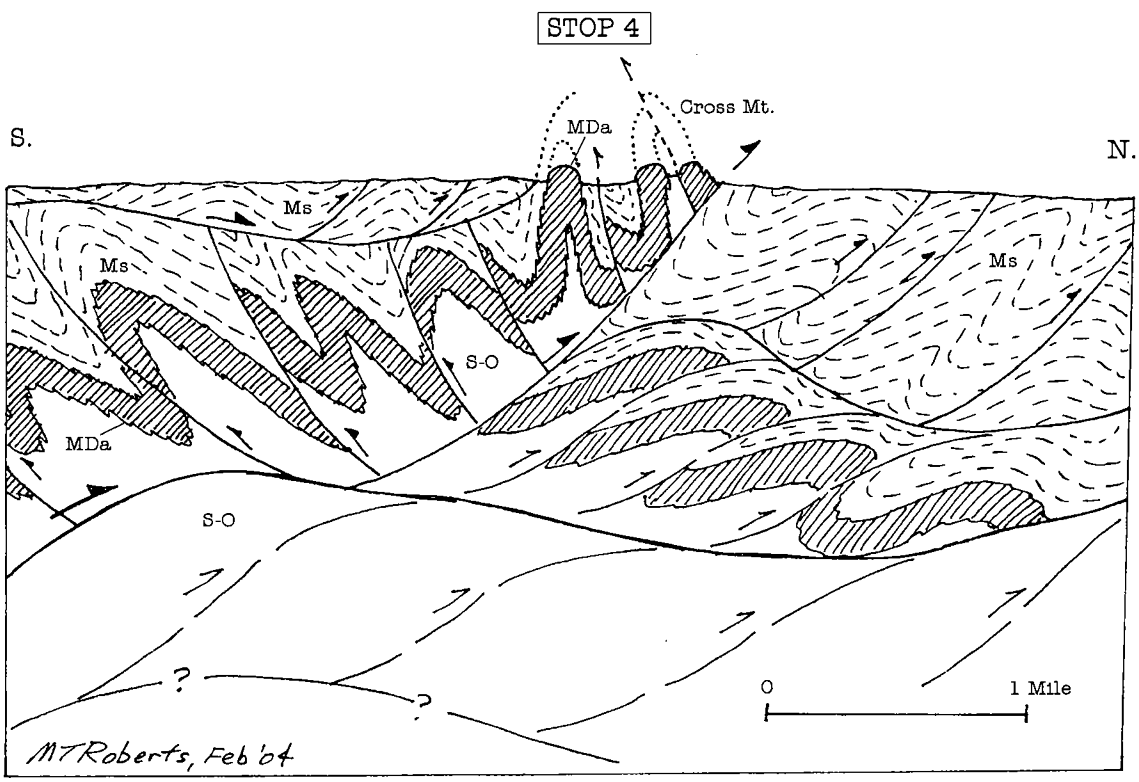


Figure 38. Cross section through the area of Stop 4, based on surface mapping by Boyd Haley and Charles Stone. S–O = Silurian and Ordovician units; MDa = Arkansas Novaculite; Ms = Stanley Group.

Figure 39. Small-scale thrust-faulted fold in the Missouri Mountain Shale (Silurian), exposed by quarrying in the core of the Cross Mountain Anticline (Stop 4).

starved condensed-zone deposits of siliceous shale/chert, and water-laid tuffs. Paleocurrent directions in Stanley strata associated with the tuff beds indicate a southern and/or southeastern source (Niem, 1976).

Discussion

The main purpose of this stop is to contrast the facies and structures of the Ouachita core zone with those of the frontal Ouachitas and the Arkoma Basin. The first stop was in an Arkoma Basin thrusted fold to view the Hartshorne Sandstone, a Desmoinesian late-stage foredeep basin fill. The northern Arkoma Basin is dominated by Atokan and younger fluvial-deltaic deposits and is relatively mildly deformed by low-angle thrusts and broad folds. The Ouachita frontal zone is mostly a complexly thrust-faulted and folded series of deep-water Atokan and Morrowan clastic strata, including thick submarine-fan deposits.

In the Benton Uplift at Hatton, however, we find even more complex structures, and our interpretations/mapping typically are hindered by poor exposures and numerous small-scale (subsidiary) structures that verge in the opposite direction to the main thrust-belt structures. The section around Hatton is dominated by thick deposits of deep-water shales and cherts with some interbedded sandstones and tuffs. (Stanley sandstones are well exposed along the river at Cossatot State Park a few miles east–northeast of Hatton as well as in the quarries.) Map relationships in the Benton Uplift are suggestive of suggest duplexes, refolding, back thrusts, and other complexities, and subsurface data are suggestive of basement duplexes beneath the uplift. Many discussions have taken place among various workers concerning the amount and nature of displacements on the typically low-angle, folded décollements in this area and throughout the region.

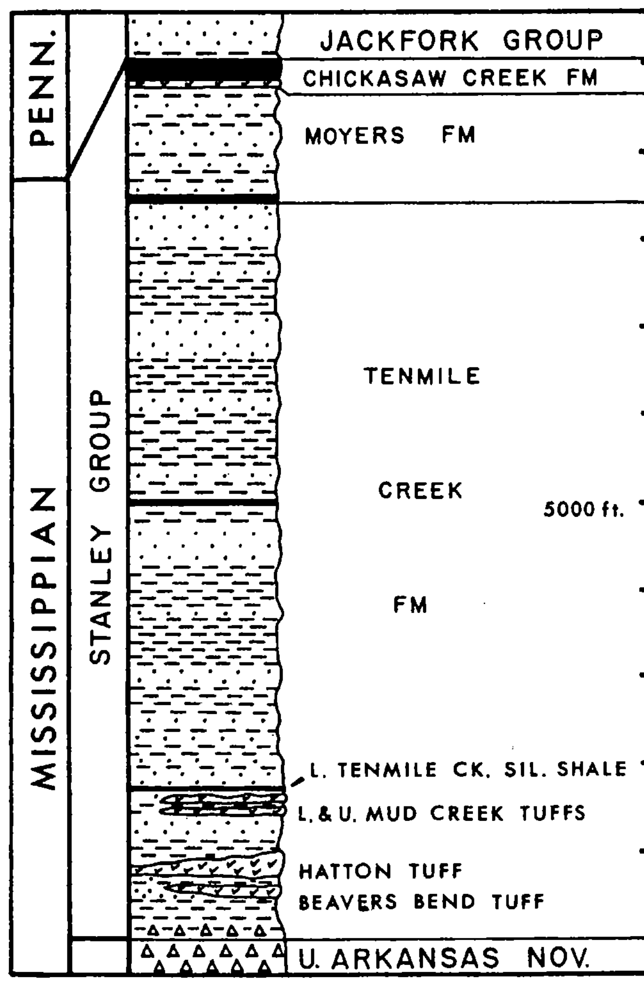


Figure 40. Generalized stratigraphic column of the Stanley Group (from Niem, 1976), showing position of the Hatton Tuff (Stop 4) and other associated tuffs.

These décollements generally separate sand-rich lithic units above from shalier strata below within the 11,000-ft-thick Stanley Group. Boyd Haley (personal communication, 1995) and Charles Stone interpret the décollement near this stop to have many thousands of feet of northward displacement over deformed Stanley Group strata. Many miles of northward displacement may be present in décollements mapped in the Hurricane Creek antimony district to the south and the Potter–Mena area to the north.

It has been suggested that some deposition in the region was syntectonic. The comparatively simple Arkoma Basin structures, as indicated by surface mapping and subsurface studies, consist of a block-faulted basement and an early Paleozoic shelf section detached from the overlying Carboniferous section by low-angle thrusts, which, in places, ramp up steeply to the surface from a sole fault. Many of these thrusts show evidence of having once been listric normal faults that were active during deposition of the Pennsylvanian clastic sediments.

The Ouachita frontal belt is a deceptively simple imbricate thrust belt except in the area of the field trip from Boles through Y City and Mena, where much complexity exists. This area is still not totally understood, despite extensive detailed mapping by Haley, Stone, and others. For example, the steeply dipping Jackfork Group and Johns Valley Formation, arrayed in a set of east–west imbricate thrust sheets, are juxtaposed against a gently dipping bowl-shaped section of lower Atoka clastic strata west of the Boles–Y City area. The relationship there may be a low-angle detachment or an unconformity, but the contact is poorly exposed. Also, the traces of the major thrust faults of Oklahoma, such as the Ti Valley Fault, are not easy to identify in the area. Clearly, however, a major fault comparable to the Ti Valley Fault, which has transported basinal Ouachita facies strata far to the north of their site of deposition, is present in the Boles–Y City area. Whereas Arkoma Basin thrusts may have involved a few miles of displacement, the frontal Ouachita thrust faults merge into a sole fault that involves >45 mi of displacement and offsets core-zone strata. This great detachment was later folded by duplex formation in the basement, creating the Benton–Broken Bow Uplift. What we see at Hatton, then, is the exposed complex that once formed the substructure of the great detachment, arched and refolded by underlying basement thrusts. Devonian metamorphic dates in the core-zone strata (Denison and others, 1977), however, are evidence that an earlier period of deformation occurred, and that the Devonian–Ordovician units may have been deformed prior to deposition of the Carboniferous units.

120.6	1.6	Return to Hatton, Arkansas, and turn right (north) on U.S. 59/71.
126.7	6.1	Cove, Arkansas. Turn left (west) on S.H. 4. For the next 3 mi you will drive over steeply dipping lower Stanley Group sandstones and shales.
129.7	3.0	Leave Polk County, Arkansas; enter McCurtain County, Oklahoma. Continue west on Oklahoma State Highway 4 to Smithville, Oklahoma. Turn right (north) on U.S. Highway 259 for return to Poteau.

DAY TWO

Origin and Distribution of Friable and Cemented Sandstones in Outcrops of the Pennsylvanian Jackfork Group, Southeastern Oklahoma: Application to Gas Exploration in the Jackfork

Roger M. Slatt
University of Oklahoma

with discussion of Arkoma Basin–Ouachita Mountains transition zone by
Ibrahim Çemen
Oklahoma State University

and road log by
Neil H. Suneson
Oklahoma Geological Survey

INTRODUCTION

Today's field trip will focus on reservoir sandstones in the Jackfork Group, which produces gas in the Talihina Northwest, Buffalo Mountain, and Potato Hills gas fields. As our understanding of facies relations in the Jackfork (and other similar deep-water sandstones, such as the Atoka) improves, and as we are able to interpret and model subsurface structure more accurately, new areas in the Ouachita Mountains will undoubtedly become prospective.

The first few miles of the trip cross the southern part of the Arkoma Basin and pass near some of Oklahoma's earliest energy development—the coal mines near Howe and Heavener (Fig. 41). Today, this coal is being "mined" in a far different way than in the past: relatively shallow coal-bed-methane wells are contributing significantly to Oklahoma's energy economy. Improvements in drilling practices, well design, and completion techniques, including the ability to drill horizontal wells in 3-ft-thick coal beds, have made much coalbed methane economic and a viable exploration target. Stop 5 on the flanks of Poteau Mountain will allow us to see some of the relatively broad, open structures typical of the Arkoma Basin, and we will discuss the transition zone between the basin and the Ouachita Mountains fold-and-thrust belt.

Exploration wells in the transition zone and Ouachita Mountains in this part of far eastern Oklahoma are few and far between. Why? Possible answers are that (1) the strata are too thermally mature to contain hydrocarbons; (2) the Spiro sandstone, a principal reservoir to the west, is not present or is poorly developed here; and (3) sandstones in the Atoka Formation, most of which are sheet sandstones, are too cemented to be potential reservoirs. Another possible explanation is that (4) too few modern seismic lines have been run through this area to allow new geological interpretations, and models developed a few townships to the west, to be applied here.

South of the Choctaw Fault the steeply tilted turbidites and olistostromes of the Atoka Formation, Johns Valley Formation, Jackfork Group, and Stanley Group are well exposed. Questions about the nature of the base of the Atoka Formation that we will discuss tomorrow may apply in this far eastern part of Oklahoma; and hints that the sequence-stratigraphic architecture of the Atoka may one day be understood may be preserved in the Spring Mountain Anticline. Stops 6A, 6B, and 7 will focus on the stratigraphy, sedimentology, fracturing, and reservoir potential of the Jackfork Group. We will pass through the Stanley Group, which probably plays a key role in the structural/tectonic segmentation of the Ouachitas (discussed on Day One), but we will not discuss its hydrocarbon potential, despite the fact that the first-used hydrocarbons in the Ouachitas came from the Stanley: Native Americans used asphaltite to bind projectile points to shafts in making arrows. Hundreds, and possibly thousands, of years later, oil and gas were discovered in and produced from the Stanley.

ROAD LOG

Cumulative mileage	*Interval*	
0.0	0.2	Start trip at Kerr Conference Center parking lot (Fig. 41). Drive north on blacktop road to first intersection.
0.2	0.2	Turn right (east) and follow road up dip slope of Savanna sandstone no. 2.
0.4	0.2	Crest of ridge; road curves to northeast.
1.3	0.9	Intersection with section-line road to west. Leave Wister 7.5′ quadrangle; enter Poteau West 7.5′ quadrangle. Continue straight on top of Savanna sandstone no. 2.
1.7	0.4	Road turns to north.
2.4	0.7	Second intersection. Turn right (east) and drive to intersection with U.S. Highway 59.
2.5	0.1	Turn right (south) onto U.S. 59.

2.9	0.4	Cross crest of ridge (Savanna sandstone no. 2).
3.2	0.3	Descend onto flood plain of Poteau River on shale in the McAlester Formation; drive on Quaternary alluvial deposits.
3.5	0.3	Bridge over Long Lake, an abandoned channel segment of the Poteau River.
3.6	0.1	Leave Poteau West 7.5′ quadrangle; reenter Wister 7.5′ quadrangle.

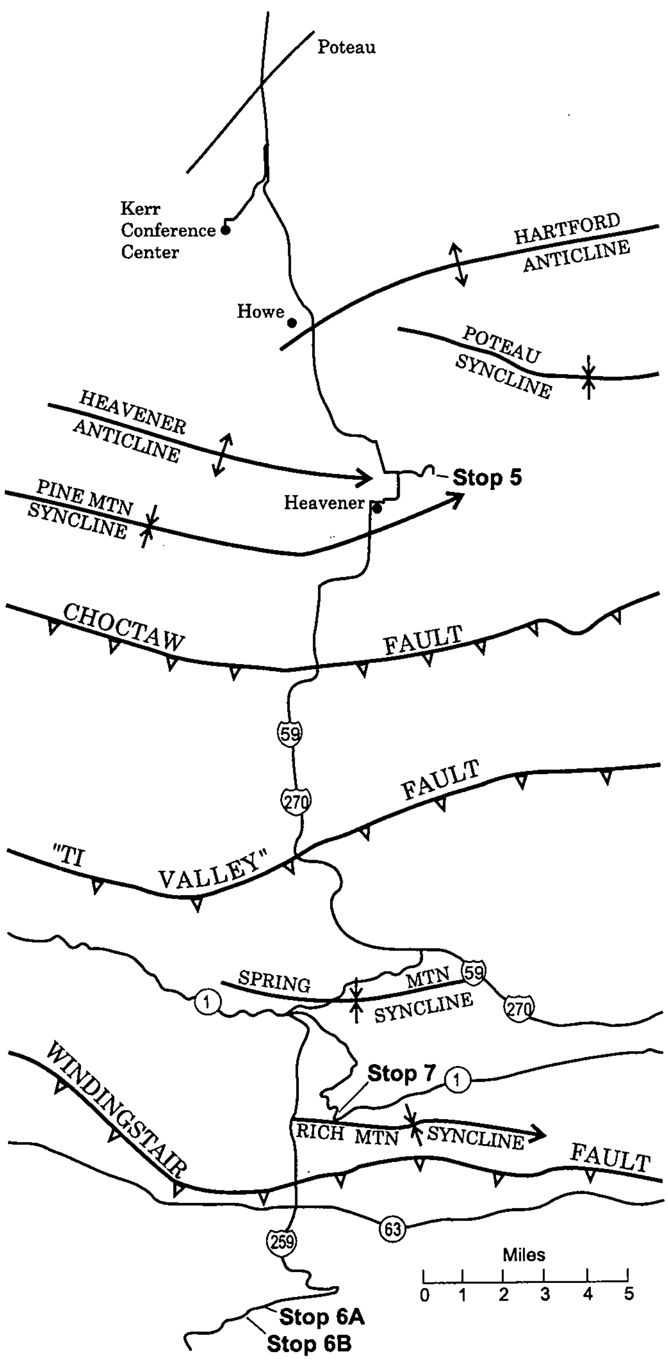


Figure 41. Map showing field-trip route for Day Two, major towns, locations of stops, and some major geologic features.

4.3	0.7	Bridge over Poteau River. Continue due south on Quaternary terrace and flood-plain deposits.
5.6	1.3	Contact between Quaternary terrace deposits and McAlester Formation. Ascend low ridge formed by poorly developed Cameron Sandstone Member of McAlester Formation.
5.7	0.1	Descend onto flood plain of Morris Creek.
6.2	0.5	Bridge over Morris Creek. Begin ascent of ridge formed by upper Warner Sandstone.
6.4	0.2	Drive onto Quaternary flood-plain deposits of Morris Creek. Ridge to the right (southwest) formed by lower Warner Sandstone.
6.7	0.3	Road to right (west) leads to Howe. The 1994 field trip examined the McCurtain Shale and Warner Sandstone Members of the McAlester Formation just up this road.

For the next 1.2 mi, the road crosses Quaternary flood-plain and terrace deposits.

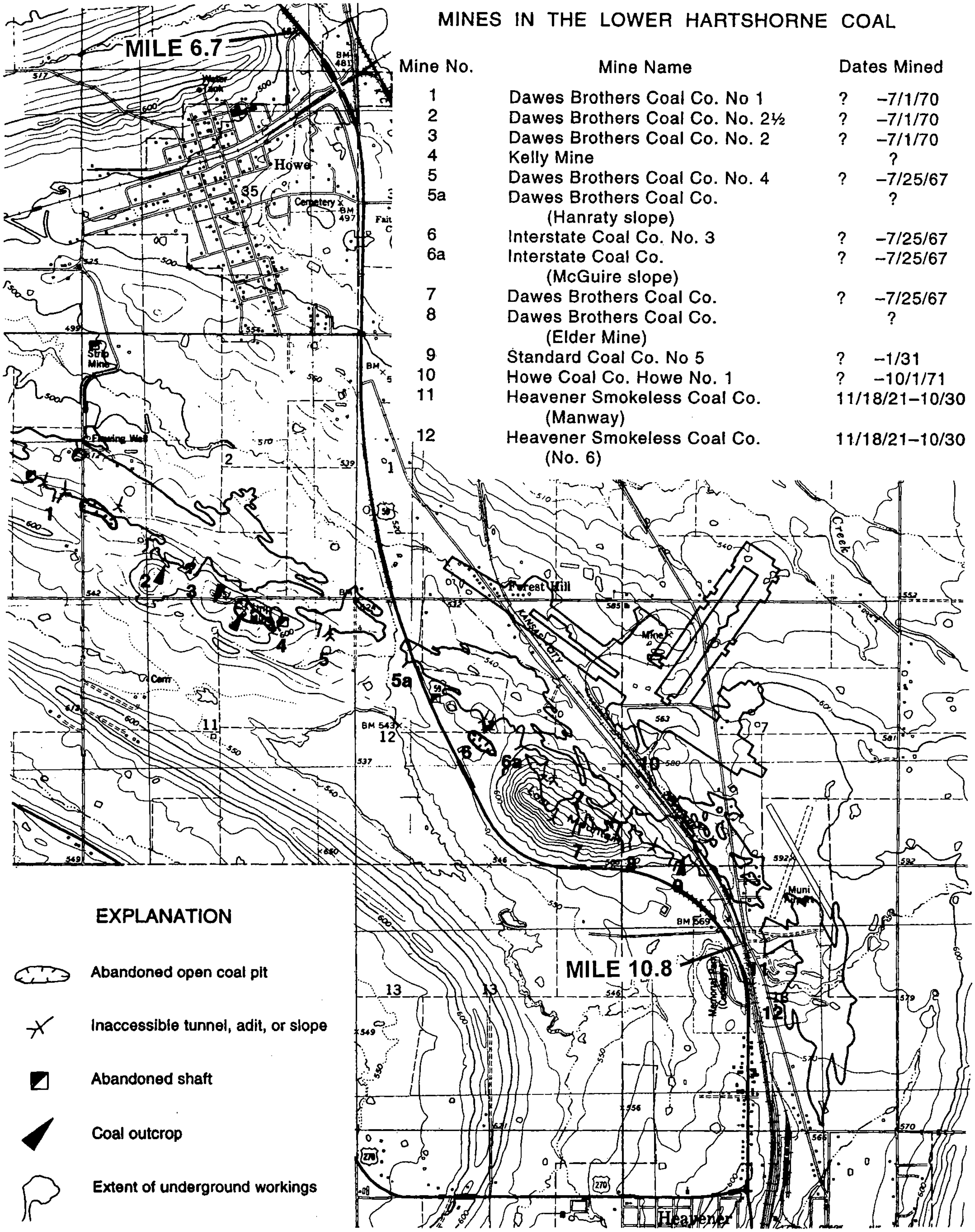
Howe, Oklahoma

The town of Howe, originally known as Klondike, has always been a coal-mining center. A post office was established here on May 5, 1889. At the turn of the 20th century, ~2,000 people lived in Howe, then the largest town in Le Flore County. The population had grown so quickly that "one found only rocky, dusty streets with no drainage; winding roads with stumps, ruts, and rocks leading from it into the county. There were no bridges, few fences, with the principal building consisting of miner's [sic] shacks, and of course, lots of children, with no schools or churches" (Peck, 1963, p. 305).

The major industries were the coke ovens, a brick plant, and the nearby coal mines. Coal has been produced commercially from the Lower Hartshorne coal in the Howe area since about 1890. Most of the miners worked for Degnan and McConnell, which was the largest mining interest in the Indian Territory at that time. Production records have been kept by counties since 1907, when Oklahoma became a state, so total coal production is unknown (Hendricks, 1939, p. 279).

Most of the coal was mined underground. Between 1900 and 1905, a battery of 40 coke ovens at Howe manufactured coke (Hendricks, 1939, p. 281). The remains of the beehive ovens are south of town. The coke produced was of good quality, but the coking was abandoned because of the distance to an adequate market (Hendricks, 1939, p. 281).

On May 5, 1961, a tornado destroyed a 36-block area in the residential part of Howe. At the time, 360 people were living in Howe; 13 people were killed, and 56 were injured by the tornado. Only two weeks earlier, the nearby town of Wister was severely damaged by a major flood.



MINES IN THE LOWER HARTSHORNE COAL

Mine No.	Mine Name	Dates Mined
1	Dawes Brothers Coal Co. No 1	? -7/1/70
2	Dawes Brothers Coal Co. No. 2½	? -7/1/70
3	Dawes Brothers Coal Co. No. 2	? -7/1/70
4	Kelly Mine	?
5	Dawes Brothers Coal Co. No. 4	? -7/25/67
5a	Dawes Brothers Coal Co. (Hanraty slope)	?
6	Interstate Coal Co. No. 3	? -7/25/67
6a	Interstate Coal Co. (McGuire slope)	? -7/25/67
7	Dawes Brothers Coal Co.	? -7/25/67
8	Dawes Brothers Coal Co. (Elder Mine)	?
9	Standard Coal Co. No 5	? -1/31
10	Howe Coal Co. Howe No. 1	? -10/1/71
11	Heavener Smokeless Coal Co. (Manway)	11/18/21-10/30
12	Heavener Smokeless Coal Co. (No. 6)	11/18/21-10/30

Figure 42. Map showing locations of shafts, adits, and abandoned underground-mine workings in the Lost Mountain area, north of Heavener (from Suneson and Hemish, 1994, fig. 60; modified from Donica, 1978, pl. 1).

7.1 0.4 Cross concealed axis of the Hartford Anticline.

7.7 0.6 Start to ascend subtle ridge formed by an unnamed sandstone in the McCurtain Shale Member of the McAlester Formation. The rocks dip 3–6° northeast here, away from the axis of the Heavener Anticline (see Stop 5).

8.1 0.4 Cross ridge and continue due south on McCurtain Shale and Quaternary alluvial deposits.

9.0 0.9 Drive onto Hartshorne Formation.

Mountain on the left (east) side of highway, just ahead, is Lost Mountain; at the top is a thick, channel-fill facies of the upper Hartshorne Sandstone. The mountain and nearby area are honeycombed by abandoned underground mines (Fig. 42 [on facing page]). An exposure of the Lower Hartshorne coal is visible from the highway at the southeast end of Lost Mountain. The coal is ~4 ft thick in the area.

Lost Mountain and much of sec. 18 make up the Dawes Coal Company Problem Area. Open portals, vertical openings (air shafts), and subsidence were the principal environmental hazards. The area has been reclaimed under the Oklahoma Conservation Commission's Abandoned Mine Land program.

Follow curving road into the outskirts of Heavener.

9.1 0.1 Leave Wister 7.5′ quadrangle; enter Heavener 7.5′ quadrangle.

10.8 1.7 Turn left (east) and cross Kansas City Southern railroad tracks.

10.9 0.1 Turn right (south) at first intersection beyond railroad tracks; abandoned coal plant to the left.

11.6 0.7 Turn left (east) and follow road to Poteau Mountain and Heavener Runestone State Park, straight ahead.

11.8 0.2 Cross north–south section-line road (Seventh Street). Continue straight (east).

12.1 0.3 Heavener water tower, on north side of road, sits on resistant ridge of Warner Sandstone.

The Warner Sandstone Member can be mapped as only a single unit from sec. 17, T. 5 N., R. 26 E., southward and eastward around the base of Poteau Mountain to the Arkansas state line. The Warner Sandstone consists of two sandstone-dominated sequences separated by shale on the north side of Poteau Mountain and to the west of here (near Wister Lake).

12.9 0.8 Stop 5. Overview of structural geology of the southern part of the Arkoma Basin and transition to the Ouachita fold-and-thrust belt. (This was stop 17B on the 1994 field trip.)

STOP 5

STRUCTURAL GEOLOGY OF ARKOMA BASIN–OUACHITA MOUNTAINS TRANSITION ZONE

Ibrahim Çemen and Kris R. McPhail
Oklahoma State University

Location: at end of parking area,
Heavener Runestone State Park,
NW¼NE¼NE¼ sec. 20, T. 5 N., R. 26 E.,
Le Flore County, Oklahoma

Two of the most spectacular folds of the Ouachita Mountains—the Pine Mountain Syncline and Heavener Anticline—are easily visible from this overlook and on SAR images of the area (Fig. 43). The two folds plunge to the west and involve Atokan strata. The Choctaw Fault, which strikes ~N. 60° W. and dips to the south, is south of the anticline. South of the Choctaw Fault a series of imbricate faults have thrust middle and lower Atokan strata, creating numerous tight folds. The Pine Mountain Fault is exposed to the south of the Choctaw Fault; the Pine Mountain thrust sheet also consists entirely of Atokan strata. Farther south, Morrowan strata are exposed in the hanging wall of the Ti Valley Fault, where splays of this fault contain steeply dipping sections of Atoka Formation, Jackfork Group, and Johns Valley Formation (Fig. 44).

McPhail (2001) constructed three balanced structural cross sections ~12 mi west of here to delineate the subsurface structural geometry of the thrust faults and associated structures in the Summerfield and Leflore SE quadrangles (Fig. 44). Ronck (1995) constructed five balanced structural cross sections to determine the structural geometry of the thrust faults in the Leflore and Blackjack Ridge quadrangles, which include the southeastern part of the Red Oak–Norris gas field. The cross sections by McPhail (2001) and Ronck (1995) are based on interpretations of electric logs of wells drilled in the area and available seismic-reflection profiles. McPhail's (2001) cross section B–B′ is shown in Figure 45.

The footwall of the Choctaw Fault contains a basal detachment fault within the Devonian Woodford Shale, well recognized in the area as the Woodford Detachment Fault. The fault is ~20,000 ft below sea level in the southern part of the Leflore SE quadrangle. Northward, it gently rises 1,000 ft over a distance of 8 mi. At this point the detachment turns up-section, leaves the Woodford Shale, and rises into the Morrowan Springer Shale. The Springer Detachment serves as the floor thrust of a duplex structure whose base is ~16,000 ft below sea level.

In addition to the Springer Detachment, another detachment is present in the footwall of the Choctaw Fault. Branching off from the ramp that forms the Springer Detachment, the Lower Atoka Detachment acts as a roof

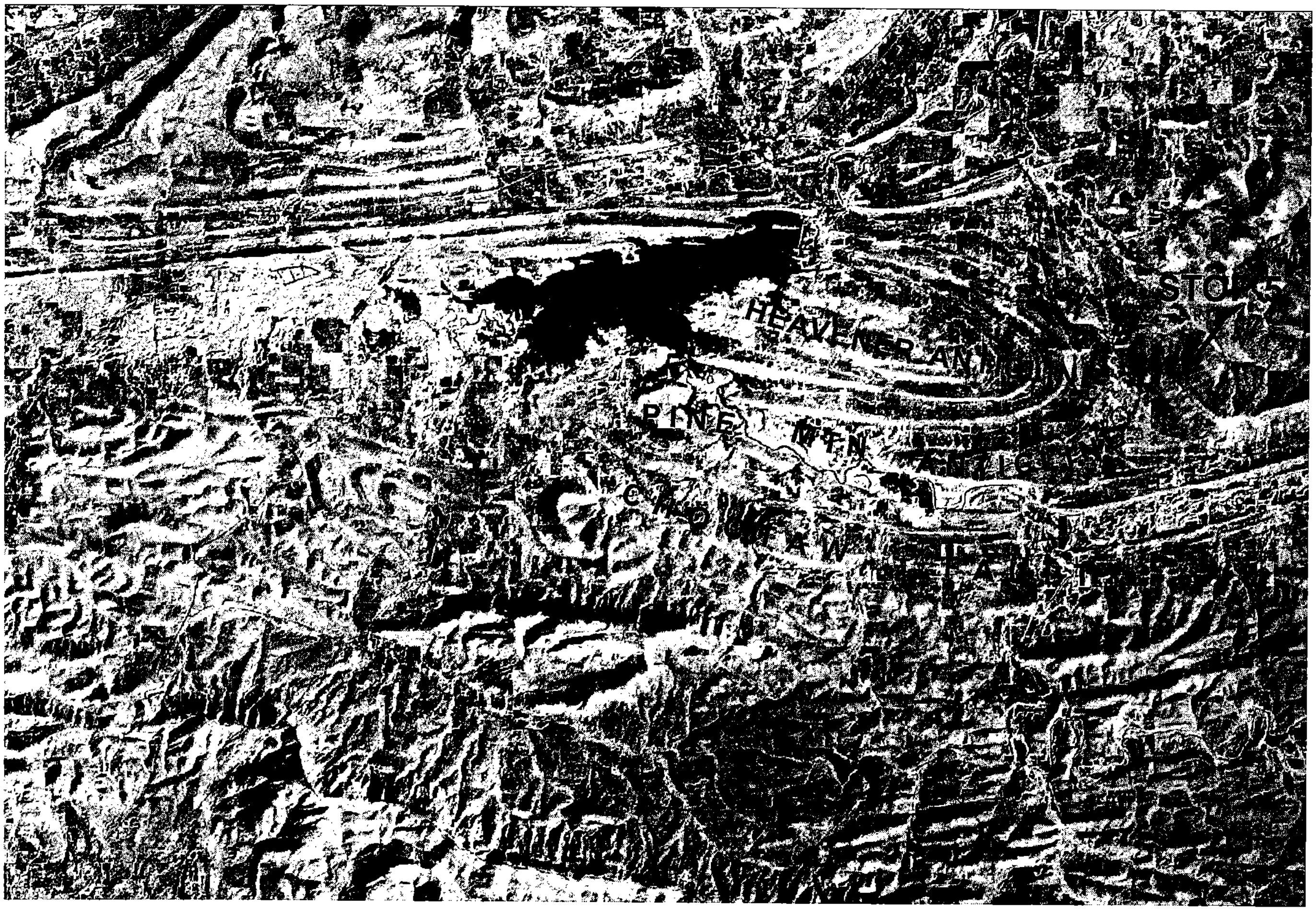


Figure 43. SAR (synthetic-aperture radar) image of the Wister Lake area, showing the Pine Mountain Syncline, Heavener Anticline, and Choctaw Fault.

thrust for a large duplex structure (Fig. 45). It rises to a depth of 12,000 ft below sea level, where it continues horizontally for some distance northward.

Between the Lower Atoka Detachment and Springer Detachment are numerous south-dipping faults. These imbricate faults branch from the floor thrust and extend to the roof thrust, creating a series of horses. These horses are hinterland-dipping and decrease in displacement to the north.

Data from wells and seismic profiles in the Summerfield and Leflore SE quadrangles suggest that the triangle zone described in the Wilburton area by Çemen and others (2001a) may not extend into the Wister Lake area. However, the triangle zone is present in the subsurface in the Leflore and Blackjack Ridge quadrangles (Ronck, 1995) and in the Red Oak and Talihina quadrangles (Day Three, Stop 8).

If time permits, we will look at the famous Heavener runestone, which some use as evidence that Vikings visited this part of Oklahoma about 1,000 years ago.

		Retrace route to Seventh Street (north–south section-line road).
14.0	1.1	Turn left (south) on Seventh Street.
14.7	0.7	Turn right (west) on C Street. Enter Heavener, Oklahoma.
15.2	0.5	Turn left (south) on Main Street.
15.25	0.05	Turn right (west) and cross Kansas City Southern railroad tracks.

Heavener, Oklahoma

The area near Heavener, Oklahoma, was known to early Native Americans as the "Prairie of the Tall Grass." With the arrival of the Choctaws in the mid-1800s, the town became a missionary center known locally as "Choctaw City" (not to be confused with the Choctaw City [Chahta Tamaha] near Durant, the capital of the Choctaw Nation from 1863 to 1882). With the establishment of the Kansas City Southern railroad in 1896, the town was renamed after Joseph Heavener, a local merchant who had intermarried into the Choctaw tribe and who owned the land on which the town was built.

In 1910 the railroad built a roundhouse in Heavener. The town thrived as railroad men established their homes there.

15.3 0.05 Intersection with U.S. 59/270. Turn left (south).

16.3 1.0 Leave Heavener 7.5′ quadrangle; enter Hontubby 7.5′ quadrangle. Road to now-closed and reclaimed Pine Mountain Coal Mine on right.

17.4 1.1 Heavener road cut. (This was stop 18 on the 1994 field trip, and stop 15 on the 1998 field trip.)

Many field trips to the Ouachita Mountains stop here. The most recent published description of this outcrop is by Suneson (1998).

Hartshorne Formation–Atoka Formation Contact

The contact between the Hartshorne and Atoka Formations is perhaps better exposed at this outcrop than anywhere in the Arkoma Basin of Oklahoma (Fig. 46). Thus, this exposure provides a suitable stage for a discussion of

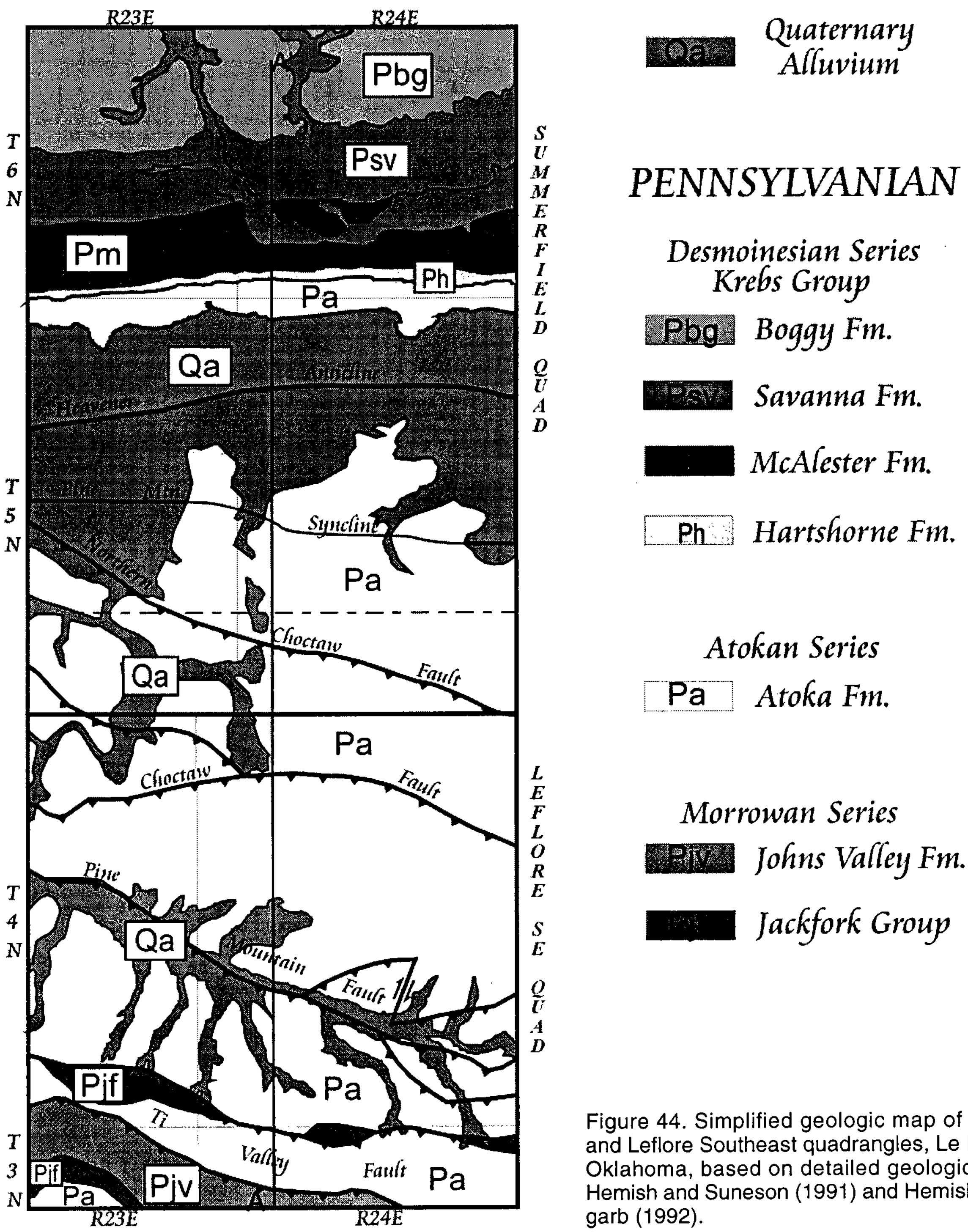


Figure 44. Simplified geologic map of Summerfield and Leflore Southeast quadrangles, Le Flore County, Oklahoma, based on detailed geologic mapping by Hemish and Suneson (1991) and Hemish and Mazengarb (1992).

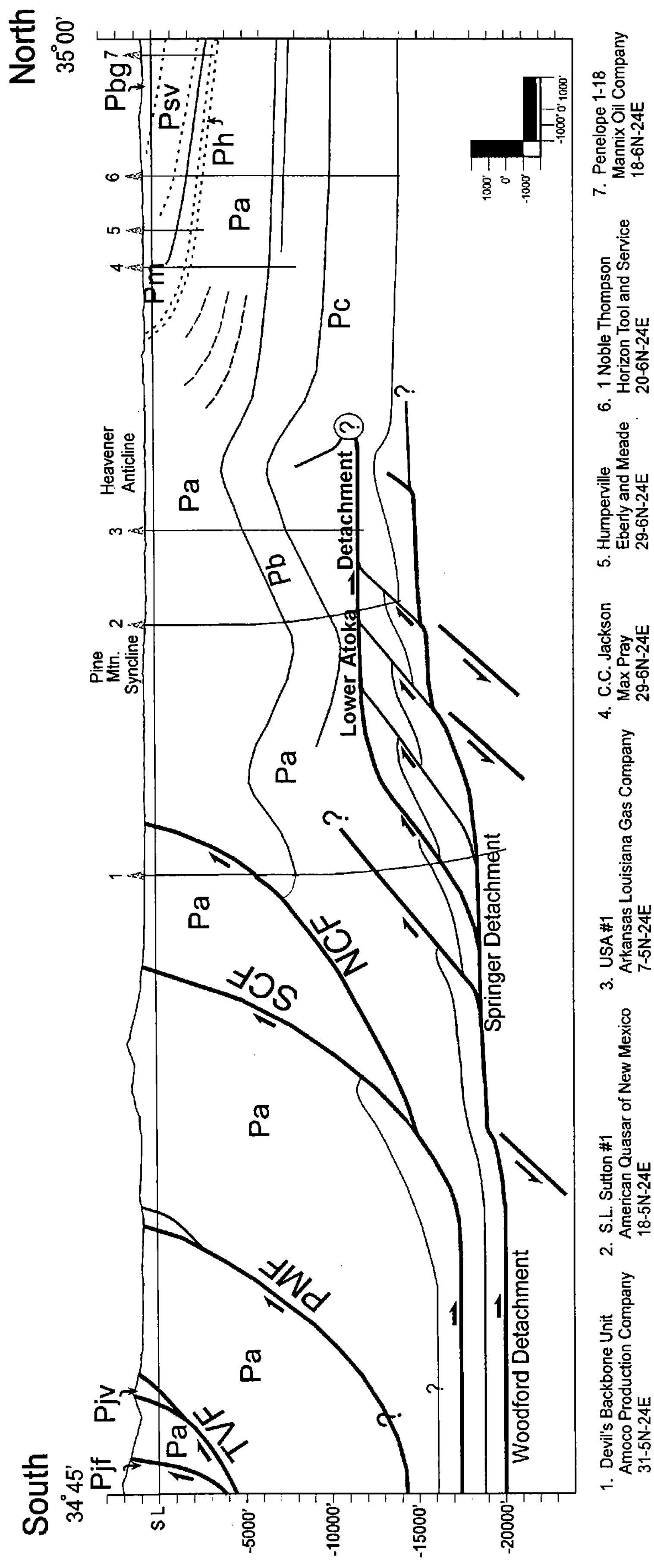


Figure 45. Balanced structural cross section B–B′, showing subsurface geology ~12 mi west of Stop 5. Faults: TVF = Ti Valley Fault; PMF = Pine Moutain Fault; SCF = Southern Choctaw Fault; NCF = Northern Choctaw Fault. Rock units: Pjf = Jackfork Group; Pjv = Johns Valley Formation; Pa = Atoka Formation; Pc = Cecil sandstone; Pb = Brazil sandstone; Ph = Hartshorne Formation; Pm = McAlester Formation; Psv = Savanna Formation; Pbg = Boggy Formation.

the nature of the contact and how the Atoka and Hartshorne Formations are defined. Central to the discussion is the question: is the contact fundamentally lithologic (outcrop vs. subsurface), paleontologic, environmental, sequence-stratigraphic, or a combination of two or more of these criteria?

Type Section and Lithology (Outcrop)

Details of the history of nomenclature of the Hartshorne Formation are given by Suneson (1998). The Oklahoma Geological Survey currently accepts the definition proposed by McDaniel (1961), which identifies the base of the formation as the base of the lower Hartshorne sandstone and the top as the top of the Upper Hartshorne coal. (North of the coal-split line, the top of the formation is the top of the Hartshorne coal.) There is no identified type section of the Hartshorne Formation, although it is generally presumed to be near the town of Hartshorne. Mapping in the Arkoma Basin by the U.S. Geological Survey (Hendricks, 1937; Knechtel, 1937; Hendricks, 1939) also recognized the base of the formation as the base of the Hartshorne sandstone, but noted that the character of this sandstone varies greatly, in some cases over relatively short distances. Following common mapping practices, the Oklahoma Geological Survey maps the base of the Hartshorne Formation at the base of the lowest "mappable" sandstone. In many areas in the Arkoma Basin the Hartshorne Formation is finely stratified, silty to shaly, and contains no or only relatively thin sandstone beds. In these areas, mapping the lowest sandstone is highly subjective.

A brief history of the nomenclature of the Atoka Formation is given by Suneson (1987). Like the Hartshorne Formation, there is no type section of the Atoka Formation; however, four "type areas" have been suggested. Branson (1962) chose an area close to the town of Atoka; Strimple and Watkins (1969) chose an area northwest of Clarita in Coal County; Lane and West (1984) recommended the southern edge of the Arkoma Basin in Latimer and Le Flore Counties; and Shaver (1984) included all the southern part of the Arkoma Basin and the northern Ouachita Mountains. The Atoka Formation consists mostly of mudstone in

Figure 46. Heavener road cut. Dark-colored strata on left at bottom of outcrop are mostly shales in the Atoka Formation; lighter colored strata above are the lower part of the Hartshorne Formation. Upper Hartshorne sandstone is exposed at the top of road cut, underlain by a conspicuous black band of Lower Hartshorne coal (from Suneson and Hemish, 1994, fig. 68).

all its "type" areas. As noted by Knechtel (1937, p. 100) in his report that included Atoka County, "the Atoka Formation is composed chiefly of shale . . . in which are intercalated at widely spaced intervals fairly well-exposed sandstone members."

In summary, despite the absence of a type locality or type section for either the Atoka Formation or the Hartshorne Formation, and despite the variable character of the lower part of the Hartshorne Formation, the Atoka–Hartshorne contact is recognized as the base of the lowest mappable Hartshorne sandstone.

Lithology (Well Logs)

Andrews (1998) maps the Atoka–Hartshorne contact in the subsurface throughout the Arkoma Basin at an inflection point on gamma-ray and resistivity logs. This inflection point marks the contact between "pure" shale below and "silty" shale or finely interbedded siltstone and shale above. Where the contact between the Atoka and Hartshorne is gradational, and thin siltstones or sandstones would not be exposed on the surface, this definition might be useful. However, this difference between the outcrop definition of uppermost Atoka and the log definition highlights the confusion over picking the base of the Hartshorne: siltstones and thin sandstones probably are more readily apparent on logs than in outcrops, particularly where Atoka shale grades into Hartshorne sandstone. Thus, the base of the Hartshorne Formation generally would be lower on logs than in outcrop.

