Field Trip 7

2004 AAPG Annual Convention, Dallas, TX

Overview of Coal and Coalbed Methane in the Arkoma Basin, Eastern Oklahoma

April 21-22, 2004

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Sponsored by the AAPG Energy Minerals Division (EMD) and Dallas Geological Society

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Road Log and Geological Guide

The field trip begins at Best Western Inn of McAlester (1215 George Nigh Expressway (U.S. Highway 69). The road log includes quotes from Friedman (1991).

The field trip starts in the town of McAlester where coal mining began in Oklahoma. The town of McAlester was founded by James J. McAlester. He married a Chickasaw Indian woman, which made him a citizen of the Choctaw Nation. The founding date of the town is 1872 when the tracks of the Missouri-Kansas-Texas Railroad reached McAlester's store. Following the arrival of the railroad, "McAlester and other Choctaw citizens began mining coal under a Choctaw constitutional provision allowing a citizen to mine any mineral discovered by him for a mile in every direction" (adapted from Fugate and Fugate, 1991).

Distance in miles

Cumulative	Interval	
0.0	0.0	Turn right (southwest) and stay on service road. (**Map 1**)
0.7	0.7	Turn right (north) on U.S. Highway Business 69 (Main Street)
3.0	2.3	Turn right on Comanche Avenue.
3.1	0.1	Turn left on 3rd Street.
3.2	0.1	Turn right into parking space. **STOP 1**: Pioneer Coal Miners' Memorial Plaza in Chadick Park (10 S. 3rd Street., McAlester Oklahoma). Continue north on 3rd Street.
3.8	0.6	Turn left on Adams Avenue.
3.9	0.1	Turn left into parking space. **STOP 2**: McAlester Coal Miner's Museum in Old McAlester High Building School and Historical Museum (McAlester Building Foundation; 200 E. Adams Avenue, McAlester, Oklahoma).
4.0	0.1	Turn right on 3rd Street.
4.1	0.1	Turn left on Carl Albert Parkway (U.S. Highway 270).
~7.8	3.7	Road joins and follows McAlester coal outcrop, bypassing abandoned underground mines in the McAlester coal (right) and crossing the axis of the Savanna Anticline (**Maps 2 and 3**).
	3.4	Spoil piles on left derived from abandoned underground mines in McAlester coal.
15.2	4.0	Road crosses the axis of the Kiowa Syncline.
16.2	1.0	Road crosses outcrop of the McAlester coal (just before Peaceable Creek).
	2.2	Enter town of Hartshorne. "Haileyville and Hartshorne are underlain by McCurtain Shale and the Upper and Lower Hartshorne coals, which dip NW, N, and E due to erosion of a hill composed of Hartshorne sandstones. This is the type area of the Hartshorne coals and the Hartshorne Formation."
19.5	1.1	Road crosses Upper Hartshorne coal outcrop.
20.0	0.5	Turn left (north) to stay on U.S. Highway 270 East. The McAlester Formation underlies the highway. Warner Sandstone (McAlester

		Formation) caps Round Top Mountain on left and Belle Star Mountain on right. The Hartshorne Syncline passes east-west through these mountains. "The whole Hartshorne-Gowen area is underlain by abandoned, large underground mines, once operated by the Rock Island Railroad to supply its steam engines." The mines in the Lower Hartshorne coal average ~400 feet deep.
23.3	3.3	Latimer County line. (**Map 4**)
25.0	1.7	Cross covered boundaries of the Upper Hartshorne coal and Lower Hartshorne coal (abandoned surface mines on left side of road) on the north flank of the Hartshorne syncline. "South of Gowen, P&K Ltd. completed reclaiming its 2 mile long strip mine in 1989. Hartshorne Sandstone dips 13°S".
27.0	2.0	We descend a hill formed by sandstones in the Lower Hartshorne member. The top of the Atoka Formation is at the base of the hill. Just east of Gaines Creek we pass a well pad on the north side of the road for BP America 2, 3, and 6 Bennett State wells (NE¼ SW¼ NE¼ Sec. 19, T.5N., R.18E.). The Ouachita Mountains are to the right, south of the Choctaw Fault (~2 miles southeast).

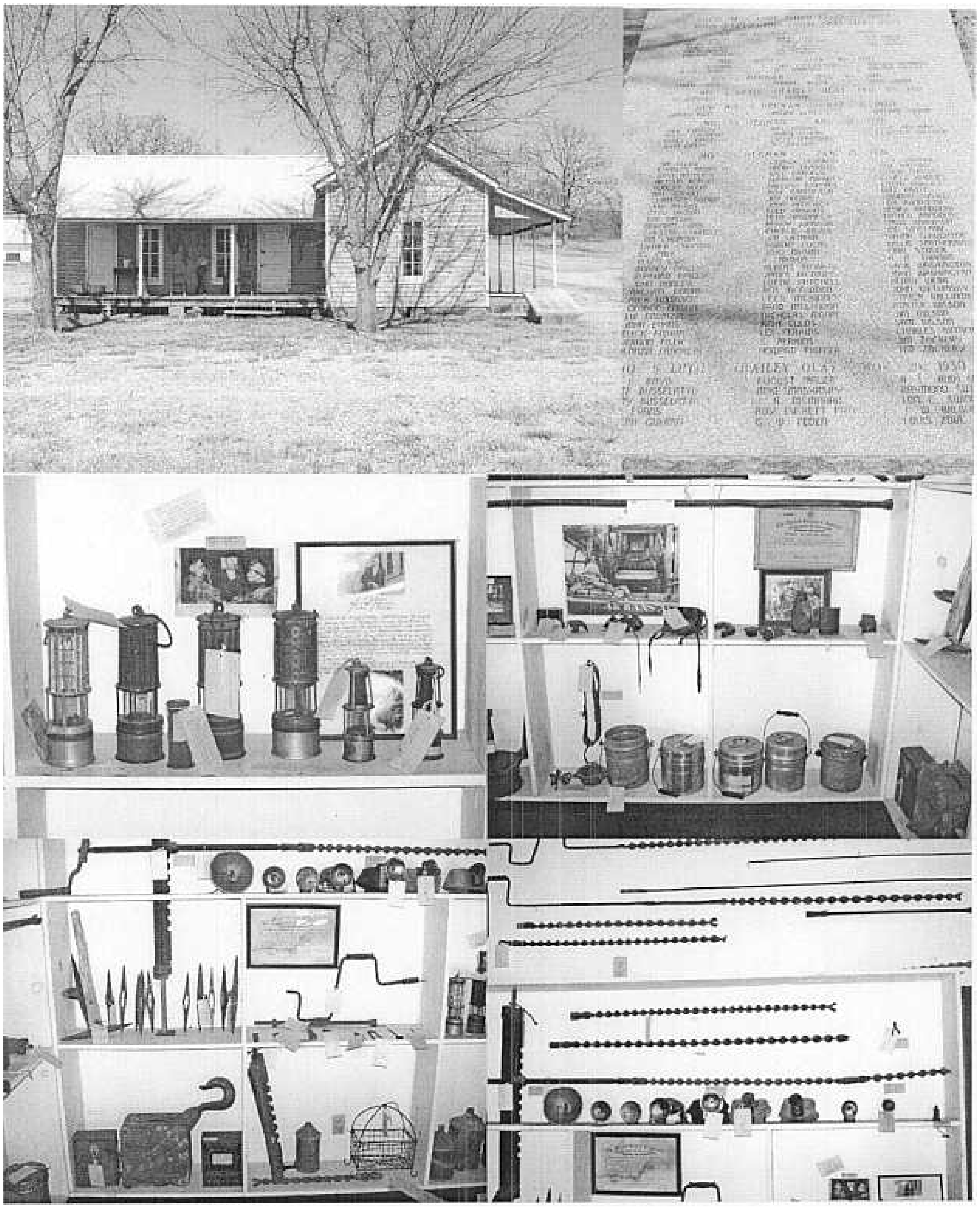
ARCO Oil & Gas Co. 2-19 Bennett State (API 35-077-20481); NE¼ SW¼ NE¼ Sec. 19, T.5N., R.18E.; completed 12/17/1988; Arbuckle 13,444-13,762 ft [IP 9,195 Mcfd, 151 Bwd; ISIP 5,042, FTP 4,665]; Arbuckle 13,836-13,985 ft [IP 8,280 Mcfd, 182 Bwd; ISIP 5,050, FTP 4,445].

ARCO Oil & Gas Co. 3-19 Bennett State (API 35-077-20504); E½ E½ E½ NW¼ Sec. 19, T.5N., R.18E.; completed 6/2/1989; Spiro 9,271-9,301 ft [IP 1,620 Mcfd; ISIP 766, FTP 182]; Morrow sand 9,936-9,947 ft [IP 239 Mcfd; FTP 103]; Spiro subthrust 11,332-11,338 ft [IP 1,780 Mcfd; FTP 794]; Wapanucka 11,408-11,424 ft.

BP America Production Co. 6-19 Bennett State (API 35-077-21311); NE¼ NE¼ SW¼ NE¼ Sec. 19, T.5N., R.18E.; completed 8/21/2002; Simpson 12,815-12,960 ft [IP 5,240 Mcfd, 10 Bwpd; ISIP 2,316, FTP 1,305].

32.0	5.0	~2.5 miles to the north (Sec. 35, T.6N., R.18E.): Upper and Lower Hartshorne coals merge to form a 10-ft thick Hartshorne coal (Wilson, 1970; Hemish, 1999). The coal dips ~64°N.
33.5	1.5	Ridge of Hartshorne sandstone to the left (north). We are driving on the Atoka Formation.
35.4	1.9	City of Wilburton. Cross covered boundary of Upper and Lower Hartshorne coals (dip ~22°N). "The Wilburton water tower sets on the Warner Sandstone Member (McAlester Formation) to the north, while the Hartshorne Sandstone forms a ridge on the south." The city is underlain by the McCurtain Shale Member (base of the McAlester Formation). The Upper Hartshorne and Lower Hartshorne coals have been extensively mined both by surface and underground methods east and northwest of Wilburton (see portions of maps by Friedman and Woods (1982) and Hendricks (1939, plate 27)). The Choctaw Fault is about 1 mile to the south.

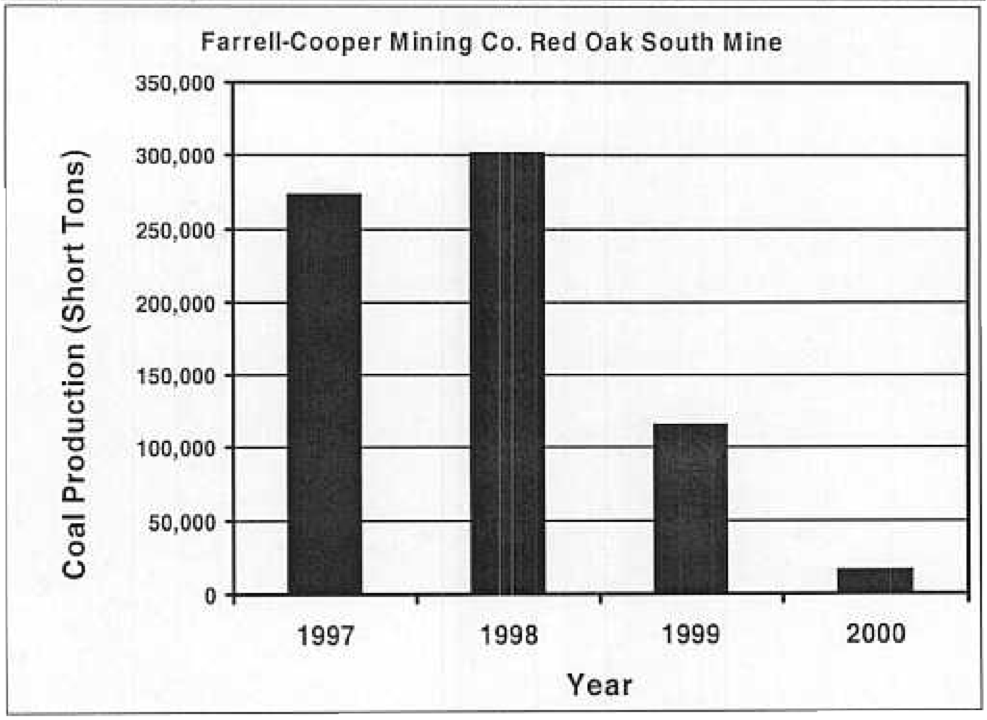
38.0 2.6 Lutie Coal Miners Museum in Hailey Ola Coal Company mine home built in 1901. The museum was dedicated in 1982.



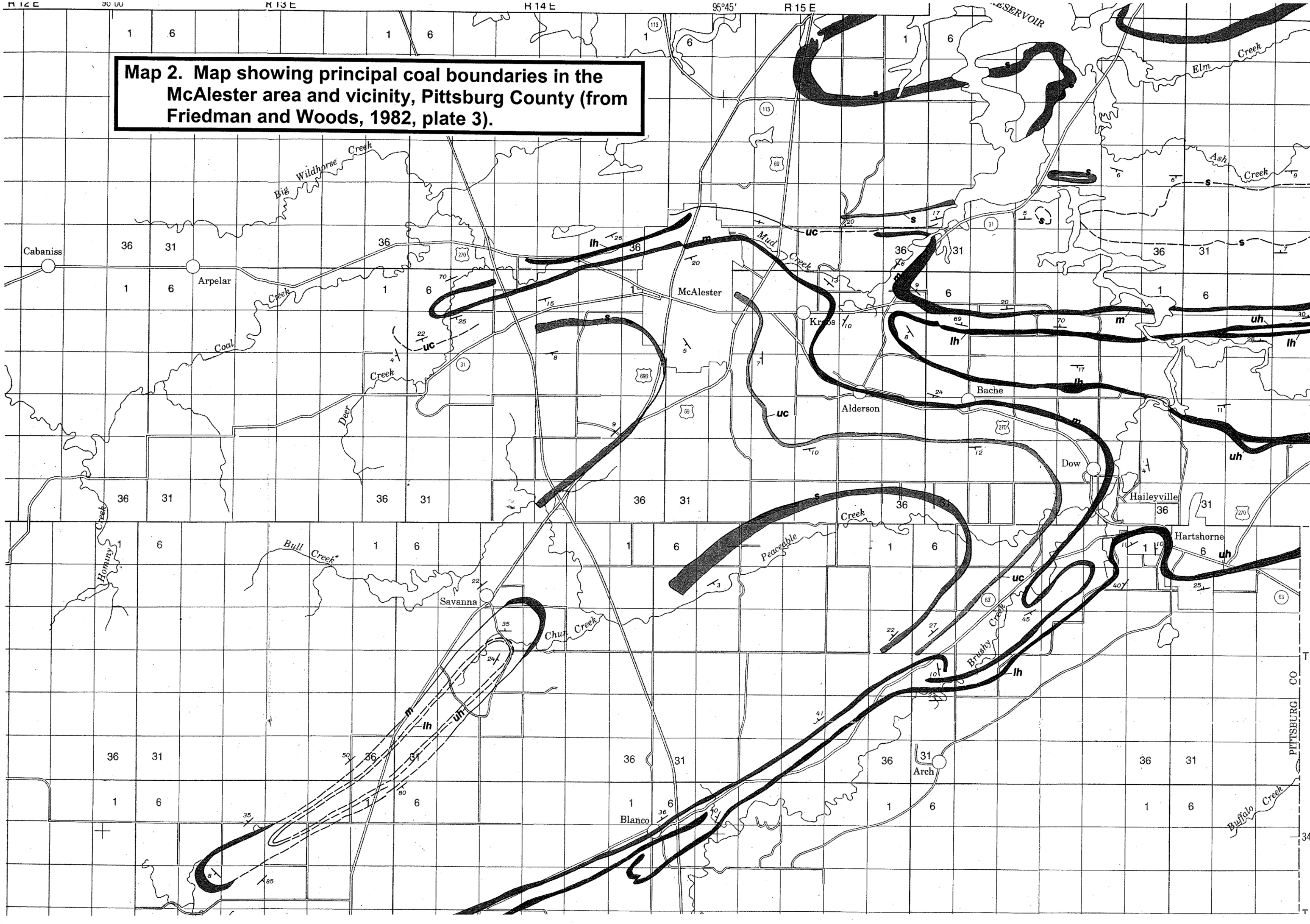
39.7 1.7 We are driving along strike in the McCurtain Shale Member in between the Lower Hartshorne coal to our right and the McAlester coal to our left. Strata are dipping ~20°NW.

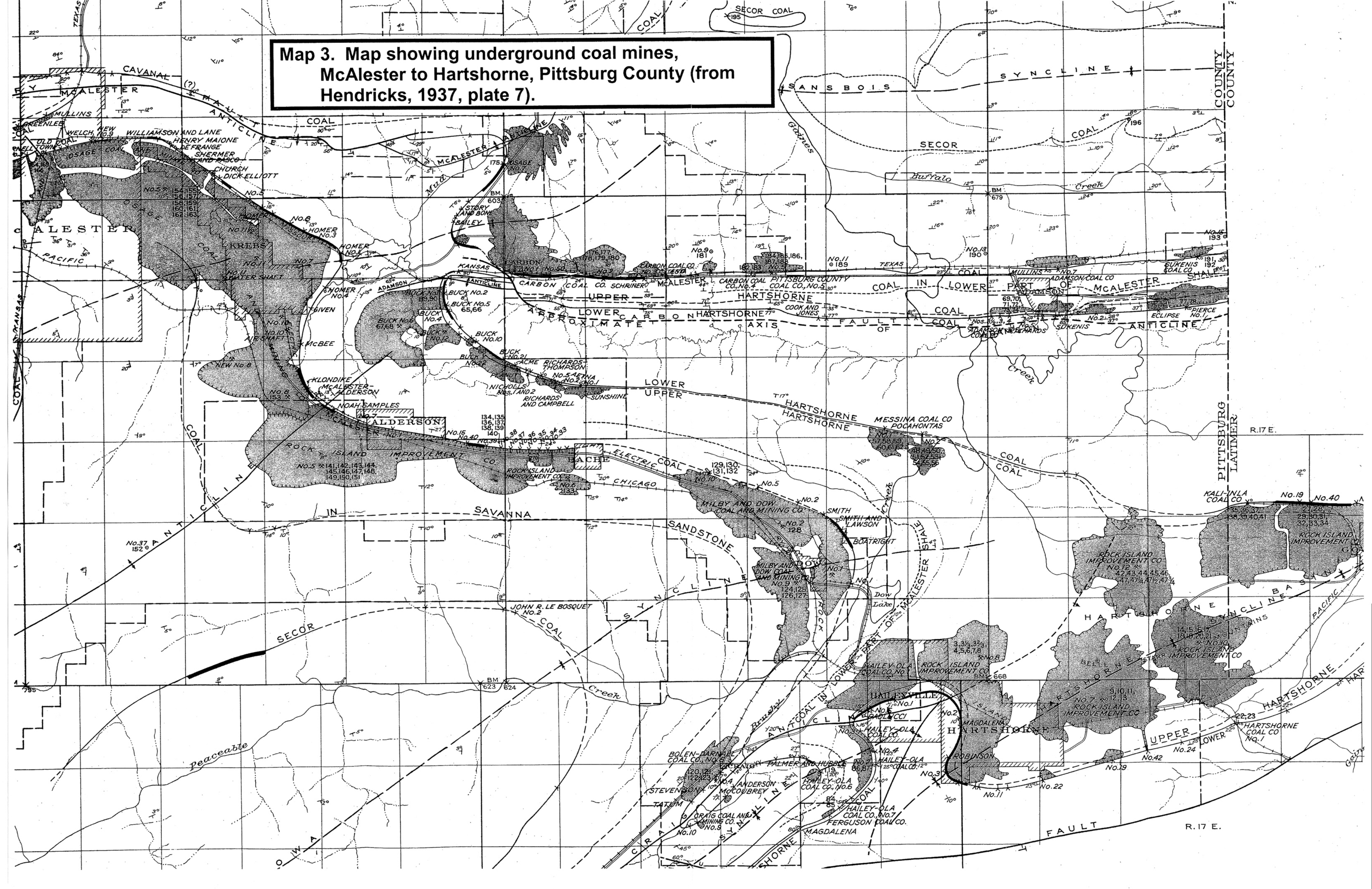
46.5 6.8 Road crosses covered boundary of McAlester coal (at Little Fourche Maline).

48.4 1.9 Entrance to reclaimed Farrell-Cooper Red Oak Mine South on the right. 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.6N., R.21E. to mine the McAlester coal (2.1 ft thick, 3.3% sulfur) and Upper McAlester coal (1.7 ft thick, 4.6% sulfur).

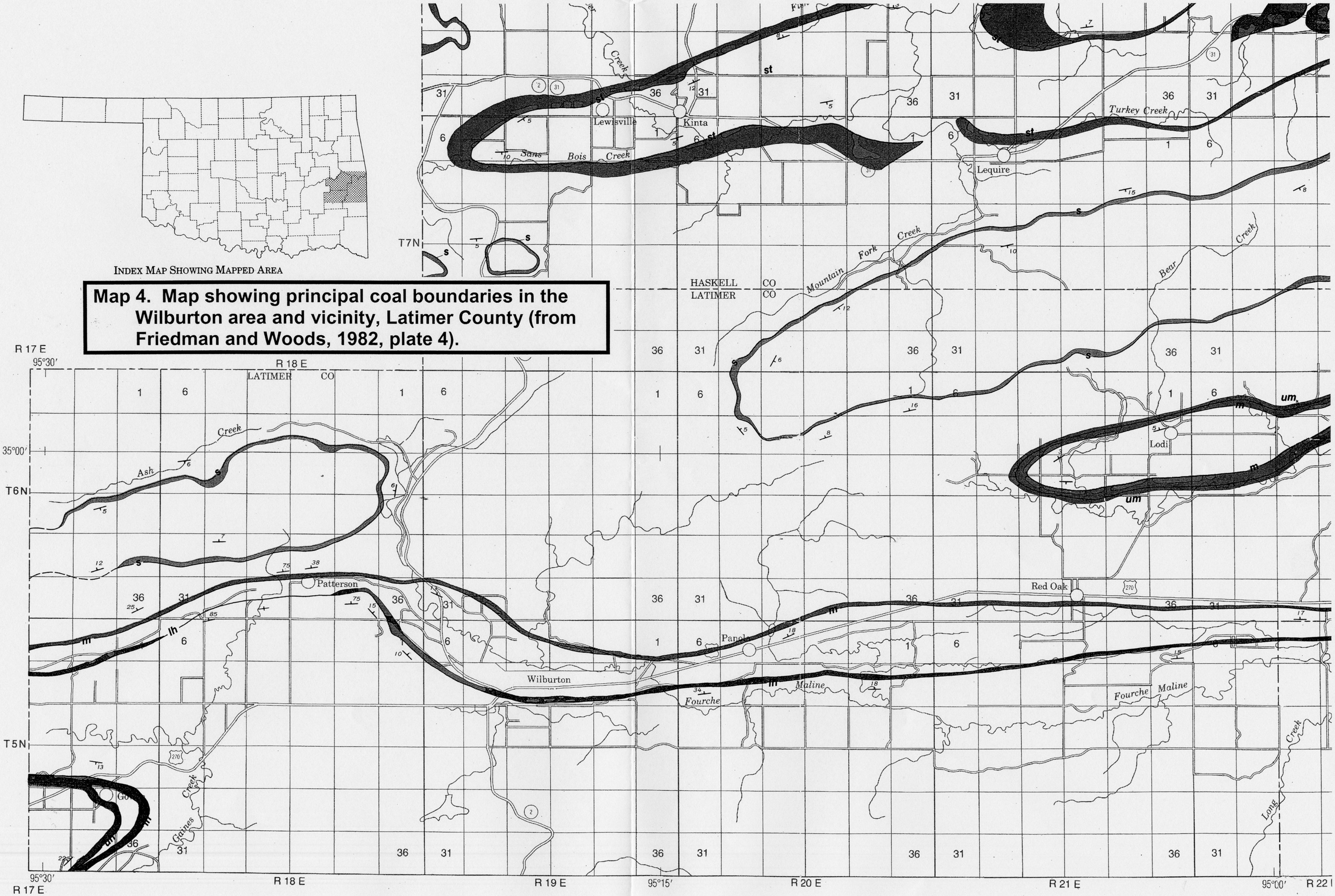


Map 2. Map showing principal coal boundaries in the McAlester area and vicinity, Pittsburg County (from Friedman and Woods, 1982, plate 3).

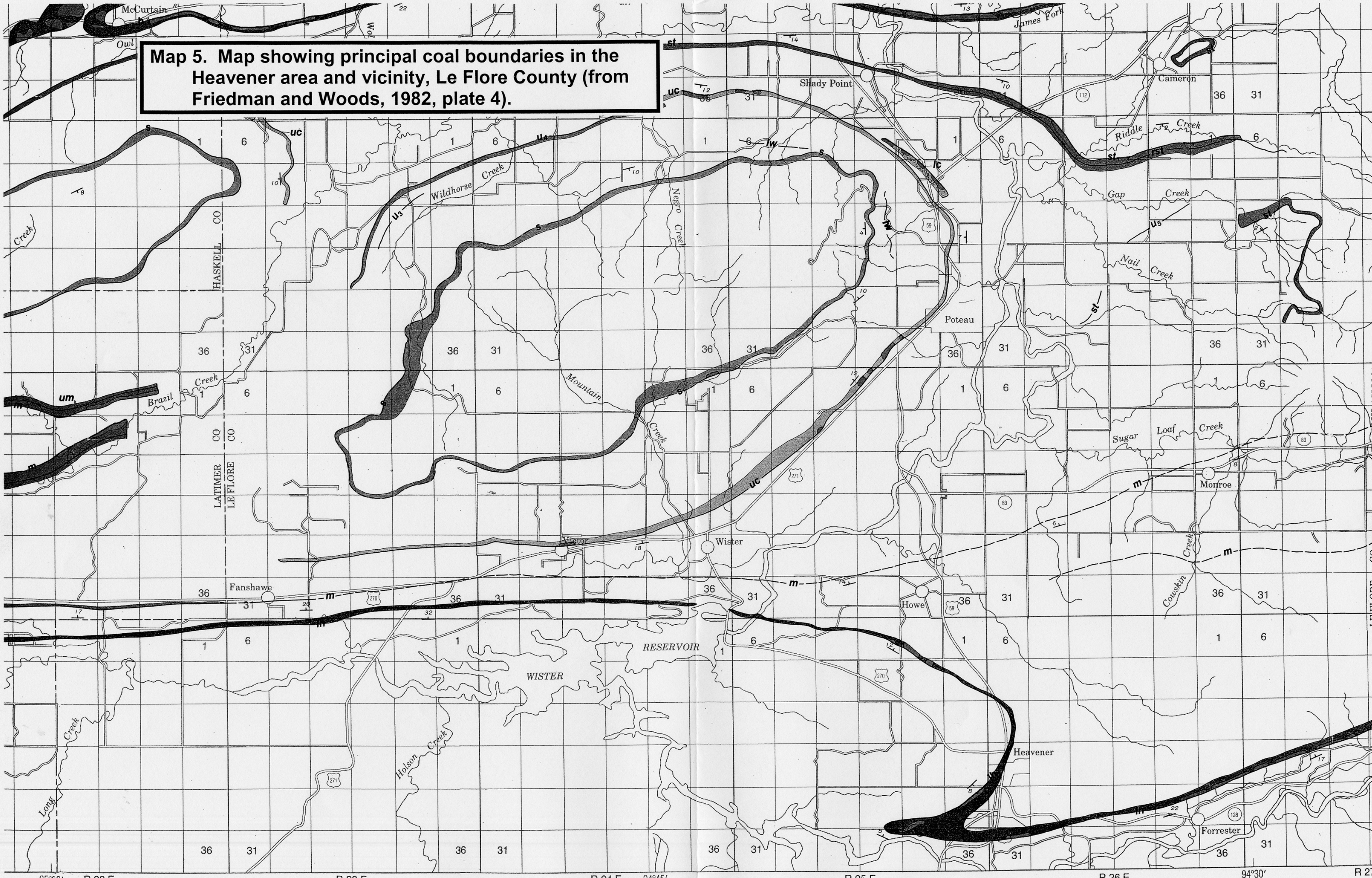




Map 3. Map showing underground coal mines, McAlester to Hartshorne, Pittsburg County (from Hendricks, 1937, plate 7).



Map 4. Map showing principal coal boundaries in the Wilburton area and vicinity, Latimer County (from Friedman and Woods, 1982, plate 4).

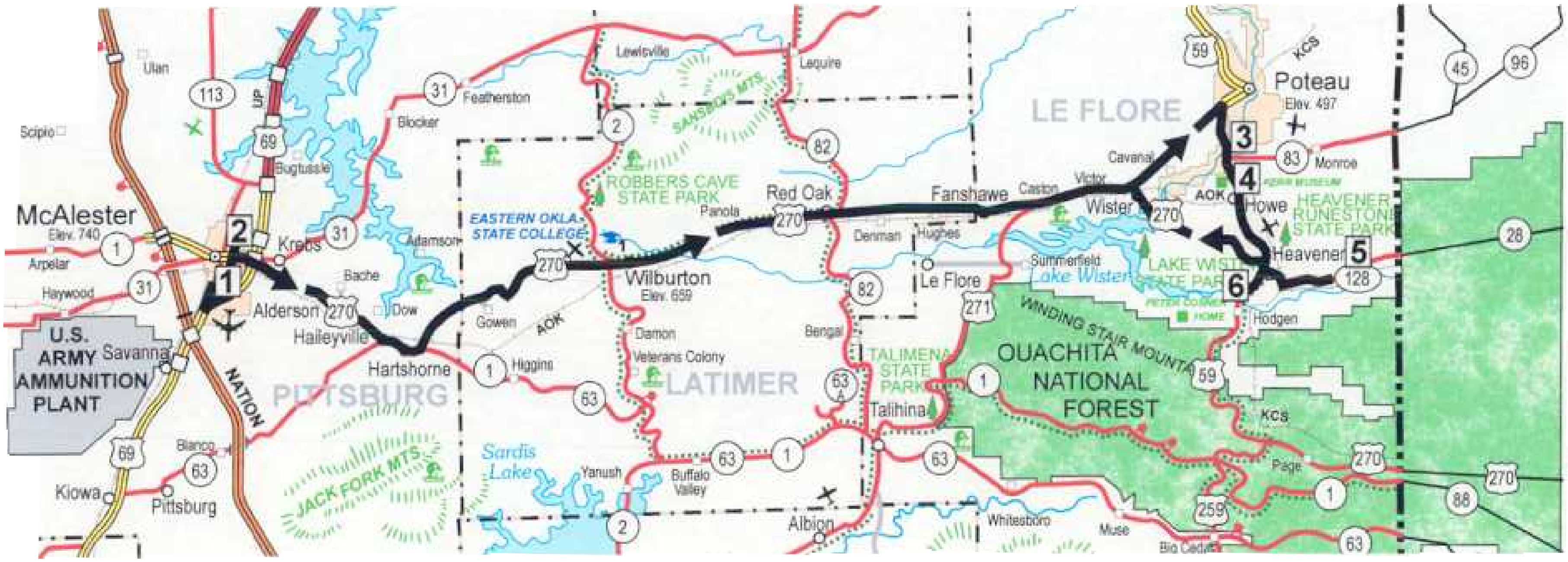


Map 5. Map showing principal coal boundaries in the Heavener area and vicinity, Le Flore County (from Friedman and Woods, 1982, plate 4).

	1.6	Red Oak Mountain (1 mile north of Red Oak) and Red Oak Peak (northeast of Red Oak) are capped by the Savanna Formation and are cut east/west by the axis of the Cavanal Syncline.
55.0	5.0	Turkey Creek. (**Map 5**)
58.6	3.6	Enter Le Flore County. We have been driving along the outcrop of the McAlester and Upper McAlester coals just to the south of the road. The McAlester coal is ~2 feet thick and dips ~20°N.
64.7	6.1	We begin to diverge from the outcrop of the McAlester coal and travel up section.
	2.0	The road (Highway 270 west of Wister and Highway 271 east of Wister) parallels the Upper Cavanal coal (~2.5 feet thick, dips ~18°N; Savanna Formation) outcrop on the north for the next 9 miles.
70.1	3.4	Wister city limit.
70.7	0.6	Intersection of U.S. Highways 270 and 271.
71.7	1.0	Cavanal Mountain can be seen at ~10:00. Sugarloaf Mountain is at ~2:00. Poteau Mountain is at ~3:00.
75.1	4.4	Poteau city limit.
77.0	1.9	Turn left on to access loop for U.S. Highway 59 south.
80.3	3.3	Turn left on Old Highway 59 road.
		STOP 3. El Paso Production Company 4-14H Wood horizontal coalbed-methane well.
80.5	0.2	Turn left on U.S. 59.
81.1	0.6	Junction with Oklahoma Highway 83.
81.5	0.4	Turn left on dirt driveway.
		STOP 4. El Paso Production Company 2-23 Blake vertical coalbed-methane well.
	3.8	~1 mile east of the road is the location of the Howe Coal Co. Howe No. 1 underground mine **(see notes and maps on pages 84-86**).
	2.2	Turn left on industrial road, cross railroad tracks and turn right on Old Pike Road.
88.4	0.9	Turn left on Burns Lane toward Runestone State Park.
88.8	0.4	Enter Runestone State Park.
90.0	1.2	Overlook and **LUNCH** at pavilion.
91.2	1.2	Turn left on Morris Creek Road.
92.9	1.7	Turn left on Oklahoma Highway 128.
93.7	0.8	South of the railroad tracks we follow the outcrop of the Lower Hartshorne coal for about 1 mile.
96.8	3.1	Turn left on Sugar Creek Lane.
98.3	1.5	Entrance to Farrell-Cooper Heavener East mine.
98.9	0.6	**STOP 5.** Mine office.
101.0	2.1	Turn right on Oklahoma Highway 128.
106.0	5.0	Turn left on U.S. Highway 59 at stop light.
107.0	1.0	Reclaimed coal mine on right.
107.3	0.3	Entrance to Farrell-Cooper Pine Mountain reclaimed surface coal mine.

107.8	0.5	**STOP 6.** Highway 59 road cut
108.	0.3	Continue south Highway 59 and turn left Old Highway 59 Make U-turn back on Highway 59 North
111.0	2.9	Turn left U.S. Highway 270
122.3	1.3	Turn left 270/271 Retrace route back hotel
190.3	68.0	Arrive at Best Western Hotel

Map 1. Road map showing field-trip route and stops.

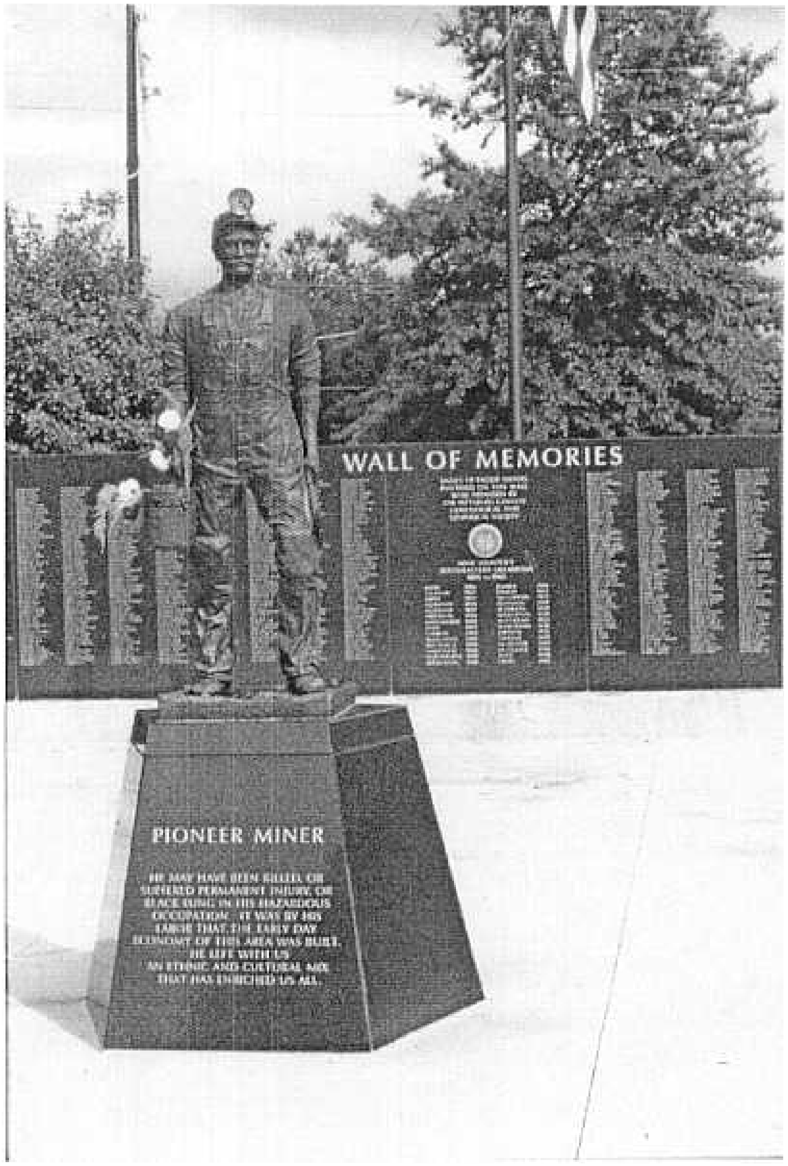


1 Field trip stops

Stop 1. Pioneer Coal Miners' Memorial Plaza

Location: Chadick Park, 10 S. 3rd St., McAlester, OK

Introduction: The Pioneer Miner and Wall of Memories were dedicated on September 30, 1992 to commemorate the coal miners that were killed in area mining accidents.



The engraving on the life-size bronze statue states:

"He may have been killed, or suffered permanent injury, or black lung in his hazardous occupation. It was by his labor that the early day economy of this area was built. He left with us an ethnic and cultural mix that has enriched us all."

Inscribed on the Wall of Memories (42-feet long and 6-feet high) are the names of 1,700 fallen miners and 28 mining disasters from 1885 to 1945.

Krebs	1885				
Savanna	1887				
Krebs	1892				
Alderson	1893				
Alderson	1897				
Alderson	1901				
Hartshorne	1901				
Dow	1902				
Carbon	1903				
Wilburton	1905				
Witteville	1906				
Haileyville	1908				
Hartshorne	1909				
Wilburton	1910	Jumbo	1910	Lehigh	1912
McCurtain	1912	Adamson	1914	Alderson	1919
Wilburton	1920	McCurtain	1922	Wilburton	1926
Tahona	1926	Tahona	1929	McAlester	1929
McAlester	1930	Lutie	1930	Craig	1945

Stop 2. McAlester Coal Miner's Museum

Location: McAlester Building Foundation, 200 E. Adams, Room 209, McAlester OK

Introduction: The McAlester Coal Miner's Museum displays authentic tools and equipment used by underground coal miners in this area. Coal was mined in Indian Territory and Oklahoma strictly by underground methods until 1915. Artifacts in the museum include a breathing apparatus, miners' lamps, drills, photographs, lunch buckets, maps, and coal samples. Displayed outside on the west side of the building is the largest (2.5 tons) lump of McAlester coal from the Osage Coal and Mining Company Homer mine. The Homer mines were located east of the town of McAlester (see Map 3). Cleat orientation and spacing can be seen clearly on the east side of the coal block.

