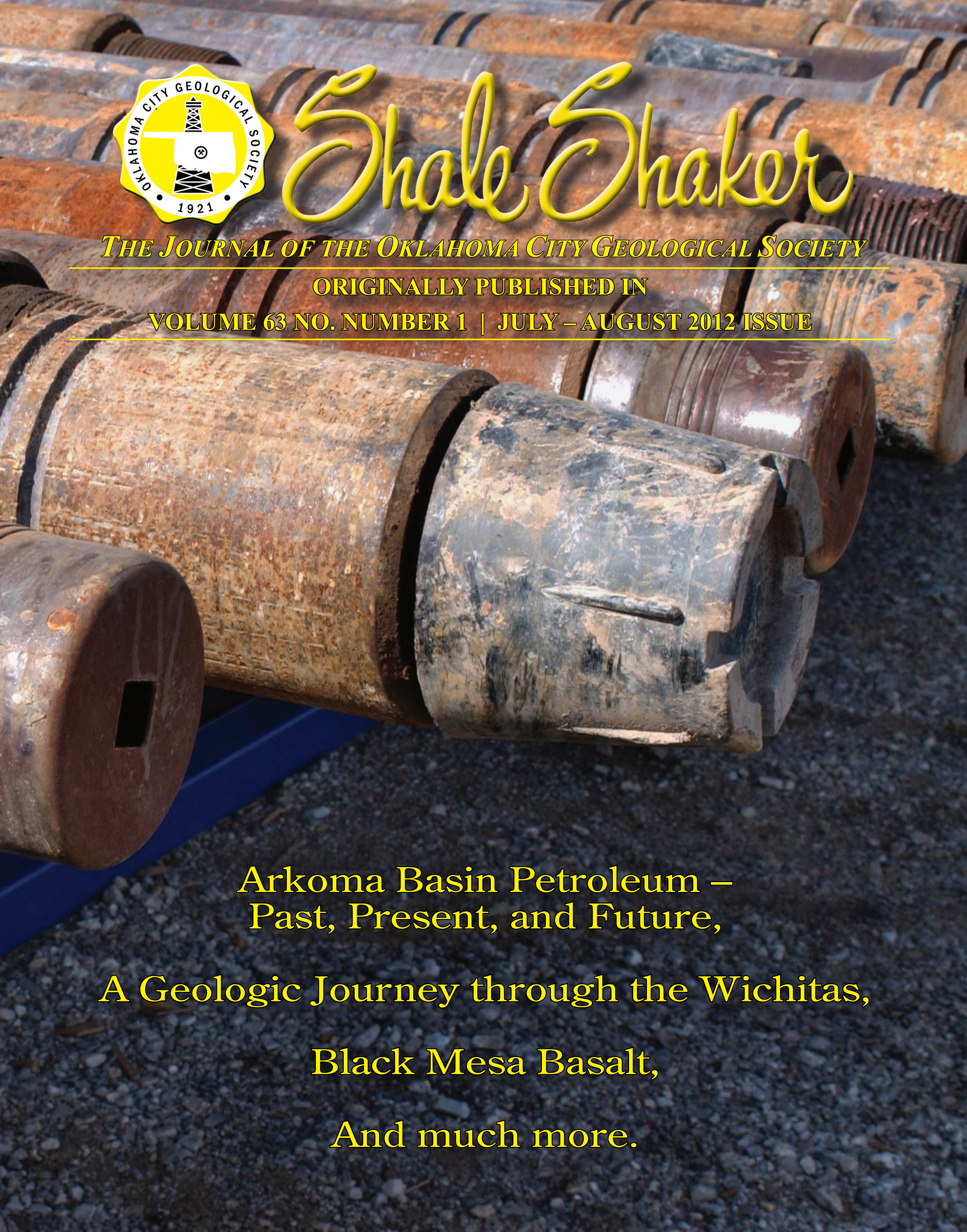

Shale Shaker

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Arkoma Basin Petroleum –
Past, Present, and Future,

A Geologic Journey through the Wichitas,

Black Mesa Basalt,

And much more.

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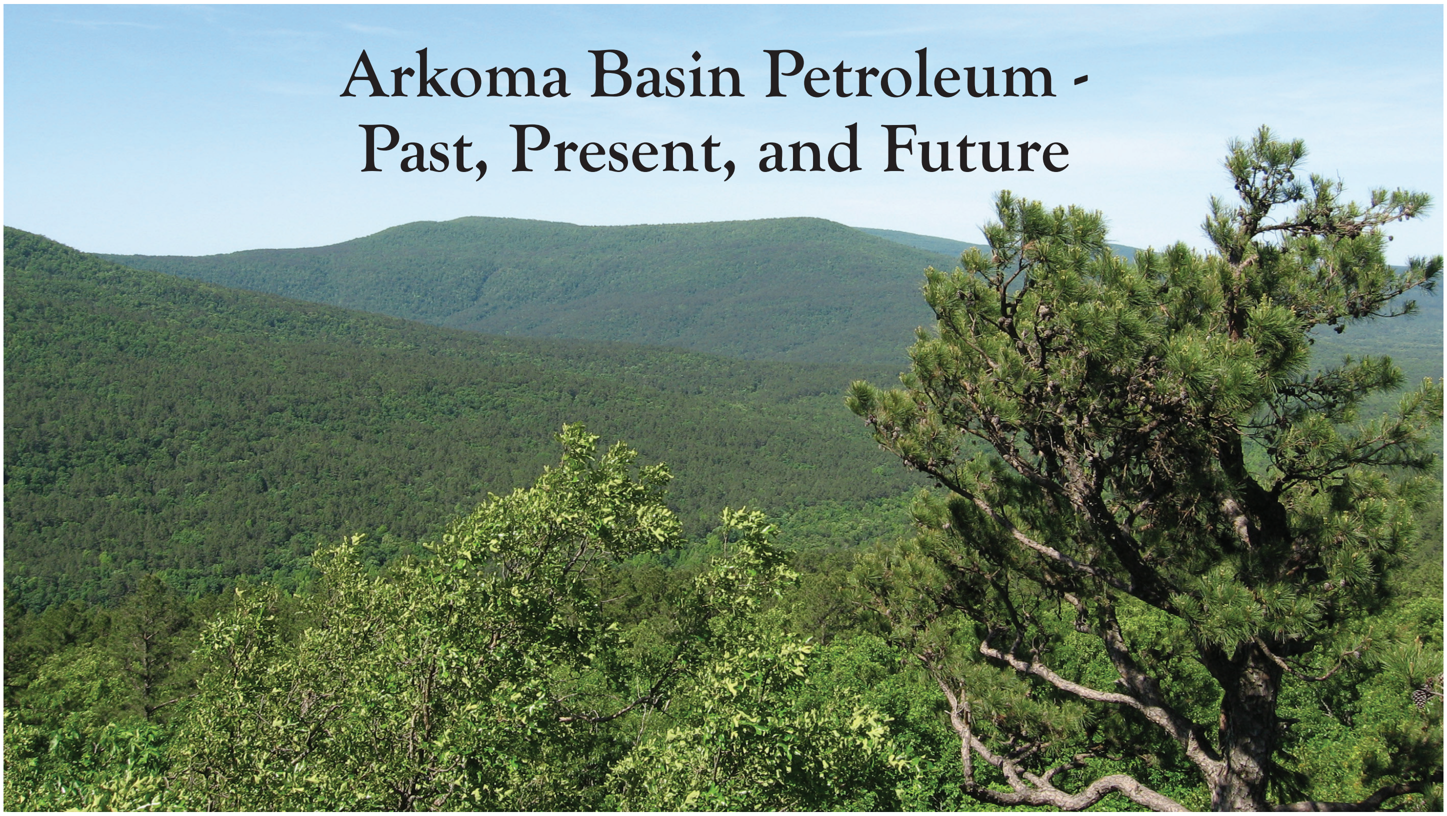


Arkoma Basin Petroleum - Past, Present, and Future

ABSTRACT

The Arkoma Basin is a classic peripheral foreland basin bounded on the south side by a fold-and-thrust belt – the Ouachita Mountains. Thus, the basin can be viewed as the most northern, least deformed, and youngest part of a northward-migrating foreland basin that began forming in the Early Mississippian and contains the Stanley and Jackfork Groups, Johns Valley Shale, and Atoka Formation. The three oldest of these units, and much of the youngest, are now complexly deformed and were incorporated into the also northward-advancing tectonic belt. Some petroleum reservoir types occur (or should occur) in the Arkoma Basin and the Ouachita Mountains, and others are unique (or are they?) to one or the other. Applying what we know about the different reservoir types to other areas and/or other units will form the basis for future petroleum discoveries in southeast Oklahoma.

The history of Arkoma Basin and Ouachita tectonic belt hydrocarbon exploration and development started with coal and asphaltite. Early drilling for oil and gas focused on surface anticlines. During WWII, the US and Oklahoma governments produced a number of geologic maps designed to better understand the coal and petroleum resources of southeastern Oklahoma. Subsequent deeper drilling led to a better understanding of the structural geology of the area and facies relations of the different reservoir units. Most recently, advances in horizontal drilling and hydraulic fracturing have turned coal and shale into viable gas (and oil) reservoirs.

Introduction – A Foreland Basin

(Note: This paper follows up an oral presentation given by me at a workshop sponsored by the Oklahoma Geological Survey and the Oklahoma City Geological Society on March 7, 2012, titled "Oklahoma Structural and Stratigraphic Oil and Gas Workshop." The powerpoint for that talk is available at http://www.ogs.ou.edu/MEETINGS/Presentations/OilGasMar2012/SunesonArkOuach.pdf)

The Arkoma Basin in southeastern Oklahoma and west-central Arkansas is one of the most prolific petroleum-producing basins in North America. It is one of several Carboniferous foreland basins that surrounds the craton; in the southern midcontinent, these include the Black Warrior, Arkoma, Fort Worth, Kerr, and Val Verde Basins (Figure 1). This report describes the history of petroleum exploration and development in the Oklahoma part of the Arkoma Basin, highlights certain aspects of the geology where questions remain, and speculates on how answers to those questions might lead to important discoveries in the future. Some aspects of Arkoma Basin petroleum geology, however,

(Note: Throughout this paper I have tried to distinguish formally named stratigraphic units – those identified and described from surface outcrops and named in the professional literature, from informal units – those typically identified in the subsurface and used by industry geologists. Formal names are capitalized, e.g., Wapanucka Limestone; informal names are lower-cased, e.g., Spiro sandstone. In some cases, however, I have chosen to shorten the names of reservoir units, e.g., "Jackfork sandstones" rather than the more formal (and technically correct) "sandstones in the Jackfork Group.")

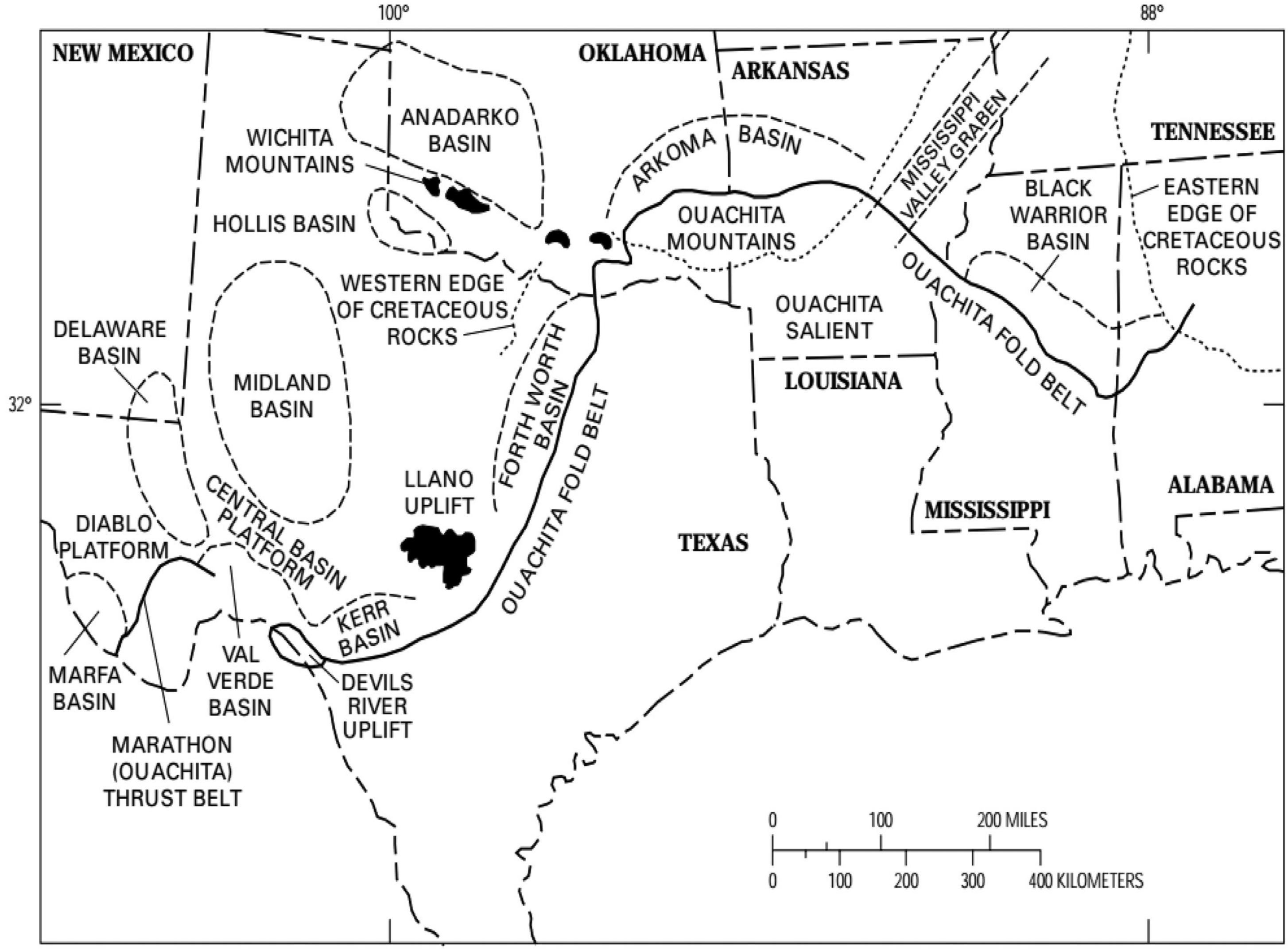


Figure 1. Map of petroleum-producing basins in the southern midcontinent. Foreland basins are those that are adjacent to the Ouachita fold belt including, from east to west, the Black Warrior, Arkoma, Fort Worth, Kerr, and Val Verde Basins. (From Perry, 1997)

are well beyond my expertise and I will make no attempt to address them, including the geology of the Arkansas part of the basin, geophysical exploration efforts, and economics/infrastructure issues surrounding possible petroleum production. In addition, others have addressed issues such as the thermal maturity of the sediment pile and the effect of diagenesis on the reservoir quality of individual units, and I will not review these studies.

The Arkoma Basin is a peripheral foreland basin (PFB) (as described by Allen et al. (1986), Miall (1995), and DeCelles and Giles (1996)) caused by the collision of the North American and Gondwanan plates starting in the Early Mississippian and ending in the Middle Pennsylvanian. One of the characteristics of foreland basins is that they are adjacent and parallel to a compressional orogenic belt; in this case, the sedimentary and structural history of the Arkoma Basin is closely related to that of the Ouachita fold-and-thrust belt. The commonly recognized southern boundary of the Arkoma Basin – the trace of the Choctaw Fault (Figure 2) – is arbitrary; had tectonism not ceased when it did in the Desmoinesian, what we now map as the Arkoma Basin would be part of the Ouachita belt and the southern part of the Cherokee Platform would have subsided and become a foreland basin. In addition and as will be discussed below, several petroleum-exploration plays are common to both regions. Therefore, for the purposes of this paper, the Ouachita orogenic belt is included with the Arkoma Basin.