Age

Early reports (cited in Knechtel, 1937; Hendricks, 1937; Hendricks, 1939) by the U.S. Geological Survey in the Arkoma Basin show the Atoka Formation to be Pottsville in age and the Hartshorne Formation to be Allegheny in age on the basis of flora. These ages, however, are difficult to relate to modern Pennsylvanian series nomenclature—specifically, the Atokan and Desmoinesian. As pointed out by Sutherland and Manger (1984b, p. 1):

> The main divisions of the Appalachian Pennsylvanian . . . were used principally in a lithostratigraphic sense . . . with boundaries placed at arbitrarily designated coals or limestones. . . . Biostratigraphic control, where available, was and is based almost entirely on megaflora. . . . [Later work] focused attention . . . on the mid-continent Pennsylvanian record [where] fossiliferous marine zones, in addition to some floras . . . provided a firm basis for continental and intercontinental correlations.

A precise paleontological definition for the Atokan Series is difficult, given the problems associated with locating a type section, type locality, or type area for the Atoka Formation. Sutherland and Manger (1984a) highlight some of the problems in defining the Atokan Series and suggested using certain marine microfossils to identify the top of the series. Unfortunately, sections with few (or no) marine strata, such as the Heavener road cut, offer little hope for identifying the top of the Atokan Series.

Branson (1954) identified the Hartshorne Formation as the lowest unit in the Desmoinesian Series but did not show why he did so. No worker, however, has suggested that the Hartshorne Formation is younger than Desmoinesian.

In summary, despite the difficulty and confusion surrounding defining the Atokan Series and its relation to the Atoka Formation, most of the Atoka Formation is Atokan and the Hartshorne Formation is Desmoinesian.

Environment of Deposition

Although the lithology of the uppermost part of the Atoka Formation generally is fine grained (either mudstone or interbedded mudstone and siltstone), the depositional environment of the sequence has rarely been interpreted. This may be because the fine-grained Atoka Formation typically is unexposed or, at best, poorly exposed beneath the resistant sandstone of the Hartshorne Formation. The upper part of the Atoka Formation (~400 ft to 1,300 ft below the Hartshorne) near Wister, Oklahoma is marine (Chaplin, 1994). Elsewhere in the Arkoma Basin the outcrops of the uppermost part of the Atoka Formation include distal-marine, prodelta, bar-transition, and marine-bar environments (Suneson, 1998). Regardless of exactly where the contact is picked, the uppermost part of the Atoka Formation typically is marine. The only exception to this is the Heavener road cut, where the uppermost part of the Atoka Formation, if it has been correctly identified, consists of bay-fill shale and marsh (coal) deposits (Suneson, 1998, p. 60).

The depositional environment of the lowest "recognizable" sandstone in the Hartshorne Formation on the surface, in contrast, varies from marine bar to incised-valley fill to delta-plain crevasse splay and bay fill (Suneson, 1998). Thus, except where the Hartshorne consists of channel-fill sandstone and the Atoka Formation consists of distal-marine or prodelta shale, the depositional environment of both formations is similar, and the contact between the two reflects a shallowing-upward sequence and is gradational.

Sequence Stratigraphy

The contact between the Atoka and Hartshorne Formations also can be defined by using modern sequence-stratigraphic concepts. Saleh (2004) suggests that the upper part of the Atoka Formation consists of five coarsening-upward highstand parasequences. The Hartshorne, in contrast, consists of two fining-upward lowstand channel systems capped by a fine-grained transgressive systems tract. Saleh (2004) also recognizes an unconformity between the highstand upper part of the Atoka and the mostly lowstand Hartshorne. He further suggests that the Atoka–Hartshorne contact is easy to recognize where the Hartshorne channels eroded into prodelta shale of the Atoka; but the "contact should be cautiously defined" where the Hartshorne, particularly its overbank/splay facies, overlies the "shallow marine or delta-plain marsh/swamp deposits" (p. 107) at the top of the highest Atoka parasequence.

Summary

The contact between the Hartshorne and Atoka Formations can be based on lithostratigraphy, paleontology, depositional environment, or sequence stratigraphy. Because formal stratigraphic nomenclature is based on surface exposures, the base of the Hartshorne Formation is defined as the base of the lowest mappable sandstone overlying the dominantly fine-grained Atoka Formation. Most geologists agree that the lowest sandstone is diachronous. In the subsurface, some workers map the base of the Hartshorne at the lowest deflection from a (marine-) shale baseline—that is, at the first indication of silt or thin sands. Paleontologically, most of the Atoka Formation is Atokan, and most of the Hartshorne Formation is Desmoinesian, but identifying a key marker bed (like the K–T boundary!) anywhere near the type sections would require much biostratigraphic work. Most of the upper part of the Atoka consists of relatively deep-water deposits; the Hartshorne varies from relatively shallow marine to delta plain to fluvial. The contact may be gradational where the marine facies of both formations are juxtaposed. A contact based on sequence stratigraphy requires distinguishing a coarsening-upward sequence on logs (or presumably in outcrop) from a fining-upward sequence.

17.5 0.1 Leave Hontubby 7.5′ quadrangle; enter Hodgen 7.5′ quadrangle.

17.9 0.4 Cross Poteau River.

19.0 1.1 Intersection with paved road to Summerfield (west) and Loving (east).

19.1 0.1 Enter Hodgen, Oklahoma.

Hodgen, Oklahoma

This town was founded in 1896 and named *Houston* after the famous Texan, Sam Houston. The name was changed in 1910 to *Hodgen*, a misspelling of the name of J. W. Hodgens, a timber buyer for the Kansas City Southern Railway.

19.9 0.8 Cross trace of Choctaw Fault.

The exact location of the trace of the Choctaw Fault cannot be determined here. It can be located to within ~2,000 ft 1.5 mi to the east and 2 mi to the west. At these localities, strata in the upper part of the Atoka Formation north of the fault dip steeply and face north. Strata in the middle(?) part of the Atoka Formation south of the fault are turbidites, face north, and dip steeply (upright to overturned).

20.1 0.2 Highway bends right (west).

Outcrops on the right (north) are turbidites in the Atoka Formation. This section was measured by McDonald (1986, fig. 77). Sedimentary structures, such as sole marks (flutes, grooves, prod marks, and bounce casts), incomplete Bouma sequences, and convolute stratification, characterize many of the sandstone beds.

For the next 3 mi the road crosses steeply dipping, imbricately thrust-faulted Atoka Formation turbidites.

24.1	4.0	Cross Cedar Creek.
24.8	0.7	Intersection with Holson Valley Road to right (west). Continue south on U.S. 59/270.
26.2	1.4	Leave Hodgen 7.5′ quadrangle; enter Hontubby 7.5′ quadrangle.
26.6	0.4	Village of Stapp. Harlton (1938, p. 893) named the Stapp Conglomerate Member of the Union Valley Formation (Morrowan) from exposures along the Kansas City Southern railroad 1 mi south of Stapp. These strata are now included in the Johns Valley Formation (Hart, 1963).

Stapp, Oklahoma

The village of Stapp was founded as Thomasville in 1897; a post office was maintained there from 1918 to 1944. The town originally was a thriving lumber town with a population of about 1,000. Nothing remains of the old town; U.S. 59/270 passes through what used to be the lumber yards and single-bandsaw mill of the Buschow Lumber Company. In contrast to the Dierks Lumber Companies (bought by Weyerhaeuser Company in 1969), which were some of the first in the timber industry to institute conservation practices (such as selectively cutting old, damaged, or diseased trees and leaving young ones; thinning forest stands with too many trees; and fire prevention), the Buschow operation was "the ultimate in devastation, . . . one of the bad ones, . . . a cut-out-and-get-out operation" (Smith, 1986, p. 120).

26.8	0.2	Leave Hontubby 7.5′ quadrangle; reenter Hodgen 7.5′ quadrangle.
27.1	0.3	Leave Hodgen 7.5′ quadrangle; enter Big Cedar 7.5′ quadrangle.
27.2	0.1	Cross Shawnee Creek.
27.3	0.1	Road to Ouachita Vocational Technical Camp to right (west).
27.4	0.1	Excellent outcrop of Johns Valley Formation on right (west).

This was stop 19 on the 1994 field trip and has been visited by countless geology field trips to the Ouachita Mountains. Suneson and Hemish (1994, p. 103–106) describe the significance of this stop. Figure 47 shows two interpretations of this outcrop; Figure 48 is the much-photographed boulder bed at the north end of the outcrop. The Johns Valley Formation is described and discussed in detail at Stops 3 (Day One) and 13 (Day Three) in this guidebook and briefly at Stops 9 and 12 (Day Three).

27.7	0.3	Leave Big Cedar 7.5′ quadrangle; enter Page 7.5′ quadrangle.
29.8	2.1	Intersection of U.S. Highway 259 to right (south) and U.S. 59/270 straight (east). Turn right (south) on U.S. 259.
30.4	0.6	Excellent outcrop of turbidite sandstones in the Atoka Formation on left (south). This was stop 20 on the 1994 field trip.
31.9	1.5	Creek on north side of road marks the axis of the Spring Mountain Syncline.
32.1	0.2	Approximate top of measured section of Atoka Formation (Hart, 1963, p. 71–76). The following is a discussion of Hart's measured section from OGS Guidebook 29 (1994 field trip) with some comments (in parentheses and brackets) added in light of Dennis Kerr's studies of the basal Atoka to the west (see Day Three, this guidebook) and modern sequence-stratigraphic concepts.

Atoka Formation, Spring Mountain Syncline

Beginning here, Hart (1963) measured ~5,600 ft of Atoka Formation turbidites on the south flank of the Spring Mountain Syncline. Of particular interest are the following observations made by Hart (1963, p. 71–76) and previously discussed by Suneson and Hemish (1994):

1. Fossil molds in intervals 220, 218, 206, 211, 149, and 147. (One of us [N.H.S.] attempted to relocate Hart's fossil-mold sandstones but was able to identify only nos. 220 and 147.) Our (N.H.S., L.A. Hemish) experience elsewhere in the frontal belt is that fossil molds are present only at the base of the Atoka Formation (Hart nos. 149 and 147). Kerr (this guidebook) identified moldic sandstones very near the base of the Atoka Formation at a number of localities in the frontal belt. Longden and others (2000) suggested that these unusual basal Atoka sandstones were deposited as small, sand-rich fans derived from the shelf to the north during a period of sea-level lowstand. If moldic "Spiro-like" sandstones, derived from a sandy shelf to the north, occur not only at the base of the Atoka but throughout the Atoka as suggested by Hart's (1963) measured section, they could represent several periods of sea-level lowstands. Furthermore, these intervals might be the most likely places to look for significant thicknesses (channels?) of reservoir-quality Atoka sandstone in the Ouachita Mountains frontal belt.

2. A siliceous shale(?) (Hart's interval 167) ~900 ft above the base of the formation. Hendricks and Averitt (in Tulsa Geological Society, 1947, p. 32) described a siliceous shale ~160 ft above the base of the Atoka Formation at the hairpin curve (SE¼ sec. 3, T. 3 N., R. 19 E.). A siliceous shale is present near the base of the Atoka Formation in the C sec.

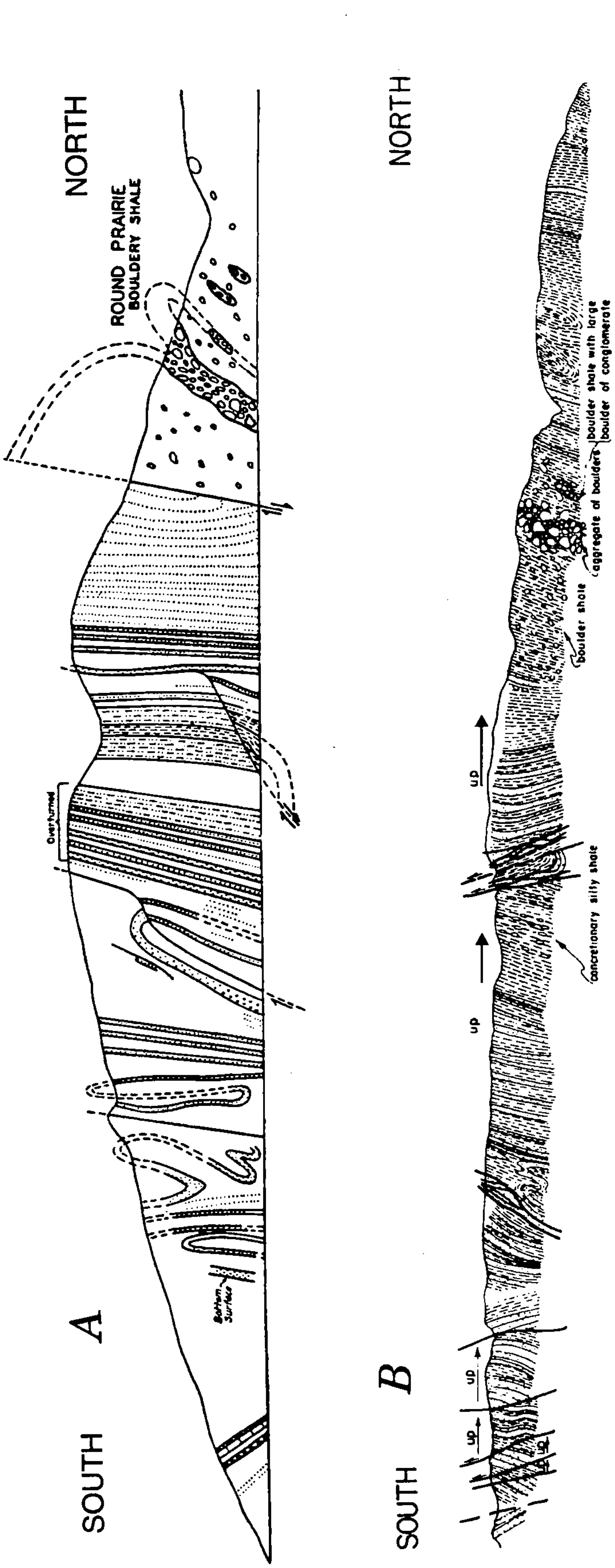


Figure 47. Johns Valley Formation outcrop at Stapp (modified from Suneson and Hemish, 1994, fig. 69). (A) "Diagram of beds exposed in road cut south of Stapp, showing position of boulders in Round Prairie Shale referred to in text" (from Harlton, 1938, fig. 19). (B) Sketch of same road cut by Misch and Oles (1956).

5, T. 3 N., R. 18 E., in the Higgins 7.5′ quadrangle. Possibly owing to the degraded condition of the outcrop, in comparison to its condition when Hart described it, Hart's siliceous shale could not be identified. (These siliceous shales may represent condensed sections or sea-level high-stands and, as such, may be the most reliable marker beds for mapping purposes in the Atoka Formation in the frontal belt.)

3. A general fining upward of the sandstones in the Atoka Formation. Nearly all the sandstones above Hart's interval 163 are fine grained or very fine grained, whereas many of the sandstones below that interval are fine to medium grained. This feature was noted also by Suneson (1991) and Hemish and Suneson (1991) in the Blackjack Ridge and Leflore Southeast 7.5′ quadrangles to the west.

32.6	0.5	Leave Page 7.5′ quadrangle; re-enter Big Cedar 7.5′ quadrangle.
33.5	0.9	McDonald (1986) also measured several sections of the Atoka Formation on the left (south) side of the highway. Overall, he considered this to be a sandstone-rich part of the Atoka.
34.0	0.5	Intersection of U.S. 259 and State Highway 1 (Talimena Drive). (We will return to this intersection and turn east.) Continue straight (south) on U.S. 259.

The highway gradually descends stratigraphically through moderately north-dipping lower part of the Atoka Formation.

34.5	0.5	Contact between Atoka Formation and Johns Valley Formation. Here, the Johns Valley contains numerous blocks of Mississippian Caney Shale.
35.3	0.8	Spring on left (east) side of road is on the trace of the Briery Fault. Hart (1963, p. 50) described the Briery Fault as follows:

> This is one of the large faults of the Ouachitas. . . . It is at least 60 miles long and probably much longer. A good exposure of the Briery Fault, one of the few faults actually to be seen in the Ouachitas, is on an east road cut where the fault trace crosses State Highway 103 [now U.S. 259] (fig. 13). Here Stanley shales are in fault contact with the Jackfork Group about 373 feet below the upper contact of the Markham Mill Formation. All of the lower and most of the middle Jackfork sediments are eliminated. The stratigraphic displacement at this point is at least 6,500 feet and is probably more because the Stanley shales resemble those in the Ten-mile Creek Formation.

For the next several miles the highway crosses poorly exposed and topographically low Stanley Group strata.

37.8 2.5 Cross trace of Windingstair Fault. Here, the Stanley Group occurs on both sides of the fault.

39.0 1.2 Big Cedar, Oklahoma. Intersection of U.S. 259 and State Highway 63. Continue straight (south) on U.S. 259.

A monument on the southwest side of the intersection notes that on October 29, 1961, President John F. Kennedy, in Oklahoma as a guest of Senator Robert S. Kerr, dedicated the highway over the Ouachita Mountains.

39.7 0.7 Cross Kiamichi River.

40.6 0.9 Leave Big Cedar 7.5′ quadrangle; enter Octavia 7.5′ quadrangle.

41.3 0.7 Outcrop of Chickasaw Creek Siliceous Shale, uppermost formation in Stanley Group, on right (west) side of road.

For the next several miles the highway passes through several outcrops of the moderately south-dipping Wildhorse Mountain Formation (Briggs, 1973), the lowest formation in the Jackfork Group. Cline and Moretti (1956) measured the section along the highway, but to my (N.H.S.) knowledge, no one has been able to duplicate their section.

42.4 1.1 Hairpin curve. Highway turns sharply right (south). Continue ascending through the Wildhorse Mountain Formation.

44.0 1.6 Three Sticks Monument at top of Kiamichi Mountain. Elevation, 2,034 ft.

Figure 48. "Boulder bed" (of Harlton, 1938, fig. 19) in Johns Valley Formation at stop 19 on 1994 field trip. Map case on left side of outcrop is ~1 ft^2.

44.3 0.3 Park on turnoff on left (south) side of road to examine large dip-slope outcrop of sandstone in Jackfork Group. Please be careful! This highway is the major north–south highway in this part of the State and is very busy.

STOP 6A

FRIABLE AND CEMENTED SANDSTONES OF THE JACKFORK GROUP— LYNN MOUNTAIN SYNCLINE

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University of Oklahoma

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Southwest Research Institute, San Antonio, Texas

Location: on north side of U.S. Highway 259, N½SW¼SE¼ sec. 27, T. 2 N., R. 25 E., Le Flore County, Oklahoma

Introduction

The Jackfork Group turbidites of eastern Oklahoma were deposited in the east–west-trending Ouachita Basin during Morrowan (Early Pennsylvanian) time from diverse source areas (Fig. 49). The onset of Jackfork deposition corresponds to a major global drop in sea level ~320 m.y. ago (Fig. 50). Tectonically induced perturbations were superimposed on several periods of glacioeustatic sea-level fluctuations throughout deposition of the Jackfork Group.

Sandstones in the Jackfork produce gas in the Potato Hills, Buffalo Mountain, and Talihina Northwest fields (see Day Three). Gas production in general is believed to be from fractured rock because the Jackfork is a notorious "hammer ringer," and because in these areas the Jackfork is highly folded and faulted. Although much of the Jackfork is quartz-cemented sandstone, making it brittle and subject to fracturing, some Jackfork is weakly cemented and has substantial porosity and permeability (Pauli, 1994). This stop and the next two stops (Stops 6B and 7) illustrate

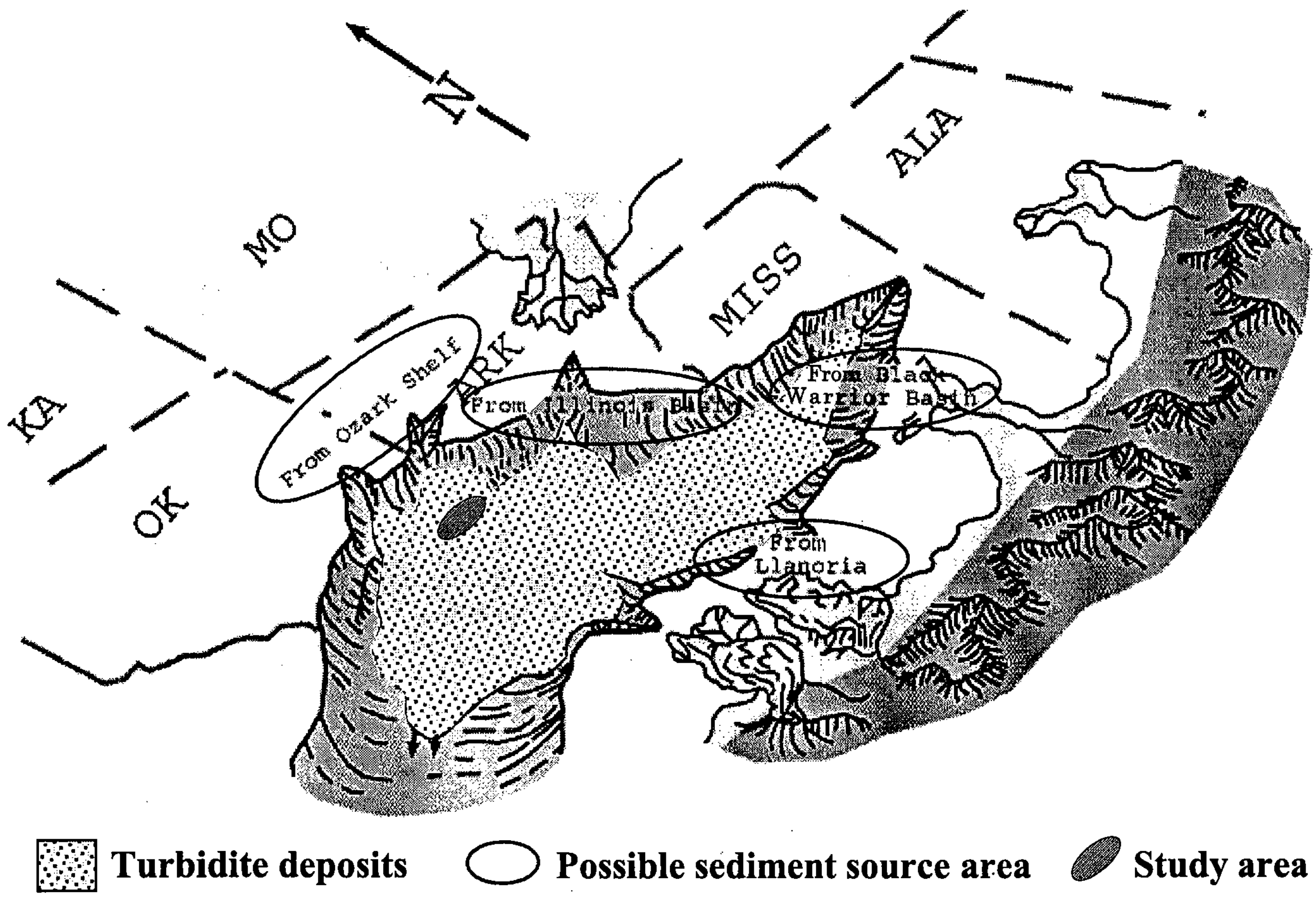


Figure 49. Ouachita Basin during deposition of the Jackfork Group. Source areas of sediments are from the northeast (Illinois Basin), north (Ozark Shelf), and south (Llanoria and Black Warrior Basin). General sediment-transport direction within the basin was from east to west, along the axis of the basin (from Slatt and others, 2000).

the relation between cemented (with fracture porosity) and weakly cemented (with matrix porosity) sandstones. The work presented here formed the basis for four recently completed M.S. theses in the School of Geology and Geophysics at the University of Oklahoma (Omatsola, 2003; Garich, 2004; Busetti, 2003; Romero, 2004).

The locations of Stops 6A, 6B, and 7 are shown in Figure 41. Several hundred feet of strata in the upper part of the Wildhorse Mountain Formation (Jackfork Group) of Briggs (1973) are superbly exposed along moderately dipping bedding planes on the north flank of the Lynn Mountain Syncline at Stops 6A and 6B, which can be seen on U.S. 259 just west of Three Sticks Monument. Stop 7, along S.H. 1 (Talimena Drive), is north of the Windingstair Fault on the north flank of the Rich Mountain Syncline.

Stratigraphy and Structure

Generalized sedimentary architectural elements associated with deep-water deposition are shown in Figure 51. These include sheet sands, channel sands, and levee beds. All three of these elements can form reservoirs. Sheet and channel sandstones are present at the outcrop locations of today's field trip.

Approximately 110 ft of strata in the upper part of the Wildhorse Mountain Formation is well exposed at Stop 6A (Omatsola's [2003] outcrop A, section 2) (Pl. 1, in pocket). The lower part of the section consists of interbedded, highly cemented Jackfork sheet sandstones (Fig. 52) and interbedded shales, and the upper part consists of more massive (i.e., no shale interbeds), friable channel sandstones. The depositional interpretation is based on a number of criteria developed for the Jackfork Group (Slatt and others, 2000), such as the nature of bed boundaries, the presence or absence of shale clasts in sandstones, and stratification style. Sheet sandstones are interpreted as having been deposited in a basinal or base-of-slope setting (Fig. 53). Channel sandstones are interpreted to have been deposited in a somewhat more proximal setting on the slope of the Ouachita Basin.

Numerous bedding surfaces were analyzed to assess the potential relationship between stratigraphic and structural controls on fracture development in the quartz-cemented sheet sandstones (Fig. 53). Linear scan lines were used to collect orientation and spacing data from the beds exposed at this and other outcrops. Stratigraphic- and mechanical-bed thicknesses were recorded for each measured bed. Outcrop measurements identified two

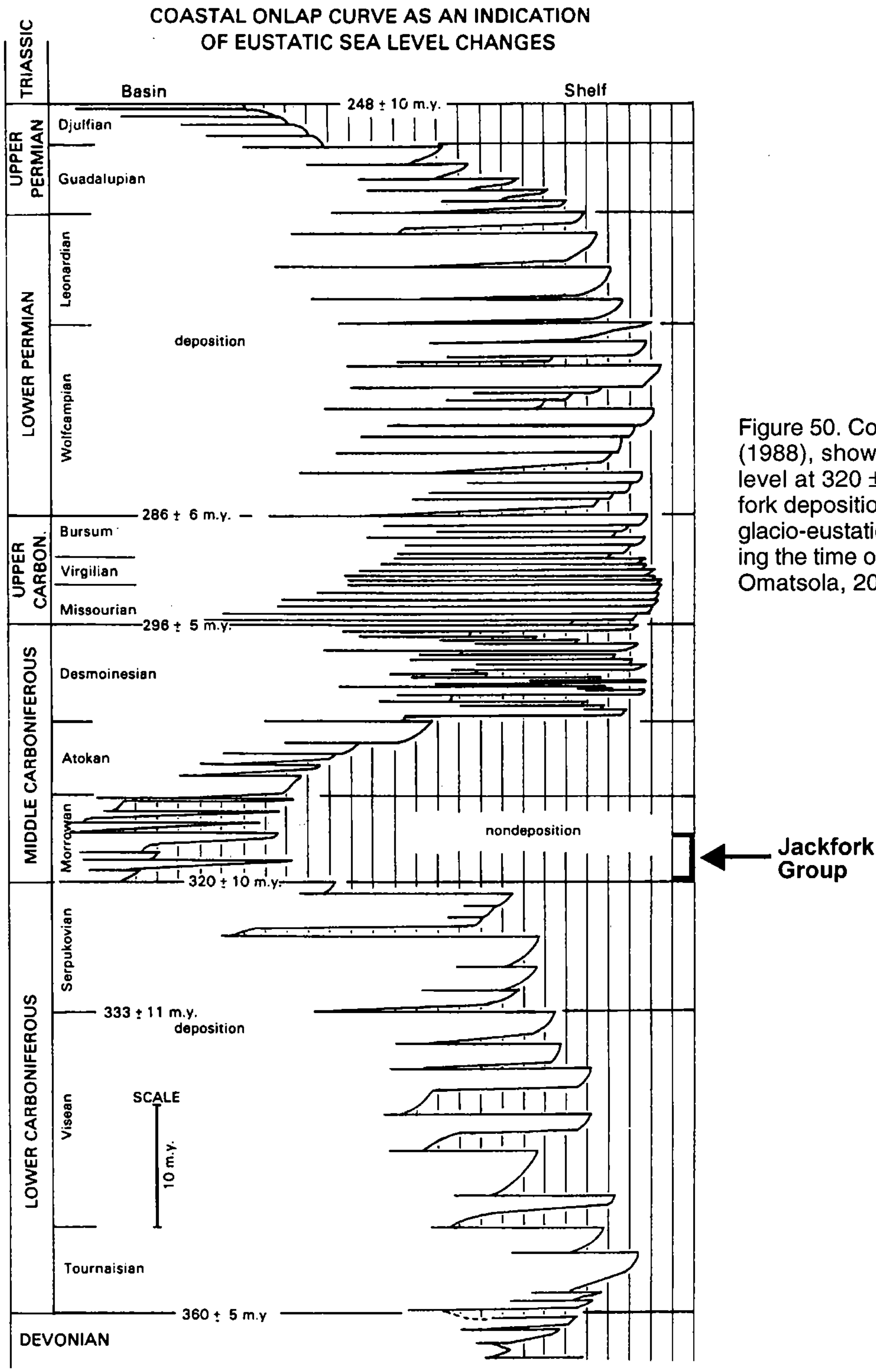
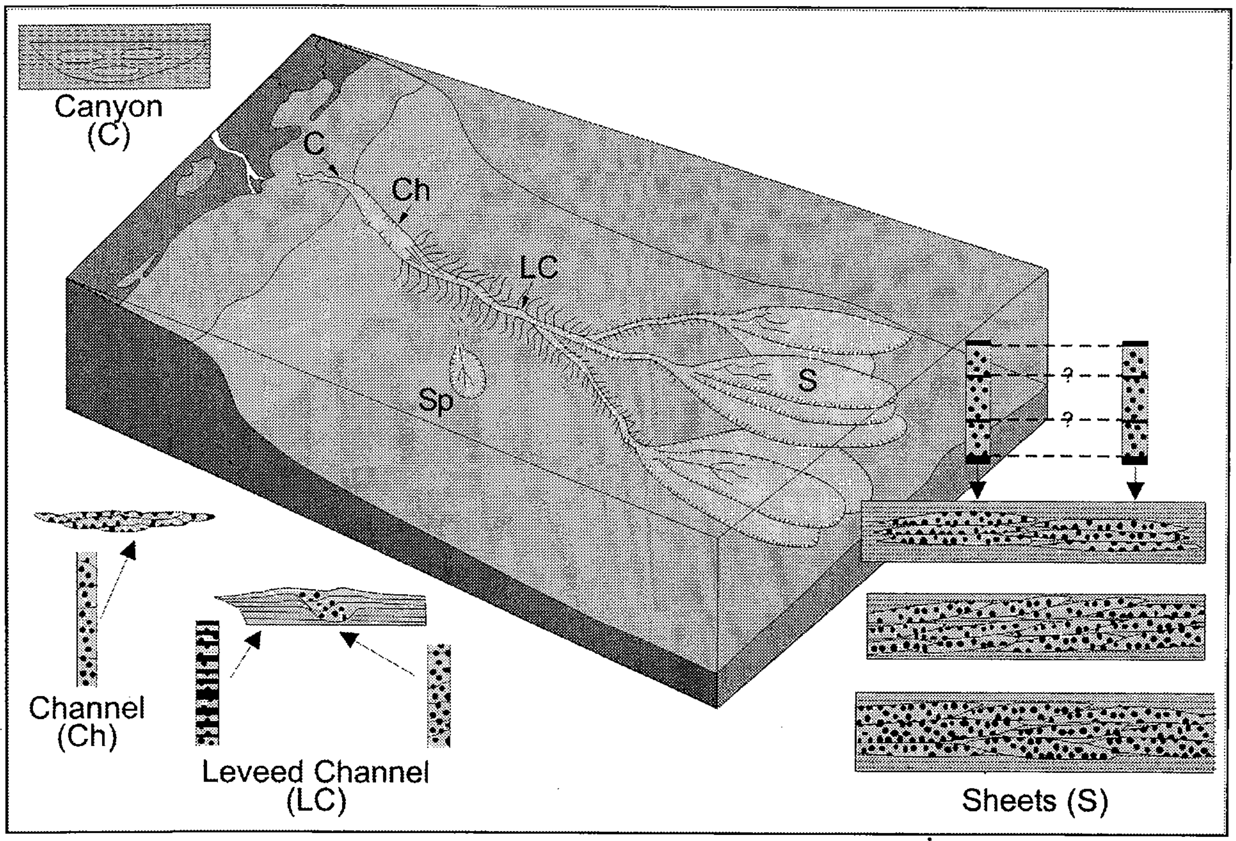


Figure 50. Coastal onlap curve of Ross and Ross (1988), showing a major third-order drop in sea level at 320 ± 10 m.y. ago at the onset of Jackfork deposition (Morrowan). Multiple episodes of glacio-eustatic sea-level fluctuation occurred during the time of Jackfork deposition (modified from Omatsola, 2003).

dominant fracture sets oriented orthogonal to one another and normal to bedding. The attitude of the primary set of fractures is N. 71° W., 59° N.; the strike of this set is approximately parallel to the strike of the bedding planes. The attitude of the second set of fractures is N. 13° E., 87° W.; this strike is approximately parallel to the dip of the bedding planes, and in general these fractures terminate against the primary set. Additional discussion of fractures in the Jackfork sandstones is included in the description of Stop 7.

Return to vehicles and continue south on U.S. 259.

45.2 0.9 Turn left (south) on dirt road and park. We will walk back to examine the large outcrop of Jackfork strata. Again, please watch for traffic and be careful!



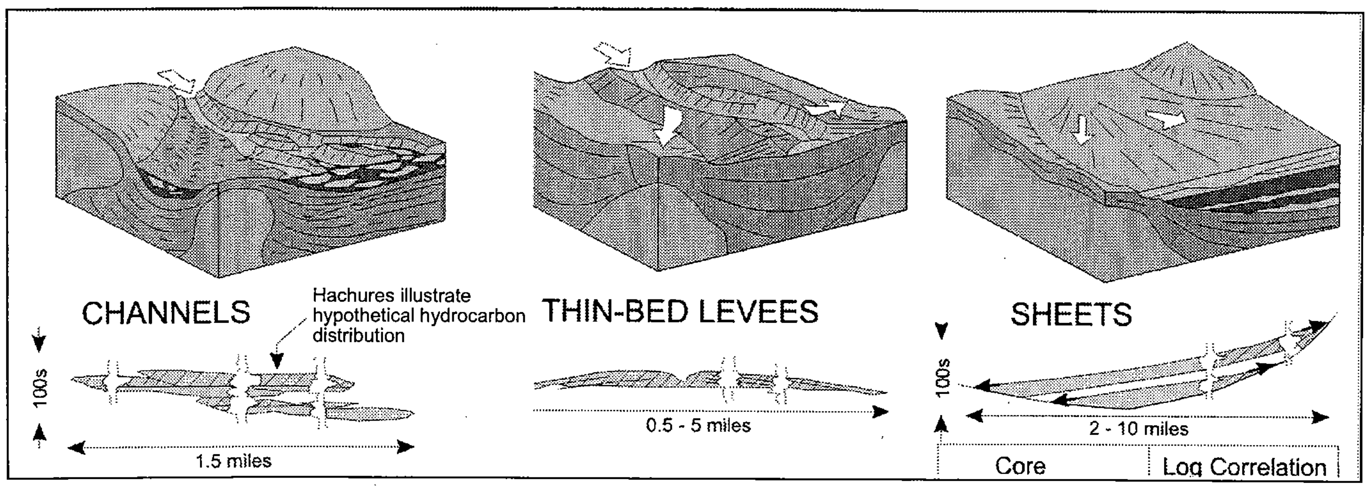


Figure 51. Generalized diagram of deep-water sedimentary architectural elements (after Chapin and others, 1994). Those elements that are recognized in Jackfork outcrops and in petroleum wells are principally channel and sheet sandstones. Levee deposits are rare in Jackfork strata in this area. Block diagram modified from Bouma (2000).

Figure 52. Highly quartz-cemented sandstone at Stop 6A (outcrop A, section 2, of Omatsola, 2003). Fractures exhibit two orientations. Fracture spacing is, in part, related to bed thickness (Busetti, 2003).

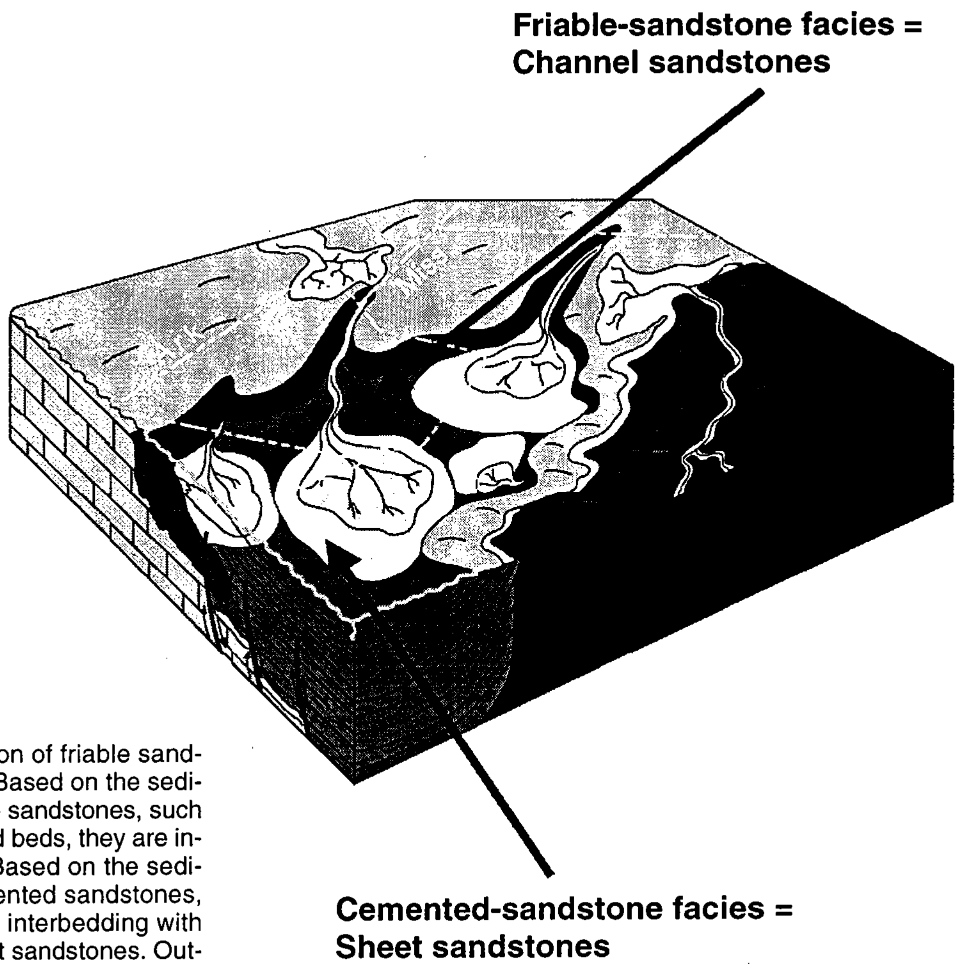


Figure 53. Depositional interpretation of friable sandstones and cemented sandstones. Based on the sedimentary characteristics of the friable sandstones, such as lenticularity and erosionally based beds, they are interpreted as channel sandstones. Based on the sedimentary characteristics of the cemented sandstones, such as sharp bases and tops, and interbedding with shales, they are interpreted as sheet sandstones. Outcrop A, section 2, of Omatsola (2003).

STOP 6B

FRIABLE AND CEMENTED SANDSTONES OF THE JACKFORK GROUP—LYNN MOUNTAIN SYNCLINE

(continued)

Location: on north side of U.S. Highway 259, N½N½NW¼NW¼ sec. 34, T. 2 N., R. 25 E., and SE¼SW¼SW¼ sec. 27, T. 2 N., R. 25 E., Le Flore County, Oklahoma

Approximately 175 ft of the upper part of the Wildhorse Mountain Formation is exposed at Stop 6B (Pl. 2, in pocket). (The base of this outcrop is ~321 ft above the top of the outcrop at Stop 6A.) Like Stop 6A, the Jackfork here (outcrop A, section 3, of Omatsola, 2003) consists of a succession of lower, interbedded, quartz-cemented sheet sandstones and shales and an upper interval of massive, weakly lithified channel sandstones (Fig. 54).

The contact between the cemented and friable sandstones is sharp (Fig. 54). Lithologically, the quartz-cemented sandstones are very fine to fine grained, moderately to well sorted, and planar-tabular bedded with characteristic deep-water sedimentary structures; bases and tops of beds are sharp and generally non-erosive. By contrast, the friable sandstones are medium to fine grained, predominantly poorly to moderately sorted, massive and amalgamated, and commonly have undulatory bed boundaries. Petrographic studies show different diagenetic features in the two sandstone types. Quartz overgrowths and pressure solution characterize the quartz-cemented sandstones, and feldspar dissolution and clay are common in the friable sandstones.

The depositional history of the sequence at Stop 6B is illustrated in Figure 55. During an early stage of sea-level lowstand, sheet sands were deposited in the basin or at the base of slope. With sea-level rise, thinner beds and more mud were deposited over the sheet sands, and the axis of deposition moved in the paleolandward direction. With the next stage of falling sea level, the axis of deposition moved basinward, and channel sands were deposited over the preceding sequence. The two sets of strata are now separated by a depositional sequence boundary (Fig. 54).

The relation between cementation and depositional environment can be explained in terms of sedimentary processes and burial diagenesis. Quartz cementation is restricted to the sheet sandstones as a result of long-distance transport via turbidity currents, which sorted the sands and removed most of the clay fraction (Omatsola, 2003). During burial diagenesis, silica-rich fluids migrated through the sands, and quartz precipitated around granular quartz nuclei. By contrast, the more poorly sorted, clay-rich channel sandstones were not transported as far, and more detrital clay was deposited with the sand. During diagenesis, clay coatings on the quartz grains prevented silica nucleation and cementation. Thus, we believe that the channel sandstones were never fully cemented. As discussed at Stop 7, the weakly cemented sandstones in outcrop typically are iron stained. Siderite cement occurs in the sandstones in the subsurface but not in outcrop. It is possible that the iron stain, which is restricted to the channel facies, may have been derived by dissolution of siderite cement, either near the surface or in the subsurface: this would also result in the lack of cementation that is observed.

		Return to vehicles and retrace route through Big Cedar to Talimena Drive.
56.4	11.2	Intersection of U.S. 259 and S.H. 1 (Talimena Drive). Turn left (west) onto access road to Talimena Drive.
56.6	0.2	Intersection with Talimena Drive. Turn left (east).
57.3	0.7	Big Cedar Vista. Good view of Kiamichi Mountain (north flank of Lynn Mountain Syncline), Rich Mountain, and Simmons Mountain.

Figure 54. Friable sandstones and underlying cemented sandstones. Geologist (for scale) is standing at the contact between the two sandstone types. Note that the cemented sandstone beds are tabular and have sharp tops and bases. The porous sandstones tend to be more lenticular, with erosional bases. Outcrop A, section 3, of Omatsola (2003).

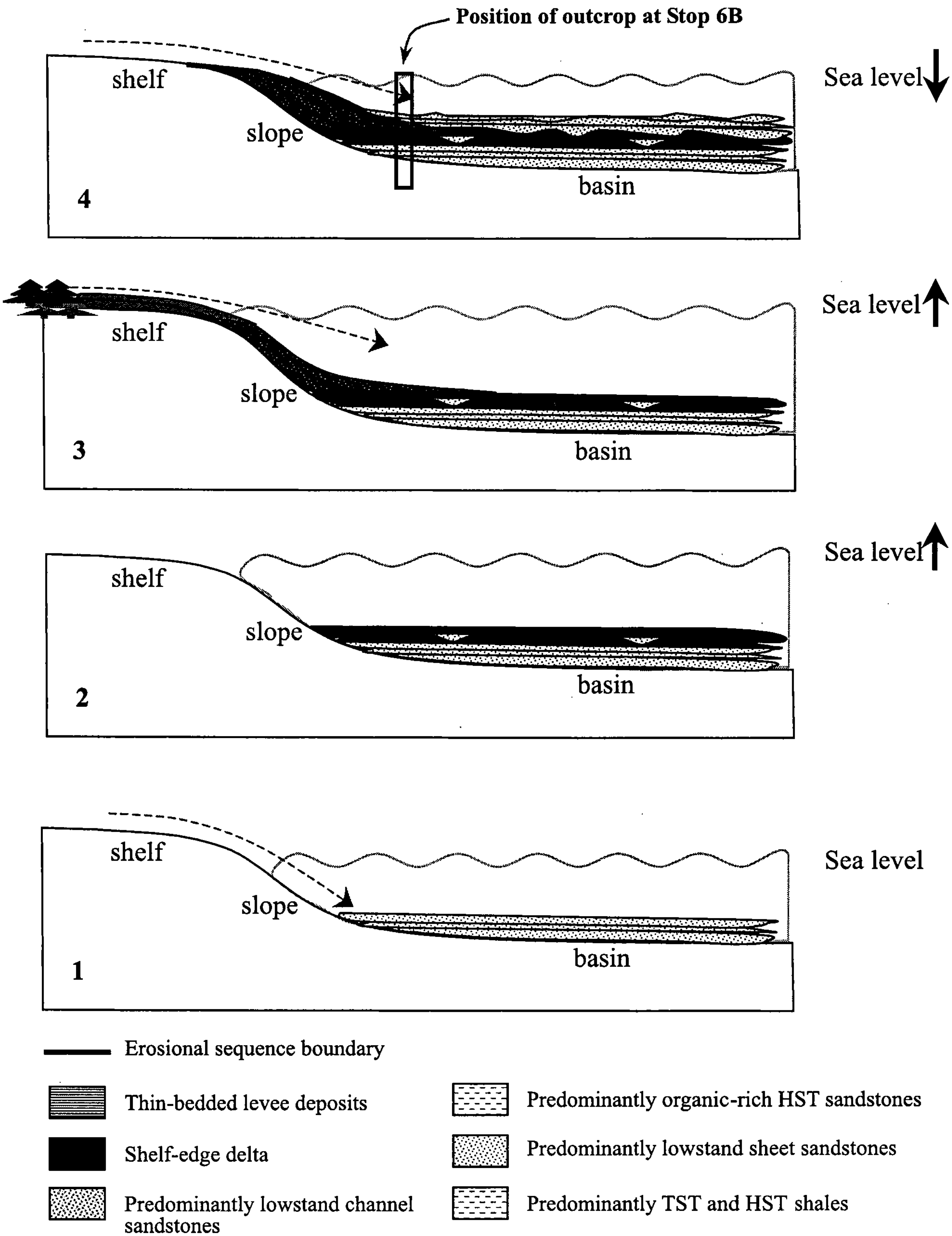


Figure 55. Sequence-stratigraphic interpretation of the deposition of the outcrop at Stop 6B. During stage 1 (lower figure), basin-floor (sheet) sands are deposited in the basin during sea-level low-stand. During stages 2 and 3, sea level rises and thin beds of sand and mud are deposited. During stage 4, sea level falls, providing a seaward shift in the depositional axis and resulting in an erosional sequence boundary and deposition of more proximal channel sands on top of more basinal sheet sands (modified from Omatsola, 2003).