A 4.1 ft thick channel sample of the McAlester coal from a surface coal mine (K&R Coal Co. Savanna Test Burn; Sec. 10, T.4N., R.14E.) had 4.8% moisture, 3.0% ash, 36.5% volatile matter, 55.7% fixed carbon, 0.83% vitrinite reflectance (high volatile A bituminous rank), 87.9% vitrinite, 5.1% liptinite, 7.0% inertinite.

A 4.0 ft thick core sample of the McAlester coal (Sec. 19, T.4N., R.16E.) had 3.1% moisture, 5.5% ash, 32.1% volatile matter, and 59.3% fixed carbon (high volatile A bituminous rank).

Coal display at coal museum.

Coal face on back side of coal display. Note the cleat orientation (quarter in lower left for scale).

A Brief History of
Coal Mining in Oklahoma

Nuttall (1821, p. 146–177) recorded the presence of coal in what is now Oklahoma as early as 1821, but mining on a commercial scale did not begin until railroads were built in 1872. McAlester became the hub city for the Missouri–Kansas–Texas Railroad. Branch lines were built to haul coal from nearby mines to the main line at McAlester; similarly, commercial-scale mining in other parts of the coal field was made possible by the arrival of railroad lines (Trumbull, 1957).

In 1872, the Choctaw, Oklahoma, and Gulf Railroad was built eastward from McAlester through Hartshorne, Wilburton, Howe, and other points. Later, extension of the line eastward to Memphis, Tennessee, and westward across Oklahoma, widely increased the market for coal. The St. Louis–San Francisco Railway was built across the east side of Indian Territory (Oklahoma) about 1885. Building of the Kansas City Southern Railway followed, and the coal field was linked to the Gulf of Mexico at Port Arthur, Texas (Trumbull, 1957).

Statistics on the coal trade in Oklahoma (Indian Territory) in two of the early years, 1887–88, were published by Ashburner (1890, p. 124). He listed coal production as 685,911 short tons for 1887 and 761,986 short tons for 1888. In 1888, 1,700 men were employed by the industry in the Indian Territory, according to Ashburner (1890, p. 137), and the value at the mine for "soft coal" was $1.95 per ton.

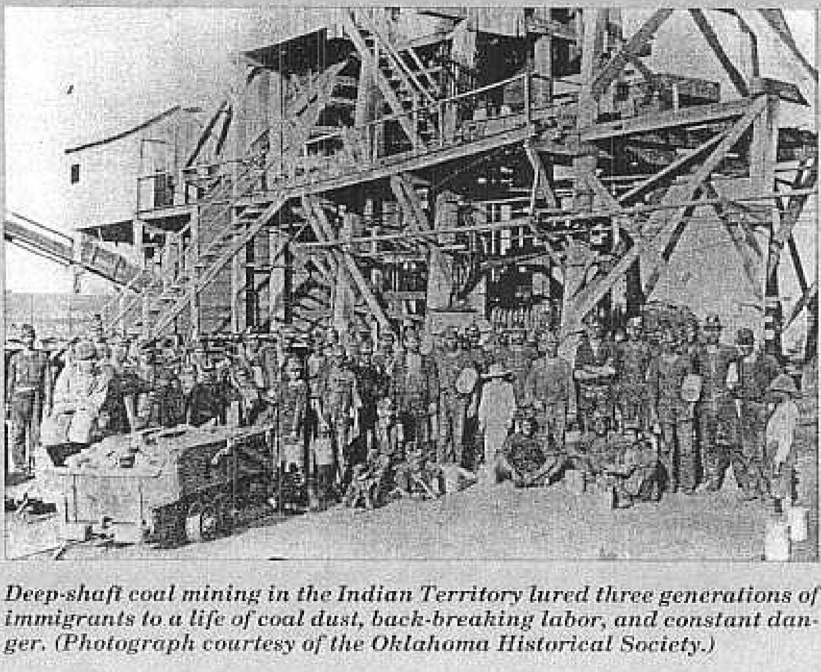
Even at that time, wages paid for mining coal were "the subject of an almost constant dispute between the employer and the employee" (Ashburner, 1890, p. 135). Wages were based primarily on the market price received for the product of the mine. If the employer did not meet wage demands—and mines could not be kept in active operation at a direct loss to the operator—miners would strike. Ashburner (1890, p. 135) eloquently expressed the difficulties of the times:

> The inevitable result of such a strike is that while the operator loses much money during these periods, in case there is a legitimate demand for his coal, yet the actual personal suffering is at all times infinitely greater to the miner and his family, whose distress for the want of proper food and clothing, and even at times shelter from the weather, is frequently heartrending.

Average wages in 1888 were 80¢ per net ton per miner. The coal miners worked an average of 300 days per year. Their work consisted of removing the coal from the bed and placing it on railroad cars and wagons at the mouth of the mine for shipment to market (Ashburner, 1890, p. 136–137).

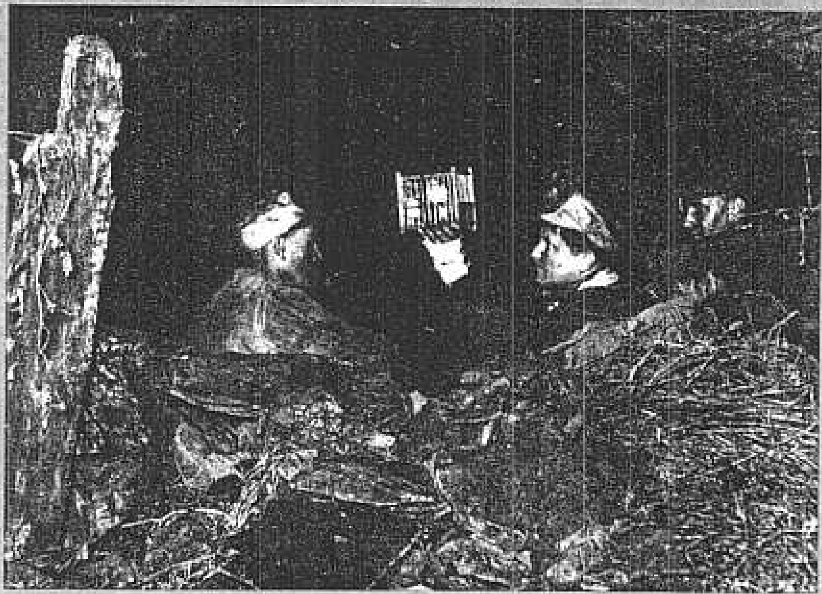
As a result of the completion of the four new railroad lines in the late 1880s, and of the increased market for coal, coal production in Oklahoma had reached a million tons per year by 1891. By 1903, production from 117 mines throughout the coal field exceeded 3.5 million tons per year (Trumbull, 1957, p. 362).

Between 1873 and 1883, there were about 1,000 coal miners in the Indian Territory. Ten years later, there were twice as many, and, by 1904, the number of coal miners stood at more than 8,000. In the early history of coal mining in the Indian Territory, most of the miners were immigrants from the British Isles. However, around the turn of the century, more and more immigrants from southern and eastern Europe arrived to work in the coal mines and find a home (Hightower, 1985).



Deep-shaft coal mining in the Indian Territory lured three generations of immigrants to a life of coal dust, back-breaking labor, and constant danger. (Photograph courtesy of the Oklahoma Historical Society.)

From Suneson and Hemish 1994 pages 42-43)



In the early days of coal mining, miners used canaries to detect deadly gases. A dead bird meant extreme danger! (Photograph courtesy of the Oklahoma Historical Society.)

Mining towns in the Indian Territory were built to imitate those in Pennsylvania. Miners were paid in scrip that was used as legal tender and backed by the mining companies, most of which were owned by the railroads. The economic system has been described as semi-feudal. Communities were totally dependent on the production of coal. It was not until the 1920s that company stores began to decline in importance and a measure of free enterprise was introduced (Hightower, 1985).

From 1900 through WWI, Oklahoma was an important coal producer. Coal was a major fuel in Oklahoma and a major ingredient in steel production in adjacent states (Friedman, 1974, p. 44). During the past 120 years, coal production in Oklahoma has gone through a series of cycles, generally controlled by demands of steel manufacturing for fuel and coke.

Prior to 1920, production of coal by strip mining was insignificant. In 1920, 95% of all coal mined was produced by underground methods. Since then, the trend toward surface mining has increased steadily; at present, only one underground mine is operating.

Oklahoma's underground mines—where the men were surrounded by crude machinery and worked by maneuvering in near darkness—were among the most dangerous in the country. The bituminous coal produced a great deal of fine dust that was inhaled by the miners. Explosions were common. Gas seeps in mine shafts could be deadly, so miners used birds as an early-warning system.

The immigrant miners were thought of as no better than pit mules. They went into the coal mines at daybreak and came out after dark. There were no eight-hour days. It was not unusual for the miners to walk 2 or 3 miles to the mines, put in a day's work, then—sweaty and grimy—walk home. Beginning wages were $1.15 per day. Experienced miners were paid somewhat better (Hightower, 1985).

The coal mining industry in Oklahoma has had a history of disasters, in which a number of men have lost their lives. Much of the blame for coal mining accidents rests with mine operators whose lack of safety precautions contributed to hundreds of injuries and deaths in the early days of mining. Gas and dust explosions in underground mines were the primary cause of the disasters. The earliest records of deaths go back to 1885 when 13 men lost their lives in a mine at Krebs. Other disasters followed; a few of the major ones are listed here: in 1892 another underground mine explosion at Krebs killed 96 men; in 1912, 73 men were killed in a mine at McCurtain; and, in 1926, 91 men were killed in a mine at Wilburton (Oklahoma Department of Mines, 1988).

Earliest published mapping and discussion of coals in the field-trip area were by Chance (1890, p. 653–661). He wrote a description of the Choctaw coal field, which, in general, included the area from just west of McAlester to the Arkansas state line. It was bounded on the south by the Choctaw fault and, on the north, by the San Bois Mountains and Cavanal Mountain. As would be expected, subsequent, more detailed work revealed many errors in his mapping. Names he had given coal beds were changed or abolished as geologic work progressed. For example, the name "Grady" coal was dropped in favor of "Hartshorne" coal, and the "Mayberry" coal was shown to be equal to the "Secor" coal. The "Norman" coal could not be identified, and the name was never used again (Oklahoma Geological Survey, 1954).

In 1899, 1901, and 1903, the U.S. Geological Survey mapped the geology of parts of the Choctaw coal field. In 1900, the report, "Geology of the Eastern Choctaw Coal Field, Indian Territory," was published (Taff and Adams, 1900). A second report on the geology of coal in Indian Territory, Arkansas, and Texas, entitled "The Southwestern Coal Field," was published in Part III of the Twenty-Second Annual Report of the U.S. Geological Survey (Taff, 1902b).

Many familiar stratigraphic names, such as "Atoka Formation," "Hartshorne Sandstone," "McAlester Shale," "Savanna Formation," and "Boggy Shale," had their origins in these reports (Taff, 1902b; Taff and Adams, 1900). Considering the limited resources available at the time to aid field workers in their research, as well as the adverse working conditions in the region, the quality of this early work is truly remarkable.

2

Introduction to coal geology of Oklahoma

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Cardott, B.J., 2002, Introduction to coal geology of Oklahoma, *in* Fourth annual Oklahoma coalbed-methane workshop: Oklahoma Geological Survey, Open-File Report 9-2002, p. 34-55.

Introduction to Coal Geology of Oklahoma

Brian J. Cardott
Oklahoma Geological Survey

INTRODUCTION

The Oklahoma coalfield is in the eastern part of the State and occupies the southern part of the Western Region of the Interior Coal Province of the United States (Campbell, 1917; Friedman, 2002). The coal region continues northward into Kansas and eastward into Arkansas (Tully, 1996). The Oklahoma coalfield is bounded on the northeast, south, and southwest by the Ozark, Ouachita Mountain, and Arbuckle Mountain Uplifts, respectively, and on the west by noncommercial coal-bearing strata of Missourian to Wolfcampian age (**Figure 1**). Some noncommercial Pennsylvanian-age coal resources occur in the Anadarko Basin (Wood and Bour, 1988) and Ardmore Basin (Trumbull, 1957; Tomlinson, 1959), but these are not part of the Oklahoma coalfield.

Friedman (1974) divided the Oklahoma coalfield into the northeast Oklahoma shelf and the Arkoma Basin based on physiographic and structural differences (**Figure 2**). The commercial coal belt contains coal beds ≥ 10 in. (25 cm) thick that are mineable by surface methods at depths < 100 ft (30 m) and coal beds ≥ 14 in. (36 cm) thick that are mineable by underground methods (Hemish, 1986). The noncommercial coal-bearing region has limited information on coal thickness and quality or contains coals that are too thin, of low quality, or too deep for surface mining. The western boundary of the noncommercial coal-bearing region is uncertain. Coalbed methane (CBM) production has been developed in both the commercial coal belt and the noncommercial coal-bearing region.

Figure 3 shows coal outcrop and potentially strippable areas in the Oklahoma coalfield (Friedman, 1982b). Coal beds in the northeast Oklahoma shelf strike northeast in outcrop and dip as much as 2° westward and northwestward from the outcrop to depths > 2,500 ft (760 m; **Figure 4**). Coal beds in the Arkoma Basin are present at the surface and to depths > 6,000 ft (1,830 m)(Iannacchione and Puglio, 1979a); they are faulted and folded into narrow, northeastward-trending anticlines and broad synclines (Figure 4). Coal beds in the Arkoma Basin dip from 3° to nearly vertical (Friedman, 1982b, 2002). Major deformation of the Oklahoma coalfield occurred during the peak of the Ouachita orogeny (Middle to Late Pennsylvanian)(McBee, 1995).

COAL STRATIGRAPHY

The age of commercial coal-bearing strata in the Oklahoma coalfield is Desmoinesian (Middle Pennsylvanian). Thin, noncommercial coal beds occur in Morrowan, Atokan, Missourian, Virgilian, and Wolfcampian strata (Cardott, 1989). **Figures 5 and 6** are generalized stratigraphic columns of the northeast Oklahoma shelf and Arkoma Basin, showing about 40 named and several unnamed coal beds and their range in thickness measured from outcrops, mines, and shallow core samples. Coal beds are 0.1 to 6.2 ft (0.03 to 1.9 m) thick in the shelf and 0.1 to 7.0 ft (0.03 to 2.1 m) thick in the basin. The thickest known occurrence of coal in the Oklahoma coalfield is an exposure of the Hartshorne coal (10 ft) in Latimer County (sec. 35, T. 6 N., R. 18 E.; Wilson, 1970; Hemish, 1999). The thickest known occurrence of coal in the shelf is the Weir-Pittsburg coal (6.2 ft) in a coal-company drill hole at a depth of 408 ft (124 m) in Craig County (sec. 28, T. 29 N., R. 18 E.; Hemish, 1986, Plate 4; Hemish, 2002).

Hemish (2001, p. 78) described the following differences in the coal-bearing strata between the Arkoma Basin and the northeast Oklahoma shelf: "1) Coal-bearing rocks present above the Senora Formation in the shelf area are absent in the Arkoma Basin; 2) Stratigraphic units are generally much thicker in the Arkoma Basin; 3) Commercial coal beds in the northern shelf area pinch out to the south and are absent in the basin; conversely, certain well-developed commercial coals in the Arkoma Basin, such as the Hartshorne coal, pinch out to the north, or have no commercial value in the shelf area, owing to thinness; 4) Quality of the same coal in the two regions often varies because of different depositional environments. Additionally, strata in the Arkoma Basin are much more deformed than they are in the shelf area. Beds have been folded into broad, northeast-trending synclines and narrow anticlines, resulting in steep dips of the beds in some areas. Faulting is also common throughout the Arkoma Basin."

In ascending order, the coal beds yielding commercial methane in the northeast Oklahoma shelf include the Riverton and McAlester (McAlester Formation), Rowe and Drywood (Savanna Formation) and Bluejacket and Wainwright (Boggy Formation) in the Krebs Group; Weir-Pittsburg, Tebo, Croweburg, Bevier, Iron Post, and Mulky (Senora Formation) in the Cabaniss Group; and Dawson (Holdenville Formation) in the Marmaton Group of Desmoinesian age. Hemish (2002) correlated coals from the surface to subsurface in a 2,700-mi^2 area in the northeast Oklahoma shelf to assist operators in correctly identifying methane-producing coal beds. Two type logs were designated in the northern and southern parts of the study area. The northern type log is in **Figure 7.** Persistent marker beds are identified to correlate the coal beds.

The nomenclature of Oklahoma and Kansas coal-bearing strata and coal beds differ slightly. The Kansas Geological Survey includes the Krebs and Cabaniss Formations in the Cherokee Group (Brady, 1997), whereas the Oklahoma Geological Survey assigns the Krebs and Cabaniss to group level in the Desmoinesian Series. The Rowe coal of Kansas and Missouri is equivalent to the Keota coal of Oklahoma, whereas the Drywood coal of Missouri and Dry Wood coal of Kansas are equivalent to the Spaniard coal of Oklahoma (Hemish, 1990b).

The Mulky coal is one of the most important CBM reservoirs in the northeast Oklahoma shelf (Cardott, 2002b). The Mulky, the uppermost coal in the Senora Formation, occurs at the base of the Excello Shale Member and varies in composition from pure to impure coal with increasing amounts of mineral matter. (As defined by Schopf (1956), carbonaceous shale contains >50% mineral matter by weight or <30% carbonaceous matter by volume. According to the ASTM (1994), impure coal contains 25 to 50 weight % mineral matter as ash.) Hemish (1986, p. 18) recognized the Mulky coal in three drill holes in northern Craig County, where its maximum thickness is 10 in. Hemish (2002, p. 3) indicated that "The occurrence of the Mulky coal downdip to the west in Nowata, Washington, and Osage Counties has not been verified by the OGS from coring. It seems probable that the methane is being produced from the Excello black shale."

In ascending order, the methane-producing coal beds in the Arkoma Basin are the Hartshorne (undivided), Lower Hartshorne, and Upper Hartshorne (Hartshorne Formation), McAlester and "Savanna" (interpreted to be the McAlester coal, McAlester Formation; a CBM completion in Coal County reported to be in the "Lehigh" coal is equivalent to the McAlester coal), Secor (Boggy Formation), and unnamed coal in the Krebs Group of Desmoinesian age. The McAlester coal and Stigler coal are correlative (Friedman, 1974, p. 29).

The Hartshorne coals are the most important CBM reservoirs in the Arkoma Basin (Cardott, 2002b). The Hartshorne coal contains a thin claystone parting and splits into two beds (Upper and Lower Hartshorne coals) where the parting is thicker than 1 ft (Friedman, 1982a). The coal is a single bed north and west of the coal split line (**Figure 8**). South and east of the line, two beds are identifiable. The interval between the upper and lower coal beds increases southeastward to a maximum of 120 ft (37 m)(Friedman, 1978, p. 48; Iannacchione and Puglio, 1979a, p. 5). The top of the Hartshorne coal or Upper Hartshorne coal, where present, marks the top of the Hartshorne Formation in Oklahoma. The nomenclature of Oklahoma and Arkansas coal beds differ slightly. The Arkansas Geological Commission includes the Upper and Lower Hartshorne coals in the McAlester Formation (Prior and White, 2001), whereas the Oklahoma Geological Survey includes the Hartshorne coals in the Hartshorne Formation (Hemish and Suneson, 1997). The Paris and Charleston coals (Savanna Formation; Prior and White, 2001) of Arkansas are not present in Oklahoma.

COAL RESOURCES, RESERVES, AND PRODUCTION

Remaining identified bituminous coal resources (using measured, indicated, and inferred resource categories of reliability) in beds ≥ 10 in. (25 cm) thick total 8.09 billion short tons in 19 counties in eastern Oklahoma, an area of approximately 8,000 mi^2. Approximately 76% of these resources are in the Arkoma Basin and 24% are in the northeast Oklahoma shelf (Friedman, 2002).

Identified coal resources were determined by S.A. Friedman and L.A. Hemish of the Oklahoma Geological Survey. Friedman (1982b) showed the distribution of strippable coal resources to depths of 100 ft (30 m) or 150 ft (46 m), and areas where coal has been mined by surface methods. Friedman (1974) summarized the coal resources and reserves in 7 counties (Atoka, Coal, Haskell, Latimer, Le Flore, Pittsburg, and Sequoyah) in the Arkoma Basin. County coal reports with updated estimates of strippable coal resources and reserves in the northeast Oklahoma shelf are available for the following 12 counties: Craig and Nowata (Hemish, 1986), Rogers and Mayes (Hemish, 1989), Tulsa, Wagoner, Creek, and Washington (Hemish, 1990a), Okmulgee and Okfuskee (Hemish, 1994), Muskogee (Hemish, 1998a), and McIntosh (Hemish, 1998b).

The demonstrated reserve base (economically recoverable portion of identified coal resource from measured and indicated resource categories for beds ≥ 28 in. (71 cm) thick at depths to 1,000 ft) for Oklahoma is 1.57 billion short tons of coal (Energy Information Administration, 2002, table 33). Oklahoma ranks 19th of 32 coal-bearing states in the U.S. demonstrated reserve base.

From 1873–2001, 281.3 million short tons of coal were produced in Oklahoma (Federal and State data). Peak annual coal production was 5.73 million short tons in 1981, with smaller production peaks during and immediately following World War I and World War II (**Figure 9**). Coal was mined in Oklahoma exclusively by underground methods until 1915. The predominant mining method shifted from underground to surface in 1943. Oklahoma produced 1.59 million short tons of coal from 11 mines in 2000 (Oklahoma Department of Mines, 2001). Oklahoma imported 18.0 million short tons of low-sulfur, subbituminous coal from Wyoming in 2000 for electricity generation at five Oklahoma public-utility power plants (Energy Information Administration, 2002, tables 64, 65).

Abandoned underground coal mines are areas where coal has been removed by room-and-pillar type mining in Oklahoma. Coal mine methane migrates to mine workings and is vented to the atmosphere during mining (Diamond, 1994; Brunner, 2000). Mine and gob gas (in caved zone of mine) may be present in abandoned underground mines. Maps showing the location of abandoned underground coal mines in Oklahoma are in Hendricks (1937, 1939), Knechtel (1937, 1949), Dane and others (1938), Oakes and Knechtel (1948), Hemish (1990a), and Friedman (1978, 1979, 1994, 1996).

COAL STRUCTURE AND THICKNESS

Maps showing structure, overburden (to depths >100 ft (30 m)), coal isopach, and mined areas in the northeast Oklahoma shelf are in Hemish (1986, 1989, 1990a, 1994, 1998a, 1998b). **Figure 10** shows the regional structure on the top of the Hartshorne Formation. Additional structure and/or overburden maps of the Hartshorne Formation are in Dane and others (1938), Hendricks (1939), Oakes and Knechtel (1948), Knechtel (1949), Catalano (1978), Agbe-Davies (1978), Craney (1978), Donica (1978), Williams (1978), Iannacchione and Puglio (1979a, 1979b), Iannacchione and others (1983), and Gossling (1994). A structure map on the McAlester coal is in Knechtel (1937).

Hartshorne coal isopach maps of limited coverage are in Catalano (1978), Agbe-Davies (1978), Craney (1978), Donica (1978), Williams (1978), Iannacchione and Puglio (1979a, 1979b), Iannacchione and others (1983), Brady (1981a-c; 1983a,b), and Brady and Querry (1985a-i). Hartshorne coal isopach maps in parts of Haskell, Latimer, Le Flore, McIntosh, and Pittsburg Counties are in Gossling (1994). An isopach map of the Stigler (McAlester) coal is in Karvelot (1973).

RANK

Coal rank, generalized for all coals at or near the surface, ranges from high-volatile bituminous in the shelf and western Arkoma Basin to medium- and low-volatile bituminous in the eastern Arkoma Basin in Oklahoma (**Figure 11**). Rank increases from west to east and with depth in the Arkoma Basin, attaining semianthracite in Arkansas (Prior and White, 2001). For example, the Hartshorne coal is medium-volatile bituminous at 2,574 ft (785 m) in Continental Resources' 1-3 Myers well in Pittsburg County (sec. 3, T. 7 N., R. 16 E.) in the high-volatile bituminous area in Figure 11.

CLEAT

Cleat is a miners' term for the natural, opening-mode fractures in coal. Two orthogonal cleat sets, perpendicular to bedding, are the face cleat (primary, well developed; extends across bedding planes of the coal) and the butt cleat (secondary, discontinuous; terminates against face cleat). Cleats control the directional permeability of coal beds (Diamond and others, 1988). Vertical CBM wells drain gas from an elliptical area elongated in the face-cleat direction. Horizontal coalbed-methane wells drilled perpendicular to oblique to the face cleat drain more gas from a larger area than would a vertical well. Cleat spacing is closest in medium- and low-volatile bituminous coals (Close, 1993).

Coal beds in the northeast Oklahoma shelf exhibit average face-cleat directions of N39°–47°W and butt-cleat directions of N46°–56°E (Andrews and others, 1998; Hemish, 2002; **Figure 12**). Face and butt cleats in the Hartshorne coal beds in the eastern Arkoma Basin trend N17°–32°W and N52°–77°E, respectively (**Figure 13**). In general, face cleats are oriented parallel to the axis of compression and butt cleats are oriented subparallel to the structural fold axes (McCulloch and others, 1974). **Figure 14** is a map summarizing face-cleat direction in the Oklahoma coalfield.

Secondary mineralization (e.g., authigenic minerals) in cleats decrease the permeability of coal. Clay, carbonate, quartz, and sulfide minerals are common cleat-filling minerals (Close, 1993; Gamson and others, 1996). **Figure 15** illustrates the distribution of common cleat-filling minerals in Oklahoma coals.

CONCLUSIONS

The Oklahoma coalfield contains bituminous-coal resources in about 40 coal beds of Middle Pennsylvanian age in 19 counties. Commercial coal beds range from 10 in. to 7 ft thick from the surface to depths > 6,000 ft in the Arkoma Basin. Coal beds in the northeast Oklahoma shelf dip gently westward and northwestward, whereas coals in the Arkoma Basin are folded and faulted. Coal and coalbed-methane resources in Oklahoma are suitable and available for combustion, carbonization, and gasification.

REFERENCES CITED

Agbe-Davies, V.F., 1978, The geology of the Hartshorne coals in the Spiro and Hackett quadrangles, LeFlore County, Oklahoma: Norman, University of Oklahoma unpublished M.S. thesis, 132 p.

Andrews, R.D., B.J. Cardott, and T. Storm, 1998, The Hartshorne play in southeastern Oklahoma: regional and detailed sandstone reservoir analysis and coalbed-methane resources: Oklahoma Geological Survey Special Publication 98-7, 90 p.

ASTM, 1994, Standard terminology of coal and coke, *in* Annual book of ASTM standards: gaseous fuels; coal and coke: American Society for Testing and Materials, sec. 5, v. 5.05, Standard D 121-94, p. 137-148.

Brady, B.T., 1981a, Federal coal resource occurrence and federal coal development potential maps of the northwest quarter of the Red Oak 15-minute quadrangle, Latimer County, Oklahoma: U.S. Geological Survey Open-File Report OF 79-304.

____ 1981b, Federal coal resource occurrence and federal coal development potential maps of the northeast quarter of the Red Oak 15-minute quadrangle, Latimer County, Oklahoma: U.S. Geological Survey Open-File Report OF 79-305.

____ 1981c, Federal coal resource occurrence and federal coal development potential maps of the Stigler East quadrangle, Muskogee and Haskell counties, Oklahoma: U.S. Geological Survey Open-File Report OF 79-307.

____ 1983a, Federal coal resource occurrence and federal coal development potential maps of the Wilburton 7.5-minute quadrangle, Latimer County, Oklahoma: U.S. Geological Survey Open-File Report OF 79-303.

____ 1983b, Federal coal resource occurrence and federal coal development potential maps of the Stigler West quadrangle, Muskogee and Haskell counties, Oklahoma: U.S. Geological Survey Open-File Report OF 79-306.

Brady, B.T., and J.L. Querry, 1985a, Federal coal resource occurrence and federal coal development potential maps of the Krebs 7.5-minute quadrangle, Pittsburg County, Oklahoma: U.S. Geological Survey Open-File Report OF 79-301.

____ 1985b, Federal coal resource occurrence and federal coal development potential maps of the Blocker 7.5-minute quadrangle, Pittsburg and Latimer counties, Oklahoma: U.S. Geological Survey Open-File Report OF 79-302.

____ 1985c, Federal coal resource occurrence and federal coal development potential maps of the McCurtain 7.5-minute quadrangle, Haskell and Le Flore counties, Oklahoma: U.S. Geological Survey Open-File Report OF 79-493.

____ 1985d, Federal coal resource occurrence and federal coal development potential maps of the Bokoshe 7.5-minute quadrangle, Haskell and Le Flore counties, Oklahoma: U.S. Geological Survey Open-File Report OF 79-494.

____ 1985e, Federal coal resource occurrence and federal coal development potential maps of the Panama 7.5-minute quadrangle, Le Flore County, Oklahoma: U.S. Geological Survey Open-File Report OF 79-495.

____ 1985f, Federal coal resource occurrence and federal coal development potential maps of the Spiro 7.5-minute quadrangle, Le Flore County, Oklahoma: U.S. Geological Survey Open-File Report OF 79-496.

____ 1985g, Federal coal resource occurrence and federal coal development potential maps of the Hackett 7.5-minute quadrangle, Le Flore County, Oklahoma, and Sebastian County, Arkansas: U.S. Geological Survey Open-File Report OF 79-497.

____ 1985h, Federal coal resource occurrence and federal coal development potential maps of the northeast quarter of the Heavener 15-minute quadrangle, Le Flore County, Oklahoma: U.S. Geological Survey Open-File Report OF 79-498.

____ 1985i, Federal coal resource occurrence and federal coal development potential maps of the southeast quarter of the Heavener 15-minute quadrangle, Le FLore County, Oklahoma: U.S. Geological Survey Open-File Report OF 79-499.

Brady, L.L., 1997, Kansas coal resources and their potential for coalbed methane, *in* G. McMahan, ed., Transactions of the 1997 AAPG Mid-Continent Section Meeting: Oklahoma City Geological Society, p. 150-163.

Brunner, D., 2000, Enhanced gob gas recovery: U.S. Environmental Protection Agency, 18 p. (www.epa.gov/coalbed)

Campbell, M.R., 1917 (1929), The coal fields of the United States; general introduction: U.S. Geological Survey Professional Paper 100-A, 33 p.

Cardott, B.J., 1989, A petrographic survey of high-volatile bituminous Oklahoma coal beds: Oklahoma Geology Notes, v. 49, p. 112-124.

____ 2002a, Coalbed methane development in Oklahoma, *in* S.D. Schwochow and V.F. Nuccio, eds., Coalbed methane of North America, II: Rocky Mountain Association of Geologists, p. 83-98.

______ 2002b, Coalbed-methane activity in Oklahoma, 2002 update, *in* B.J. Cardott, compiler, Fourth annual Oklahoma coalbed-methane workshop: Oklahoma Geological Survey Open-File Report 9-2002, p. 56-82.

Catalano, L.E., 1978, Geology of the Hartshorne coal, McCurtain and Lafayette quadrangles, Haskell and LeFlore Counties, Oklahoma: Stillwater, Oklahoma State University unpublished M.S. thesis, 61 p.

Close, J.C., 1993, Natural fractures in coal, *in* B.E. Law and D.D. Rice, eds., Hydrocarbons from coal: AAPG Studies in Geology 38, p. 119-132.

Craney, D.L., 1978, Distribution, structure, origin, and resources of the Hartshorne coals in the Panama Quadrangle, Le Flore County, Oklahoma: Norman, University of Oklahoma unpublished M.S. thesis, 126 p.

Dane, C.H., H.E. Rothrock, and J.S. Williams, 1938, Geology and fuel resources of the southern part of the Oklahoma coal field; part 3, the Quinton-Scipio district, Pittsburg, Haskell, and Latimer Counties: U.S. Geological Survey Bulletin 874-C, p. 151-253.

Diamond, W.P., C.H. Elder, and P.W. Jeran, 1988, Influence of geology on methane emission from coal, *in* M. Deul and A.G. Kim, Methane control research: summary of results, 1964-80: U.S. Bureau of Mines Bulletin 687, p. 26-40.

Diamond, W.P., 1994, Methane control for underground coal mines: U.S. Bureau of Mines, Information Circular 9395, 44 p.

Donica, D.R., 1978, The geology of the Hartshorne coals (Desmoinesian) in parts of the Heavener 15' quadrangle Le Flore County, Oklahoma: Norman, University of Oklahoma unpublished M.S. thesis, 128 p.

Energy Information Administration, 2002, Coal industry annual 2000: U.S. Department of Energy DOE/EIA-0584(2000), 308 p.

Friedman, S.A., 1974, Investigation of the coal reserves in the Ozarks section of Oklahoma and their potential uses: Oklahoma Geological Survey Special Publication 74-2, 117 p.

______ 1978, Desmoinesian coal deposits in part of the Arkoma Basin, Eastern Oklahoma: Oklahoma City Geological Society Guidebook, 62 p.

______ 1979, Map showing locations of underground coal mines in eastern Oklahoma: Oklahoma Geological Survey, scale 1:500,000.

______ 1982a, Determination of reserves of methane from coal beds for use in rural communities in eastern Oklahoma: Oklahoma Geological Survey Special Publication 82-3, 32 p.

______ 1982b, Map showing potentially strippable coal beds in eastern Oklahoma: Oklahoma Geological Survey Map GM-23, scale 1:125,000, 4 sheets.

______ 1994, Map showing location of abandoned underground coal mines in Okmulgee and Okfuskee Counties, Oklahoma, *in* Hemish, L.A., Coal geology of Okmulgee County and eastern Okfuskee County, Oklahoma: Oklahoma Geological Survey Special Publication 94-3, plate 7.

______ 1996, Map showing the distribution of underground mines in the Hartshorne and McAlester coals in the Hartshorne 7.5' quadrangle, Pittsburg and Latimer Counties, Oklahoma: Oklahoma Geological Survey Open-File Report 7-96, scale 1:24,000.

______ 2002, Coal geology of Oklahoma, *in* Keystone Coal Industry Manual: Chicago, Primedia Business Magazines & Media Inc., p. 584-590.

Gamson, P., B. Beamish, and D. Johnson, 1996, Coal microstructure and secondary mineralization: their effect on methane recovery, *in* R. Gayer and I. Harris, eds., Coalbed methane and coal geology: London, Geological Society Special Publication 109, p. 165-179.

Gossling, J.H., 1994, Coalbed methane potential of the Hartshorne coals in parts of Haskell, Latimer, Le Flore, McIntosh and Pittsburg Counties, Oklahoma: Norman, University of Oklahoma, unpublished M.S. thesis, 155 p.

Hemish, L.A., 1986, Coal geology of Craig County and eastern Nowata County, Oklahoma: Oklahoma Geological Survey Bulletin 140, 131 p.

______ 1988, Report of core-drilling by the Oklahoma Geological Survey in Pennsylvanian rocks of the northeastern Oklahoma coal belt, 1983-1986: Oklahoma Geological Survey Special Publication 88-2, 174 p.

______ 1989, Coal geology of Rogers County and western Mayes County, Oklahoma: Oklahoma Geological Survey Bulletin 144, 118 p.

______ 1990a, Coal geology of Tulsa, Wagoner, Creek, and Washington Counties, Oklahoma: Oklahoma Geological Survey Map GM-33.

______ 1990b, Lithostratigraphy and core-drilling, Upper Atoka Formation through Lower Senora Formation (Pennsylvanian), northeastern Oklahoma shelf area: Oklahoma Geological Survey Special Publication 90-2, 54 p.

______ 1994, Coal geology of Okmulgee County and eastern Okfuskee County, Oklahoma: Oklahoma Geological Survey Special Publication 94-3, 86 p.

______ 1997, Lithologic descriptions of Pennsylvanian strata north and east of Tulsa, Oklahoma: Oklahoma Geological Survey Special Publication 97-2, 44 p.

______ 1998a, Coal geology of Muskogee County, Oklahoma: Oklahoma Geological Survey Special Publication 98-2, 111 p.

______ 1998b, Coal geology of McIntosh County, Oklahoma: Oklahoma Geological Survey Special Publication 98-6, 74 p.

______ 1999, Hartshorne coal bed, Latimer County – thickest known coal in Oklahoma: Oklahoma Geology Notes, v. 59, p. 34, 78.

______ 2001, Coal stratigraphy of the northeast Oklahoma shelf area, with an overview of Arkoma Basin coal geology, *in* B.J. Cardott, compiler, Oklahoma coalbed-methane workshop 2001: Oklahoma Geological Survey Open-File Report 2-2001, p. 72-92.

______ 2002, Surface to subsurface correlation of methane-producing coal beds, northeast Oklahoma shelf: Oklahoma Geological Survey Special Publication 2002-2, 22 p.

Hemish, L.A., and N.H. Suneson, 1997, Stratigraphy and resources of the Krebs Group (Desmoinesian), south-central Arkoma Basin, Oklahoma: Oklahoma Geological Survey Guidebook 30, 84 p.

Hendricks, T.A., 1937, Geology and fuel resources of the southern part of the Oklahoma coal field; part 1, the McAlester district, Pittsburg, Atoka, and Latimer Counties: U.S. Geological Survey Bulletin 874-A, 90 p.

______ 1939, Geology and fuel resources of the southern part of the Oklahoma coal field; part 4, the Howe-Wilburton district, Latimer and Le Flore Counties: U.S. Geological Survey Bulletin 874-D, p. 255-300.

Iannacchione, A.T., and D.G. Puglio, 1979a, Methane content and geology of the Hartshorne coalbed in Haskell and Le Flore Counties, Oklahoma: U.S. Bureau of Mines Report of Investigations 8407, 14 p.

______ 1979b, Geological association of coalbed gas and natural gas from the Hartshorne Formation in Haskell and Le Flore Counties, Oklahoma: Ninth International Congress of Carboniferous Stratigraphy and Geology, Compte Rendu, Volume 4, Economic Geology: Coal, Oil and Gas, A.T. Cross, ed., Southern Illinois U. Press, p. 739-752.

Iannacchione, A.T., C.A. Kertis, D.W. Houseknecht, and J.H. Perry, 1983, Problems facing coal mining and gas production in the Hartshorne coalbeds of the Western Arkoma Basin, OK: U.S. Bureau of Mines Report of Investigations 8795, 25 p.

Johnson, K.S., 1974, Maps and description of disturbed and reclaimed surface-mined coal lands in eastern Oklahoma: Oklahoma Geological Survey Map GM-17, 12 p., 3 sheets, scale 1:125,000.