Allen et al. (1986), Miall (1995), and DeCelles and Giles (1996) list a number of features that characterize PFBs that, when combined with Wickham et al.'s (1976) plate-tectonic model of the Ouachita belt, explain many aspects of the geology of the Arkoma Basin and the Ouachita Mountains. For example:

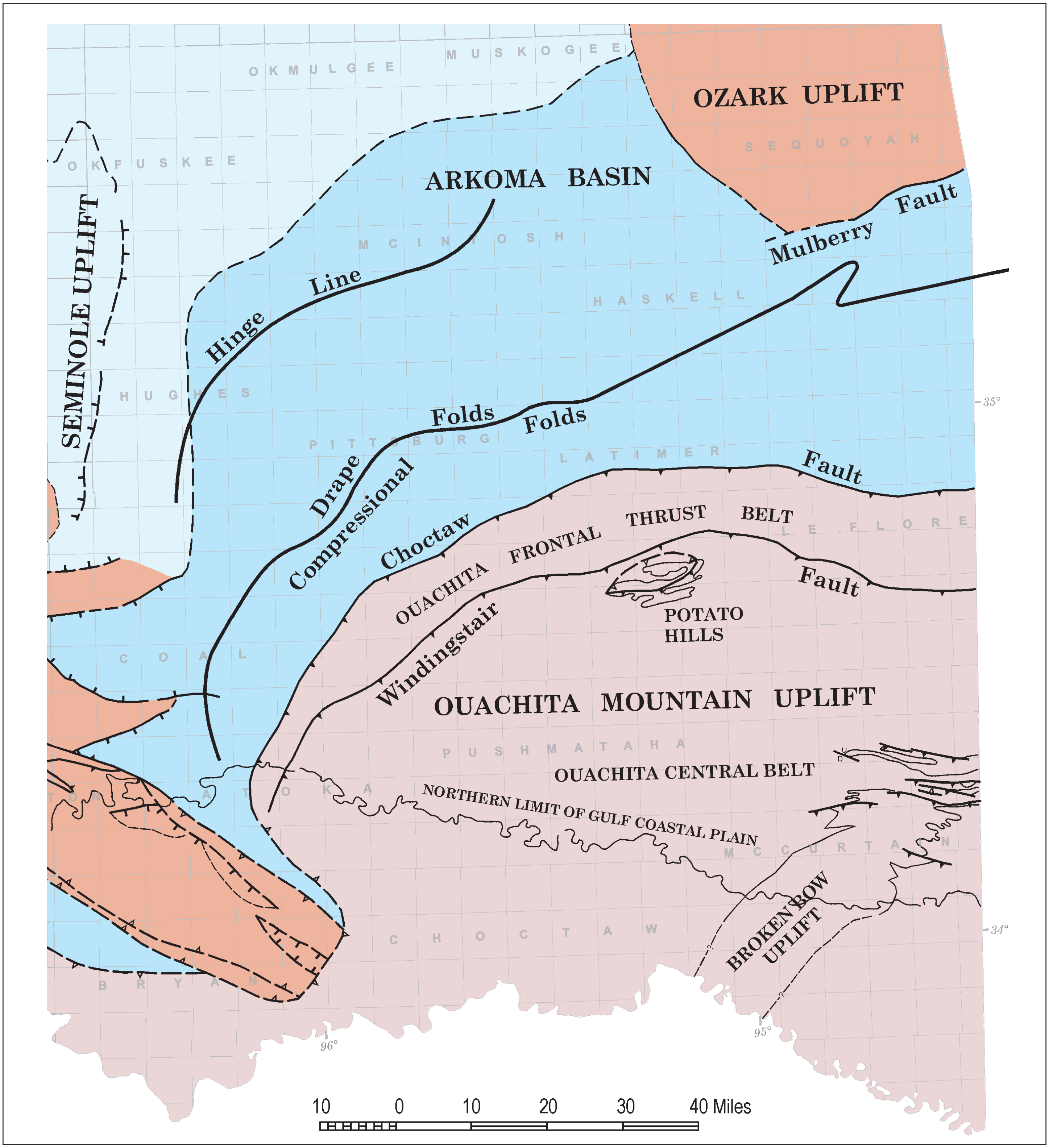
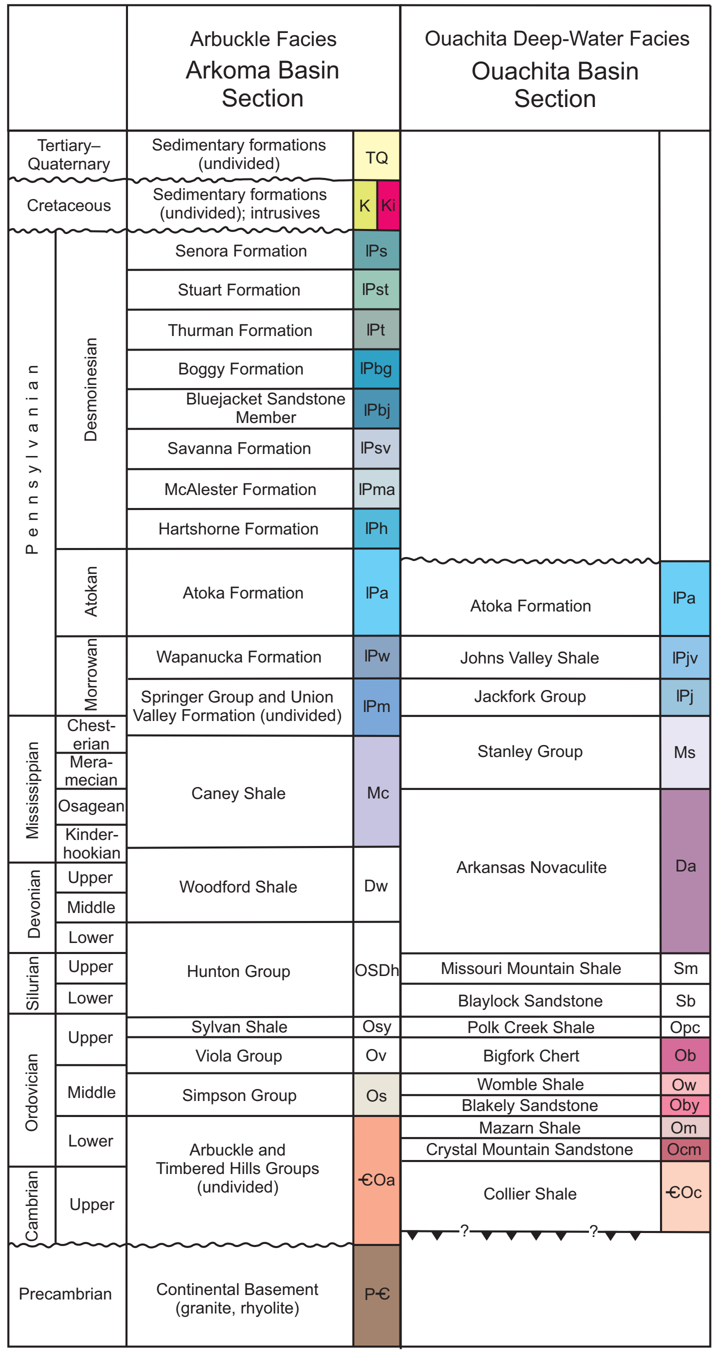


Figure 2. Map of Arkoma Basin and Ouachita Mountains (modified from Northcutt and Campbell, 1995). Northern boundary used by Northcutt and Campbell (1995) is 0-ft isopach of the Atoka Formation from Weirich (1953). Hinge line is of McAlester Formation and is from Busch (1974, fig. 101). Boundary between areas of drape folds and compressional folds is from Arbenz (2008, pl. 1). Outline of Broken Bow Uplift is shown as the contact between the Arkansas Novaculite and Stanley Group.

1. Oversteepening and faulting of the continental slope as a result of thrust loading may result in slump and slide masses. This is the origin of many of the olistostromes in the Johns Valley Shale (Figure 3).
2. Foreland basins may contain several clastic pulses. In the Ouachita belt, these are represented by the Stanley and Jackfork Groups and Atoka Formation (Figure 3).
3. The stratigraphic sequence typically reflects the filling of the basin and the progression from deep- to shallow-water deposits. This is marked in the Arkoma Basin by the transition from middle Atoka Formation turbidites to upper Atoka and Hartshorne Formation shallow-marine and fluvial-deltaic deposits.
4. Axial sediment dispersal is common in many PFBs. Paleoflow directions in most of the turbidites in the Ouachita belt are from east to west, parallel to the axis of the Arkoma Basin.
5. Bally et al. (1966) (cited in Miall, 1995, p. 415) identified foreland basins as "migrating foredeeps." Some reconstructions of the Arkoma Basin – Ouachita belt suggest a south-to-north migration of the Stanley, Jackfork, and Atoka depocenters (e.g., Morris, 1974) and the cross sections shown in Figure 4 assume such a history.

Figure 3. Stratigraphy of the Arkoma Basin and Ouachita Mountains and correlation of Arbuckle and Ouachita facies strata. (Modified from Arbenz, 2008, pl. 2)



Many other examples exist.

In fact, so many characteristics of PFBs are observed in Arkoma Basin – Ouachita Mountains geology that those characteristics that have not been positively identified in the past (e.g., a forebulge, reactivation of normal faults into reverse faults, transverse sediment sources) should be and are being looked for. Recently, Mazzulo et al. (2011) have suggested that features within Mississippian strata in northern Oklahoma and adjacent states are evidence for a Ouachita-related forebulge. Brief observations by R.M. Slatt and me in Choctaw County suggest that some sandstones in the Jackfork Group may have been sourced to the south.

Arkoma Basin – Boundaries and Subdivisions

The boundary between the Arkoma Basin and Ouachita orogenic belt is well defined in Oklahoma as the trace of the Choctaw Fault (Figure 2). The Choctaw Fault is the northernmost continuous exposed fault of the Ouachita fold-and-thrust belt. The Choctaw Fault is listric; at the present level of erosion it dips steeply south, but it flattens to the south and is more properly considered a thrust fault. The Choctaw Fault as a boundary is convenient but arbitrary because reverse faults (albeit discontinuous) are present north of the Choctaw Fault. In addition, to the east in western

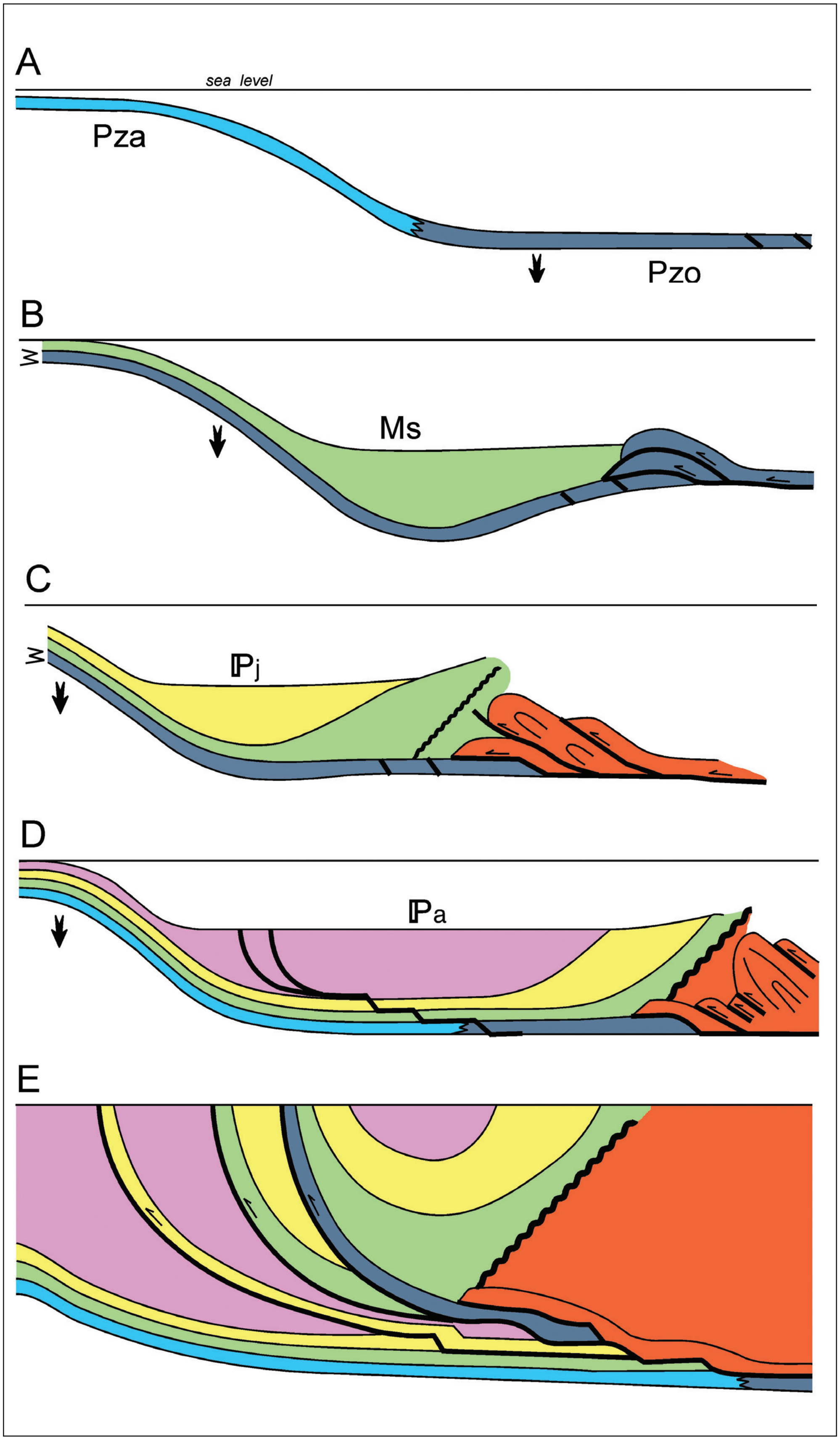


Figure 4. Cross sections showing the development of the Ouachita tectonic belt and Arkoma Basin in Oklahoma (based largely on Arbenz, 2008, pl. 9). A. Cambrian – Devonian. Long-lived shelf (north) – slope – basin (south). Arbuckle facies strata (Pza) deposited on shelf at same time as Ouachita facies strata (Pzo) deposited in basin. Location of facies transition unknown, but certainly south of present-day Red River. Arrows in all cross sections show location of subsequent basin depocenter. B. Subsidence of Stanley (Ms) foreland basin in response to thrusting and tectonic loading. Wedge zone composed of thrust-faulted Pzo develops on south margin of Stanley basin. Wedge zone is subaqueous and contributes little sediment to basin, resulting in dominantly axial sediment dispersal. C. Subsidence of Jackfork (IPj) foreland basin north of axis of Stanley basin in response to continued thrusting and tectonic loading. Lower part of Stanley (shown below wavy line) possibly incorporated into wedge zone. Wedge zone is still subaqueous resulting in dominantly axial distribution of Jackfork sediments. D. Subsidence of Atoka (IPa) foreland basin north of axis of Jackfork basin in response to continued thrusting and tectonic loading. Wedge zone remains below sea level. Heavy lines show location of subsequent thrust faults. E. Severe telescoping of all but northern part of Arkoma Basin to form Ouachita tectonic belt. Desmoinesian foreland basin subsides slightly. Tectonic belt rises above sea level in latest Atokan in southwest (present-day Atoka County) and early Desmoinesian to northeast (Pittsburg County). Not shown – late-stage uplift of wedge zone to south forming Broken Bow Uplift.

Arkansas, displacement on the Choctaw Fault decreases to zero and the Ross Creek Fault serves as the boundary between the two geologic provinces. Arbenz (2008) recognized that this tectonic boundary is somewhat arbitrary and chose to call that part of the Arkoma Basin characterized by folds and reverse faults the Southern Arkoma Fold Belt.

In Oklahoma the south-side-down Mulberry Fault separates the Arkoma Basin from the Ozark Uplift near the Arkansas border (Figure 2). The "traditional" boundary is geomorphic along the southwest edge of the Ozark Uplift where it follows the Arkansas River.

The northwestern boundary of the Arkoma Basin can be defined in two ways that are partly, if not largely, coincident (Arbenz, 1989). Stratigraphically, middle Atokan through middle Desmoinesian (Cherokee) strata thicken southward off the Cherokee Platform into the Arkoma Basin (e.g., Visher et al., 1971, fig. 3) and the hinge line for this thickening is used by some as the margin of the Arkoma Basin. (For example, Busch (1974, fig. 101) uses the hinge line of the Desmoinesian McAlester Formation as the shelf-basin boundary (Figure 5).) Obviously, the hinge line for any individual unit is not precise and would differ from unit to unit; thus, the boundary is similarly imprecise. Structurally, the northwestern boundary of the Arkoma Basin can be defined as separating folded (to the south) from unfolded (to the north) strata (e.g., Branan, 1968, fig. 5) (Figure 6). Like the stratigraphic boundary, the structural boundary is also somewhat imprecise.

The western boundary of the Arkoma Basin (Figure 2) can be defined as the eastern margin of the subsurface Seminole Arch or the western limit of folded Desmoinesian strata. Like the northwestern boundary, these are largely coincident. The southwestern limit is the partly buried (by Cretaceous strata) Arbuckle Mountains.

Arbenz (1989; 2008, pl. 1) divides the Arkoma Basin into two regions (Figure 2). The shallow geology of the southern part is dominated by compressional structures – thrust-cored anticlines that are the traps for most of the major gas fields in the basin (Figure 7A). Folds in the northern part of the basin are "drape" anticlines over mostly middle Atokan south-side-down normal faults; there is no evidence here for compression (Figure 7B). Like their counterparts to the south, these folds also form traps. As is discussed below, identification of these structures (folds, normal faults, thrust faults) has been one key to the development of Arkoma Basin gas reservoirs, and further delineation of triangle-zone structures such as duplexes will continue to be important, particularly in the very southern part of the basin adjacent to the Choctaw Fault.