57.4 0.1 Forest Service Road 6007 to left (east).

57.8 0.4 Excellent outcrops of northeast-facing Atoka Formation sandstones on south flank of Spring Mountain Syncline. A wide variety of sole marks and soft-sediment-deformation features occur in these strata. Paleocurrent directions based on sole marks are mostly south–southeast to north–northwest; some indicate a current direction to the west–northwest.

58.1 0.3 Beautiful view of Rich Mountain directly in front.

58.3 0.2 Forest Service Road 6029-2 to right (west).

58.9 0.6 Leave Big Cedar 7.5′ quadrangle; reenter Page 7.5′ quadrangle. Entrance to Robert S. Kerr Arboretum. This valley is underlain by Johns Valley Formation.

59.4 0.5 Leave Page 7.5′ quadrangle; reenter Big Cedar 7.5′ quadrangle.

59.5 0.1 Rock glacier on left (south).

Stone and McFarland (1979) note that more than 100 similar rock-glacier deposits are present in the northern part of the Ouachita Mountains in Arkansas and Oklahoma, some of which are active. They suggest that the boulder fields are evidence of periglacial conditions and/or semipermanent ice fields in the higher elevations of the Ouachitas during the Illinoian and Wisconsinan glacial stages.

59.8 0.3 Several large outcrops of Stanley Group strata (Moyers Formation) on left (south).

The following features are worth noting in the Stanley Group at this locality: (1) most of the outcrops consist of extremely fissile, "flaky" shale; (2) the less abundant sandstone occurs in beds ranging from 1 in. to 3 ft thick as thin discontinuous pods and lenses, and as large (1.5-ft diameter) isolated boulders; rounded grains are conspicuous in some of the sandstones; (3) sole marks on some of the sandstone beds indicate a N. 85° E. to S. 85° W. paleocurrent direction.

60.1 0.3 The large outcrop on the left (south) exposes the uppermost part of the Moyers Formation (Stanley Group) at the base, the Chickasaw Creek Siliceous Shale, and the lowermost part of the Wildhorse Mountain Formation (Jackfork Group) at the top. This was stop 21 on the 1994 field trip.

61.0 0.9 Forest Service road to right (south). Turn off Talimena Drive and park on Forest Service road. We will walk back down the road to Stop 7.

STOP 7

FRIABLE AND CEMENTED SANDSTONES OF THE JACKFORK GROUP— RICH MOUNTAIN SYNCLINE

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University of Oklahoma

Botosan Omatsola and Alison M. Garich-Faust
BP Exploration, Houston, Texas

Gloria A. Romero and Seth A. Busetti
University of Oklahoma

Kevin J. Smart
Southwest Research Institute, San Antonio, Texas

Location: on east side of State Highway 1 (Talimena Drive) immediately downhill from hairpin curve, NW¼SW¼NE¼ sec. 1, T. 2 N., R. 25 E., Le Flore County, Oklahoma

Stratigraphy and Structure

This outcrop within the Wildhorse Mountain Formation (Seely, 1963) is an unusual and uncommon type of Jackfork strata. The Jackfork here consists of 280 ft of poorly consolidated sandstone (Pl. 3, in pocket; Fig. 56) that appears to be more feldspathic and siltier than that exposed at Stops 6A and 6B.The weakly consolidated strata, however, are stratified and contain some lithified shale beds, including one that is conspicuously maroon. Perhaps the most interesting aspect of this outcrop is that silica-cemented, "hammer-ringing," fractured sandstones are present at the top and the bottom of the overall poorly consolidated section. If a section such as this were discovered in the subsurface, the positive aspect of it would be that of a thick section of unconsolidated, moderately porous, potentially gas-bearing Jackfork; the negative aspect would be that the high silt content would decrease the porosity and permeability and might plug the wellbore. The poorly consolidated section also contains fractures, suggesting that it may have once been lithified. The diagenetic history of this section is as yet not fully understood.

Data on fracture orientation and spacing and bedding thicknesses were collected at this outcrop in the same manner as at Stop 6A. Measurements were made of cemented sandstones. The attitude of the primary fractures here is N. 85° E., 57° N., and the strike, like that in the Lynn Mountain Syncline, is approximately parallel to the strike of the bedding. A second set of fractures is oriented N. 17° E., 85° W.; this strike is approximately parallel to the dip of the bedding. Like those at Lynn Mountain, the second set of fractures terminates against the primary set. Although spacing-to-layer thickness (S/T) ratios are slightly higher at Lynn Mountain than at Rich Mountain, both localities generally show similar fracture orientations and spacing.

Figure 56. Outcrop at Stop 7 (Omatsola's [2003] outcrop B) on S.H. 1 (Talimena Drive). Bedding is clearly visible in this outcrop; however, all sandstone beds and most shale beds are completely unconsolidated.

An approximately linear correlation exists between fracture spacing and bed thickness; that is, thicker beds typically exhibit more widely spaced fractures. Primary-set fractures closely correlate to bed thickness; S/T ratios range from 0.3 to 0.96. Secondary-set fractures exhibit a weaker correlation to bed thickness, and S/T ratios range from 0.56 to 2.4. Additionally, secondary-set fracture spacing is related to primary-set spacing by a factor of approximately 0.7 times. These data are evidence that the primary set of fractures was controlled by bed thickness, rock strength, and interaction with adjacent layers, until the fracture-saturation limit (S/T $\approx$ 1) was achieved. Continued stress transfer between adjoining fractures controlled further fracture development, possibly including the formation of secondary-set fractures. In general, the secondary-set fractures do not saturate the rock mass, indicating that they were controlled, in part, by lithologic constraints and the preexisting primary-set fractures.

Identification and Significance of Friable and Cemented Jackfork Sandstones in the Subsurface

Facies analysis (mainly from dipmeter logs and cuttings) of Jackfork Group sandstones from six wells in Potato Hills, Talihina Northwest, and Buffalo Mountain gas fields (Garich, 2004; Romero, 2004) reveal the presence of friable and highly cemented sandstones in the subsurface; this may have implications for gas production in the area. Cuttings analysis (including petrography) shows that three sandstone types are present: highly quartz-cemented, friable, and siderite-cemented sandstones (Fig. 57). Bitumen is present locally in all three sandstone types.

The structural complexity of the fields and the lateral variability in turbidite facies make well-to-well correlations and interpretation of depostional environments from logs difficult. In all three fields, fault zones were identified first by using cumulative-dip and dip-vector azimuth plots derived from dipmeter logs (Hurley, 1994), and second by using borehole-image logs where available. Dips affected by faults were not used in the facies analysis.

A combination of conventional logs, dipmeter logs, and cuttings analysis provided information for building a facies classification for the Jackfork sandstones. Cuttings examination (including petrography) enabled the well logs to be calibrated to drilled lithologies and helped to differentiate zones containing highly porous sands from well-cemented sandstones. Several criteria (but especially gamma-ray and dipmeter logs) differentiated the sheet and channel sandstones on the logs (Fig. 58). Based on these criteria, the friable sands appear to be associated with channel facies (from well logs), and cemented sandstones are associated with sheet facies (Fig. 59), as is the case for the outcrops. This association provides a means for differentiating porosity types when using conventional well logs (i.e., by differentiation of sheet and channel sandstones from log properties).

The similarity between outcrop and subsurface observations is evidence that the surface exposures of parts of the Jackfork Group are excellent analogs to potential subsurface Jackfork gas sands, and that it may be possible to improve well-log correlations by using a sequence-stratigraphic approach (Fig. 60). To use such an approach, faults must be identified from the well logs. Then, dipmeter logs and gamma-ray-log shapes can be utilized to develop a framework between faults that relates the stratigraphic positions of depositional systems tracts and thus allows prediction of the anticipated porosity type.

Return to vehicles and retrace route to U.S. 259, Heavener, and the Kerr Conference Center.

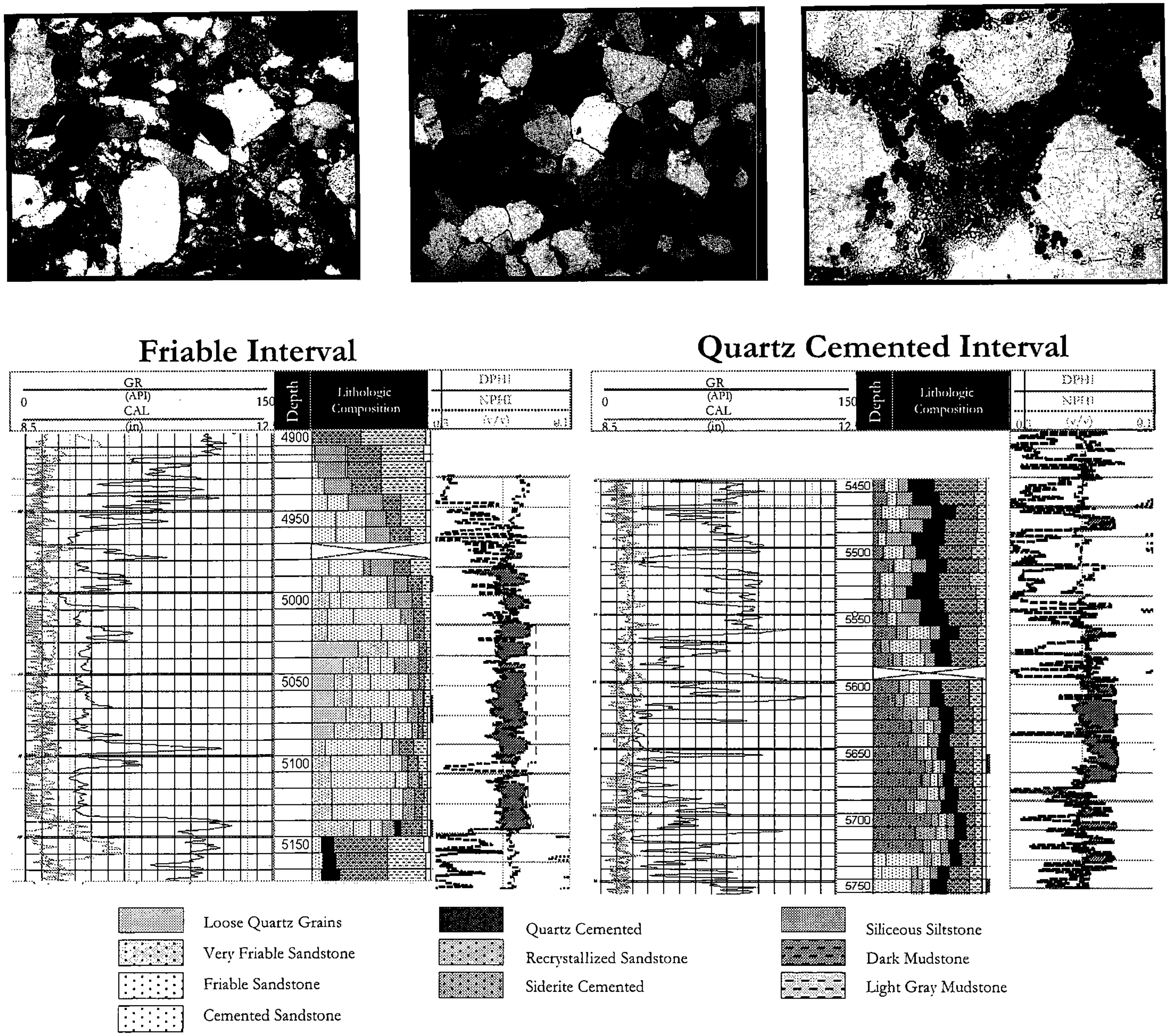

Figure 57. Thin-section photomicrographs of friable (left), quartz-cemented (center), and siderite-cemented (right) sandstone cuttings. Bottom: relationship of cuttings analysis, gamma-ray log, and density logs of Jackfork Group sandstones in the GHK No. 1-12 Edmonds well (Potato Hills field). The cuttings analysis indicates which sandstones are mostly friable and which are mostly cemented with quartz. The gamma-ray log of the friable-sandstone interval shows very few shale interbeds. By contrast, the quartz-cemented interval contains more shale interbeds. These features are diagnostic of channel- and sheet-sandstone facies, respectively. Modified from Romero (2004).

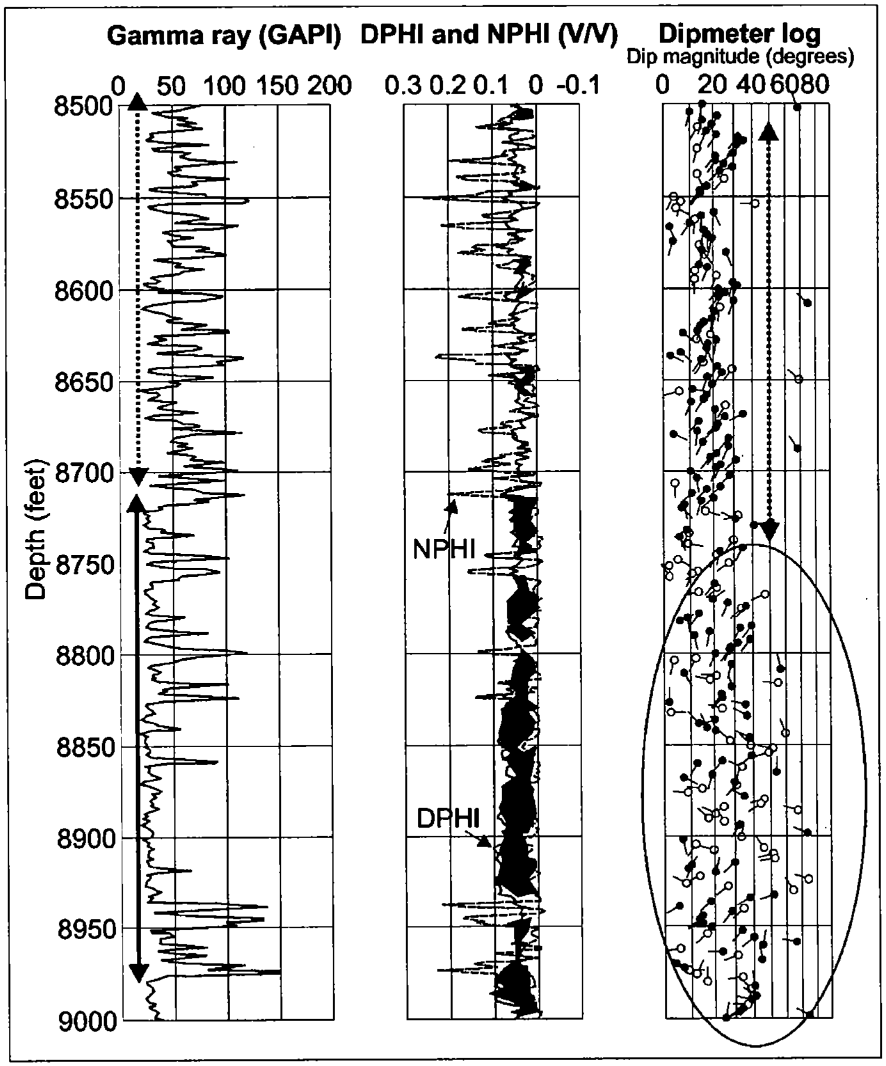

Figure 58. Part of Jackfork interval in the Ward No. 1-2 Frieling well, showing cemented sheet-sandstone zone characterized by interbedded sandstones and shales (from well logs) and uniformly low and consistent dips above ~8,710 ft and a channel-sandstone interval characterized by a blocky-sandstone log response and diverse dips (modified from Garich, 2004).

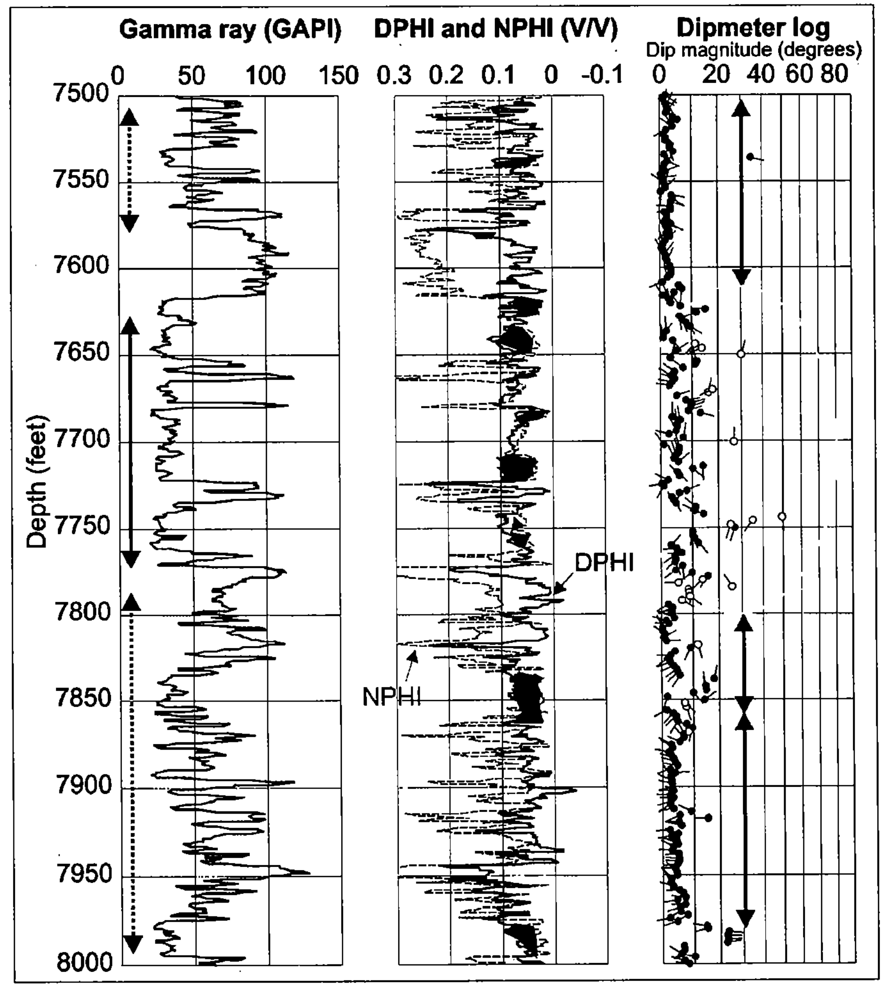

Figure 59. Part of Jackfork interval in the Ward No. 1-25 Brandt well (Talihina Northwest field), showing two cemented sheet-sandstone zones above 7,600 ft and below 7,780 ft, and a friable channel-sandstone interval from 7,770 to 7,620 ft. Log characters of the different facies are the same as in the No. 1-2 Frieling well (modified from Garich, 2004).

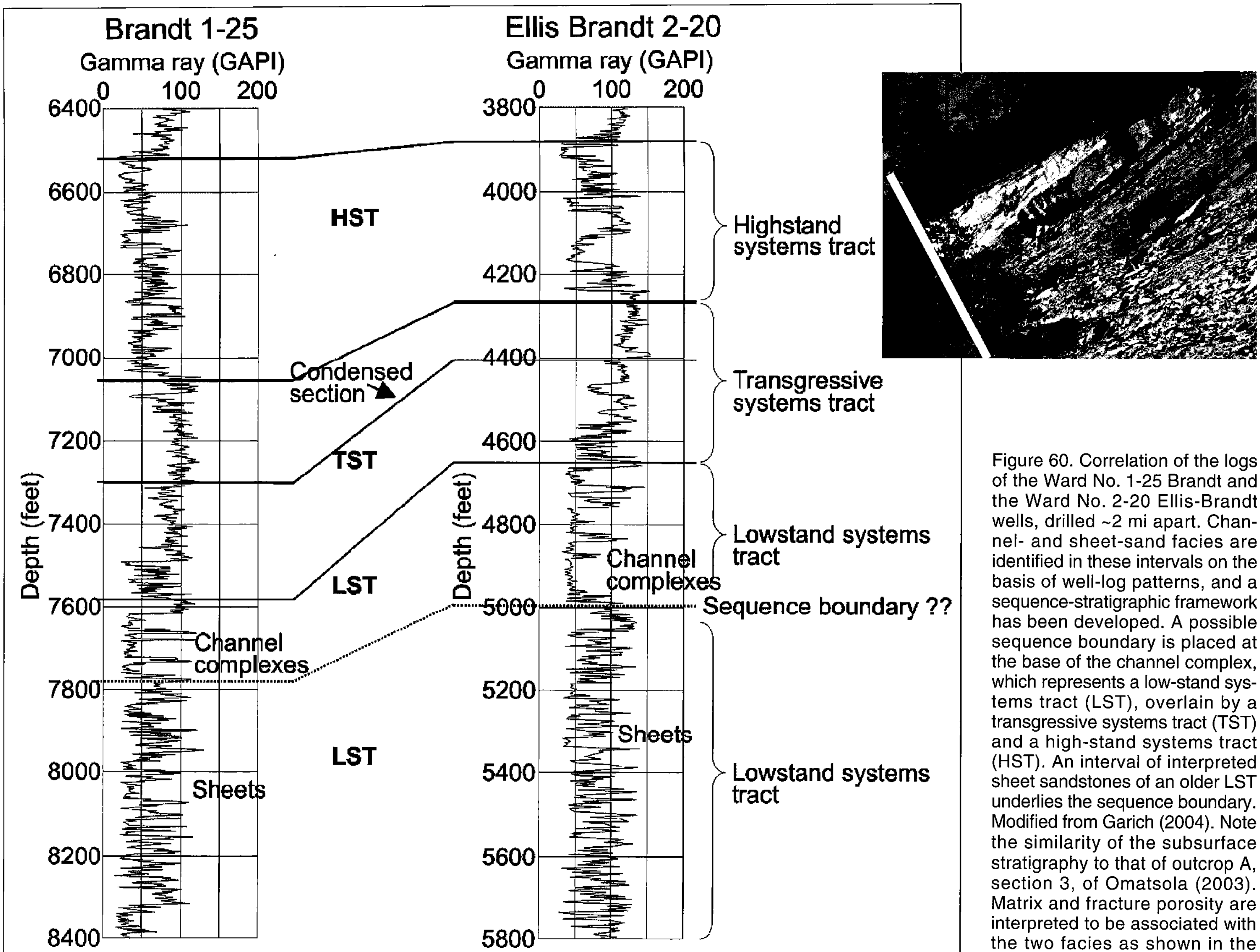

Figure 60. Correlation of the logs of the Ward No. 1-25 Brandt and the Ward No. 2-20 Ellis-Brandt wells, drilled ~2 mi apart. Channel- and sheet-sand facies are identified in these intervals on the basis of well-log patterns, and a sequence-stratigraphic framework has been developed. A possible sequence boundary is placed at the base of the channel complex, which represents a low-stand systems tract (LST), overlain by a transgressive systems tract (TST) and a high-stand systems tract (HST). An interval of interpreted sheet sandstones of an older LST underlies the sequence boundary. Modified from Garich (2004). Note the similarity of the subsurface stratigraphy to that of outcrop A, section 3, of Omatsola (2003). Matrix and fracture porosity are interpreted to be associated with the two facies as shown in the well logs.

DAY THREE

Stratigraphy and Structure of the Arkoma Basin–Ouachita Mountains Transition Zone and Frontal-Belt Reservoir Facies: Implications for Exploration and Development

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INTRODUCTION

Most of the drive at the beginning and end of today's field trip approximately parallels the Choctaw Fault (Fig. 61), which separates the Ouachita Mountains fold-and-thrust belt to the south from the Arkoma Basin (or Arkoma fold belt) to the north. Much of the strata along this part of the route face north and, in general, dip moderately north; dips are steeper to the south toward the Choctaw Fault, and they lessen to the north. This geometry, combined with the south-facing and steeply south-dipping strata south of the fault, is evidence that parts of the Ouachita–Arkoma Basin structural transition is a triangle zone, although, as shown at Stop 5, a triangle zone may not mark the transition everywhere. Discussions at several stops will examine subsurface data that substantiate this. The geology along the eastern part of the southern Arkoma Basin is mostly within the McAlester Formation, and ridges are underlain by sandstone-dominated sequences within the McAlester; these sequences have different names where they are exposed (Fig. 3), but in the subsurface all the sandstones are named *Booch* and are prolific gas producers in the central and northern parts of the basin. Several coals in the McAlester (McAlester), Savanna (Cavanal), and Boggy (Secor and Secor Rider) Formations

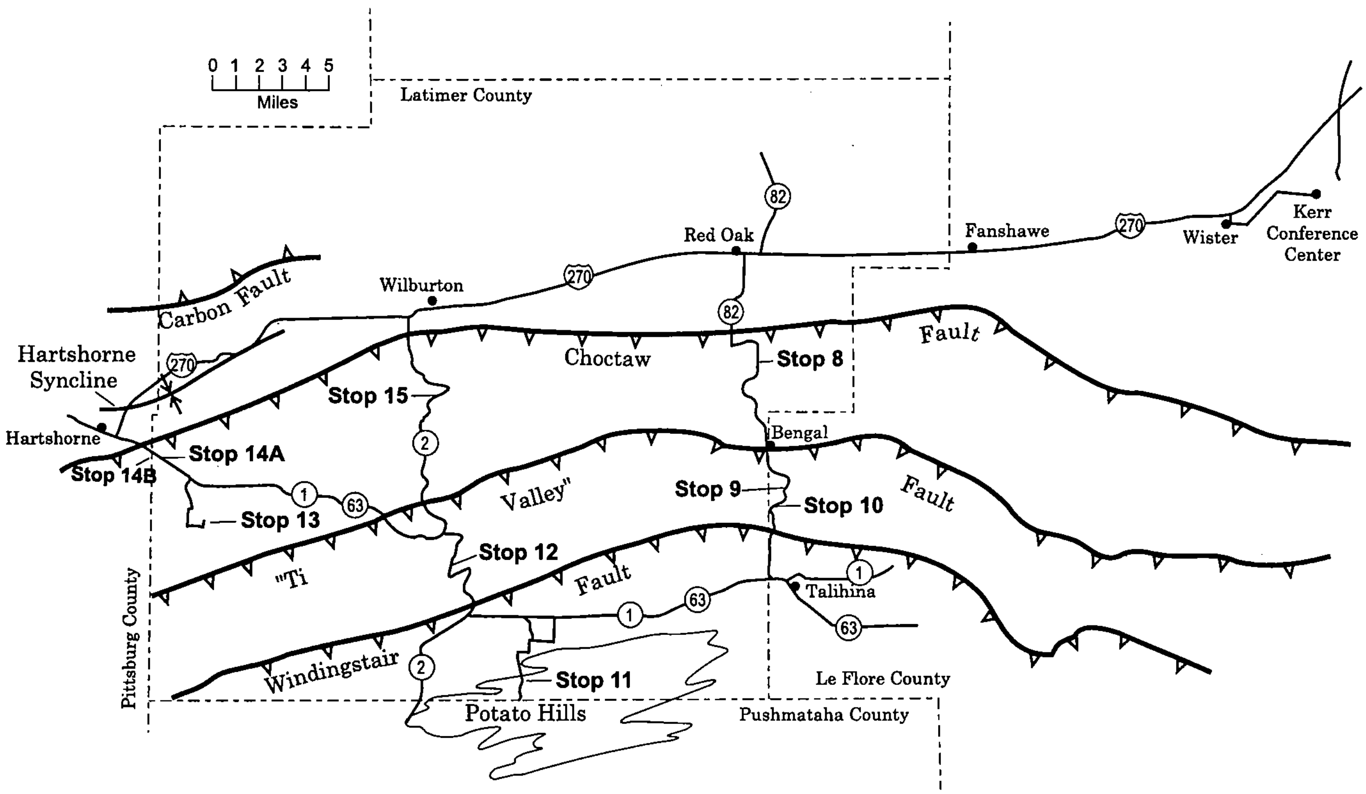


Figure 61. Map showing route of field trip on Day Three, field-trip stops, some major towns, and some major geologic features.

have been mined in recent years and in the distant past (many tens of years).

Except for a stop in the Potato Hills to examine early and middle Paleozoic Ouachita-facies strata, most of today's stops will be to examine the lower part of the Atoka Formation and the immediately underlying units—the Johns Valley Formation and Wapanucka Limestone (Fig. 2). The Spiro sandstone, closely associated with the Wapanucka Limestone and one of the most productive sandstones in the Arkoma Basin and frontal Ouachita Mountains, is well exposed and has been extensively studied in the northernmost thrust sheets of the tectonic belt. The first map produced by the OGS as part of the USGS-sponsored COGEOMAP program (Higgins 7.5′ quadrangle [Suneson and Ferguson, 1989a]) identified Spiro sandstone overlying the Johns Valley Formation south of the Ti Valley Fault. Subsequent work identified a Spiro-like sandstone at the base of the Atoka Formation in several thrust sheets. The origin of this distinctive sandstone, and what its presence implies with regard to the position of the late Morrowan to early Atokan shelf edge, are important for paleogeographic reconstructions and the possible existence of more Spiro plays in the Ouachita Basin.

The principal reservoir units in the gas fields south of the Choctaw Fault that we will pass through today are, from older to younger, the Jackfork Group, the Spiro sandstone, and sandstones in the Atoka Formation. Day Two focused on the Jackfork Group; applying outcrop information to the reservoir units in these fields will allow geologists to extend and more efficiently produce the fields and discover new ones. The Spiro sandstone will be examined at two stops; unfortunately, neither are of reservoir quality, but understanding facies relations within the Spiro is key to finding and producing this important unit. Sandstones in the Atoka Formation have the reputation as "bail-out" units and typically are completed only if primary targets prove unproductive. On the surface, most Atoka Formation sandstones are very fine grained and well cemented; thus, operators might produce them as fractured reservoirs. However, the last stop today is evidence that not all Atoka sandstones are created equal and that some of the concepts that apply to the Jackfork may apply equally to the Atoka.

ROAD LOG

Cumulative mileage	*Interval*	
0.0	0.0	Start road log at the entrance to the Kerr Conference Center (Fig. 61). Turn left (west) onto blacktop road. Descend into valley on dip slope of sandstone in Savanna Formation. Flat area at base of slope is underlain by shale in Savanna Formation.

The Kerr Conference Center is located near the southwest limit of the Poteau Southeast coalbed-methane field. See Day One for a discussion of the coalbed-methane activity in the Poteau area.

1.6	1.6	Turn left on old U.S. Highway 271 and continue southwest on Savanna shale and Quaternary alluvium (in low-lying areas along streams) toward town of Wister.
2.9	1.3	Cross Rock Creek and ascend onto Quaternary terrace deposits associated with Mountain Creek and Caston Creek. The main part of Wister is built on terrace deposits and alluvium.
4.1	1.2	Turn right (north) in downtown Wister onto U.S. Highway 270.
4.4	0.3	Turn left (west) on U.S. 270/271.
5.0	0.6	Cross Mountain Creek. Two small adits in the Cavanal coal are on the west bank of Mountain Creek. The adits were constructed by the Wister Coal Company before 1931 (Hendricks, 1939).
5.8	0.8	Leave Wister 7.5′ quadrangle; enter Summerfield 7.5′ quadrangle. The low ridges on the right (north) and the very low ridges on the left (south) are underlain by sandstones in the Savanna Formation.
8.0	2.2	Cross county road to right (north) in small community of Victor. Continue straight on U.S. 270/271. The 1994 Ouachita–Arkoma Basin field trip took this county road to visit Farrell-Cooper Mining Company's Wister Mine in the Secor and Secor Rider coals (Boggy Formation) (Fig. 62). This mine is now reclaimed.

About a tenth of a mile north of the highway, the county road crosses a small pre-1931 strip mine in the Cavanal coal. According to the owner, this area was first mined before statehood (Oklahoma Conservation Commission [OCC] files). No hazards are associated with the area.

Figure 62. View of the Wister Mine, showing part of the strip-mining operation as it appeared in October 1993. At base of highwall is a front-end loader stockpiling coal, and at center is a dragline removing overburden (from Suneson and Hemish, 1994, fig. 29).

Enter the small Caston East gas field (Boyd, 2002).

Caston East Gas Field

The Caston East gas field is a one-well field discovered by the Eberly and Meade No. 1-29 Humphreyville (SW¼ NE¼ sec. 29, T. 6 N., R. 24 E.). The well was spudded on April 24, 1980, reached total depth at 3,260 ft on May 20, and was completed in lower Booch sandstone at 2,122–2,146 ft on November 19, 1980. (All drilling and completion information is from Geo Information System's Natural Resources Information System database and is based on Oklahoma Corporation Commission 1002A forms.) Several other nearby wells drilled and/or tested Hartshorne sandstone, Atoka sandstones, Spiro sandstone, and Wapanucka Limestone; all tested or showed dry. However, the Jacobs, Stewart, Hart, and Coleman No. 1 Judy-Jackson well, also drilled in section 29, production-tested the McAlester coal at 480–484 ft for 39 Mcf gas per day. Despite this, the well was declared dry.

9.8 1.8 Cross Caston Creek. The Keota Sandstone, Tamaha Sandstone, McAlester coal, and Cameron Sandstone are exposed in the creek bed south of the bridge. Beds dip north at 22–28° in this area on the south flank of the Cavanal Syncline. The Keota, Tamaha, and Cameron are named *Booch* in the subsurface (Fig. 3).

10.7 0.9 Intersection of U.S. 270 and U.S. 271 in community of Caston. Continue straight (west) on U.S. 270. The 1994 field trip (Suneson and Hemish, 1994) examined the Warner Sandstone Member of the McAlester Formation (lower Booch sandstone) (Fig. 3) ~1 mi to the south along U.S. 271. A small adit in the Hartshorne coal is present just south of the 1994 stop, and another is present ~2.5 mi to the east near Braidwood.

Three small adits in the Cavanal coal are present ~0.5 mi north of the highway. The coal in the westernmost adit (~C E½ sec. 26, T. 6 N., R. 23 E.) is 1 ft 8 in. thick (Hendricks, 1939).

13.1 2.4 Leave Summerfield 75′ quadrangle; enter Leflore 7.5′ quadrangle.

A discontinuous Keota(?) coal is present at the base of the ridge just to the right (north) of the highway, and the McAlester and Upper McAlester coals are present but poorly exposed just to the left (south) of the highway.

14.5 1.4 Cross Coal Creek. The Cavanal coal is absent west of Coal Creek.

15.0 0.5 Enter small town of Fanshawe. A very small strip pit in the McAlester coal, operated circa 1920 (OCC files), is present on the southeast side of Fanshawe. No hazards are associated with the mine.

Fanshawe Sandstone, Atoka Formation

The Fanshawe sandstone is one of several productive Atoka Formation sandstones in the Arkoma Basin (Fig. 63). Some geologists place the Fanshawe in the upper part of the Atoka Formation (e.g., Suneson and Hemish, 1994, p. 51), but no formal division of the Atoka into upper, middle, and lower parts has been made in Oklahoma.

The Fanshawe sandstone was first named in the Midwest No. 1 Lewis well, which spudded on December 23, 1961, and was completed on February 20, 1962. The well is in the SE¼NW¼SE¼ sec. 4, T. 6 N., R. 22 E., ~7 mi northwest of the town of Fanshawe. Based on Oklahoma Corporation Commission form 1002A reports, most Fanshawe sandstone production is in townships 6 N., 21 E., and 6 N., 22 E. (88 wells). There is little Fanshawe sandstone production west of R. 21 E. (14 wells in five townships) and east of R. 24 E. (three wells in two townships). The westernmost Fanshawe producer is in T. 6 N., R. 17 E., and the easternmost is in T. 9 N., R. 26 E.

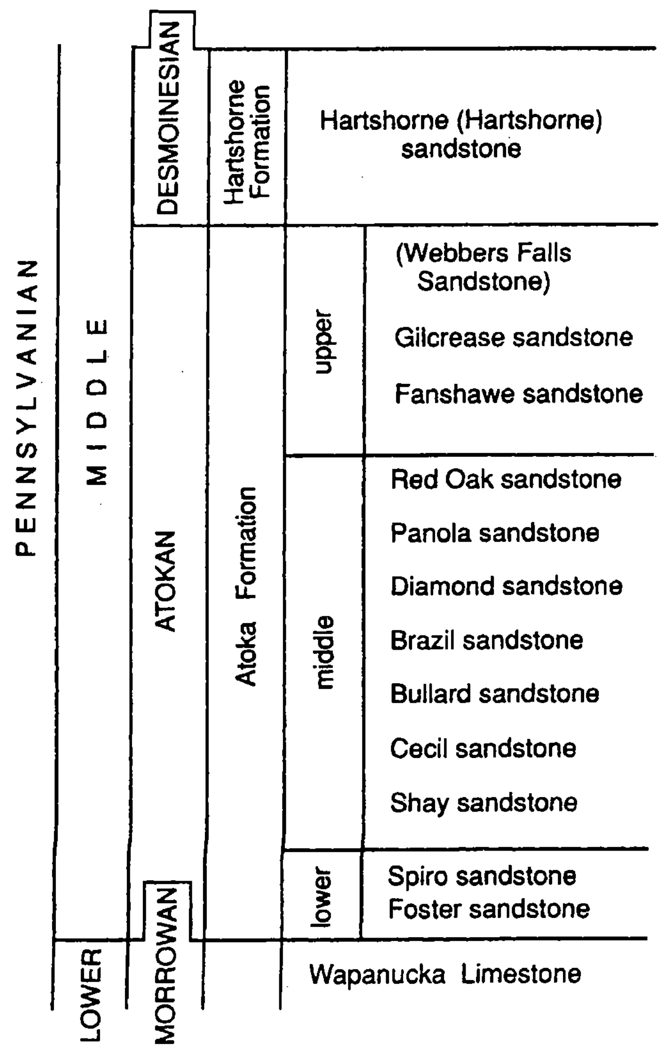


Figure 63. Principal named sandstones of the Atoka Formation in the eastern part of the Arkoma Basin, Oklahoma (modified from Suneson and Hemish, 1994, fig. 35).

16.1 1.1 Leave Le Flore County; enter Latimer County. The 1994 field trip examined an outcrop of the Cameron Sandstone along the county road ~0.25 mi to the south.

18.6 2.5 County road to left (south). Location: C sec. 34, T. 6 N., R. 22 E.

Three small strip pits in the McAlester and upper McAlester coals are present south of the highway just west of here. A number of adits and two underground mines (Texas Coal Company, Le Bosquet Coal and Mining Company) in the Hartshorne coals are present ~1 mi south of here. Three McAlester sandstones (Cameron, Upper Warner, and Lower Warner) also are well exposed to the south.

The Hartshorne coal mines are within the OCC's Turkey Coal Company Problem Area. The mines were active in 1931, when Hendricks (1939) did the field work for his report, and were still active in 1943 (OCC files). The easternmost of the underground mines—Le Bosquet (NW¼ sec. 2, T. 5 N., R. 22 E.)—is the site of an OCC clean streams initiative project funded by the U.S. Office of Surface Mining. The project is designed to neutralize acid water coming out of the mine and precipitate metal contaminants.

Sandstones in the Savanna Formation form the skyline to the north. This area is part of the giant Red Oak–Norris gas field.

Red Oak–Norris Gas Field

The following description of the history of the Red Oak–Norris gas field is modified from Suneson and Hemish (1994, p. 49–52). Some parts have been updated on the basis of information from Horn (1997) and Andrews and others (1998) and data from IHS Energy.

The Red Oak–Norris gas field is the largest gas field in the Arkoma Basin. It is in northeastern Latimer County, southeastern Haskell County, and west-central Le Flore County, Oklahoma. At the present time the field covers 105.5 mi^2. Production is mostly from several Middle Pennsylvanian sandstones. The history of the field is typical of many other Arkoma Basin gas fields: initial discovery on surface structure; later exploratory drilling on the structure, based on nearby discoveries of deeper reservoirs; still later drilling off-structure, based on improved interpretation of seismic data, sedimentology, and diagenesis.

The discovery well for the field was drilled by the Gladys Belle Oil Company in 1912 near the crest of the surface expression of the east–west-elongated Brazil Anticline in sec. 10, T. 6 N., R. 21 E., ~4 mi north of the town of Red Oak. The well followed earlier Arkoma Basin discoveries: the Mansfield gas field in 1902 (Day One, mile 41.5), the Poteau–Gilmore gas field in 1910 (see Day One), and the Cameron gas field in 1911 (Day One, mile 9.7), all of which were drilled on surface anticlines. The Gladys Belle well discovered gas in the Hartshorne Formation at a depth of ~1,500 ft. That well and a few development wells supplied gas to the town of Red Oak for several years, but no other development took place immediately (Houseknecht and McGilvery, 1990).

The Le Flore County Gas and Electric Company acquired the leases in 1928 and began to develop the Hartshorne along the eastern part of the Brazil Anticline. Fifty-five wells were drilled: 43 were completed as gas wells at 1,500–2,100-ft depths. Locally, production was established from sandstones in the McAlester Formation (Booch sandstones) above the Hartshorne. The Hartshorne still produces gas in the Red Oak–Norris field.

Between 1928 and 1950, several deep tests (maximum 6,510 ft deep) were drilled on the Brazil Anticline into Atoka sandstone below the Hartshorne Formation. Gas shows were reported, but all were completed as dry holes (McClain and Planalp, 1961). Between 1924 and 1958, several gas fields north of the Red Oak–Norris field produced gas from the Spiro sandstone at the base of the Atoka Formation along the Milton Anticline and the subsurface Kinta Fault. In 1955, production from middle Atoka sandstones was established at the Gragg field (Day One, mile 33.3) in west-central Arkansas, nearly 50 mi east of the Red Oak–Norris field. This production demonstrated that reservoir-quality sandstones existed in the lower and middle Atoka Formation in Arkoma Basin anticlines (Houseknecht and McGilvery, 1990).

The Red Oak–Norris deep-field discovery was made by the Midwest Oil No. 1 Orr well in sec. 8; T. 6 N., R. 22 E. The surface location of the well was on the crest of the Brazil Anticline, and drilling began in May 1959. At 7,190 ft (drilled depth) the top of the Red Oak sandstone was penetrated and gas was discovered; the sandstone in the well was 145 ft thick and flowed 11.7 MMcf gas per day on a 0.5-in. choke with 1,850 psi tubing pressure on a subsequent production test (McClain and Planalp, 1961). The well continued to drill, and the top of the basal Atoka Spiro sandstone was penetrated at 11,510 ft (drilled depth). The well drilled 73 ft of gross sandstone, and a later production test gauged 5.5 MMcf gas per day on a 0.25-in. choke with 3,009 psi flowing tubing pressure (McClain and Planalp, 1961).

The Midwest No. 1 Orr was completed officially in April 1960. Within 2 years, 25 development wells had been completed, and ultimate gas recovery was estimated at >1.1 Tcf: the Red Oak sandstone contributed 84%, and the Spiro sandstone 16% (Houseknecht and McGilvery, 1990). By the end of 1965 the main production limits of the field had been established. Of the 80 wells drilled, 71 were completed as gas producers: the Red Oak sandstone was productive in 56 wells; the Spiro in 19; the Fanshawe (a local upper Atoka sandstone) in 11; the Panola (a local middle Atoka sandstone underlying the Red Oak) in two; and unnamed Atoka sandstones in three (Six, 1968).

In the mid-1960s, Amoco acquired most of the Red Oak–Norris field production. In the mid-1980s, Amoco received state approval to increase drilling density from one to two wells per 640 acres. Between 1985 and 1988, 42 infill wells were completed, and the gas deliverability was expected to increase from 70 MMcf to 160 MMcf gas per day.

The geology of the Red Oak–Norris field was described by Houseknecht and McGilvery (1990), and the following discussion is based on that report.