Johnson, K.S., and B.J. Cardott, 1992, Geologic framework and hydrocarbon source rocks of Oklahoma, *in* K.S. Johnson and B.J. Cardott, eds., Source rocks in the

southern Midcontinent, 1990 symposium: Oklahoma Geological Survey Circular 93, p. 21-37.
Karvelot, M.D., 1973, The Stigler coal and collateral strata in parts of Haskell, Le Flore, McIntosh, and Muskogee Counties, Oklahoma: Oklahoma City Geological Society Shale Shaker Digest, v. 7, p. 144-169.
Knechtel, M.M., 1937, Geology and fuel resources of the southern part of the Oklahoma coal field; part 2, the Lehigh district, Coal, Atoka, and Pittsburg Counties: U.S. Geological Survey Bulletin 874-B, p. 91-149.
______ 1949, Geology and coal and natural gas resources of Northern Le Flore County, Oklahoma: Oklahoma Geological Survey Bulletin 68, 76 p.
McBee, W., Jr., 1995, Tectonic and stratigraphic synthesis of events in the region of the intersection of the Arbuckle and Ouachita structural systems, Oklahoma, *in* K.S. Johnson, ed., Structural styles in the southern Midcontinent, 1992 symposium: Oklahoma Geological Survey Circular 97, p. 45-81.
McCulloch, C.M., M. Deul, and P.W. Jeran, 1974, Cleat in bituminous coalbeds: U.S. Bureau of Mines Report of Investigations 7910, 25 p.
Oakes, M.C., and M.M. Knechtel, 1948, Geology and mineral resources of Haskell County, Oklahoma: Oklahoma Geological Survey Bulletin 67, 136 p.
Oklahoma Department of Mines, 2001, Annual report for calendar year 2000: Oklahoma Mining Commission, Department of Mines, 54 p.
Prior, W.L., and B. White, 2001, Arkansas coal geology and potential for coalbed methane, *in* B.J. Cardott, compiler, Oklahoma coalbed-methane workshop 2001: Oklahoma Geological Survey Open-File Report 2-2001, p. 44-71.
Schopf, J.M., 1956, A definition of coal: Economic Geology, v. 51, p. 521-527.
Tomlinson, C.W., 1959, Best exposures of various strata in Ardmore Basin, 1957, *in* J.W. Mayes, J. Westheimer, C.W. Tomlinson, and D.M. Putman, eds., Petroleum geology of southern Oklahoma, v. 2: AAPG, p. 302-334.
Trumbull, J.V.A., 1957, Coal resources of Oklahoma: U.S. Geological Survey Bulletin 1042-J, p. 307-382.
Tully, J., 1996, Coal fields of the conterminous United States: U.S. Geological Survey Open-File Report 96-92, 1 plate. http://energy.er.usgs.gov/products/openfile/OF96-92/index.htm
Williams, C.E., 1978, The economic potential of the Lower Hartshorne coal on Pine Mountain, Heavener, Oklahoma: Stillwater, Oklahoma State University unpublished M.S. thesis, 109 p.
Wilson, L.R., 1970, Palynology of Oklahoma's ten-foot coal seam: Oklahoma Geology Notes, v. 30, p. 62-63.
______ 1984, Evidence for a new Desmoinesian-Missourian boundary (middle Pennsylvanian) in Tulsa County, Oklahoma, U.S.A., *in* A.K. Sharma, G.C. Mitra, and M. Banerjec, eds., Proceedings of the symposium on evolutionary botany and biostratigraphy: Evolutionary Botany and Biostratigraphy, v. 10, p. 251-265.
Wood, G.H., Jr., and W.V. Bour, III, 1988, Coal map of North America: U.S. Geological Survey coal map, 2 sheets, scale 1:10,000,000.

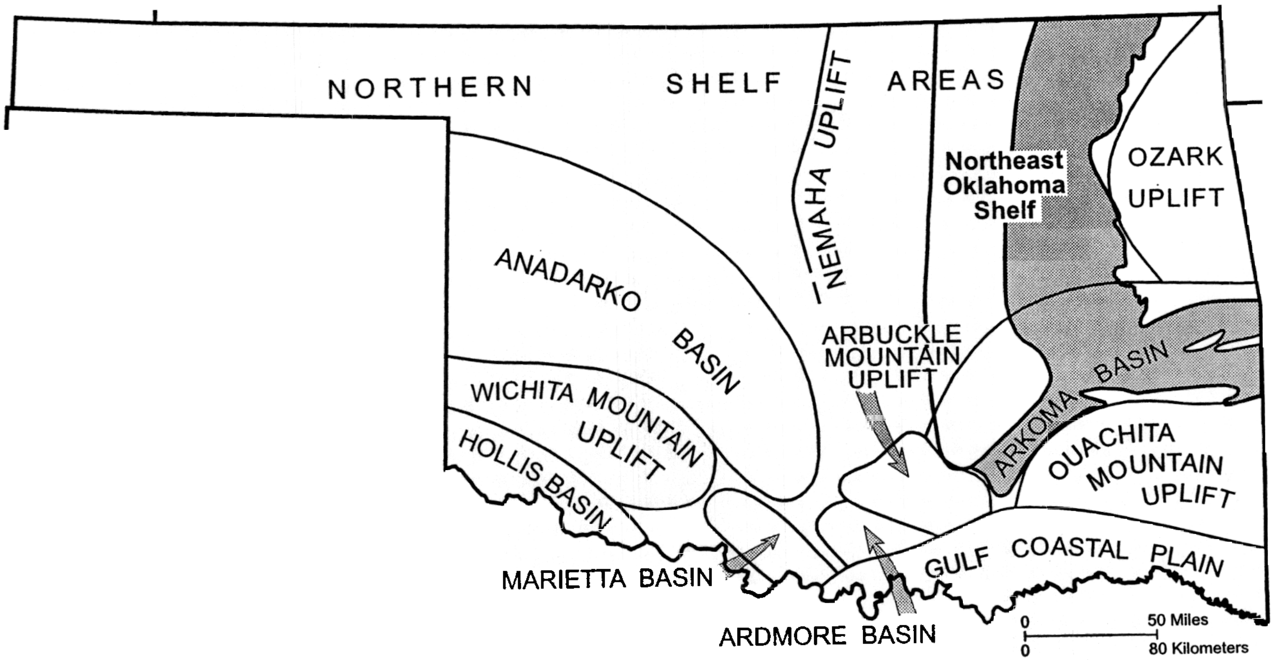


Figure 1. Map of Oklahoma coalfield (modified from Friedman, 1974) in relation to the major geologic provinces of Oklahoma (modified from Johnson and Cardott, 1992).

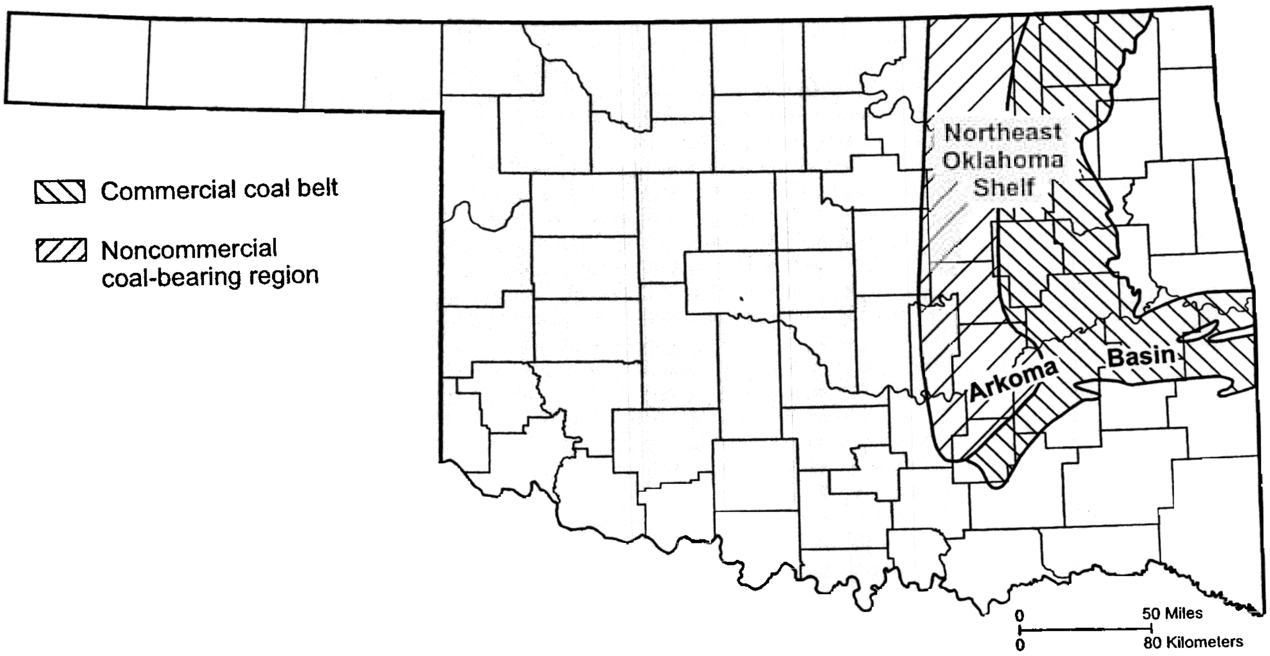


Figure 2. Map of Oklahoma coalfield. Modified from Friedman (1974).

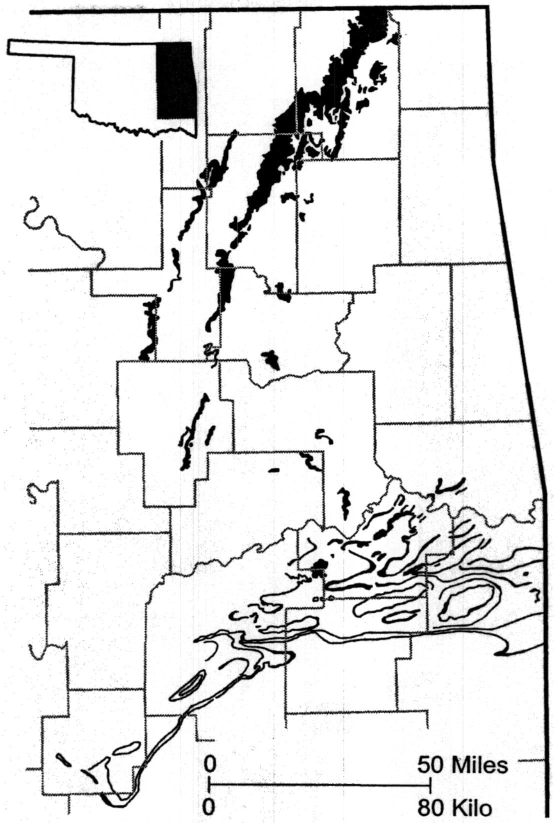


Figure 3. Map showing potentially strippable coal beds in eastern Oklahoma (modified from Friedman, 1982b).

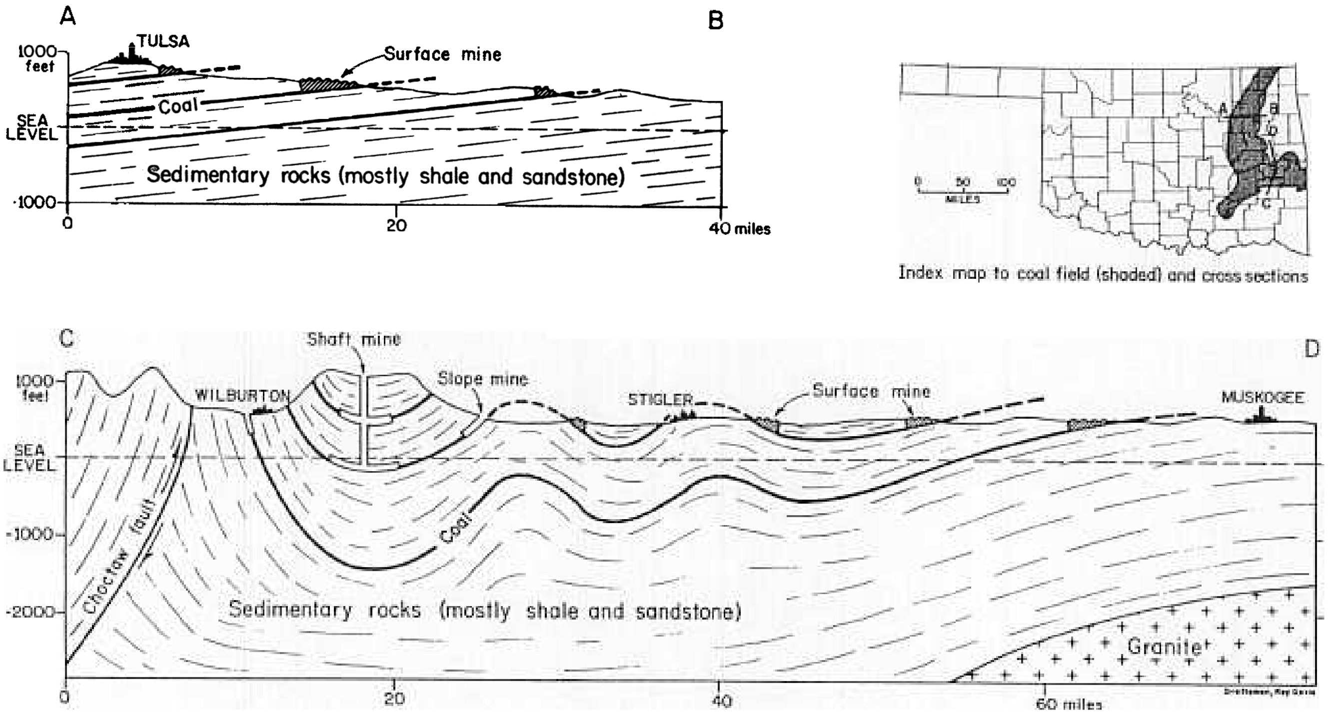


Figure 4. Schematic sections showing geologic structure and types of mines in the Oklahoma coalfield (from Johnson, 1974).

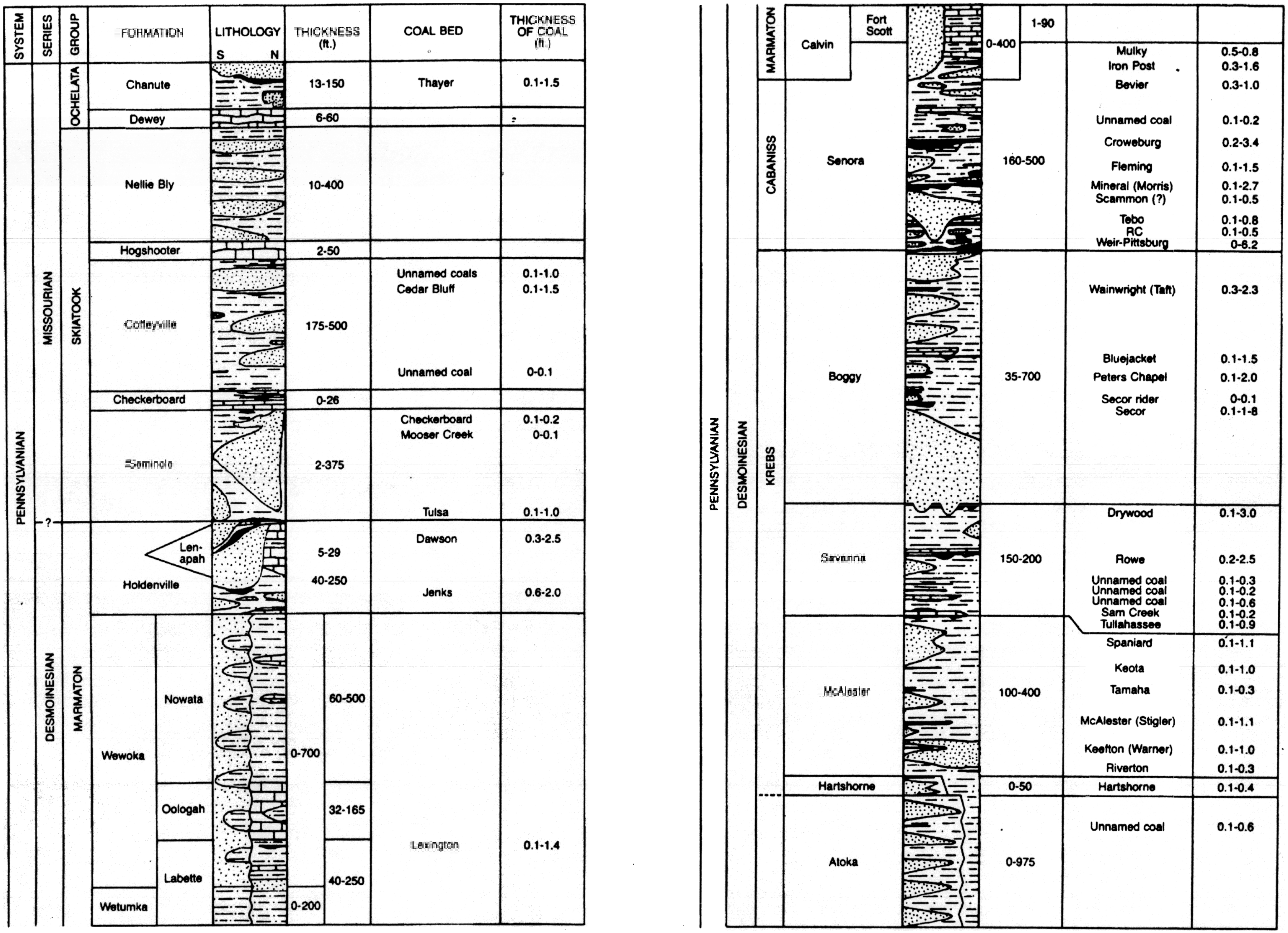


Figure 5. Generalized stratigraphy of coal-bearing strata of the northeast Oklahoma shelf (from Hemish, 1988).

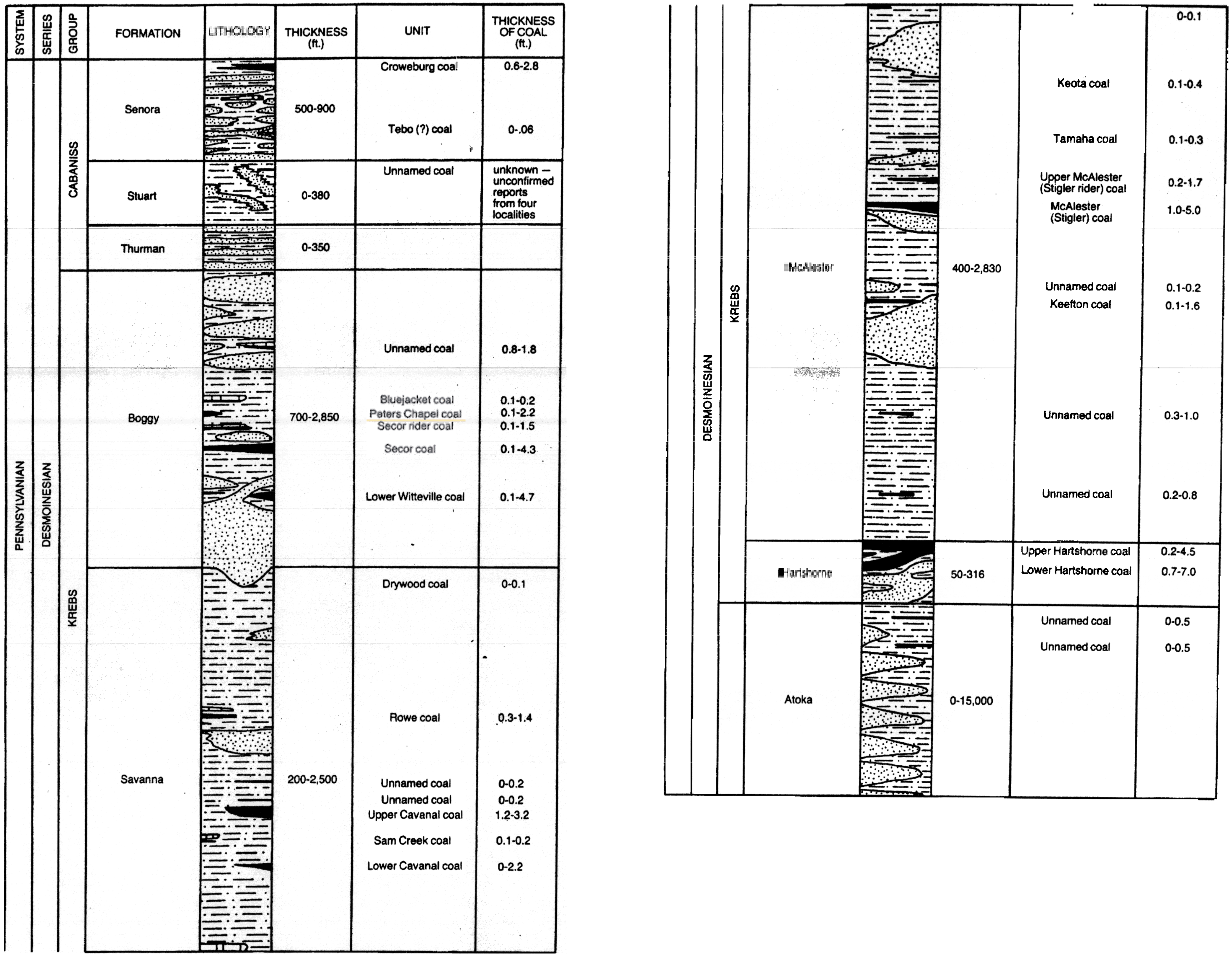


Figure 6. Generalized stratigraphy of coal-bearing strata of the Arkoma basin (from Hemish, 1988).

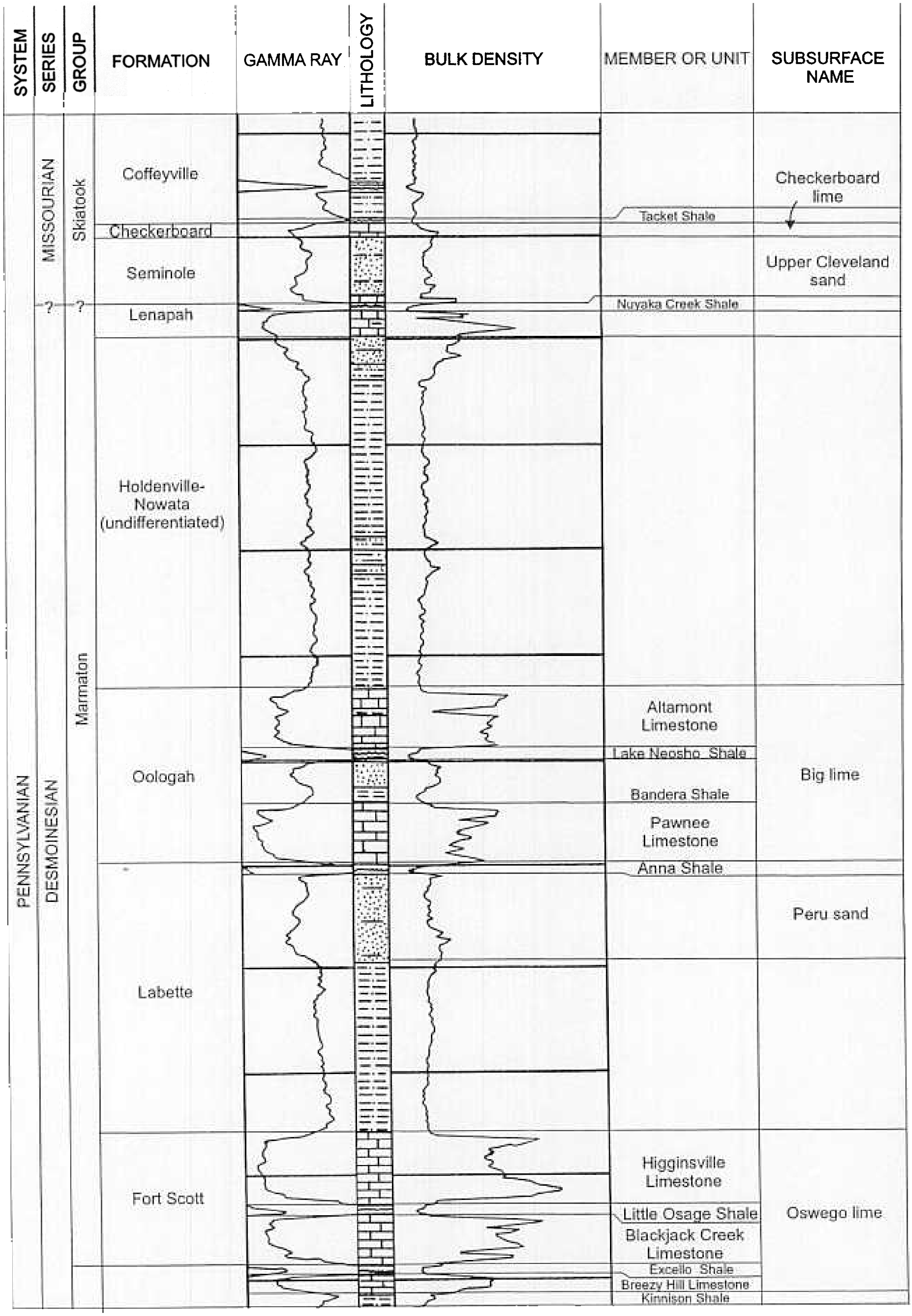
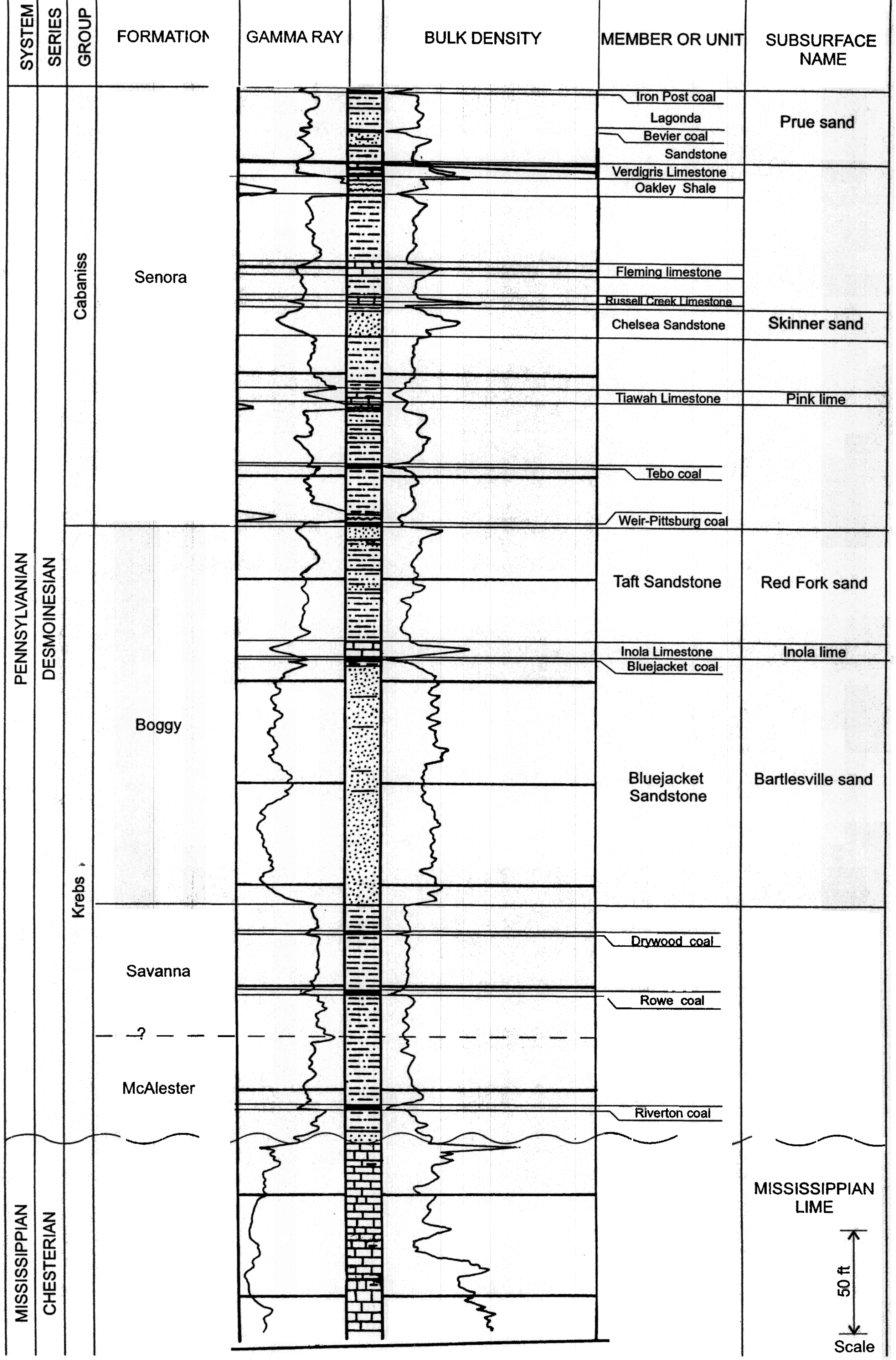


Figure 7. Type log for northern part of northeast Oklahoma shelf (from Hemish, 2002, fig. 18).


SYSTEM
SERIES
GROUP
FORMATION
GAMMA RAY
BULK DENSITY
MEMBER OR UNIT
SUBSURFACE NAME
PENNSYLVANIAN
DESMOINESIAN
Cabaniss
Krebs
Senora
Boggy
Savanna
McAlester
Iron Post coal
Lagonda
Bevier coal
Sandstone
Verdigris Limestone
Oakley Shale
Fleming limestone
Russell Creek Limestone
Chelsea Sandstone
Tiawah Limestone
Tebo coal
Weir-Pittsburg coal
Taft Sandstone
Inola Limestone
Bluejacket coal
Bluejacket Sandstone
Drywood coal
Rowe coal
Riverton coal
Prue sand
Skinner sand
Pink lime
Red Fork sand
Inola lime
Bartlesville sand
MISSISSIPPIAN
CHESTERIAN
MISSISSIPPIAN LIME
50 ft
Scale

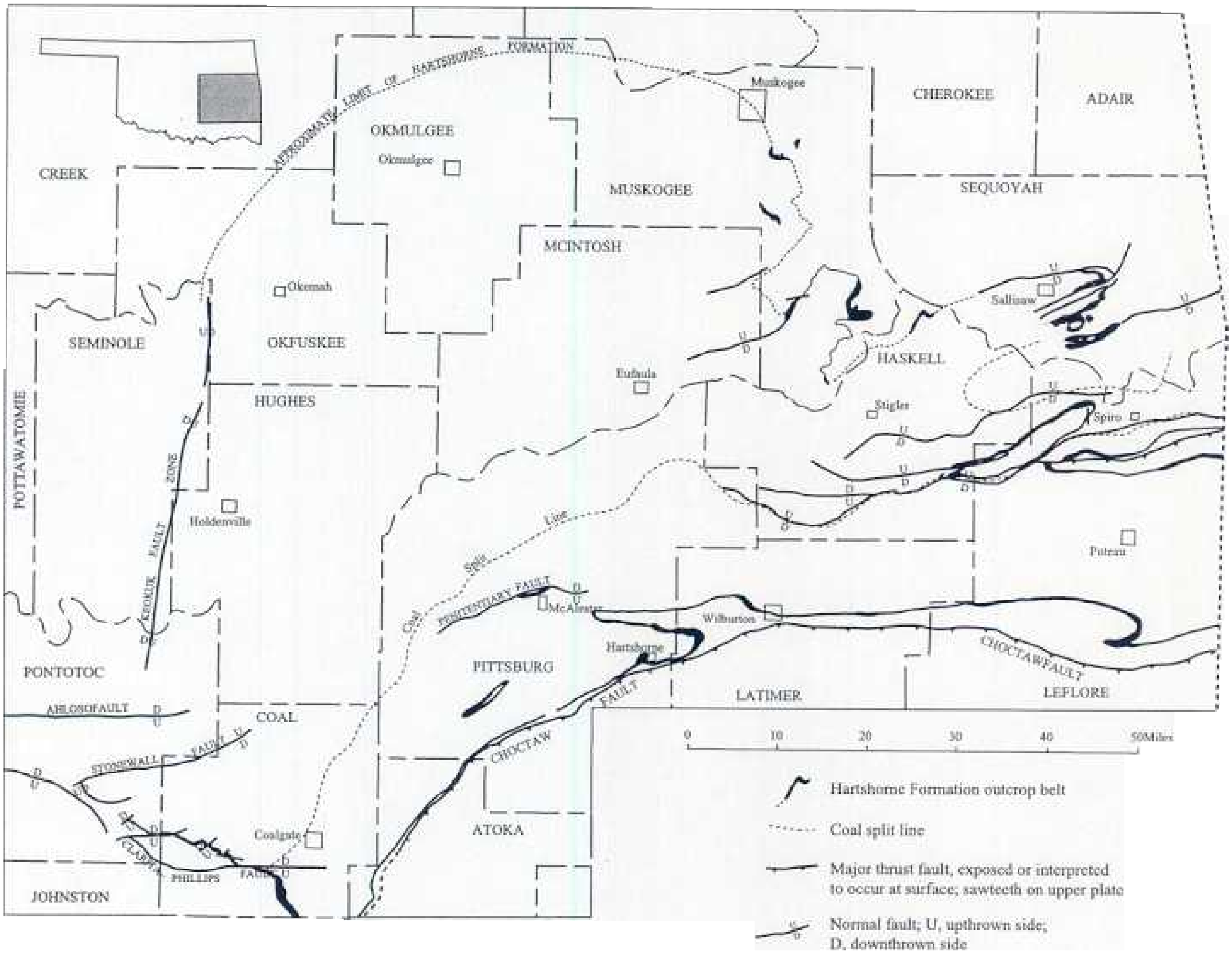


Figure 8. Distribution of the Hartshorne coal in the Arkoma basin, showing the coal split line (from Cardott, 2002a)

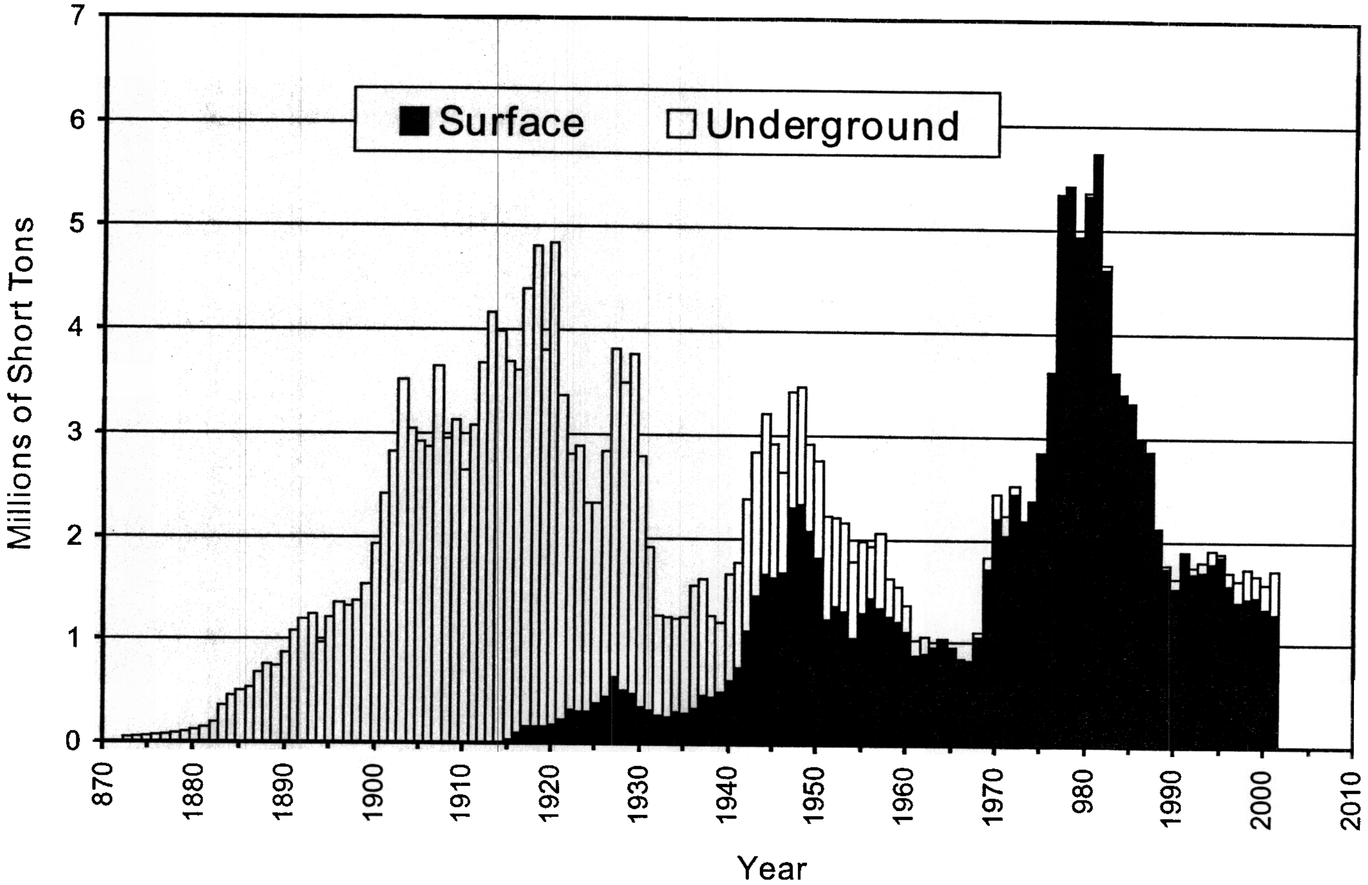


Figure 9. Coal production in Oklahoma, 1873-2001
(from Federal and State data).