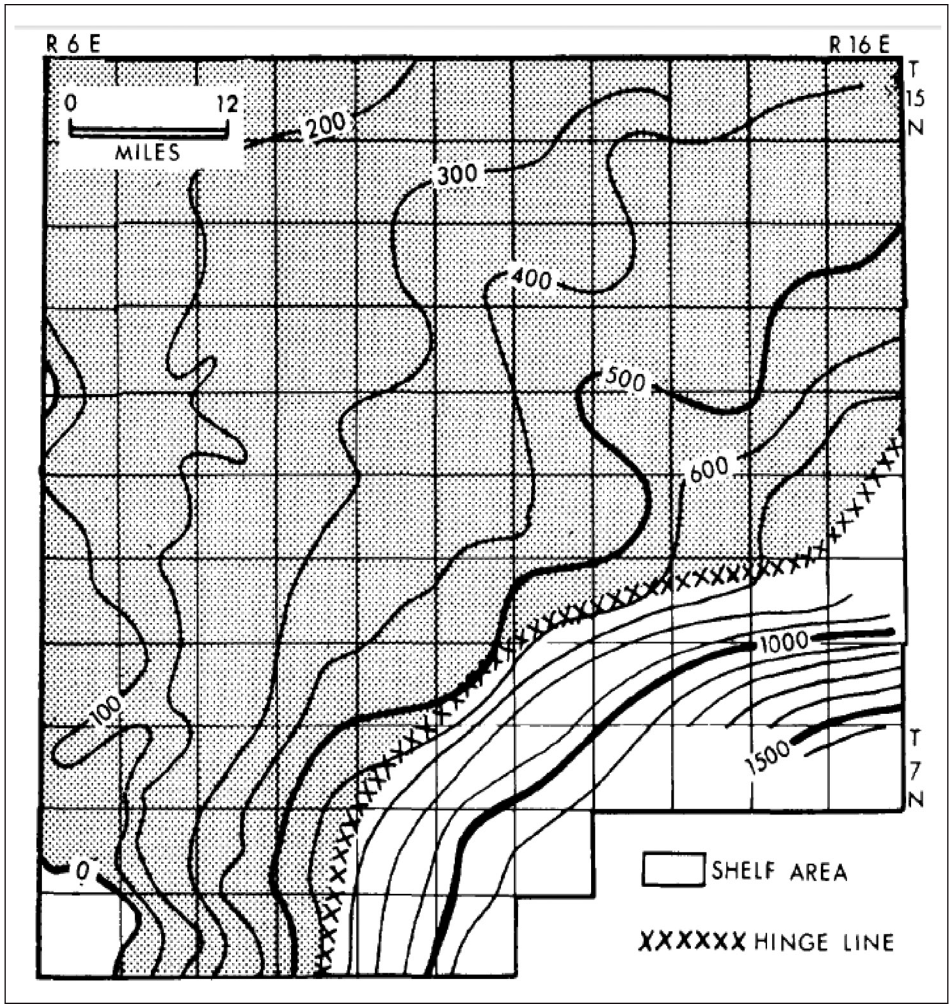


Figure 5. Isopach map of McAlester Formation. Hinge line used by some to separate Cherokee Platform to north from Arkoma Basin to south. (From Busch, 1974, figure 101)

Ouachita Mountains – Boundaries and Subdivisions

Unlike most of those in the Arkoma Basin, the boundaries of the Ouachita fold-and-thrust belt in Oklahoma are well defined. The northern boundary is the trace of the Choctaw Fault (Figure 2). Along most of its length in Oklahoma, the Choctaw Fault juxtaposes steeply south-dipping shale in the Atoka Formation to the south against moderately north-dipping shale in the Atoka Formation to the north. Because the shale is easily weathered the fault is not exposed; however, it can commonly

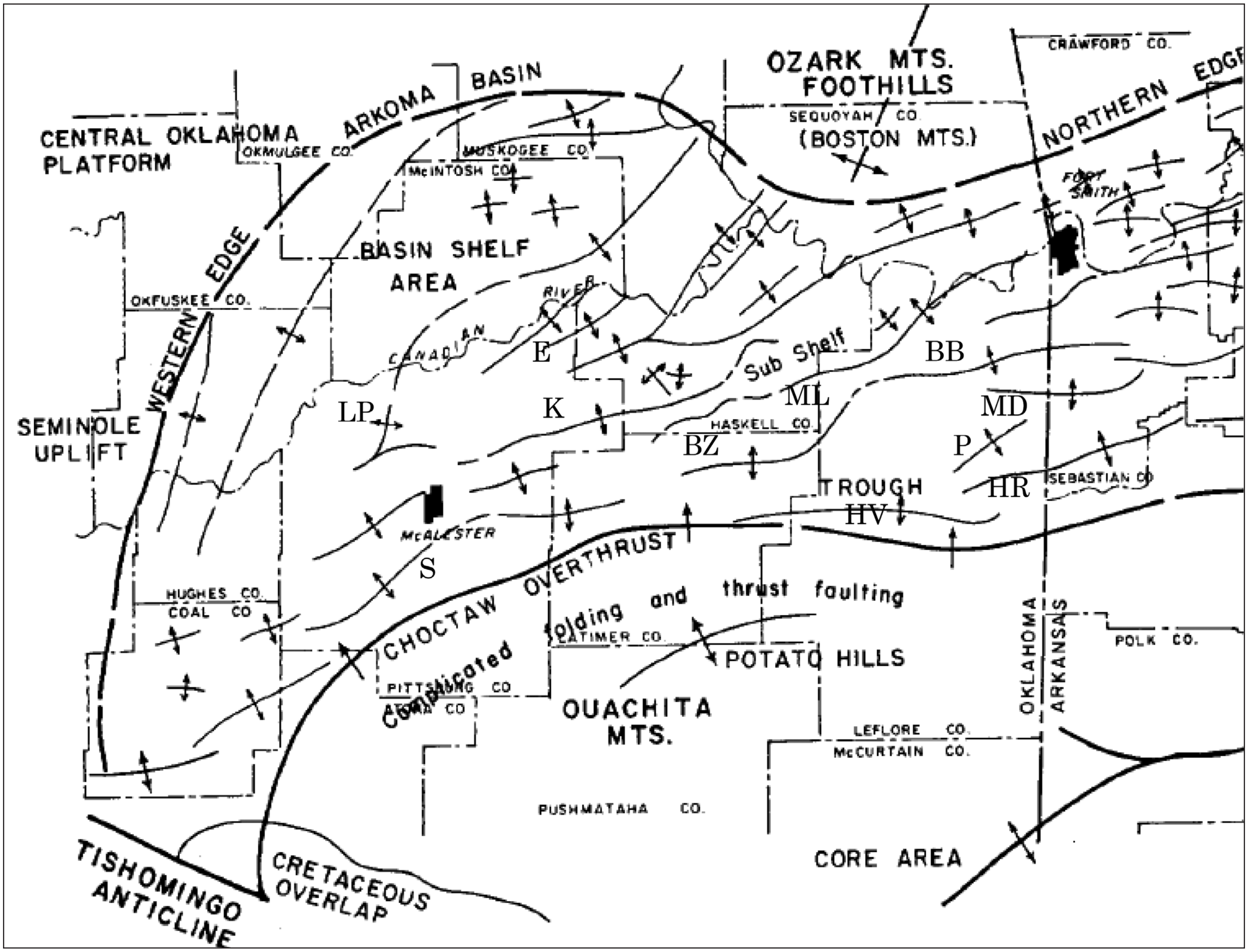


Figure 6. Map of major anticlines in the Arkoma Basin. (Modified from Branan, 1968, figure 5). Abbreviations: HV – Heavener; BB – Backbone; ML – Milton; P – Poteau; HR – Hartford; MD – Midland; BZ – Brazil; K – Kinta; S – Savanna; LP – Lily Pad Creek; E – Enterprise.

be mapped to within about a quarter-mile. The southern boundary of the Ouachitas is the Cretaceous overlap (Figure 2); in Oklahoma highly deformed Paleozoic strata are unconformably overlain by subhorizontal Lower Cretaceous Antlers Formation, De Queen Limestone, or Holly Creek Formation (west to east, younger to older). Ouachita strata remain buried beneath younger strata for 400 mi to the southwest where they are exposed in the Marathon Mountains of west Texas (Figure 1).

Suneson et al. (1990) divided the Ouachita belt into three parts based on surface structural geology (Figure 2): a northern part (frontal belt) characterized by closely spaced imbricate reverse faults (thrust faults in subsurface) and tight to isoclinal and locally overturned north-vergent folds; a central part (central belt) dominated by broad, open synclines separated by tight, typically thrust-cored anticlines; and the Broken Bow Uplift, an area of complex isoclinally folded and thrust-faulted Early Ordovician to Early Mississippian strata. The frontal and central belts are separated by the Windingstair Fault. Suneson et al. (1990) suggested that the boundary between the central belt and Broken Bow Uplift is stratigraphic and marked by the Arkansas Novaculite – Stanley Group contact. In contrast, Arbenz (2008) mapped a zone of decollement in the upper part of the Stanley separating complexly deformed, shale-dominated strata below from sandier, structurally simpler strata above.

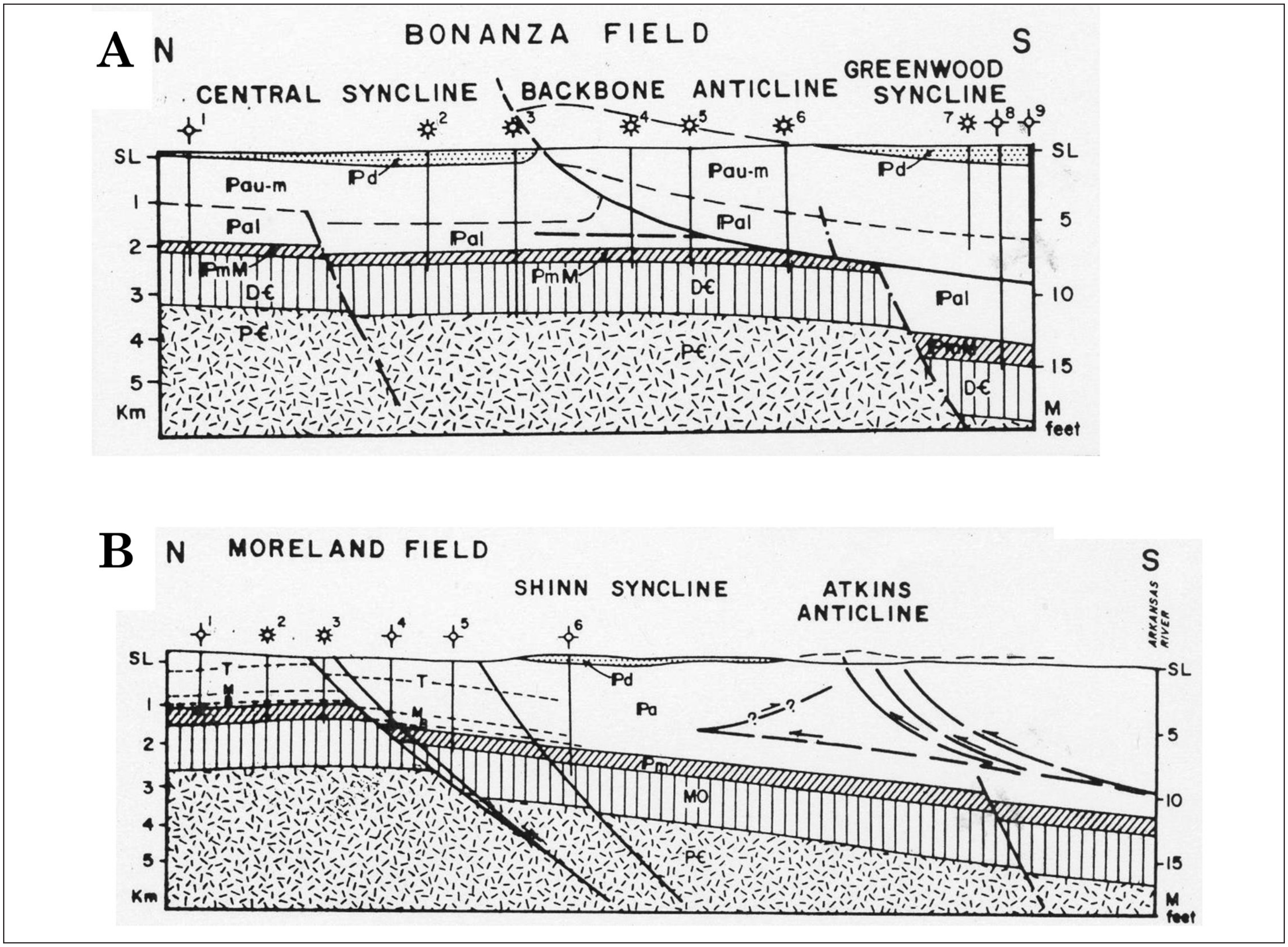


Figure 7. A. Cross section across the Bonanza Anticline and Bonanza Gas Field, Sebastian County, Arkansas, showing example of compressional-style trap (from Arbenz, 1989, figure 1). IPd – Desmoinesian; IPau-m – upper and middle Atokan; IPal – lower Atokan; IPmM – Morrowan and Mississippian; DC – Devonian through Cambrian; PC – Precambrian basement. B. Cross section across the Moreland Field, Pope County, Arkansas, showing example of drape-folded trap (from Arbenz, 1989, figure 2). IPd – Desmoinesian; IPa – Atokan; IPm – Morrowan; MO – Mississippian through Ordovician; PC – Precambrian basement. T, M, and B are marker-bed sandstones.

Most of the frontal belt is underlain by Morrowan and Atokan strata. Mississippian Stanley Group is present north of the Windingstair Fault near the Arkansas state line, and Ordovician and younger strata are present at Black Knob Ridge near the town of Atoka for about 10 mi north of the Cretaceous overlap. (Here, however, positive identification of the Windingstair Fault is difficult because all the faults form a complex anastomosing pattern (Hendricks et al., 1947).) Most of the central belt consists of Mississippian through Atokan deep-water strata; an exception is the Potato Hills – an anticlinorium of Ordovician through Devonian strata and the site of the prolific Potato Hills Gas Field.

Review of (Reservoir) Stratigraphy of the Arkoma Basin

The Middle Pennsylvanian reservoir stratigraphy of the Arkoma Basin reflects the initial shelf environment, subsidence and filling of the basin, the nature of the shelf – slope transition, and the direction and composition of the sediment source terrane, and can be divided into three very general groups (Figure 8). The youngest group (Desmoinesian and upper Atokan) consists mostly of fluvial-deltaic sediments (e.g., Hartshorne Formation), some of which show significant tidal influence (e.g., Booch sandstones). These strata extend across most of the Arkoma Basin and are locally well exposed on the surface. Surface studies have proven useful for understanding subsurface reservoir geometries, facies relations, e-log character-

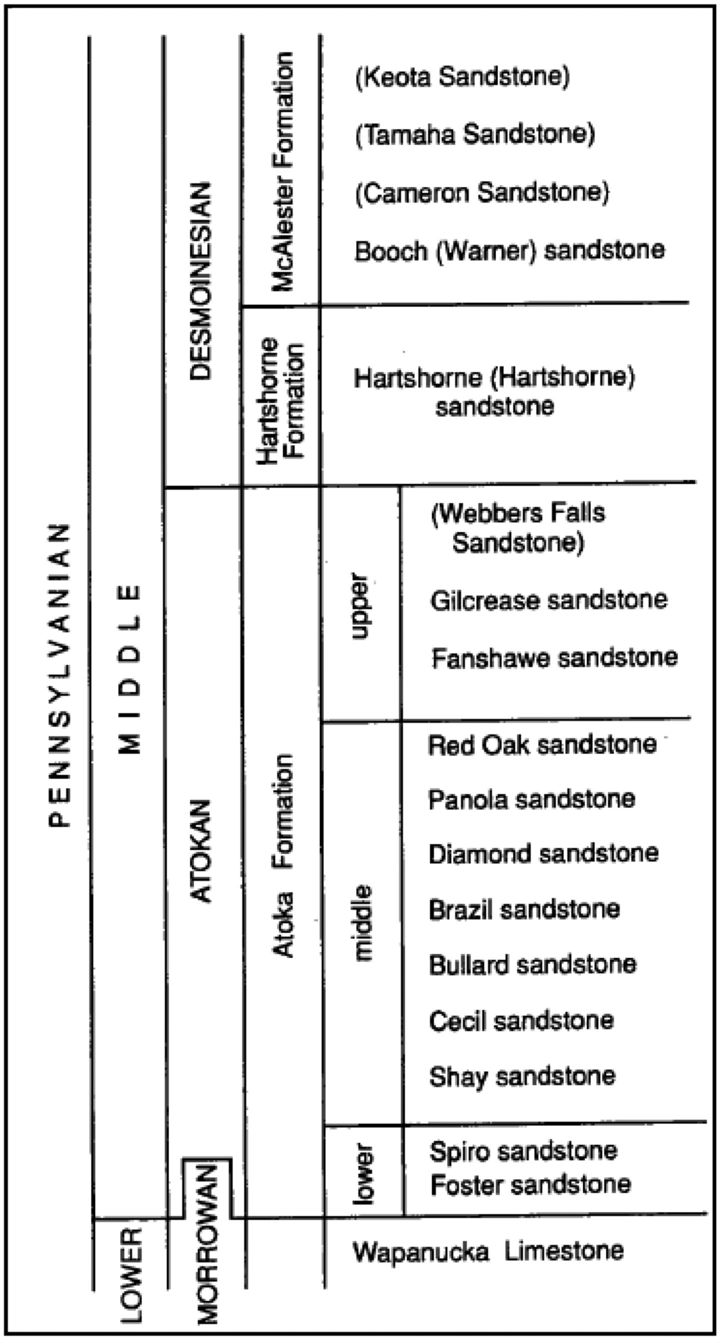


Figure 8. Composite lower Middle Pennsylvanian stratigraphy and principal gas-producing sandstones in the Arkoma Basin. Some operators include the Cameron Sandstone as one of the Booch sandstones. (Modified from Suneson and Hemish, 1994, figure 35)

istics, compartmentalization, etc. Most of the next older group are middle Atokan, consist primarily of deep-water clastic strata, and are restricted to the southern part of the basin south of its hinge line and to the tectonic belt; the Red Oak sandstone is the best-studied of these reservoirs. This part of the section is undoubtedly exposed in thrust sheets south of the Choctaw Fault, but correlations across the fault are speculative, at best. The oldest producing units in the Arkoma Basin that are related to basin subsidence are the earliest Atokan Spiro sandstone and the Morrowan Wapanucka Limestone; these were deposited in a shelf environment and immediately predate subsidence of the basin. The Spiro and Wapanucka (Figure 9) are exposed only in thrust sheets in the northern part of the frontal belt south of the Choctaw Fault.

Older reservoir units in the Arkoma Basin are less clearly related to its formation, but all reflect a shallower-water marine environment than their equivalents in the Ouachita Mountains; these include the Cromwell sandstone, Caney Shale, Woodford Shale, Hunton Limestone, Viola Limestone, Simpson Group, and Arbuckle Group (Figure 3). All of these units form reservoirs elsewhere in Oklahoma.

The most productive Desmoinesian reservoirs in the Arkoma Basin are the Hartshorne Formation and Booch sandstones (within the McAlester Formation) (Figure 8). The Hartshorne produces gas from sandstone (Andrews, 1998; Suneson, 1998) and coal (Cardott, 1998) (and references cited therein). The Hartshorne is predominantly a fluvial – deltaic unit located throughout the basin and north on to the Cherokee Platform. Most of the sediment in the unit was derived from the east (paleoflow directions are mostly east to west or southwest) except for local fan-delta deposits in the extreme southwestern part of the basin. Productive sandstones were deposited in several different deltaic environments that include shallow marine (distributary-mouth bar), distributary channel, and overbank (splay) (Figure 10A). The best reservoirs, however, are the stacked incised-valley fills that locally have over 100 ft of gross sandstone (Andrews, 1998, pl. 1) (Figure 10B) (Figures 11A, 11B). Over 2700 CBM wells have been drilled in the Arkoma Basin, and most are in the Hartshorne coal. The depositional environment of the Booch sandstones is similar to that of the Hartshorne sandstone, except that the Booch sands were derived from the north and many of the sands show evidence for tidal reworking (Boyd, 2005; Suneson and Boyd, 2008; and references cited therein). Like the Hartshorne, the best reservoir-quality Booch sandstones are stacked incised-valley fills; locally, these are more than 250 ft thick.