The Spiro sandstone represents the final phase of stable-shelf sedimentation that began in the Cambrian. It is a blanket sandstone that is most productive in northwest-trending, fluvially and tidally dominated channels. Interchannel deposits were deposited in shallow, subtidal to tidal-flat environments and are thinner, finer grained, and less porous than the channel sandstones. Horn (1997) interpreted the Spiro sandstone at Red Oak–Norris in terms of sequence stratigraphy and recognizes three distinct sandstone reservoirs. The oldest sandstone unit within the Spiro sandstone (defined as those units above the Wapanucka Formation, including the sub-Spiro shale) is a sequence of shoreface sandstones (highstand systems tract) immediately below a major sequence boundary (Foster unconformity). These shoreface sandstones are of reservoir quality in the Kinta gas field. The major part of the Spiro at Red Oak–Norris consists of valley-fill sediments overlying the unconformity that developed following a drop in sea level. The valley fill consists of fluvial, estuarine, and marine strata deposited during a base-level rise, followed by a base-level fall. Horn (1997) interprets a third, "upper Spiro" sand as part of a transgressive systems tract.

Following Spiro deposition, the Arkoma Basin subsided along a series of south-side-down normal (growth) faults. The major fault of this type in the Red Oak–Norris field is the Sans Bois Fault, which has ~7,000 ft of offset at the Spiro level. The Red Oak sandstone accumulated on the footwall of the Sans Bois Fault, adjacent to the fault. The sandstone forms a multistoried, slope–channel deposit trending approximately east–west to northeast–southwest, parallel to the Sans Bois Fault but perpendicular to the overall slope of the Arkoma Basin.

Movement on the Arkoma Basin growth faults stopped in the late Atokan, but downwarping at a much slower rate continued. Deltaic deposits (Hartshorne Formation) advanced from east to west across the shallow basin. Andrews and others (1998) showed that the most productive facies in the Hartshorne is fluvial and probably fills incised valleys. Lower delta-plain and marginal-marine facies are productive locally.

Following deposition of the early Desmoinesian Krebs Group, the Red Oak area was mildly compressed. North-directed, bedding-plane thrusts associated with Ouachita tectonism ramped up-section near the Sans Bois Fault but did not offset the Hartshorne. Thrusting caused local repetition of strata in the Atoka and folding at the Hartshorne level (Brazil Anticline).

In summary, Hartshorne, Red Oak, and Spiro production at Red Oak–Norris is controlled by structural features superposed on channel location and geometry. In the case of the Red Oak sandstone, channel location was controlled by syndepositional structures.

As of February 1, 2004, there were 697 producing and formerly producing wells in the Red Oak–Norris gas field, of which 490 were still active (data courtesy IHS Energy). Producing formations and the number of wells (in parentheses) are as follows: Arbuckle (1), Wapanucka (1), Booch (2), Atoka (including upper and basal) (39), Brazil (plus commingled) (19), Fanshawe (plus commingled) (103), Hartshorne (plus commingled) (72), Panola (plus commingled) (24), Red Oak (plus commingled) (351), Spiro (plus commingled) (85). Total gas production through July 2004 was 1.99 Tcf gas (data courtesy IHS Energy).

19.6 1.0 Cross Turkey Creek. A core hole near the bridge, described by Hendricks (1939), drilled 2 ft 8 in. of McAlester coal and 2 ft 2 in. of Upper McAlester coal.

20.2 0.6 Leave Leflore 7.5′ quadrangle; enter Red Oak 7.5′ quadrangle.

22.1 1.9 County road to left (south). The low ridge ~1.5 mi to the south is called Bull Hill and is underlain by the Hartshorne Formation. Both Hartshorne coals are present and were underground mined by the Oak Ridge Coal Company and the Bache and Denman Coal Company before 1931 (Hendricks, 1939). The OCC identifies this area as the Bull Hill Problem Area; modern hazards include open portals, polluted water, and subsided areas.

A small pre-1931 adit in the McAlester coal is present just south of the highway ~0.7 mi west of here.

23.4 1.3 On the left (south) is the loading dock for McAlester coal, mined by Farrell-Cooper Coal Company northeast of Red Oak. The isolated peak capped by Savanna sandstone no. 3 north of the town of Red Oak (~1 mi ahead) is Red Oak Mountain. The axis of the Cavanal Syncline trends east–west through the center of the mountain.

23.7 0.3 Intersection with State Highway 82 to the right (north).

The Butterfield Overland Mail

This location and the gap between Red Oak Peak (immediately behind us and to the north) and Red Oak Mountain are areas of historical significance. Butterfield Overland stagecoaches traveled through the pass and crossed the modern highway near here in the mid-19th century. For $200 you could ride from Tipton, Missouri, to San Francisco. Meals were not included in the fare. The trip took less than 25 days and the stage ran 24 hours a day, stopping only for meals and to change horses or make repairs. Not to worry about sleeping—"the seat backs would let down for beds at night" (Wooldridge, 1976, p. 9).

From here, the stage line headed almost due west, staying just south of U.S. 270. It stopped at Riddle Station, ~3 mi east of Wilburton (see mile 116.9), and again at Pusley Station southwest of Higgins (see mile 82.0).

24.4 0.7 Intersection with S.H. 82 to the left (south). Turn left (south) on S.H. 82.

24.6 0.2 Cross poorly exposed Tamaha Sandstone. In the subsurface the Tamaha is referred to as upper Booch.

Here, the Tamaha dips ~10° N. and is ~1,800 ft above the base of the McAlester Formation. Southward, toward the Choctaw Fault, the northward dip of the McAlester and underlying Hartshorne and Atoka Formations gradually, but steadily, increases. Strata directly south of the trace of the Choctaw Fault dip to the south. This geometry is evidence that a triangle zone is present in the subsurface (Stop 8).

24.8 0.2 Cross poorly exposed McAlester coal beds. The lower bed was surface mined ~0.4 mi to the east at some unknown time in the past, but after 1931, when Hendricks (1939) mapped the area. A small underground mine, active before 1931, is present ~0.4 mi west of the highway on the southwest side of town.

25.6 0.8 Cross ridge of Warner Sandstone. In this area, the Warner dips 20–25° north and consists of an upper bed ~60 ft thick and a lower bed ~150 ft thick, separated by ~150 ft of shale.

25.8 0.2 The flat valley on both sides of the road trends east–west and is underlain by the McCurtain Shale Member of the McAlester Formation.

26.0 0.2 Road turns right (southwest) and begins to climb ridge of Hartshorne Formation. Covered Upper Hartshorne coal at top of Hartshorne Formation at bend in road.

26.4 0.4 Top of Red Oak Ridge. This outcrop was stop 11 on the 1998 field trip.

The Lower Hartshorne coal is present, but covered, immediately north of the top of the ridge. In this area the Hartshorne Formation is ~300 ft thick and dips 30° north. The base of the Hartshorne is between the bend in the road at the top of the ridge and the very steep hairpin curve just south of the ridge crest.

26.6 0.2 Excellent outcrop of uppermost Atoka Formation on right (north).

26.9 0.3 This flat area, known as Long Prairie, is underlain by shale in the upper part of the Atoka Formation.

27.4 0.5 Cross low ridge (Little Ridge on Red Oak 7.5′ quadrangle).

This ridge is underlain by sandstone that is ~3,200 ft below the top of the Atoka Formation, about the same interval occupied by the Fanshawe sandstone in wells to the north. Here, the Fanshawe(?) is ~370 ft thick and dips 45–50° north. The sandstone is yellowish brown, silty and shaly, thin to medium bedded, and extensively ripple marked. To the east and west the sandstone on the ridge is offset by several northwest-striking strike-slip faults; most show left slip, but some show the opposite sense of movement.

27.9 0.5 Cross Fourche Maline.

28.0 0.1 Cross buried (by alluvium) trace of Choctaw Fault, the leading edge of the Ouachita fold-and-thrust belt at the present level of exposure. Here, the fault juxtaposes shale in the upper part of the Atoka Formation (in the footwall) against shale in the lower part of the Atoka (in the hanging wall).

28.6 0.6 Turn left (east) on S.H. 82. Ridge immediately to south is Limestone Ridge, which is capped by the Spiro sandstone.

29.1 0.5 Power lines cross over road.

29.6 0.5 County road to Salonia and Leflore continues straight (east). S.H. 82 to Talihina bends right (south). Follow S.H. 82.

29.9 0.3 Large outcrop of massive, fractured Spiro sandstone on right (west) (Fig. 64). A thrust fault that ramps up-section to the east terminates the Spiro outcrop; as a result, the Spiro does not crop out at the road.

30.4 0.5 Outcrop of folded lower Atoka Formation on both sides of road (Fig. 65). This was stop 9 on the 1994 field trip. Although complicated at first glance, most of the structures are out-of-the-syncline flexural-slip folds and small thrust faults. The axis of the syncline is exposed at the north end of the outcrop on the east side of the road.

30.5 0.1 Outcrop of Spiro sandstone on right (west). This outcrop was stop 10 on the 1994 field trip and will be revisited today. Stay on side of road and watch for traffic.

Figure 64. Massive and highly fractured Spiro sandstone just west of S.H. 82.

Figure 65. Folded and faulted turbidite sandstones and shales in the lower part of the Atoka Formation along S.H. 82 (from Suneson and Hemish, 1994, fig. 45).

STOP 8

FACIES CHANGES IN SPIRO SANDSTONE AND FRONTAL-BELT STRUCTURE

Neil H. Suneson
Oklahoma Geological Survey

Ibrahim Çemen
Oklahoma State University

Syed Mehdi
Anadarko Petroleum Corporation
Houston, Texas

Justin Evans
ExxonMobil Exploration Company
Houston, Texas

Location: 6 mi south of Red Oak on west side of S.H. 82, C SW¼SW¼ sec. 23, T. 5 N., R. 21 E., Latimer County, Oklahoma

The following description of the Spiro sandstone at this stop is by Richard D. Fritz and Ellen O. Hooker and is modified slightly from the 1994 field-trip guidebook.

Spiro Sandstone

Introduction

The Spiro–Wapanucka interval is a mixed clastic–carbonate sequence that is complicated by the presence of several unconformities. The Wapanucka Formation is upper Morrowan and usually is separated from the overlying Spiro sandstone by the so-called sub-Spiro shale, which appears to be uppermost Morrowan. The Spiro is lowermost Atokan and rests unconformably on the sub-Spiro shale or, where the latter is absent, on the Wapanucka Formation.

The Spiro sandstone can be subdivided into upper and lower units. The lower unit is a valley-fill sandstone that typically is found north of the Ouachita Mountains. The upper unit is a complex of cyclic shallow-marine sandstones and carbonates that are found in both the Arkoma Basin and the Ouachita Mountains of Oklahoma.

Outcrop Description

This outcrop (Fig. 66A) is ~6 mi south of Red Oak on the west side of S.H. 82. Strata strike N. 80° E., dip 75° S., and are overturned. Although the Spiro in this outcrop is composed predominantly of sandstone, it does contain a limestone bed near the top. The Spiro has a gradational basal contact with the sub-Spiro shale. The Wapanucka does not occur at this outcrop.

The Spiro sandstone is 228 ft thick at this outcrop and can be divided into six intervals:

94–228 (top) ft:

106–228 ft—The upper part of the uppermost interval consists of five thick, covered intervals separated by clean tan to red, fine- to medium-grained sandstone.

94–106 ft—The lower part of the uppermost interval is composed of red, medium-grained, friable sandstone that contains abundant fossil molds and cross-bedding.

79–94 ft—The second interval from the top consists of gray, massive, micritic limestone.

57–79 ft—The third interval from the top is composed of fine- to medium-grained, poorly to well-sorted sandstone.

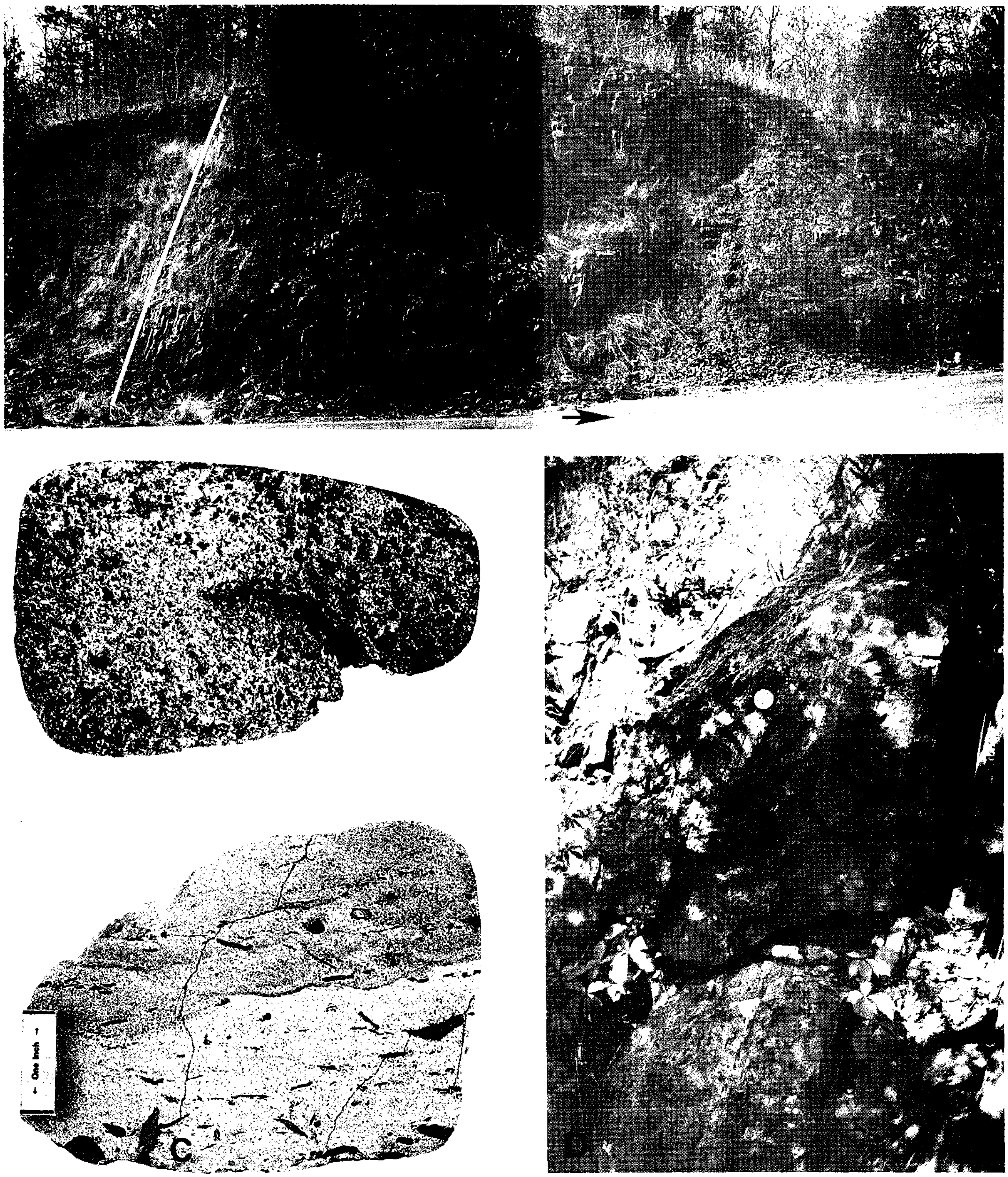


Figure 66 *(above and facing page)* (from Suneson and Hemish, 1994, fig. 49). (A) Road cut of the Spiro sandstone at Stop 8. White line marks the transition from the sub-Spiro shale to the Spiro sandstone (arrow shows facing direction). (B) Medium- to coarse-grained, friable sandstone with abundant fossil molds, 64 ft above the sub-Spiro shale. (C) Medium-grained sandstone containing abundant shale and clay intraclasts and scattered fossils, 28 ft above the sub-Spiro shale. (D) Outcrop of cross-bedded sandstone containing abundant shale and clay intraclasts, 28 ft above the sub-Spiro shale. Coin (quarter) in upper center for scale. *(Part E of this figure is shown on next page.)*

Figure 66. (E) Intensely bioturbated sandstone near the base of the Spiro sandstone, 10 ft above the sub-Spiro shale.

Fossil molds are common from 57 to 66 ft (Fig. 66B). Cross-bedding occurs near the base. Burrows occur from 66 to 79 ft, as do echinoderm and other fossil fragments.

35.5–57 ft—The fourth interval from the top contains red to tan, fine-grained, well-sorted sandstone. It is thin to medium bedded with shale laminae, shale wisps, and current bedding. Ripples and burrows are common sedimentary structures. Glauconite occurs in trace amounts throughout.

26–35.5 ft—The second interval from the base is composed of tan to gray, fine- to medium-grained, poorly to moderately well sorted sandstone. Clay and shale intraclasts are abundant in the section from 26 to 32 ft (Fig. 66C). Fossils are also common in this interval, as is glauconite. The dominant sedimentary structures are cross-bedding in beds between 26 and 32 ft (Fig. 66D) and ripples and burrows from 32 to 35.5 ft. This interval has a sharp basal contact.

7 (base)–26 ft—The lowermost interval consists of tan to gray, fine-grained, well-sorted sandstone. Traces of glauconite are present throughout. Burrows and ripples are common sedimentary features. The basal part of the sandstone at 10 ft is intensely bioturbated and burrowed (Fig. 66E). It has a gradational contact (7–10 ft) with the sub-Spiro shale (0–7 ft).

Petrographic Analysis

Quartz is the primary detrital constituent in the sandstones. Grains, which are mainly monocrystalline, have straight extinction. Quartz grains with undulatory extinction and polycrystalline grains also occur. Feldspar is present as a trace in one sample. Rock fragments include chert, shale, and siltstone. Muscovite, zircon, and tourmaline are present as accessories.

Fossil fragments are common in some intervals. Many grains are partially dissolved. Echinoderm fragments are the most common type.

Glauconite and chamosite occur in small amounts. Most glauconite grains are deformed and show dissolution. Some grains are altered to pseudomatrix or brown glauconite. A few chamosite peloids are recognizable in some samples. Oolitic chamosite coatings on quartz grains also occur, but either they are partially dissolved or they are replaced almost entirely by calcite.

Clays incude illite and chlorite. Illite is predominantly recrystallized matrix and pseudomatrix. Authigenic chlorite, probably iron-rich, coats quartz grains in a few samples. In the more porous intervals, limonite and hematite are common as grain coatings.

Silica-quartz overgrowth, the most common cement type, is developed most extensively where there was little clay to inhibit its growth. Calcite cement, which is less common, occurs mainly in rocks that contain some fossils.

Porosity is characteristic of the Spiro at this locality. Some intergranular, primary porosity occurs at grain contacts and in zones where it was preserved by early chlorite grain coatings. The dissolution of glauconite, matrix, chamosite, fossils, and quartz contributes to secondary porosity.

Interpretation

The occurrence of burrows, bioturbation, fossils, and glauconite suggests that the Spiro sandstone at this outcrop probably was deposited in a shallow-marine environment. The cross-bedding and coarser grain size at the base of the uppermost interval, in the third unit from the top, and in the second interval from the base suggest possible channeling. The limestone in the second interval from the top apparently represents a period when the sand source was cut off.

Additional Observations by N.H.S. and I.Ç.

The Spiro sandstone at this location is very different from the Spiro sandstone exposed immediately to the north (mile 29.9), but the cross section by Suneson and Hemish (1994, fig. 44) suggests that both outcrops are part of an overturned, north-vergent syncline. If this cross section is correct and the two outcrops are not separated by a fault, the abrupt facies change from thick, massive, very poorly stratified Spiro sandstone at mile 29.9 to well-stratified Spiro here must be explained.

Gross and others (1995) suggest that much of the Spiro sandstone in the Arkoma Basin in Latimer County consists of barrier-island deposits separated by tidal channels. They describe the channel deposits as stacked, crinoidal, and bioclastic; these features typify the massive sandstone at mile 29.9. In contrast, the stratified sandstone at this stop probably was deposited in a marine-bar environment. It is possible that the marine-bar deposits grade along strike or up-section into barrier-island deposits. If the Spiro in the northernmost thrust sheets of the fold-and-thrust belt are similar to those studied by Gross and others (1995) in the Arkoma Basin, it would be evidence that (1) the Spiro shelf was very wide, or (2) the Choctaw Fault has relatively little displacement at this location. Alternatively, the stratified Spiro sandstone here

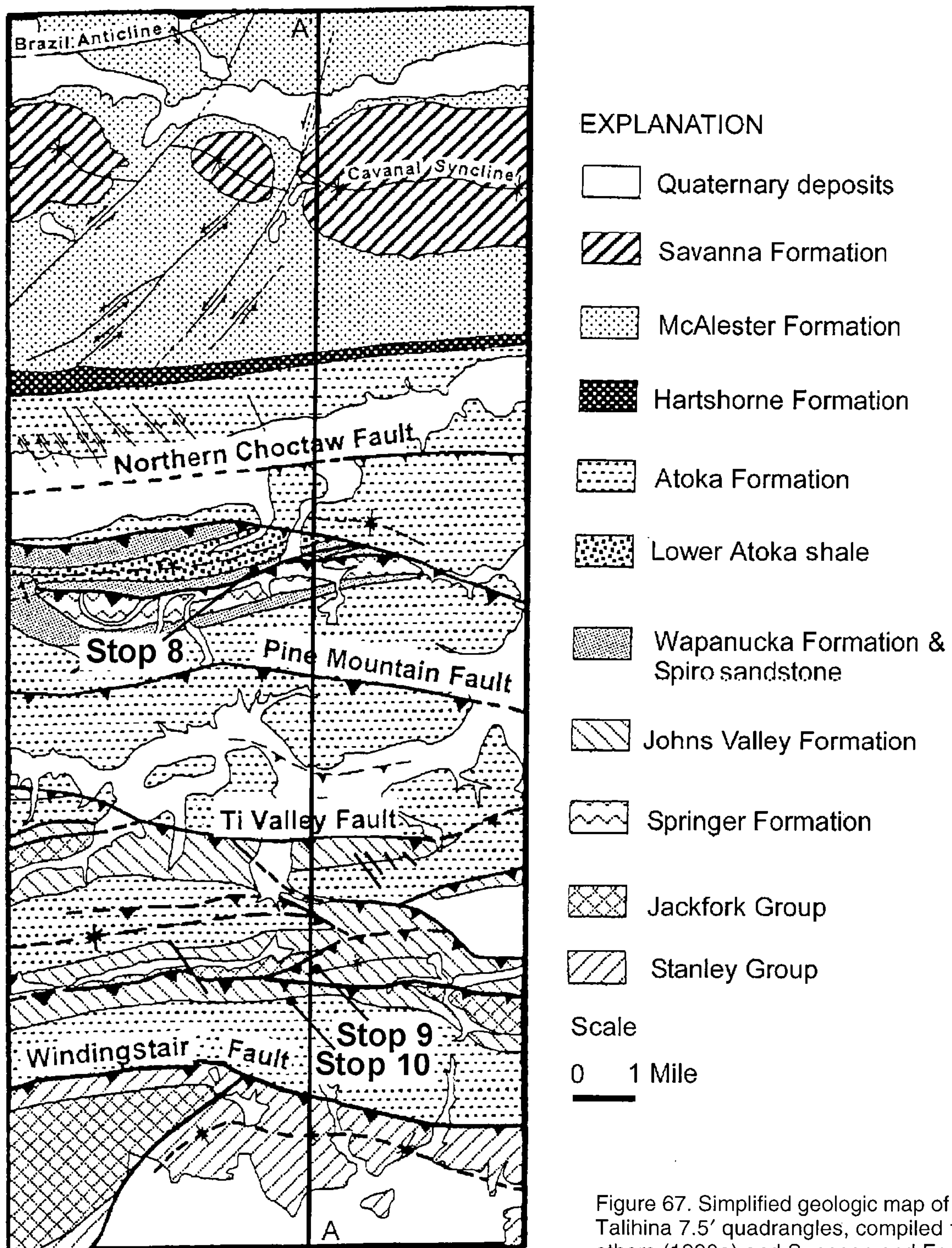


Figure 67. Simplified geologic map of the Red Oak and Talihina 7.5′ quadrangles, compiled from Hemish and others (1990a) and Suneson and Ferguson (1990).

may be a marine-bar deposit such as proposed by Grayson and Hinde (1993) that is closely associated with a channel (tidal?) deposit.

Frontal-Belt Structure

The subsurface structural geometry of the thrust faults and associated structures in the Red Oak and Talihina 7.5′ quadrangles was described by Mehdi (1998). Evans (1997) constructed balanced structural cross sections and described the geometry of the thrust faults in the Baker Mountain and Panola quadrangles to the west of Mehdi's (1998) area. The studies by Evans (1997) and Mehdi (1998) are based on surface geology (Fig. 67 [on facing page]), interpretation of electric logs of the wells drilled in the area, and available seismic-reflection profiles. Mehdi's (1998) cross section A–A′ is very close to this outcrop and is shown in Figure 68.

Cross section A–A′ (Fig. 68) is constructed perpendicular to the tectonic-transport direction. Therefore, it shows displacements along the thrust faults where appropriate piercing points are located in the hanging wall and footwall. The Atoka Formation is the dominant rock unit at the surface and in the subsurface. In the subsurface it contains many recognizable sandstones such as the Spiro, Cecil, Panola, and Red Oak (Fig. 63). These can be used to define the subsurface structural geometry because of their recognizable well-log signatures. The Wapanucka Limestone and the Spiro sandstone are not identified individually but rather are referred to as the Spiro and are assumed to have uniform thicknesses. The tops of the Spiro, Cecil, Panola, and Red Oak sandstones are used in the cross-section construction, and their thicknesses are considered to be constant throughout the study area. When restored to the time of Spiro deposition, using the Spiro sandstone as a key bed, cross section A–A′ suggests a shortening of ~52%.

Along cross section A–A′ (Fig. 68) the hanging-wall block of the Choctaw Fault zone contains several south-dipping thrusts, including the Pine Mountain Fault. These thrusts join the Choctaw Fault zone where it begins to flatten out to the south. They form a leading imbricate-fan structure with the Choctaw Fault zone as the leading thrust. Çemen and others (2001a) proposed that the Choctaw

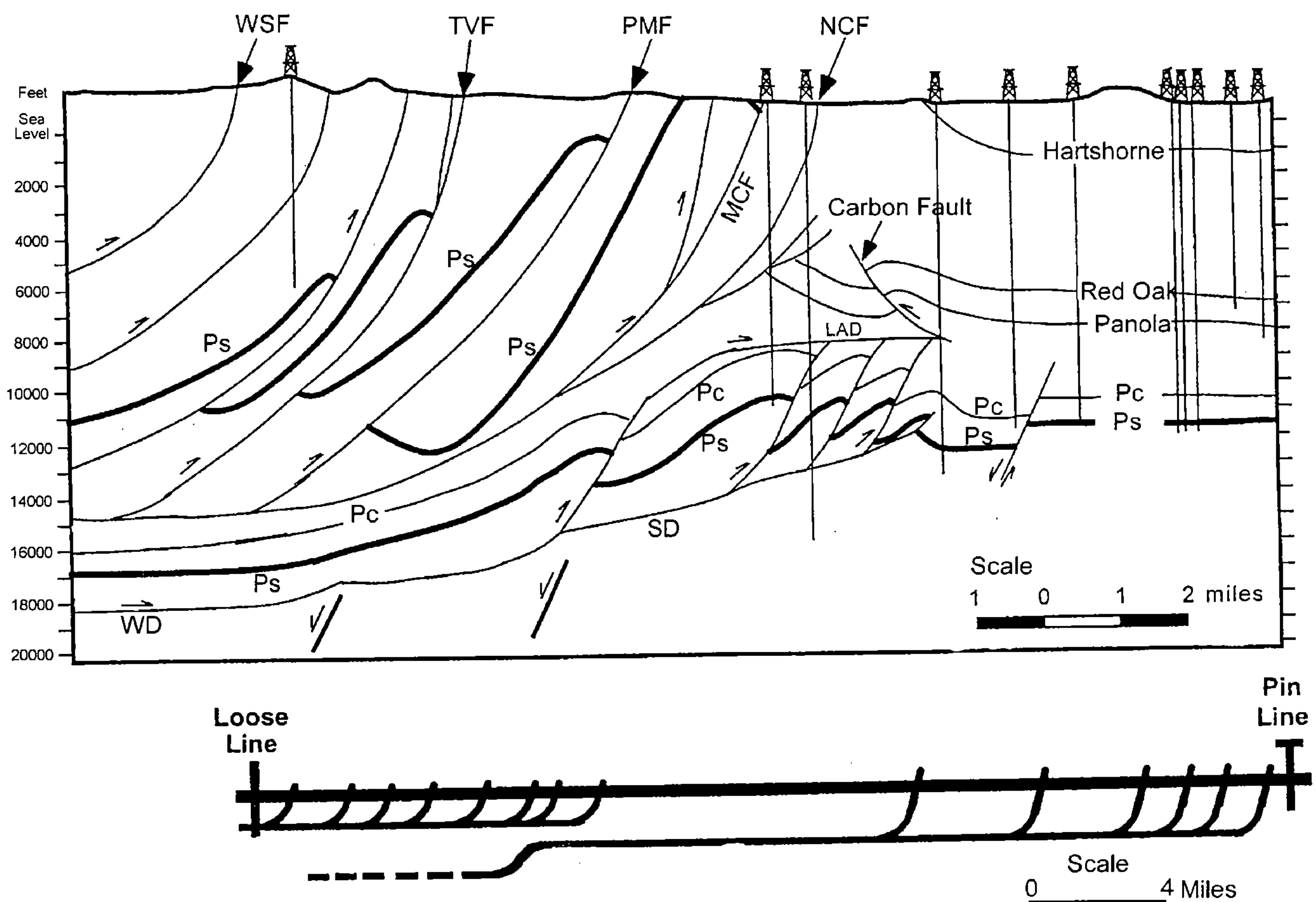


Figure 68. Balanced cross section along line A–A′ of Mehdi (1998) and its restoration, using the Spiro sandstone as the key bed. The restoration suggests about 52% shortening. NCF = Northern Choctaw Fault; MCF = Main Choctaw Fault; PMF = Pine Mountain Fault; TVF = Ti Valley Fault; WSF = Windingstair Fault; LAD = Lower Atoka Detachment; SD = Springer Detachment; WD = Woodford Detachment; Ps = Spiro sandstone; Pc = Cecil sandstone. Note that the scale of the restored section is two times smaller than the balanced section.

Fault branched off the Woodford Detachment. This splay must have occurred south of the area of cross section A–A′.

The Woodford Detachment is named for the Woodford Shale, which is the "host" for the fault (Hardie, 1988). It is a gently south-sloping detachment that is ~18,000 ft below sea level in T. 3 S. at the south end of cross section A–A′ (Fig. 68). Northward, the detachment rises to the level of the Springer Shale and is called the *Springer Detachment.* This ramping may have been caused by normal faults in the pre-Pennsylvanian "basement." The Springer Detachment propagates northward into the Arkoma Basin and loses its separation under the Sans Bois Syncline.

To the west in the northern part of T. 5 N., R. 20 E., in the Panola 7.5′ quadrangle, the Spiro and Cecil sandstones are repeated above the Springer Detachment in many wells (Evans, 1997). This suggests the presence of small thrust faults that displace the sandstones. This geometry could be interpreted in two ways: (1) the sandstones are displaced by blind thrust faults that die out in the shaly part of the Atoka Formation above the Cecil sandstone, or (2) a roof thrust above the Cecil sandstone separates the imbricately thrusted section below from the folded section above. Çemen and others (2001a) provided evidence for the second interpretation in the Wilburton gas field area. They named the roof thrust the *Lower Atoka Detachment* surface. The Lower Atoka Detachment is also present in the Red Oak area (Mehdi, 1998) (Fig. 68).

Seismic lines in the Red Oak gas field area, donated by Amoco, provide evidence for the presence of a back thrust below the southern limb of the Sans Bois Syncline. The back thrust dies out into the Atoka Formation where a zero-displacement point exists (Fig. 68). This back thrust is the eastern subsurface continuation of the Carbon Fault of the Wilburton area. This geometry defines a triangle zone in the manner proposed by Jones (1982) for the foothills of the southern Canadian Rockies. The triangle zone is floored by the Lower Atoka Detachment and flanked by the Choctaw Fault to the south and the blind Carbon Fault to the north.

Below the triangle zone is a well-developed duplex structure, which is formed by hinterland-dipping imbricate thrust faults splaying from a floor thrust and joining to the Lower Atoka Detachment in the Atoka Formation. The placement of horses within duplex structure is based on the depths of the Spiro and Cecil sandstones in the well logs that were used to construct the cross sections and our interpretation of several north–south 2-D seismic-reflection profiles. The thrust faults separating the horses are shown as hinterland-dipping thrusts in conjunction with the break-forward sequence of thrusting established by Çemen and others (2001a) in the hanging wall of the Choctaw Thrust Fault near Wilburton.

Continue south on S.H. 82.

29.9 0.4 Good exposure of "Springer" Formation in borrow ditch on left (east) side of road.

This structure is called the *Pigeon Creek Anticline* on the geologic map of the McAlester 2° sheet published by the OGS (Marcher and Bergman, 1983). Detailed mapping by the OGS as part of the COGEOMAP program shows that this structure does not exist.

31.1 0.2 Fair exposure of Spiro sandstone on right (west) side of road. This is the structurally highest and, presumably, most basinward outcrop of Spiro sandstone in this part of the Ouachita frontal belt. However, as discussed below, a very Spiro-like sandstone is present in the lowest part of the Atoka Formation in several thrust sheets to the south.

31.5 0.4 Leave Red Oak 7.5′ quadrangle; enter Talihina 7.5′ quadrangle.

32.0 0.5 Most of the Atoka Formation (best exposed on left [east] side of highway) faces south and dips south, but small areas with north-facing and overturned strata are evidence that the Atoka is complexly folded.

32.5 0.5 Excellent outcrop of steeply south-dipping Atoka Formation turbidites on left (east) side of road (Fig. 69). The 1994 field trip stopped here (stop 11).

33.6 1.1 Cross Long Creek.

34.9 1.3 Bengal, Oklahoma. The imaginary ancestral Ouachita mountain range of "Bengalia" (Fig. 70) is named for this small town (see Powers, 1928). (Suneson and Hemish [1994, p. 73–74] discuss the history of the "Bengalia" concept.)

Figure 69. Turbidite sandstones and shales (mostly grass covered) of the Atoka Formation at mile 32.5. Facing direction is to the right (from Suneson and Hemish, 1994, fig. 50).

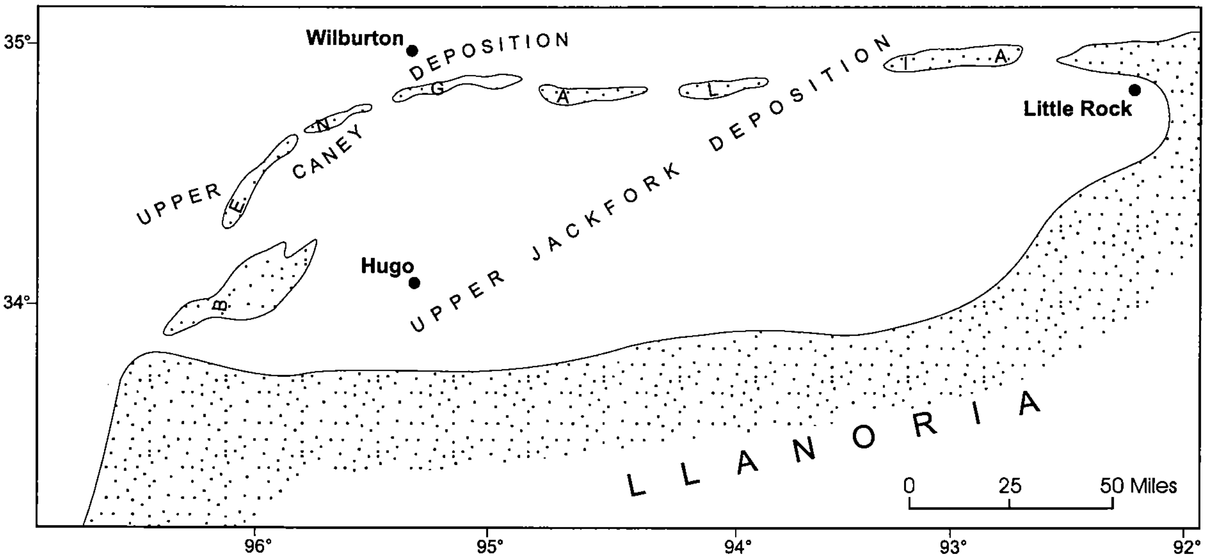


Figure 70. Paleogeographic map of the Ouachita region during Johns Valley epoch of later Caney (Mississippian and Pennsylvanian), according to Powers (1928, fig. 4).

A 2,000-ft-long Woodford Shale–Caney Shale olistolith in the Johns Valley Formation is present ~0.7 mi west of Bengal (stop 12, 1994 field trip).

35.0 0.1 Cross trace of "Ti Valley Fault." Following Suneson's (1988a) suggestion, quotation marks are used because it is difficult, if not impossible, to map and name individual thrust faults in this part of the Ouachita Mountains.

35.7 0.7 Cross West Fork of Rock Creek.

35.8 0.1 Dirt road to left (east), and then immediately right (south).

This road follows the old St. Louis–San Francisco railroad grade and is passable for most passengers cars, vans, and SUVs. It is not passable for buses. The 1994 field trip examined the Johns Valley Formation at Compton Cut, ~2 mi to the south. The exposure at Compton Cut probably was visited by most, if not all, of the early geologists who worked in the Oklahoma Ouachita Mountains and fueled arguments about the age and origin of the Johns Valley.

36.5 0.7 Outcrop of Johns Valley Formation on uphill (right, south) side of highway (Fig. 71). This was stop 14 on the 1994 field trip. Unfortunately, highway widening since 1994 has obliterated some of the outcrop.

Among other lithofacies, this outcrop contains a thin, skeletal and limestone-clast sandstone bed similar in many respects to the "Spiro equivalent" beds at Stops 9, 10, and 12.

37.5 1.0 S.H. 82 turns left. Pull off on wide shoulder on right. Again, please be careful and watch for traffic on this highway. (Do more than just "watch" for it. Avoid it.)

STOP 9

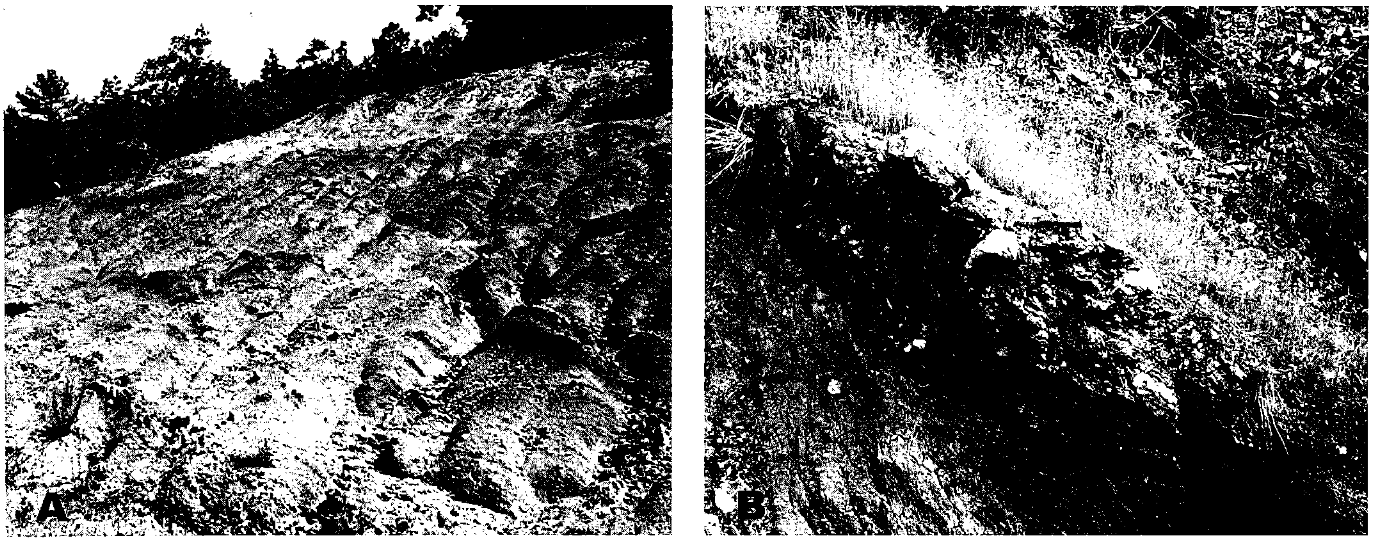
DEEP-WATER ATOKA FORMATION AND "SPIRO EQUIVALENT," GOBBLERS KNOB

Dennis R. Kerr
University of Tulsa

Location: on north slope of Gobblers Knob on southeast side of S.H. 82, C W½NE¼ sec. 24, T. 4 N., R. 21 E., Latimer County, Oklahoma

Introduction—Stratigraphy of the "Spiro Equivalent"

A distinctive bituminous, skeletal-moldic sandstone occurs near the base of the Atoka Formation at localities along S.H. 82 and State Highway 1/2 (Stop 12). Kerr (2003) referred to this unit as the "Spiro equivalent," believing it to be correlative with the lower Atoka Formation Spiro sandstone, which crops out between the Choctaw and Pine Mountain Faults in the frontal Ouachitas (Suneson and Ferguson, 1989b, 1990). At the Gobblers Knob and Winding Stair Mountain sections (Stops 9 and 10), the "Spiro equivalent" is ~1 ft thick and is found 102 ft and 135 ft, respectively, above the lithostratigraphic base of the Atoka Formation (Fig. 72). At both of these locations it is included in deep-water channel–levee deposits. At the hairpin turn exposure on S.H. 1/2 (Stop 12), the "Spiro equivalent" is 71 ft above the base of the Atoka (Fig. 72) and is part of a 15-ft-thick succession of sandstones (bed no. 30 of Haveman, 2003) that includes dispersed molds



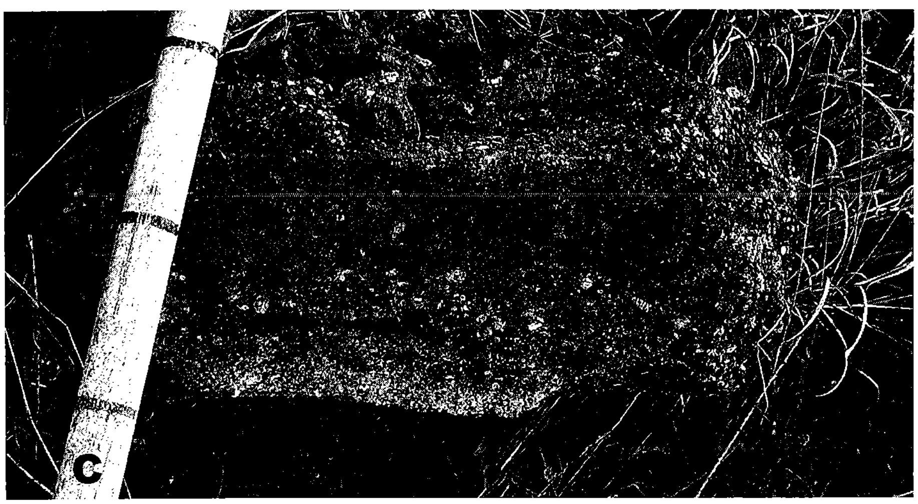


Figure 71. (A) Johns Valley Formation. Note even-bedded shale and small size of erratic boulders (from Sutherland and Manger, 1979, fig. 94). (B) "Pod" of matrix-supported boulder conglomerate in the Johns Valley Formation. The pod probably is a large clast (olistolith) in a shale-rich debris-flow deposit (from Suneson and Hemish, 1994, fig. 54). (C) "Spiro equivalent" in the Johns Valley Formation. A discontinuous ~0.8-in.-thick bed of skeletal and carbonate-lithic-clast-rich sandstone is encased in typical mud and clay shale of the Johns Valley. Shaft divisions are equal to ~4 in.

of skeletal detritus. A similar skeletal- and limestone-clast sandstone (i.e., carbonate framework grains are not extensively dissolved) is found in the Johns Valley Formation ~85 ft below the base of the Atoka at an exposure south of Bengal on S.H. 82 at mile 36.5 (Fig. 71C). Across the Damon 7.5′ quadrangle (Suneson and Ferguson, 1989b), including the north limb of the Anderson Creek Syncline (mile 68.4), Suneson (1988b, and personal communication, 2003) also reports a "sparse fauna" near the base of the Atoka, which is "vaguely reminiscent of the fauna that is profuse in the 'Spiro' sandstone" (p. 89). Bowsher and Johnson (1968) refer to locations where "Spiro sand" is exposed along S.H. 2. Pauli (1994) gives a general reference to a skeletal-moldic sandstone exposed in the north limb of the Anderson Creek Syncline; here, the "Spiro equivalent" is 98 ft above the base of the Atoka (Fig. 72).

Unless this distinctive lithology is part of a thicker, more resistant sandstone succession, it weathers readily and is easily overlooked. In spite of its poor exposure, other geologists have made reference to similar occurrences of skeletal-moldic sandstones near the base of the Atoka Formation elsewhere in the Ouachita Mountains. Hart (1963; see also Suneson and Hemish, 1994), Cline and Stark (1966), and Cline and Berry (1968) describe fossil molds in lower Atoka sandstones exposed along U.S. 259 in southern Le Flore County, Oklahoma. Cline (1956) reports several localities in the central Ouachitas (in the vicinity of eastern Pushmataha County, Oklahoma), and he further discusses the correlation to Honess's (1924) "Morrowan fauna." In the Athens Plateau area of Pike County, Arkansas, Walthall and Bowsher (1966) report a fossil-mold fauna near the base of the Atoka. More recently in a short abstract, Longden and others (2000) remarked on the similarity (i.e., texture and composition of framework, including skeletal debris) between basal Atoka deep-water sandstones exposed in the Ouachitas and the Spiro sandstones of the shelf areas of the Arkoma Basin. Roberts and Stone (Day One, mile 70.4) describe skeletal-moldic sandstones in the lower part of the Atoka Formation near Eagleton, Arkansas.