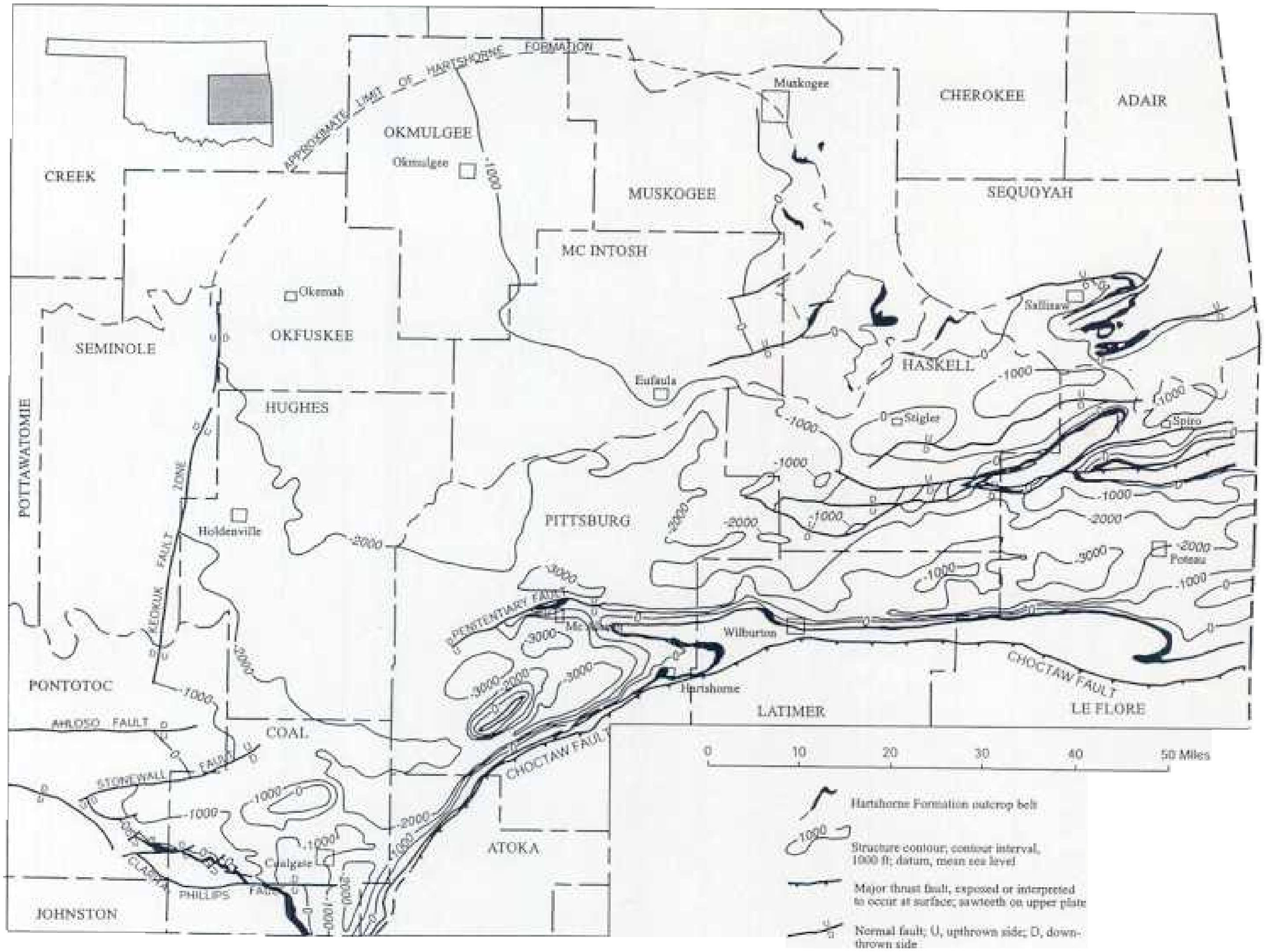


Figure 10. Regional structure on the top of the Hartshorne Formation (from Cardott, 2002a).

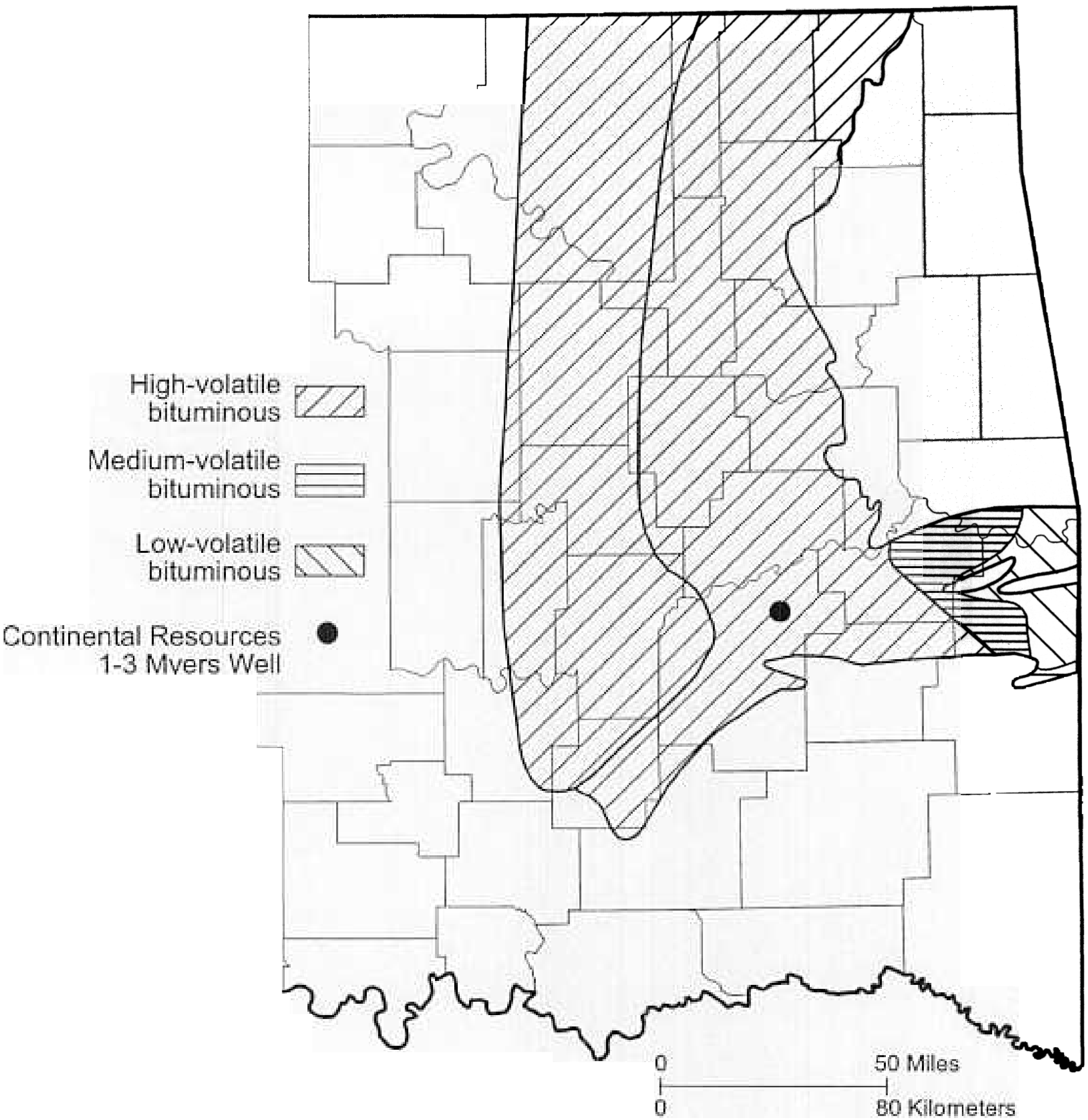


Figure 11. Generalized rank of all coal beds at or near the surface in the Oklahoma coalfield. Modified from Friedman (1974) and Andrews and others (1998).

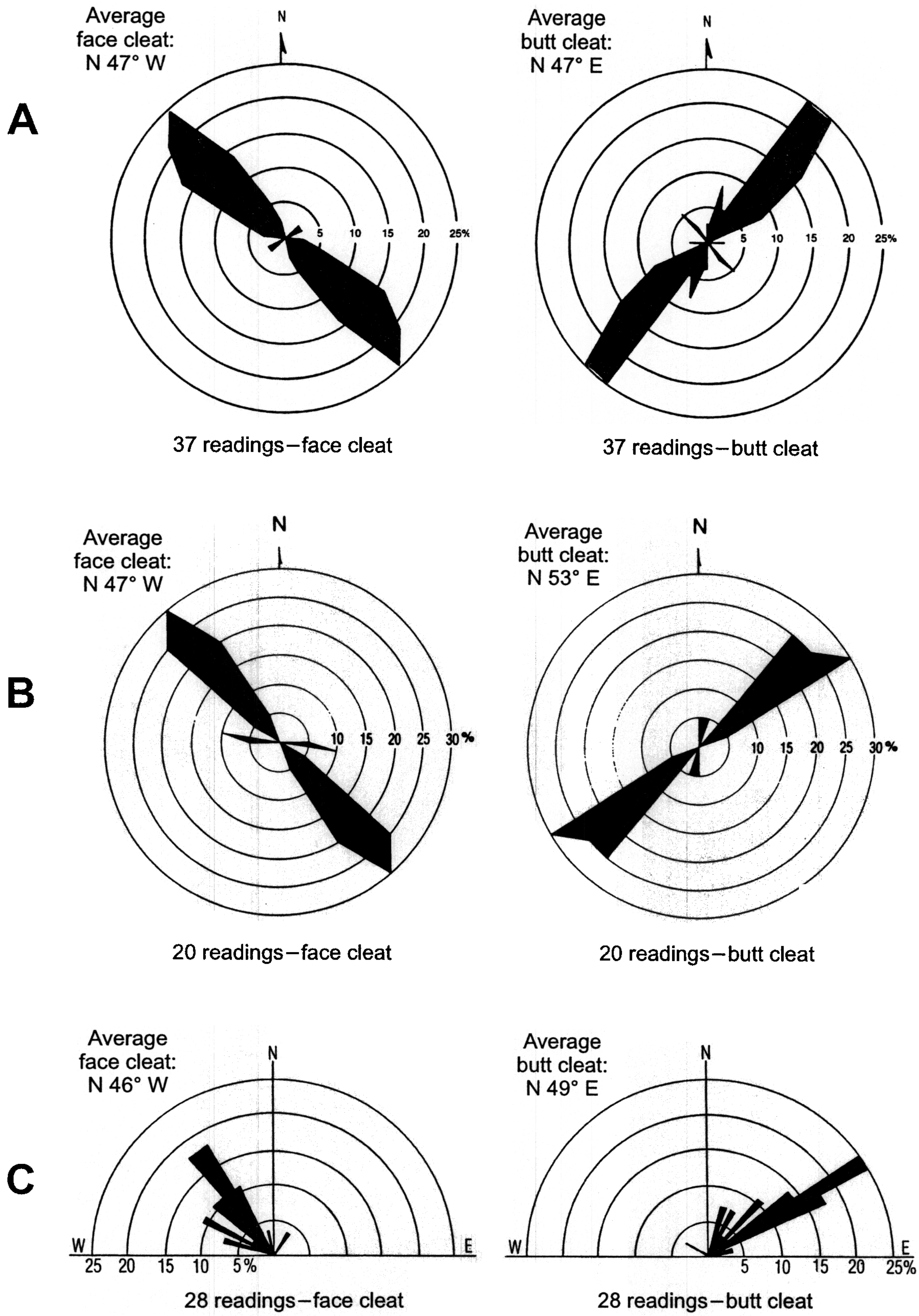


Figure 12. Rose diagrams of cleat orientations in coal beds (from Hemish, 2002). A. Craig and Nowata Counties. B. Rogers and Mayes Counties. C. Tulsa and Wagoner Counties.

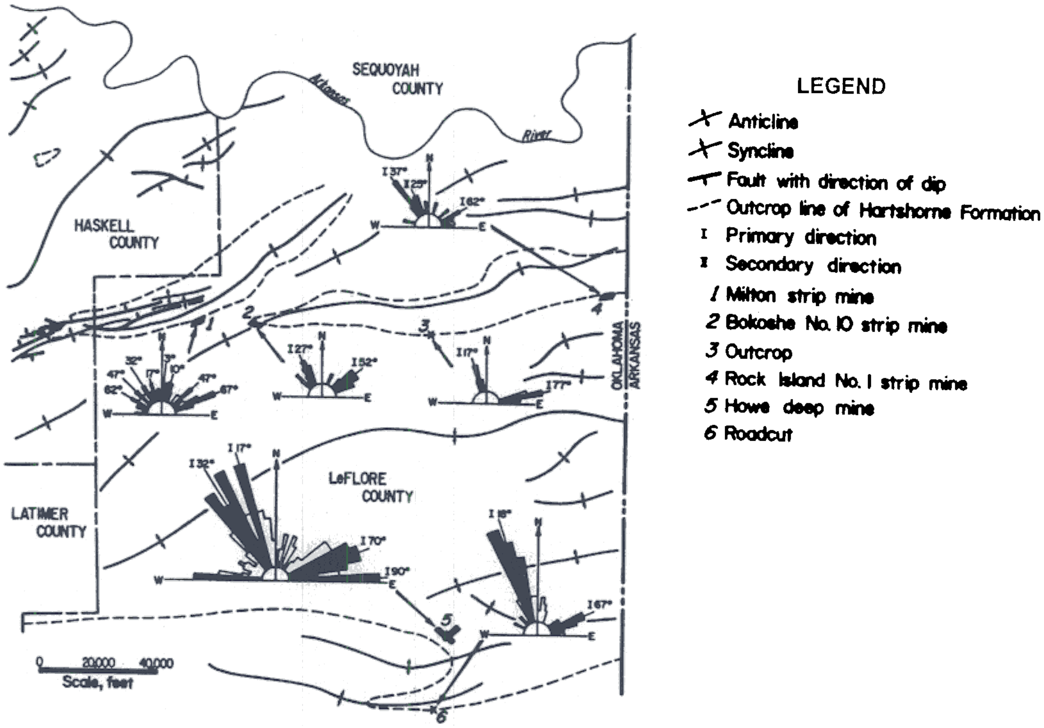


Figure 13. Coal cleat orientations of the Hartshorne coal, Le Flore County, Oklahoma (from Iannacchione and Puglio, 1979a).

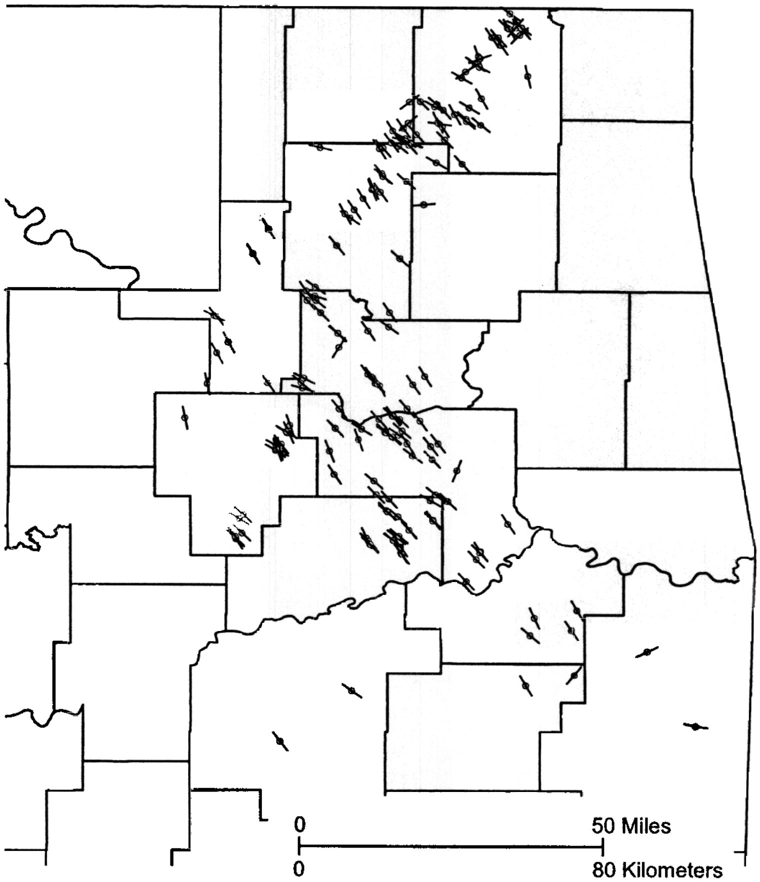


Figure 14. Map of face-cleat orientations in the Oklahoma coalfield from data in Hemish (1986, 1989, 1990a, 1994, 1998a, 1998b) and Friedman (unpublished).

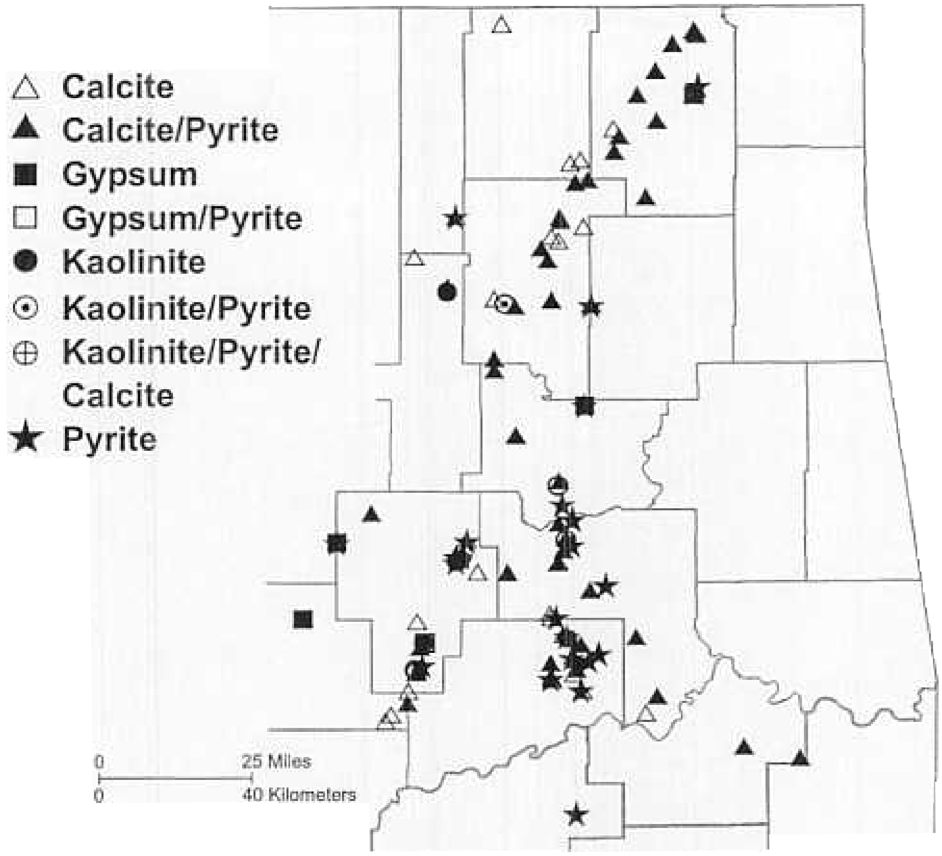
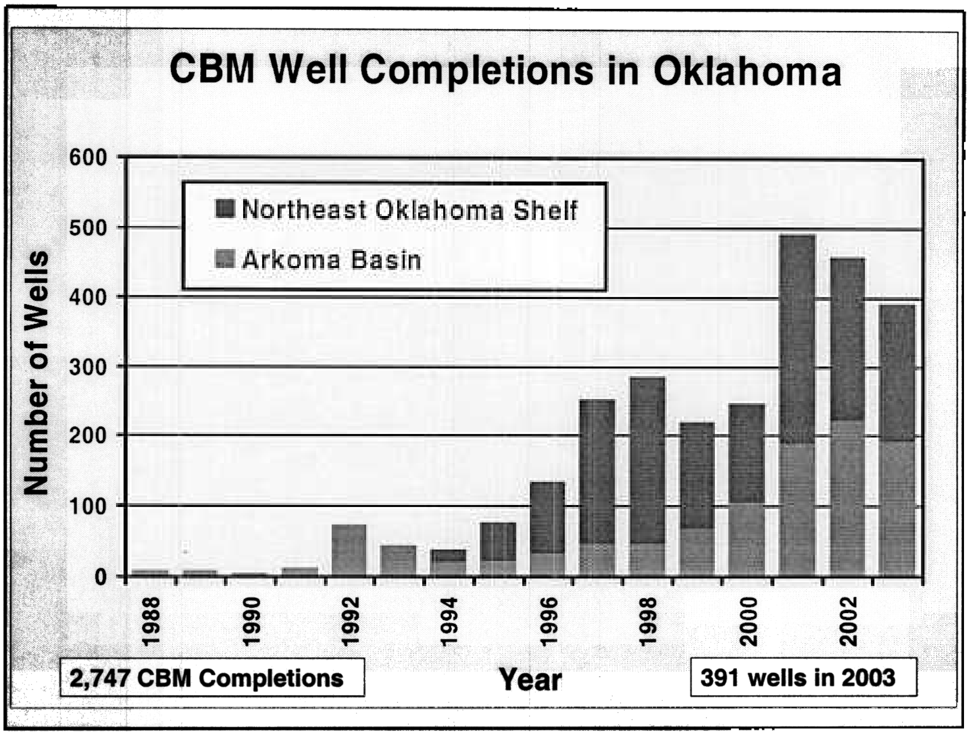
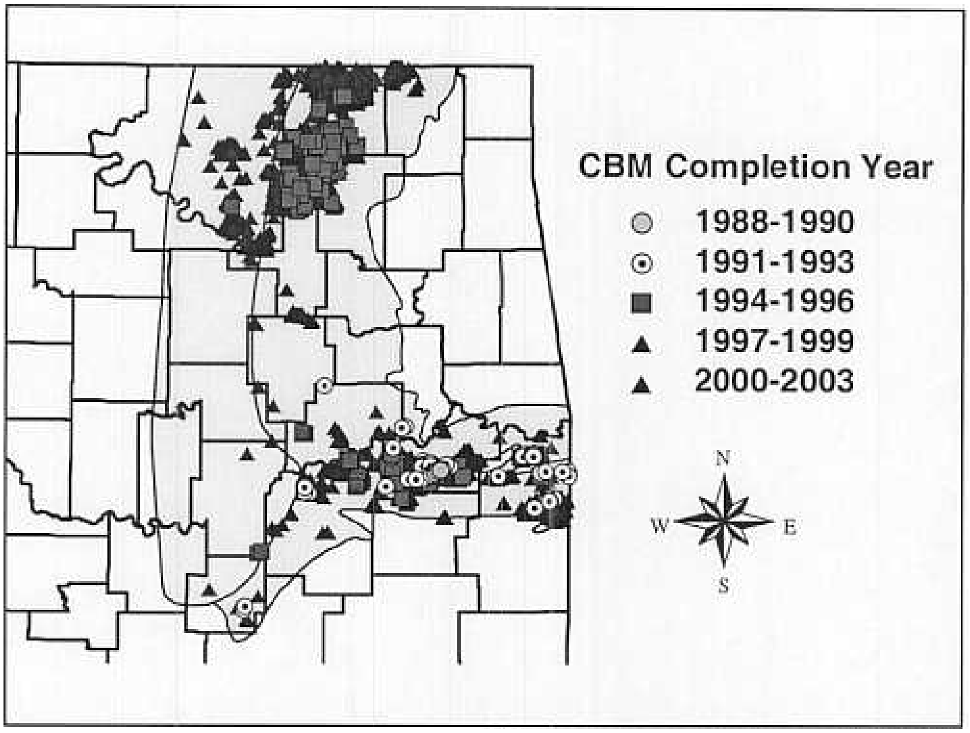


Figure 15. Map showing the distribution of cleat-filling minerals in northeast Oklahoma coal beds from data in Hemish (1986, 1988, 1989, 1990a, 1990b, 1994, 1997, 1998a, 1998b) and Friedman (unpublished).

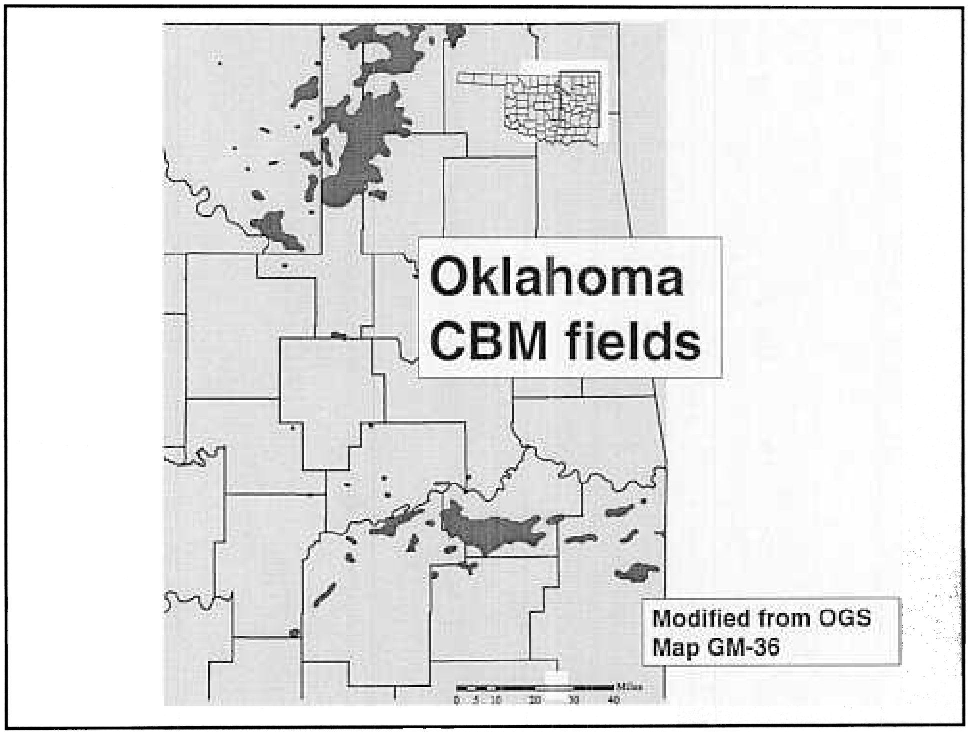
Coalbed-methane activity in Oklahoma, 2004 update

Brian J. Cardott
Oklahoma Geological Survey

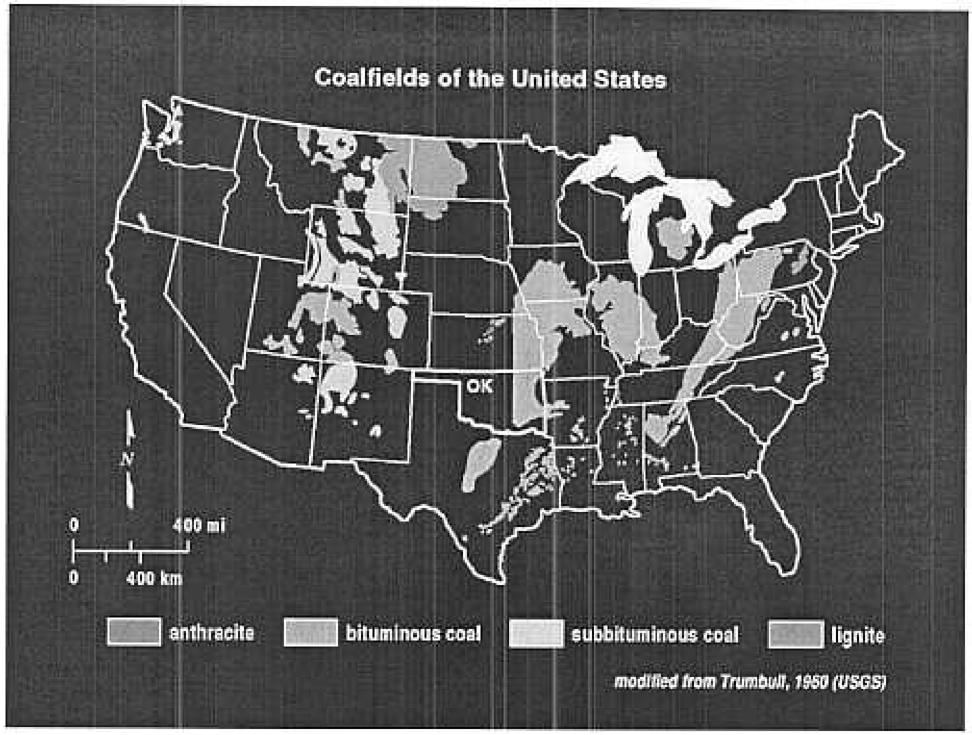


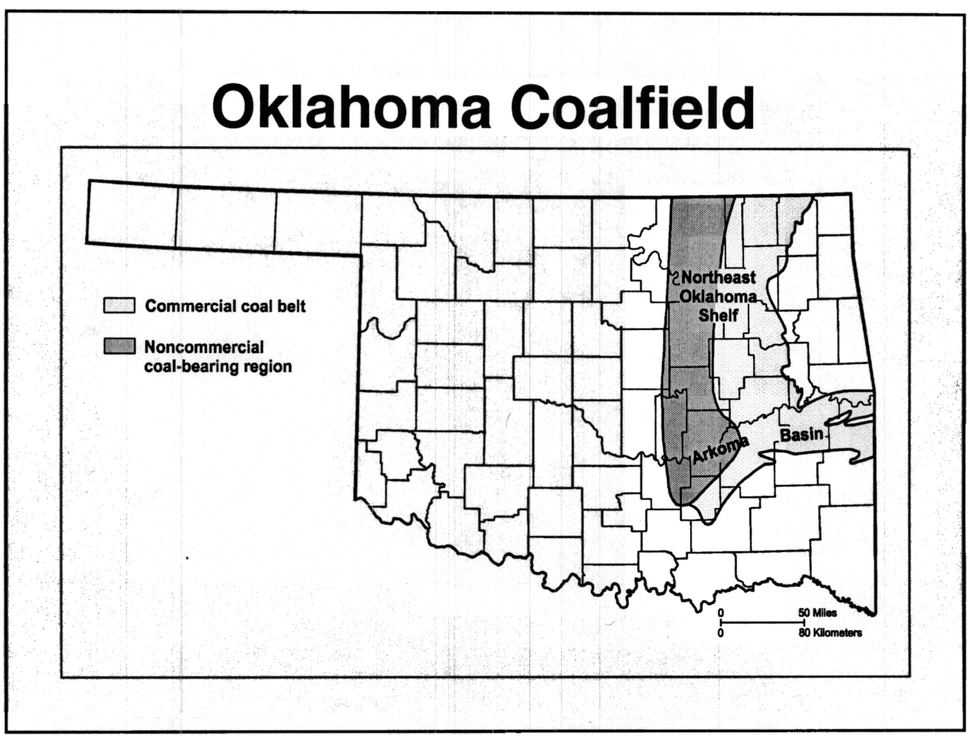


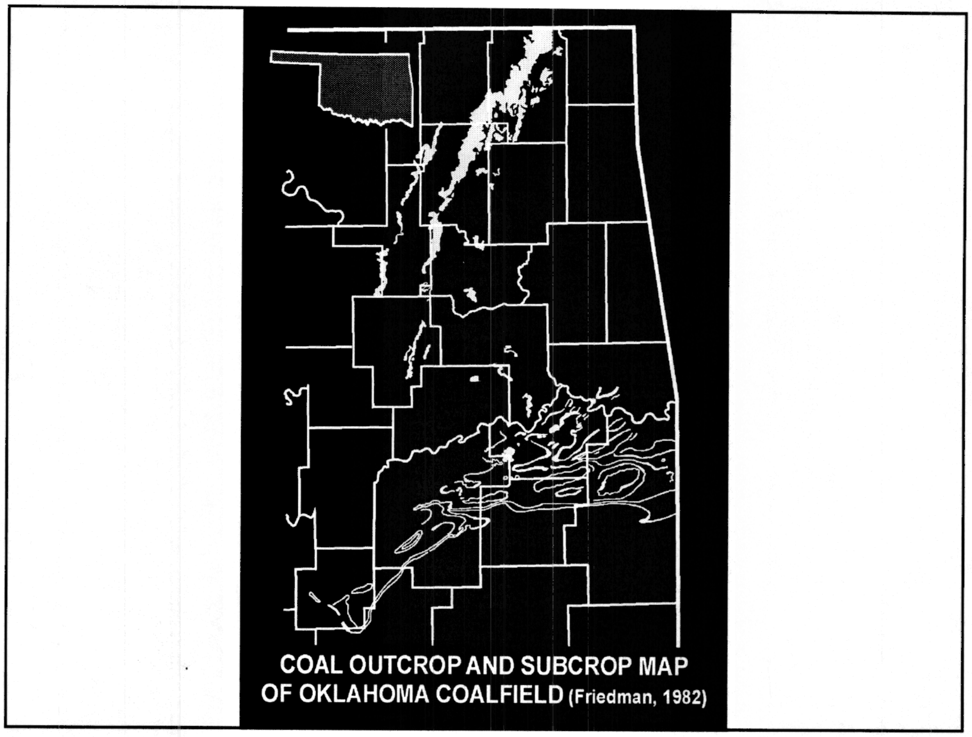
CBM Completion Year
1988-1990
1991-1993
1994-1996
1997-1999
2000-2003
N
W
E
S

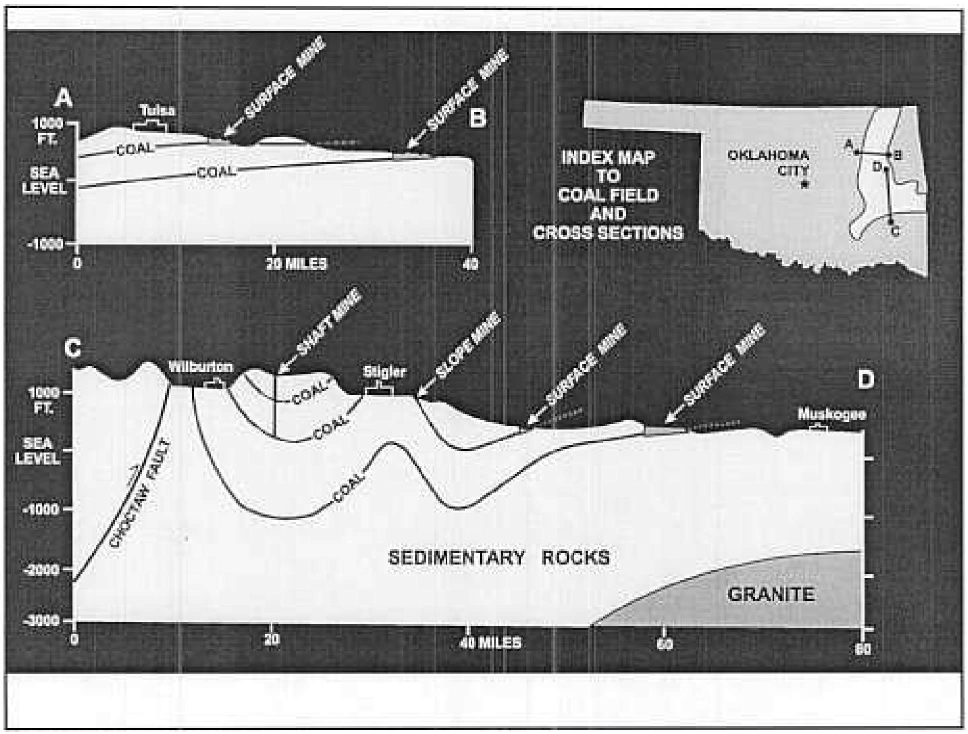


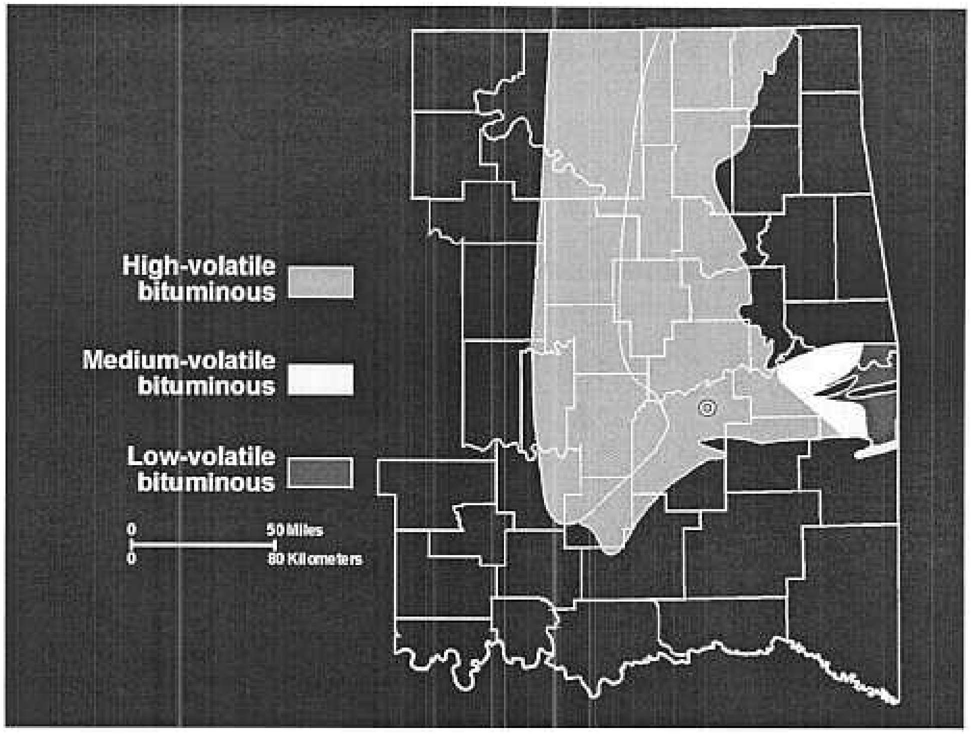
Oklahoma
CBM fields
Modified from OGS
Map GM-36


Coalfields of the United States
OK
N
0
400 mi
0
400 km
anthracite
bituminous coal
subbituminous coal
lignite
modified from Trumbull, 1960 (USGS)

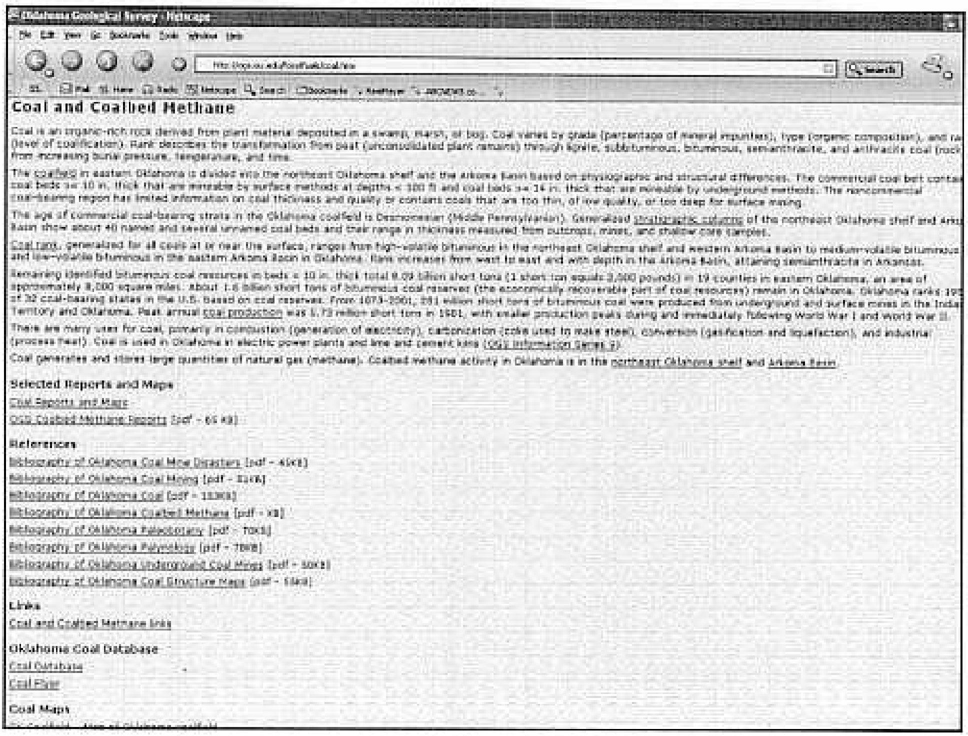

Oklahoma Coalfield
Commercial coal belt
Noncommercial coal-bearing region
Northeast Oklahoma Shelf
Arkoma
Basin
0
50 Miles
0
80 Kilometers