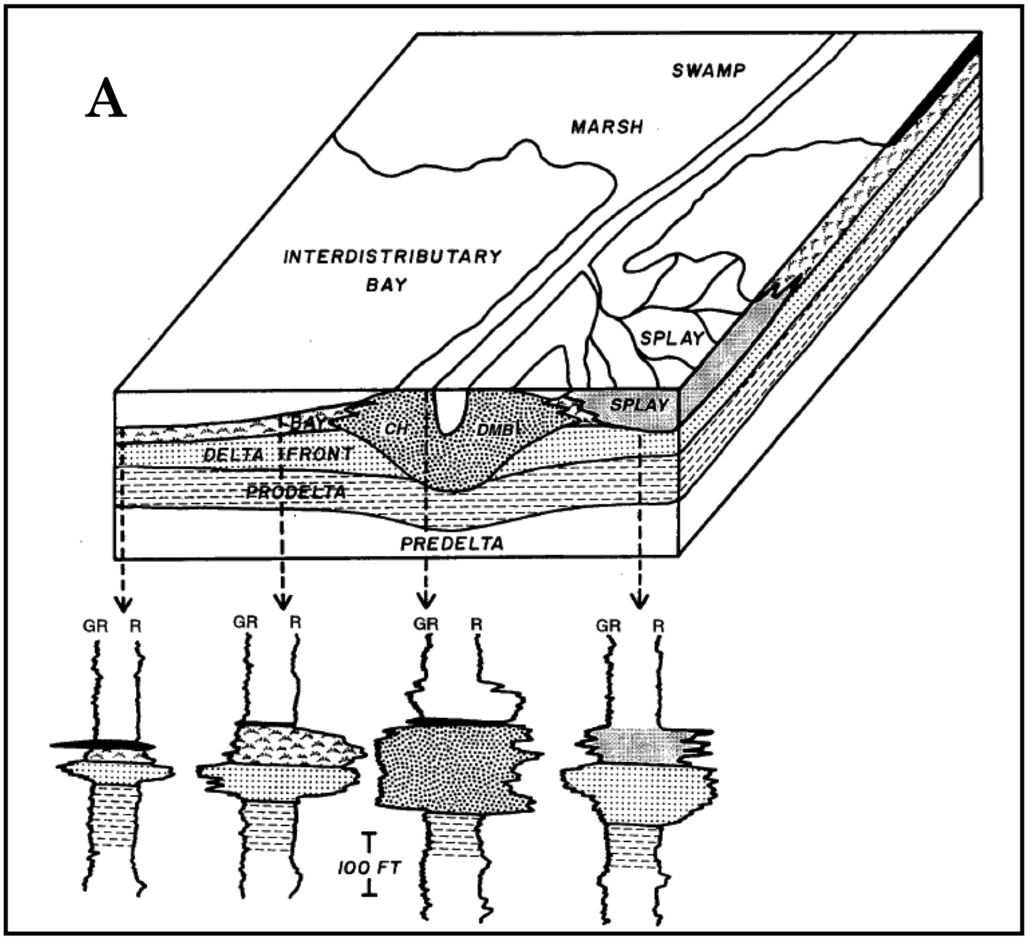
The best-studied middle Atokan reservoir

Figure 9. Tilted Wapanucka Limestone immediately south of trace of Choctaw Fault (SE¼ SW¼ sec. 10, T. 4 N., R. 17 E.).

in the Arkoma Basin is the Red Oak sandstone (Figure 8). Houseknecht (1986) and McGilvery and Houseknecht (2000) interpret the Red Oak to consist of two deep-water facies: a relatively narrow, east-west-trending slope-channel facies and a generally south-directed marginal-fan facies (Figure 12). The channel sands were deposited on the footwall of and adjacent to the San Bois Fault; the locus of deposition on the seafloor was a low area caused by footwall rotation on the listric (lower dips to the south) San Bois Fault. Where the Red Oak ceased following the fault, it "spilled" over the slope and was deposited as a marginal submarine fan. McGilvery and Houseknecht (2000) also describe "longitudinal-apron complexes" in the deeper parts of the Arkoma Basin to the south with a predominant east-to-west paleoflow direction. These, however, do not appear to correlate with or be connected to the Red Oak system. Some authors (e.g., Bowsher and Johnson, 1968; McGilvery and Houseknecht, 2000 (see discussion by Kerr (2005b, p. 119)) have suggested that the Red Oak sandstone is present on Blue Mountain just south of Wilburton, but this is in the thrust-faulted frontal belt south of the Choctaw Fault. Correlations are difficult to prove without a cross section showing how the sandstones are connected across the fault.

Other middle Atokan deep-water sandstones (Panola, Diamond, Brazil, Bullard, Cecil, Shay) (Figure 8) have been little studied. Based on gross-sandstone isopach maps of the Panola Gas Field, Andrews (2008) suggested that the Panola sandstone was derived from the north, the Diamond from the south, and the Bullard from the east, but he did not examine detailed facies relationships. These Atokan sandstone reservoirs typically are repeated and in order to be fully understood, individual thrust sheets must be restored to their pre-fault position.

The primary deep reservoirs in the Arkoma Basin are the earliest Atokan Spiro sandstone (also called basal Atoka sandstone by some operators) and the Morrowan Wapanucka Limestone (Figure 8). These units were deposited prior to subsidence of the Arkoma Basin; as such, they have a shallow-water origin throughout the basin



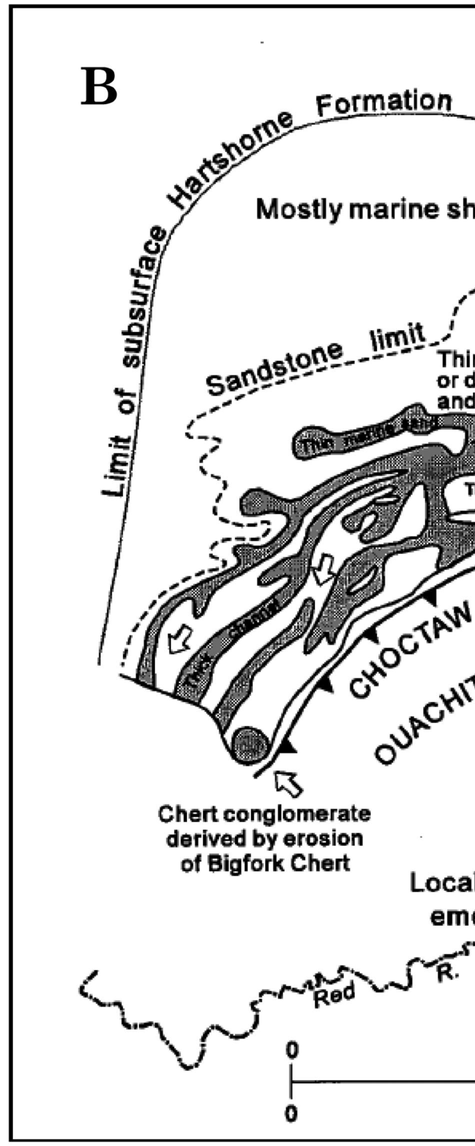
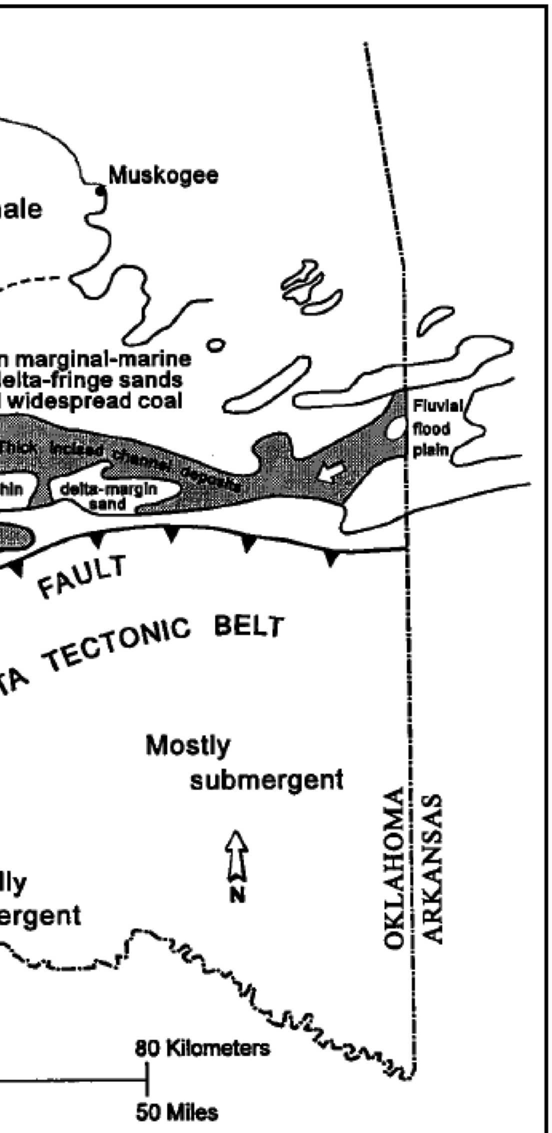


Figure 10. A. Idealized block diagram of Hartshorne deltaic environments and facies showing typical gamma-ray log responses. These facies can produce moderate amounts of gas. (From Houseknecht et al., 1983, p. 59, reproduced courtesy Midcontinent SEPM) B. Generalized distribution and depositional environments of the Hartshorne Formation. The gray areas mark thick, incised-valley-fill sandstones which are the most productive reservoir facies in the Hartshorne Formation. (From Andrews, 1998, figure 3)

and in the tectonic belt. In the western part of the Ouachitas in Oklahoma, one or both units are thrust faulted – in some places as many as six times (Hardie, 1988, fig. 3).

The Spiro sandstone interval consists predominantly of sandstone to the east with an increasing amount of shale and limestone to the west (Figure 13). Grayson and Hinde (1993) interpret the Spiro sandstone as offshore marine bars (including bar-crest, bar-flank, and bar-margin facies) separated by interbar carbonates, whereas Gross et al. (1995) suggest the Spiro consists of barrier islands separated by tidal channels and offshore bars (possibly river-mouth bars). Historically, the Spiro sandstone has always been considered as having been deposited in a shelf environment north of the northward-advancing Morrowan – earliest Atokan foreland basin; for example, Arbenz (2008, pl. 9) suggests that shelfal Spiro may have originally extended 40 mi south of the present trace of the Choctaw Fault. However, new studies by Kerr (2005a) suggest that a recognizable facies of the Spiro extended into the deep basin.

Gas production from the Wapanucka Limestone is mostly in the western part of the Arkoma Basin, in contrast to production from the Spiro sandstone; this reflects



the nature of the Morrowan – earliest Atokan shelf which was dominantly clastic to the east and carbonate to the west. Mauldin and Grayson (1995) suggested that three carbonate facies are potential hydrocarbon reservoirs; two (oolitic and phylloid-algal) might show sufficient porosity (either primary or diagenetic) to be reservoir quality and one (sponge boundstone/spiculitic) might develop fracture porosity. To the west, a deeper-water facies of the Wapanucka Limestone – the Chicachoc Chert – is present in some of the more southeasterly thrust plates.

As stated previously, pre-Wapanucka reservoir units are productive not only in the Arkoma Basin but throughout Oklahoma and are therefore beyond the scope of this report. One unit (Arbuckle Group carbonates), however, has proven to be highly productive in the Wilburton "Deep" Field and is discussed below.

Review of (Reservoir) Stratigraphy of the Ouachita Mountains

Reservoir characterization of units in the Ouachita Mountains is in its infancy; despite a long history of hydrocarbon production, few studies have addressed the question, "What makes a good reservoir?" and fewer have asked, "Where are those good reservoirs?". Reservoir units in the Ouachita Mountains can be subdivided based either on type (i.e., intergranular porosity or fractures or both) or environment of deposition (turbidites or slow sedimentation or pelagic "rain"). Other reservoirs may exist beneath the thrust sheets of the Ouachita Mountains, but they should be (and are) more properly discussed as Arkoma Basin-type reservoirs. For the purposes of this report, Ouachita Mountains reservoirs are those that are only within the fold-and-thrust belt and are therefore allochthonous. Sandstones within the Atoka Formation (Atokan), Jackfork Group (Morrowan) and Stanley Group (Middle to Upper Mississippian) (Figure 3) form one type of reservoir, and fractured cherts in the Arkansas Novaculite (Devonian to Middle Mississippian) (Figure 14) and Bigfork Chert (Middle to Upper Ordovician) form another. However, fractures may be an important factor influencing reservoir quality in the Carboniferous sandstones.

Atoka Formation sandstones in the frontal belt are mostly relatively thin, sheet-like turbidites. They are typically quartzose and well-cemented and locally they produce small quantities of gas. Fractures probably are a significant factor controlling production. It is likely, however, that there are important facies variations within the Atoka Formation, possibly similar to those present in the Jackfork Group described below and/or those in the Red Oak sandstone described above, that would also impact reservoir quality. These facies variations have not been the subject of surface or subsurface studies.

The Jackfork Group consists primarily of turbidites derived from the east, presumably the Appalachian Mountains, although a (very) minor amount may have been derived from a subaerial orogenic wedge of the advancing Ouachita front to the southeast (Figure 4). Thus, in Oklahoma, most of the Jackfork Group turbidites fine to the west. However, an unusual facies of the Jackfork was sourced to the north off the craton. Pauli (1994) first described a sequence of stacked, friable, porous, medium- to coarse-grained, locally pebbly and fossiliferous sandstones with a clear channelform outcrop pattern in the upper part of the Jackfork Group (Figures 15A, B). He suggested these are midfan channels eroded off the continental shelf to the north (Figure 16) that differ greatly from the surrounding fine-grained, quartz-cemented, sheet-like turbidite sandstones derived from the east. Suneson and Slatt (2004) discussed Jackfork reservoir characteristics based on logs and highlighted some issues a Jackfork exploration program would encounter; significantly, they noted the importance of provenance studies and suggested that southern-sourced sands may be present.

Oil was first discovered and developed in the Ouachita Mountains in 1914 in what later became known as the Redden Field. The producing unit was a local sandstone within the Stanley Group called the "Miller tar sand" and the trap was up-dip, near-surface, intergranular biodegraded tar. The Stanley Group consists mostly of deep-water turbidite sandstones and shales; shale is more common and the sandstones are more poorly sorted and contain more clay than those in the Jackfork. Parts of

Figure 11. A. Photograph of thick (more than 50 ft), incised-valley-fill sandstone in lower part of the Hartshorne Formation (NW¼ sec. 12, T. 5 N., R. 20 E.). B. Close-up photograph of lower part of Hartshorne showing nested sandstone channels (same outcrop as A).

the Stanley Group have a high Volcaniclastic component, which suggests a southerly provenance, but most paleocurrent data show an east-to-west flow direction. Attempts to develop the Stanley Group have been sporadic but almost continuous since it was discovered. A key concern may be the type(s) of clay in the sandstones and how best to treat wells completed in the Stanley.

The Devonian to Lower Mississippian Arkansas Novaculite is the basinal equivalent of the Woodford Shale and was the last pre-tectonic unit to have been deposited in the Ouachita Mountains area. It consists of thin-bedded, typically highly fractured chert interbedded with less-fractured laminated siliceous shale and little-fractured dark shale (Figures 14A and B). Like the Stanley, the Arkansas Novaculite (and the underlying and generally similar Ordovician Bigfork Chert) have been tested in a number of wells with limited success (Voight and Sullivan, 1982), however, the discovery of oil in the novaculite and the development of the Isom Springs Field in southern Marshall County has proved its potential as a petroleum reservoir (Morrison, 1985). Modern concepts of natural and induced fractures in low-permeability reservoirs such as the Woodford Shale should be applicable to these Ouachita cherts.

Review of Structural Geology of Arkoma Basin and Ouachita Mountains

The first successful wells in southeastern Oklahoma were drilled on the crest of the Poteau Anticline (see section below on Anticlines), and much of the early drilling occurred on anticlines, thus, structure has played a key role in the development of Arkoma Basin petroleum resources. More recently, understanding fractured reservoirs has become increasingly important as has the role of natural (Pennsylvanian?) versus induced fractures. In the Ouachita Mountains, folds and thrust faults complicate the geology to differing degrees in the frontal belt (isoclinal folds, closely spaced anastomosing faults) and the central belt (broad, open synclines; tight thrust-cored anticlines).