Stratigraphy—Gobblers Knob Section

The Johns Valley and Atoka Formations crop out on the north flank of the Gobblers Knob Syncline (Suneson and Ferguson, 1990). The Johns Valley exposures in general are poor and are covered with soil and vegetation; however, scattered exposures are found in recent washouts along gullies and the highway drainage ditch. The Atoka Formation exposures are intermittent, with thick, resistant sandstones being well exposed, and interstratified mudrocks typically being covered with soil and vegetation.

The Johns Valley Formation is predominantly clay and mud shale with boulders of deformed and "rolled" sandstones found at a few locations. No so-called exotic clasts have been observed here. Shale fissility dips south, but strikes and dips vary considerably from place to place; part of this variability is the result of hillside slumping. Although the exposures are limited, the sedimentologic character is not inconsistent with the interpretation of deposition by submarine slumping or debris-flow processes.

The fine- to medium-grained sandstones in the Atoka Formation exhibit physical and biogenic structures typical of deep-water sedimentation. In the lower 164 ft of the section, half-foot-thick sandstones contain incomplete Bouma successions, with lithofacies T_{a-b}, T_b, and $T_{a,c}$ being most common. T_c units typically are convolute laminated and chaotic-contorted laminated, with subcritical climbing-ripple lamination and contorted lamination showing vergence direction being less common. The incomplete Bouma successions are regarded as the record of surging turbidity currents with bypass of the more dilute upper parts of the flow. One-foot-thick sandstone units are structureless, with relict contorted laminations (lithofacies S_s) or inch-scale, inversely graded parallel- to low-angle stratification (lithofacies S_2). These sandstones are interpreted to be the record of fluidization and/or liquefaction processes and traction-carpet processes, respectively. Dark-gray, carbonaceous clay shales (lithofacies H) are interstratified with the above-described sandstones; these shales are the deposits of hemipelagic sedimentation. Single-set-thick, half-foot wavelength ripple-cross-laminated inch-thick sandstones (lithofacies S_r) are interlaminated with lithofacies H. Such ripple-cross-laminated sandstones are the record of so-called starved ripples—that is, the deposits of traction currents having a limited sand supply.

A wide variety of biogenic structures belonging to the *Nereites* ichnofacies are associated with these lower Atoka deep-water sandstones. Most are found on the soles of sandstone beds, with *Paleodictyon* (including *Megagrapton*) being most common. *Chondrites* is rare and penetrates the upper inch of thicker sandstones. Chamberlain (1978) provides descriptions, discussions, and a field-trip guide of the biogenic structures found in the sandstones of the Ouachita Mountains.

The upper 49 ft of the measured section at Gobblers Knob contrasts with the lower part of the section. Here, sandstones dominate, and the maximum bed thickness is 15 ft. Large-scale, trough-cross-stratified sets, which include dish structures in the cross-stratification (lithofacies S_x), are developed. Other lithofacies include T_a, T_b, T_{a-b}, T_{a-c}, S_s, and S_2. This upper succession thickens at the expense of the lower succession eastward a short distance into the woods from road level. It is estimated that ~23 ft of the upper part of the lower section has been removed by erosion. It is noteworthy that this sand-rich portion of the lower Atoka develops ~82 ft above the "Spiro equivalent" (compare to Stop 10 at the Winding Stair Mountain section).

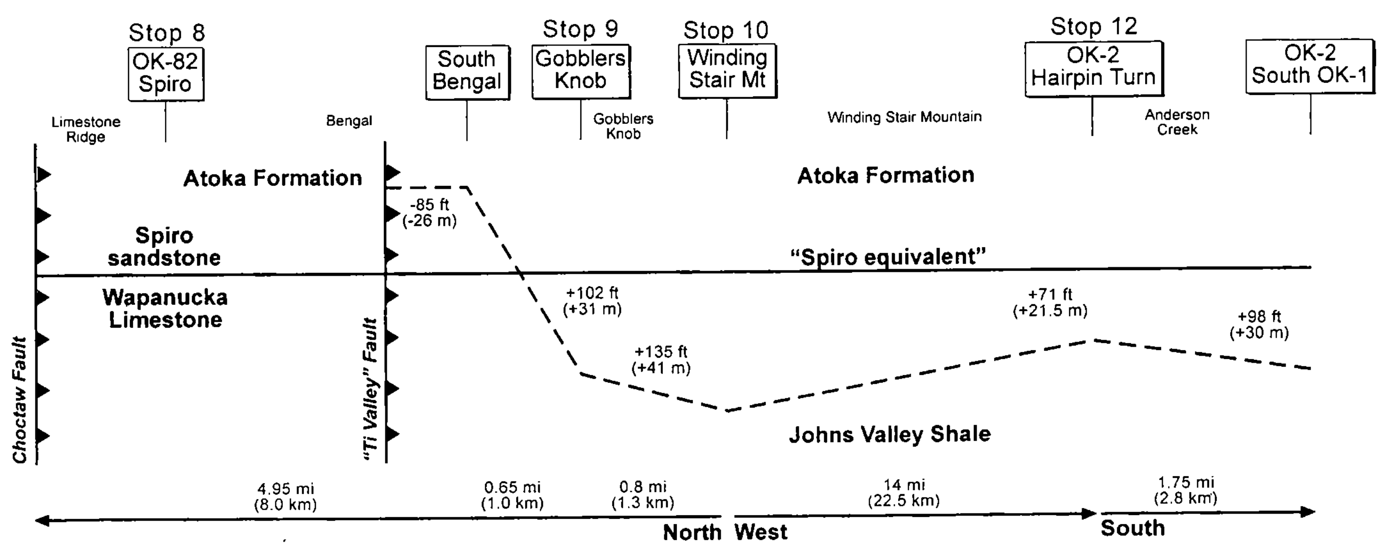


Figure 72. Schematic diagram illustrating the stratigraphic position of the "Spiro equivalent" in sections along S.H. 82 south of Red Oak and State Highway 2 south of Wilburton. Measurements of the height of the "Spiro equivalent" relative to the lithostratigraphic contact between the Johns Valley Formation and Atoka Formation are indicated. Note changes in direction and distance across the illustration.

Paleocurrent measurements and sedimentologic interpretation are discussed at the next stop.

Continue south on S.H. 82.

38.4 0.9 Top of Winding Stair Mountain (elev. 1,401 ft). Pull off on right side of highway and stop. We will walk back down the highway a few hundred yards. Please be careful: this is a very busy highway with many blind curves, and many drivers drive faster than they should.

STOP 10

DEEP-WATER ATOKA FORMATION AND "SPIRO EQUIVALENT," NORTHERN SLOPE OF WINDING STAIR MOUNTAIN

Dennis R. Kerr
University of Tulsa

Location: north side of crest of Winding Stair Mountain, south side of S.H. 82, NW¼SW¼SE¼ and NE¼SE¼SW¼ sec. 24, T. 4 N., R. 21 E., Latimer County, Oklahoma

Lower Atoka sandstones strike N. 75° W. and dip 65° S. According to Suneson and Ferguson's (1990) mapping, the Atoka Formation along S.H. 82 is a structurally intact section southward for ~1.5 mi to where it encounters the overriding thrust block of the Windingstair Fault. As at Gobblers Knob, the Johns Valley Formation is poorly exposed, thinner sandstone-and-mudrock-dominated sections of the Atoka are poorly to moderately exposed, and the sandstone-dominated Atoka is well exposed.

The total thickness of the Johns Valley cannot be determined at this location. Typical Johns Valley lithology, which includes "exotic" clasts, is exposed for 21 ft below the lithostratigraphic base of the Atoka Formation. Below this interval is a 17-ft-thick interstratified sandstone and shale interval with lithofacies similar to those of the overlying Atoka.

The lower Atoka contains deep-water lithofacies that are similar to those described at Gobblers Knob. However, there are two noteworthy differences here compared with the exposures just seen at Gobblers Knob. First, the "Spiro equivalent" occurs 136 ft above the lithostratigraphic base of the Atoka (Figs. 72, 73). Second, a well-exposed, 28-ft-thick channel-fill succession is present beneath the "Spiro equivalent." This channel-fill succession is made up mostly of lithofacies S_s organized into thinning-upward amalgamated beds that also show westward lateral shifting of cut and fill.

Paleocurrent indicators measured in the Gobblers Knob and Winding Stair sections present interesting relationships when differentiated by the types of sedimentary structures and lithofacies. Paleocurrent directions from flute casts range from south (190°) to northwest (315°) and average west (278°). Lithofacies S_r ripple-cross-lamination and forms indicate paleoflow directions ranging from east (100°) to west (265°) and averaging south (185°). Trough-cross-stratification of lithofacies S_x indicates a general southeastward paleocurrent direction.

Although detailed sedimentologic studies are in progress (by Dennis Kerr and his students at the University of Tulsa), the character of the lower Atoka at Gobblers Knob and Winding Stair Mountain are interpreted to be the record of mud-rich, submarine-fan, channel–levee depo-

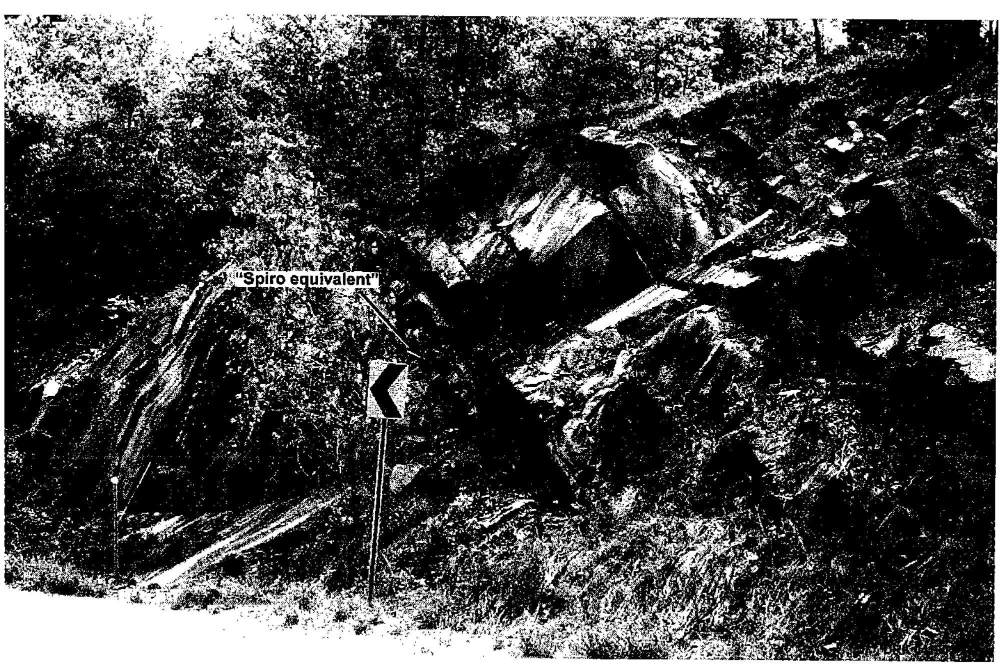


Figure 73. Exposure of lower Atoka deep-water channel-fill successions containing the "Spiro equivalent" as a discrete bed at the Winding Stair Mountain section.

Table 3. — Producing Wells in Talihina Northwest Gas Field by Spud Date

Operator, number, farm, spud date, total depth, producing formation, depth of producing formation (data from NRIS as reported by operator to Oklahoma Corporation Commission on Form 1002A).

1. H&H Star Energy 1-28 Lady Luck; 12/30/91; 9,976 ft; Spiro; 8,946–9,032 ft
2. Ward Petroleum 1-21 Secor; 6/16/94; 8,600 ft; Atoka Lower; 7,702–7,953 ft
3. Ward Petroleum 1-20 Ellis-Brandt; 2/24/95; 6,700 ft; Atoka Middle; 3,975–4,320 ft; Atoka Lower; 6,056–6,465 ft
4. Ward Petroleum 1-23 Sara; 5/20/95; 8,239 ft; Jackfork; 6,104–6,307 ft
5. Chesapeake Operating 1-22 Weyerhaeuser; 5/27/95; 9,500 ft; Lower Jackfork; 5,640–9,368 ft
6. Ward Petroleum 1-30 Lyons; 8/27/95; 7,905 ft; Lower Jackfork; 5,220–7,742 ft
7. Chesapeake Operating 1-16 Bear Mountain; 11/25/95; 9,992 ft; Upper Jackfork; 7,476–8,256 ft
8. Ward Petroleum 1 Ellis; 2/5/96; 10,052 ft; Upper Jackfork; 4,698–6,718 ft
9. Ward Petroleum 1-29 Ford; 8/28/97; 8,850 ft; Lower Jackfork; 8,656–8,698 ft
10. Ward Petroleum 1-21 Mary Grace; 1/1/99; 8,000 ft; Atoka Lower; 7,163–7,455 ft; Atoka Middle; 5,115–6,818 ft
11. Ward Petroleum 2-20 Ellis-Brandt; 10/8/01; 7,304 ft; Atoka Lower; 6,878–6,928 ft; Atoka Lower; 6,436–6,607 ft
12. Chesapeake Operating 2-22 Weyerhaeuser; 7/14/02; 7,500 ft; Upper Jackfork; 4,600–5,694 ft; Lower Jackfork; 6,282–7,122 ft
13. Ward Petroleum 1-21 Blake; 6/5/03; 8,100 ft; Atoka Upper; 5,539–5,588 ft; Atoka Upper; 5,302–5,388 ft

sition. The type of incomplete Bouma successions, the presence of thick fluidized/liquefied (S_s) and trough-cross-stratified (S_x) beds in channel-fill successions, and the development of starved-ripple-cross-stratified (S_r) sandstones in addition to paleocurrent patterns are the principal evidence for this interpretation. The Gobblers Knob section subjacent to the "Spiro equivalent" consists predominantly of levee deposits on the west side of a submarine channel; Suneson and Ferguson's (1990) map shows the western edge of a sandstone lens 820 ft east of the road-cut exposures at about the same stratigraphic position relative to the base of the Atoka. Relative to the "Spiro equivalent," thick channel-fill successions are exposed along S.H. 82 above this marker at Gobblers Knob and below at Winding Stair Mountain. These channel-fill deposits trend southeast in the lower Atoka exposures. Although the exposures in the frontal Ouachitas are largely two dimensional, the presence of the "Spiro equivalent" as a marker bed provides geographic constraints on detailed facies-architecture reconstruction. At Stop 12, this same lower Atoka interval is interpreted to be deposits of submarine-fan lobes (Haveman, 2003).

The Talihina Northwest gas field extends for ~5 mi just west of here.

Talihina Northwest Gas Field

The Talihina Northwest gas field includes all or parts of 12 sections in T. 4 N., R. 21 E. (Boyd, 2002) (Fig. 74). The discovery well for the field is the H&H Star No. 1-28 Lady Luck, in the SE¼NW¼SE¼ sec. 28, T. 4 N., R. 21 E., at the southern edge of the field (Table 3). The well spudded on December 30, 1991, and drilling finished on May 29, 1992. The well was completed in the Spiro sandstone [sic] at 8,946–9,032 ft and tested 4,590 Mcf gas per day. The follow-up well, the Ward No. 1-21 Secor, in the NW¼ of the same section, did not spud until mid-1994.

The field consists of 13 producing gas wells. As reported to the Oklahoma Corporation Commission, one produces from the upper Atoka Formation, two produce from the middle and lower Atoka (commingled), two from the lower Atoka, one from the Jackfork Group, one from the upper and lower Jackfork (commingled), two from the upper Jackfork, three from the lower Jackfork, and one from the Spiro sandstone [sic]. Some of the listed Atoka wells, however, probably produce from the Jackfork. The Ward No. 1 Ellis well (Fig. 75) shows a typical log pattern

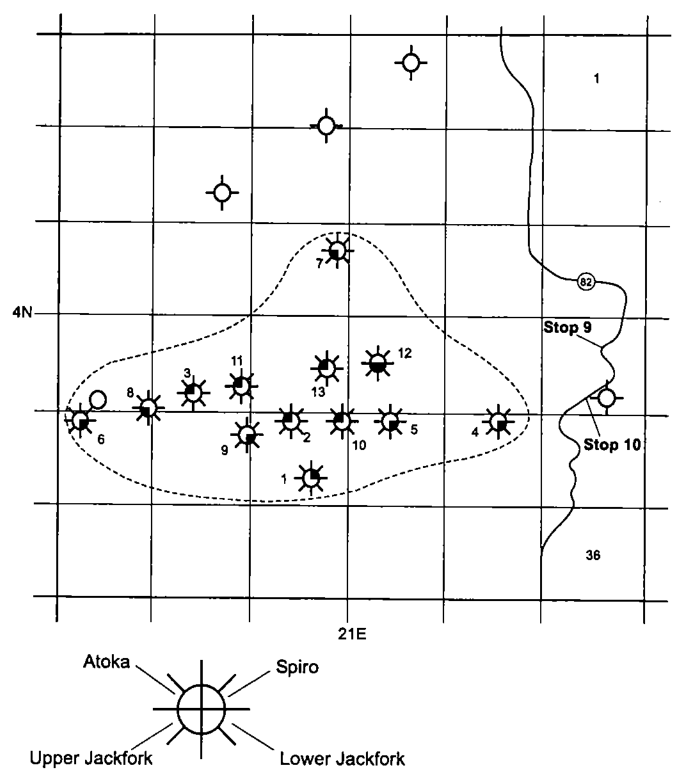


Figure 74. Production map of the Talihina Northwest gas field, showing surface locations of gas wells, field outline (from Boyd, 2002), and nearby field-trip stops. Numbers next to wells refer to those in Table 3.

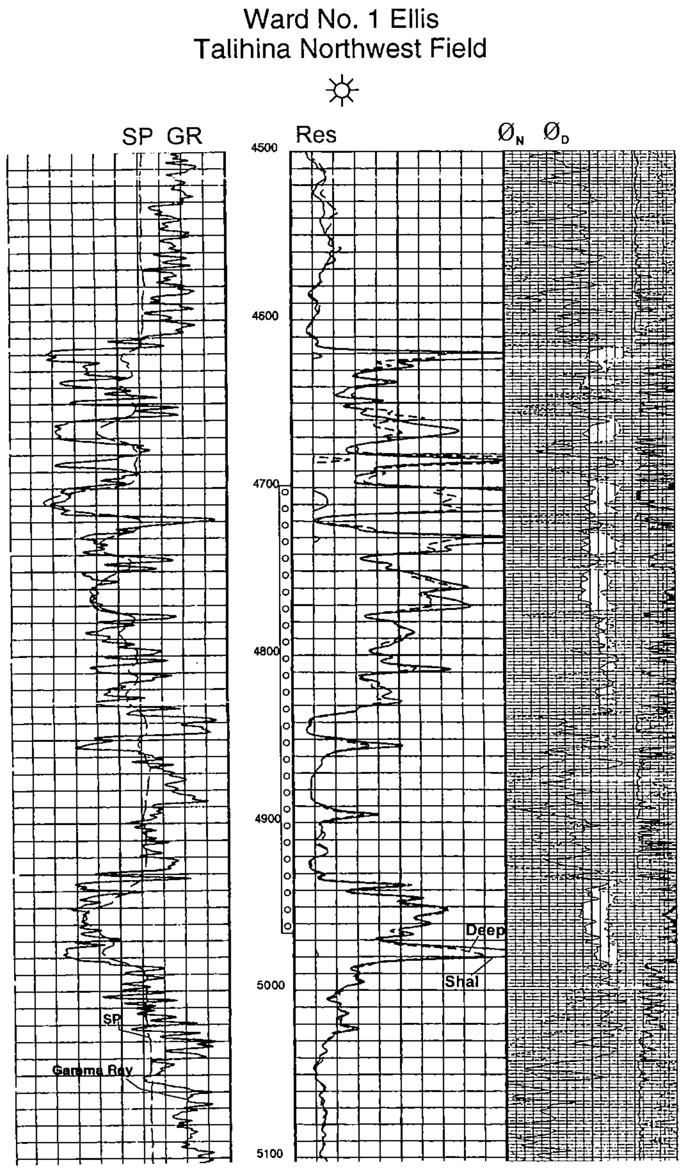


Figure 75. Part of log from the Ward No. 1 Ellis (well no. 8 in Fig. 74), showing the spontaneous-potential, gamma-ray, resistivity, and porosity log patterns for typical Jackfork sheet sandstones. Many of the sandstones show neutron-porosity–density-porosity crossover. Additional intervals were perforated in addition to that shown.

for the Jackfork Group in the field; in contrast, the perforated interval in the Ward No. 2-20 Ellis-Brandt well (Fig. 76) is somewhat anomalous. Garich (2004) suggests that a blocky gamma-ray pattern for Jackfork sandstones (e.g., Fig. 76) is evidence for channels, whereas a highly irregular pattern (interbedded sandstones and shales) (e.g., Fig. 75) is suggestive of thinner sheet sandstones (Fig. 60).

As of July 2004, the field had produced ~9.3 Bcf gas (data courtesy IHS Energy).

Continue south on S.H. 82.

For the next ~1.4 mi, the road descends the south side of Winding Stair Mountain and ascends through ~4,000 ft of moderately (30–60°) south-dipping, south-facing Atoka Formation.

39.8 1.4 Cross trace of Windingstair Fault. This fault probably has among the largest throws of any of the thrust faults in the Ouachita Mountains, and here it juxtaposes the Stanley Group in the hanging wall to the south against the Atoka Formation in the footwall to the north.

39.9 0.1 Entrance to Talihina city dump on right (west). The Windingstair Fault zone is exposed in the dump (Cline, 1968, p. 22).

40.8 0.9 County road to right (west) to Lake Carl Albert. The 1994 field trip examined an outcrop of the Stanley Group at the spillway for Lake Carl Albert.

At this point, S.H. 82 follows the county line. Latimer County is to the right (west), and Le Flore County is to the left (east).

41.4 0.6 Road makes gentle turn to left.

41.7 0.3 Meade Energy drilled their No. 1-1 Stottsberry well (NW¼SW¼NE¼SW¼ sec. 1, T. 3 N., R. 21 E.) at the top of the hill a couple of tenths of a mile to the left (northeast) of the highway. Originally planned as a 12,000-ft Stanley test, the well spudded on July 6, 2001, and finished drilling at 7,424 ft on September 17, 2001. The well tested three Jackfork intervals from ~6,175 ft to 6,835 ft; all were dry. Oklahoma Corporation Commission form 1002A shows the top of the Jackfork Ratcliff sand at 6,090 ft and the top of the Jackfork Cedar Creek sand at 6,527 ft. These units are informally named locally gas-producing sandstones in the Jackfork. The well also tested a small amount of gas from the Stanley at 4,404–4,429 ft.

41.9 0.2 Intersection with State Highway 1 and 63 on west side of Talihina. Turn right (west) on S.H. 1/63.

42.1 0.2 Leave Le Flore County; enter Latimer County.

42.2 0.1 Cross Rock Creek.

The bouldery material on either side of the highway probably represents debris-flow deposits that flowed out of Devils Hollow just north of Buffalo Mountain.

43.1 0.9 State Highway A63 to right (north). Continue straight on S.H. 1 and 63.

About 0.3 mi north of here is the one-well "Talihina oil field." The field does not appear on Boyd's (2002) map of Oklahoma's oil and gas fields, and the "discovery" well, the Select No. 1 Warren (Fig. 77), does not appear in Geo Information System's NRIS database. Scout tickets show that the well was spudded on March 15, 1985, total depth (225 ft) was reached the same day, and the well was completed on September 6, 1985. The projected depth and

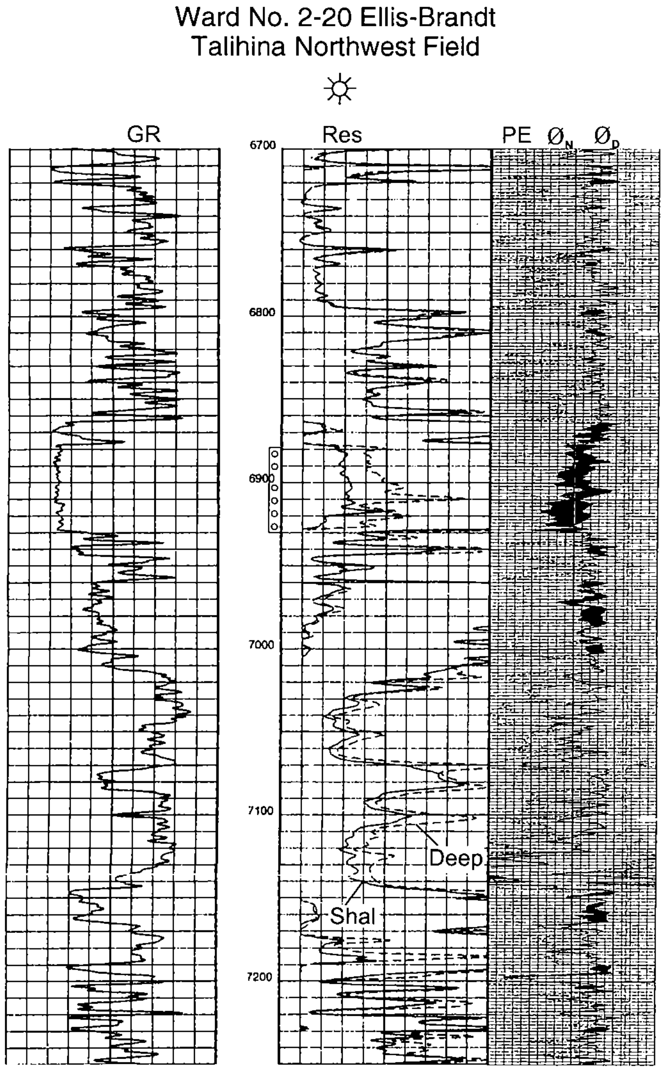


Figure 76. Part of log from the Ward No. 2-20 Ellis-Brandt (well no. 11 in Fig. 74). The well is listed by the Oklahoma Corporation Commission as an Atoka producer, but the log character of the producing intervals resembles that of the Jackfork Group. The perforated interval has a distinctly blocky character with an abrupt base, suggestive of a channel sandstone. The blocky sandstone shows significant neutron-porosity–density-porosity crossover. The interval from 7,177 to 7,184 ft was tested and found to be dry.

formation are listed as 1,450 Hartshorne [sic]. The well is shown on the scout tickets as dry and abandoned, but the local landowner told N.H.S. that the well was occasionally pumped and the oil used to preserve wooden fences and soften pigs' skins.

Weber (1994) analyzed the oil from the No. 1 Warren well. She correctly showed the reservoir as Stanley Group at 156 to 164 ft, in contrast to the scout tickets, which showed Pennsylvanian. Despite the shallow depth, the oil gravity is 37° API. Weber (1994) concluded that the oil from the No. 1 Warren is geochemically similar to the oils from other shallow oil fields in the Ouachita Mountains to the west and that a variety of geochemical features "describe a moderately mature to mature, algal-based, predominantly marine-type oil, generated in clastic source rocks under mildly reducing conditions" (p. 29). She also concluded that the most likely source rocks for the Ouachita crude oils are the Caney Shale, Woodford Shale, Arkansas Novaculite, and/or Polk Creek Shale.

If the source for this oil and most other Ouachita oils to the west is, as Weber (1994) suggests, an organic-rich shale or chert, and if the migration path for those oils was not down the regional dip (i.e., south or southeast), the Caney, Woodford, Arkansas Novaculite, and/or Polk Creek must underlie much of the area south and southeast of the small Ouachita oil fields. This area may one day become prospective for unconventional (e.g., shale-gas) resources.

43.7 0.6 Leave Talihina 7.5′ quadrangle; enter Albion 7.5′ quadrangle. The next three quadrangles (Albion, Kiamichi, Yanush) were not part of the OGS's COGEOMAP or STATEMAP programs; therefore, modern geologic maps are not available for them.

For the next 10 mi the road crosses over very low topography, underlain by the Stanley Group. Poorly documented faults and folds occur within the Stanley, but little (nothing?) is known about their location or origin.

46.1 2.4 Leave Albion 7.5′ quadrangle; enter Kiamichi 7.5′ quadrangle.

47.2 1.1 Highway turns slightly to right and heads due west.

Figure 77. Neil Suneson and Jock Campbell hand-operating the pumpjack on the Select No. 1 Warren, December 5, 1988. After 45 minutes of back-breaking labor, oil was recovered. This method of oil collection is not recommended (photograph courtesy of Jane L. Weber, OGS) (from Suneson and Hemish, 1994, fig. 58).

The Potato Hills are on the left (south), and Buffalo Mountain is on the right (north). A welded tuff is present about two-thirds of the way up Buffalo Mountain near the top of the Stanley Group. This tuff is considerably younger than the tuff seen on Day One.

51.9	4.7	Turn left (south) onto gravel county road.
52.1	0.2	Turn right (west).
52.6	0.5	Turn left (south).
52.9	0.3	Cross Little Buffalo Creek. Then turn left, then right.
53.4	0.5	Turn right (west) at T intersection.
53.5	0.1	Turn left (south).
54.0	0.5	Turn right (west) at T intersection.
54.4	0.4	Turn left (south).
54.8	0.4	Cross Cedar Creek. An excellent, although highly deformed, outcrop of Stanley sandstone and shale is present immediately up the creek.
55.6	0.8	Fork in road. Left fork crosses Cedar Creek. Stop at fork.

STOP 11

EARLY AND MIDDLE PALEOZOIC STRATIGRAPHY IN POTATO HILLS AND POTATO HILLS JACKFORK PLAY

Galen W. Miller
Oklahoma Geological Survey

Kevin J. Smart
Southwest Research Institute
San Antonio, Texas

Location: Brinkley Springs Road, E½E½NW¼NE¼ sec. 31, T. 3 N., R. 20 E., Latimer County, Oklahoma

Introduction

This stop is one of the best exposures of the lower and middle Paleozoic strata in the Ouachita Mountains. The outcrop is on the southern limb of an overturned, north-vergent anticline that is bounded on the north by the Cedar Creek Thrust Fault. The Cedar Creek Fault juxtaposes the Ordovician Womble Shale in the hanging wall to the south against Mississippian Stanley Group shales and sandstones in the footwall to the north. The Womble Shale is not exposed along the road and is poorly exposed along the creek just east of the road. The Bigfork Chert conformably overlies the Womble Shale and is well exposed in the creek. The Upper Ordovician Polk Creek Shale conformably overlies the Bigfork and consists of a dark-gray shale with chert stringers. An unconformity separates the Polk Creek from the overlying Lower Silurian Missouri Mountain Shale. The Missouri Mountain Shale is a platy green shale that is typically mapped with the Polk Creek Shale. The Arkansas Novaculite is Early Silurian to Early Mississippian and consists mostly of chert that has a distinctive blue to green color.

Structural Setting

The Potato Hills are located in an antiformal valley (Kiamichi Valley) between the Buffalo Mountain Syncline to the north and the Lynn Mountain Syncline to the south. They consist of a series of low, well-rounded ridges, said to resemble a sack of potatoes from a distance (Miser, 1929). The hills form a roughly elliptical exposure of Ordovician through Mississippian shale and chert units. The Potato Hills are the only place in the central Ouachita Mountains of Oklahoma that exposes these units. Early and middle Paleozoic strata are exposed only in two other areas in the Oklahoma Ouachitas—Black Knob Ridge in the frontal belt of the Ouachita fold-and-thrust belt near Atoka, and the Broken Bow Uplift near Hochatown.

Stratigraphy

The stratigraphy in the Ouachita Mountains is generally divided into two distinct sedimentary sequences (Lowe, 1989; Morris, 1989; Viele, 1989). The older sequence is "pre-orogenic" and consists of Late Cambrian to Early Mississippian siliceous shales, cherts, and some sandstones (Viele, 1989). The sedimentation rate for these deep-basin deposits was very slow (average rates <13 ft per million years) (Niem, 1977; Lowe, 1989). This stop focuses on this pre-orogenic suite.

The younger (Early Mississippian to Pennsylvanian) "syn-orogenic" strata reflect dramatically higher sedimentation rates. The Mississippian Stanley Group was deposited at a rate of ~525 ft/m.y., the Jackfork Group ~500 ft/m.y., and the Atoka Formation ~3,000 ft/m.y. (Morris, 1989). These high sedimentation rates are interpreted to reflect the closing of the Ouachita trough.

Womble Shale

The Womble Shale (Middle to Late Ordovician) consists of black fissile shale interbedded with fine-grained sandstone. The shale contains abundant graptolites and grades into the Bigfork Chert above it. The Womble Shale is <1,000 ft thick in the Potato Hills and is exposed only in the cores of anticlines and in the hanging walls of thrust faults (Arbenz, 1989b; Miller, 2003).

Bigfork Chert

The Upper Ordovician Bigfork Chert, the primary ridge former in the Potato Hills, is a black bituminous chert with beds ranging from 1 to 18 in. thick and thin interbeds of black bituminous shale (Table 4). The lower part of the Bigfork is reported by Pitt and others (1982) to contain layers of gray crystalline limestone, but this author has yet to find any limestone in the Potato Hills. Limestone is pres-

Table 4. — Measured Sections near Stop 11

Arkansas Novaculite (from Miller, 1955)
Location: NE¼ sec. 31, T. 3 N., R. 20 E., along Cedar Creek, Latimer County, Oklahoma

	Thickness (ft)
Chert, black, thin-bedded, interbedded with green shale; partly covered	24.0
Chert, black, with some interbedded 2.5-ft black-shale beds that weather green	60.0
Probable contact of **Stanley Group** with **Arkansas Novaculite**, chert, black, subconchoidally fractured	18.0
Covered interval	30.0
Chert, black, thick-bedded	24.0
Covered interval	108.0
Chert, black, with striated weathering; interbedded with black shales that weather green, especially in upper half of section	126.0
Chert, black, brown, to dark-blue, with white beds in upper 5 ft; with 0.25- to 8-in. beds, averaging 1 in. thick	36.5
Chert, light-gray to black, with some pastel-green, blue, dark-blue, and brown beds 0.25 to 8 in. thick	16.5
Chert, black, with 0.5- to 7-in. beds, weathering mottled tan to brown; strongly folded and faulted locally	36.0
Chert, dark-blue to sky-blue, milky-white, black, translucent on edges, with subconchoidal fractures; in 0.5- to 18-in. beds, averaging 1 to 2 in. thick	33.0
Covered interval; mostly chert beds	53.0
Chert, black, interbedded with black, fissile, brittle shales, weathering mottled tan and black, green, and blue	29.8
Covered interval; contact with **Missouri Mountain Shale** is here	62.0
Total measured thickness of **Arkansas Novaculite**	657.1

Bigfork Chert (from Miller, 1955)
Location: NE¼ sec. 31, T. 3 N., R. 20 E., Latimer County, Oklahoma

	Thickness (ft)
Covered interval	90.0
Chert, black; in 0.5- to 2-in. beds	19.7
Chert, black, microgranular, massive, weathering into smooth, rounded surfaces	2.8
Chert, black; in 0.5- to 2-in. beds, fractured, with sawtooth appearance	15.2
Chert, black; in 2- to 6-in. beds, weathering black	17.5
Covered interval	8.6
Chert, black; in 2- to 6-in. beds, weathering in tan and black spots; faulted, contorted	17.2
Chert, black, finely laminated, alternating with slightly metamorphosed siliceous shale	4.5
Chert, black, with white siliceous bands parallel to bedding, with some quartz veinlets	9.5
Chert, black, thinly banded; with some milky quartz veinlets	3.9
Chert, black; in 0.5- to 10-in. beds, with conchoidal fractures	11.5
Total measured thickness of **Bigfork Chert**	200.4

ent, however, in the Bigfork Chert at Black Knob Ridge. The Bigfork is highly fractured, with vein-fill composed mostly of quartz; pyrite/chalcopyrite and grahamite locally fill some fractures. A weak cleavage is visible in the shale intervals between the chert beds. The chert produces small amounts of gas locally in the Potato Hills.

Missouri Mountain and Polk Creek Shales

The Missouri Mountain and Polk Creek Shales typically are mapped as one unit in the Potato Hills because they are so poorly exposed. The Missouri Mountain Shale is a red to gray platy shale. The shale is 150–150 ft thick and is unconformable on the Polk Creek Shale. The Polk Creek is a black to gray shale with thin chert beds. The Polk Creek is 110–170 ft thick in the Potato Hills.

Arkansas Novaculite

The Arkansas Novaculite is a low-ridge former in the Potato Hills. It typically is divided into three units. The upper part is a green to brown radiolarian chert and shale. The middle part is composed of green novaculite interbedded with olive to black shale. The lower part is composed primarily of massive white spiculitic chert and black and green laminated siliceous shale. The Arkansas Novaculite ranges in thickness from 230 to 950 ft. Fractured Arkansas Novaculite locally is a gas reservoir in the Potato Hills.

Stanley Group

The Stanley Group is the youngest unit exposed in the Potato Hills and is the oldest synorogenic deposit in the Ouachita fold-and-thrust belt (Lowe, 1989; Morris, 1989; Viele, 1989; Viele and Thomas, 1989). Locally, it is divided into three formations, from oldest to youngest: Tenmile Creek, Moyers, and Chickasaw Creek Formations. The Stanley is composed mostly of olive-green to brownish-green shales and fine-grained sandstone. The sandstones display numerous sedimentary features such as flute, load, and groove casts. Some of the Stanley Group sandstones in the Potato Hills exhibit soft-sediment deformation. Morris (1989) reports "local chert breccias" in the lower part of the Tenmile Creek Formation, but he did not specifiy localities. Two to four vitric-crystal volcaniclastic tuffs occur in the Stanley Group in the Benton–Broken Bow Uplift (Niem, 1977) (Stop 4), but no tuffs are present in the Potato Hills. The Stanley Group ranges from 6,000 to 12,000 ft in thickness (Morris, 1989).

Potato Hills and Development of the Ouachitas

The Potato Hills have provided geologists with much fuel for a variety of different structural interpretations (Miser, 1929; Bennison and Johnson, 1959; Arbenz, 1968, 1989b; Pitt and others, 1982; Allen, 1990, 1994; Miller, 2003). The most compelling interpretation of the structural origin of the Potato Hills is that they are a window through a single folded thrust fault—the Potato Hills Thrust (Fig. 78). This interpretation has implications for the relative timing of movement on the major Ouachita thrusts. If correct, the Potato Hills Thrust was emplaced prior to movement on the deeper (and more foreland-ward) Windingstair, Ti Valley, and Choctaw Thrusts. Movement on and subsequent folding of the Windingstair Fault would have folded the Potato Hills Thrust. The window interpretation also requires a break-forward style of thrusting as has been suggested by Çemen and others (2001a) for areas in the frontal belt of the Ouachitas and the Arkoma Basin.

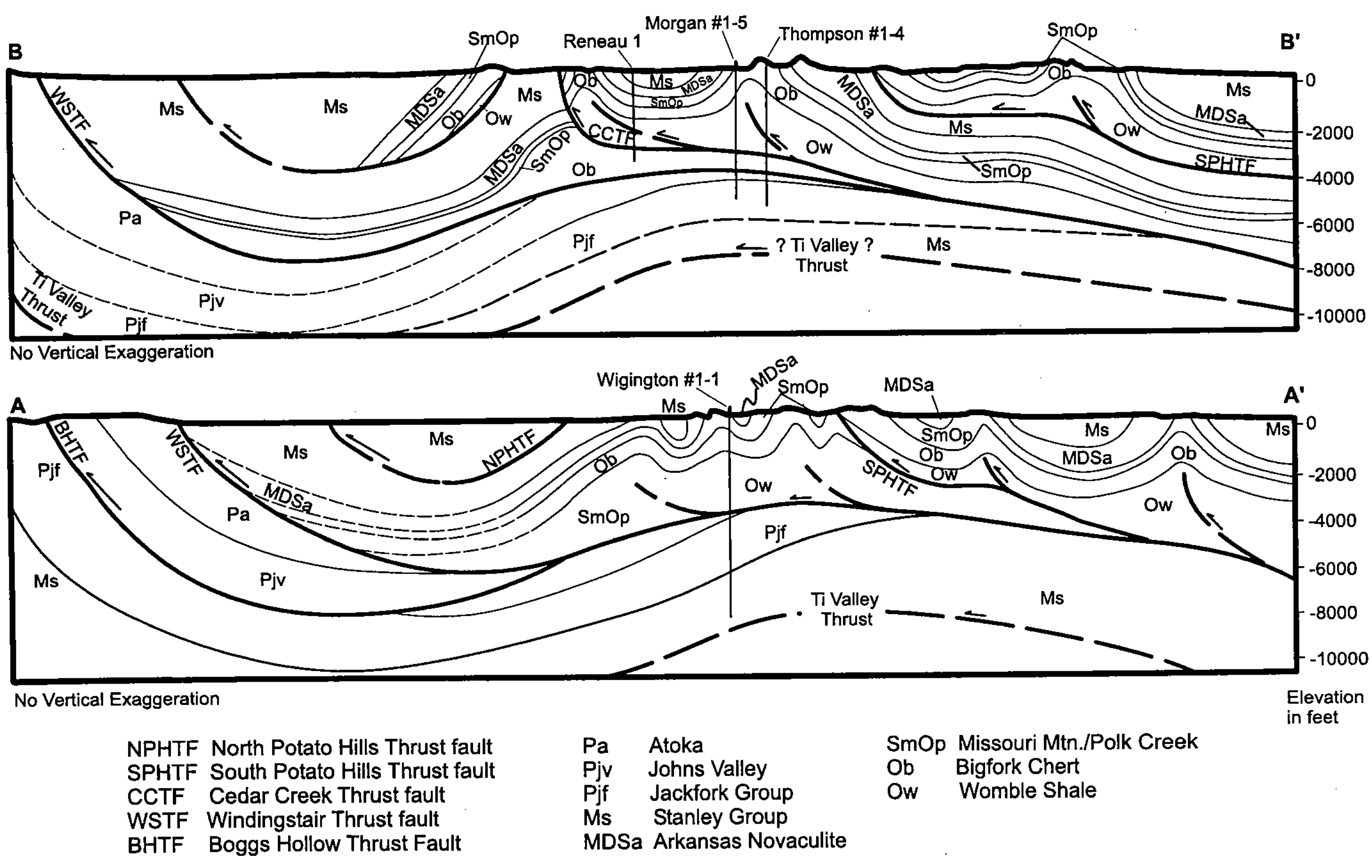


Figure 78. Cross sections through the Potato Hills (modified from Miller, 2003). Location of cross sections shown on Figure 81.

Table 5. — Wells in Potato Hills Gas Field by Spud Date

Operator, name, producing unit, total depth, spud date (data from NRIS as reported by operator to Oklahoma Corporation Commission on Form 1002A).

1. Sinclair Oil & Gas Co.; A. H. Reneau; Big Fork; 7,097 ft; 5/9/1959
2. Sinclair Oil & Gas Co.; H. H. Coussens; not reported; 2,500 ft; 10/7/1960
3. Sinclair Oil & Gas Co.; Helen Mattice; not reported; 3,000 ft; 2/14/1961
4. GHK Co.; 1-33 Ratcliff; Jackfork; 12,597 ft; 12/29/1996
5. GHK Co.; 1-34 Stevens; Jackfork; 6,115 ft; 6/5/1998
6. GHK Co.; 1-32 Bohanon; Jackfork; 6,974 ft; 7/24/1998
7. GHK Co.; 1-31 Alene; Jackfork; 6,955 ft; 9/25/1998
8. GHK Co.; 1-35 Minor; Jackfork; 5,410 ft; 11/9/1998
9. GHK Co.; 1-30 P J L; Jackfork; 7,235 ft; 5/24/1999
10. GHK Co.; 1-26 Round Prairie; Jackfork; 7,058 ft; 6/6/1999
11. GHK Co.; 1-25 Triple Tms; Jackfork; 8,905 ft; 6/18/1999
12. GHK Co.; 1-6 Guggenhime; Jackfork; 14,268 ft; 9/14/1999
13. GHK Co.; 1-4 Thompson; Jackfork; 4,918 ft; 10/4/1999
14. GHK Co.; 1-5 Morgan; Jackfork; 4,736 ft; 12/18/1999
15. Gothic Production Co.; 27-1 Cloud; Jackfork; 7,000 ft; 12/21/1999
16. GHK Co.; 2-32 Allen; Jackfork; 5,672 ft; 1/21/2000
17. GHK Co.; 1-1 Wigington; Jackfork; 8,000 ft; 1/21/2000
18. GHK Co.; 1-3 Emrw; Jackfork; 5,560 ft; 3/2/2000
19. GHK Co.; 1-2 Koopman; Jackfork; 7,220 ft; 4/2/2000
20. GHK Co.; 2-35 Hicks; Jackfork; 7,516 ft; 4/15/2000
21. GHK Co.; 2-6 London; Jackfork; 5,981 ft; 6/16/2000
22. GHK Co.; 1-3 Pettit; Arkansas Nov.; 7,546 ft; 6/20/2000
23. GHK Co.; 3-35 Jack; Jackfork; 9,824 ft; 8/6/2000
24. GHK Co.; 1-7 Four Star; Jackfork; 21,143 ft; 9/1/2000
25. GHK Co.; 2-33 Mary Ratcliff; Jackfork; 6,903 ft; 10/22/2000
26. GHK Co.; 3-33 Cedar Creek; Jackfork; 5,824 ft; 1/4/2001
27. KCS Medallion Resources Inc.; 1-26 Tami; Jackfork; 5,800 ft; 1/11/2001
28. GHK Co.; 1-12 Edmonds; Jackfork; 6,625 ft; 1/11/2001
29. GHK Co.; 1-11 Hester-Clell; Jackfork; 5,569 ft; 3/2/2001
30. GHK Co.; 1-8 Reed; Jackfork; 6,715 ft; 1/27/2001
31. GHK Co.; 1-9 Keyse; Jackfork; 7,247 ft; 3/12/2001
32. GHK Co.; 4-33 Don Stevens; Bigfork; 13,350 ft; 4/20/2001
33. GHK Co.; 1-10 Karr; Jackfork; 7,244 ft; 4/28/2001
34. GHK Co.; 2-12 Edmonds; Jackfork; 7,550 ft; 5/9/2001
35. GLB Expl. Inc.; Brown; Jackfork; 7,482 ft; 5/24/2001
36. GHK Co.; 1-2 Cannady; not reported; 7,685 ft; 6/21/2001
37. GHK Co.; 1-9 Gee; Bigfork; 8,676 ft; 7/5/2001

Speculation on the origin of the deeper structures in the Potato Hills area for the folding of the Potato Hills and deeper thrust sheets continues. Interpretation of a recently acquired, low-altitude, high-resolution aeromagnetic survey provided by the GHK Companies suggests that variations in rifted basement topography may be related to the Potato Hills structure. The aeromagnetic data suggest that a north–northeast-trending lineament cuts across the Potato Hills in the area where geologic mapping demonstrates that a detachment fault ramps up from the Womble Shale to the Stanley Group. Thus, deeper structures may be folded in response to this irregular basement configuration.