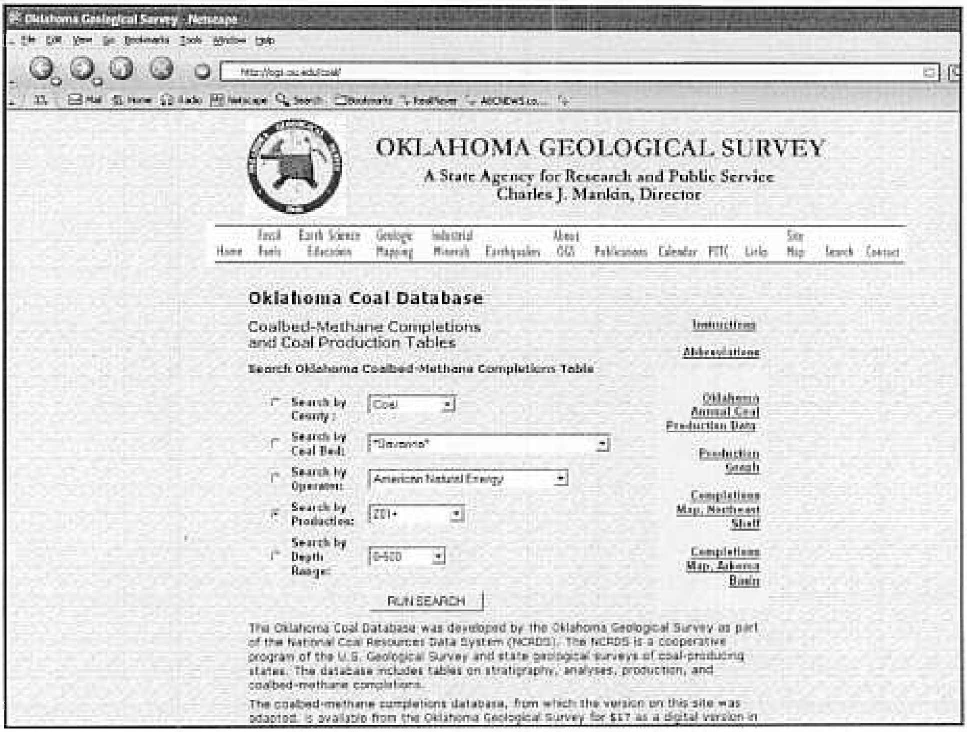

COAL OUTCROP AND SUBCROP MAP
OF OKLAHOMA COALFIELD (Friedman, 1982)

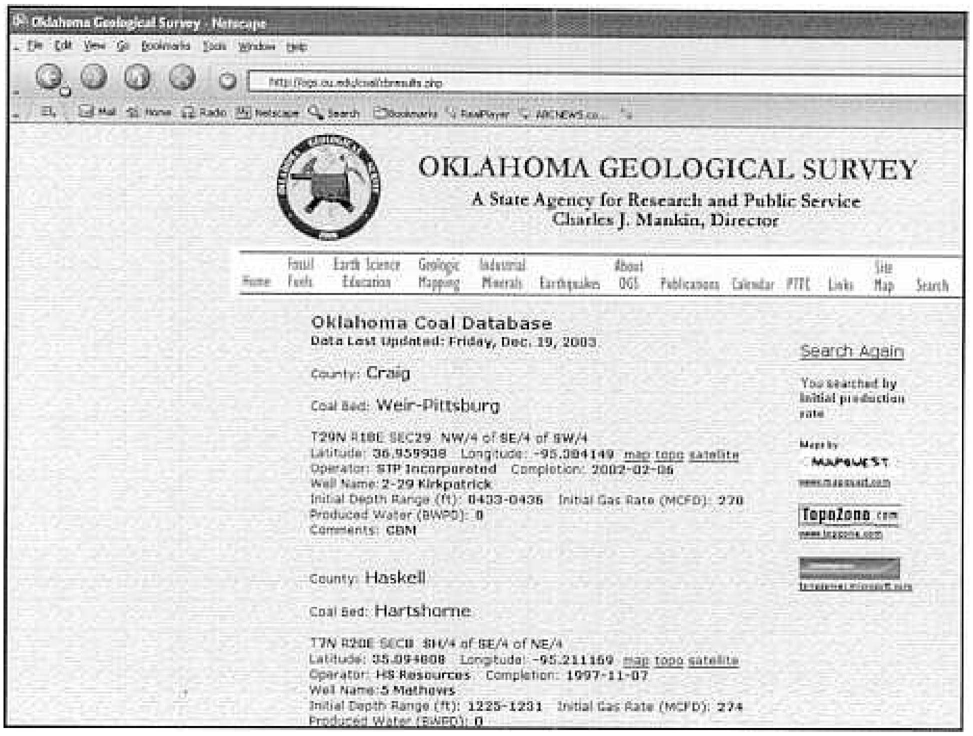

A
B
Tulsa
SURFACE MINE
SURFACE MINE
1000 FT.
SEA LEVEL
-1000
COAL
COAL
0
20 MILES
40
INDEX MAP TO COAL FIELD AND CROSS SECTIONS
OKLAHOMA CITY
C
D
Wilburton
SHAFT MINE
Stigler
SLOPE MINE
SURFACE MINE
SURFACE MINE
Muskogee
CHOCTAW FAULT
-2000
-3000
SEDIMENTARY ROCKS
GRANITE
20
40 MILES
60
80

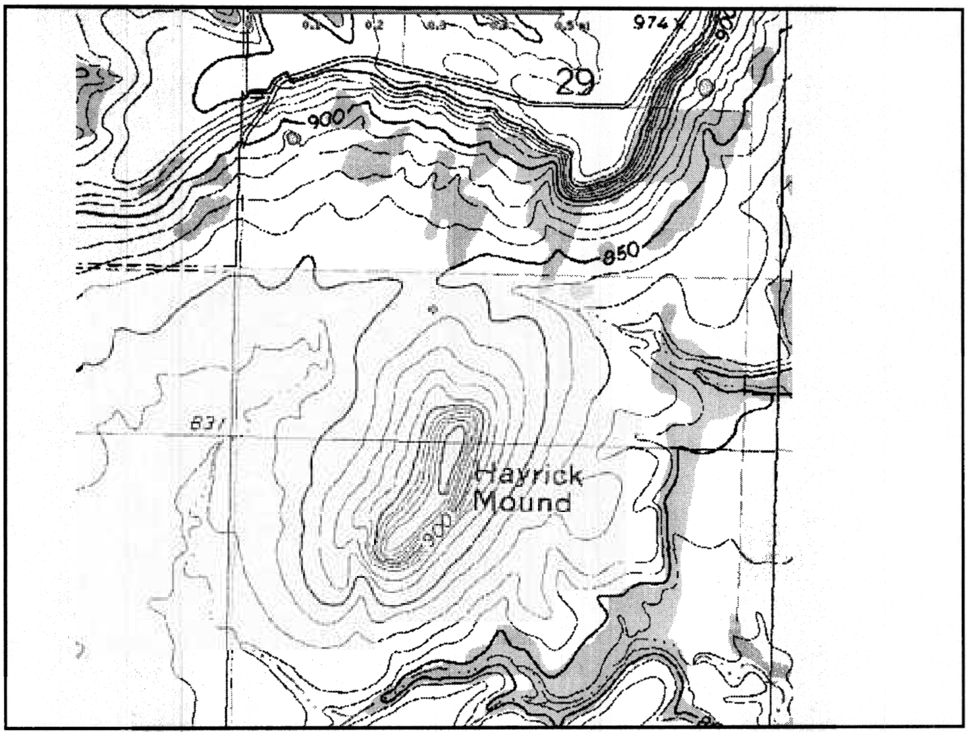


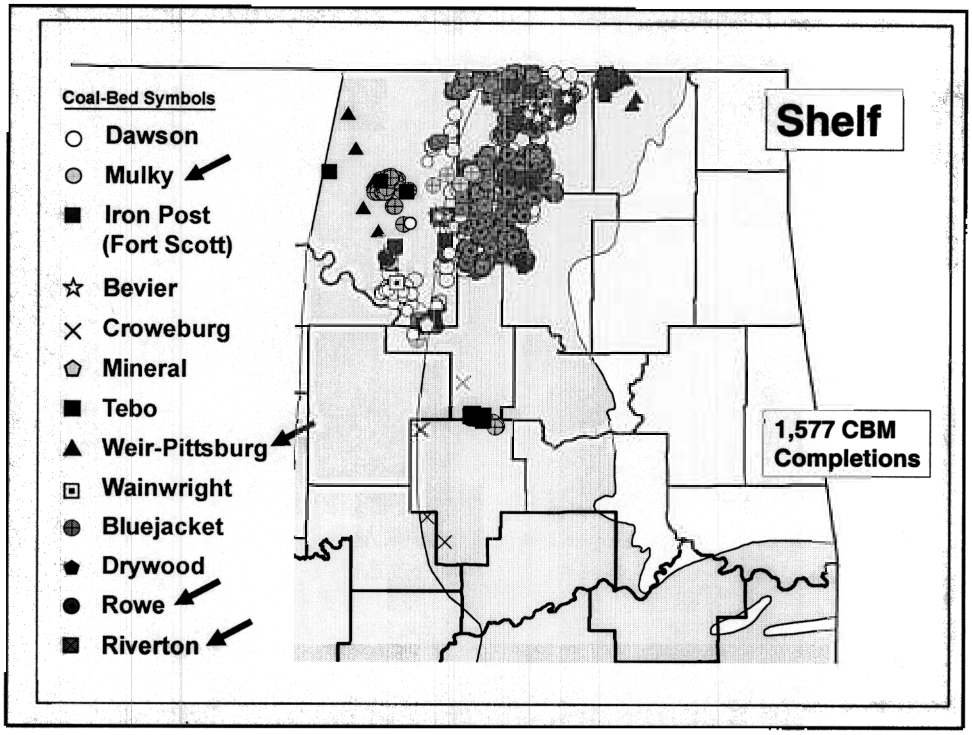
Recor	API Number	Operator	Completion_Date	Well_Name	Field_Name	Sec
2671	35-061-21844	Williams Production	5/31/2003	2-32 Penny	Kinta	32
1502	35-121-22664	Mannix Oil	11/20/2001	3-9 Snowball	Pittsburg County CBM Gas Area	9
2219	35-121-22644	Mannix Oil	11/20/2001	1-9 Snowball	Pittsburg County CBM Gas Area	9
1504	35-121-22684	Mannix Oil	11/20/2001	2-9A Snowball	Pittsburg County CBM Gas Area	10
2187	35-121-28847	Davis Operating Company	1/28/2003	1 Belt	Kinta	24
1677	35-061-21592	Mannix Oil	8/20/2001	3-13 Verdell	Kinta	13
2184	35-121-22850	Davis Operating Company	2/18/2003	1 Higgins	Kinta	24
1503	35-121-22645	Mannix Oil	11/20/2001	4-9 Snowball	Pittsburg County CBM Gas Area	9
1242	35-061-21448	Mannix Oil	10/1/2000	3-31 Molly	Kinta	31
1494	35-121-22624	Mannix Oil	12/1/2001	1-10 Hook	Pittsburg County CBM Gas Area	10
1495	35-121-22620	Mannix Oil	11/22/2001	2-10 Hook	Pittsburg County CBM Gas Area	10
2699	35-105-29365	Envirotek Fuel Systems	6/1/1999	1-11 Gillespey	Woody	11
1511	35-121-22625	Mannix Oil	12/1/2001	4-10 Hook	Pittsburg County CBM Gas Area	10
2483	35-061-21895	Questar Exploration & Production	9/20/2003	1-5 Chasyn	Brooken	5
1244	35-061-21556	Questar Exploration & Production	4/7/2001	1-33 Monks West	Brooken	28
1409	35-061-21593	Mannix Oil	8/20/2001	2-13 Verdell	Kinta	13
1278	35-061-21524	Mannix Oil	4/6/2001	4-34 Dooney	Kinta	34
2625	35-061-21839	Williams Production	5/30/2003	3-32 Penny	Kinta	32
2195	35-121-22849	Davis Operating Company	2/22/2003	1 Harris	Kinta	24
1224	35-061-21536	Mannix Oil	4/6/2001	2-34 Dooney	Kinta	34
1243	35-061-21456	Mannix Oil	11/1/2000	4-31 Molly	Kinta	31
1241	35-061-21438	Mannix Oil	10/1/2000	2-31 Molly	Kinta	31
1205	35-061-21523	Mannix Oil	4/10/2001	1-34 Dooney	Kinta	34
2670	35-121-23012	Chesapeake Operating	10/28/2003	2-24H Wadsworth	Brooken	24
2171	35-121-22863	Orion Exploration	2/14/2003	4-11 Shelton	Brooken	11
2405	35-121-22886	Brower Oil & Gas	3/18/2003	4-25 Mildred Bettis	Brooken	25
2647	35-061-21526	Williams Production	5/14/2002	2-20 Jake	Kinta	20
2032	35-121-22818	Orion Exploration	11/6/2002	2-11 South Shelton	Brooken	10
2602	35-061-21914	Questar Exploration & Production	11/4/2003	1-7 Mason	Kinta	7
2170	35-121-22857	Orion Exploration	2/11/2003	3-11 South Shelton	Brooken	11
1300	35-121-22560	Mannix Oil	6/15/2001	1-36 Kyle	Kinta	36
1240	35-061-21466	Mannix Oil	11/1/2000	1-31 Molly	Kinta	31


Oklahoma Geological Survey - Netscape
Coal and Coalbed Methane
Selected Reports and Maps
Coal Reports and Maps
OGS Coalbed Methane Reports [pdf - 65 KB]
References
Links
Coal and Coalbed Methane links
Oklahoma Coal Database
Coal Database
Coal Flyer
Coal Maps

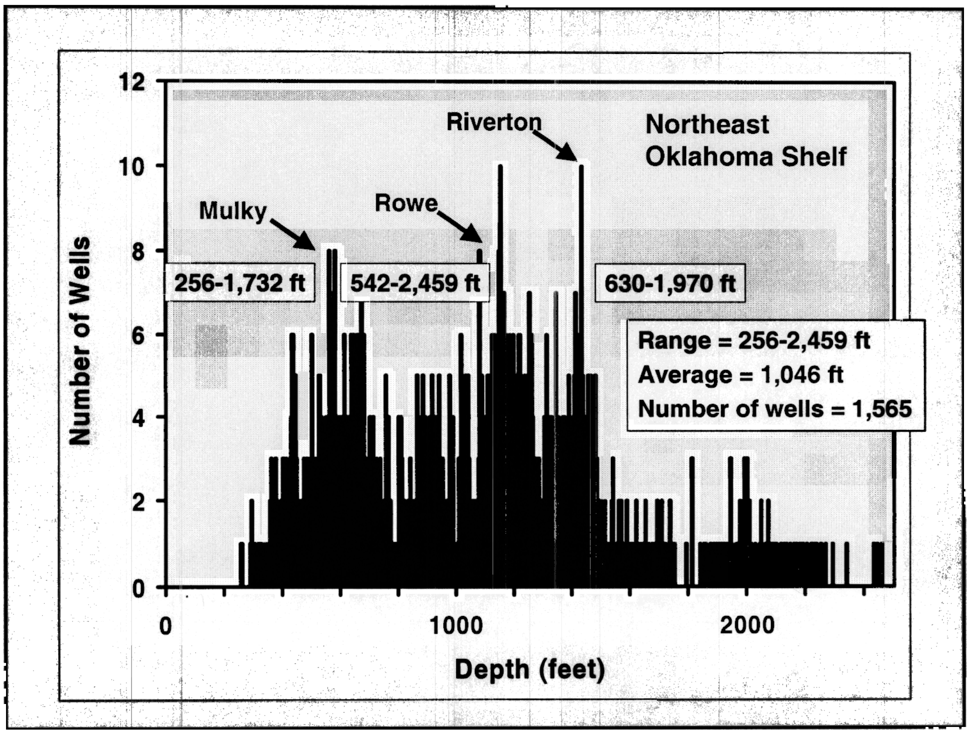

Oklahoma Geological Survey - Netscape
OKLAHOMA GEOLOGICAL SURVEY
A State Agency for Research and Public Service
Charles J. Mankin, Director
Oklahoma Coal Database
Coalbed-Methane Completions
and Coal Production Tables
Search Oklahoma Coalbed-Methane Completions Table
Search by County:
Search by Coal Bed:
Search by Operator:
American Natural Energy
Search by Production:
Search by Depth Range:
RUN SEARCH
Instructions
Abbreviations
Oklahoma Annual Coal Production Data
Production Graph
Completions Map, Northeast Shelf
Completions Map, Arkoma Basin
The Oklahoma Coal Database was developed by the Oklahoma Geological Survey as part of the National Coal Resources Data System (NCRDS). The NCRDS is a cooperative program of the U.S. Geological Survey and state geological surveys of coal-producing states. The database includes tables on stratigraphy, analyses, production, and coalbed-methane completions.


Oklahoma Geological Survey - Netscape
OKLAHOMA GEOLOGICAL SURVEY
A State Agency for Research and Public Service
Charles J. Mankin, Director
Home Fossil Fuels Earth Science Education Geologic Mapping Industrial Minerals Earthquakes About OGS Publications Calendar PTTC Links Site Map Search
Oklahoma Coal Database
Data Last Updated: Friday, Dec. 19, 2003
Search Again
You searched by initial production rate
County: Craig
Coal Bed: Weir-Pittsburg
T29N R18E SEC29 NW/4 of SE/4 of SW/4
Latitude: 36.959938 Longitude: -95.384149 map topo satellite
Operator: STP Incorporated Completion: 2002-02-06
Well Name: 2-29 Kirkpatrick
Initial Depth Range (ft): 0433-0436 Initial Gas Rate (MCFD): 270
Produced Water (BWPD): 0
Comments: CBM
Maps by MAPQUEST
TopoZone.com
County: Haskell
Coal Bed: Hartshorne
T7N R20E SEC8 SW/4 of SE/4 of NE/4
Latitude: 35.094808 Longitude: -95.211169 map topo satellite
Operator: HS Resources Completion: 1997-11-07
Well Name: 5 Mathews
Initial Depth Range (ft): 1225-1231 Initial Gas Rate (MCFD): 274
Produced Water (BWPD): 0

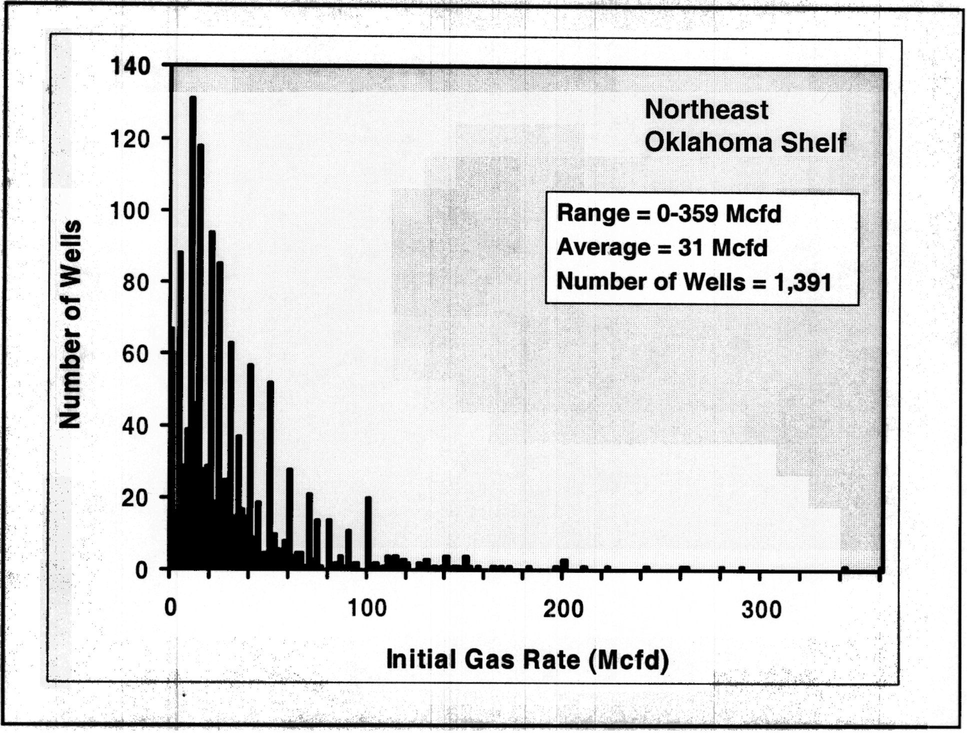

974
29
900
850
831
Hayrick Mound
900

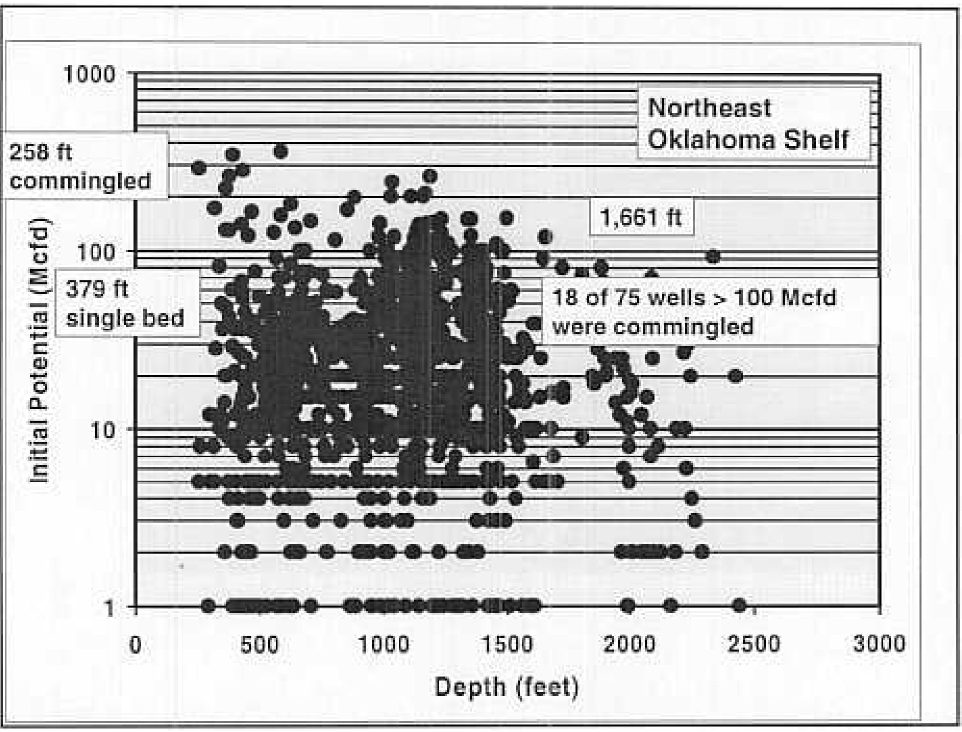


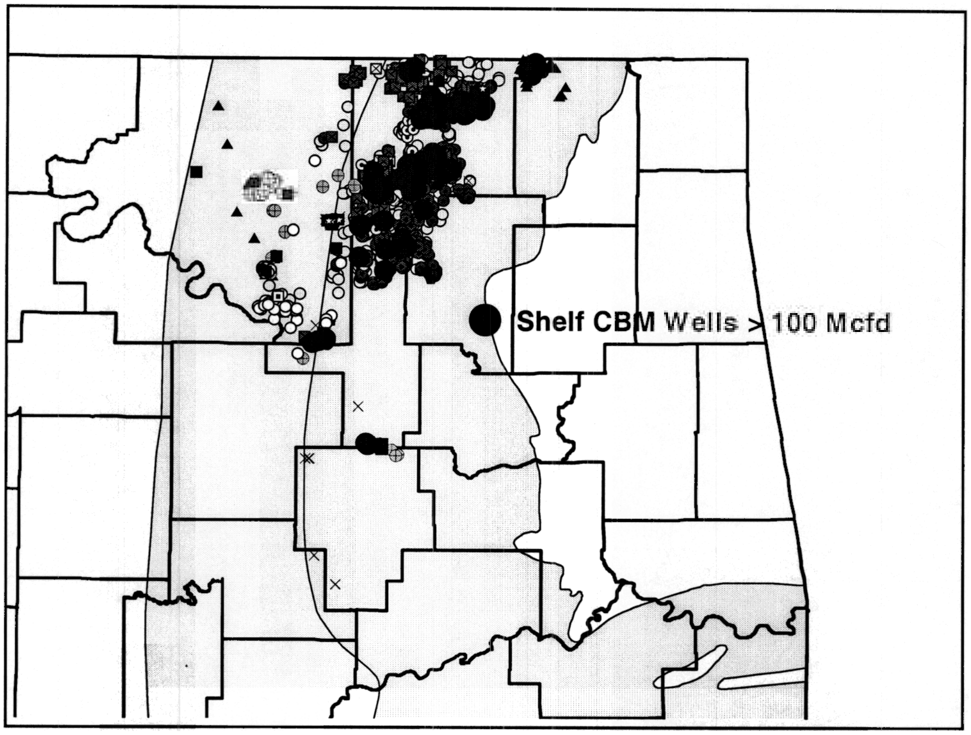
Coal-Bed Symbols
Dawson
Mulky
Iron Post
(Fort Scott)
Bevier
Croweburg
Mineral
Tebo
Weir-Pittsburg
Wainwright
Bluejacket
Drywood
Rowe
Riverton
Shelf
1,577 CBM
Completions

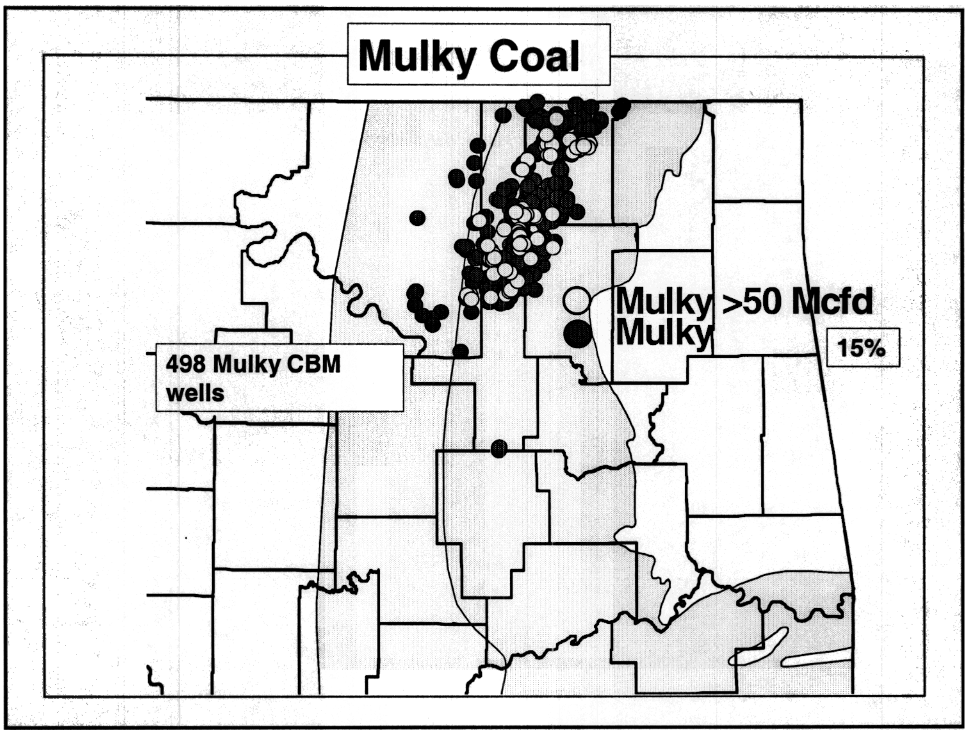


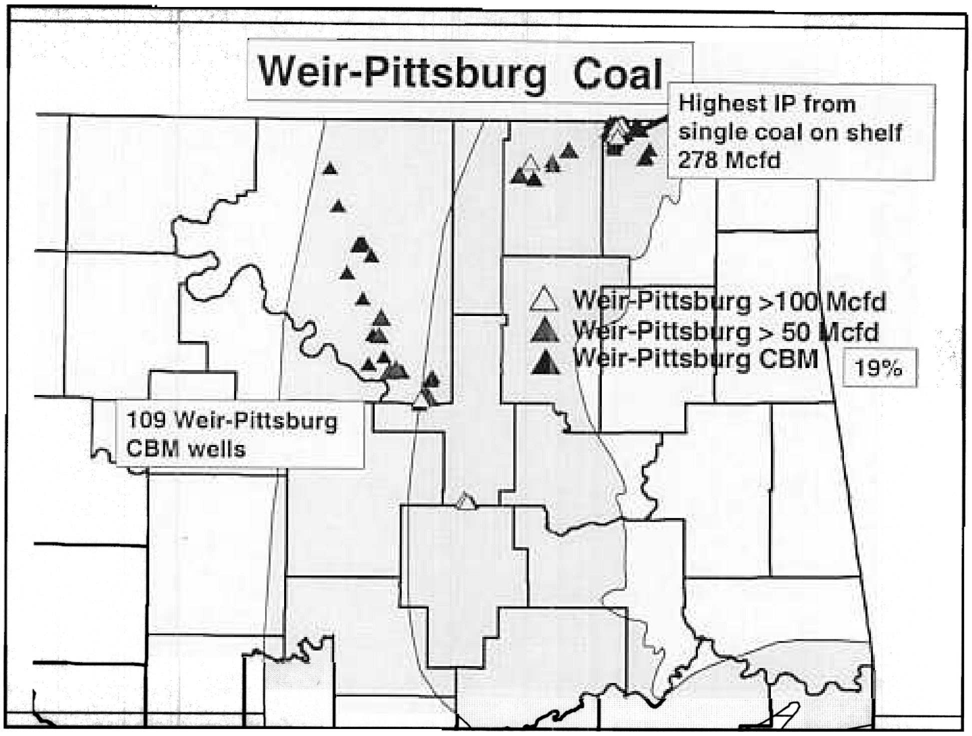
Northeast
Oklahoma Shelf
Riverton
Rowe
Mulky
256-1,732 ft
542-2,459 ft
630-1,970 ft
Range = 256-2,459 ft
Average = 1,046 ft
Number of wells = 1,565
Number of Wells
Depth (feet)
0
2
4
6
8
10
12
1000
2000


Northeast
Oklahoma Shelf
Range = 0-359 Mcfd
Average = 31 Mcfd
Number of Wells = 1,391
Number of Wells
Initial Gas Rate (Mcfd)
0
20
40
60
80
100
120
140
0
100
200
300

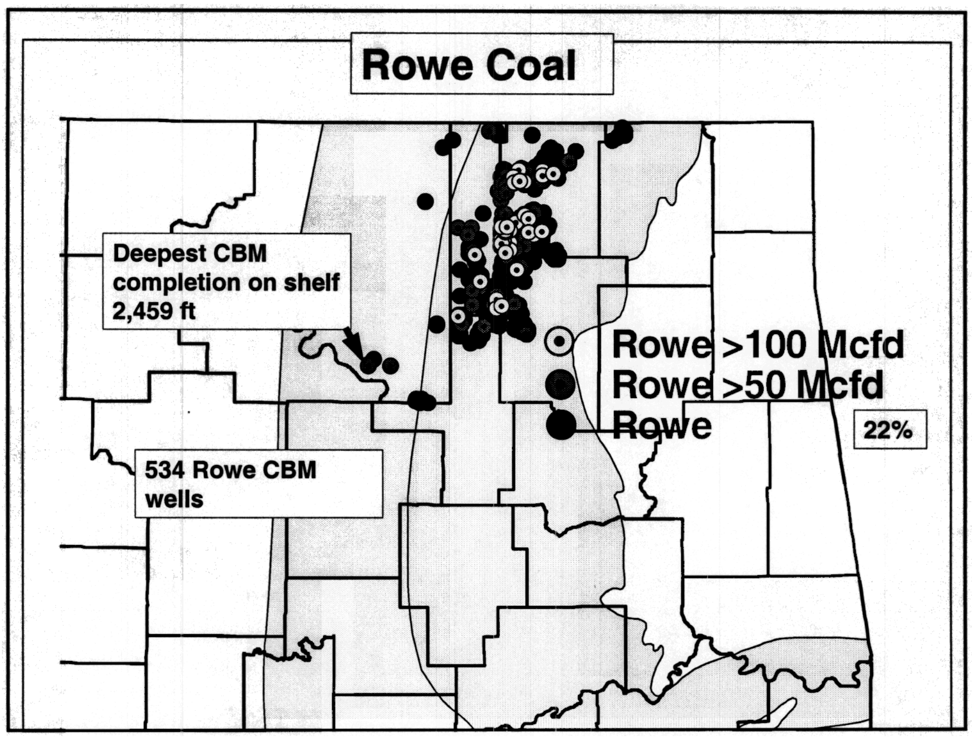

Northeast
Oklahoma Shelf
258 ft
commingled
1,661 ft
379 ft
single bed
18 of 75 wells > 100 Mcfd
were commingled
Initial Potential (Mcfd)
Depth (feet)
1
10
100
1000
0
500
1000
1500
2000
2500
3000


Shelf CBM Wells > 100 Mcfd

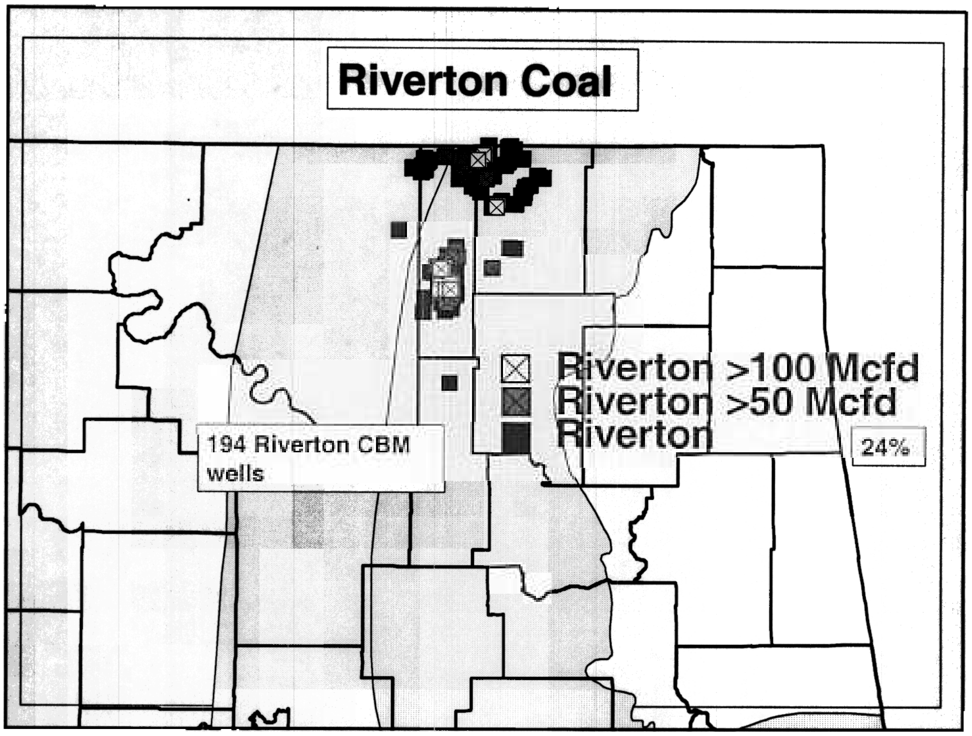

Mulky Coal
Mulky >50 Mcfd
Mulky
15%
498 Mulky CBM wells

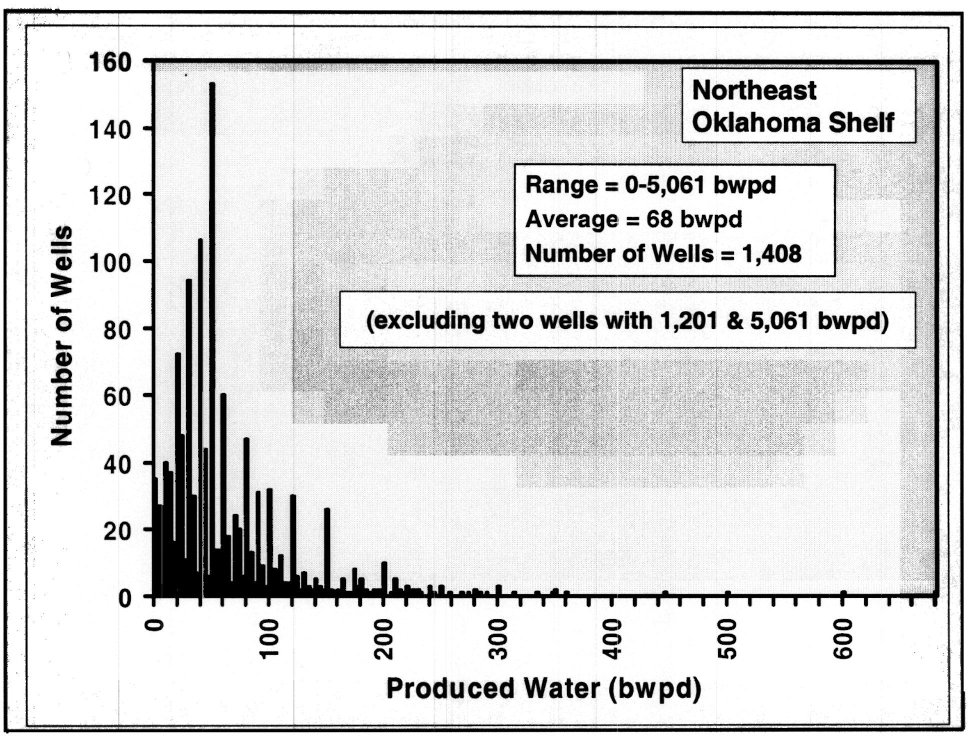


Weir-Pittsburg Coal
Highest IP from single coal on shelf 278 Mcfd
Weir-Pittsburg >100 Mcfd
Weir-Pittsburg > 50 Mcfd
Weir-Pittsburg CBM
19%
109 Weir-Pittsburg CBM wells



Rowe Coal
Deepest CBM completion on shelf 2,459 ft
Rowe >100 Mcfd
Rowe >50 Mcfd
Rowe
22%
534 Rowe CBM wells