Arbenz (2008, pl. 1) divides the Arkoma Basin into two parts based on the origin of the folds (Figures 2, 7). The northern part, which borders the Ozark Uplift and

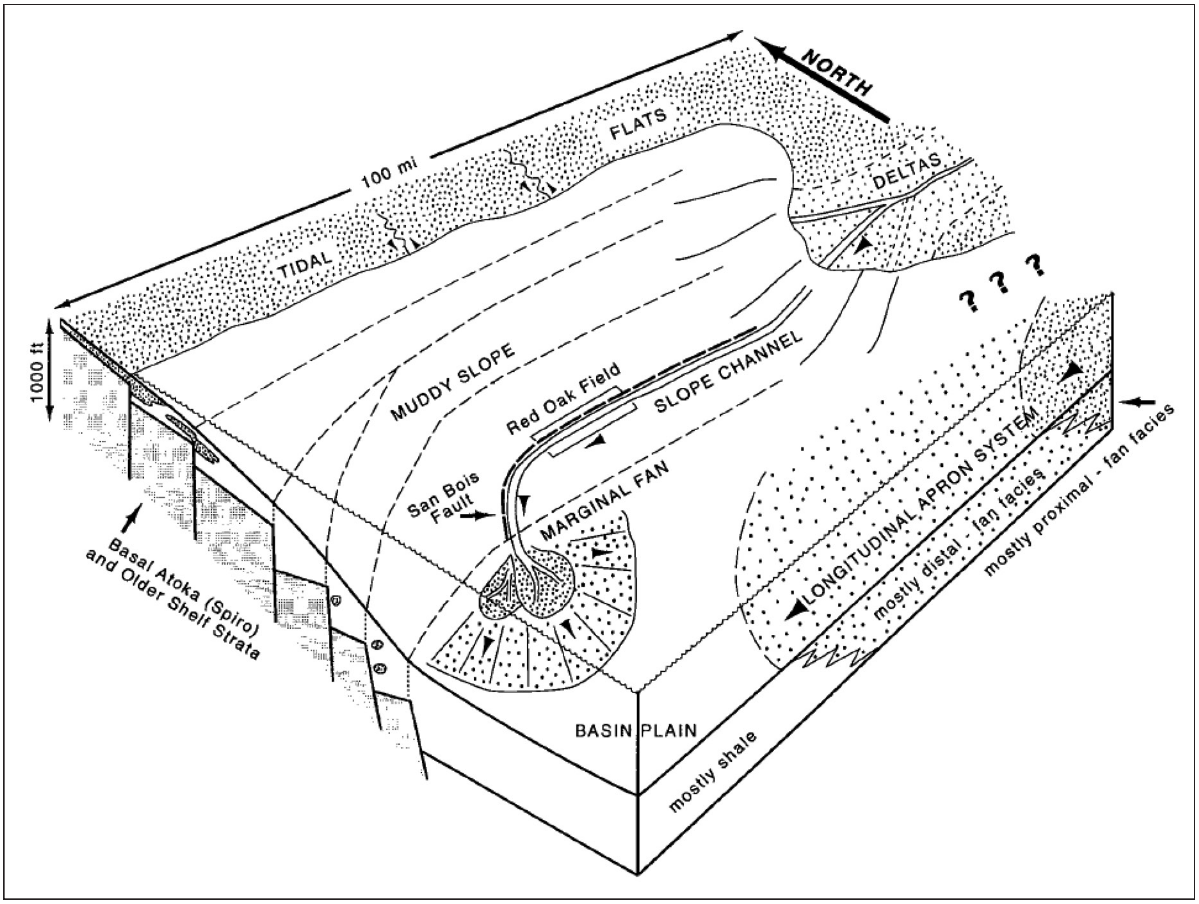


Figure 12. Depositional model for the Red Oak sandstone including east-west-oriented slope-channel sands and generally north-to-south directed marginal-fan sands. (From McGilvery and Houseknecht, 2000, figure 4)

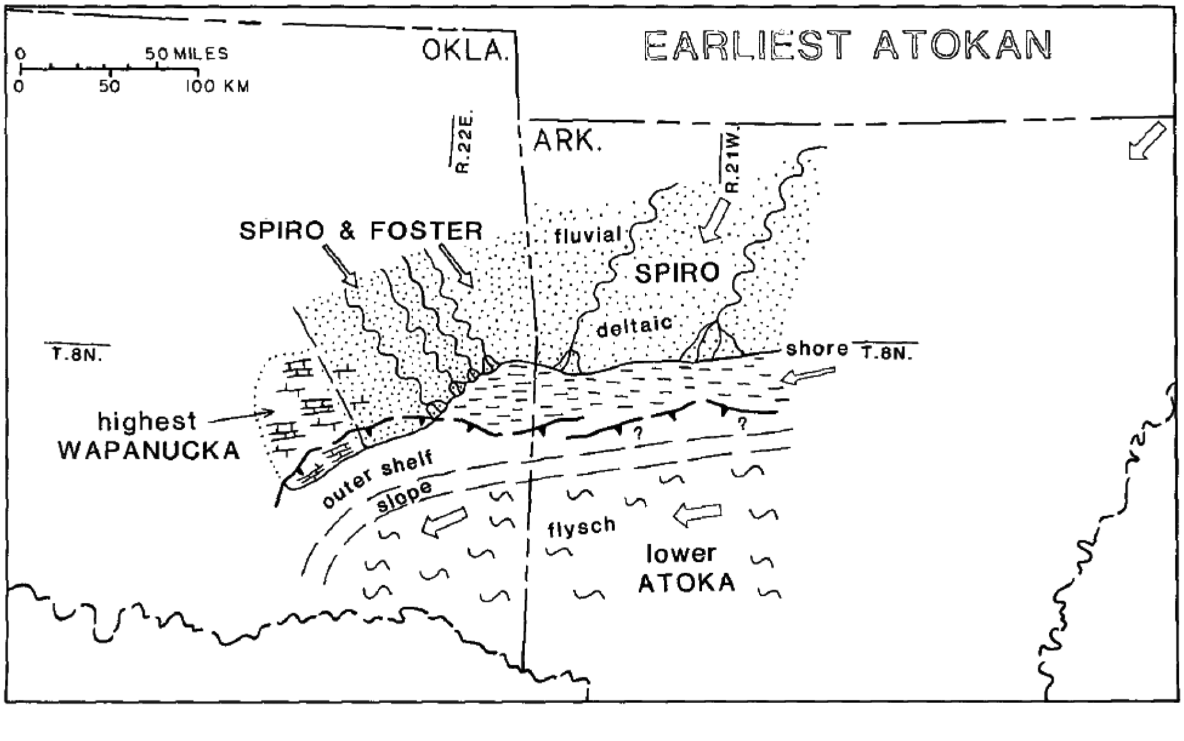


Figure 13. General depositional environment of the Spiro sandstone (earliest Atokan) (From Sutherland, 1988, figure 7). Spiro sand deposition in Oklahoma has been interpreted variously as offshore marine bars, barrier islands, tidal channels, and river-mouth bars.

Figure 14. Fractured Arkansas Novaculite, Black Knob Ridge. A. Bedding plane of siliceous facies (brittle) showing multiple fracture orientations. B. Fractured siliceous beds (resistant) interbedded with argillaceous beds. (Photographs courtesy of Brian Cardott, Oklahoma Geological Survey)

Cherokee Shelf, is characterized by "common anticlinal drape structures over deep faults (that) form numerous traps of gas fields." The faults 1) offset the basement, 2) mostly strike southwest-northeast (but exhibit at least three trends) and are south-side-down, 3) shallow with depth (and therefore result in tilted fault blocks), and are 4) the primary mechanism by which the northern margin of the Arkoma Basin subsided during the middle Atokan. These preorogenic (pre-compressional tectonics) faults are also present in the southern part of the Arkoma Basin which Arbenz (2008) calls the Southern Arkoma Basin Fold Belt. Folds in this part of the Arkoma Basin are the result of Ouachita compressional tectonism and north-directed thrusting. Two kinds of folds characterize this part of the basin: 1) fault-propagation folds occur where thrusts ramp over the older basement-involved extensional faults, and 2) thrust-cored anticlines are present where faults cut upsection and terminate.

Figure 15. A. Google™Earth image of McKinley Rocks (sec. 1, T. 1 N., R. 19 E., and sec. 6, T. 1 N., R. 20 E.) looking southwest. McKinley Rocks is distinctive outcrop forming the ridgetop in the center of the image. It is discontinuous along strike as a result of its channelform nature. B. McKinley Rocks looking west along strike.

The southernmost part of the Arkoma Basin near the trace of the Choctaw Fault is a triangle zone (Jones, 1982; Arbenz, 1984; Hardie, 1988; Suneson, 1995). The relatively simple structure on the surface is separated from duplex structures at depth by one or more decollements (e.g., Çemen et al., 2001) and each of the fault-bounded horses within the duplex structures constitute potential traps. Many of the gas fields located just south of the trace of the Choctaw Fault have developed reservoirs in the footwall of the fault in the southern part of the triangle zone; examples include the Hartshorne South and Pittsburg Gas Fields. Most completions are in repeated and/or folded Spiro sandstone and/or Wapanucka Limestone in duplex structures.

The Ouachita Mountains can be divided into three parts based on their gross structural geology (Figure 2). The northern frontal belt is dominated by steeply dipping strata, isoclinal and near-isoclinal folds typically with south-dipping axial planes, and a myriad of anastomosing thrust faults that flatten with depth. The principal reservoir type in the hanging wall of the Choctaw Fault consists of folded and probably fractured sandstones in the Jackfork Group and Atoka Formation. Fields developed in these units (e.g., Talihina Northwest, Buffalo Mountain) are drilled on anticlines similar to those exposed at the surface; they typically are tight, locally overturned to the north, and separated by thrust faults (Figure 17).

The central belt is separated from the frontal belt by the Windingstair Fault and is characterized by broad, open synclines separated by relatively tight, thrust-cored anticlines or thrust faults. With one notable exception (Potato Hills), the area is underlain by Carboniferous turbidites. Many of the oil and gas fields in the central belt are old, shallow, and small, and produce minor amounts of hydrocarbons from these turbidites. In most cases, the nature and origin of the reservoir and trap are unknown or poorly understood, however, two small gas fields – Moyers Southwest and Jumbo South – appear to be associated with an anticline in the hanging wall of the Perrin or Jumbo Thrust Fault. The Potato Hills Gas Field is unique among the central-belt fields because 1) the wells are spudded in complexly deformed lower Paleozoic to Mississippian strata (which resemble, in many respects, those in the Broken Bow Uplift); and 2) production is from Jackfork sandstones in the footwall of the Windingstair Fault (as are the frontal-belt Jackfork fields).

The third area in the Oklahoma Ouachita

Mountains is the Broken Bow Uplift, an area underlain mostly by pre-Mississippian strata that have been isoclinally folded and thrust faulted. The central part of the Broken Bow Uplift has been called the "core" area; it is an area of extremely complex geology with an unknown relation to the rest of the uplift. Some maps (e.g., Honess, 1923; Arbenz, 2008) show the principal fault (Glover Fault) as a folded, overturned thrust fault. Other maps (e.g., Miser, 1929; Miser, 1954) show the core area separated from the overlying strata by a gently folded thrust fault. Overall, the Broken Bow Uplift is a doubly plunging anticlinorium that rose late in the tectonic history of the orogenic belt; Arbenz (2008) suggests a Desmoinesian age of uplift, although it could be somewhat later. The tectonic history and petroleum potential of the Broken Bow Uplift is constrained by data collected during the drilling of the SOPC 1-22 Weyerhaeuser well on the crest (Allison, 2012).

History of Oil and Gas Exploration and Development in the Arkoma Basin and Ouachita Mountains

Introduction

The following sections of this report briefly describe the history of petroleum exploration and development in the Arkoma Basin and Ouachita Mountains of Oklahoma. I have somewhat arbitrarily divided the last 200 years (dating from when explorer John Maley first noted asphaltite in the Ouachita Mountains) into six periods, while recognizing that there is considerable overlap in the characteristics of the periods. (Note: In this report, "asphaltite" is used as a descriptive term to include any of a number of solid, black migrabitmens including, in the case of the Ouachita Mountains, grahamite (an asphaltite) and impsonite (an asphaltic pyrobitumen).) The six periods are titled: 1) Solids; 2) Anticlines; 3) Geologic Maps; 4) Deeper Drilling; 5) Thrust Plates; and 6) Horizontal Wells.

Solids (pre-1910) (Including Coal)

Hydrocarbons in southeastern Oklahoma were first used by early Native Americans to bind arrowheads to shafts. More than likely, they heated either asphaltite or tar from seeps to form some kind of glue. Explorer John Maley first recorded the presence of asphaltite(?) (which he called coal) in 1812, possibly near what is now the town of Nashoba (R.O. Fay, in Pitt et al., 1982). The English-American naturalist Thomas Nuttall was the first to write about coal in the Arkoma Basin (1819)

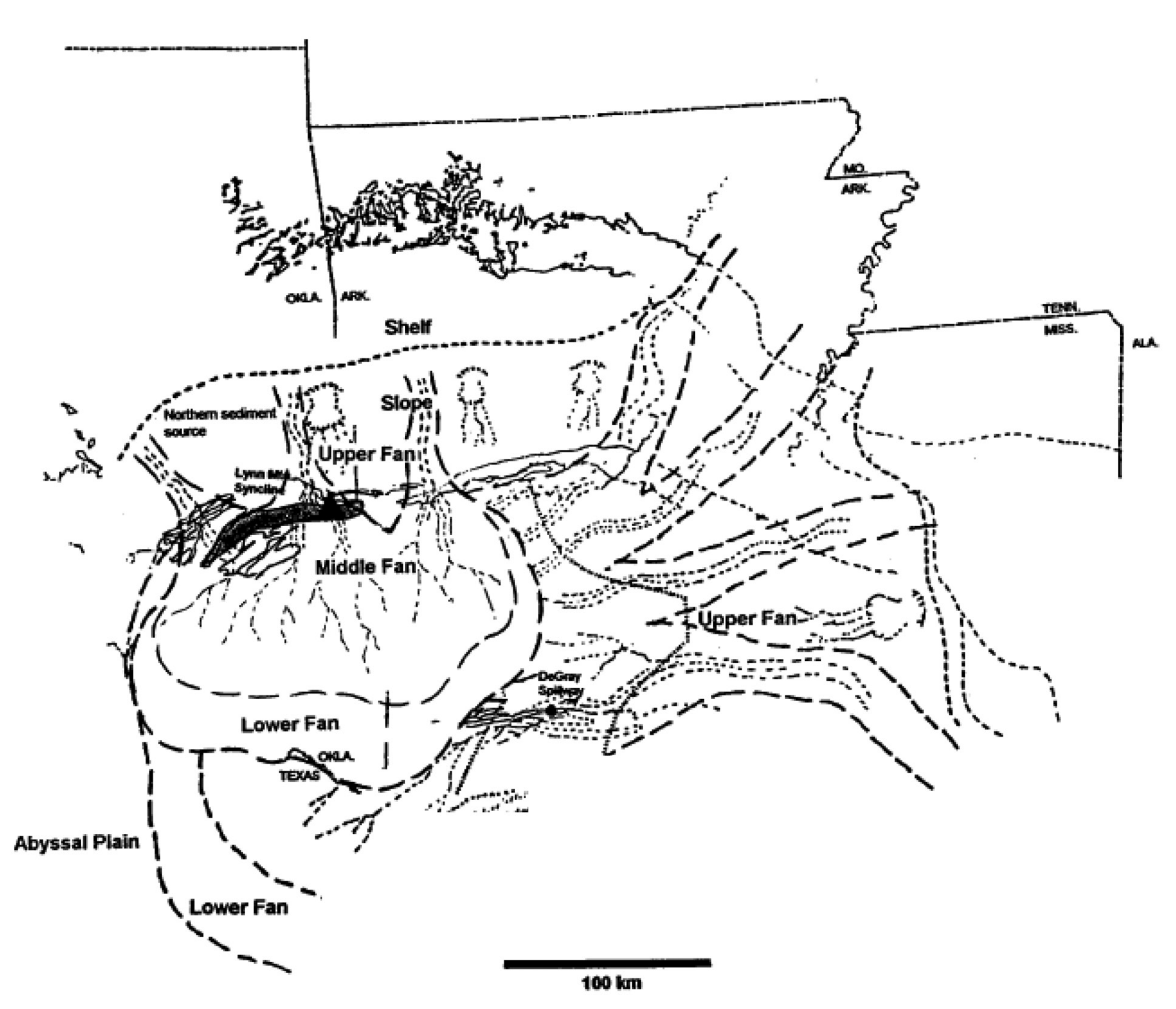


Figure 16. Jackfork Group depositional model proposed by Pauli (1994), who suggested a significant component of northerly-derived sandstone is interbedded with the more common, finer-grained sandstone derived from the east. (From Pauli, 1994, figure 15)

(Gunning, 1975). Coal continued to be noted by government and military officials in the first half of the 19th century, and coal was used in blacksmith shops along the Butterfield Overland Mail route where it passed through the Choctaw Nation between 1858 and 1861. In 1872, the Osage Coal and Mining Company opened the first commercial underground coal mine near the town of Krebs (Gunning, 1975). Production from underground mines quickly rose, peaking in 1920 at about the same time as surface mining began (1915).

In addition to coal in the Arkoma Basin, asphaltite veins were mined at several localities in the Ouachita Mountains (Cardott et al., 1993), but the largest deposits were at Sardis (sec. 9, T. 2 N., R. 18 E.) and Jumbo (sec. 28, T. 1 S., R. 15 E.) (R.O. Fay, in Pitt et al., 1982). The Jumbo grahamite deposit was discovered in 1890 and mined from 1892 to 1924 (Figure 18). The Sardis grahamite deposit was discovered in 1906, production began in 1907 and ceased in 1924. An unusual asphaltite deposit is the Page impsonite, which was discovered in 1895 and mined from about 1900 to 1924 (Cardott et al., 1989). Most of the production occurred during World War I when impsonite from the mine was burned and the ashes shipped because of their high vanadium content.