Potato Hills Gas Field

The Potato Hills gas field was named in 1960 after the Sinclair No. 1 Reneau well (SE¼SE¼NW¼ sec. 32, T. 3 N., R. 20 E.) was completed. The well spudded on May 9, 1959 (Table 5), reached a total depth of 7,097 ft on February 9, 1960, and had an open-flow potential of 1.8 MMcf gas per day from the Bigfork Chert at 2,340–2,410 ft. The well may produce from the lower overturned limb of an anticline or a thrust-repeated Bigfork section. A few more wells were drilled in the 1960s, producing a few thousand Mcf of gas per month. This gas was used locally in Clayton and Albion.

In the late 1990s, GHK LLC "rediscovered" the Potato Hills, and the area suddenly was the hottest play in Oklahoma (Fig. 79). Gas production peaked in July 2000, when almost 4 Bcf of gas was produced (Fig. 80). Approximately 35 wells are active in the Potato Hills gas field (Table 5); most wells were drilled along the trend (N. 85° E.) of the subsurface antiformal trap created by the movement of the Ti Valley and/or Choctaw Fault (Figs. 78, 81). As of July 2004, the Potato Hills field had produced ~140 Bcf gas (data courtesy IHS Energy).

		Return to S.H. 1/63.
60.3	4.7	Turn left (west) on S.H. 1/63.
60.9	0.6	Buffalo Valley School on right (north). Buildings are faced with beautiful pieces of turbidite sandstones from the Atoka Formation, showing a wide variety of sole marks including scours and trace fossils. The 1989 field trip stopped here for lunch (stop 2).
61.2	0.3	Leave Kiamichi 7.5′ quadrangle; enter Yanush 7.5′ quadrangle.
62.9	1.7	Intersection with State Highway 2. Turn right (north) on S.H. 1/2/63 (north) toward Wilburton. S.H. 2 to the south goes to Clayton.

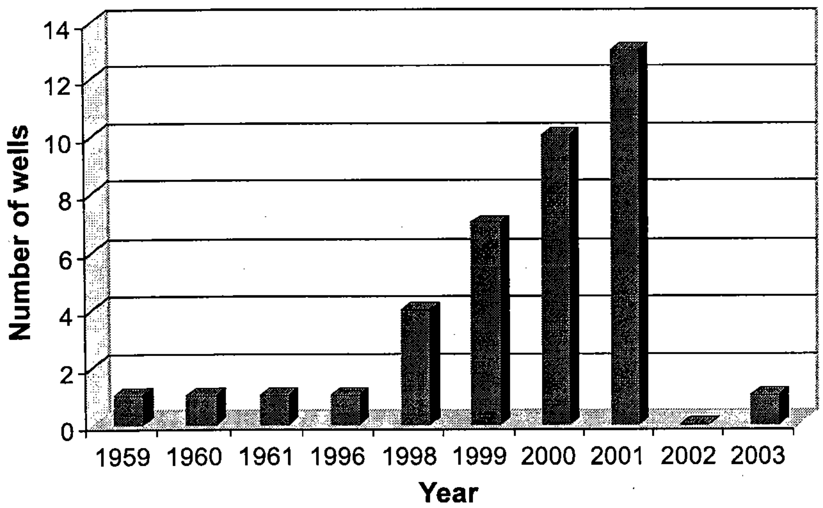


Figure 79. Graph showing drilling activity in the Potato Hills from 1996 to 2003.

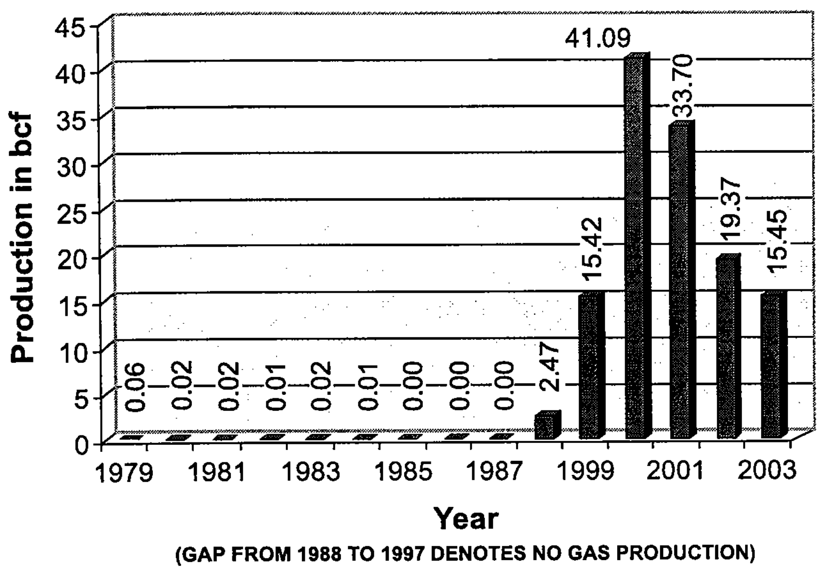


Figure 80. Graph showing natural-gas production from the Potato Hills field from 1979 to the present. Production shown in thousands of cubic feet.

63.5 0.6 Cross trace of Windingstair Fault. Here, the fault juxtaposes the Stanley Group in the hanging wall to the south against the Atoka Formation in the footwall to the north.

64.5 1.0 Leave Yanush 7.5′ quadrangle; enter Damon 7.5′ quadrangle. The remainder of the field trip passes through quadrangles mapped in detail as part of the OGS's COGEOMAP and STATEMAP programs.

65.3 0.8 S.H. 1/2/63 turns left (west). The westernmost well in the Buffalo Mountain gas field (Chesapeake No. 1-6 Reeves) is ~2 mi east of here. The field extends from that well ~6 mi to the east–northeast.

Buffalo Mountain Gas Field

The Buffalo Mountain gas field is mostly in the southern part of T. 4 N., R. 20 E., and the northern part of T. 3 N., R. 20 E. (Boyd, 2002) (Fig. 82). The discovery well for the field is the H&H Star Energy No. 1-4 Hope (Table 6), drilled in the SE¼NW¼SE¼ sec. 4, T. 3 N., R. 20 E. The well spudded on September 11, 1991, reached a total depth of 21,906 ft on March 19, 1992, and was completed on December 14, 1992, in the Spiro sandstone at 18,742–18,818 ft for 5,676 Mcf gas per day.

At present, 16 gas wells in the field are producing from a number of formations (Fig. 82). As reported to the Oklahoma Corporation Commission, two wells produce from the Atoka Formation; one from the upper Atoka; two from the upper, middle, and lower Atoka (commingled); one from the Spiro sandstone; one from the Johns Valley Formation; one from the Jackfork Group; one from the lower Jackfork; five from the upper and lower Jackfork (commingled); and one from the Stanley Group and upper Jackfork (commingled). Some of the "Atoka" wells probably are, in fact, Jackfork wells. The log from the Ward No. 2-34 Green Bay (Fig. 83) shows the typical character of the Jackfork in the field. The highly irregular and relatively thin sandstones probably are sheet sandstones, whereas the thicker, blockier sandstones may be channel sandstones. Both typically show significant neutron-porosity–density-porosity crossover. The Jackfork reservoir in this field appears to be similar to that in the Talihina Northwest field immediately to the east.

As of July 2004, the field had produced ~12 Bcf gas (data courtesy IHS Energy).

The structure of the Buffalo Mountain field is complex. Two published cross sections just west of the field (Cunningham and Namson, 1994) and across the east end of the field (Montgomery, 1996) show as many as two blind duplexes in the hanging wall of the Ti Valley Fault; these are concealed by thrust-cored anticlines and adjacent synclines that are mappable on the surface. It appears that Jackfork reservoirs may be present in the shallow structures as well as in the duplexes, but the details of the field's structural geology have not been published.

Two wells drilled in the field are key for interpreting certain aspects of the structural geology of the Ouachita Mountains frontal belt. The Texaco No. 26-1 Champagne Heirs was drilled in the SE¼SE¼NW¼ sec. 26, T. 4 N., R. 20 E. If records filed with the Oklahoma Corporation Commission are correct, the well penetrated the top of the Stanley Group at 9,550 ft drilled depth. The well is a straight hole, and the surface location is ~1.5 mi north of

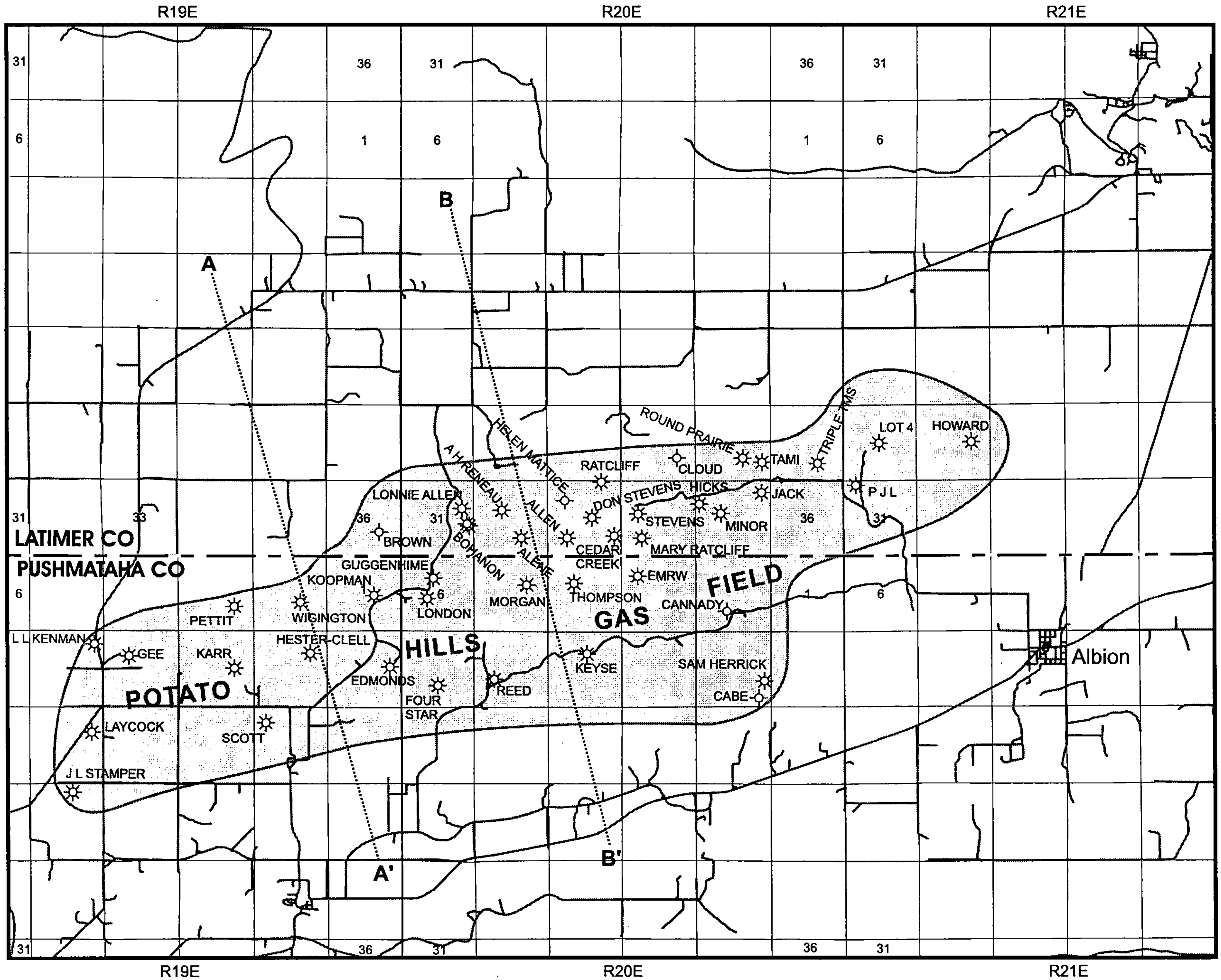


Figure 81. Map showing locations of wells in the Potato Hills gas field. Cross sections shown on Figure 78.

Table 6. — Producing Wells in the Buffalo Mountain Gas Field by Spud Date

Operator, number, farm, spud date, total depth, producing formation, depth of producing formation (data from NRIS as reported by operator to Oklahoma Corporation Commission on Form 1002A).

1. H&H Star Energy 1-4 Hope; 9/11/91; 21,906 ft; Spiro; 18,742–18,818 ft
2. H&H Star Energy 1-36 Middle Mountain; 3/18/92; 6,951 ft; Atoka; 6,565–6,580 ft
3. H&H Star Energy 1-34 Green Bay; 4/2/92; 2,703 ft.; dry; recompleted by Ward Petroleum on 6/24/92; Johns Valley; 2,335–2,476 ft
4. H&H Star Energy 1-35 Buffalo Creek; 4/3/92; 6,500 ft; Atoka; 5,856–6,154 ft
5. Ward Petroleum 2-34 Green Bay; 4/9/95; 8,500 ft; Upper Atoka; 4,327–4,725 ft; Middle Atoka; 5,750–7,678 ft; Lower Atoka; 7,875–7,964 ft
6. Chesapeake Operating 1-25 Brandt; 7/14/95; 10,050 ft; Upper Jackfork; 2,590–4,200 ft; Lower Jackfork; 4,436–9,370 ft
7. Chesapeake Operating 1-35 Henry; 8/18/95; 8,942 ft; Upper Jackfork; 4,716–5,508 ft; Lower Jackfork; 5,858–8,660 ft
8. Chesapeake Operating 1-33 Princess; 10/9/95; 8,020 ft; Upper Jackfork; 3,354–4,582 ft; Lower Jackfork; 4,750–7,564 ft
9. Ward Petroleum 2 Middle Mountain; 11/5/95; 9,524 ft; Lower Atoka; 4,902–4,980 ft; Middle Atoka; 6,225–6,692 ft; Lower Atoka; 8,518–9,448 ft
10. Amoco Production–GHK 1 Pettit; 11/26/95; 14,575 ft; Stanley; 3,144–3,185 ft; Upper Jackfork; 5,718–14,064 ft
11. Chesapeake Operating 1-6 Reeves; 4/12/96; 9,050 ft; Lower Jackfork; 5,968–8,854 ft
12. Texaco E & P 26-1 Champagne Heirs; 4/20/96; 9,869 ft; Upper Jackfork; 5,510–8,119 ft; Lower Jackfork; 9,055–9,105 ft
13. JB Drilling 2-4A Hope; 8/12/96; 2,900 ft; Atoka Upper; 1,371–1,898 ft
14. Texaco E & P 32-1 Young; 9/16/96; 8,020 ft; Jackfork; 5,000–7,404 ft
15. Chesapeake Operating 2-33 Princess; 12/15/96; 5,300 ft; Upper Jackfork; 3,044–4,582 ft
16. Chesapeake Operating 3-33 Princess; 8/16/03; 6,200 ft; Upper Jackfork; 4,090–6,114 ft

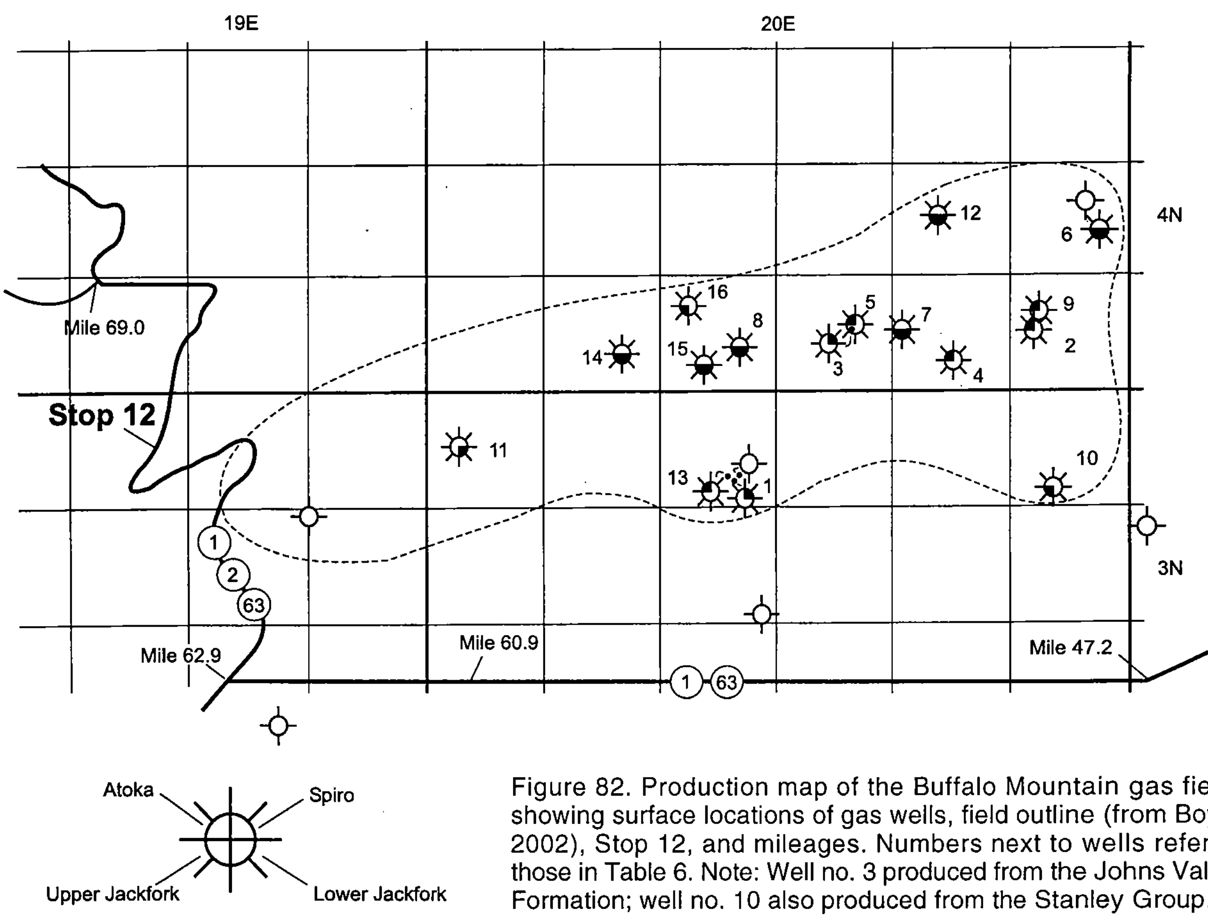


Figure 82. Production map of the Buffalo Mountain gas field, showing surface locations of gas wells, field outline (from Boyd, 2002), Stop 12, and mileages. Numbers next to wells refer to those in Table 6. Note: Well no. 3 produced from the Johns Valley Formation; well no. 10 also produced from the Stanley Group.

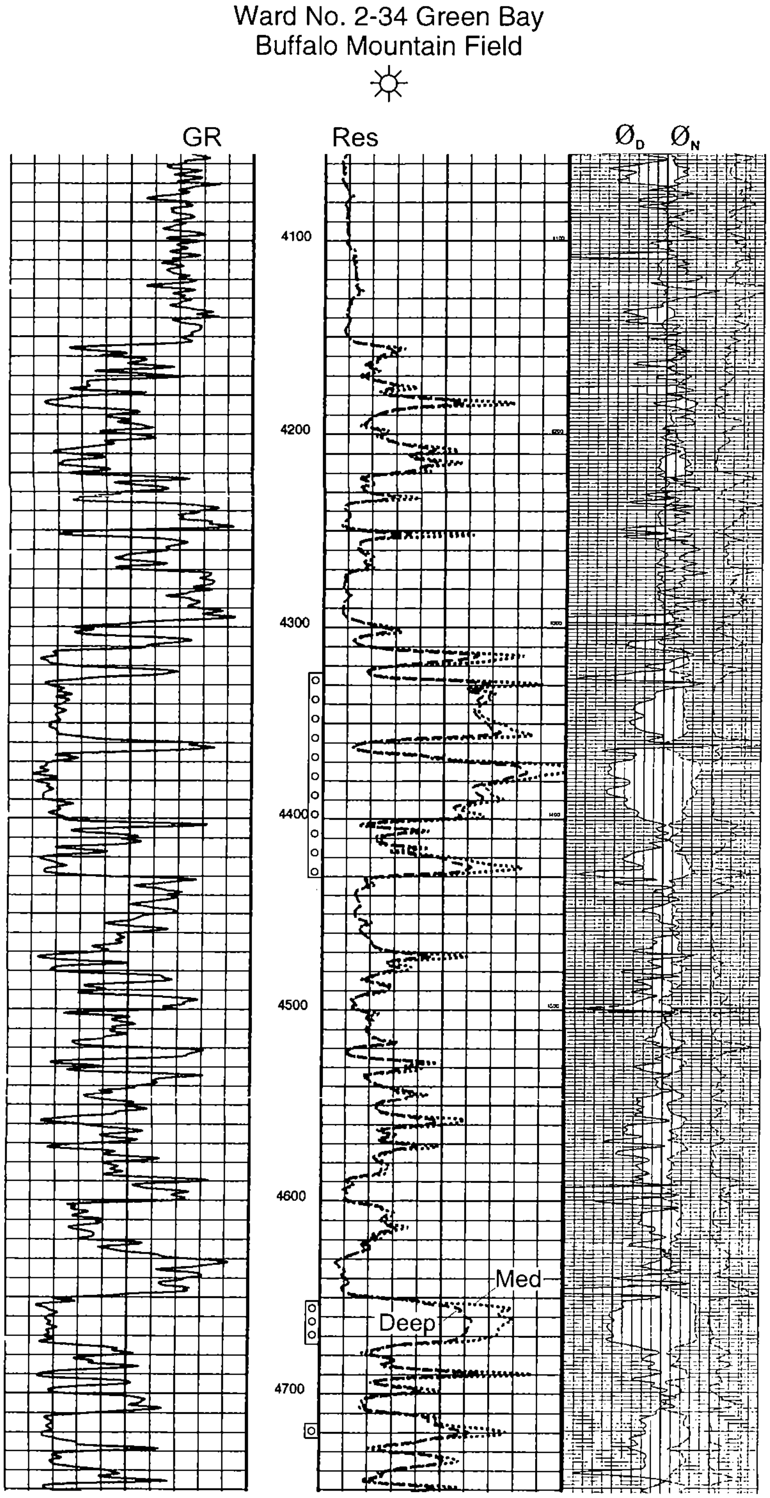


Figure 83. Part of log from the Ward No. 2-34 Green Bay (well no. 5 in Fig. 82), showing characteristic gamma-ray, resistivity, and density- and neutron-porosity log patterns of Jackfork Group sandstones in the Buffalo Mountain gas field. (Note: The well is shown by the Oklahoma Corporation Commission as an Atoka producer.) The 30–40-ft-thick blocky sandstones with abrupt bases and abrupt to fining-upward tops are characteristic of channel sandstones in the Jackfork. Other deeper intervals were also perforated and found to contain gas.

the trace of the Windingstair Fault. On the surface, the Stanley is restricted to an area south of the fault trace; this observation has been used as evidence that the Windingstair Fault has a significant amount of displacement. If, in fact, the Stanley occurs in the subsurface north of the trace of the fault, the fault may not have as much displacement as some geologists believe. Montgomery (1996, fig. 4.4) also shows the Stanley in the subsurface north of the Windingstair Fault in the hanging wall of the Ti Valley Fault.

A second important well is the discovery well of the field, the H&H Star Energy No. 1-4 Hope. This well appears to have drilled an autochthonous (unthrusted) section below about 18,736 ft drilled depth. The section is a typical Arkoma Basin section and includes, from top to bottom, the Spiro, Union Valley, Caney, Woodford, Hunton, Sylvan, Viola, McLish, and upper Oil Creek (top at 21,571 ft). Most likely this section represents the "floor" of the Ouachita thrust system at this location. Two questions alluded to briefly in the description of the Talihina oil field (mile 43.3) can be raised again here. How far to the south beneath the thrust sheets do units such as the Caney and Woodford Shales extend, and what are the implications for hydrocarbon generation and unconventional shale-gas exploration?

66.0 0.7 Sandstones in upper part of Jackfork Group on left (south).

66.2 0.2 Hairpin curve. The upper part of the Jackfork Group, the Johns Valley Formation, and the lower part of the Atoka Formation are exposed here. Just above the curve there is a wide shoulder on the right (east) side of the road. Pull off on shoulder. Outcrop is on the north side of the highway; please be careful crossing the road.

This locality probably has been visited by every geologist who has ever worked in the Ouachita Mountains and by most geologists who have ever taken a field trip in the Ouachitas. The most recent published description of this locality is by Suneson and others (1990), who also list the other field trips that have stopped here and some of the research that focused on this outcrop. Most field trips have concentrated on the Johns Valley Formation, exposed at and just above the hairpin curve (Fig. 84). Over the years the quality of the outcrop has degraded, and few depositional fabrics can be seen. In contrast to previous field trips, we will concentrate on the lower part of the Atoka Formation exposed here.

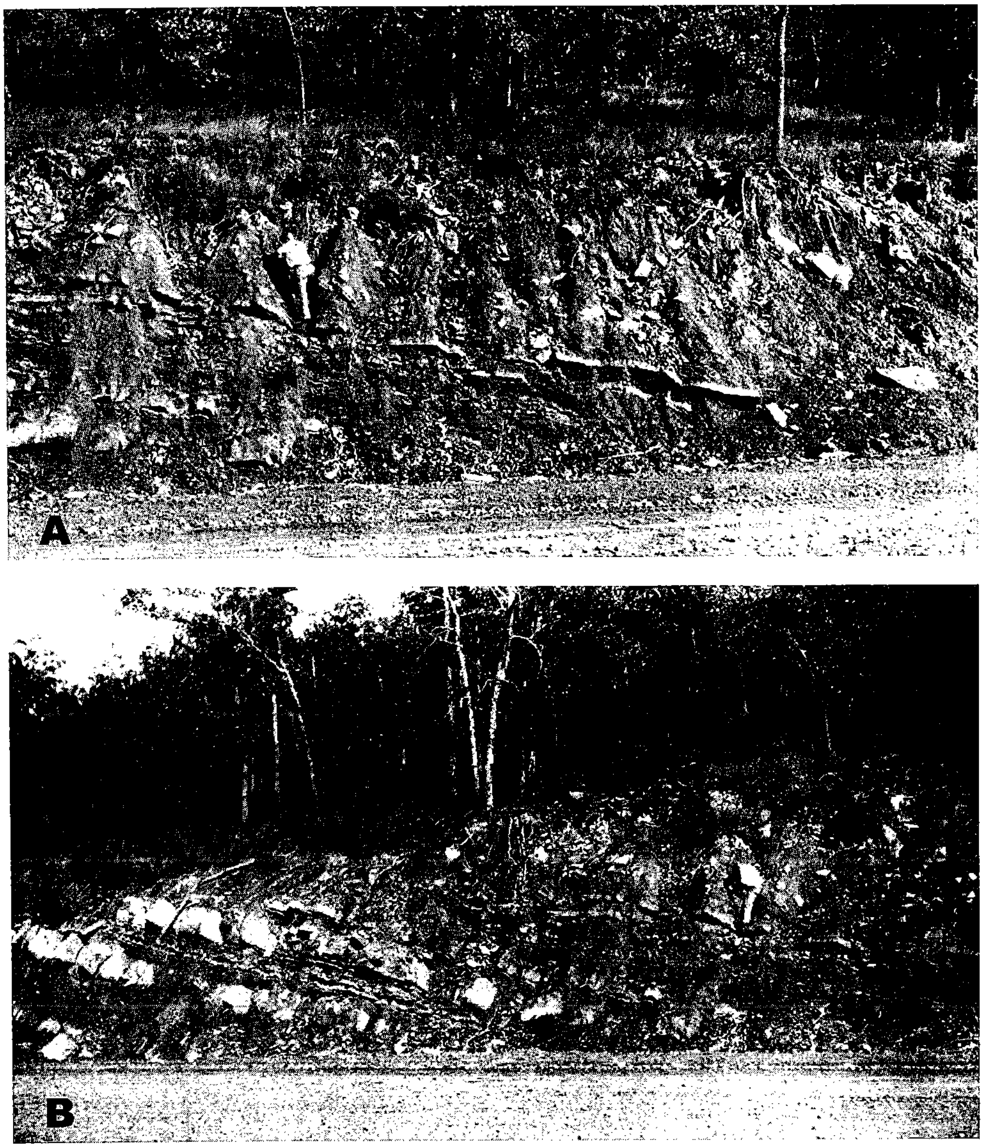


Figure 84. Photographs of the Johns Valley Formation at the hairpin curve, taken by T. A. Hendricks (USGS) shortly after the highway was constructed. (A) "Boulder beds in Johns Valley shale. . . ." (B) "Evenly bedded sandstone and shale, and boulder-bearing shale in the Johns Valley shale. . . ." (From Hendricks, 1947, figs. 8, 9.)

STOP 12

DEEP-WATER ATOKA AND "SPIRO EQUIVALENT," HAIRPIN CURVE LOCALITY

Dennis R. Kerr
University of Tulsa

Location: west side of S.H. 1/2/63 north of hairpin curve, SW¼SE¼NE¼ and NE¼NW¼SE¼ sec. 3, T. 3 N., R. 19 E., Latimer County, Oklahoma

This locality has been a popular field-trip stop for many decades (see review by Suneson, 1988b). Highway construction in the 1940s removed the soil and slope debris that typically cover the Johns Valley Formation (Fig. 84). The quality of the exposure has deteriorated to the point where only a resistant sandstone interval and exotic boulders as float are evidence for the existence of John Valley outcrops. However, the Atoka Formation is still relatively well exposed here, although the shale-rich intervals typically are covered.

Suneson and Ferguson (1989b) mapped the location of Stop 12 on the south limb of the Anderson Creek Syncline. Bedding in the Atoka generally strikes S. 75° W. and dips ~70° NW., with some beds being overturned. Haveman (2003) measured a 1,063-ft-thick detailed section, starting in the Johns Valley and continuing north to the highest Atoka beds found on the south limb of the syncline. He also measured several other sections along S.H. 2 north toward the Veterans Colony. Harris (2001) collected a spectral gamma-ray profile through the Atoka here and also at the exposure of the same section on the north limb of the Anderson Creek Syncline (mile 68.2).

The lithostratigraphic base of the Atoka Formation (first resistant quartz-arenite sandstone) is 196 ft above the base of Haveman's (2003) section. The section is made up of interstratified 1-ft-thick sandstones with mostly incomplete Bouma successions and 3- to 10-ft-thick dark-gray clay-shale interbeds (lithofacies H). Sandstones are dominated by half-ft-thick T_a-based turbidites with T_a, $T_{a,e}$, $T_{a,c}$, and $T_{a,c,e}$ being the most common. These turbidites are crudely organized into upward-thickening sandstone beds and upward-increasing sand/mud-ratio successions 100 to 130 ft thick. A prominent 15-ft-thick sandstone 61 ft above the base of the Atoka Formation (Haveman's bed no. 30) is made up of amalgamated T_a sandstones, each of which is 3–10 ft thick and has scoured basal contacts. This interval also contains scattered skeletal molds as part of the framework constituents. Near the top of the interval a 1-ft-thick bituminous, skeletal-moldic sandstone represents the "Spiro equivalent" (Figs. 72, 85).

The deep-water lower Atoka section at this locality contrasts in a number of important respects with the exposures seen along S.H. 82 ~14 mi to the east (Stops 9 and 10). The incomplete Bouma successions here contain more of the finer grained, more dilute fraction of turbidity currents (T_e). Hemipelagic deposits (lithofacies H) are thicker and make up more of the section here. Biogenic structures as sole markings on sandstone beds are much more abundant here than at Stops 9 and 10. Finally, the "Spiro equivalent" here occurs within a succession of sandstone beds containing dispersed fossil molds; at S.H. 82 it is a discrete bed.

Haveman (2003) interpreted this section, as well as the exposure on the north limb of the syncline, as mud-rich submarine-fan lobes, with the amalgamated T_a lithofacies representing a proximal-lobe deposit. Paleocurrent measurements, integrated with lithofacies, define four lobe deposits in the lower Atoka at this site; a fifth lobe deposit is present at the top of the exposure on the north limb of the syncline. The first (oldest) lobe indicates southwest sediment transport, the second west transport, the third and fourth west–southwest transport, and the fifth west–northwest transport. Typically the standard deviation about the mean azimuth of paleocurrent measurements within each lobe succession is <10°.

Continue north on S.H. 1/2/63. For the next ~0.75 mi the strata face north and dip steeply north (upright) or south (overturned) on the south flank of the Anderson Creek Syncline.

67.0	0.8	Cross axis of Anderson Creek Syncline. For the next mile the sandstones in the Atoka Formation face south and dip about 45° SSE. on the north flank of the syncline.
68.2	1.2	Thick sandstone outcrops on left (south) are basal Atoka Formation. Dispersed sparse fossil molds are present in some of the sandstone beds. The "Spiro equivalent" occurs 98 ft above the base of the Atoka (Fig. 72).
68.3	0.1	A large (several hundred feet by several hundred feet) olistolith of Woodford Shale is present in the Johns Valley Formation immediately south of the highway (Fig. 86). The outcrop is similar to the Caney Shale, but the presence of phosphate nodules is evidence that it is Woodford.
69.0	0.7	Intersection with S.H. 2 straight (north) to Wilburton and S.H. 1/63 left (west) to Hartshorne. Turn left (west).

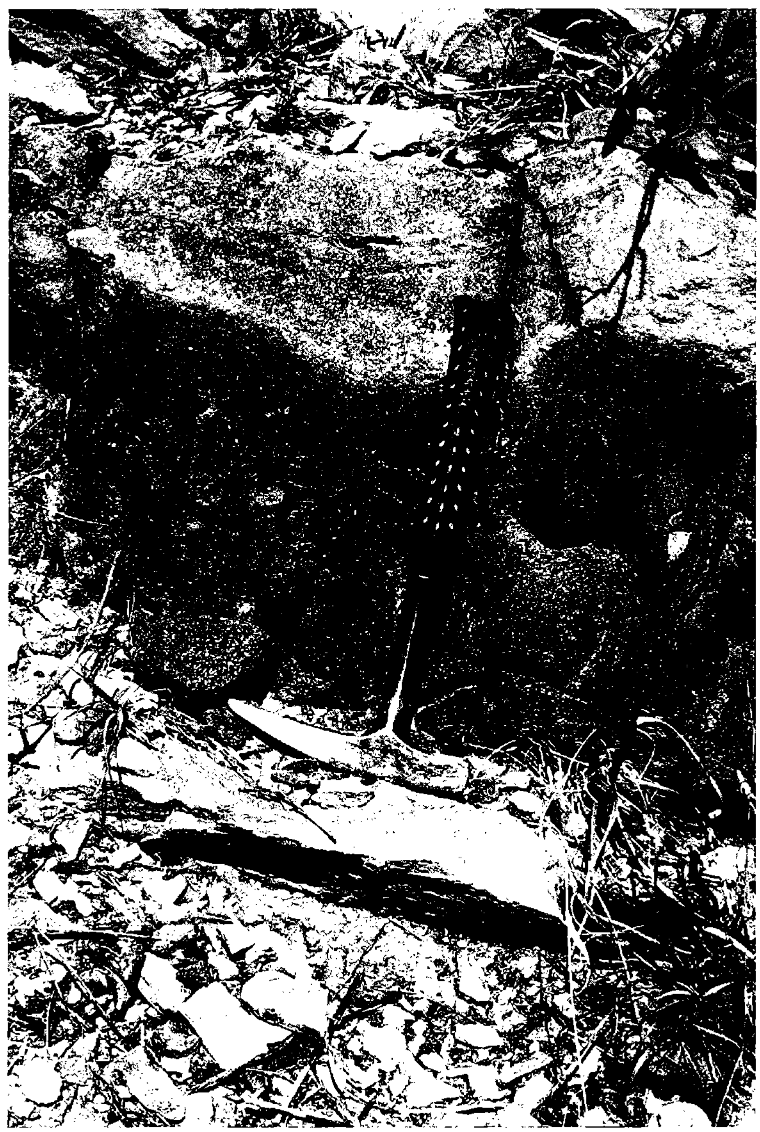


Figure 85. "Spiro equivalent" sandstone exposed in the hairpin-curve section. It is a bituminous skeletal-moldic sandstone similar to the Spiro sandstone exposed along S.H. 82 between the Choctaw and "Ti Valley" Faults at Stop 8.

Figure 86. Outcrop of large olistolith of Woodford Shale (Devonian) in Johns Valley Formation.

Bowsher and Johnson (1968, p. 50) report that "Spiro sand" is present 0.05 mi north of the highway intersection. Suneson and Ferguson (1989b) mapped a thrust fault through the intersection, juxtaposing Johns Valley Formation in the hanging wall to the south against Atoka Formation in the footwall to the north. It is possible that the trace of the fault, in fact, is north of the "Spiro" outcrop and that the "Spiro" or "Spiro equivalent" is within the Johns Valley, as at mile 36.5.

69.7	0.7	Cross trace of thrust fault that juxtaposes Johns Valley Formation to the south against Atoka Formation to the north.
72.0	2.3	Cross trace of "Ti Valley Fault."
72.3	0.3	Cross Pine Creek.
72.9	0.6	Enter Veterans Colony West gas field. Most of this gas field is north of S.H. 1/63.

Veterans Colony West Gas Field

The Veterans Colony West gas field covers ~7 mi^2, mostly in the west part of T. 4 N., R. 19 E. (Boyd, 2002) (Fig. 87). The discovery well for the field is the BTA No. 1 9001 JV-P Amason (NW¼SE¼NE¼SW¼ sec. 24, T. 4 N., R. 18 E.) (Table 7), which spudded on April 6, 1990, reached a total depth of 14,090 ft on August 16, 1990, and was completed in the Spiro sandstone at 13,649–13,696 ft for 12,118 Mcf gas per day.

At the present time there are 11 active wells in the field; one produces from the Atoka Formation, nine produce from the Spiro sandstone, and one is commingled Atoka and Spiro production. The log from the BTA No. 2-24 9001 JV-P Amason well (Fig. 88) shows the principal reservoir formation (Spiro sandstone) in the field. There is significant neutron-porosity–density-porosity crossover. The shale break at ~13,850 ft probably correlates with the sub-Spiro shale (see Stops 8, 14A, and 14B) and is underlain by the Wapanucka Limestone.

The structural geology of the field at the Spiro reservoir level consists of several blind anticlines overlying blind thrusts in the footwall of the Choctaw Fault (Çemen and others, 2001a, fig. 9). The thrusts are splays off a detachment in the Woodford Shale.

As of July 2004, the field had produced ~20 Bcf gas (data courtesy IHS Energy).

74.1	1.2	Leave Damon 7.5′ quadrangle; enter Higgins 7.5′ quadrangle. Leave Veterans Colony West gas field. For the next several miles, S.H. 1/63 crosses turbidites in the Atoka Formation.
77.1	3.0	Cross Gaines Creek.

About 1.75 mi to the south, Suneson and Ferguson (1989a) mapped a 1,000-ft by 800-ft block of chert in what had been mapped previously as the Atoka Formation. This outcrop and other nearby outcrops (e.g., Stop 13) that are similar to the Johns Valley Formation, but are 1 to

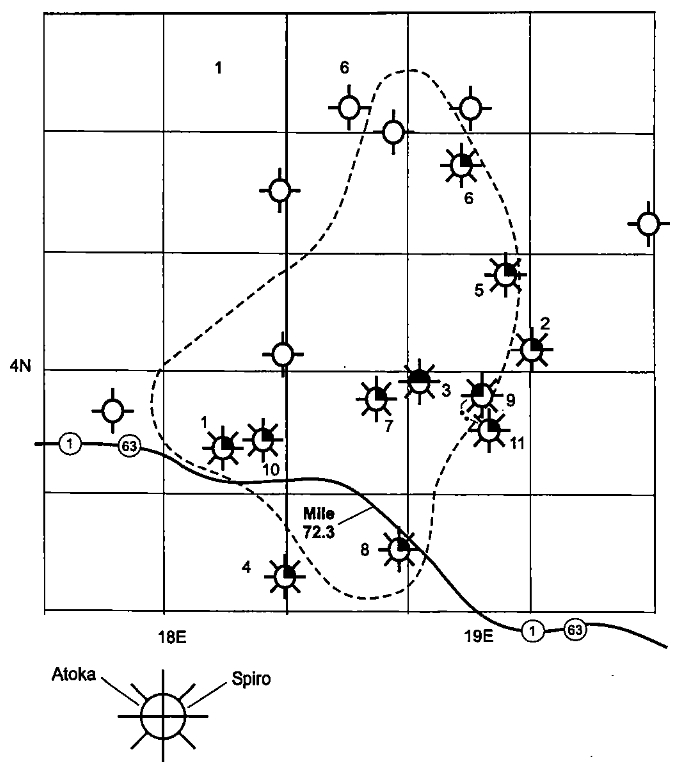


Figure 87. Production map of the Veterans Colony West gas field, showing surface locations of gas wells, field outline (from Boyd, 2002), and nearby field-trip mileage. Numbers next to wells refer to those in Table 7.

Table 7. — Producing Wells in the Veterans Colony West Gas Field by Spud Date

Operator, number, farm, spud date, total depth, producing formation, depth of producing formation (data from NRIS as reported by operator to Oklahoma Corporation Commission on Form 1002A).

1. BTA Oil Producers 1 9001 JV-P Amason; 4/6/90; 14,090 ft; Spiro; 13,649–13,696 ft
2. Arco Oil & Gas 1-17 James; 1/4/91; 15,000 ft; Spiro; 14,597–14,644 ft
3. Anadarko Petroleum 1-25 Robe A; 1/17/92; 15,550 ft; Spiro; 15,163–15,174 ft
4. H&H Star Energy 1-18 Swindle A; deepened on 6/2/92; 12,376 ft; Spiro Overthrust; 12,122–12,204 ft; Recompleted by Ward Petroleum as 1-17 Swindle on 9/27/96; 13,100 ft; Atoka; 7,017–7,041 ft
5. Texaco E & P 8-1 Johnson; 8/20/95; 15,954 ft; Spiro; 15,732–15,747 ft
6. Texaco E & P 5-1 Nation; 3/6/96; 14,640 ft; Sub Thrusted Basal Atoka (Spiro); 14,394–14,426 ft
7. Vastar Resources 1-19 Gambler Deep; 8/4/99; 13,902 ft; Spiro; 13,627–13,687 ft
8. Vastar Resources 1-30 Pine Creek; 10/26/00; 15,708 ft; Spiro; 15,488–15,558 ft
9. Vastar Resources 1-20 Big Prize; 3/15/01; 14,700 ft; Atoka Middle Overthrust; 9,006–9,230 ft; Spiro; 14,392–14,438 ft
10. BTA Oil Producers 2-24 9001 JV-P Amason; 7/6/01; 14,030 ft; Spiro; 13,778–13,829 ft
11. BP America Production 2-20 Big Prize; 1/30/02; 15,425 ft; Spiro; 15,209–15,244 ft

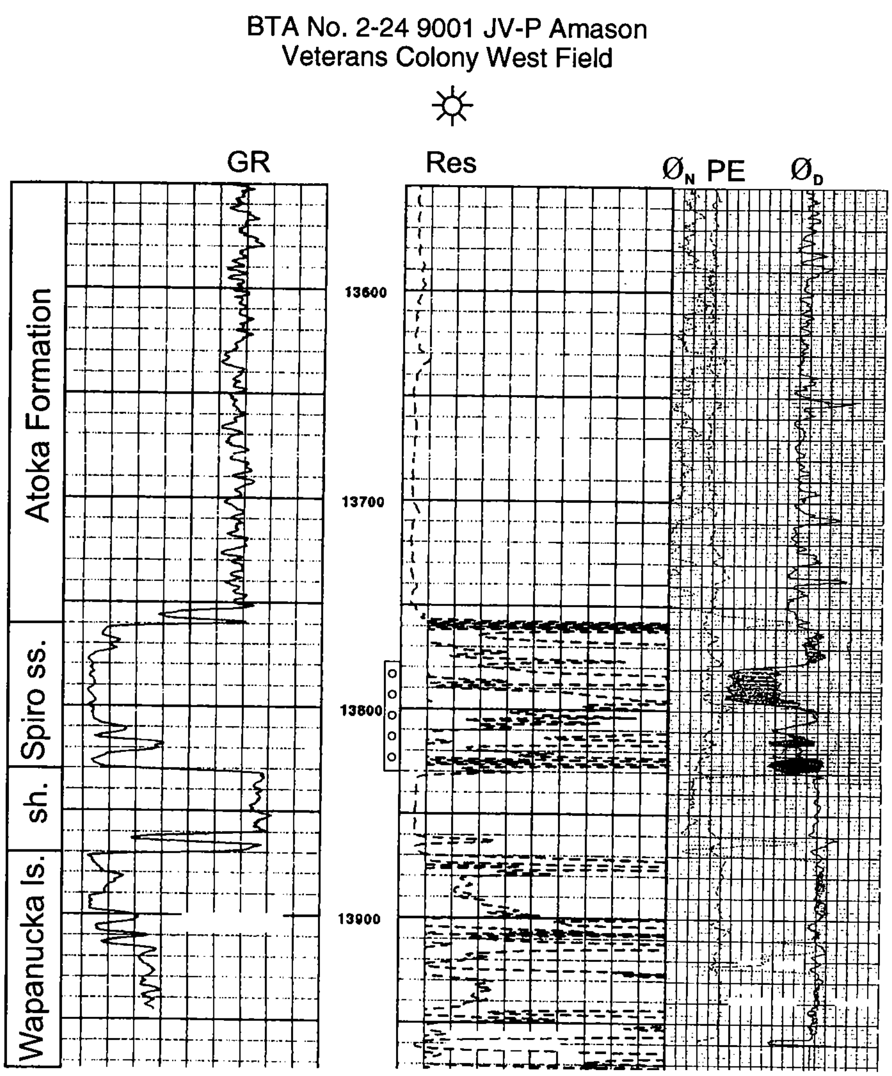


Figure 88. Part of log from BTA No. 2-24 9001 JV-P Amason (well no. 10 in Fig. 87), showing log character of the Spiro sandstone. The Spiro sandstone (13,760–13,830 ft) is similar to the Wapanucka Limestone (top at 13,870 ft) on the gamma-ray log but is distinguished from it on the photoelectric (PE) curve. The "sub-Spiro" shale (labeled *sh.*) is ~40 ft thick.