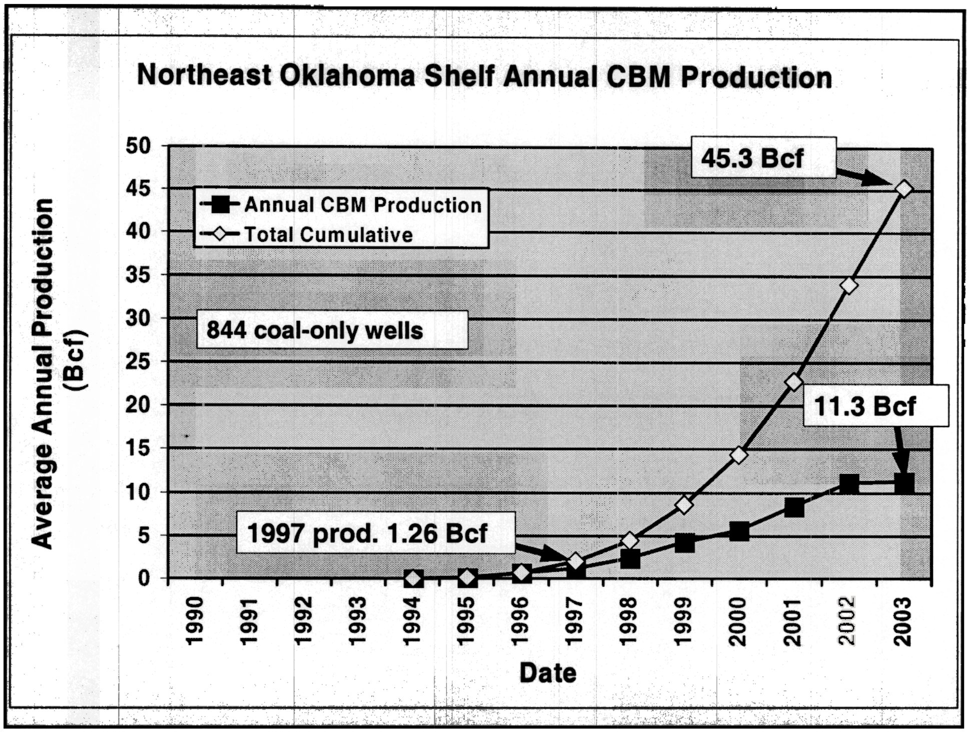

Riverton Coal
194 Riverton CBM wells
Riverton >100 Mcfd
Riverton >50 Mcfd
Riverton
24%

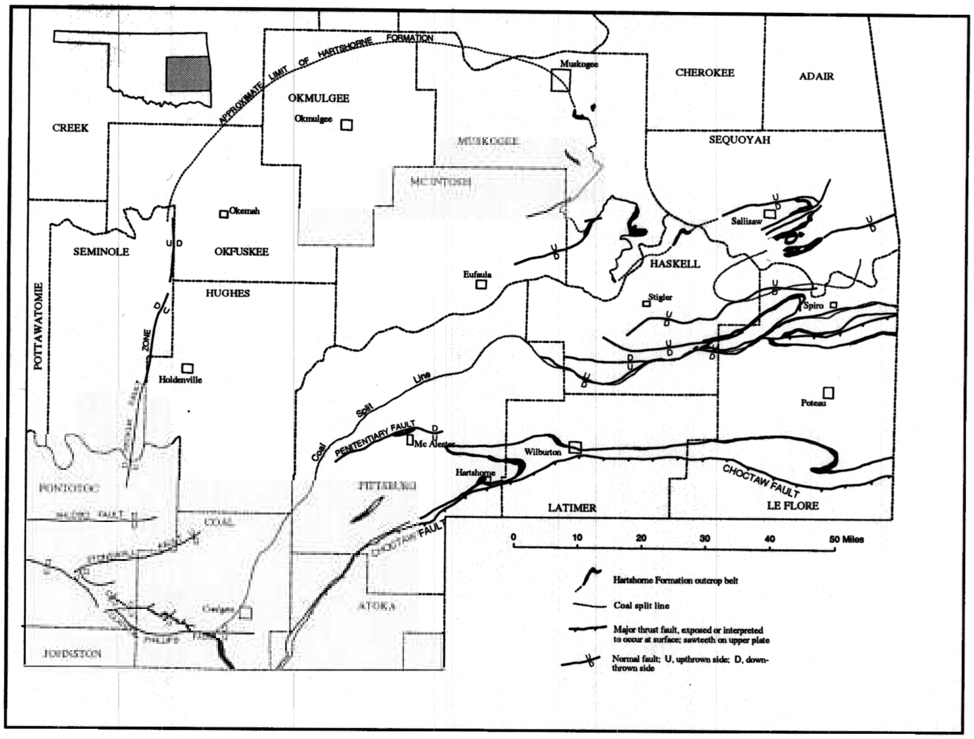

Northeast Oklahoma Shelf
Range = 0-5,061 bwpd
Average = 68 bwpd
Number of Wells = 1,408
(excluding two wells with 1,201 & 5,061 bwpd)
Number of Wells
Produced Water (bwpd)
0
20
40
60
80
100
120
140
160
0
100
200
300
400
500
600

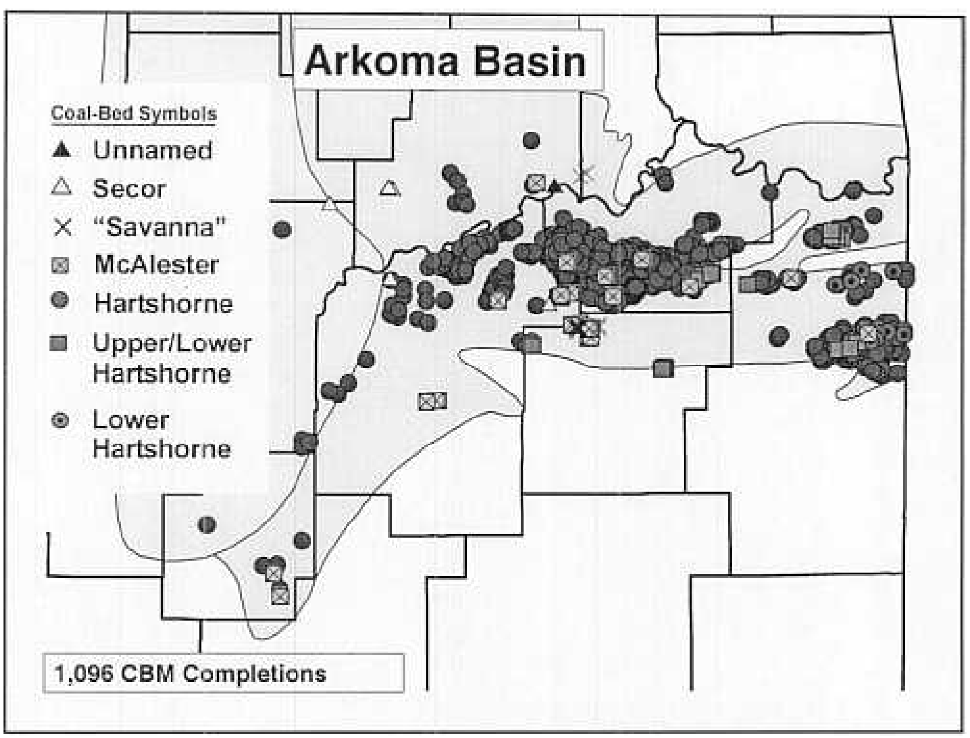
Water Quality

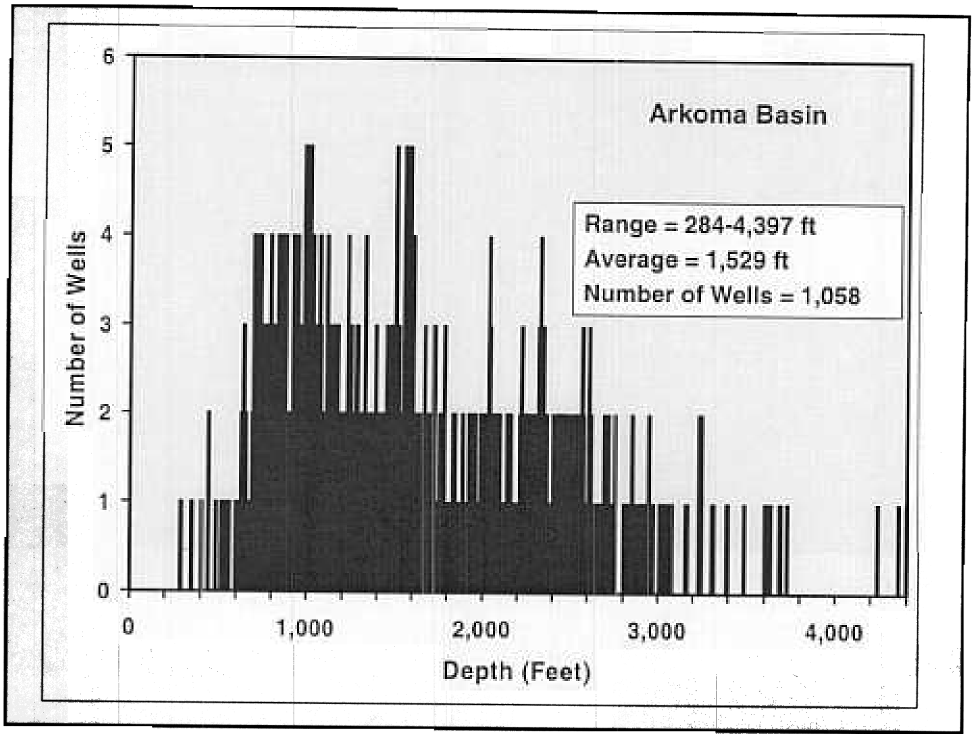
Water samples from the Mulky and Rowe coals in 4 wells in Nowata and Osage Counties had 86,200-152,900 mg/L Total Dissolved Solids (TDS)

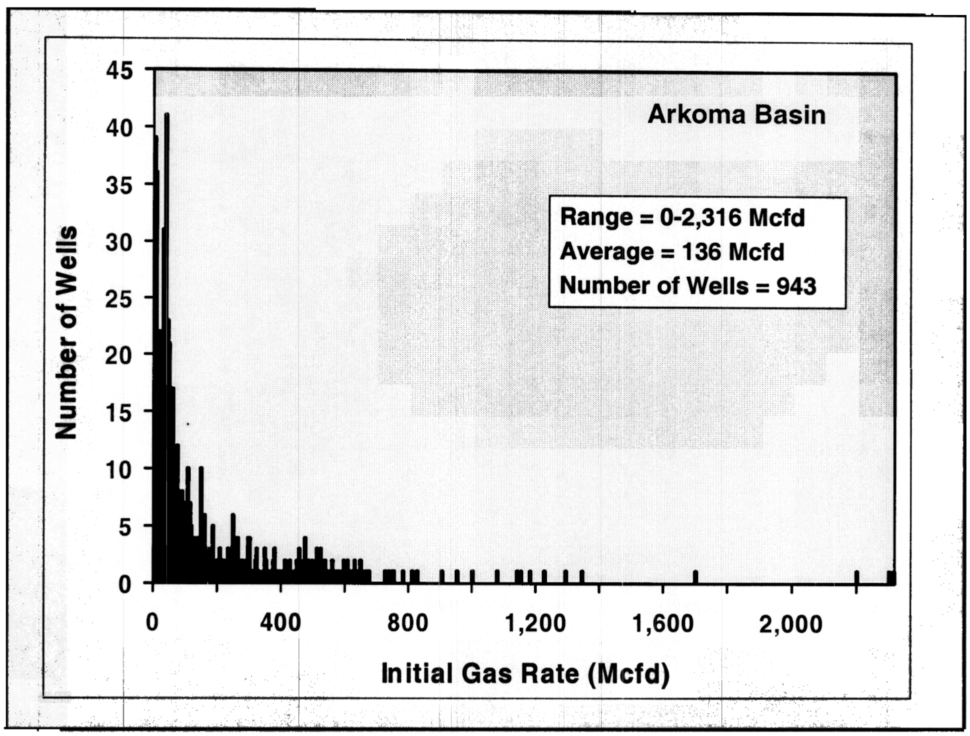
[Underground Sources of Drinking Water (USDW) contain <10,000 mg/L TDS; seawater is @35,000 mg/L TDS]

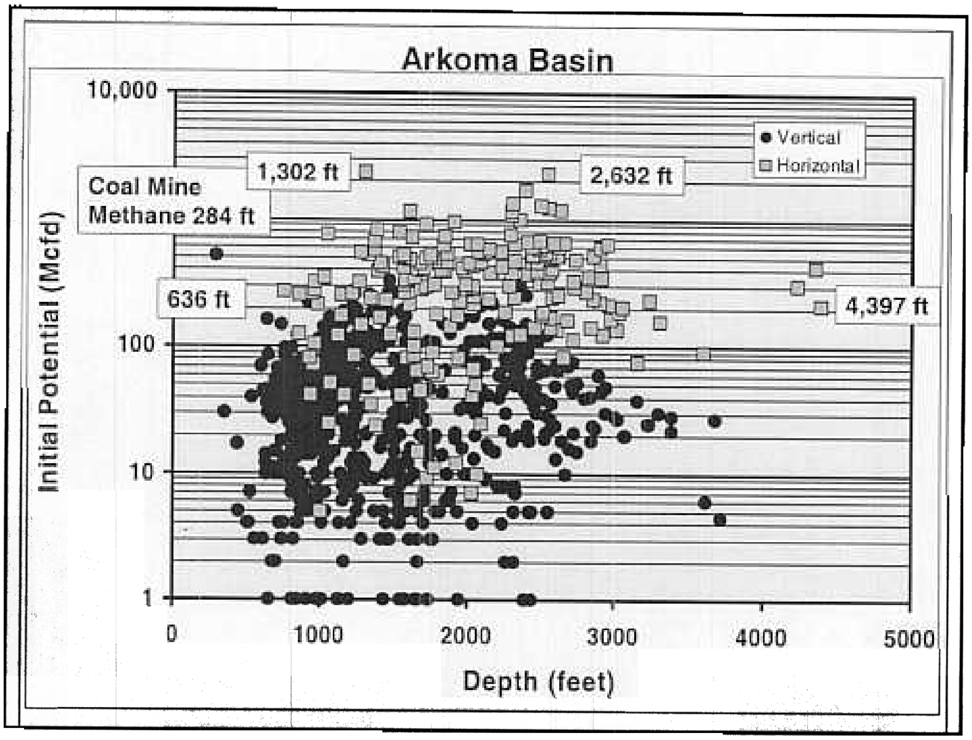


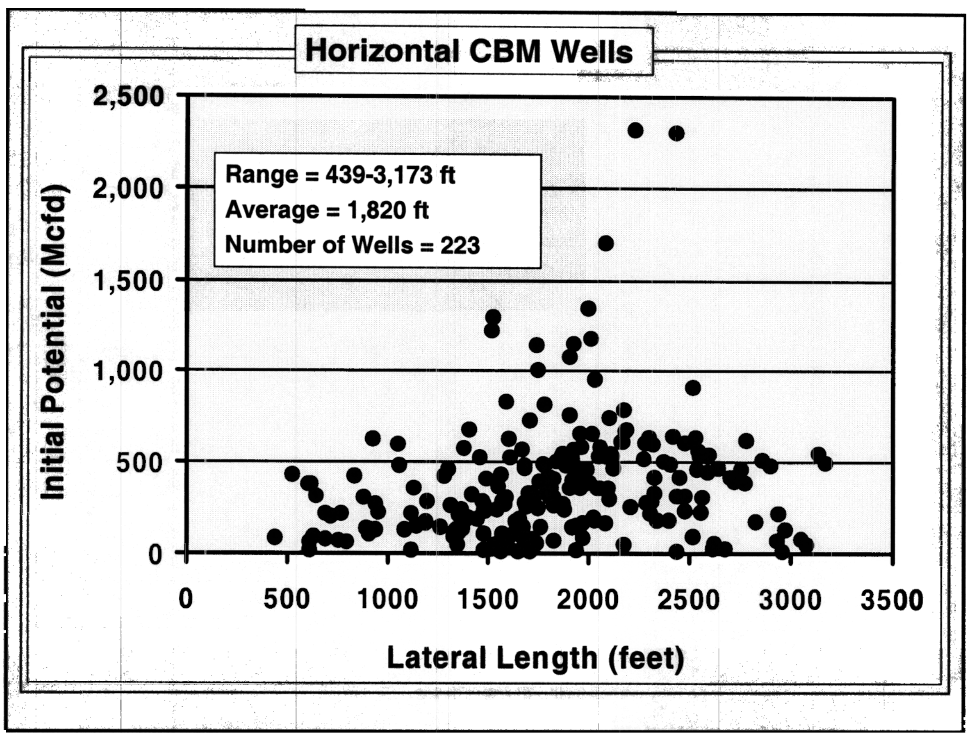

APPROXIMATE LIMIT OF HARTSHORNE FORMATION
CREEK
OKMULGEE
Okmulgee
MUSKOGEE
Muskogee
CHEROKEE
ADAIR
SEQUOYAH
MC INTOSH
Okemah
SEMINOLE
OKFUSKEE
HUGHES
POTTAWATOMIE
Holdenville
Eufaula
HASKELL
Sallisaw
Stigler
Spiro
Poteau
Coal Split Line
PENITENTIARY FAULT
Mc Alester
Wilburton
Hartshorne
PITTSBURG
LATIMER
CHOCTAW FAULT
LE FLORE
PONTOTOC
COAL
ATOKA
Coalgate
JOHNSTON
0 10 20 30 40 50 Miles
Hartshorne Formation outcrop belt
Coal split line
Major thrust fault, exposed or interpreted to occur at surface; sawteeth on upper plate
Normal fault; U, upthrown side; D, downthrown side

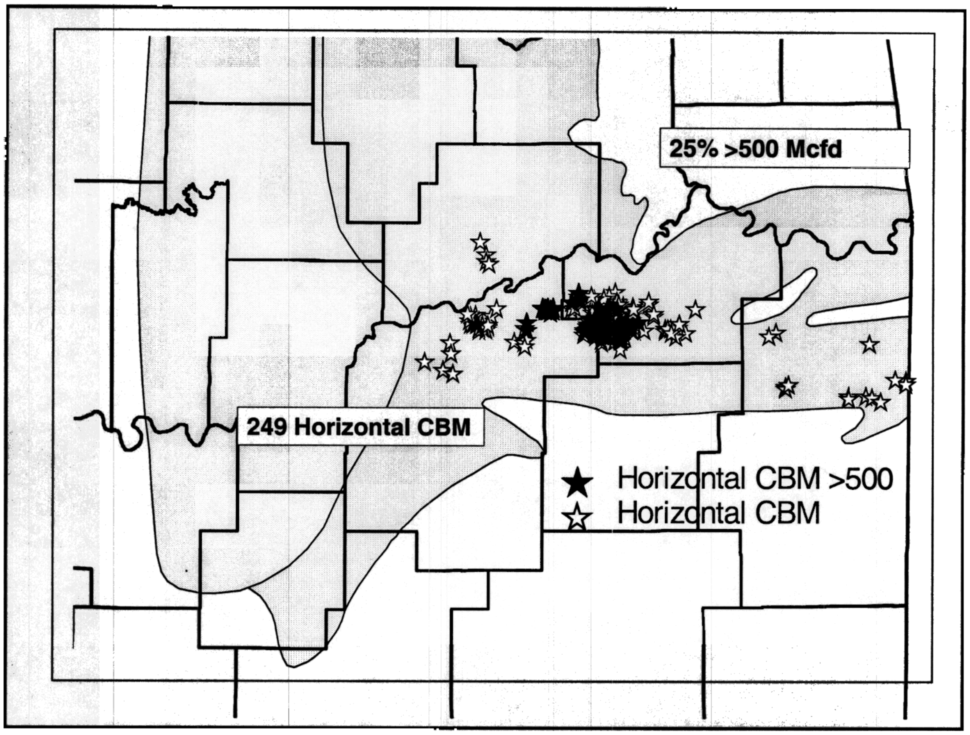

Arkoma Basin
Coal-Bed Symbols
Unnamed
Secor
"Savanna"
McAlester
Hartshorne
Upper/Lower Hartshorne
Lower Hartshorne
1,096 CBM Completions

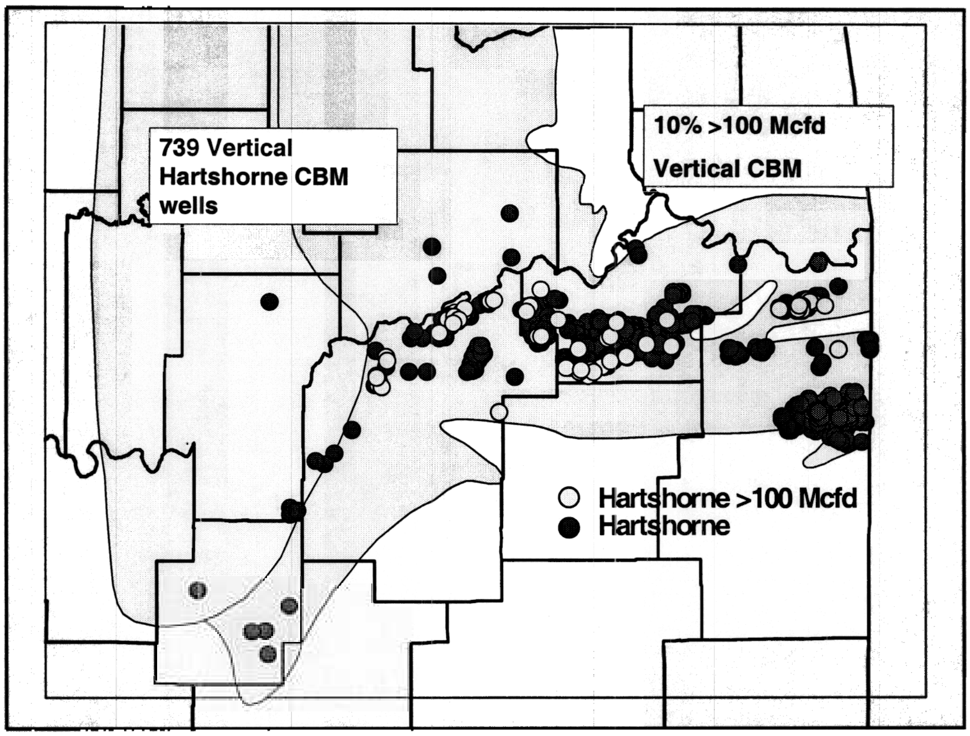

Arkoma Basin
Range = 284-4,397 ft
Average = 1,529 ft
Number of Wells = 1,058
Number of Wells
Depth (Feet)
0
1
2
3
4
5
6
0
1,000
2,000
3,000
4,000

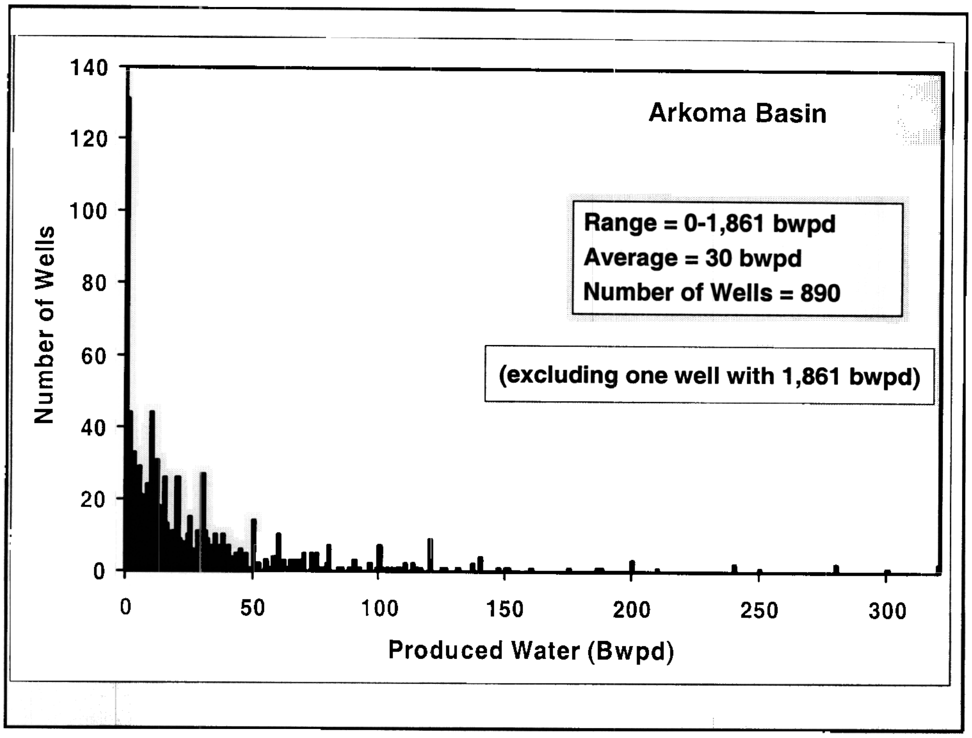

Arkoma Basin
Range = 0-2,316 Mcfd
Average = 136 Mcfd
Number of Wells = 943
Number of Wells
Initial Gas Rate (Mcfd)
0
5
10
15
20
25
30
35
40
45
0
400
800
1,200
1,600
2,000


Arkoma Basin
10,000
100
10
1
Initial Potential (Mcfd)
Vertical
Horizontal
1,302 ft
2,632 ft
Coal Mine
Methane 284 ft
636 ft
4,397 ft
0
1000
2000
3000
4000
5000
Depth (feet)

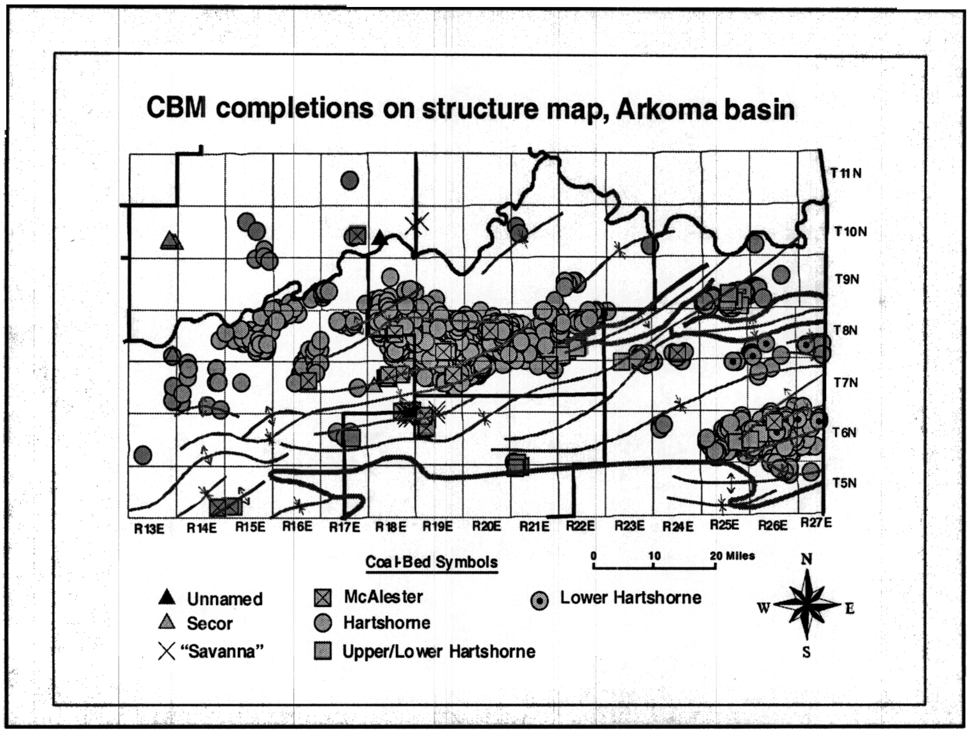

Horizontal CBM Wells
2,500
2,000
1,500
1,000
500
0
Initial Potential (Mcfd)
Range = 439-3,173 ft
Average = 1,820 ft
Number of Wells = 223
0
500
1000
1500
2000
2500
3000
3500
Lateral Length (feet)


25% >500 Mcfd
249 Horizontal CBM
Horizontal CBM >500
Horizontal CBM

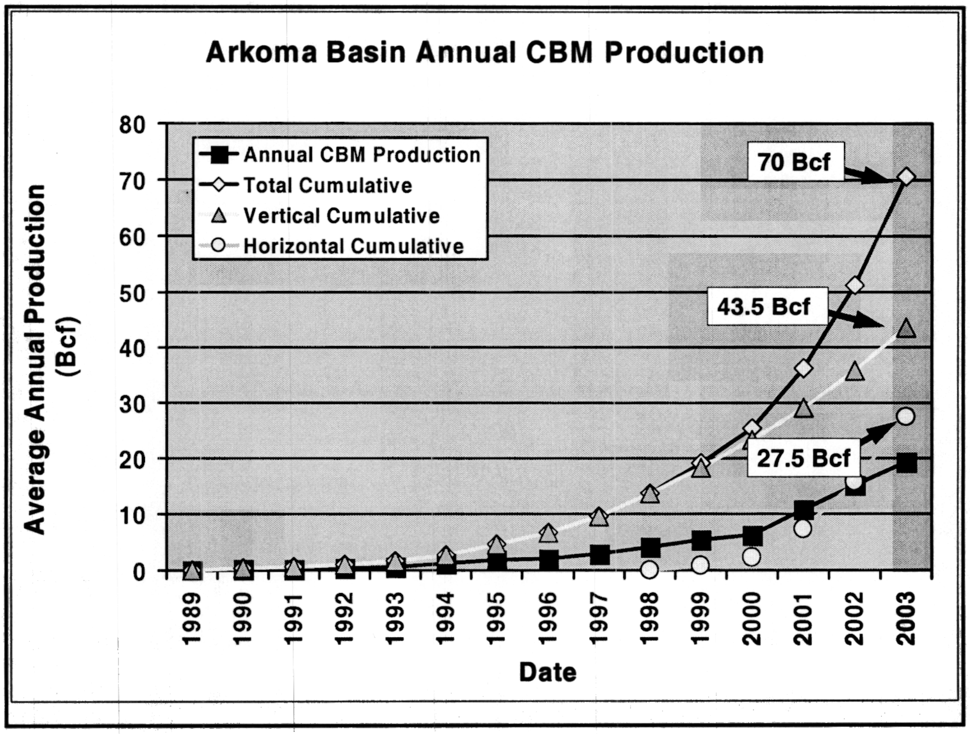

739 Vertical
Hartshorne CBM
wells
10% >100 Mcfd
Vertical CBM
Hartshorne >100 Mcfd
Hartshorne



Arkoma Basin
Range = 0-1,861 bwpd
Average = 30 bwpd
Number of Wells = 890
(excluding one well with 1,861 bwpd)
Number of Wells
Produced Water (Bwpd)
0
20
40
60
80
100
120
140
0
50
100
150
200
250
300



CBM completions on structure map, Arkoma basin
T11N
T10N
T9N
T8N
T7N
T6N
T5N
R13E R14E R15E R16E R17E R18E R19E R20E R21E R22E R23E R24E R25E R26E R27E
Coal-Bed Symbols
Unnamed
Secor
"Savanna"
McAlester
Hartshorne
Upper/Lower Hartshorne
Lower Hartshorne
0 10 20 Miles
N
W
E
S


Arkoma Basin Annual CBM Production
Annual CBM Production
Total Cumulative
Vertical Cumulative
Horizontal Cumulative
70 Bcf
43.5 Bcf
27.5 Bcf
Average Annual Production
(Bcf)
0
10
20
30
40
50
60
70
80
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
Date

WHAT ARE COAL GAS RESERVOIRS?

Jeffrey R. Levine

Coal Gas as a Type of "Unconventional Gas" Reservoir

Although the term "unconventional gas" appears frequently in the technical literature, it is only loosely defined and conveys a variety of meanings, depending on whether it is used in an economic, geologic, or legal context. Most commonly, unconventional gas refers specifically to gas produced from three types of reservoirs:

- coal seams,
- shales, and
- low permeability sandstones

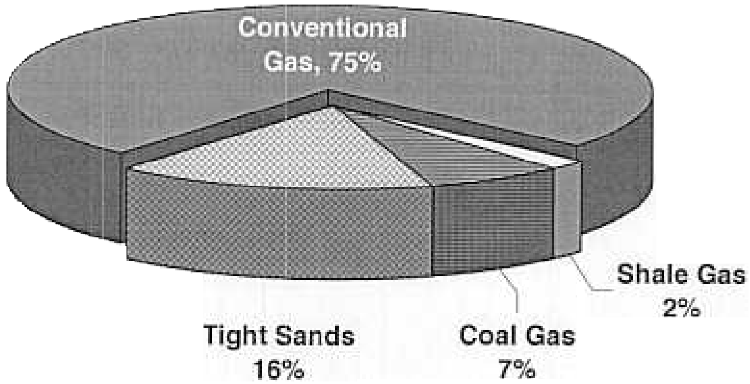


Figure 1 – Approximately 25% of current U.S. gas production comes from unconventional reservoirs , of which around 7% represents gas from coal seams.

Together, these currently represent approximately 25% of domestic U.S. gas production, of which coal seam gas represents around 7% (Figure 1)—a number that is expected to continue to grow in coming years in response to evolving market conditions.

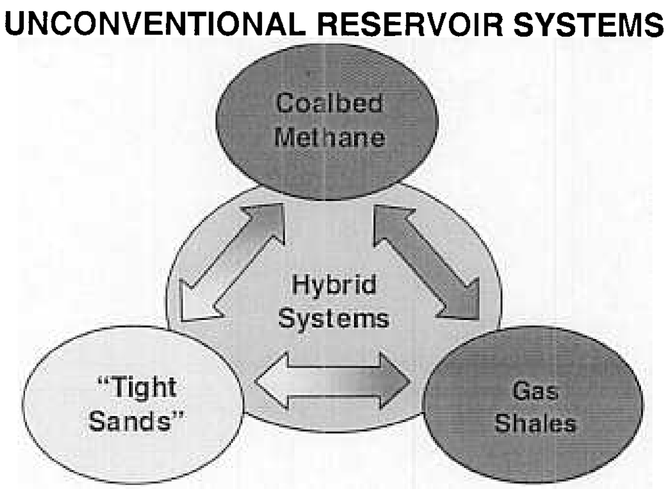


Figure 2 - Three categories of unconventional gas reservoirs are widely recognized. In fact, most reservoir systems are hybrids, with the gas resource falling into two or three of these categories.

Unconventional gas resources are classified as coal, shale, or tight sandstone according to whichever rock type is thought to be the principal source of the produced gas. When considered in detail, however, most unconventional reservoirs appear to be hybrid systems, wherein produced gas originates from more than one rock type and becomes co-mingled during production (Figure 2). Coal gas reservoirs are stratigraphically complex and may involve production from strata other than the main coal seam(s) completed. This may occur in the Arkoma Basin where associated organic matter-rich shales and sandstones may contribute toward production in some areas. Most of the gas-in-place in the Arkoma CBM play, however, can be clearly linked to the coal seams.

Natural gas produced from coal seams has come to be referred to as "coalbed methane" or "CBM", as it is commonly comprised mostly of methane, with a high ratio of methane to other hydrocarbons (i.e. very "dry" gas). Nevertheless, this term is ambiguous, as natural gas produced from coals can represent a diverse range of compositions, including higher hydrocarbons, condensate, and inert gases, especially nitrogen and carbon dioxide. The term *coalbed methane* would seem inappropriate to describe such multicomponent mixtures. Several alternate terms, such as "coal gas" or "coal seam gas" have been suggested that are less ambiguous. The term *coal gas* will be used herein wherever possible. Nevertheless, the term *CBM* is well entrenched in the literature and will remain in common use, both domestically and internationally. CBM must be understood in its broader sense to refer not solely to methane (s.s.), but to a methane-rich gas mixture produced from underground coal beds.

Coal gas produced from the Arkoma Basin represents a classic CBM composition, being comprised of 97.35 to 99.43% methane (Andrews and others, 1998).

The Origins of Coal Gas

Much of the literature on coal bed reservoirs refers to these rocks being "self-sourcing", as contrasted with conventional reservoir systems where source rock and reservoir rock are stratigraphically distinct. According to this hypothesis, the gas in sorbed gas reservoirs is interpreted to have been generated within the coal itself during thermal maturation. Unfortunately, while this makes for an interesting and ironic story, it is also misleading and inaccurate, and has led to significant errors having been made regarding coal gas reservoir potential. Sorbed gas reservoirs may be self-sourcing in part, but are subject to processes of migration, just as in any other reservoir system. Gases in coal are mobile in the subsurface, particularly over long periods of geologic time. Migration into or out of sorbed gas reservoirs can be clearly documented in many localities. Gases, including methane, are formed within coal as by-products of thermal maturation; but other processes unrelated to thermal maturation also play a role, notably biogenic gas generation and migration from other sources. Moreover, at the (higher) temperatures at which maturation occurs, coal has a lower gas storage capacity than it has today (assuming that the reservoir is cooler today than in the past), owing to temperature suppression of the isotherm. As a consequence, if thermal maturation were the only source of gas, coal should become undersaturated during uplift and cooling, unless there is some secondary source. Coals throughout the Arkoma Basin are saturated with methane for the most part, but the original source of these gases is uncertain.

Gas Storage/Trapping Mechanism

There are two aspects to the "trapping mechanism" in coal gas reservoirs: 1) sorption, which is not strictly a trapping mechanism per se, but provides a means of enhanced storage capacity at any given reservoir pressure, and 2) the seal, which is what actually "retains" the gas within the reservoir.

The phenomenon of sorption is one of the most important characteristics of coal gas reservoirs. Sorption is a term describing the molecular association (physical bonding) between a gas and any other substance in the reservoir. In the sorbed state, a "gas" exists in a highly condensed form, having density more akin to that of a liquid than a gas. Thus, the reservoir behaves as if it has much higher porosity than it has. Reservoirs where most of the *in situ* gas resource exists in the sorbed state are termed "sorbed gas reservoirs". This would include "coal gas" and most "shale gas" reservoirs. Sedimentary organic matter (OM) is the most active sorbent in sorbed gas reservoirs and is responsible for most of the sorption of methane. In comparison, minerals—even clays—have very low, essentially negligible, sorption capacity.

In conventional reservoir systems, the reservoir is sealed by low permeability strata or faults, which create structural or stratigraphic traps. In contrast, in sorbed gas reservoirs, trapping can occur either via conventional seals (i.e. structural or stratigraphic) or via "water" sealing. Water, which has a substantially lower methane sorption capacity than sedimentary organic matter, effectively "traps" the methane in the organic phase. (A third mechanism of sealing, also related to water, is the phenomenon of "capillary pressure", which augments the reservoir pressure in low permeability reservoirs and serves as gas seal as well. The role of this mechanism is uncertain in the case of coal bed reservoirs, but partially accounts for the high gas content in some shale gas reservoirs, such as the Barnett Shale in the Fort Worth Basin.)

Although sorption of methane in coal has commonly been described as "adsorption", this term is misleading in that it implies that the organic matter has a fixed structure and a definable "surface area", which is not correct. Sedimentary organic matter is comprised partly of liquid constituents which take up methane by solvation, or *ab*sorption. Moreover, the overall molecular structure of OM is non-rigid, and can expand to accommodate the sorbate (methane, carbon dioxide, water, etc.). For these reasons, the more generic term *sorption* is a better choice to describe this system. Sorption is defined as the process in which one substance takes up or holds another, by either absorption or adsorption. The key point is that by whatever mechanism—absorption or adsorption—the concentrations of methane are much higher than would be expected if the methane behaved as a free gas.

The quantity of methane sorbed in coal is proportional to the quantity present in the ambient environment. Where a free gas phase is present, this is measured by the methane pressure (or, more precisely, its partial pressure in a gas mixture). Free methane gas need not be present in the system, however, in which case the availability of methane is represented by the critical desorption pressure, which represents the pressure *below which* methane will form a free gas phase.