Prior to 1910, very little note was made of the natural gas or oil as a resource in the Arkoma Basin or Ouachita Mountains, however, a gas seep located northwest of Wilburton in sec. 6, T. 5 N., R. 18 E. appears to have "been used for heat in cooking by soldiers and campers since Civil War days" (Stone and Cooper, 1930, p. 419). This is probably the same seep described by Hendricks (1939) as Boiling Spring located in the northeast corner of section 6 on the trace of the Carbon Fault. Natural gas was frequently noted as a mine hazard, however, and a large number of mine disasters were attributed to gas explosions. In fact, "… Krebs is the site of the worst mining disaster in Oklahoma, which occurred when the Osage Coal Mining Company mine no. 11 exploded

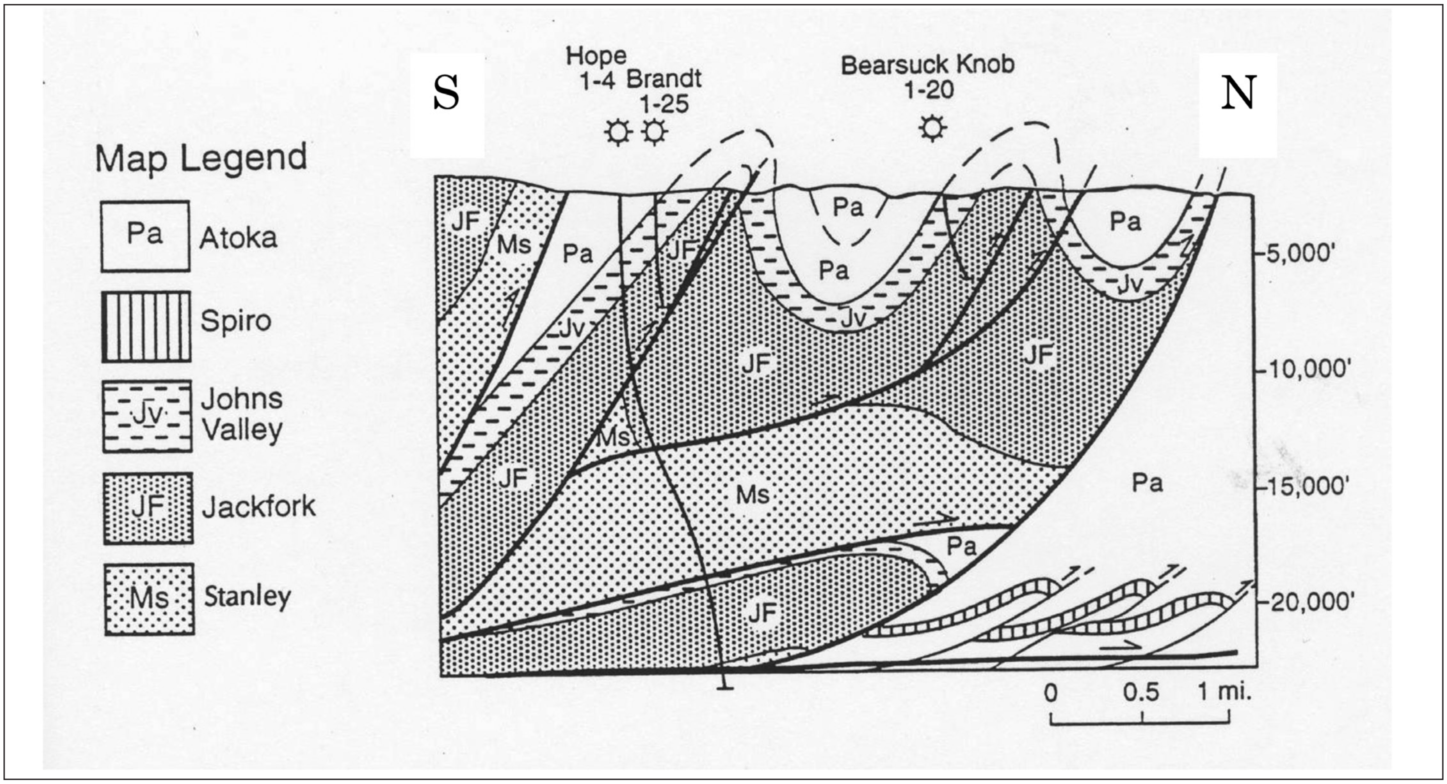


Figure 17. Generalized cross section between Buffalo Mountain and Talihina Northwest Gas Fields (from Montgomery, 1996, figure 4.4; based on Cunningham and Namson, 1994). The Windingstair Fault is on the left (south) and separates the frontal belt from the central belt. The Choctaw Fault is on the right and separates the frontal belt from the Arkoma Basin. Some gas fields are developed in the duplex structures shown in the footwall of the Choctaw Fault. North end of cross section approximately C E½ sec. 1, T. 4 N., R. 20 E.; south end approximately C NE¼ sec. 1, T. 3 N., R. 20 E.

on January 7, 1892. Ninety-six men and boys (some as young as 12 years old) were killed" (Suneson and Andrews, 2005, p. 65). The mine was producing the McAlester coal.

Anticlines (1910 – 1935)

Starting in about 1910, exploration for natural gas as a resource began in the Oklahoma part of the Arkoma Basin, although oil seems to have been the primary objective. Gas was first discovered in the Arkoma Basin near Mansfield, Arkansas, in 1902 (Branan, 1968). The first commercial well in the Oklahoma part of the Arkoma Basin is the Le Flore County Gas and Electric No. 1 Hill (NW¼ sec. 25, T. 7 N., R. 26 E.) completed in 1910 at 1687 ft TD in the Hartshorne sandstone (Knechtel, 1949). This well was drilled on the crest of the Poteau Anticline (Figure 19) and is the discovery well for the Poteau-Gilmore Field. While it is uncertain whether or not this well and the Arkansas well (drilled on the crest of the Hartford Anticline) convinced geologists that anticlines were likely targets for oil and gas reservoirs, a number of discoveries were made drilling anticlines over the next couple of decades (Figure 6). At first, shallow sandstones such as those in the Hartshorne Formation or the upper part of the Atoka Formation were developed; later efforts focused on deeper units.

The Cameron Field, discovered in 1911 but not developed until 12 years later, is on the Midland Anticline. The gas appears to come from a shallow (about 1500 ft) sandstone in the Hartshorne Formation, although Knechtel (1949) suggests the producing unit may, in fact, be a Booch sandstone. The Red Oak Field, the first giant gas field found in the U.S., was discovered in 1912 by the Gladys Belle Oil Company in a well (unknown name) drilled in sec. 10, T. 6 N., R. 21 E. near the crest of the Brazil Anticline (Houseknecht and McGilvery, 1990). Early production was from the Hartshorne at about 1500 ft. Several gas fields are located on the crest of the Kinta Anticline: Quinton (discovered in 1915), Carney (1923), and Blocker-Featherston (1916) (Dane et al., 1938). (The latter two are now part of the Kinta Gas Field.) In 1929 the Limestone Oil and Gas No. 1 Nettie McCurray (SW¼ sec. 15, T. 5 N., R. 18E.) discovered gas in an Atoka sandstone at about 2500 ft on the crest of the Wilburton Anticline. (Decades later, the Wilburton and Wilburton "Deep" Fields were discovered within about a mile of this well.) In the western part of the Arkoma Basin, the Ashland Field is located on the crest of the Savanna Anticline. No

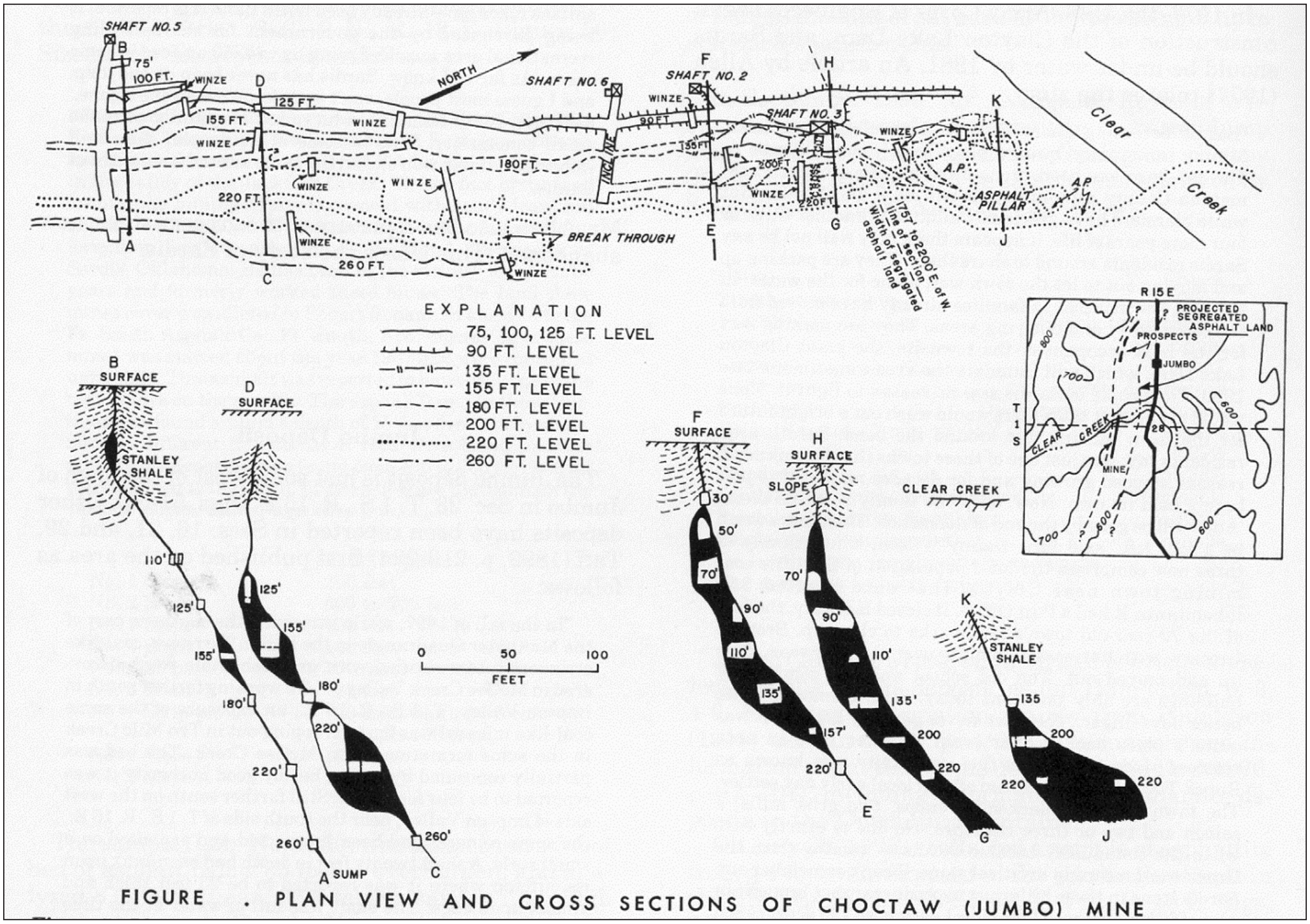


Figure 18. Map and cross sections of the Jumbo Mine. (From Pitt et al., 1982, figure 51; after Hutchinson, 1911, p. 80)

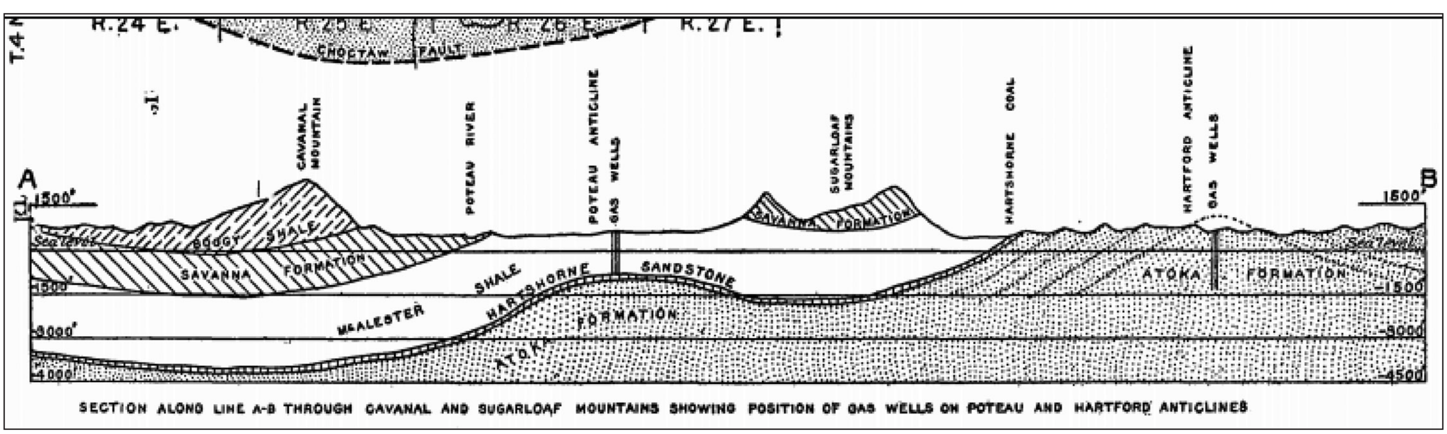


Figure 19. East-west cross section through center of T. 7 N. in Oklahoma and northern part of T. 4 N. in Arkansas from 1912 map published by the U.S. Geological Survey. Gas wells that are part of the Poteau-Gilmore Field are shown producing from the Hartshorne sandstone on the crest of the Poteau Anticline and wells in the Mansfield Field are shown on the crest of the Hartford Anticline. (From Smith, 1912, pl. II)

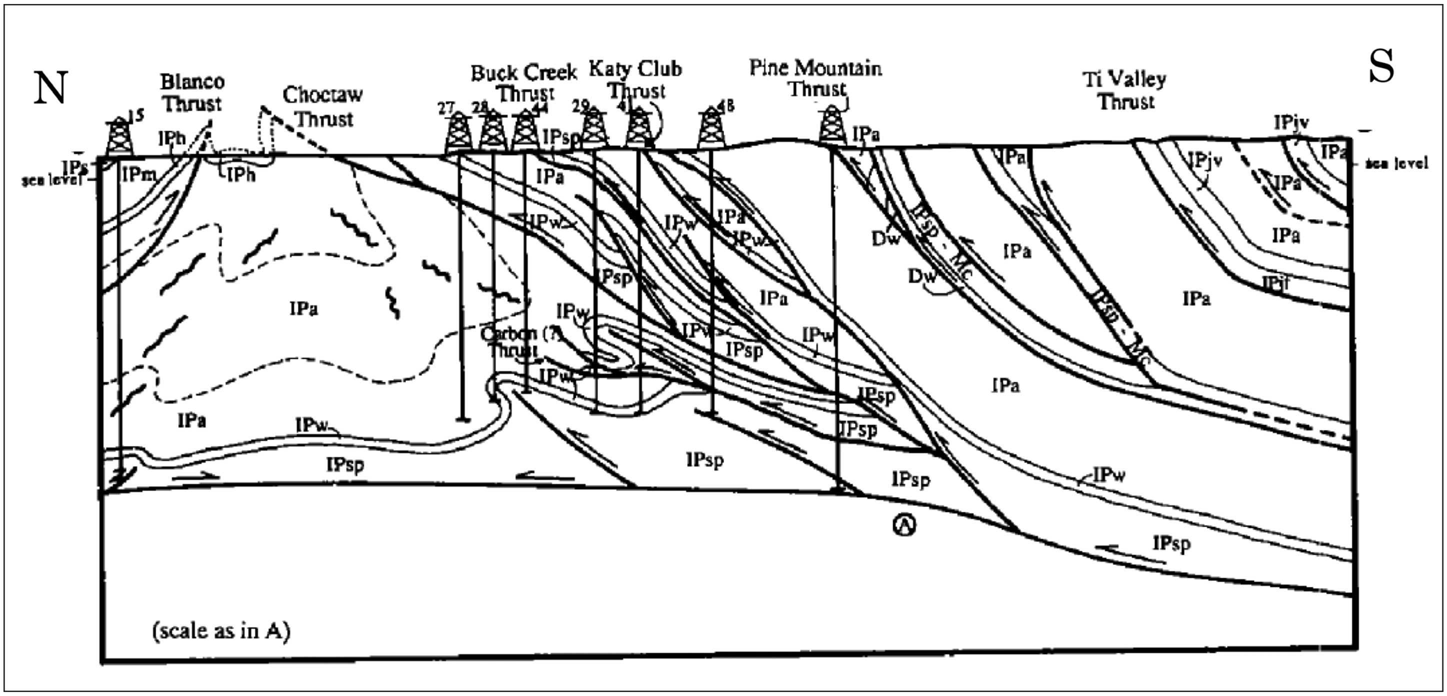


Figure 20. North-south cross section through the Blano South Gas Field showing repeated and overturned Spiro and Wapanucka reservoir strata. The discovery well of the field – the Hamilton Brothers 1-30 Indian Nation – is on strike and a mile northeast of well no. 29. North end of cross section C N line NW ¼ sec. 12, T. 3 N., R. 14 E.; south end C S line NE¼ sec. 19, T. 2 N., R. 15 E. Abbreviations: IPm – McAlester Formation; IPh – Hartshorne Formation; IPa – Atoka Formation; IPw – Wapanucka Formation; IPjv – Johns Valley Formation; IPsp – Springer Formation; IPjf – Jackfork Group; Mc – Caney Formation; Dw – Woodford Formation. (From Hardie, 1988, figure 4)

information is available about the discovery of the field, but Colton (1935) states that most wells were drilled between 1912 and 1914 to the Hartshorne.

More interesting and enigmatic fields include the Redden Oil Field, which was discovered in 1914, and a number of other small old oil fields in McGee Valley (e.g., Daisy West (discovered in 1953), Bald (1933), and Bald South (1932)). All of the early (and admittedly minor production) from these fields is from sandstones in the Stanley Group. In some cases, traps are the result of up-dip tar seals, but McGee Valley itself is in the hanging wall of the Windingstair Fault (Hendricks et al., 1947) and "is … essentially anticlinal in nature" (Chenoweth, 1959). Given the early discovery dates of most of the fields and the generally poor exposures and lack of surface mapping in McGee Valley, geologic maps probably played a small or nonexistent role in the development of the area. The presence of tar seeps and tar sands (e.g., Jordan, 1964) is the probable reason the McGee Valley oil fields were developed.

In addition to the numerous discoveries made by operators in the Arkoma Basin and Ouachita Mountains during this early period of exploration, two important concepts were introduced to the geological community. Based on work in the Cushing Oil Field, "operators began to appreciate the value of structure mapping, (and) in 1914 the word "structure" was used for the first time by oil operators" (Powers, 1928, p. 6). And in 1921, "the suggestion was offered … by Dake that the rocks of the Ouachita Mountain region were thrust northward a long distance over rocks that have the same facies as those of the Arbuckle Mountains, near-by (sic) to the west" (Miser, 1929, p. 5).