2 mi north of the mapped "Ti Valley Fault," prompted Suneson (1988a) to suggest that identifying named faults throughout the Ouachita Mountains frontal belt is misleading at best. In addition, these outcrops of the Johns Valley Formation north of the mapped "Ti Valley Fault" were used as evidence that the fault does not have the largest displacement in the Ouachita Mountains, as is commonly but erroneously assumed.

77.5 0.4 Small "village" of Higgins, Oklahoma. County road to right (north). Continue straight on S.H. 1/63.

Mountain Station

About 2 mi to the north on the county road is the Mountain Station cemetery. The cemetery is the site of the old community of Mountain Station, through which the Butterfield Overland Stage Line passed (Fox, 1961).

Gunning (undated, p. 26) reports as follows:

"Mountain Station at the time had a few houses along the hillsides and just after the Civil War the settlement grew to an estimated population of 1,500. A post office was established there in 1873 and a Martha Edwards was appointed postmistress. Also in 1869, Captain William Baird established a store or trading post just southwest of Mountain Station perhaps 200 yards, brought his family from Arkansas, built a large log home and operated the store on this site until he moved to Wilburton when the railroad came through. He was appointed Wilburton's first postmaster.

"Mountain Station was not a Butterfield station, but it did become an important mail and stage stop on later lines that operated through the area and over the same road. At the present time, a well kept cemetery rests at the site of the old community and some grave stones date back to these early times when it was the Choctaw Nation with travel by horseback, wagon, and stage coach."

78.5 1.0 Butterfield Overland Stage Line crossed highway near here.

79.9 1.4 Ridge to right (north) is underlain by south-facing, south-dipping turbidite shales and sandstones in the lower part of the Atoka Formation.

80.4 0.5 Recross Gaines Creek.

80.5 0.1 Turn left (south) on county road just after crossing Gaines Creek. Long ridge of Wapanucka Limestone–Spiro sandstone ends abruptly just to the left (east) of the road.

Some kind of north–south-trending transverse structure follows Gaines Creek. The strata on the east side of Gaines Creek at this location consist mostly of the steeply south-dipping Atoka Formation, whereas the south- to west-dipping (folded) Wapanucka Limestone and lower Atoka Formation occur on the west side. John (1995) suggests that a right-lateral tear fault separates the two areas. An alternative explanation, largely based on the folded strata west of Gaines Creek, is that the structure is a north-striking, west-dipping thrust ramp in which the west side has moved relatively up and over the east side.

81.5 1.0 Steep slope on right (west) is underlain by moderately west–southwest- to locally northwest-dipping sandstones in the Atoka Formation. These attitudes are further evidence that the Atoka and Wapanucka–Spiro on the west side of Gaines Creek ramp over the Atoka on the east side of Gaines Creek.

82.0 0.5 County road to left (east). About a mile east of here was Pusley Station, another stop on the Butterfield Overland Stage Line.

Pusley Station

Gunning (undated, p. 26–27) reports as follows:

"From Mountain Station the Butterfield Line extended southwestward at an angle down the slope of the hill, crossing the present Highway 1 about a mile west of the present Higgins School, then passed on to a crossing on Gaines Creek three fourths mile west of the Highway crossing. A mile beyond the Gaines crossing was the site of the next Butterfield Station, operated by Silas Pusley and called the Pusley Station. Pusley was a member of an old Choctaw family that settled the area shortly after the Choctaw removal and by 1858 there were many members of the family living in this area.

"Pusley's home was the usual two room log house with the breezeway and tall stone chimneys. The stable and corral were near the home in the well watered creek valley which provided excellent forage in summer and hay in winter for the Butterfield teams which Pusley cared for. The first year of operation, the stages forded Gaines Creek, but apparently the bottoms were boggy and delayed the mails, so in 1859 the Choctaw Council gave Pusley a permit to build a toll bridge across the creek. This he did, and travel for the stages and also for the freighters was improved and speeded up."

82.1 0.1 Road crosses Buffalo Creek and heads due south. Enter Hartshorne South gas field.

Hartshorne South Gas Field

The Hartshorne South gas field is one of the more prolific gas fields in the Ouachita Mountains frontal belt. The field was discovered by the Amoco No. 1 Zipperer well (Table 8), which is in the SE¼SW¼SE¼SW¼ sec. 32, T. 4 N., R. 17 E. The well spudded on March 4, 1988, and finished drilling on June 22, 1988 (13,497 ft TD). The date of first production was July 26, 1988. The Zipperer was completed in overturned Wapanucka at 12,148–12,286 ft for 15,069 Mcf gas per day, and in overturned Spiro at 12,012–12,066 ft for 45,170 Mcf gas per day.

Table 8. — Producing Wells in the Hartshorne South Gas Field by Spud Date

Operator, number, farm, spud date, total depth, producing formation, depth of producing formation (data from NRIS as reported by operator to Oklahoma Corporation Commission on Form 1002A).

1. Amoco Production 1 Zipperer; 3/4/88; 13,497 ft; Wapanucka; 12,148–12,286 ft; Spiro; 12,012–12,066 ft
2. Amoco Production 1 Patterson; 10/14/88; 14,380 ft; Spiro; 11,840–11,895 ft; Wapanucka; 11,982–12,082 ft
3. Texaco 21-1 Wayne Wallace; 12/6/88; 13,694 ft; Atoka Overthrust; 13,358–13,308 ft
4. Exxon 1 H&H Cattle Co. GU A; 1/7/89; 14,518 ft; Atoka Middle; 5,030–5,201 ft
5. Exxon 1 Elliot Davis; 5/3/89; 15,080 ft; Wapanucka; 11,994–12,116 ft; Spiro; 11,864–11,942 ft
6. Amoco Production 1-A Retherford; 7/1/89; 12,660 ft; Spiro; 12,142–12,170 ft
7. Exxon 1 Roy Retherford B; 8/11/89; 14,980 ft; Spiro; 13,338–13,365 ft
8. Amoco Production 1 Tomlin; 10/24/89; 14,087 ft; Atoka Overthrust (Spiro); 13,636–13,674 ft
9. Texaco 28-1 Manuel Rudy Estate; 12/26/89; 13,591 ft; Atoka Overthrust (Spiro Upper); 12,448–12,516 ft
10. Exxon 1 Garrett & Co. C; 1/9/90; 14,840 ft; Spiro; 14,435–14,514 ft
11. Exxon 1 Garrett & Co. Unit A; 2/1/90; 15,289 ft; Spiro; 14,814–14,878 ft
12. Amoco Production 1 Stevens; 5/20/90; 11,907 ft; Spiro; 7,520–7,610 ft; later deepened to 11,982 ft; Spiro; 11,917–11,982 ft
13. Exxon 1 Garrett & Co. Unit D; 7/14/90; 14,400 ft; Atoka Middle; 12,702–12,757 ft
14. Amoco Production 36-1 Mose Watts; 7/26/90; 13,850 ft; Atoka Basal Subthrust; 13,410–13,440 ft
15. JMC Exploration 1 Blue Mountain; 8/7/90; 14,000 ft; Spiro; 13,640–13,750 ft
16. Arco Oil & Gas 1 Moore; 8/25/90; 13,950 ft; Spiro; 13,549–13,563 ft
17. Amoco 30-1 Retherford; 12/28/90; 12,885 ft; Spiro; 9,490–9,524 ft; Atoka (Atoka Lower); 9,864–9,904 ft; Spiro (Spiro Downthrown); 12,490–12,510 ft. Recompleted as Chesapeake Operating Co. 30-1 Retherford A on 12/25/01; Atoka Middle; 6,338–8,244 ft
18. Exxon 1 Watts Brothers C; 1/3/91; 13,450 ft; Spiro; 13,107–13,135 ft
19. Anadarko Petroleum 1-5 Watt A; 3/5/91; 14,500 ft; Choctaw/Spiro; 9,930–9,982 ft
20. Amoco 36-2 Mose Watts; 6/10/91; 13,240 ft; Spiro; 12,780–12,830 ft. Recompleted as Chesapeake Operating 2-36 Mose Watts; Atoka Lower; 9,044–9,050 ft
21. Amoco 2-26 Stevens Unit A; 10/14/91; 13,957 ft; Atoka Overthrust; 4,216–4,264 ft
22 Tide West Oil 1-16 Wallace; 11/20/91; 13,753 ft; Spiro; 13,405–13,491 ft
23 Texaco E & P 21-2 Wayne Wallace; 6/18/94; 14,460 ft; Atoka Overthrust; 14,008–14,080 ft
24. Barrett Resources 1-25 Watts Ranch; 5/19/97; 12,470 ft; Spiro; 12,283–12,319 ft
25. Chesapeake Operating 3-26 Stevens; 11/22/00; 12,776 ft; Spiro; 12,357–12,480 ft

The field presently consists of 25 active wells, mostly in the southern parts of T. 4 N., R. 17 and 18 E. (Boyd, 2002) (Fig. 89). Seventeen wells produce from the Spiro sandstone, three from the Atoka Formation, three from commingled Spiro and Wapanucka Limestone, and two from commingled Atoka and Spiro. Most of the wells were directionally drilled, and most of the bottom-hole locations are between 0.25 and 0.75 mi northwest of the surface locations.

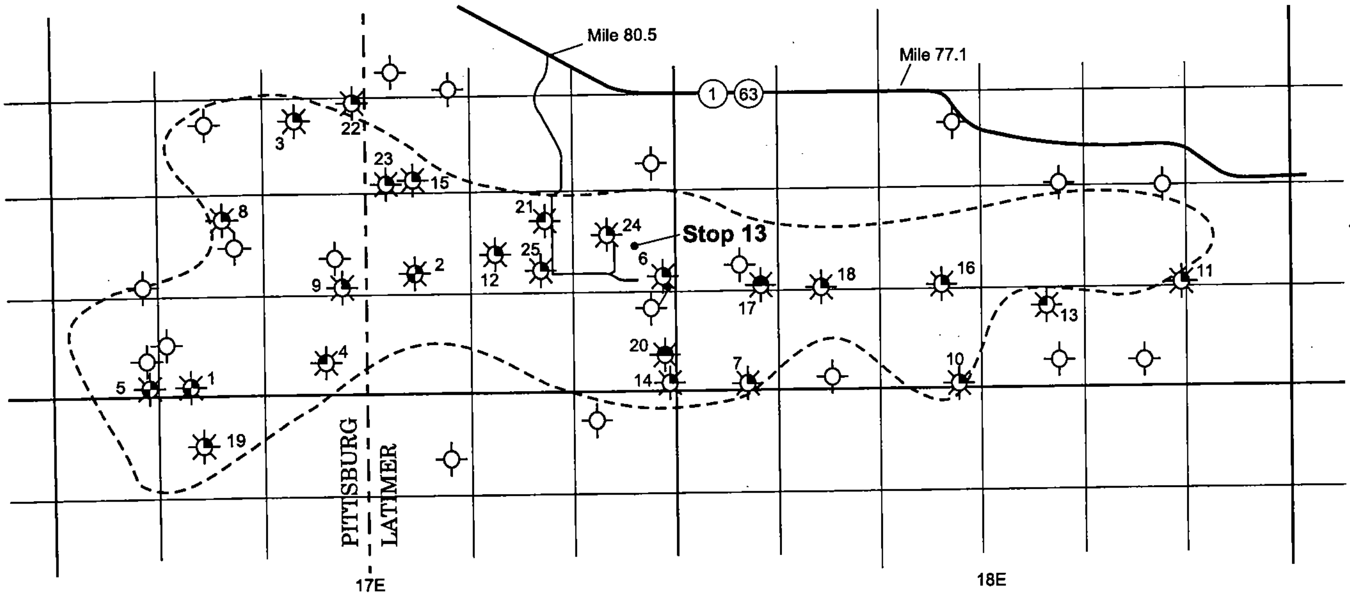
A log from the Amoco No. 30-1 Retherford well (Fig. 90A) shows the character of the Spiro sandstone reservoir in the field. The sub-Spiro shale was drilled from 12,510 to 12,545 ft, and the Wapanucka Limestone is present below 12,545 ft. Although similar in appearance on the gamma-ray log, the Spiro and Wapanucka can be distinguished on the photoelectric (PE) curve. Some wells produce minor amounts of gas from sandstones in the Atoka Formation (e.g., Fig. 90B).

The structural geology of the Spiro reservoir in the Hartshorne South field consists of at least one (and possibly more) blind anticlines and thrust faults in the footwall of the Choctaw Fault (Çemen and others, 2001a, figs. 6, 7). The reservoir geometry is similar to that of the Veterans Colony West field. Details of the stratigraphy of the Spiro sandstone and Atoka sandstones in the field have not been published.

As of July 2004, the field had produced ~134 Bcf gas.

82.8	0.7	Road turns right (east). This road services a large number of wells in the Hartshorne South gas field.
83.4	0.6	Turn left (north) on drill road to the Barrett No. 1-25 Watts Ranch well. This well, in the Hartshorne South gas field, was spudded on May 19, 1997, and was completed in the Spiro sandstone at 12,283–12,319 for 3,744 Mcf gas per day.
83.7	0.3	Drive to half-section-line fence and park. We will walk east along the fence to the creek and Stop 13.

This stop is on private property, and we have kindly been granted permission to look at the outcrops. If you wish to revisit this locality, please contact the property owner.



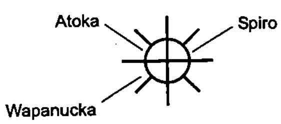


Figure 89. Production map of Hartshorne South gas field, showing surface locations of gas wells, field outline (from Boyd, 2002), and nearby field-trip stop and mileages. Numbers next to the wells refer to those in Table 8.

STOP 13

JOHNS VALLEY FORMATION, POWERS LOCALITY

Neil H. Suneson
Oklahoma Geological Survey

Location: C E½ sec. 25, T. 4 N., R. 17 E., Latimer County, Oklahoma

Hendricks and others (1947) mapped this area as Atoka Formation and showed the trace of the Ti Valley Fault ~2 mi to the south. In 1959, Hendricks suggested that the Johns Valley Formation is absent north of the Ti Valley Fault and used this as evidence that the Ti Valley Fault had more displacement than any of the other thrust faults in the frontal belt of the Ouachita Mountains (Hendricks, 1959, p. 50). However, Powers (1928) clearly showed that the Johns Valley is present in the area. It appears that Hendricks (1959) either did not read or ignored Powers's (1928) description of the strata at this locality.

Powers (1928) describes the geology of this area and, despite his sometimes confusing language, clearly describes what later workers would recognize as the Johns Valley Formation. He notes that "the [Caney] shale is found . . . near Recyl (section 25, township 4 north, range 17 east) . . . [and that] 'glacial' boulders are found only at the place last named, south of Recyl (Higgins)" (Powers, 1928, p. 1041). Powers (1928) also reported that "blocks of limestone and chert containing fossils indicating that the rocks are identical with formations exposed in the Arbuckles, and ranging in age from Ordovician (Arbuckle) to Mississippian (Woodford and Sycamore) and Pennsylvanian(?), occur in . . . beds near Recyl" (p. 1042). In his discussion of the glacial origin of the boulders, Powers (1928) noted that "the boulders are found from the west end of the Ouachita Mountains near Atoka, to the Arkansas line, a distance of 100 miles. . . . A few notably large masses have been found, most of them in Johns Valley. . . . Other large boulders . . . are found . . . at a place south of Recyl, where one 20 feet long is exposed to a thickness of 10 feet" (p. 1042–1043). Finally, Powers (1928) suggests that "the boulders near Recyl were deposited in Wapanucka(?) time" (p. 1045).

Suneson and Ferguson (1987) briefly described some of the rocks at this locality. In addition to sandstone and shale that are similar to the Atoka Formation, they listed the following olistoliths: a 4-ft-thick micritic limestone with brachiopods; 4-ft by 4-ft blocks of microcrystalline, platy, yellowish-gray limestone, chert cobbles and boulders, black siliceous shale or chert, Spiro-like sandstone; and a 6-ft by 3-ft soft, light-gray siliceous shale or chert (Fig. 91). Suneson and Ferguson (1987) also discussed the implications of the Johns Valley Formation being present well to the north of the mapped Ti Valley Fault, including the possibility that olistostromal units occur within the Atoka Formation and therefore are Atokan, and not Morrowan, in age.

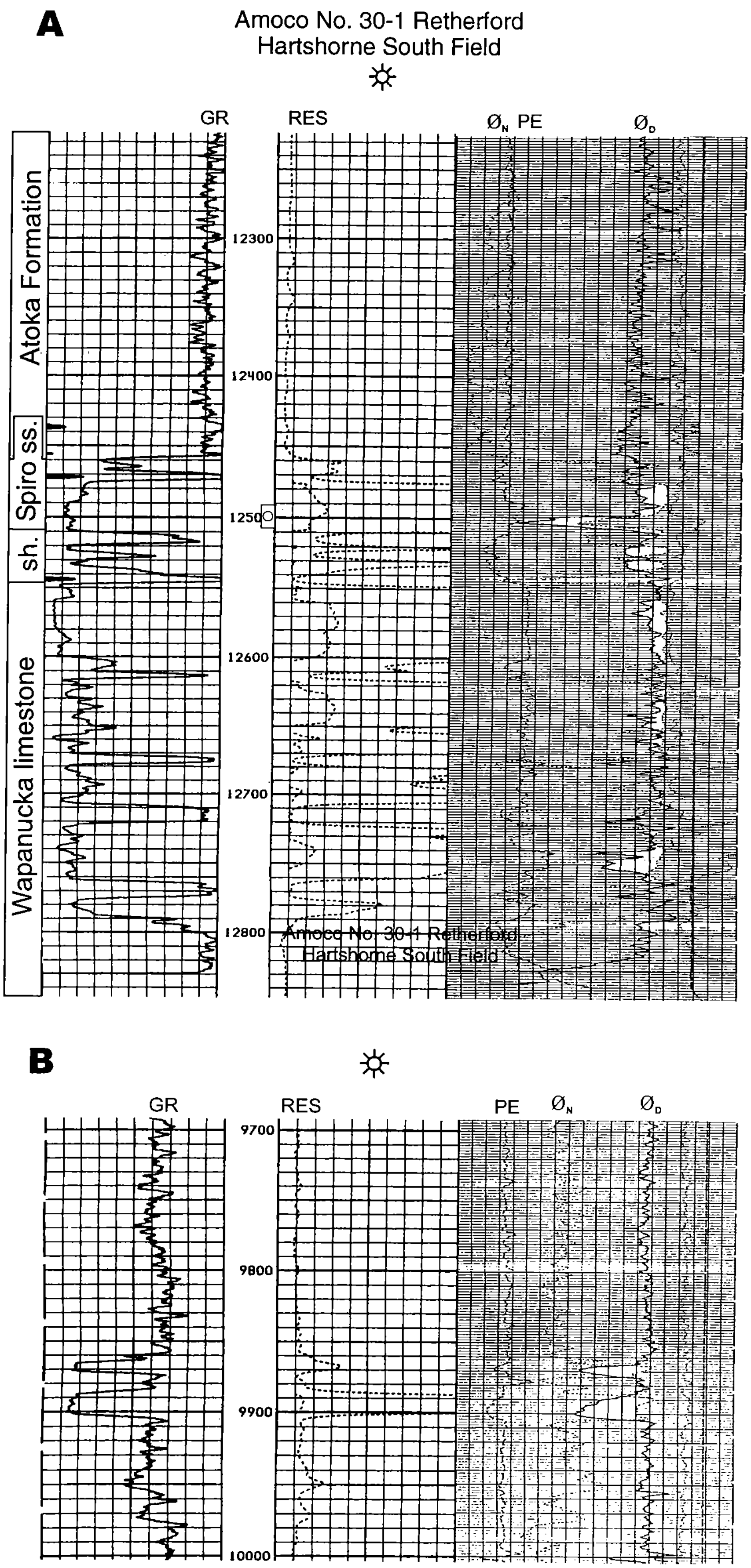


Figure 90. Parts of logs from the Amoco No. 30-1 Retherford well (no. 17 in Fig. 89). (A) Log of lower part, showing character of Spiro sandstone (12,460–12,510 ft). A thin limestone may be present at the base of the Spiro, based on the right deflection of the photoelectric (PE) curve. (B) Log of Atoka sandstone, showing significant neutron-porosity–density-porosity crossover. Relatively thin sandstones such as this commonly produce gas.

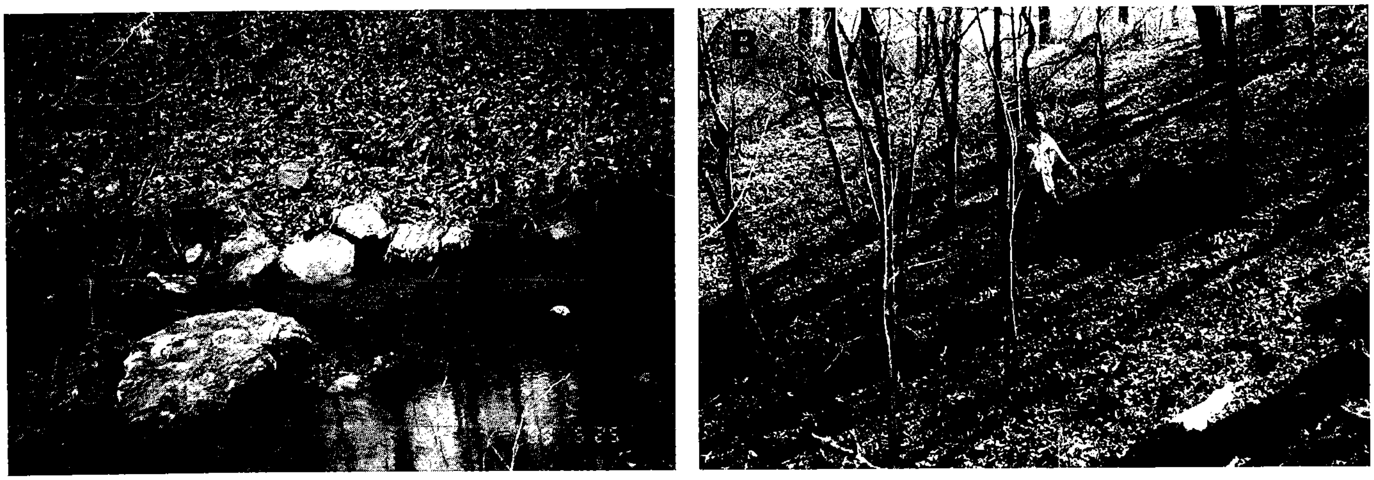


Figure 91. (A) Limestone boulders eroding out of Johns Valley Formation at Powers locality. (B) Large limestone boulder in Johns Valley Formation, Powers locality.

A second possibility, later suggested by Suneson (1988a), is that this outcrop "may represent the marginward equivalent of the largely basinal Johns Valley Formation" (p. 44). He also suggested that the presence of this outcrop and others north of the named Ti Valley Fault made "the practice of naming different faults in the frontal Ouachita Mountains, particularly the Ti Valley, as has been done to the west, [inappropriate] in the Higgins quadrangle and to the east, because the northernmost outcrops of Carboniferous Ouachita-facies strata appear to be distributed over a broad zone of thrust faults" (Suneson, 1988a, p. 44). A third possibility that would explain this outcrop of the Johns Valley north of the Ti Valley Fault is that the fault does not have the largest displacement of all the thrust faults in the Ouachita frontal belt, as proposed by Hendricks (1959).

		Return to S.H. 1/63.
86.9	3.2	Turn left (west) on S.H. 1/63.
88.1	1.2	Leave Higgins 7.5′ quadrangle; enter Hartshorne 7.5′ quadrangle.
88.5	0.4	Ridge of Wapanucka Limestone dipping 45° south. Grayson (1980, p. 277–280) measured the section on the right (north) side of the highway. Park on right side of highway for Stop 14A. Watch for traffic.

STOP 14A

WAPANUCKA LIMESTONE AND STRUCTURE OF THE ARKOMA BASIN–OUACHITA TRANSITION ZONE

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ChevronTexaco Exploration Company
Midland, Texas

Saleem Akthar
Ocean Energy Company
Houston, Texas

Location: along S.H. 1/63, just east of Pittsburg–Latimer county line, NE¼SE¼SW¼ sec. 10, T. 4 N., R. 17 E., Latimer County, Oklahoma

Wapanucka Limestone

This outcrop of Wapanucka Limestone was visited by a 1979 field trip (Sutherland and Manger, 1979) (and undoubtedly others) that examined facies changes in uppermost Mississippian, Morrowan, and Atokan shelf and basin strata in eastern Oklahoma and western Arkansas. The Wapanucka here is exposed along Limestone Ridge in the northernmost thrust sheet in the Ouachita fold and thrust belt. The Wapanucka exposed at mile 80.5 is part of a higher thrust sheet. This outcrop is in the hanging wall of the Choctaw Fault, the trace of which is ~1 mi north–northeast of here.

Table 9. — Measured Section of Wapanucka Limestone

	Thickness (ft)
Top of measured section	
Spiro sandstone	
17. Spiculiferous chert	1.8
Sub-Spiro shale	
16. Covered	99.0
Wapanucka Limestone	
15. Spiculiferous limestone, rare bioclasts	10.0
14. Spiculiferous limestone, rare bioclasts, chert layers	22.0
13. Conglomeratic limestone, large bioclasts and intraclasts	1.4
12. Spiculiferous limestone, commonly replaced by chert	10.5
11. Shale, uncommon siliceous shale, locally spiculiferous	5.0
10. Spiculiferous limestone, rare bioclasts, abundant chert nodules	30.5
9. Micritic limestone, common algal debris, rare bioclasts	12.0
8. Spiculiferous limestone, locally common bioclasts, chert nodules and thin beds	2.8
7. Conglomeratic limestone, common bioclasts and chert nodules	4.2
6. Micritic limestone, common algae and spicules, common chert nodules, argillaceous partings	4.9
5. Bioclastic limestone, common oolites	1.4
4. Micritic limestone, common algae, common spicules and bioclasts, argillaceous partings	3.5
3. Bioclastic limestone, common chert nodules	1.0
2. Spiculiferous limestone, fine skeletal debris, rare chert nodules	1.5
Total thickness	211.5

Modified from Grayson (1980).

Grayson (1980) measured the section on the northeast side of the highway and correlated it with other sections he measured along Limestone Ridge. (Some of his original unit numbers, in yellow paint, are still visible.) He used other measured sections of the Wapanucka Limestone in successively higher thrust sheets to document shelf (north)-to-basin (south) facies changes. Grayson (1979) used this outcrop and others along strike to show the interbedded nature of micritic and spiculiferous limestones in the Wapanucka. He suggested that both were deposited under low-energy lagoonal conditions, with micrites predominating under conditions of poor circulation, and spiculiferous limestones predominating under conditions of better circulation. He also used this outcrop to suggest that the interbedded limestone-pebble conglomerates, oolites, and bioclastic calcarenites (rare in this outcrop) record the transition from subaerial exposure to intertidal to shallow subtidal conditions.

The following is a modified summary of Grayson's (1980) measured section of the outcrop on the northeast side of S.H. 1/63 (Table 9; Fig. 92). Most of the section consists of bioclastic spiculiferous limestone. We will spend

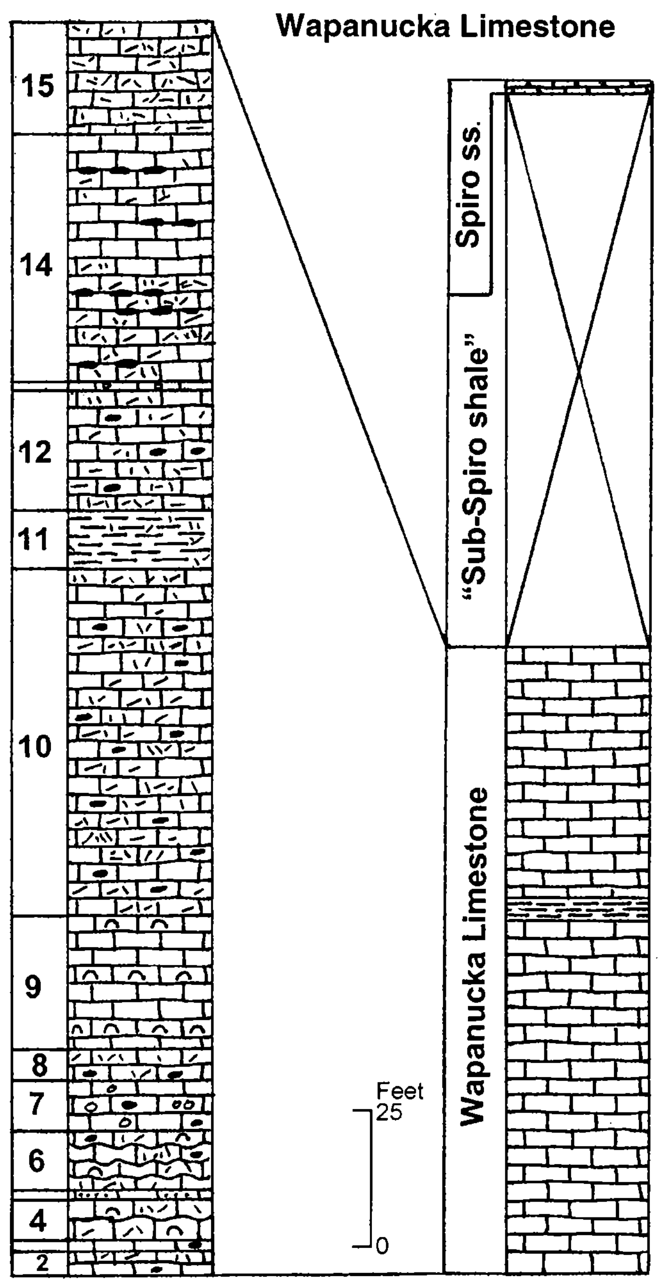

Figure 92. Measured section of Wapanucka Limestone on northeast side of S.H. 1/63 (based on data from Grayson, 1980, p. 277–280). Short lines = spicules; small, blackened ellipses = chert beds and nodules; circles = conglomerates; inverted U = algal mass.

Figure 93. (A) Photograph of solid hydrocarbons in fractures that are oblique to bedding planes in Wapanucka Limestone, Stop 14A. (B) Photograph of solid hydrocarbons along bedding planes (just above tip of hammer) in Wapanucka Limestone, Stop 14A.

most of our time examining the new outcrop on the southwest side of the highway. I (N.H.S.) have not attempted a bed-by-bed correlation from one side of the highway to the other. However, unit 11 (shale) of Grayson (1980) can be easily recognized on both sides of the highway.

Of particular interest in the new exposure of the Wapanucka Limestone on the southwest side of S.H. 1/63 are the fractures, bedding planes, and vugs that are filled with solid hydrocarbons (Fig. 93). Grayson (1980) noted "common carbonaceous matter and plant debris" in many of the units on the northeast side of the highway; however, numerous hydrocarbon-filled veins perpendicular to the bedding planes are clear evidence that the "carbonaceous matter" is post-depositional. Similar material is present in the Wapanucka Limestone ~2 mi to the west in the Dolese quarry (Suneson and others, 1990, p. 35).

The origin of this material and its relation to fracturing, diagenesis, and hydrocarbon generation and migration in the Wapanucka Limestone are unknown. Mauldin and Grayson (1995) mapped the fractures in the northeast outcrop and related fracture abundance to facies, although they were equivocal: "fracture abundance is probably influenced by lithology and/or bed thickness" (p. 253). Unfortunately, however, they did not note the hydrocarbons. Mauldin and Grayson (1995, fig. 2) did note that unit 13 of Grayson (1980), noted previously, probably is a fault breccia.

Structural Geology of the Frontal Ouachitas–Arkoma Basin Transition Zone

The frontal belt of the Ouachita Mountains contains imbricated thrust faults with tight to overturned folds typical of a fold–thrust belt. The Choctaw Fault usually is considered the boundary between the frontal Ouachitas and the Arkoma foreland basin. The Arkoma Basin is characterized by the broad to open folds and minor faults generally found in the foreland basins. It contains as much as 15,000 ft of Atokan sedimentary rocks that overlie Morrowan strata. The transition zone is that part of the southern Arkoma Basin just north of the Choctaw Fault.

Modern structural studies of the Ouachita Mountains frontal belt and the Arkoma Basin transition zone started in the mid- to late 1980s (e.g., Arbenz, 1989a). Suneson (1995) summarized the results of these studies. Several of the studies proposed the presence of a triangle zone with a back thrust (Hardie, 1988; Camp and Ratliff, 1989; Reeves and others, 1990; Milliken, 1988; Perry and Suneson, 1990; Wilkerson and Wellman, 1993; Valderrama and others, 1994). However, the geometry and areal extent of the triangle zone remain controversial. Some workers have suggested that all the thrust faults in the area are south dipping (Bertagne and Leising, 1989; Tilford, 1990) and therefore that a triangle zone does not exist. The presence of duplex structures proposed by some workers (Roberts, 1992; Wilkerson and Wellman, 1993; Velderrama and others, 1994; Çemen and others, 1994, 1997; Al-Shaieb and others, 1995) is also controversial.

We have constructed balanced structural cross sections along the frontal Ouachita Mountains–Arkoma Basin transition zone from Hartshorne to the Wister Lake area. We started these studies in 1992 as part of an Oklahoma Center for Advancement in Science and Technology (OCAST) project to examine overthrusted natural-gas reservoirs in the Wilburton gas field area of the Arkoma Basin. During the project we constructed eight balanced structural cross sections to determine detailed configuration and geometry of the thrusts in the Wilburton gas field area. The cross sections were based on surface geologic maps published by the Oklahoma Geological Survey (Suneson and Ferguson, 1989a,b; Hemish and others, 1990c; Hemish, 1992, 1995), wireline-well-log data, and our interpretation of many seismic profiles provided by ExxonMobil Corporation.

Figure 94 is a simplified geologic map of the Hartshorne–Wilburton area and shows the location of the westernmost cross section we constructed during the OCAST project. Balanced cross section A–A′ (Fig. 95) passes close

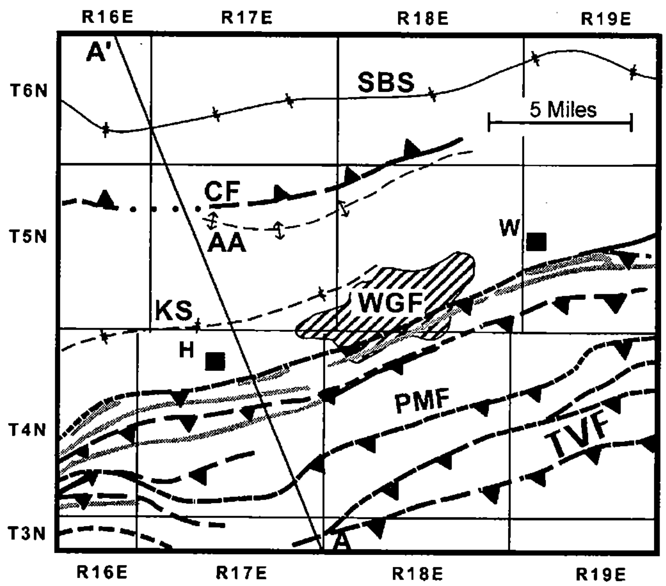

Figure 94. Simplified map of the Wilburton gas field and surrounding areas (modified from Çemen and others, 2001a), showing (a) major structural features, (b) outcrops of the Spiro sandstone (shaded pattern), and (c) the line of cross section A–A′. H = Hartshorne; W = Wilburton; AA = Adamson Anticline; CF = Carbon Fault; KS = Kiowa Syncline; PMF = Pine Mountain Fault; SBS = Sans Bois Syncline; TVF = Ti Valley Fault; WGF = Wilburton gas field.

to Stop 14A. It shows about 60% shortening when restored to the time of Spiro sand deposition, using the key-bed balancing technique. The following is a summary of the geometry of thrust faulting along the frontal Ouachitas–Arkoma Basin transition zone, based mostly on Çemen and others (2001a).

Cross section A–A′ (Fig. 95) is constructed perpendicular to the tectonic-transport direction. Therefore, it shows displacements along the thrust faults where appropriate piercing points are located in the hanging wall and footwall of the thrust faults. The Spiro sandstone is used as the key bed to determine the structural geometry. The Wapanucka Formation and the Spiro sandstone are not divided: the unit is referred to as the *Spiro* and is assumed to have uniform thickness in the study area. Other units identified in the cross section include the Red Oak sandstone, a marker bed called *marker X*, the Hartshorne sandstone, and the McAlester, Savanna, and Boggy Formations. Like the Spiro sandstone, the Red Oak sandstone and marker X are identified in the logs at their tops, and their thicknesses are assumed to be constant throughout the study area.

In the cross section the hanging wall of the Choctaw Fault contains many south-dipping listric thrust faults, splaying both from the Choctaw Fault and the main detachment surface within the Woodford Shale (Woodford Detachment).

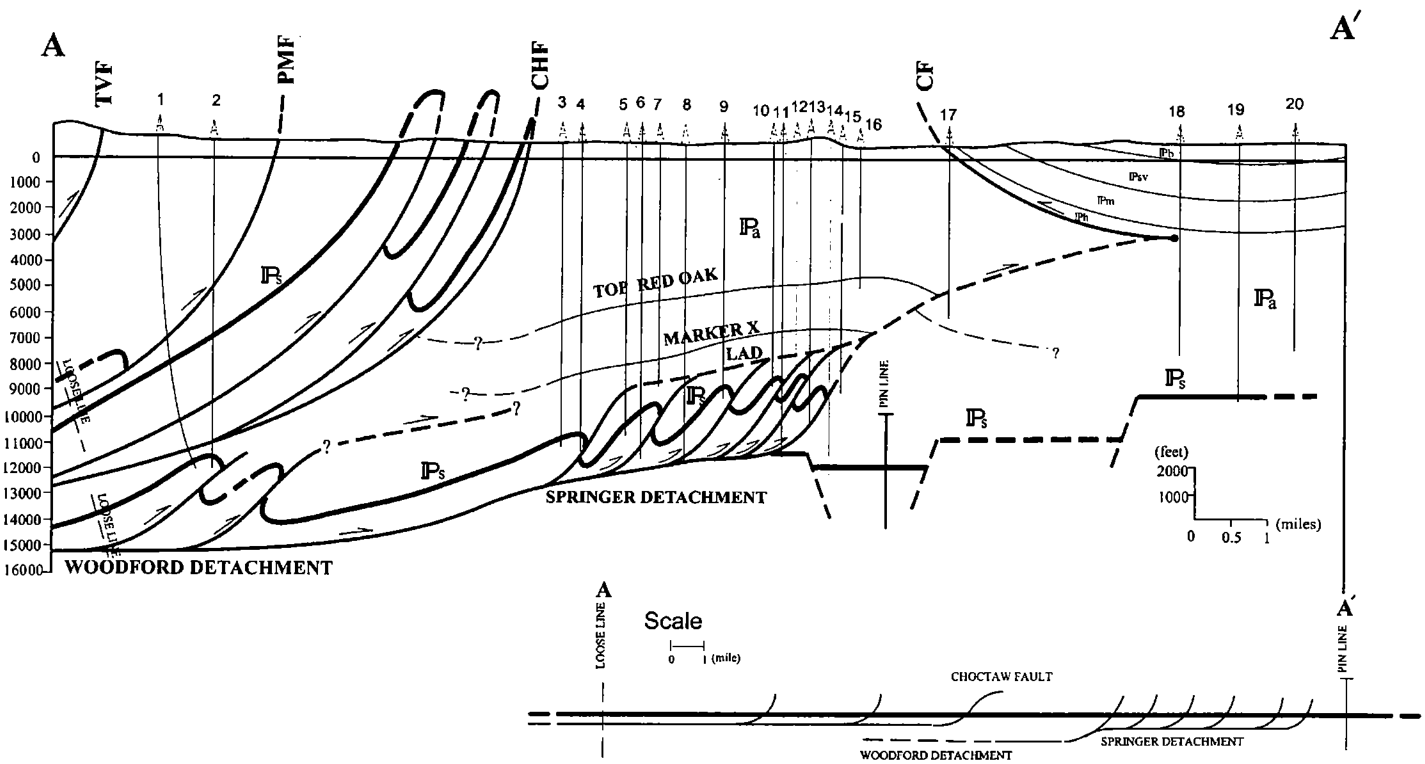

Figure 95. Balanced structural cross section A–A′ (see Fig. 94 for line of section) and its restoration (from Çemen and others, 2001a). The cross section shows the presence of the Wilburton triangle zone, the duplex structure, and other structural features. The restored cross section suggests ~60% shortening along the original length of the Spiro sandstone owing to Pennsylvanian thrusting. Note that the scale of the restored section is 2 times smaller than the deformed cross section. See text for explanation. CF = Carbon Fault; CHF = Choctaw Fault; LAD = Lower Atoka Detachment; PMF = Pine Mountain Fault; TVF = Ti Valley Fault; Ps = Spiro sandstone; Pa = Atoka Formation.

We suggest that a triangle zone is present along the line of cross section A–A′ (Fig. 95). The triangle zone is bounded by the Choctaw Fault on the south and the Carbon Fault on the north. It is floored by a possible detachment surface in the Atoka Formation. We informally name this detachment surface the *Lower Atoka Detachment* (Fig. 95). Below the triangle zone a duplex structure contains hinterland-dipping imbricate thrust faults splaying from a detachment surface within the Springer Formation (the floor thrust), which is usually recognized as the *Springer Detachment.* The hinterland-dipping faults join the Lower Atoka Detachment in the Atoka Formation (the roof thrust). The detachment continues in the Atoka Formation northward and displaces the Red Oak sandstone before reaching a shallower depth and forming the Carbon Fault as a north-dipping back thrust below the Sans Bois Syncline and involving Desmoinesian strata (Fig. 95).

The surface trace of the Carbon Fault disappears north of Wilburton. However, the triangle zone continues to the east in the subsurface because the Carbon Fault becomes a blind back thrust east of Wilburton (Çemen and others, 2001b), as it is shown along the cross section through the Red Oak gas field (Fig. 68).

The hanging wall of the Choctaw Fault, the leading-edge thrust of the Ouachita fold-and-thrust belt, contains several south-dipping imbricate thrust faults. These faults, including the Ti Valley and Pine Mountain Faults, probably join the Choctaw Fault at depth. We interpret the duplex structure in the Wilburton area as having been formed by a break-forward sequence of thrusting similar to the mechanism first proposed by Boyer and Elliot (1982).

Detachment Surfaces, Duplex Structure, and Triangle Zone

The Woodford and Springer Detachments have long been recognized as the two basal detachment surfaces in the frontal Ouachitas fold–thrust belt. Locating these two detachment surfaces in the subsurface was primarily dependent on the availability of data. To date, the seismic profiles available to us cover only the southern part of the study area, where the Woodford Detachment can be seen above the Hunton Group. The Springer Detachment was located primarily by using a limited number of logs from deep wells.

The Woodford Detachment propagates within the Woodford Shale. It is a relatively flat detachment surface ~15,000 ft below sea level 3–4 mi southeast of this stop. There, two imbricate thrust faults splay from the Woodford Detachment (Fig. 95). These thrust faults probably form the Gale–Buckeye thrust system of Wilkerson and Wellman (1993). Farther north the Woodford Detachment ramps up-section and reaches a shallower depth (~12,000–13,000 ft below sea level) in the Springer Shale (Fig. 95), where it is named the *Springer Detachment.* It continues northward in the Springer and forms the floor thrust of the duplex structures in the study area.

Cross section A–A′ (Fig. 95) shows a hinterland-dipping duplex structure in the footwall of the Choctaw Fault. The duplex structure is floored by the Springer Detachment and bounded on top by a roof thrust termed here the *Lower Atoka Detachment.* Horses found within the duplex structure are probably formed by the upward propagation of the imbricate thrust faults splaying from the basal detachment. These imbricate faults join the Lower Atoka Detachment.

The presence and location of a roof thrust is suggested by the great difference in geometry above and below the interval between the imbricately thrusted Spiro sandstone and a sand unit in the Atoka Formation named *marker X.* In the wireline well logs, marker X is identified by its higher gamma-ray and resistivity values. An attempt to correlate this sand unit with one of the other sand units within the Atoka Formation was unsuccessful because of the unavailability of type well-log signatures. Therefore, we have informally called it marker X. In all wells examined, marker X is found in exactly the same stratigraphic position. It displays a fold pattern similar to that of the Red Oak sandstone above it. In contrast, the Spiro sandstone is imbricately thrusted below marker X. This great difference in geometry suggests the presence of a roof thrust. However, this geometry can be interpreted in two ways: (1) that the part of the Atoka Formation below marker X contains imbricate blind thrust faults that die out in the shaly part of the section above the Spiro sandstone, or (2) that a roof thrust below marker X separates the imbricately thrusted section below from the folded section above.