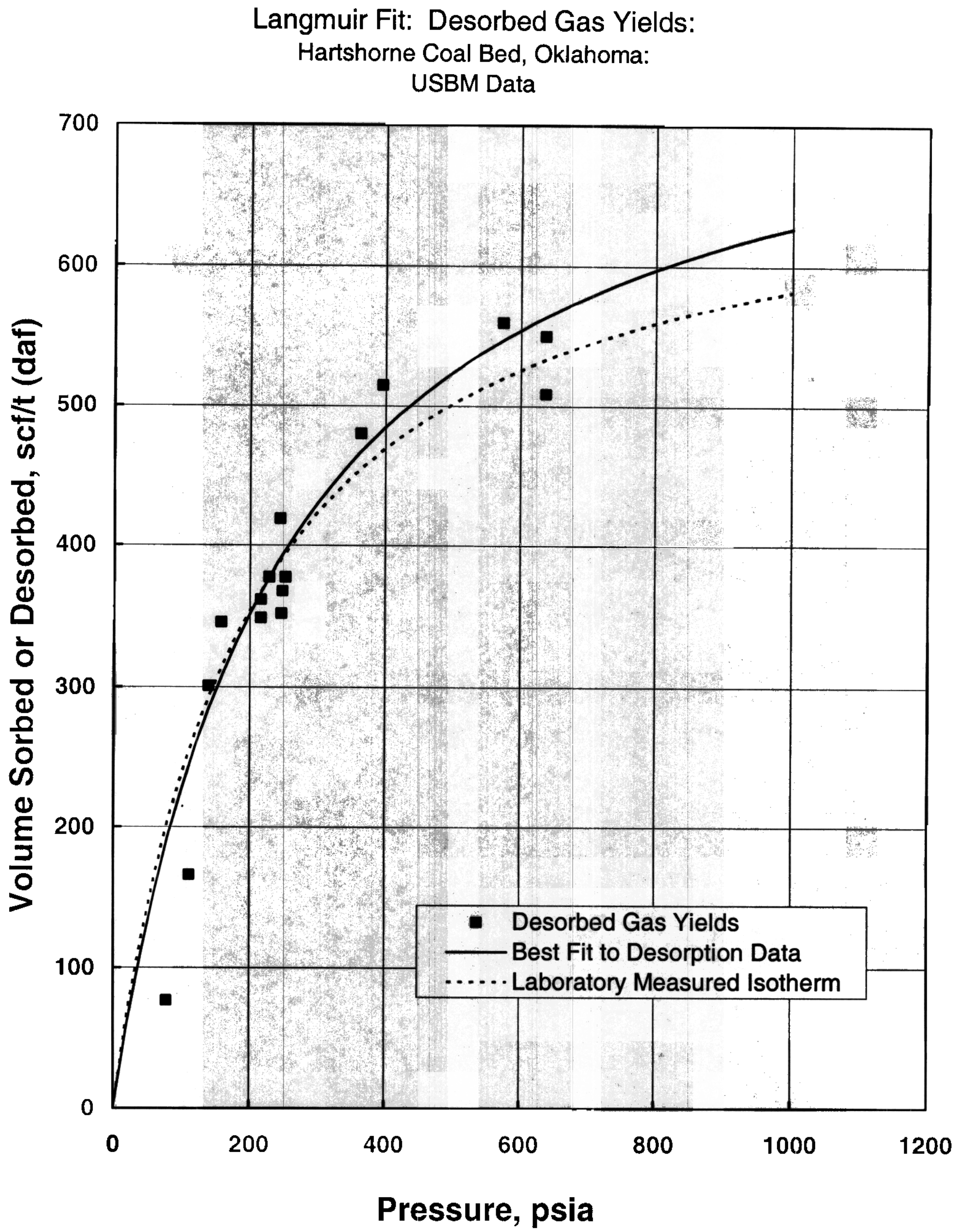


Figure 3 - Methane sorption isotherm for a coal from the eastern part of the Arkoma Basin, Oklahoma (Joubert et al., 1974), together with U.S. Bureau of Mines desorption test data from the same general area. Owing to regional variations in coal rank, the actual isotherms for any given locality may differ from the curve depicted here.

Geometric Elements of Coal Bed Reservoirs

Stratigraphic Elements.

Sorbed gas reservoirs do not require a "cap rock" or "seal" *per se* to entrap the gas they contain. Accordingly, the overall reservoir geometry is essentially determined by the thickness and three-dimensional configuration of the stratum, or strata, containing the gas. Owing to variations in the composition of the sedimentary strata—particularly stratigraphic variations in the organic matter content—coal gas reservoirs are comprised of multiple layers having variable reservoir quality (Figure 4). The concentration of gas-in-place as well as the permeability will vary from layer to layer. These variations may range from subtle to extreme. The thickness and character of the sedimentary layers will vary laterally as well.

Subdividing the reservoir system into a reasonable, meaningful number of stratigraphic elements depends on the scale of view and the goal of the subdivision. In the case of coal, stratigraphic variability may be observed down to millimeter-scale, where "lithotypes" may be observed which have variable fracture development, gas sorption capacity, and other reservoir characteristics. On a well bore or prospect scale, much larger scale subdivisions are made, on the order of 0.5 to several meters in thickness.

Fracture and Matrix Block Elements.

Each layer within a sorbed gas reservoir is segmented by fractures into three-dimensional elements of complex shape, size and configuration termed "matrix" blocks. Fractures are an important feature of sorbed gas reservoirs, as the permeability of the reservoir matrix is normally too low to allow commercial production rates of gas. Adequate gas flow depends upon movement of fluids (gas and water) through the fracture network. Fracture spacing and aperture varies from layer to layer, depending on the mechanical properties, stress-strain history (including fluid pressures) and other controls. In the case of coal (>50% OM), there are closely spaced fractures termed "cleat". Cleat spacing in coals from the Arkoma Basin range from centimeters down to a few millimeters spacing. Fractures in associated sedimentary rocks tend to have wider fracture spacings.

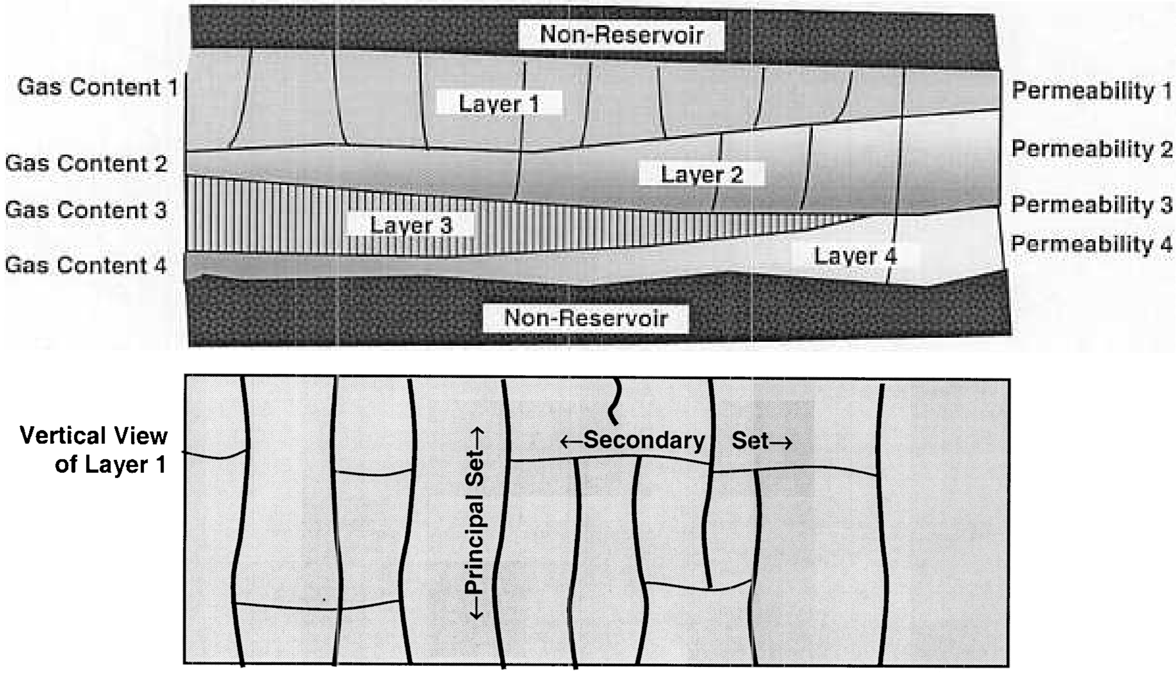


Figure 4 - Diagrammatic representation of the principal geometric elements of sorbed gas reservoirs, which includes stratigraphic layering and fractures

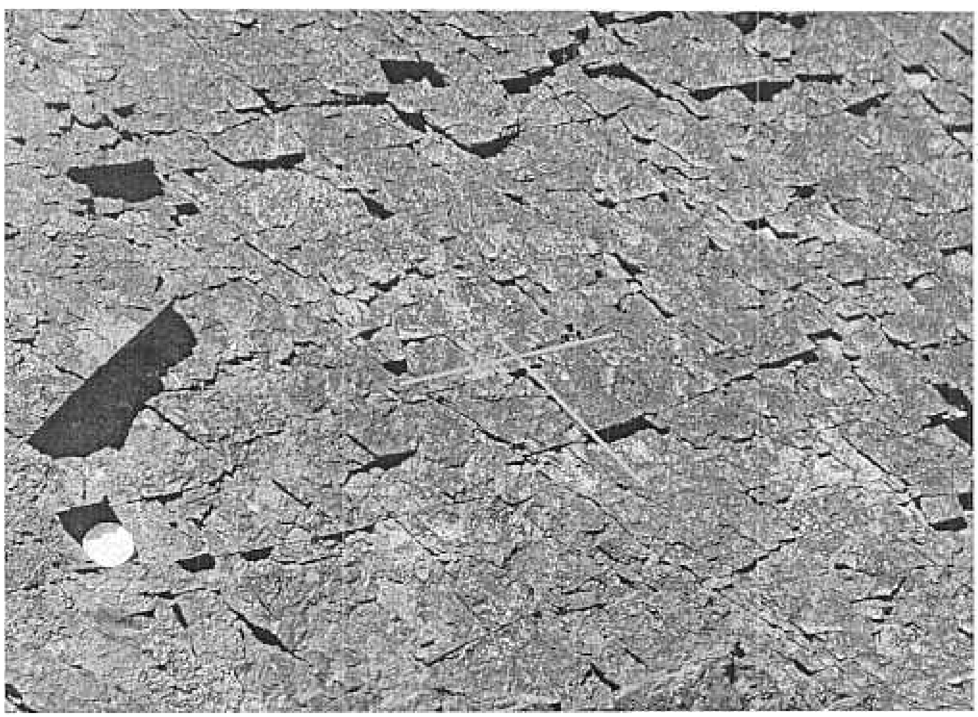


Figure 5 - Rhomboidal pattern of intersection of two non-orthogonal cleat directions, visible in a large block of McAlester Seam coal, Old McAlester High School Building, McAlester, OK U.S. quarter dollar for scale.

CHARACTERISTICS AND ORIGIN OF CLEAT IN COAL

Description and Terminology

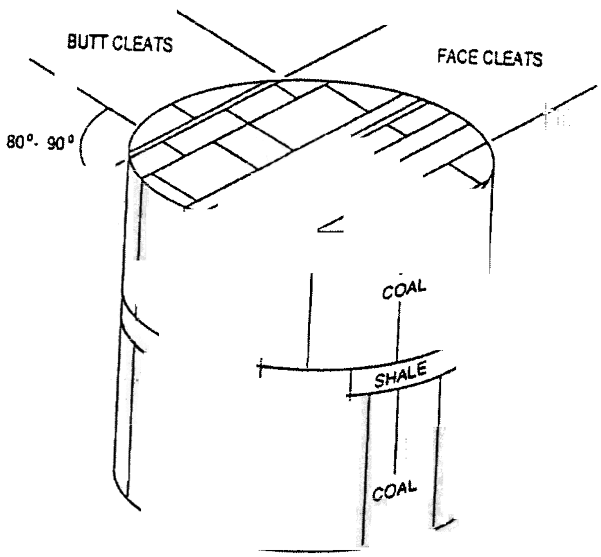


Figure 6 - Schematic diagram depicting a "classic" face and butt cleat arrangment in coal (modified from Law, 1993).

The permeability of the coal matrix to gas flow being very low, reservoir drainage is interpreted to occur via a network of interconnected fractures termed "cleat". In this regard, coal beds are similar to other fractured reservoirs, except that cleat has a much closer spacing, and may be well developed even when fractures are absent in other rocks. Cleats are a type of joint, where the *joint* refers to a quasi-planar fracture across which there has been no lateral displacement. As discussed subsequently, cleats are interpreted to form in response both to tectonic stresses and to volumetric shrinkage of the coal matrix during coalification.

The term *cleat* originated in the mining industry, where it is used to describe the system of closely spaced fractures naturally occurring in most coal seams. Classically, the cleat system comprises two sets of fractures, each oriented roughly perpendicular to bedding (Figure 6) and perpendicular to one another. One set of fractures, termed the "face cleat" is the dominant set, with individual fracture surfaces being relatively planar and continuous. Face cleat is so-named because, prior to the onset of highly mechanized mining methods, coal mines were laid out such that their working faces would advance in the direction *perpendicular* to the face cleat. In this way, the coal could be more easily broken away from the coal "face". The other cleat set, termed the "butt cleat", is perpendicular—or nearly so—to the face cleat. Butt cleats are "non-systematic" joints, having discontinuous non-planar surfaces. Butt cleats usually terminate against face cleat surfaces. This cross-cutting relationship indicates that the face cleat is formed earlier than the butt cleat.

Owing to the greater continuity and better development of the face cleats, coal seams can be highly anisotropic in regards to movement of fluids—permeabilities being on the order of 2.5 – 10X higher in the face cleat direction than in the butt cleat direction.

In the "real world", cleat patterns may be considerably more complex than the simple "model" depicted in Figure 6. Rather than being precisely aligned, as in the diagram, the fracture orientations are usually scattered across a range of azimuths. Sometimes the mode is obvious, while other times it is difficult to discern. Commonly, more than one non-coaxial cleat sets are overprinted, thus producing a polymodal distribution of azimuths (e.g., Figure 5 and Figure 7). In some cases, it is difficult to distinguish between face and butt cleat, both sets being more-or-less equally well developed, whereas in other cases, butt cleat is not developed at all. Moreover, cleat patterns are complicated by the fact that they occur over a range of dimensional scales and tend to be better developed in some coal lithotypes than in others. Vitrinite rich layers tend to be well cleated, whereas dull coal bands are relatively less cleated.

Tremain et al. (1991) have classified coal cleats into several hierarchical categories, depending on their vertical continuity (Table 1). This classification scheme can be useful for describing the sometimes bewildering welter of fractures present in coal.

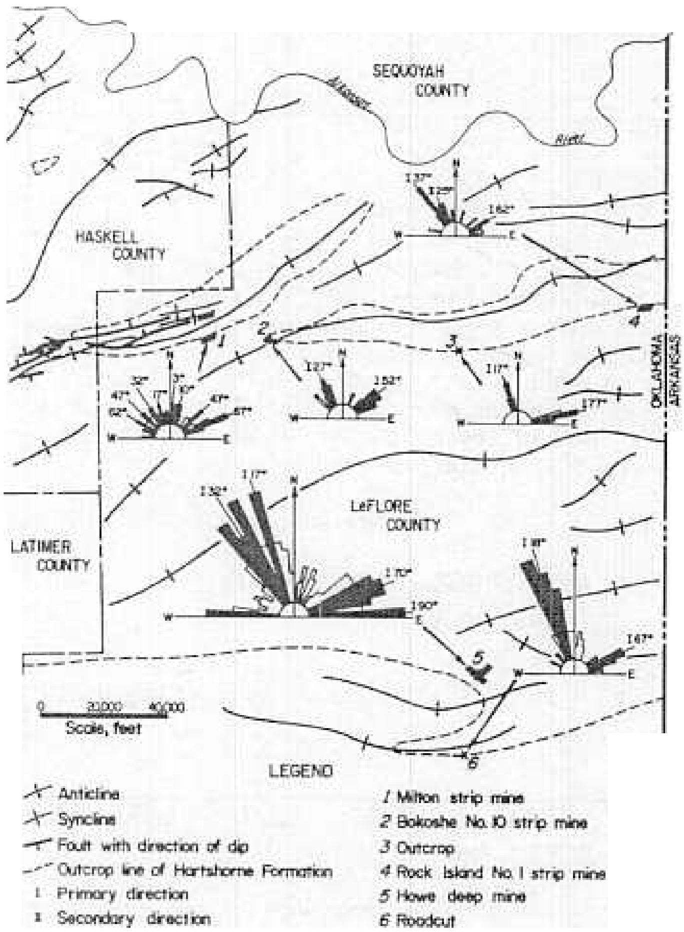


Figure 7 – A complex pattern of cleat orientations is expressed in coals in the eastern Arkoma Basin. Several modes are evident, suggestive of multiple, overprinted structural events or, possibly, rotation of the maximum compressive stress direction during deformation. Face cleat direction is generally oriented 17 to 32° west of north in this area (from Iannacchione and Puglio, 1979)

Table 1- Classification of cleat types based on continuity across lithotype boundaries (Tremain et al., 1991).

master cleats - are prominent, well developed, planar cleats which, by definition, cross several coal-type layers and may cross the entire coal seam. Master cleats are relatively widely spaced, depending on a variety of controlling variables. Spacing may be on the order of 30 to 100 cm
primary cleats - are prominent, well developed, planar cleats which extend across the full thickness of the coal lithotype band in which they occur, but do not cross major lithotype boundaries. In some coals, shale partings as thin as a few mm can serve as barriers to primary cleats. Primary cleat tends to be spaced on the order of 4 to 9 cm, depending on rank, lithotype composition, and other factors.
secondary cleats - are fractures which lie parallel to the primary cleat, but do not extend across the entire lithotype band in which they occur. Spacing of secondary cleats is strongly dependent on rank and lithotype composition. Spacing may range over an order of magnitude, from a few mm to several cm.
tertiary cleats - are very closely spaced fractures or fissures, occurring between the primary and secondary cleats. Tremain et al. (1991) suggest that these features may be primarily a phenomenon of near-surface weathering and stress release

Origins of Cleat

Geological evidence suggest two main mechanisms for cleat genesis in coal:

1) volume-loss shrinkage causing internal (tensile) stress

2) brittle mechanical failure under (external) stress.

   2a) hydraulic fracture,

   2b) load-parallel extension fracture

   2c) stress release fracture

The terms *endo*genetic (meaning that these fractures are formed in response to processes occurring *within* the coal) and *exo*genetic (meaning that the fractures develop in response to stresses imposed from *outside* the coal) have also been used to describe these mechanisms (Ammosov and Eremin, 1963; Close, 1993).

Morphological features on cleat surfaces, including plumose structures, twist-hackle fringes, and arrest lines imply an extensional origin for cleat. In contrast, shear fractures, both in coal and in non-coal strata, tend to have polished, glassy, slickensided surfaces.

Commonly, lineations are present on shear displacement surfaces indicating the direction of motion in the fracture plane whereas cleat is free of such features. Shear fractures in coal tend to be more abundant in structurally deformed terranes, especially in proximity to faults. In coal-bearing sequences that have suffered extensive compressive deformation, shear displacement (slippage) between layers tends to be concentrated in coal seams, owing to their low mechanical strength. Although shear fractures represent surfaces of mechanical discontinuity, shear fractures are generally impermeable to fluid flow. Moreover, shear fractures tend to destroy the cleat system in the coal. For these reasons, shearing is generally unfavorable for CBM production. Shearing is present sporadically in coals in the Arkoma Basin,

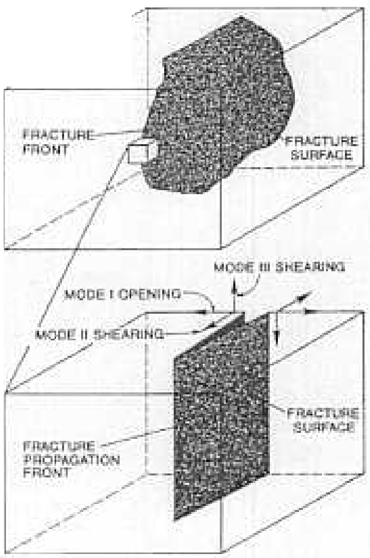


Figure 8 - Face cleat apparently forms as a "Mode 1" type extensional fracture. The fracture propogates in the direction of maximum horizontal compressive stress (Pollard and Aydin, 1988).

Geological evidence demonstrates that the fracture network in coal is polyphase—that is, it formed at different times in the geological evolution of the basin, in response to different processes. Accordingly, the timing and mechanism of various cleat sets may be different. Some fracture sets may form via volume-loss shrinkage (e.g., shrinkage fractures in vitrain), some may form via brittle mechanical failure. Contextual evidence suggests that face cleat forms by processes 1 and 2b acting simultaneously, which implies that the formation of the fractures is abetted by volumetric shrinkage of the coal matrix and generation of hydrocarbon overpressure (during maturation). A preferred orientation to these fractures is imparted by whatever ambient stresses are acting on the coal at the time. By inference, one of the two processes acting alone or in succession would not produce the same result. In other cases, fractures may form as a result of two processes occurring in sequence. For example, an orthogonal set of face and butt cleats may form as a result of Process 1 being followed by process 2c.

PRODUCTION OF GAS FROM SORBED GAS RESERVOIRS

<u>General Production Characteristics of Sorbed Gas Reservoirs</u>

Production of gas from coal bed reservoirs occurs in a sequence of three sequential steps: 1) Desorption, 2) Diffusion through the matrix blocks, and 3) Darcy flow through the fracture network (Figure 9). During actual production, however, the mass transfer of methane is effected in the reverse order: Darcy flow, followed by diffusion, followed by desorption (Figure 10). Specifically, fluid pressure of the free fluid phase in the reservoir, is reduced, either by pumping water out of the fractures or by releasing gas, thus creating a zone of low pressure near the well bore. Free fluids in the reservoir fracture network will begin to flow down the pressure gradient towards this zone. Assuming that the permeability is not too high, this results in an expanding zone of reduced fluid pressure within the fracture network. The progressive decrease in effective pressure in the fractures then allows a net flux methane from the matrix into the fractures. The progressive loss of free methane into the fracture network allows, in turn, a net flux of methane from sorbed to desorbed state.

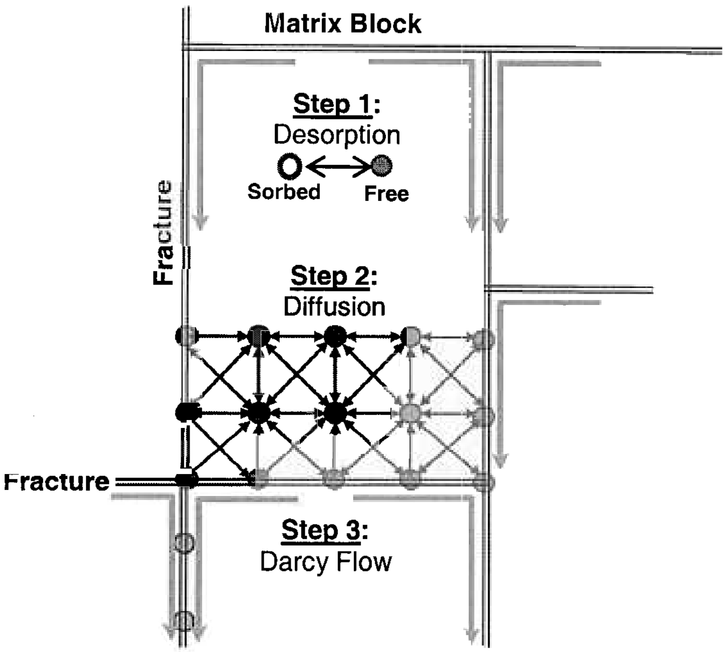


Figure 9 - Diagram representing the mass transport of methane through a sorbed gas reservoir

The speed with which these processes occur influences the gas production profiles of sorbed gas reservoirs. Desorption (Step #1) is by far the most rapid process, requiring less than 1 second but the relative speed of steps #2 (Diffusion) and #3 (Fracture Flow) will depend on: 1) diffusivity rate, 2) fracture spacing, and 3) fracture permeability. For coal bed reservoirs, which tend to have very short path lengths for diffusion—based on cleat spacing being on the order of 0.5-2 cm in most cases, the sorbed gas in the matrix may be considered to be always at equilibrium with the free gas in the adjacent cleat. For shales, however, where the fracture spacing is considerably larger, this same assumption cannot be made.

Gas and water production curves for sorbed gas reservoirs can also vary substantially depending on whether there is free gas initially present in the fracture system (Figure 10; Figure 11). If the reservoir is initially gas saturated, gas production rates should decline with time, just as in a normal reservoir, owing to the progressive loss of pressure drive. A "negative decline" (i.e. increasing rate) indicates increasing permeability to gas flow. This can represent either an increase in relative permeability as gas saturation increases or, (in the case of coal gas reservoirs) an increase in absolute permeability due to matrix shrinkage. All these phenomena may be inferred for production from Arkoma Basin coals.

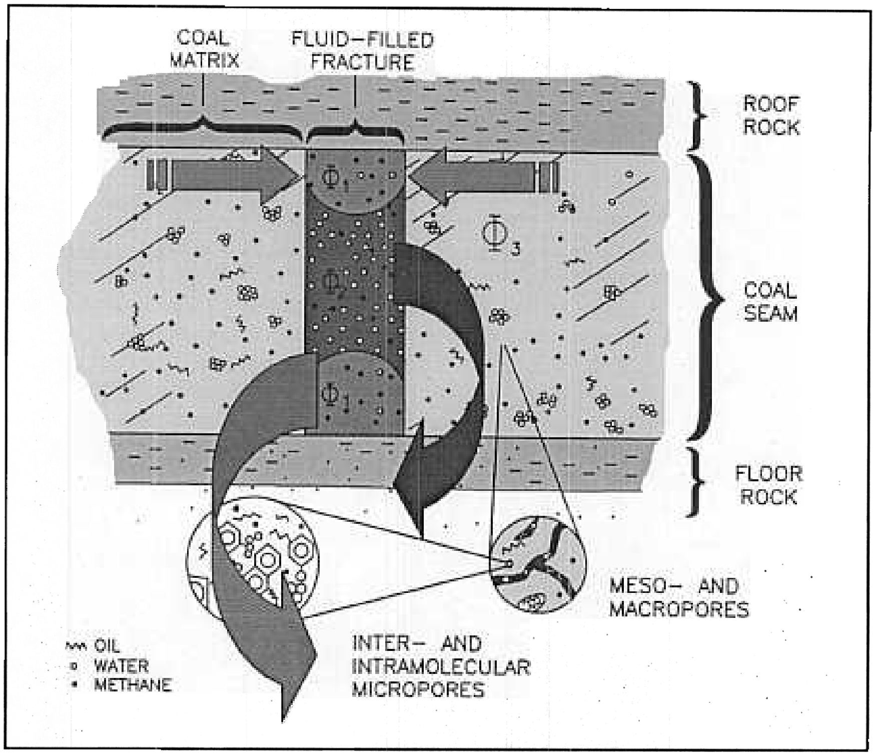


Figure 10 - Representation of the dynamics of production from sorbed gas reservoirs. Most of the gas-in-place is initially stored in molecular-scale "microporsity" within the organic matter (Φ_1), and moves via diffusion to a fracture, then flows toward a production well. Fracture porosity is initially filled with an water (Φ_2) or gas (Φ_3) or a combination of the two.

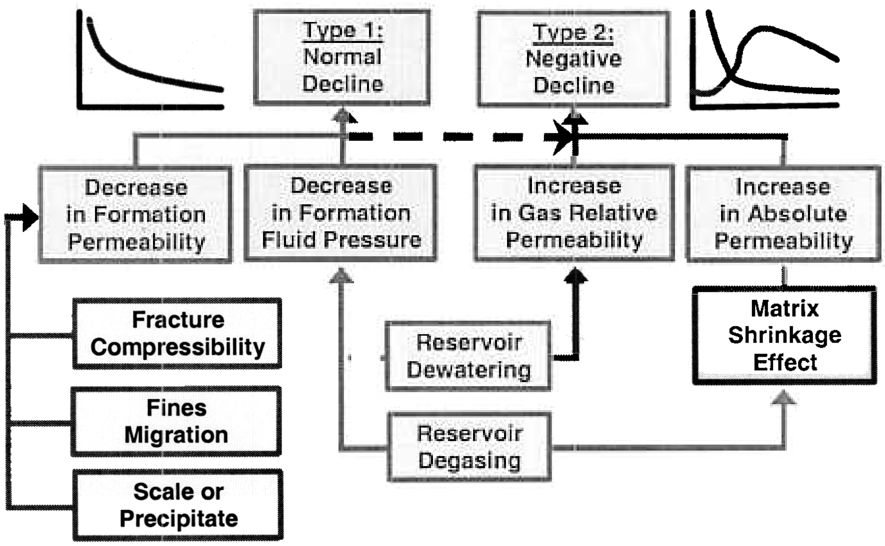


Figure 11 – Normal decline and negative decline profiles are both observed in unconventional reservoirs, depending on the initial gas saturation and changes in permeability with time. High initial gas saturation gives rise to normal decline profile. Negative decline implies increasing relative or absolute permeability, and occurs where the reservoir is initially water saturated. Matrix shrinkage effect probably occurs only in coal gas reservoirs.

Production Characteristics of Arkoma Basin Coal Gas Wells

Coal gas wells from the Arkoma Basin may exhibit either high initial gas production rates, with relatively rapid decline, with little or no initial water production, or low initial gas rates with moderate to high initial water rates. On a per well basis, water rates may range from 0 to more than 1,800 BWPD. For wells having negative decline, gas rates will increase until a peak rate is achieved, although the reservoir behavior and the influence of offset wells may create a flat production profile or an early decline in gas rate. In contrast with coal gas wells in other basins, Arkoma Basin wells tend to reach peak gas production rates very quickly—typically within a few months of initial production (Figure 12).

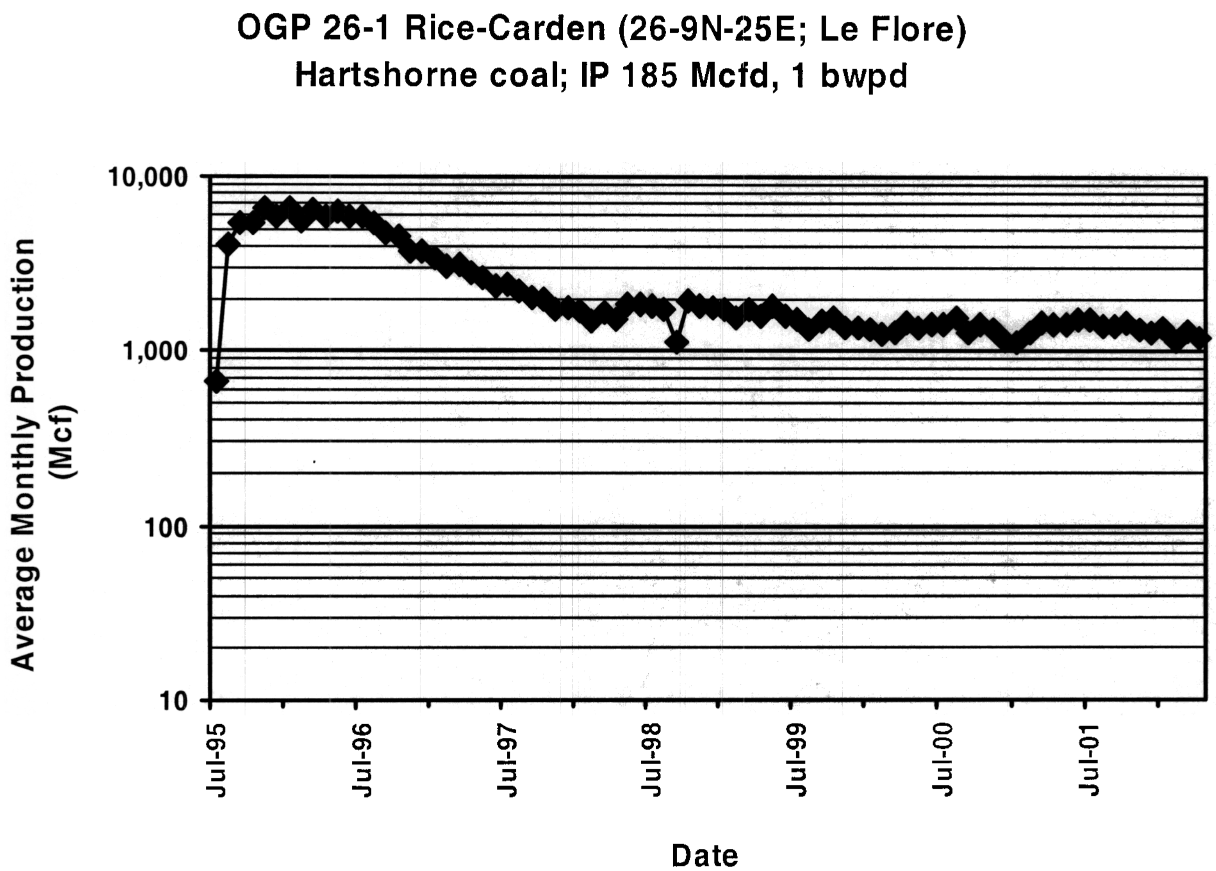
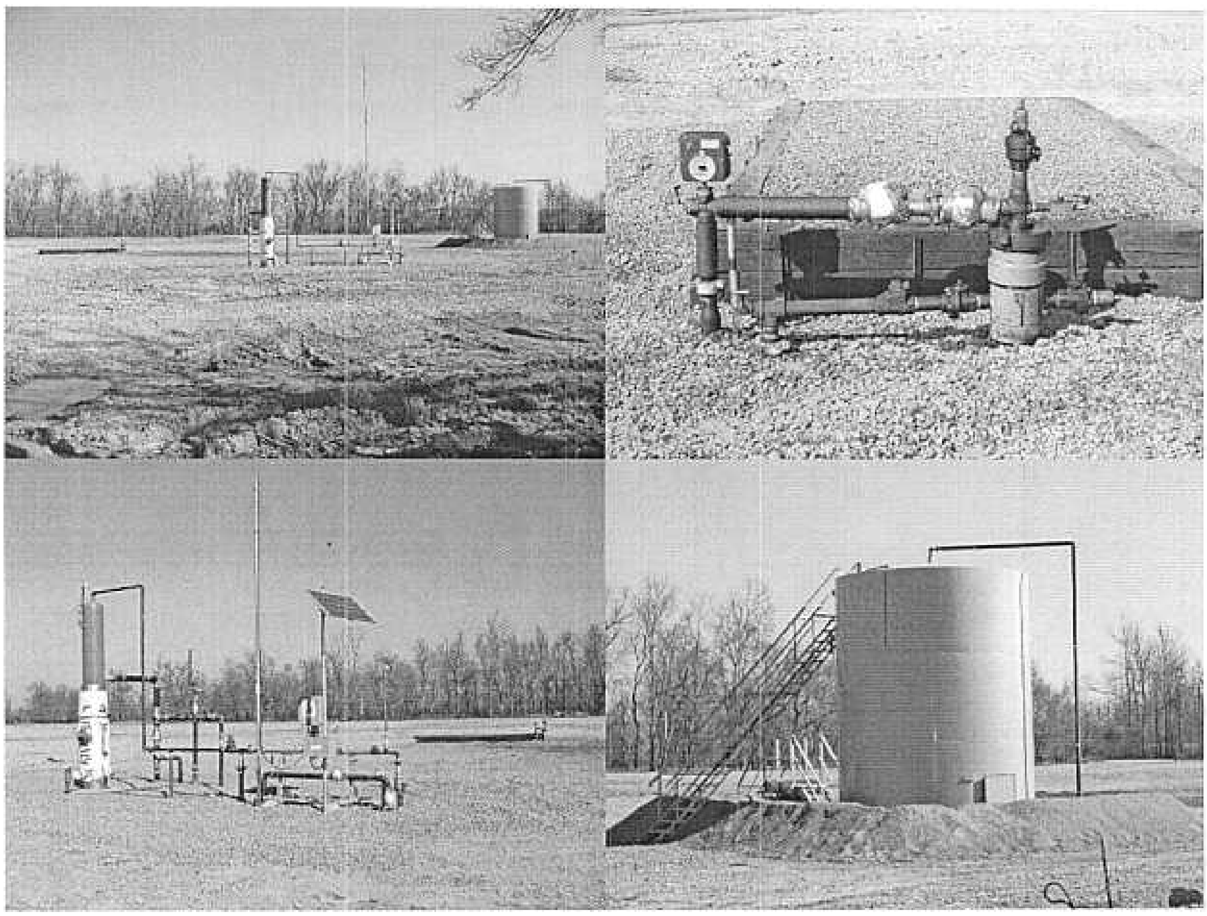


Figure 12 – Example production curve for Arkoma basin coal gas well (vertical completion).

Stop 3. El Paso Production Company 4-14H Wood horizontal CBM well

Location: SH NW¼ Sec. 14, T.6N., R.25E., Le Flore County, Oklahoma.

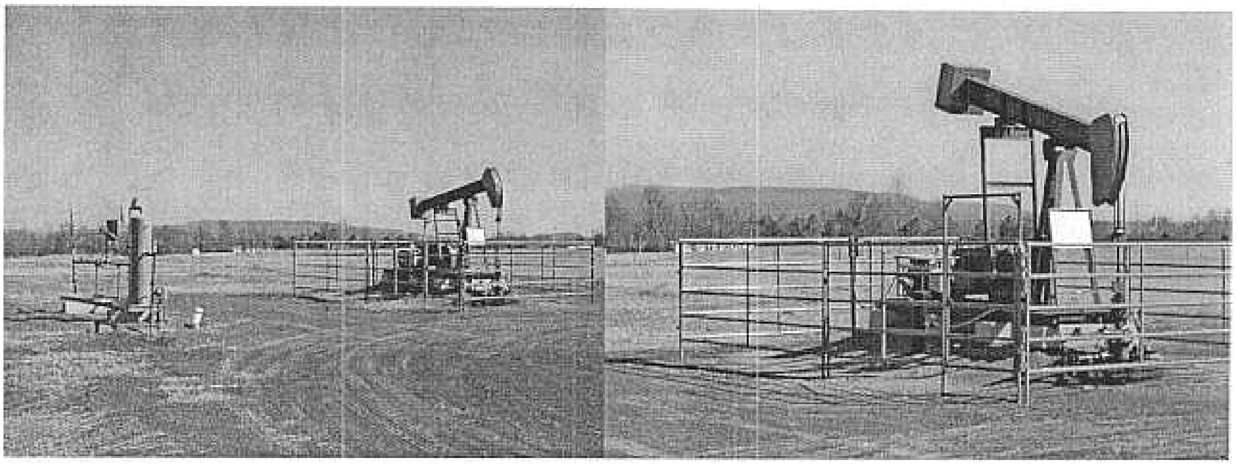
Introduction: The 4-14H Wood well was completed on February 27, 2004 with IP 145 Mcfd and 50 Bwpd. Production will increase when water production decreases. The casing shoe is at 2,323 ft with a surface displacement of 438 ft. The Lower Hartshorne coal was encountered at 2,246 ft measured depth (2,084 ft vertical depth; 350 ft surface displacement). Lateral length is El Paso's current record of 3,213 ft (100% in coal). The lateral was drilled updip at 92.5° (2.5° above horizontal). The total surface displacement is 3,651 ft.