Geologic Maps (1935 – 1950)

During the war years, the U.S. and Oklahoma Geological Surveys published a number of detailed surface geologic maps of the Arkoma Basin and Ouachita Mountains that greatly improved geologists' knowledge of the structure and stratigraphy of the area. Although some of the mapping started as early as 1930, the reports and maps were published between 1937 and 1949. At least one study – that of the Lehigh Coal District – was funded by the Federal Emergency Administration of Public Works, later called the Public Works Administration, one of President Roosevelt's New Deal agencies. Two of the later studies – those of northern Le Flore and Haskell Counties, were the result of a cooperative agreement between the U.S. and Oklahoma Geological Surveys. All of the studies, and in particular those of parts of the Arkoma Basin, arose

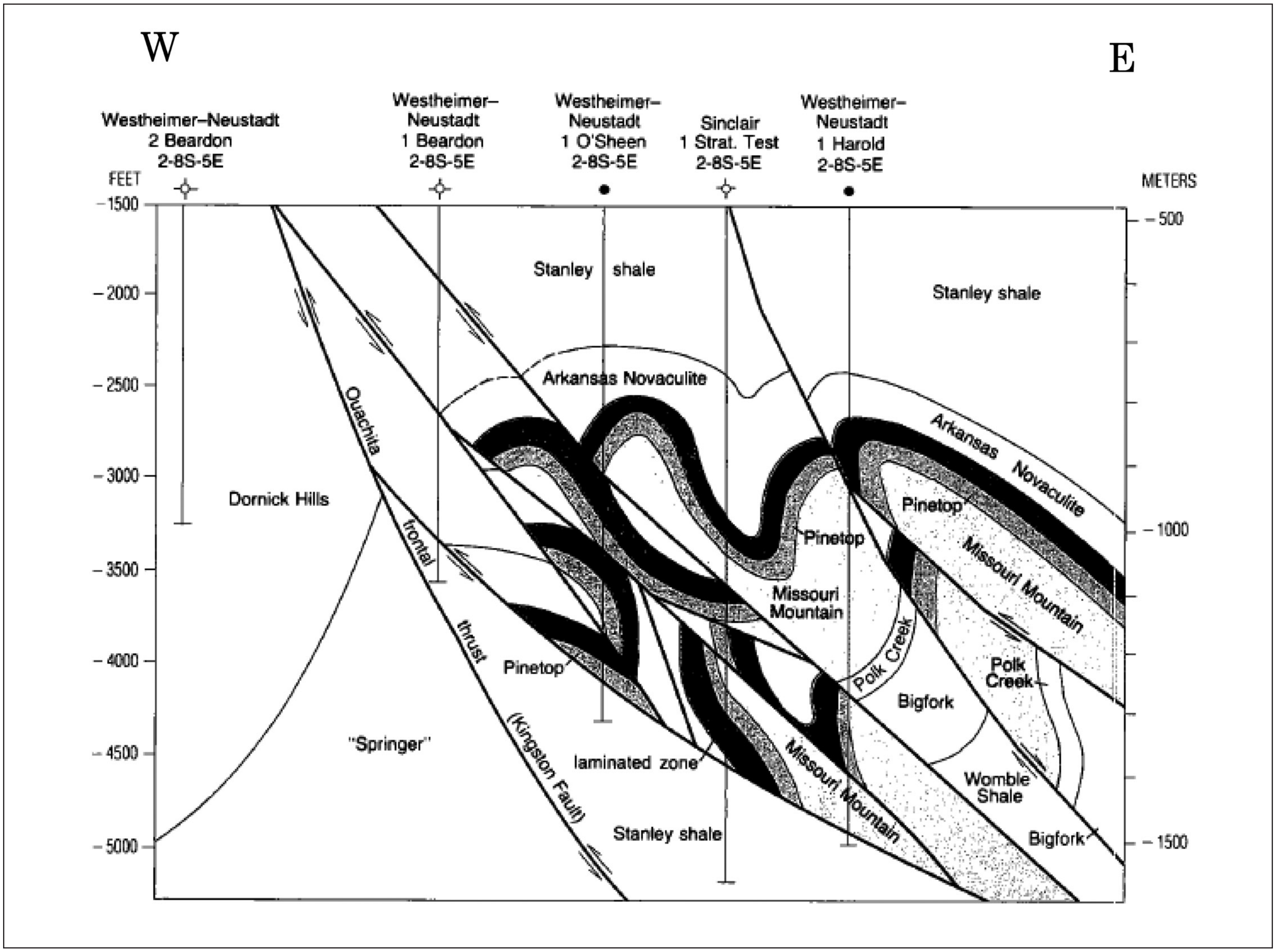


Figure 21. East-west cross section through Isom Springs Field showing complex structure, thrust faults, and overturned folds. West end of cross section approximately C SW¼ NW¼ sec. 2, T. 8 S., R. 5 E.; east end of cross section approximately C NW¼ NW¼ sec. 1, T. 8 S., R. 5 E. (From Huffman et al., 1987, figure 50)

as a result of a need to know more about the coal and petroleum resources of southeastern Oklahoma.

The key maps published between 1935 and 1950 are:

Knechtel (1937); Lehigh District; Coal, Atoka, and Pittsburg Counties; map scale 1:63,360.
Hendricks (1937); McAlester District; Pittsburg, Atoka, and Latimer Counties; map scale 1:63,360.
Dane et al. (1938); Quinton – Scipio District; Pittsburg, Haskell, and Latimer Counties; map scale 1:62,500.
Hendricks (1939); Howe – Wilburton District; Latimer and Le Flore Counties; map scale 1:63,360.
Hendricks et al. (1947); western part of Ouachita Mountains; Atoka, Pushmataha, Pittsburg, and Latimer Counties; map scale 1:42,240.
Oakes and Knechtel (1948); Haskell County; map scale 1:63,360.
Knechtel (1949); northern Le Flore County; map scale 1:63,360.

Prior to this mapping, the only detailed geologic map of either the Arkoma Basin or the Ouachita Mountains was of the Broken Bow Uplift by Honess (1923). This map has been little improved upon in the last 90 years. Starting in 1955, a number of students under the direction of J.K. Arbenz of the University of Oklahoma, L.M. Cline of the University of Wisconsin – Madison, and W.D. Pitt of the University of Oklahoma mapped different parts of the Ouachita Mountains. The quality of these maps is highly variable.

Deeper Drilling and New Sedimentology – Stratigraphy Concepts (1950 – 1980)

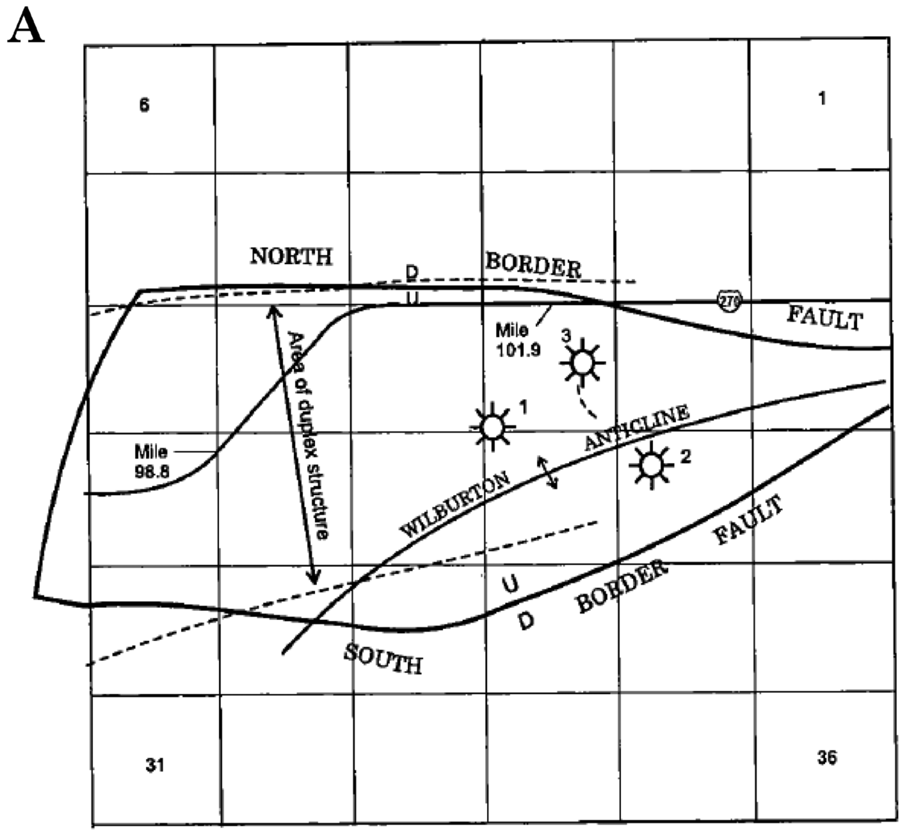
Beginning in about 1950, three major types of gas discoveries were made in the Arkoma Basin and Ouachita Mountains. Whether improved seismic techniques, improved drilling techniques, and/or serendipity played the major role is debatable. One type of discovery was the identification of deeper reservoirs in the long-productive anticlines in the Arkoma Basin. Another type of discovery was made mostly in the southern part of the basin in the transition zone between the basin and the fold-and-thrust belt as well as sub-Choctaw Fault reservoirs. A third type was of unconventional reservoirs – in this case, fractured chert reservoirs. During this period the concept of plate tectonics was introduced, enabling sedimentary basins and mountain belts to be put into a broader perspective. In addition, at least two key papers on sedimentary facies and depositional environments relevant to the Arkoma Basin and Ouachita Mountains were published.

A focus on deep drilling in the Arkoma Basin began with the discovery of gas in the Red Oak and Spiro sandstones in the Red Oak Field by the Midwest Oil No. 1 Orr (SW¼ sec. 8, T. 6 N., R. 22 E.) in 1959 (Branan, 1968). Shallow Hartshorne production from the Red Oak Field began in 1912, and the Spiro (or basal Atoka) sandstone had produced gas in the Kinta Field since 1930. But Spiro production at Kinta was significantly shallower (about 5400 ft) than in the Midwest well (11,500 ft), and the Midwest well started a leasing and drilling boom in the area. The Midwest well also established the Spiro and middle Atoka Red Oak sandstones as major gas reservoirs in the Arkoma Basin and encouraged additional deep drilling for other Atoka sandstones and the Spiro. In 1960, the Wilburton Field was "rediscovered" by the Ambassador Oil No. 1 W.M. Williams (NW¼ sec. 23, T. 5 N., R. 18 E.). The well produced from the Spiro sandstone at about 8800 ft. Interestingly, this well is only slightly over a mile east of the Limestone Oil and Gas No. 1 Nettie McCurray (SW¼ sec. 15, T. 5 N., R. 18 E.), which "originally" discovered gas in shallow (2500 ft) Atoka sandstones in 1929. Although both wells are near the crest of the Wilburton Anticline, shallow production is from the anticline, whereas the deeper production is from duplex structures beneath the crest.

Three fields – Pittsburg, Pittsburg South (merged with Pittsburg), and Blanco South – established production from the western part of the Arkoma Basin immediately adjacent to and under the Choctaw Fault (Richardson, 1986). The first discovery well (Pittsburg Field) – the Hamilton Brothers No. 1 Chitty-Scott (NE¼ sec. 30, T. 3 N., R. 14 E.) – spudded in 1978 immediately north of the trace of the Choctaw Fault (Hardie, 1988, fig. 3) and discovered gas in the Wapanucka Limestone at 9400 ft and in the Cromwell sandstone at 10,300 ft. In 1981 the Hamilton Brothers No. 1-8 Blue Creek spudded almost three miles south of the trace of the Choctaw Fault, drilled several repeated lower Atokan – upper Morrowan sections in the hanging wall of the fault, and discovered gas in the Cromwell and Wapanucka below the fault. The Blue Creek well is the discovery well of the Pittsburg South Field. Shortly after the Blue Creek well was completed, Hamilton Brothers spudded their 1-30 Indian Nation well (NW¼ sec. 30, T. 3 N., R. 15 E.) over a mile south of the trace of the Choctaw Fault. It discovered gas in multiple (repeated) Wapanucka Limestone; later wells in the Blanco South Field also encountered repeated as well as repeated *and* overturned reservoir-quality limestone (Figure 20). These fields demonstrated the presence of sub-(Choctaw) thrust reservoirs, multiply thrust-faulted and folded reservoirs in the hanging wall of the Choctaw Fault, and the Wapanucka Limestone as a fractured reservoir (Mauldin and Grayson, 1995).

In addition to deeper drilling in the Arkoma Basin and subthrust exploration in the Arkoma Basin – Ouachita Mountains transition zone, two significant discoveries were made in unconventional reservoirs in the fold-and-thrust belt. In 1959, Sinclair spudded their No. 1 Reneau well in NW¼ sec. 32, T. 3 N., R. 20 E. in the Potato Hills. The well TD'd at 7097 ft on February 9, 1960, and later reported an open-flow potential of 1.8 MMcf gas per day from the Bigfork Chert at about 2400 ft. The Arkoma Basin Study Group (1961, p. 77) suggested that the production was from "small vugs and fractures, most of which do not appear to be connected." Despite disagreement over the sequence that the well penetrated and whether the well TD'd in Pennsylvanian or Ordovician strata (see discussion in Suneson et al., 1990, p. 55-60), the well proved that fractured chert could form gas reservoirs. The Bigfork Chert also tested and/or produced gas at several other localities in the Ouachita Mountains, including the Jumbo South Field (T. 2 S., R. 15 E.) and the Daisy West Field (T. 1 N., R. 14 E.).

A second unconventional reservoir in the Ouachita tectonic belt is the Arkansas Novaculite, which is the principal producing unit in the Isom Springs Oil Field in southern Marshall County (Morrison, 1980, 1985; Huffman et al., 1987). The field was discovered in 1977 by the Westheimer-Neustadt No. 1 Wallace in the NE¼ of sec. 2, T. 8 S., R. 5 E. Although Morrison (1980, 1985) recognized the complex structure (thrust faults, overturned folds) (Figure 21) and production from fractures and attempted to establish a stratigraphy within the unit, he did not discuss the details of the fractures and how they might relate to different lithologies within the novaculite. More than likely, the logs he had available simply were not advanced enough to enable him to do this. He did point out, however, that the Bigfork Chert also produces at Isom Springs and like the Bigfork, the novaculite also tested small amounts of gas at scattered wells throughout the Ouachitas (e.g., U.S. Minerals and Royalty No. 1 Perrin Estate (SW¼ sec. 9, T. 2 S., R. 15 E.); Max Pray No. 1 Wyrick (SE¼ sec. 26, T. 1 N., R. 14 E.) (Pitt et al., 1982, p. 44)).



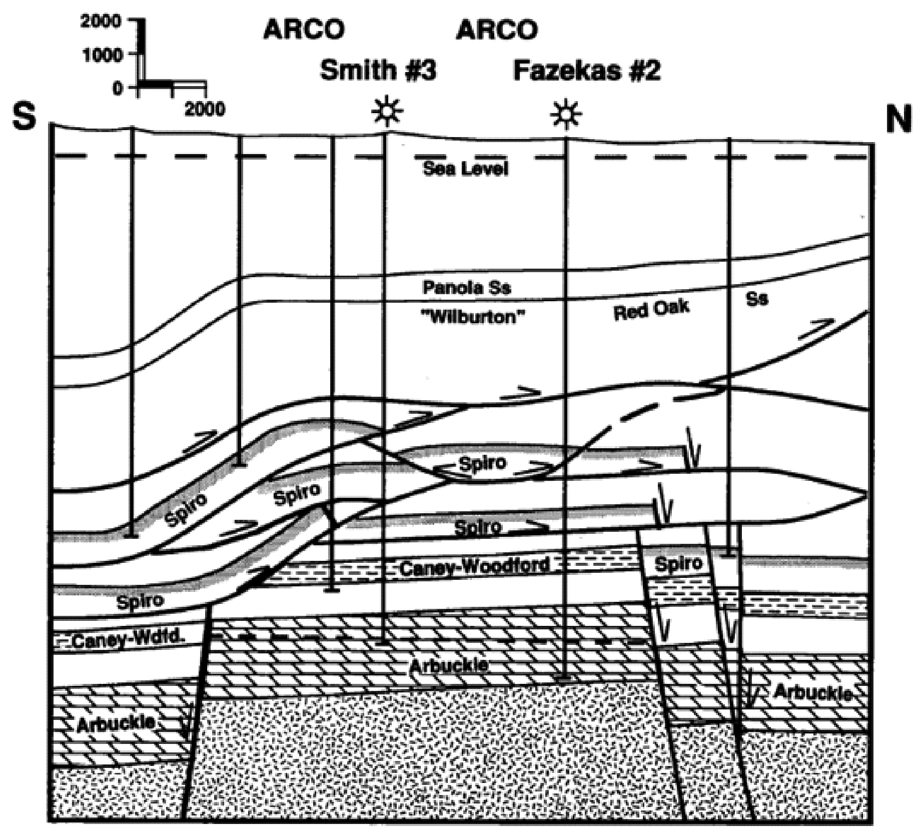


Figure 22. A. Map of T. 5 N., R. 18 E., showing Wilburton Gas Field "discovery" wells and surface and subsurface structures. The Limestone Oil and Gas No. 1 Nettie McCurray (well no. 1) may have been drilled on the crest of the Wilburton Anticline as exposed on the surface. The Ambassador No. 1 Williams (well no. 2) discovered gas in duplex structures in the Spiro sandstone. The Arco No. 2 Yourman (well no. 3) discovered gas in a horst block (north and south border faults shown) of Arbuckle carbonates. (From Suneson et al., 2005, figure 100) B. North-south cross section across the Wilburton Gas Field showing duplex-structured Spiro sandstone ("Wilburton intermediate") overlying horst block in Arbuckle Group strata ("Wilburton deep"). South end of cross section approximately C S½ S½ sec. 29, T. 5 N., R. 18 E.; north end approximately C E ½ E ½ sec. 8, T. 5 N., R. 18 E. (From Mescher et al., 1993, figure 2)

During this period, three authors published papers that proved key to future petroleum exploration and development in the Arkoma Basin and Ouachita Mountains. The first was Dan Busch (Busch, 1959) who discussed the different facies within the Pennsylvanian delta systems in the Arkoma Basin. He followed his 1959 paper two subsequent papers that further refined his model (Busch, 1971, 1974). Lewis Cline (Cline, 1960; Cline and Shelburne, 1959) first documented the deep-water depositional environment of the Stanley and Jackfork Groups, the Johns Valley Shale, and Atoka Formation in the Ouachita Mountains. What he called flysch we now recognize as turbidites; and he applied the term wildflysch (now called olistostrome) to the Johns Valley Shale and correctly recognized its sedimentary (as opposed to tectonic) origin. John Wickham and colleagues (Wickham et al., 1976) put the Ouachita fold-and-thrust belt and Arkoma foreland basin into a plate-tectonic framework.