We prefer the second interpretation on the basis of the following evidence. Several wells east of cross section A–A′ penetrated the Red Oak sandstone twice, one in the hanging wall of a thrust fault, and another in the footwall of a thrust fault (Çemen and others, 2001b). We interpret this thrust as a part of the shallow-dipping Lower Atoka Detachment surface, the roof thrust. Therefore, in cross section A–A′ we show the Lower Atoka Detachment as a south-to-north-propagating detachment, located 8,000–9,000 ft below sea level. The Lower Atoka Detachment gradually ramps to the north of the leading imbricate thrust of the duplex structure and becomes shallower.

It should be noted that the Lower Atoka Detachment is shown in the middle of the interval separating two different structural geometries (Fig. 95) and was not observed on the seismic profiles, nor could it be inferred from the well-log signatures. The seismic profiles do not provide a well-developed velocity contrast, and the well logs do not suggest a characteristic log signature for the roof thrust. The absence of supporting evidence for the roof thrust is because the Lower Atoka Detachment is propagating within the shales of the Atoka Formation.

The geometry formed by the south-dipping Choctaw Fault, the Lower Atoka Detachment, and the north-dipping Carbon Fault qualifies as a triangle zone (Fig. 95), similar to those in the southern Cordilleran foreland in Canada (Dahlstrom, 1970; Jones, 1982, 1994; Price, 1986; Sanderson and Spratt, 1992) and in the Himalayan foreland in Pakistan (Jadoon and Frisch, 1997).

Amount of Shortening

Cross section A–A′ (Fig. 95) is restored, using the key-bed restoration method for the Spiro sandstone. South of the Choctaw Fault, shale in the Atoka Formation dominates the stratigraphic column at the surface and in the subsurface. Shales have characteristic responses to deformation: because they are incompetent, they can be easily deformed, and to select bed boundaries within shales would be very difficult. Consequently, we could restore the cross sections only by using the Spiro sandstone as a key bed. Moreover, the Spiro is the only continuous marker in the Hartshorne–Wilburton area.

The pin lines for the restored cross section are north of the leading duplex, or the blind thrust, where the Spiro sandstone is not affected by shortening in the frontal belt. The loose lines are to the south, where there is no piercing point for the thrusted Spiro sandstone. Calculations suggest about 60% shortening for the Spiro sandstone in this area.

Continue west on S.H. 1/63.

88.9	0.4	Enter Wilburton gas field. This large gas field is discussed at mile 101.9 near the Wilburton Airport.
89.0	0.1	Leave Latimer County; enter Pittsburg County. County road to left (south) follows county line. Turn left (south) on county road.
89.3	0.3	Top of Limestone Ridge, and excellent exposure of Spiro sandstone. Park near top of ridge.

STOP 14B

SPIRO SANDSTONE

Neil H. Suneson
Oklahoma Geological Survey

Location: west line SW¼SW¼SW¼ sec. 10, T. 17 E., R. 4 N., Latimer–Pittsburg county line, Oklahoma

The Spiro sandstone is one of the principal reservoir units in the Arkoma Basin and frontal Ouachita Mountains. For example, it is the primary producing formation in the Veterans Colony West gas field (mile 72.9), Hartshorne South gas field (mile 82.1), and Wilburton gas field (mile 101.9). The Spiro produces gas from both thrusted and sub-thrust positions. A review of Spiro sandstone studies is beyond the scope of this field-trip stop; Gross and others (1995), Grayson and Hinde (1993), and the references therein provide a relatively complete bibliography of Spiro studies.

Approximately 60 ft of the lower part of the Spiro sandstone is exposed at this outcrop (Fig. 96). About 75 ft of sub-Spiro shale (covered) underlies the Spiro, and the top of the Wapanucka Limestone is exposed beneath the covered interval.

The Spiro sandstone consists of four lithofacies at this outcrop: from bottom to top, these include ripple-bedded sandstone, probable shale (covered interval), limy bioclastic sandstone, and spiculitic sandstone (Fig. 96). The basal sandstone is medium to fine grained, well sorted, and well stratified (Fig. 97). Burrows are common on bedding planes and also occur oblique to bedding. Ripple-bedding is pervasive, but cross-bedding, channeling, and pinch-and-swell structures are absent to poorly developed. The sequence does not appear to fine or coarsen upward,

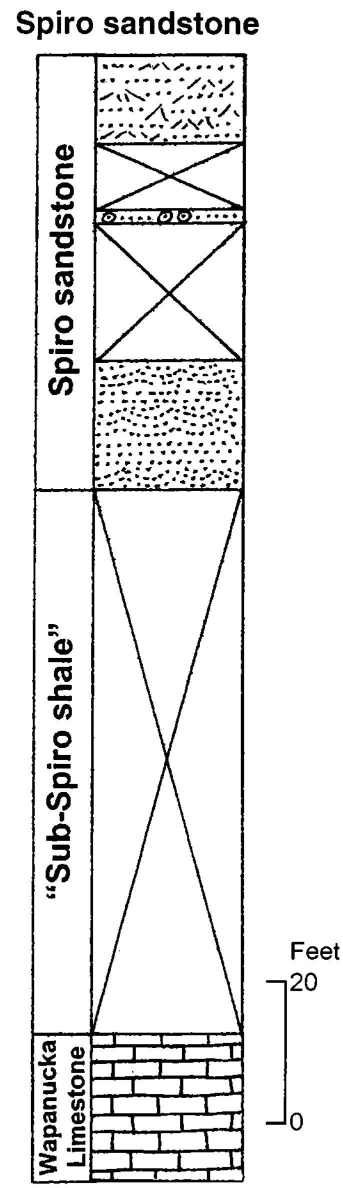

Figure 96. Measured section of Spiro sandstone at Stop 14B. Short lines = spicules; circles with dots = fossil fragments.

nor do the beds appear to thin or thicken upward; rather, the sandstone appears to have a relatively sharp base and top, although neither is well exposed. The bioclastic sandstone is relatively thin and shows poorly developed low-angle cross-stratification. The spiculitic sandstone is well stratified but highly irregularly bedded.

The Spiro sequence at this outcrop was deposited in a shallow-marine environment. The basal sandstone probably represents an offshore-bar deposit. Low-energy wave action probably caused the good sorting and abundant ripple marks. Abundant burrows also are evidence that the energy was low. The absence of channels is evidence for deposition in a dominantly constructional setting as opposed to deposition and reworking in, for example, a tidal channel. The "ideal" marine-bar sequence would coarsen or thicken upward, but the apparent sharp base of this unit is not strong evidence against a marine-bar origin.

Figure 97. Photograph of Spiro sandstone at Stop 14B, showing stratification. Top of section is to the left (south).

The covered intervals, presumably shale, probably were deposited under quiet-water conditions, possibly in slightly deeper water than the basal sandstone. The thin, bioclastic sandstone is interpreted to be a storm deposit; the low-angle cross-stratification may be hummocky cross-stratification or a cut-and-fill structure, but it, too, is too poorly exposed to determine which it may be. The spiculitic sandstone clearly is marine, but it, too, is too poorly exposed to identify a depositional environment. The marine-bar origin of the Spiro sandstone at this outcrop agrees with that proposed by Grayson and Hinde (1993), who also based their interpretations on outcrop studies. It agrees less well with a barrier-island origin, favored by Gross and others (1995); however, the barrier islands are sub-thrust, autochthonous, and therefore more like shelfal Spiro sandstone deposits, whereas the marine bars are thrusted, allochthonous, and therefore probably were deposited farther out on the shelf than the barrier islands.

Return to S.H. 1/63.

89.6 0.3 Turn left (west) on S.H. 1/63.

90.0 0.4 Low ridge is highly deformed Atoka Formation. The trace of the Choctaw Fault is between this outcrop and the base of the Hartshorne Ridge (top of ridge at mile 90.6).

90.6 0.6 Ridge is underlain by Hartshorne Formation. A measured section of the Hartshorne Formation at this locality is part of the 1998 guidebook (stop 7).

Numerous adits into the Hartshorne coals are present on the north side of the ridge. The Hartshorne SE Problem Area, reclaimed from 1988 to 1990, was considered hazardous by the OCC because vertical openings, open portals, polluted water, and subsided areas were present. The 18 Hill mine, located immediately west of the highway in the NE¼ sec. 8, T. 4 N., R. 17 E., and operated from the late 1940s to the early 1950s, was associated with 14 portals, 13 vertical openings, and 24 areas of subsidence (Cox, 1991). It was reclaimed in 1988 for $16,000.

91.2 0.6 Intersection with U.S. 270. Turn right (west) on U.S. 270 toward Wilburton.

The town of Hartshorne is ~1 mi west–northwest of the intersection. Two sites in the downtown area are part of the OCC's Hartshorne/Dow Underground Mines Project. One area of subsidence is ~3 ft from a heavily traveled street. Another is in an alley behind some downtown stores. Several years ago a 20-ft-deep by 2-ft-diameter hole appeared in the same alley. The city filled it with dirt and gravel. Both areas probably are over mined-out areas. The OCC is planning to excavate and clean out the subsided areas and stabilize and fill the voids.

91.6 0.4 Enter area of underground mines in the Hartshorne coals.

For the next several miles the field-trip route crosses the McAlester Formation, preserved within the Hartshorne Syncline. At this point, the axis of the syncline is ~1 mi north of the highway. Large underground mines in the Upper and Lower Hartshorne coals, originally operated by the Rock Island Improvement Company, underlie much of the syncline for the next 4.3 mi (Fig. 98). The mines are somewhat of a problem for drillers in the area.

92.0 0.4 Ruins to shaft no. 7, Rock Island Improvement Company, in small clump of trees to right (east) (Fig. 99). The pond just south of the ruins is contaminated with acid mine water containing high concentrations of iron, magnesium, and aluminum. A project

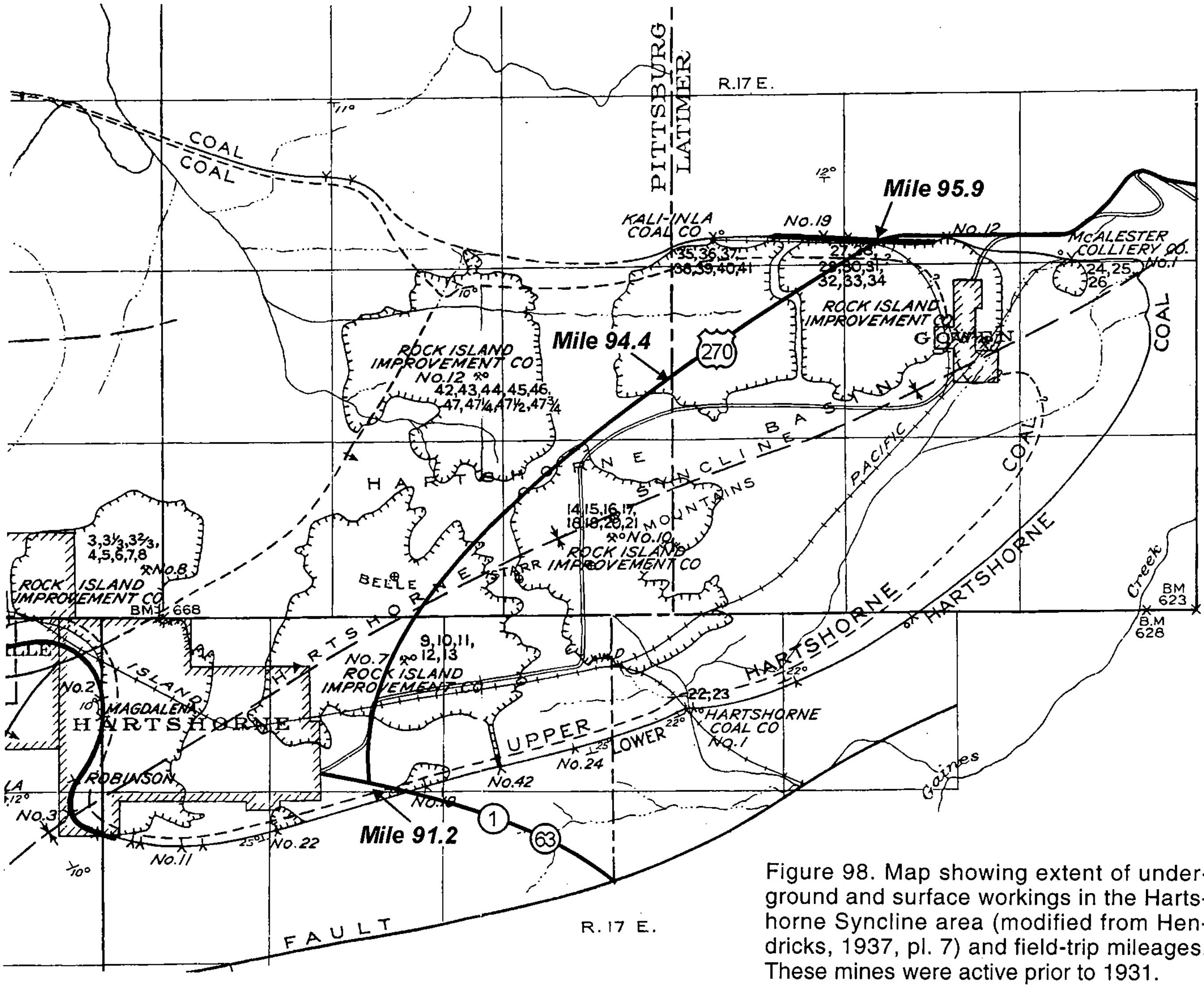

Figure 98. Map showing extent of underground and surface workings in the Hartshorne Syncline area (modified from Hendricks, 1937, pl. 7) and field-trip mileages. These mines were active prior to 1931.

to neutralize the water and improve the water quality is being designed by the OCC.

92.4 0.4 Highway passes between two small, flat-topped hills—Belle Starr Mountain to right (east) and Round Top Mountain to left (west). Both are capped by the Lower(?) Warner Sandstone Member of the McAlester Formation, which is preserved in the axis of the Hartshorne Syncline.

93.6 1.2 Road to left (north) to Jones Academy.

93.9 0.3 Large, flat-topped hill on right (south) is Number 10 Mountain and is capped by the Lower(?) Warner Sandstone.

94.2 0.3 Leave Hartshorne 7.5′ quadrangle; enter Adamson 7.5′ quadrangle.

94.4 0.2 Leave Pittsburg County; enter Latimer County.

94.9 0.5 Leave Adamson 7.5′ quadrangle; enter Gowen 7.5′ quadrangle.

Jones Academy

Jones Academy was established in 1891 as the Jones Male Academy for Choctaw boys. Currently, it is a coeducational boarding school for children in grades 1–12. Children attend the Hartshorne public schools during the day and are supervised and counseled the remainder of the time. The academy hosts an all-Indian rodeo.

95.6 0.7 Borrow ditch on right (south) of road appears to contain some acid mine water. The water is coming from some reclaimed strip mines just north of the highway.

95.9 0.3 Cross old strip pits in Hartshorne coal (Fig. 98). These are shown by Hendricks (1937) and therefore must have been active prior to 1931. OCC files show them as active underground mines in 1940 and surface mines in 1955.

Figure 99. Photograph of ruins to shaft no. 7 of the Rock Island Improvement Company mine. This mine was active in 1930 (Hendricks, 1937, p. 53) and covered ~1.5 mi^2 near the axis of the Hartshorne Syncline.

A strip pit (Fluid Haulers' Pit, E½NE¼SE¼SW¼ and NW¼SW¼SE¼ sec. 22, T. 5 N., R. 17 E.) was used in 1981–82 to dispose of oil- and gas-field fluid wastes. Responding to complaints from residents downdip of the pit, the Oklahoma Water Resources Board determined that the pit was connected to the coal bed, which served as a local aquifer.

97.0 1.1 Highway curves to left (north). The Hartshorne coal has been extensively strip-mined by P&K Coal Company just south of the highway, starting in 1985. The area has since been reclaimed.

97.4 0.4 Top of ridge capped by Hartshorne sandstone. The axis of the Hartshorne Syncline is about half a mile to the south. Here, the syncline plunges to the west.

98.1 0.7 Outcrops of uppermost part of Atoka Formation locally present near bottom of slope.

98.8 0.7 Cross Gaines Creek.

98.9 0.1 Historical marker on right (south) side of road reads:

De La Harpe. 1719.

This French explorer, seeking trade with the Wichita Indians, came north from Louisiana. On August 25, 1719, he camped three miles east of Hartshorne and the next day, following Gains [sic] Creek, passed here on his way to the Canadian River and the Wichita villages to the north.

100.5 1.6 U.S. 270 turns gently right at small village of Bowers.

About 2 mi north and 1 mi west of Bowers is the small village of Chilli. Chilli is located where Boiling Springs Creek forms a gap in a long ridge of Hartshorne sandstone. Hendricks (1939, pl. 27) shows a "Boiling Spring" ~0.2 mi southwest of Chilli, along the creek, and near the base of the ridge. The spring issues from very near the trace of the Carbon Fault. Hendricks (1939, p. 277) notes that "Boiling Spring, a gas seep in sec. 6, T. 5 N., R. 18 E., is situated on the Carbon fault plane, which serves as an avenue of escape for gas present in beds beneath the surface at that locality."

101.9 1.4 County road to Wilburton Airport to left (north). This location is at the middle of the section line between secs. 10 and 15, T. 5 N., R. 18 E., and is near the center of the Wilburton gas field.

Wilburton Gas Field

Three "discovery" wells in the Wilburton field were drilled just south of here (Suneson and others, 1990, p. 7) (Fig. 100). The "first" discovery well is the Limestone Oil and Gas No. 1 Nettie McCurray in the SW¼SW¼SW¼ sec. 15, T. 5 N., R. 18 E. It was spudded on May 12, 1927, and drilling finished on December 9, 1929, at a total depth of 4,038 ft. The driller's 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 MMcf gas per day was from a gray sand at 2,518–2,548 ft (Hendricks, 1937). Logs of

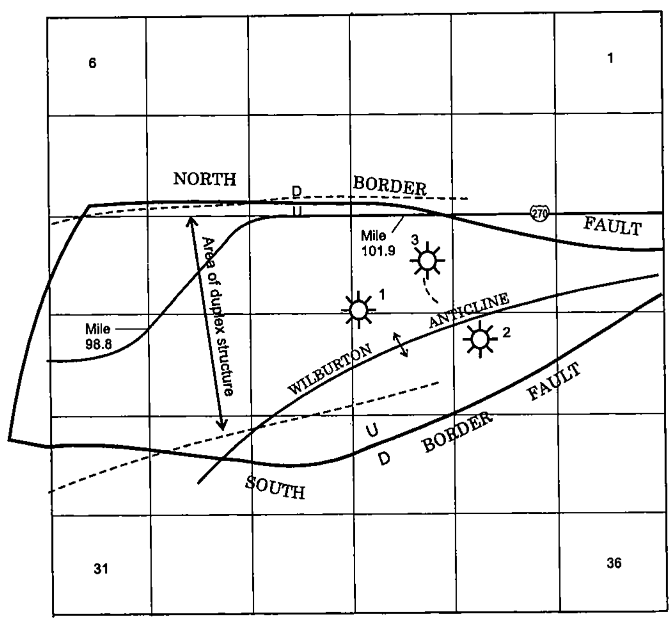

Figure 100. Map of T. 5 N., R. 18 E., showing Wilburton gas field "discovery" wells and surface and subsurface structures. The Limestone Oil and Gas No. 1 Nettie McCurray (well no. 1) probably was drilled on the Wilburton Anticline (from Hemish, 1992; Hemish and others, 1990c), exposed at the surface. The Ambassador No. 1 Williams (well no. 2) discovered gas in thrust-faulted Spiro sandstone (duplex structure of Çemen and others, 2001a). The Arco No. 2 Yourman (well no. 3) discovered the "Wilburton Deep" field in a horst block of Arbuckle carbonate strata (north and south border faults from Mescher and others, 1993).

nearby wells show the base of the Atoka Formation to be ~9,000 ft deep; therefore, this well produced gas from a shallow sandstone in the Atoka Formation. Gas from the Nettie McCurray supplied nearby residents.

The "second" discovery well is recognized by the Oklahoma Nomenclature Committee of the Mid-Continent Oil and Gas Association as *the* discovery well of the Wilburton field. The Ambassador Oil Corporation No. 1 W. M. Williams Unit was drilled in the SW¼SW¼NE¼NW¼ sec. 23, T. 5 N., R. 18 E., ~1.25 mi east of the McCurray well. It was spudded on September 21, 1960, and drilling finished on November 11, 1960, at a total depth of 9,704 ft. It was completed on December 15, 1960, in the Spiro sandstone at 8,811–8,831 ft, with an open-flow potential of 8.3 MMcf gas per day.

The "unofficial" discovery well of the "Wilburton Deep" field is the Arco No. 2 Yourman, in the S½S½NE¼ sec. 15, T. 5 N., R. 18 E., about half a mile south of here and a mile northeast of the McCurray well. It was spudded on February 8, 1987, and reached a total depth of 15,391 ft on June 25, 1987. Arbuckle carbonates were perforated between 14,259 and 14,500 ft. The well had an open-flow potential of 73 MMcf gas per day and an initial-flow potential of 9.3 MMcf gas and 128 bbl water per day.

Interestingly, all three "discovery" wells are within a little over a mile of each other and are near the crest of the Wilburton Anticline (Fig. 100). Despite their close apparent structural proximity, they are not simply deeper pools associated with the same structure but are, in fact, separate pools separated by significant structural discontinuities.

102.9 1.0 Leave Gowen 7.5′ quadrangle; enter Wilburton 7.5′ quadrangle. Note the low mounds on either side of the highway (Fig. 101). These are known as mima mounds, and their origin is somewhat controversial.

Mima Mounds

Mima mounds (also called hogwallows, prairie mounds, pimple mounds, pimpled plains, prairie pimples, silt mounds) are relatively common in some of the flat valley floors in the Arkoma Basin and Ouachita Mountains (Knechtel, 1952). They also occur in a number of other places throughout North America and the world. They are enough of a geological curiosity that they are the feature attraction at Mima Mounds Natural Area Preserve just southwest of Olympia, Washington. The origin of mima mounds is controversial, and a single origin may not apply to all places where they occur. However, areas with mima mounds share several characteristics (Washburn, 1988): they are treeless to partially vegetated, consist of thin unconsolidated material overlying coarser or harder material, occur on a land surface of considerable age, and are present in a former or current non-permafrost climate.

Washburn (1988) placed the more than 30 different hypotheses offered to explain the origin of mima mounds into eight general categories; a ninth was proposed by Berg (1990): (1) The *gilgai* hypothesis suggests that mima mounds form as a result of the shrinking and swelling of expansive clays in the soil, including the infilling of desiccation cracks and subsequent swelling and diapiric rise. (2) The *fluvial deposition alone* hypothesis likens mima mounds to accretion ridges on point bars in an alluvial deposit. (3) *Fluvial deposition with vegetation anchoring* requires that small clumps of vegetation stabilize and serve as the loci for sediments in an alluvial deposit. (4) A popular and widely accepted origin for many mima mounds suggests that *fossorial rodents* (typically the pocket gopher) tunneling outward from nest sites cause the backward displacement of soil toward a center. (5) The *runoff erosion alone* hypothesis suggests that the mounds are formed as a result solely of fluvial, slopewash, or other unorganized erosional processes. (6) Two ideas suggest that mima mounds may have formed as a result of thermal-contraction cracking of soil: (6a) Several versions of the *runoff erosion with polygonal permafrost cracking* hypothesis all require the growth of ice wedges in permafrost cracks and subsequent thawing of the wedges. (6b) *Runoff erosion with polygonal seasonal-frost cracking* is similar to 6a but does not require the cold temperatures necessary for permafrost. (7) *Runoff erosion with desiccation cracking* was originally proposed by Knechtel (1952) for the mounds in eastern Oklahoma. He suggested that the low intermound areas are the sites of desiccation cracks, enhanced by erosion. (8) The *erosion runoff with vegetation anchoring* hypothesis requires clump vegetation and trees. (9) Berg's (1990) *seismic* hypothesis requires a veneer of unconsolidated fine sediment over a

Figure 101. Photograph of mima mounds. See text for explanation.

hard substrate and the occurrence of earthquakes.

Other, more fanciful explanations for mima mounds include deposition from polygonally fractured, sediment-covered lake ice, eolian activity with vegetation anchoring, bedrock jointing (e.g., mounds developed on columnar basalts), and, in Oklahoma, old bison wallows. For those interested in the origin of mima mounds, an extensive bibliography is available on the Web at www.intersurf.com/~chalcedony/pimple2.html.

Allgood and Gray (1973, 1974) studied the size, density, height, distribution, soil properties, and substrates of some mounds and intermound areas in eastern Oklahoma. They noted that the mounds are closely associated with the 40+-in. rainfall belt, that most form on dense substrates with perched water tables in the spring, and that the soil between the mounds typically is saturated with water during the rainy season. Compared to intermound soils, those of the mounds are more friable, less dense, have thicker soil horizons, and are less leached; all of these characteristics they ascribe to the high density of organisms in the mounds, especially pocket gophers, moles, and earthworms. Allgood and Gray (1974) suggest that the mounds form because of the large volume of material added to the mounds to make nests, the increase in soil volume from earthworm activity, and sheet erosion in intermound areas. The origin suggested by Allgood and Gray (1974) is similar to no. 4 of Washburn (1988).

105.4	2.5	Eastern Oklahoma State College (formerly Oklahoma School of Mines and Metallurgy) on left (north).
105.9	0.5	Intersection with State Highway 2. Turn right (south) on S.H. 2.
106.6	0.7	Cross trace of Choctaw Fault. Here, the fault juxtaposes shale probably in the lower part of the Atoka Formation in the hanging wall to the south against shale in the upper part of the Atoka Formation in the footwall to the north.
107.0	0.4	Cross poorly exposed Wapanucka Limestone on north limb of north-vergent, overturned Bandy Creek Anticline. A thrust fault separates the Wapanucka from the Atoka Formation immediately to the north.
107.3	0.3	Ridge to west is underlain by south-dipping Wapanucka Limestone–Spiro sandstone. This ridge continues for many miles to the west and east. Another thrust fault separates it from the overturned anticline at mile 107.0.
107.4	0.1	Cross Bandy Creek.

A field trip led by Arthur Bowsher and Norman Johnson of Sinclair Oil and Gas Company (Tulsa) stopped here in 1968 and walked down Bandy Creek across the axis of the north-vergent Bandy Creek Anticline (Cline, 1968). The Spiro sandstone and Wapanucka Limestone are exposed on both limbs of the anticline, and the "Springer Formation" (Morrowan shale) is exposed in the core. The Spiro sandstone along Bandy Creek contains abundant molds of a variety of fossils and is unlike the Spiro sandstone at Stop 14B but is similar to the "Spiro equivalent" sandstone in the basal part of the Atoka Formation ~9 mi south of here at Stop 12, mile 68.2, and mile 69.0.

107.7	0.3	For the next several miles, S.H. 2 crosses moderately south-dipping sandstones in the Atoka Formation.
108.8	1.1	Leave Wilburton 7.5′ quadrangle; enter Damon 7.5′ quadrangle.

Oklahoma School of Mines and Metallurgy

The Oklahoma School of Mines and Metallurgy was established on May 28, 1908. According to Miller (1940), its purpose was to "teach such branches in mining and metallurgy as will give a thorough technical knowledge of mines and mining, and of subjects pertaining thereto, including physics and mining engineering, mathematics, chemistry, geology, mineralogy, metallurgy, and subjects of shop work and drawing, the technical knowledge and properties of mine gases, assaying, surveying, drafting of maps and plans, and such other subjects pertaining to mining engineering as may add to the safety and economical operations of mines within the state."

The school's first president was Dr. George E. Ladd, who graduated from Harvard University. When the school opened in January 1909, about 100 students were enrolled. At that time, the school was located in a rented building on Main Street. In April 1911, newly constructed buildings on the campus just west of town were opened. Three courses (mine engineering, metal mining, and coal mining and metallurgy) and a number of short courses (chemistry and assaying, surveying and drafting, ore dressing) were offered.

Ladd resigned in early 1914 to become president of the New Mexico School of Mines (Wooldridge, 2004), and the school had a number of presidents, each lasting about a year. In 1916–17, courses in music, art education, and languages were offered, but in 1917 the school closed for 2 years because of the World War I draft. It reopened in the summer of 1919 as a school of trades and industry for disabled veterans. At that time, nearly 200 students were enrolled.

Enrollment dropped between 1919 and 1924, when courses in agriculture, trades, education, and the liberal arts were added. The school changed its name to Eastern Oklahoma State College in 1927, to Eastern Oklahoma Agricultural and Mechanical College in 1939, and back to Eastern Oklahoma State College in 1971. Currently, EOSC is a public college offering 2-year programs with associates' degrees. About 2,000 students are enrolled.

Oklahoma Miner Training Institute

Eastern Oklahoma State College (EOSC) is also the home of the Oklahoma Miner Training Institute (OMTI), which operates the Oklahoma Mine Safety Program (OMSP). The OMSP started operating in 1974, when buses equipped as mobile classrooms traveled to mine sites to provide training. In 1977 the old Carbon mine building, 4 mi east of Krebs, was renovated and housed the newly designated OMTI beginning in 1978. In 1988 OMTI was relocated to the campus of EOSC.

A brochure distributed by the OMTI states:

"The State of Oklahoma is a national leader in the promotion of mine safety. Employees of all mines in the state are required to be certified by the Oklahoma Mining Commission and the Mine Safety and Health Administration for their particular occupations. Approximately 1800 miners from Oklahoma and other states receive training from OMTI each year.

"The Mine Safety and Health Administration also requires operators to establish training plans and provide training for the miners they employ.

"Additionally, the Oklahoma Department of Mines performs monthly health and safety inspections on all minesites in the state.

"OMTI offers a variety of courses, ranging from new miner training to advanced training for supervisors. These courses vary from eight hours to ninety hours of instruction. All courses are approved by the Mine Health and Safety Administration."

109.9 1.1 Top of Blue Mountain (elev. 1,050 ft). Park here for Stop 15. We will walk down the road a few hundred yards and examine some thick amalgamated(?) sandstones in the Atoka Formation. Be very careful along this highway. The road is narrow, and the drivers are fast.

The sandstone sequence is ~500 ft thick and ~6,500 ft stratigraphically above the Spiro (Suneson and others, 1990, p. 14). The Red Oak sandstone in nearby Arkoma Basin gas fields is also ~6,500 ft above the Spiro. Bowsher and Johnson (1968, p. 43) suggested that this sandstone may be the Red Oak, but Suneson and others (1990) noted that the two are separated by three thrust faults and therefore probably were deposited in very different parts of the Arkoma/Ouachita Basin.

STOP 15

ATOKA SANDSTONE

Dennis R. Kerr
University of Tulsa

Location: south of the crest of Blue Mountain on north side of S.H. 2, NW¼NW¼ sec. 34 and NE¼NE¼ sec. 33, T. 5 N., R. 19 E., Latimer County, Oklahoma

"Red Oak Sand"(?) of the Atoka Formation

Atoka Formation sandstones crop out, as well as support, the south side of Blue Mountain in this road-cut exposure that is slightly oblique to strike (S. 80° W., dip 40° S.). Suneson and Ferguson (1989b) mapped this area as a continuous southward-dipping succession of Atoka Formation. Based on stratigraphic position above the base of the Atoka exposed in Bandy Creek, these middle Atoka sandstones have been correlated with the "Red Oak sand" (Bowsher and Johnson, 1968) in the Arkoma Basin to the north. In the Red Oak–Norris gas field, the Red Oak reservoir produced 658,552 MMcf gas through 1993 from 154 wells (Suneson and Hemish, 1994).

The "Red Oak sand" at this locality is made up of quartz-cemented, subarkosic, fine-grained sandstones (based on a description by Bowsher and Johnson, 1968) with thinly interstratified mudrocks. Most sandstones are structureless with a variety of sole markings. However, the upper surfaces of some sandstones display short-crested ripple marks, pebble-size mudstone intraclasts (many are at present molds) and gravel-sized carbonaceous fragments, and sandstone dikes. Ripple marks indicate eastward-directed paleocurrents. Most investigators who have measured paleocurrent orientations in the deep-water Atoka sandstones report westward-directed paleocurrents. Intraclast and carbonaceous-fragment long-axis orientations, as well as weak imbrication, are aligned transverse and parallel to the ripple-mark paleocurrent trends. Ferguson and Suneson (1988) demonstrated the prevalence of eastward-directed paleocurrent indicators throughout the Atoka between the Choctaw and Pine Mountain Faults from southern sections of T. 5 N., R. 19 E., southwestward to eastern sections of T. 4 N., R. 17 E. In addition, they suggested that structural elements active at the time of deep-water Atoka sedimentation subdivided the basin and controlled paleodispersal patterns. McGilvery and Houseknecht (2000) report southward- and westward-directed sole marks from the Atoka elsewhere on Blue Mountain (exact location not disclosed). They also suggest that this sandstone was deposited in a channel near the center of a marginal submarine-fan lobe (p. 136). Although McGilvery and Houseknecht (2000) do not explicitly state that this sandstone correlates with the Red Oak sandstone to the north, their figures 4 and 7A strongly imply it.

This is the last stop on the field trip. The road log continues to just east of Red Oak and mile 24.4 of this day's field trip.

		Return to cars and retrace route to U.S. 270 just west of Wilburton.
113.9	4.0	Turn right (east) on U.S. 270.
114.4	0.5	Intersection with S.H. 2 to left (north). Continue straight on U.S. 270.
114.9	0.5	Enter Wilburton, Oklahoma. Continue west on U.S. 270 through the center of town. The boundary of Wilburton gas field is ~1 mi east of town.

Wilburton Area Coal-Mine Hazards

The Hartshorne coals have been extensively underground-mined near Wilburton and strip-mined west of town. Although some coal was mined for use by the Butterfield Overland Stage Line (mile 116.9), large-scale mining in the area began "in 1887 with the construction of the Choctaw Coal and Railway Company line from Wister to McAlester" (Gunning, 1975, p. 39). Hendricks (1939, pl. 27) shows the extent of the underground mines as of 1931 and lists the major coal companies: Missouri Kansas and Texas Coal, Eastern Coal and Mining, Degnan and McConnell, Great Western Mining, Hailey–Ola Coal, among others. The OCC estimates that ~1,500 acres is undermined in the Wilburton area. In the mid-1930s, most of the underground mines closed, and in the early 1940s strip mines opened along the outcrops of the Hartshorne coals. Most of the strip-mining operations had ceased by 1960.

The OCC divides the Wilburton area into a number of "problem areas" because of the modern hazards left as a result of the old mining operations. These problem areas are, from west to east, the Degnan Underground and Strip Mines P.A., Wilburton West Underground and Strip Mines P.A., Wilburton East Underground and Strip Mines P.A.,

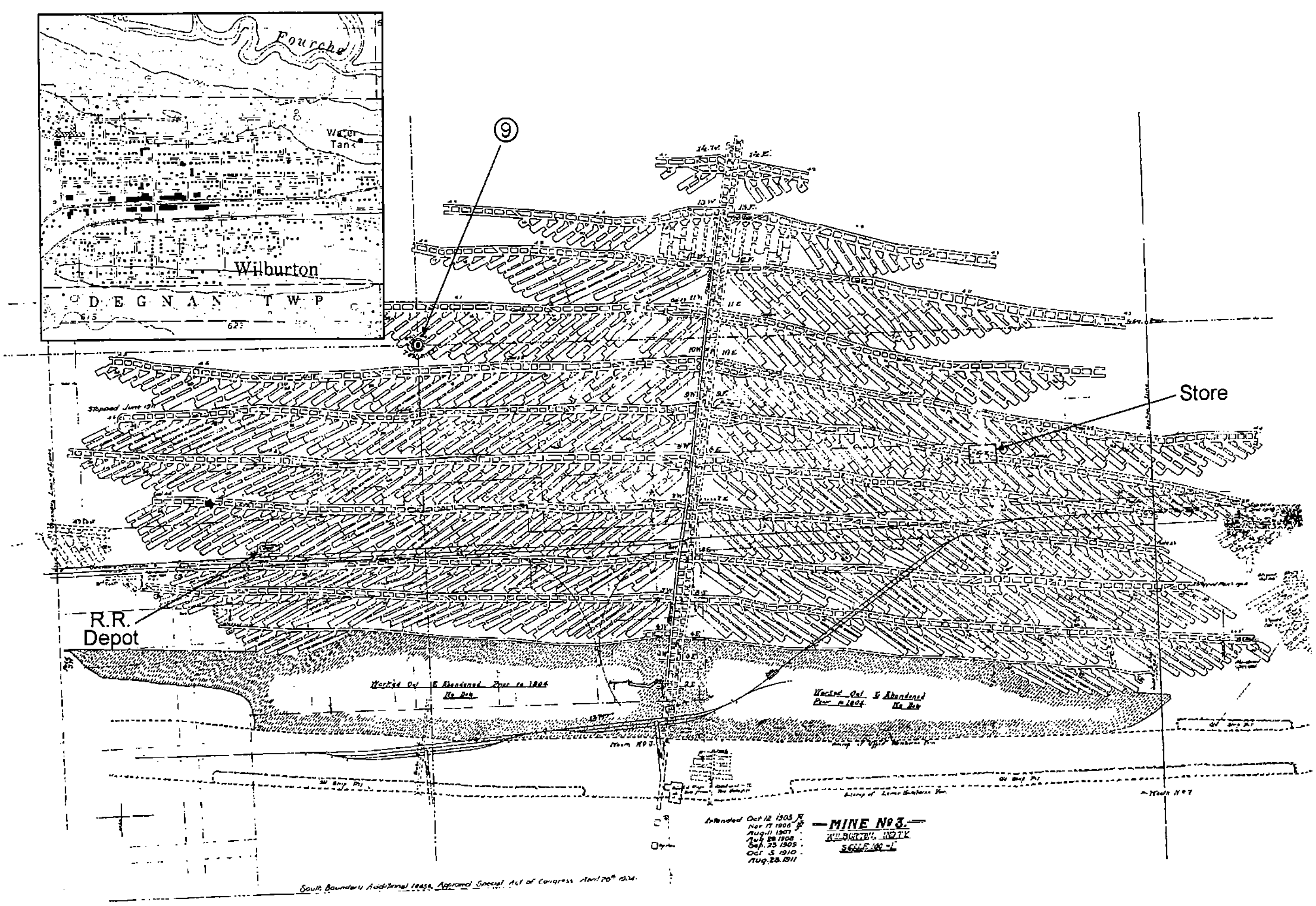

Figure 102. Mine map of the Great Western Mining Company Mine No. 3. For orientation, the circled 9 is the center of sec. 9, T. 5 N., R. 19 E.; the north–south line on the right side of the map is the east line of sec. 9; the railroad depot is the small rectangle on the left side of the map, and the railroad runs east–west just south of the depot; and the store on the right side (rectangle) may have been located on the east side of town at mile 115.4. Inset map is USGS 1971 topographic map of sec. 9.

Lutie Underground Mines P.A., and the Panola Underground Mines P.A. Hazards associated with the old operations include subsidence, vertical openings, steep slopes of spoil piles and highwalls, water bodies, and unauthorized recreation. Perhaps the most serious and continuing hazard is subsidence over the Great Western Mining Company Mine No. 3 (Fig. 102 [on facing page]), particularly in that part south of Wilburton south of the railroad tracks. Periodically, houses, roads, and utilities are damaged owing to surface subsidence into the mine.

Strip mines in the McAlester coal are present north of town.

115.4 0.5 Road forks. Stay left on U.S. 270. An old store used to be at the fork.

116.9 1.5 Lutie Coal Miner's Museum on left (north). This is an excellent small museum and well worth a visit (Fig. 103).

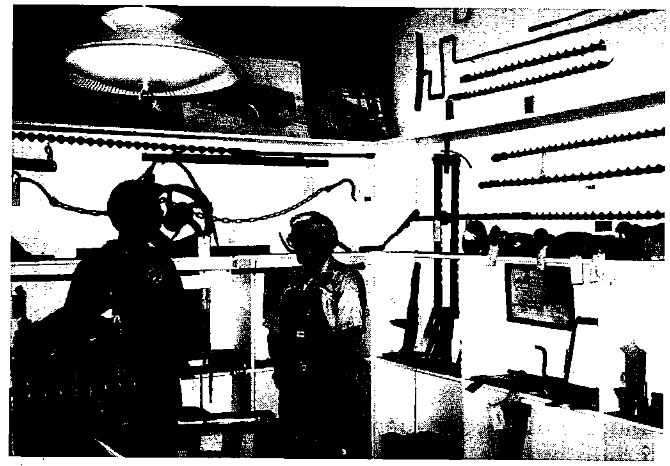

Figure 103. Lutie Coal Miner's Museum. OGS geologist Brian Cardott (left) and owner Tom Pate (right).

Riddle Station

About 1 mi east of the Lutie Museum and just south of U.S. 270 is the Lutie Cemetery. The cemetery is very close to the site of Riddle Station, another stop on the Butterfield Overland Stage Line.

From Gunning (undated, p. 25):

"The Riddle Station was east of the present city limits of Wilburton, being just east and across the road from the Lutie Cemetery. The station was a two room log house with breezeway and the usual stone chimneys. Riddle was from Irish stock and his mother was Choctaw. He is believed to have moved to the Choctaw Nation in young manhood and settled near where the station was established. Riddle's land formed a large plat between Big Fourche Maline Creek and Bandy Creek, a nearby tributary. Some of the land was bottom, some prairie, and some hillside. The westward extension of the hillside formed what is now South Hill in Wilburton. Wood, water and shale were abundant here in the station area and seams of good coal outcropped in the hillside to the south of the station. This coal was mined and used for fuel and forge. There was considerable blacksmithing to do in the Butterfield business as well as for the Choctaw farmers and ranchers, and the coal was a boon to the blacksmith forges. It is known that much coal was mined and shipped by wagon to other blacksmith shops east and west of the Riddle Station along the Butterfield Road. The Company itself operated blacksmith shops at intervals along the route."

Enter Panola gas field.

Panola Gas Field

The Panola gas field was discovered by the Mobil No. 1 Pete Parks well (SE¼SW¼SW¼ sec. 33, T. 6 N., R. 20 E.), which was spudded on September 1, 1963. Drilling was finished on January 14, 1964, and the well was completed on February 18, 1964, in the Spiro sandstone at 13,089–13,114 ft for 831 Mcf gas per day.

As of July 2004, there were 65 wells in the Panola field, of which 53 were active; the field has produced ~119 Bcf gas (data courtesy IHS Energy). The principal reservoirs are sandstones in the middle part of the Atoka Formation, including, from top to bottom, the Red Oak, Panola, Diamond, Bullard, Cecil, Shay, and Spiro. The only middle Atoka sandstone that does not appear to produce gas in the Panola field is the Brazil sandstone. In addition, Oklahoma Corporation Commission 1002A forms show "lower" and "upper" Atoka sandstones as producers.

Andrews (in preparation) is completing a detailed study of the Panola field.

118.2 1.3 Leave Wilburton 7.5′ quadrangle; enter Panola 7.5′ quadrangle.

120.4 2.2 County road to right (south) in small town of Panola.

The 1998 field trip examined the Hartshorne Formation ~1 mi south of here (stop 9). The Upper and Lower Hartshorne coals have been extensively underground-mined west of Panola, and the area is now part of the Oklahoma Conservation Commission's Panola Underground Mines Problem Area.

Three small adits in the McAlester coal are present immediately north and west of Panola just north of the highway. The McAlester and Upper McAlester coals are present.

123.8 3.4 Leave Panola gas field.

124.3 0.5 Craven Corner; county road to right (south).

The 1994 field trip examined the Hartshorne Formation ~1.5 mi south of here (stop 8). The same outcrops also were visited on the 1998 field trip on the Hartshorne Formation (stops 10A and 10B).

From north to south, the county road crosses a low ridge underlain by the Tamaha Sandstone (upper Booch), then a higher ridge underlain by the Cameron Sandstone

Figure 104. Photograph of Farrell-Cooper Mining Company's dragline at Red Oak South mine site. "The Page 736 dragline (26 yard bucket, 200 ft boom) was moved south across U.S. Highway 270 in December 1996 to sec. 32, T. 6 N., R. 21 E., to mine the McAlester coal (2.1 ft thick, 3.3% sulfur) and Upper McAlester coal (1.7 ft thick, 4.6% sulfur)" (Cardott and Levine, 2004, p. 4).

(middle Booch), and then a double ridge underlain by the Upper and Lower Warner Sandstones (lower Booch). Finally, the road crosses a low ridge underlain by an unnamed sandstone in the McCurtain Shale Member of the McAlester Formation. Unlike the ridge underlain by the Hartshorne Formation, the ridges underlain by sandstones in the McAlester Formation are discontinuous and vary from low, subdued ridges to relatively high, sharp ridges. Most likely these topographic differences reflect variations in the amount of sandstone at any particular interval in the McAlester. Thus, on the basis of topographic expression, the sandstones in the McAlester Formation in this part of the Arkoma Basin are discontinuous, and the sandstone members contain varying amounts of sandstone, siltstone, and shale.

125.6 1.3 Leave Panola 7.5′ quadrangle; enter Red Oak 7.5′ quadrangle.

126.6 1.0 Farrell-Cooper's Red Oak South coal mine is immediately south of the highway (Fig. 104). The McAlester coal was mined, and the area is now completely reclaimed.

128.3 1.7 Intersection with S.H. 82 to the right (south). This is the same point as mile 24.4.

End of road log.

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