Thrust Plates and New Structural Concepts (1980 – 1990)

The decade of the 1980s started with the publication of a key paper that put some previous discoveries into a geologically reasonable structural setting and undoubtedly assisted subsequent exploration efforts in the Ouachita tectonic belt. Jones (1982) described the transition from fold-and-thrust belt to foreland basin in the Rocky Mountains of Alberta, Canada, and his model of a triangle zone became widely accepted. He applied principles of structural balancing to the transition from tectonic belt to foreland basin and illustrated how duplex structures and backthrusts accounted for the anomalous thickening of the stratigraphic section immediately in front of the tectonic belt. In the southern part of the Arkoma Basin, many duplex structures form traps and some traps have yet to be recognized as duplex structures.

The Pittsburg South and Blanco South Gas Fields, discovered in the early 1980s and described above, fit the triangle-zone model. These fields are similar to the prolific Hartshorne South Gas Field, discovered in 1988 by the Amoco No. 1 Zipperer (SW¼ sec. 32, T. 4 N., R. 17 E.). The Zipperer produces from overturned Wapanucka Limestone and overturned Spiro sandstone in the footwall of the Choctaw Fault. Çemen et al. (2001, figs. 6 and 7) show the duplex-like structure of the reservoir in the field. The Hartshorne South Field is similar to the Veterans Colony West Field immediately to the east, and both locally produce gas from thin Atoka sandstones in the hanging wall of the Choctaw Fault.

Although discovered just after the decade of the 1980s, the Buffalo Mountain and Talihina Northwest Gas Fields successfully developed reservoirs in the fold-and-thrust belt, although the discovery well for the former – the H&H Star Energy No. 1-4 Hope (SE¼ sec. 4, T. 3 N., R. 20 E) – was completed in autochthonous subthrust Spiro sandstone (Suneson et al., 2005, p. 99). Both fields produce from a number of sandstones in the Atoka Formation and Jackfork Group; the Stanley, Johns Valley, and Spiro are minor producers. And the structural geology of both fields is similar and consists of truncated and blind duplex structures (Cunningham and Namson, 1994; Montgomery, 1996) (Figure 17).

In 1987, two significant events occurred in southeastern Oklahoma; one in the Arkoma Basin and the other in the Ouachita tectonic belt. In February Arco began drilling their No. 2 Yourman in the NE¼ sec. 15, T. 5 N., R. 18 E., interestingly, about a mile from the discovery wells of the "Wilburton shallow" and "Wilburton intermediate" fields (discussed above) (Figure 22A). The well TD'd in June in a horst block of Arbuckle Group carbonates (Figure 22B) and tested an open-flow potential of 73 MMcf gas per day from perforations at 14,259 – 14,500 ft. This well is the discovery well for the prolific "Wilburton Deep" Field, with production from karst zones formed as a result of subaerial exposure and from fractures (Mescher et al., 1993). Following Arco's successful discovery, a number of wells were drilled looking for similar structures (e.g., Arco 1 Runestone (SE¼ sec. 9, T. 6 N., R. 25 E.); Nicor 4 Bowman (SW¼ sec. 20, T. 5 N., R. 17 E.); Texaco 29-1 Burnett (SE¼ sec. 29, T. 2 N., R. 14 E.) (Suneson and Campbell, 1990). None of the wells successfully completed the Arbuckle and to date, the Wilburton "Deep" horst remains a unique reservoir in the area. On April 9, 1987, about two months after Arco spudded their Yourman well, Standard Oil Production Company (previously SOHIO) spudded their 1-22 Weyerhaeuser well on the crest of Broken Bow Uplift (NE¼ sec. 22, T. 5 S., R. 24 E.) (Allison, 2012; Allison et al., 2012). This rank wildcat was drilled to explore for reservoir-quality rocks in Ouachita facies strata, to determine the nature of a regional decollement separating Ouachita facies strata from underlying Arbuckle facies strata, and to determine the nature of those Arbuckle strata if they, indeed, existed. Although few indications of hydrocarbons were found, the well proved to be key for modern tectonic interpretations of the Ouachita tectonic belt (e.g., Arbenz, 2008), having TD'd in autochthonous Arbuckle facies strata. The well proved that all the strata exposed in the Ouachita Mountains were deposited south of the Broken Bow Uplift and probably in what we now call Texas.

Lastly, in 1988, Sutherland (1988) published a paper on the depositional history of the Arkoma Basin. This paper clearly described the evolution and relation of the shelf sediments (to the north) to the basinal sediments (to the south), the changing source terranes of the different sedimentary units, and the relation between clastic and carbonate units. Sutherland (1988) also suggested that the Ouachita orogenic front did not rise above sea level until Thurman time (early middle Desmoinesian), although recent research has revised this timing somewhat to late Atokan.

Horizontal Wells – Coalbed Methane and Gas Shales (1990 – present)

The first coalbed methane (CBM) well in the Arkoma Basin was drilled in 1988

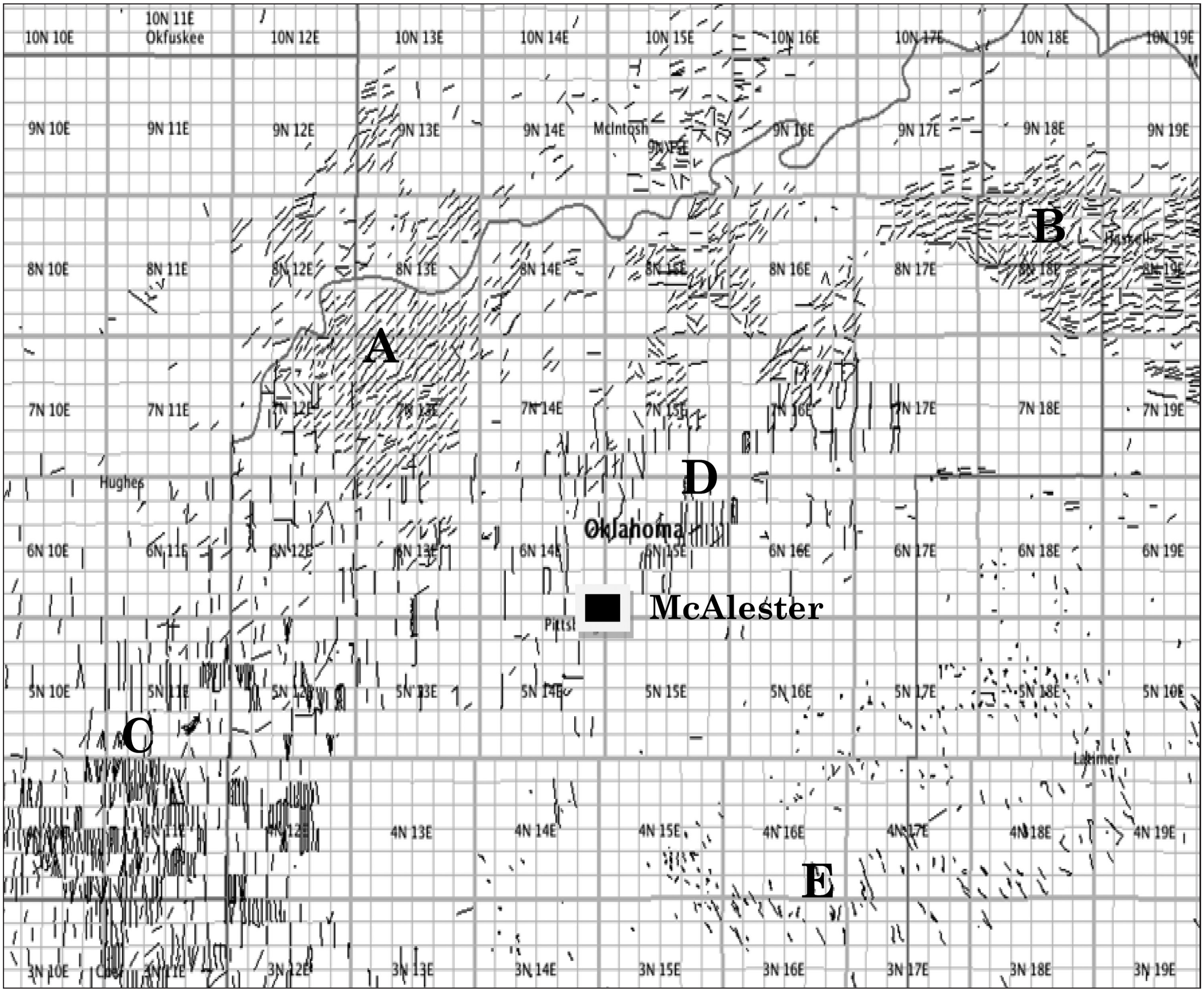


Figure 23. Map of horizontal and deviated wells near McAlester, Oklahoma. Area A – horizontal Hartshorne CBM wells drilled subparallel to and northwest of axis Lily Pad Creek Anticline (Arbenz, 1956). Area B – horizontal Hartshorne CBM wells drilled subparallel to axes of Enterprise Anticline and Russellville Syncline (Arbenz, 1956). Areas C and D - horizontal Woodford wells drilled subparallel to present-day S_{hmin} (approximately N15W – S15E) (Heidbach et al., 2009). Area E – deviated wells drilled to northwest into southeast-dipping thrust sheets. Base map from IHS Energy.

and the first horizontal CBM well in 1998. The peak of vertical CBM drilling occurred in 2002 after which activity rapidly dropped off (http://www.ogs.ou.edu/coal/pdf/2010TSOPRankRev.pdf). The peak in both vertical plus horizontal CBM drilling (353 wells) and horizontal drilling (333 wells) occurred in 2005. CBM activity throughout Oklahoma (Arkoma Basin and Northeast Cherokee Shelf area) dropped drastically in 2009; in 2011, only seven CBM wells (all horizontal) were drilled in the Arkoma Basin (Cardott, 2012). Much of the CBM activity in Oklahoma was the result of federal income tax credit programs between 1980 and 2002, although advances in horizontal-drilling techniques beginning in 1999 probably contributed towards extending that activity (Cardott, 2010). Boyd (2010) suggested that the drop in natural-gas prices resulted in the steep decline in CBM drilling from 2008 to 2009 (see also http://www.ogs.ou.edu/fossilfuels/pdf/2012OCCWoodford.pdf).

Most of the CBM wells in the Arkoma Basin are completed in the Hartshorne coal, and most are horizontal and drilled parallel to regional structure (Figure 23). Most of the factors that affect productivity are related to completion technique rather than reservoir geology; for horizontal wells, these factors include length of lateral, relation of lateral to face-cleat direction, dip of beds in relation to lateral, and production of fines during stimulation (which might result in plugging of fractures) (Cardott, 2005a). Geological factors affecting productivity include density of natural fractures, thickness and thermal maturity of coal bed, wellbore crossing unmapped fault, and mineralogy and rock fabric (which affect porosity and mechanical strength, and therefore ability to frac).

Following the successful development of the Mississippian Barnett Shale in the Ft. Worth Basin, horizontal drilling and hydraulic fracturing of black shales completely revised the short- and long-term U.S. energy picture. The Late Devonian – Early Mississippian Woodford Shale, long-recognized as a major hydrocarbon-source rock, is the principal target in Oklahoma, and a major area of the frac'd Woodford development is in the western part of the Arkoma Basin. At a 2004 symposium, Cardott (2005b) showed a map with 39 Woodford oil and gas wells, none in the Arkoma Basin; from 2004 to 2011, 2005 Woodford-only (excluding commingled with Caney or Sylvan Shales) wells had been completed, with most in the Arkoma Basin (Cardott, 2012). The vast majority of these wells are horizontal and oriented north-south (Figure 23), approximately perpendicular to the present-day maximum horizontal stress direction of N75E – S75W (Heidbach et al., 2009). (The slightly oblique lateral direction is probably based on land-ownership considerations.) Most of the Woodford wells in the Arkoma Basin are dry gas; some on the far western and southern edges of the basin are oil and/or condensate.

Little detailed information has been published on the Woodford play in the Arkoma Basin, and many questions remain concerning the role various geologic, drilling, and completion factors play in well productivity.

Future

A review of the history of Arkoma Basin petroleum exploration and development and an understanding of the Ouachita Mountains as a telescoped foreland basin suggests that lessons learned in one place or in one unit should be applicable to other places and other units. For convenience, I separate questions related to the future development of petroleum resources into the classic division of Arkoma Basin to the north of the Choctaw Fault and Ouachita Mountains to the south, but it is evident there is considerable overlap.

Arkoma Basin

1. Have the middle Atokan sandstone reservoirs been fully explored? Do we know as much about the Panola, Brazil, Shay, etc. sandstones as we do about the Red Oak? Does the Red Oak model apply to the other units, or do the different sandstones have completely different origins?

2. Are the voluminous shales within the middle Atoka possible reservoirs, knowing what we do now about horizontal drilling and hydraulic fracturing?

3. Woodford Shale development will undoubtedly continue throughout the area, but have we fully optimized completion techniques and will the geologic factors that control sweet spots vary across the basin?

4. In places transition-zone structure is well understood (triangle zone, duplex structures, etc.), but does it change along the length of the Choctaw Fault and what effect does this have on potential traps? For example, is the absence of transition-zone fields in Le Flore County the result of unfavorable geology or lack of subsurface data?

5. Is the horst beneath the Arbuckle "Deep" Field really the only such structure in the Arkoma Basin?

Ouachita Mountains

1. The Atoka Formation is a modest producer locally, but very few published studies have attempted to identify facies variations in the thrust-faulted and folded Atoka turbidites. Would studies similar to those done on the Red Oak and Jackfork highgrade certain parts of the section or certain areas?

2. Are fractures really the controlling factor in Atoka sandstone production? Are there certain parts of structures that are more favorable for fracture development than others?

3. What is the potential for Atoka shale-gas production? Are all the shales in the Atoka equally viable (or not viable) as shale-gas reservoirs?

4. Channel sandstones in the Jackfork Group locally are excellent reservoirs; is the Potato Hills the only place where such high-quality reservoir strata exist? What is the possibility for southern-sourced Jackfork sandstones? Exactly what is the role of fractures vs. primary porosity in Jackfork wells?

5. The Stanley is a producer throughout much of the central belt of the Ouachita Mountains, albeit a poor one. Given the high and possibly variable clay content, are we properly treating Stanley completions? Do some of the old wells tell us what doesn't work?

6A. How far beneath the thrust sheets does the Woodford Shale extend? Where it is too deep to be a possible reservoir rock, could it be a source rock for overlying thrust-faulted strata? B. And where beneath the thrusts and Cretaceous overlap is the early-middle Paleozoic facies change? It must be south of the Weyerhaeuser 1-22 well. What are the implications for having basinal source rocks near shelfal or slope reservoir rocks?

7. The Arkansas Novaculite is a proven reservoir at Isom Springs and is a "teaser" in several Ouachita wells. Why hasn't a major novaculite reservoir been discovered in the Ouachitas?

8. Any questions that apply to the novaculite apply to the Bigfork Chert. Shouldn't we be able to apply our new understanding of chert reservoirs, natural fractures, and induced fractures to finding and developing a Bigfork or novaculite reservoir?

9. Many of the central belt faults have relatively tight, hanging wall anticlines at the surface. What happens to these structures at depth, and could the Stanley, Arkansas Novaculite, or Bigfork Chert be developed on these structures?

Editor's Note: The opening image is a picture of Poteau Mountain within the Ouachita National Forest provided by the U. S. Forest Service.

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Biographical Sketch

Neil Suneson has worked for the Oklahoma Geological Survey since 1986, when he and some colleagues started mapping the frontal belt of the Ouachita Mountains and the southern part of the Arkoma Basin as part of the USGS-sponsored COGEOMAP and later STATEMAP programs. After working in the Ouachitas, he did some reconnaissance mapping in northwestern Oklahoma and more detailed mapping in the Oklahoma City metro area.

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Oklahoma Geological Survey

When the Survey became part of the Mewbourne College of Earth and Energy at OU, more of Neil's time was devoted to teaching (including the School of Geology's summer field camp outside of Cañon City, Colorado) and advising students on their theses. His interests range from the Late Tertiary geology of the Oklahoma Panhandle to the Early Paleozoic geology of the Broken Bow uplift in southeastern Oklahoma and everything in between. He even likes (some) igneous rocks.

Prior to working for the Survey, Neil was a petroleum development geologist with Chevron USA where he worked on the Lost Hills Oilfield. He also worked with Chevron Resources Company in geothermal exploration throughout the western U.S. All his college degrees are in geology. He received at B.A. from Amherst College in 1972, an M.S. from Arizona State University in 1976, and a Ph.D. from the University of California – Santa Barbara in 1980. His dissertation, largely funded by the U.S. Geological Survey, was based on mapping in the highly extended terrane of west-central Arizona.

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