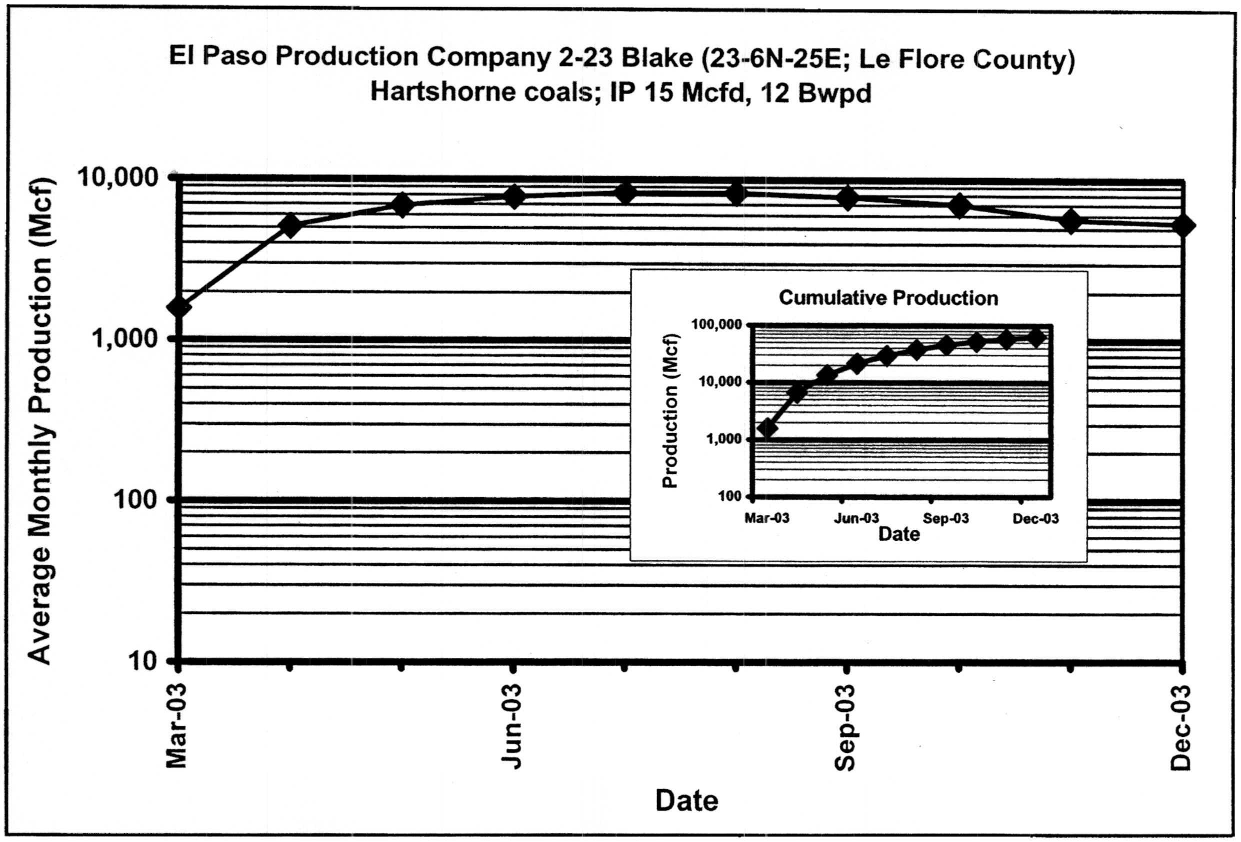


Stop 4. El Paso Production Company 2-23 Blake vertical coalbed-methane well

Location: NW¼ SW¼ NE¼ Sec. 23, T.6N., R.25E., Le Flore County, Oklahoma.

Introduction: The 2-23 Blake well (API 35-079-21423) was completed on February 10, 2003. Perforations were in the Upper Hartshorne coal (1,757-1,759 ft), middle Hartshorne coal (1,798-1,810 ft), and Lower Hartshorne coal (1,870-1,875 ft). Initial potential gas rate was 15 Mcfd; initial produced water rate was 12 Bwpd.

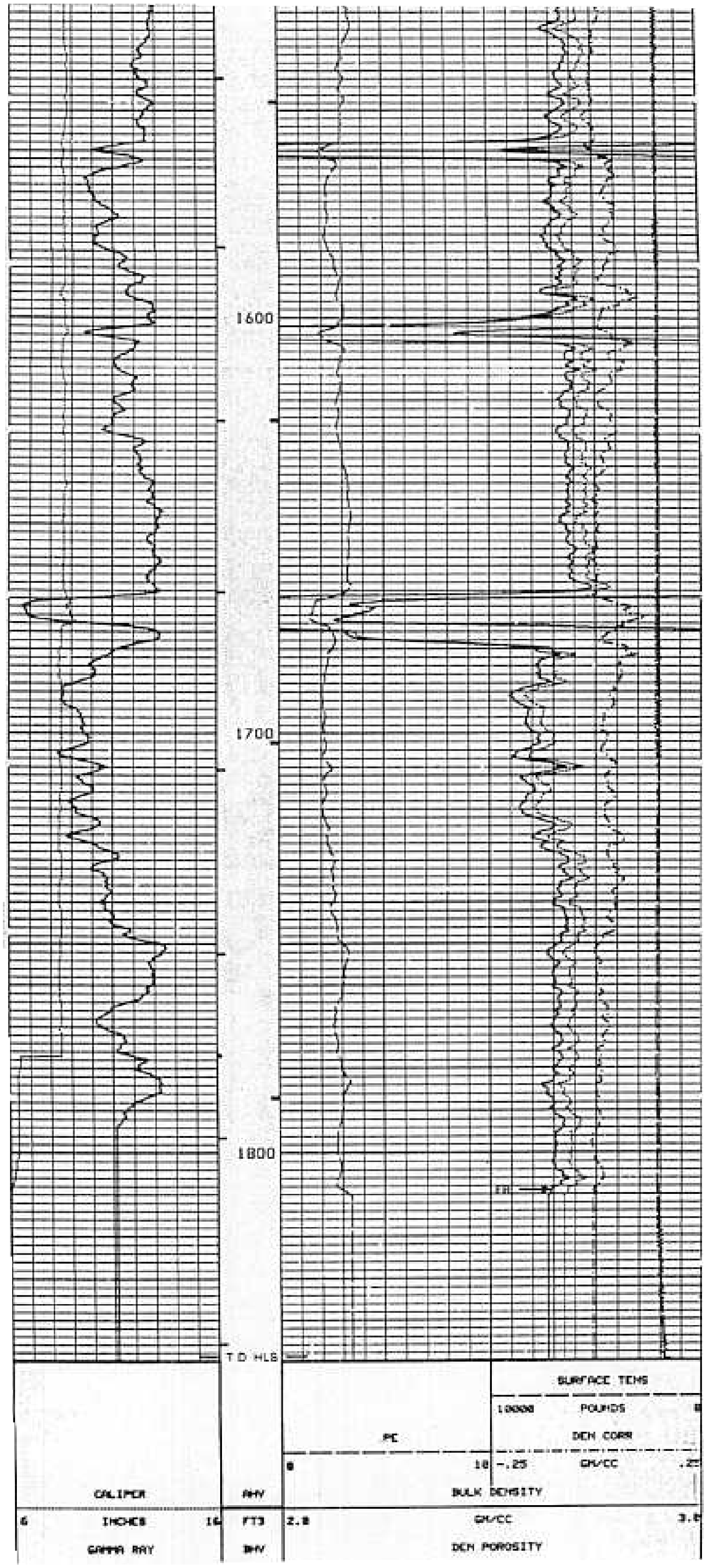




An electric log was not available for the El Paso Production Company 2-23 Blake well.

Electric log from
Okland Oil Co.
1-23 Blake well
(API 35-079-20846)
C NW¼ SE¼
Sec. 23, T.6N., R.25E.
Completed 6/26/92
Upper Hartshorne coal
1,558-1,561 ft
Middle Hartshorne coal
1,602-1,605 ft
Lower Hartshorne coal
1,667-1,674 ft

IP 30 Mcfd, 8 Bwpd
ISIP 175
FTP 50



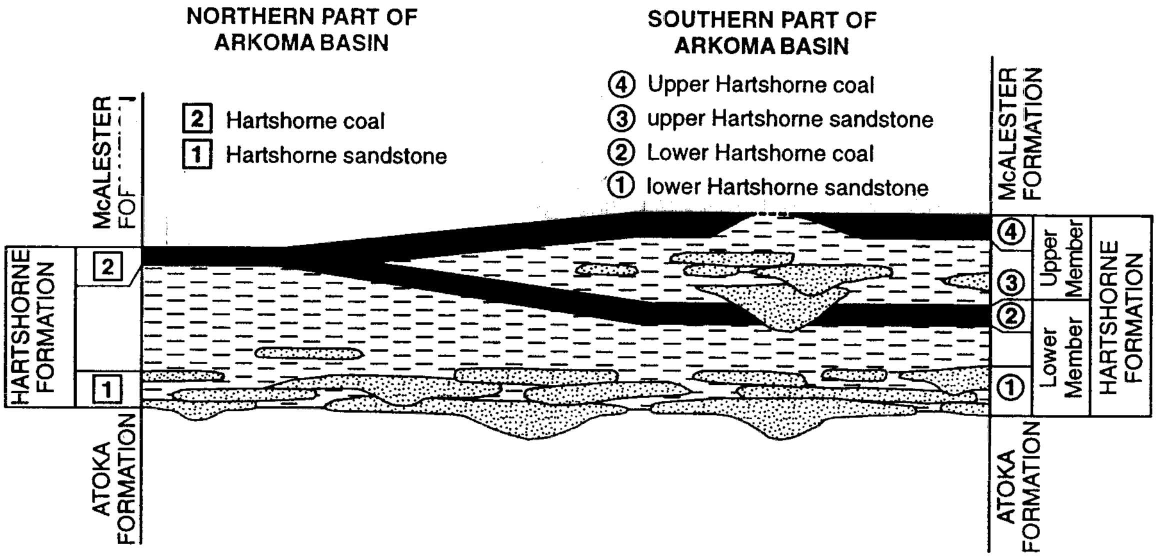
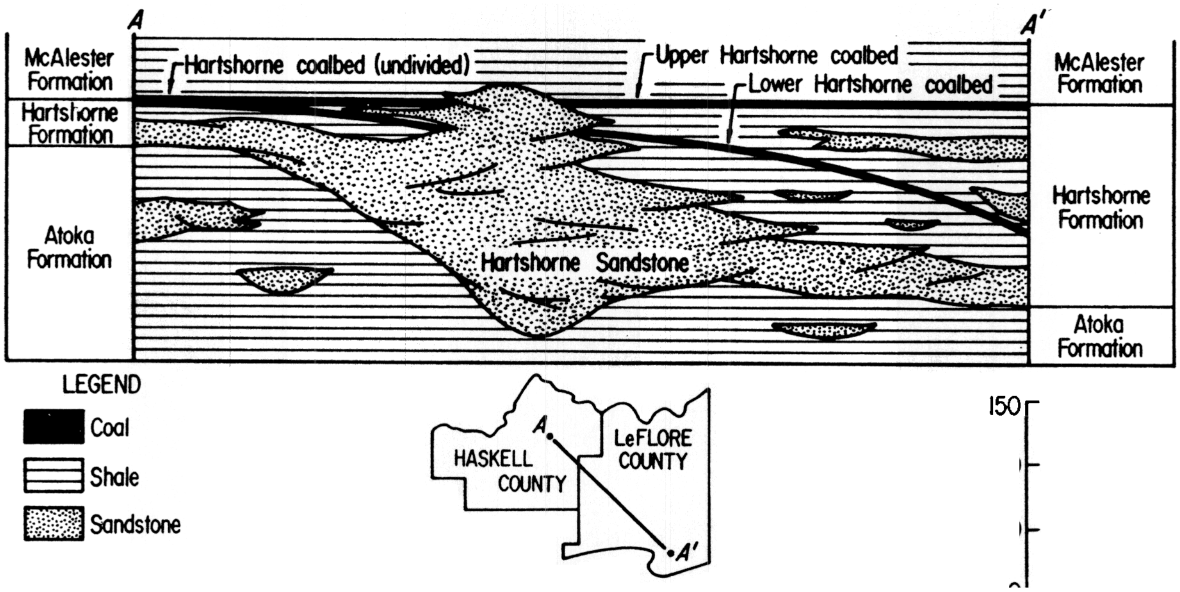
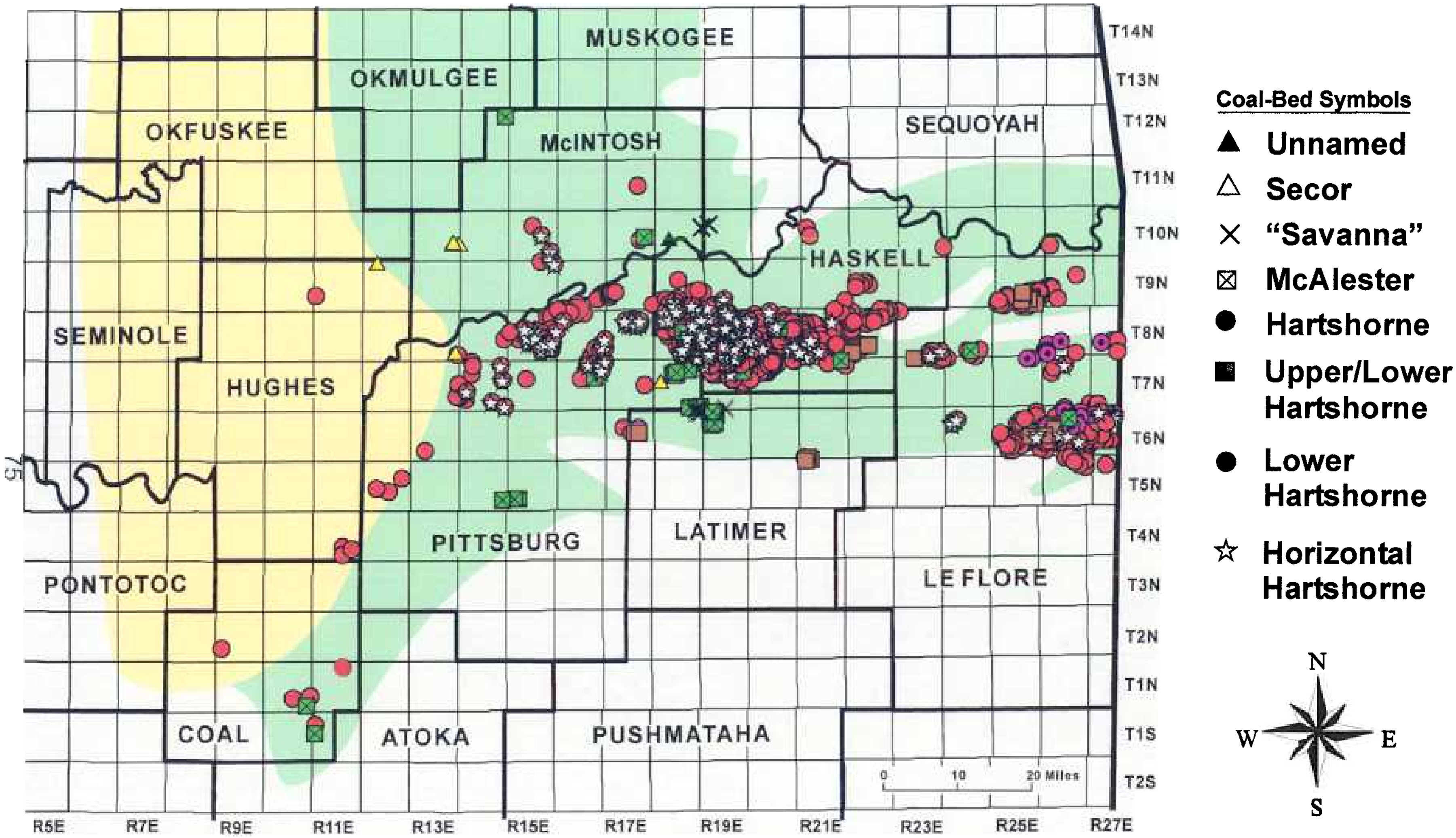


Figure 4. General relationship of different stratigraphic units (formal and informal) that constitute the Hartshorne Formation in the northern and southern parts of the Arkoma basin in Oklahoma. Note: Locally (including areas within the field-trip area) the Upper Hartshorne coal merges with the Lower Hartshorne coal, or the Upper Member of the Hartshorne Formation appears to pinch out. (From Hemish and Suneson, 1997, fig. 4.)

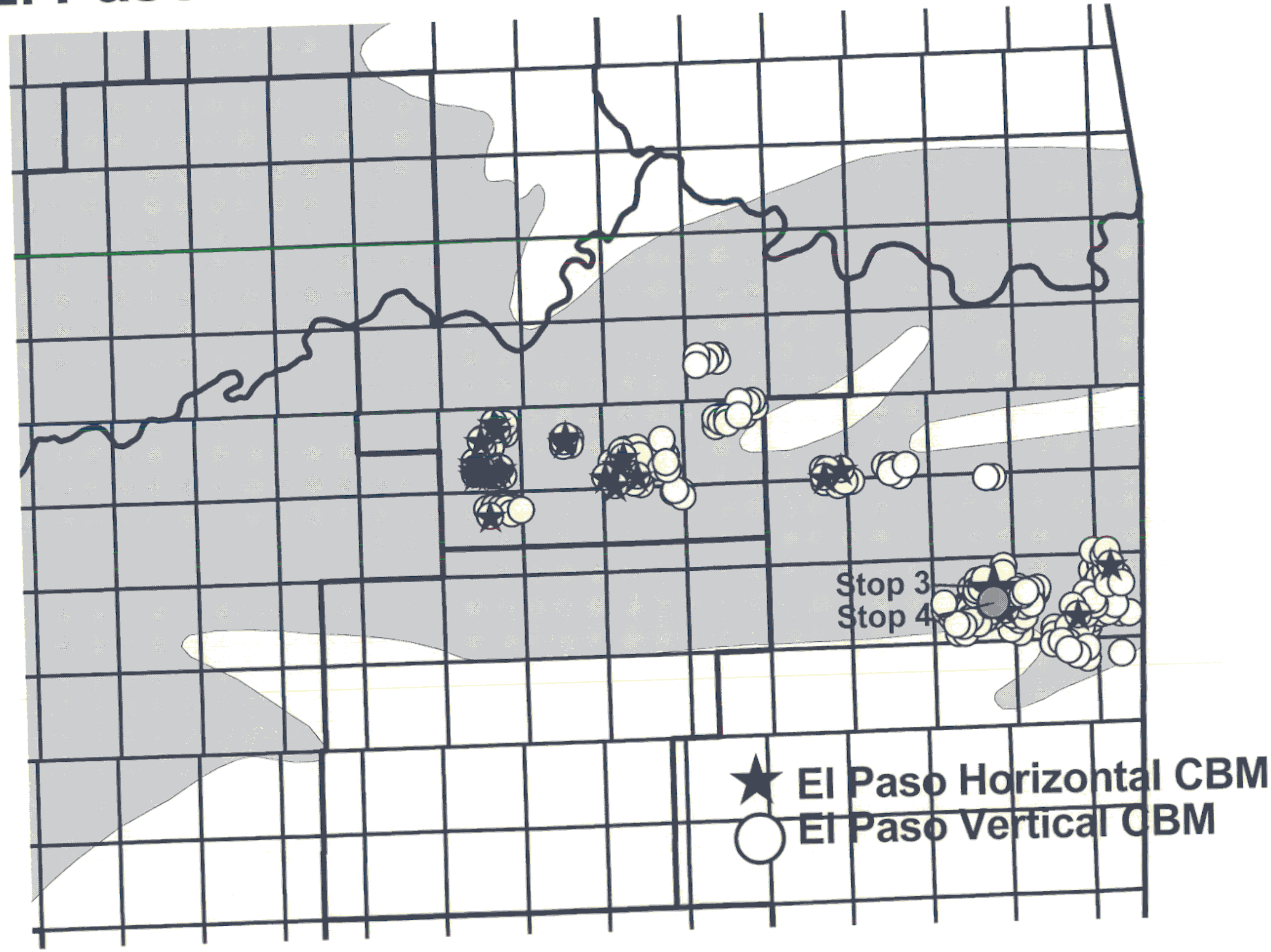
From Suneson (1998, Figure 4).





MUSKOGEE
OKMULGEE
OKFUSKEE
McINTOSH
SEQUOYAH
HASKELL
SEMINOLE
HUGHES
PITTSBURG
LATIMER
LE FLORE
PONTOTOC
COAL
ATOKA
PUSHMATAHA
T14N
T13N
T12N
T11N
T10N
T9N
T8N
T7N
T6N
T5N
T4N
T3N
T2N
T1N
T1S
T2S
R5E
R7E
R9E
R11E
R13E
R15E
R17E
R19E
R21E
R23E
R25E
R27E
75
0
10
20 Miles
Coal-Bed Symbols
Unnamed
Secor
"Savanna"
McAlester
Hartshorne
Upper/Lower Hartshorne
Lower Hartshorne
Horizontal Hartshorne
N
S
W
E

El Paso Production Company CBM Wells



Lunch and overlook at Heavener Runestone State Park. Le Flore County, NE¼ Section 20, T.5N., R.26E.

Emphasis: View location of Howe Coal Company Howe No. 1 underground coal mine, Heavener anticline, and Pine Mountain syncline (Stop 6). Reclaimed surface coal mines in Lower Hartshorne coal can be seen west and southwest from the overlook.

Text from Suneson and Hemish, 1994, p. 93-99.

STOP 17A

Savanna Sandstone and Heavener Runestone

Location: SW¼NE¼SE¼SE¼ sec. 17, T. 5 N., R. 26 E., Le Flore County

The Savanna Formation includes all strata from the top of the youngest unnamed shale unit in the McAlester Formation to the base of the Bluejacket Sandstone Member of the Boggy Formation. The Savanna Sandstone (Savanna Formation) was defined originally by Taff (1899) in the vicinity of Savanna, Pittsburg County, Oklahoma. He described the Savanna as "a series of sandstones and shales about 1,150 feet thick" (Taff, 1899, p. 437). The boundaries of the Savanna have been redefined at various times in the past (Fig. 5), which makes it confusing to read about certain beds in the older literature.

In the field-trip area the Savanna Formation is ~1,700 ft thick and consists predominantly of pale yellowish brown, to olive gray, to medium dark gray shales and

Measured Section, Stop 17A

Savanna Formation (Savanna sandstone #2)

SW¼NE¼SE¼SE¼ sec. 17, T. 5 N., R. 26 E., Le Flore County. Measured ~60 ft northeast from foot bridge above waterfall, just above runestone shelter house, and in bluff west of waterfall in Heavener Runestone State Park.

	Thickness (feet)
KREBS GROUP:	
SAVANNA FORMATION:	
5. Shale, dark gray (N3) to grayish black (N2), weathers light brown (5YR5/6) to moderate yellowish brown (10YR5/4), brittle, breaks into small flakes on the outcrop, contains dark yellowish orange (10YR6/6) clay-ironstone concretions, top covered, basal contact sharp	3.0
4. Sandstone, grayish orange (10YR7/4) to moderate yellowish brown (10YR5/4), very fine grained, shaly, very thin to thin-bedded, wavy-, parallel-bedded; contains small-scale scour features; ripple-marked; includes abundant dusky brown (5YR2/2) carbonized plant fragments on stratification surfaces	1.5
3. Sandstone, light olive gray (5Y5/2) with moderate reddish brown (10R4/6) and moderate yellowish brown (10YR5/4) weathered surfaces, very fine grained, noncalcareous; mostly thin bedded and parallel-, wavy- to flat-bedded; parting surfaces commonly display interference ripple marks; includes a 10-in.-thick deformed bed containing flow rolls near the middle of the unit; base juts out over less resistant underlying strata	13.4
2. Siltstone, interstratified with very fine grained sandstone and shale, medium dark gray (N4), weathers brownish gray (5YR4/1), very thin bedded to laminated, wavy- to lenticular-bedded, obscurely ripple marked, trace fossils and black comminuted plant material on bedding surfaces, unit coarsens upward, heterolithic throughout, grades into underlying unit	17.0
1. Shale, dark gray (N3) to olive black (5Y2/1), oxidized moderate reddish brown (10R4/6) in part, noncalcareous, concretionary structures abundant; base covered	3.5
Total thickness of section	38.4

STOP 17A

Savanna Formation (Savanna sandstone #2)

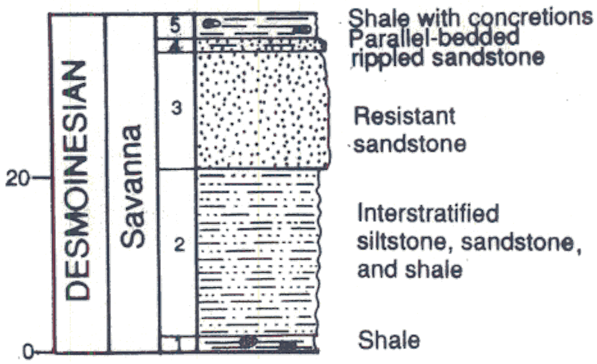


Figure 61. Graphic columnar section of part of the Savanna Formation (Savanna sandstone #2) at Stop 17A.

seven mappable, moderate brown, to grayish orange, to moderate reddish brown, very fine to fine-grained, noncalcareous sandstone units. In this report the seven sandstones are referred to informally as "#1 sandstone of the Savanna Formation" (oldest) through "#7 sandstone of the Savanna Formation" (youngest). The sandstones are massive to thin-bedded and shaly, commonly cross bedded and ripple marked, and in places they contain abundant soft-sediment deformation features. Sole marks (flutes, grooves, brush and prod marks, load casts, and trace fossils) at the base of some sandstone beds are common locally (Hemish, 1991,1992; Hemish and Mazengarb, 1992; Hemish and Suneson, 1993,1994; Hemish and others, 1990a,b,c).

The Savanna Formation includes two thin marine limestones. One is at the base (see Stops 1A and 1B) and the other is ~170 ft higher stratigraphically. They have been correlated tentatively with the Spaniard and Sam Creek Limestones, respectively, of the shelf area to the northwest (Hemish, 1993b).

Figure 62. View of the #2 sandstone of the Savanna Formation in Heavener Runestone State Park. Note the thin, parallel-bedded character of the rock in this vicinity. Many of the characteristics of the sandstone (thin, wavy beds; interference ripples; abundant comminuted plant material; soft-sediment slump features) suggest deposition in a shallow-water, deltaic environment.

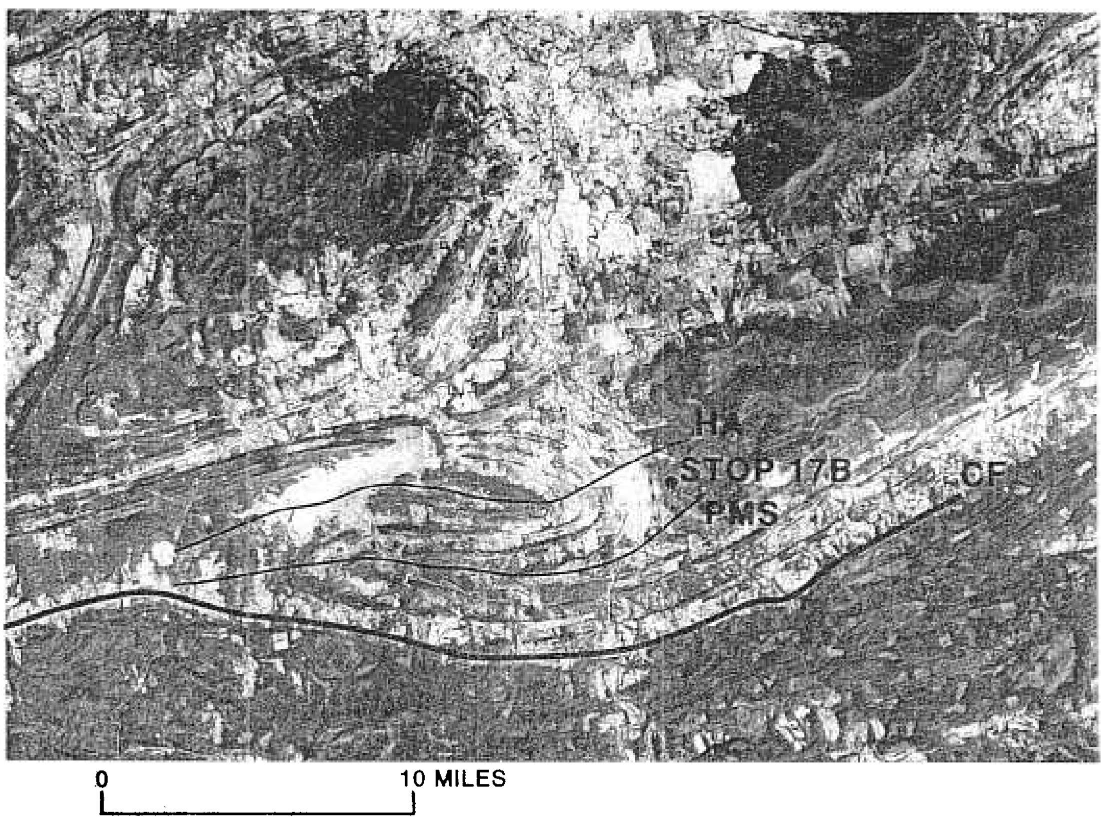


Figure 63. SPOT image of Heavener anticline (HA) and Pine Mountain syncline (PMS). Trace of Choctaw fault (CF) near boundary between mostly cultivated fields to north and mostly forest to south. Poteau Mountain on right side of image, Sugarloaf Mountain in upper right, and Cavanal Mountain in upper left. (Image by SPOT Image Corp. courtesy Dr. P. Jan Cannon, Planetary Data, Tecumseh, Oklahoma.)

The Savanna Formation contains one minable coal (Cavanal coal) in the field-trip area. A thick shale section at the top of the formation underlies the Bluejacket Sandstone Member of the Boggy Formation. The base of the Bluejacket marks the contact between the Savanna and Boggy Formations.

The #1 sandstone of the Savanna Formation crosses the steep, curving road to the park just west of the park boundary. It is a dark yellowish brown, very fine grained, blocky sandstone ~5 ft thick. In the field-trip area, its base marks the contact between the underlying McAlester Formation and the overlying Savanna Formation in the absence of the Spaniard(?) Limestone (see Stop 1A) (Hemish and Suneson, 1993).

The #2 sandstone of the Savanna Formation is well exposed throughout the park. Measured Section, Stop 17A gives a detailed description of the #2 sandstone of the Savanna Formation near the runestone shelter house (Fig. 61). Figure 62 shows the bedding characteristics of the sandstone in the vicinity of the foot trail leading down to the runestone.

Walk up road to the overlook.

STOP 17B

View of Heavener Anticline

On a clear day, the Heavener anticline is visible to the west from the overlook parking area. The anticline is marked by folded, tree-covered ridges of sandstones in the upper part of the Atoka Formation and in the Hartshorne Formation (Fig. 63). The shale intervals that separate the sandstones underlie the mostly cultivated valleys between the ridges.

The relatively high, irregular topography in the core of the anticline is formed by the informally named sandstone of Glendale (Hemish and Suneson, 1993). This unit is the oldest Atoka sandstone exposed in the southern part of the Arkoma Basin. It consists of as many as five mappable sandstones, the highest of which is ~2,400 ft below the top of the Atoka Formation. The sandstone of Glendale includes those identified as "Atoka C, E, and F" in the ARCO No. 1 Runestone (sec. 9, T. 6 N., R. 25 E.), as reported to the Oklahoma Corporation Commission (Fig. 64). In general, the strata in this unit dip moderately to steeply away from the axis of the Heavener anticline; locally, however, the beds are overturned.

The clearly curved ridge surrounding the core of the anticline is underlain by the sandstone of Potts Mountain (informal) (Hemish and Suneson, 1993). The top of this unit is ~1,000 ft below the top of the Atoka Formation and is called "Atoka B" in the ARCO No. 1 Runestone well. There are excellent exposures of this sandstone at the Wister Dam spillway (see Stop 3).

The next curved, tree-covered ridge marks the sandstone of Horseshoe Ridge (informal) (Hemish and Suneson, 1993). It is ~500 ft below the top of the Atoka Formation and correlates with the "Atoka A" in the ARCO No. 1 Runestone well. Although exposures are common along the top of the ridge, they are typically poor. Good exposures (road cut along U.S. 270 ~1 mi west of Heavener; outcrops west of dirt road in NE¼ sec. 23, T. 5 N., R. 24 E.) show clear evidence of channeling.

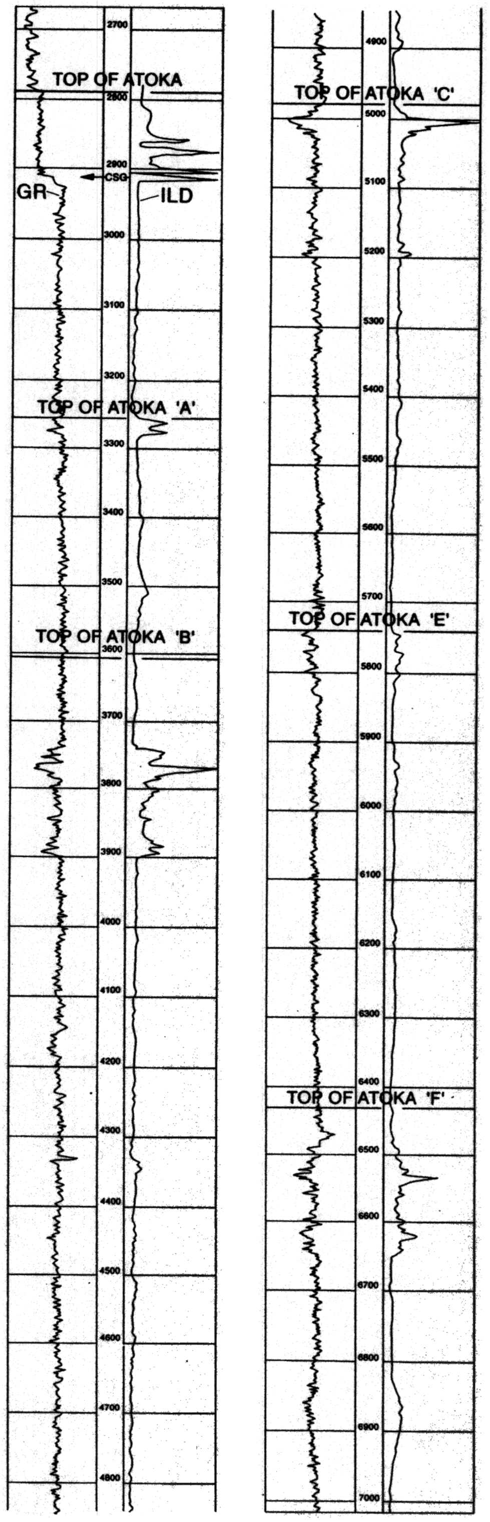


Figure 64. Gamma-ray and resistivity logs of ARCO No. 1 Runestone showing depth, thickness, and log character of sandstones in upper part of Atoka Formation. (Note: Strata are subhorizontal in this well.)

The Heavener Runestone

The Heavener runestone is one of the most visited tourist attractions in southeastern Oklahoma. It is also, perhaps, one of the most controversial. The controversy centers on when the runes were carved into the piece of Savanna sandstone as well as on their translation. The best discussion of what runes are is that of Shirk (1959, p. 365):

> Runes are characters used by Teutonic tribes of northwestern Europe. There are three classes: Anglo-Saxon, German, and Scandinavian. There are not great differences in the form of the characters as used by the three, just as today many languages use the identical alphabet form. In Anglo-Saxon the word *run* means secret and the word *runa* means magician. The use of runes was limited to a small class or profession of priests and magicians. With the introduction of Christianity in northwestern Europe, the use of runes was condemned; and the Church insisted upon the use of the Latin alphabet....Their earliest use was in the 4th century and the latest use was in the 13th in Scandinavia. Their use in England was limited to the period from the 6th to the middle of the 10th centuries.

According to local oral history, the inscriptions were first discovered in the 1830s by a Choctaw hunting party (Farley, 1973, 1990). The stone was rediscovered by early white settlers several times in the late 1800s and early 1900s, when it was known locally as "Indian Rock." In 1923, Carl F. Kemmerer sent a copy of the inscriptions to the Smithsonian Institution, which responded that the characters are runic, but that "whoever made the inscription had a Scandinavian grammar as a guide" (Farley, 1990). In subsequent years, the stone was apparently "lost" until Gloria Farley, a longtime resident of Heavener who had visited the stone with Kemmerer in 1928, rediscovered it once again in 1951. It is through her persistent efforts that foreign experts in runic inscriptions have studied what is now known as the Heavener runestone and that a state park was established in October 1970.

Four ideas have been proposed to explain the origin of the inscriptions. Two support the claim that the runes document Viking exploration of southeastern Oklahoma in about 1000 A.D. One suggests that the runes were carved in the early 1700s, and another, that the runes are of even more recent (1800s or 1900s) origin.

Shirk (1959) was the first to suggest that the Heavener runes are quite ancient; his description is based largely on the interpretations of Mr. Frederick J. Pohl, "a recognized scholar and student of Norse and Viking matters" (p. 364). The eight characters are from an established alphabet of runes: the second and last are "Medieval runes" that were developed and used in Scandinavia after about 900 A.D.; the other characters are "Ancient runes" that are part of an alphabet that was fully developed by about 500 A.D. (Landsverk, 1970). Pohl attached little significance to the different alphabets. The closest translation of the characters into Latin alphabet would be: GNOMEDAL. GNOME has been translated as "sun dial," "monument," or "boundary marker." DAL translates as "valley." GNOMEDAL could therefore mean "monument valley" (not to be confused with the more famous Monument Valley in Arizona) or "valley of the boundary marker" (Shirk, 1959, p. 366).

Alternatively, each character could have a "rune meaning" (an individual word or thought), in which case the Heavener characters could translate as: GIVE SUPPLICATION GOD MAN BEFORE DAY HAS SET (Shirk, 1959, p. 366).

Shirk (1959, p. 367) concluded that the Heavener characters are runic and that "the carving must have been done prior to Columbus; and undoubtedly prior to A.D. 1000." However, he left open the possibility, albeit slight, that the inscriptions were carved during the French period of settlement in the Arkansas River Valley.

McRill (1966) offered a substantially different explanation for the origin of the Heavener runes based on the work of Mr. Kaj Monrad, an archivist at the National Museum at Copenhagen, Denmark. The translation GNOMEDAL can be separated into two words. GNOM refers to "an elemental earth spirit, subterranean goblin, a mountain spirit" (McRill, 1966, p. 125). E is a possessive suffix and DAL is "dale" or "valley." GNOMEDAL can therefore be translated as: EARTH SPIRIT'S DALE. Furthermore, Mr. Monrad suggests that the word "gnome" was derived from the Latin word "gnomus," which means "earth-dweller" (McRill, 1966, 126). Such a derivation is significant, he believes, because southeastern Oklahoma was inhabited by a flourishing mound-building culture prior to European exploration.

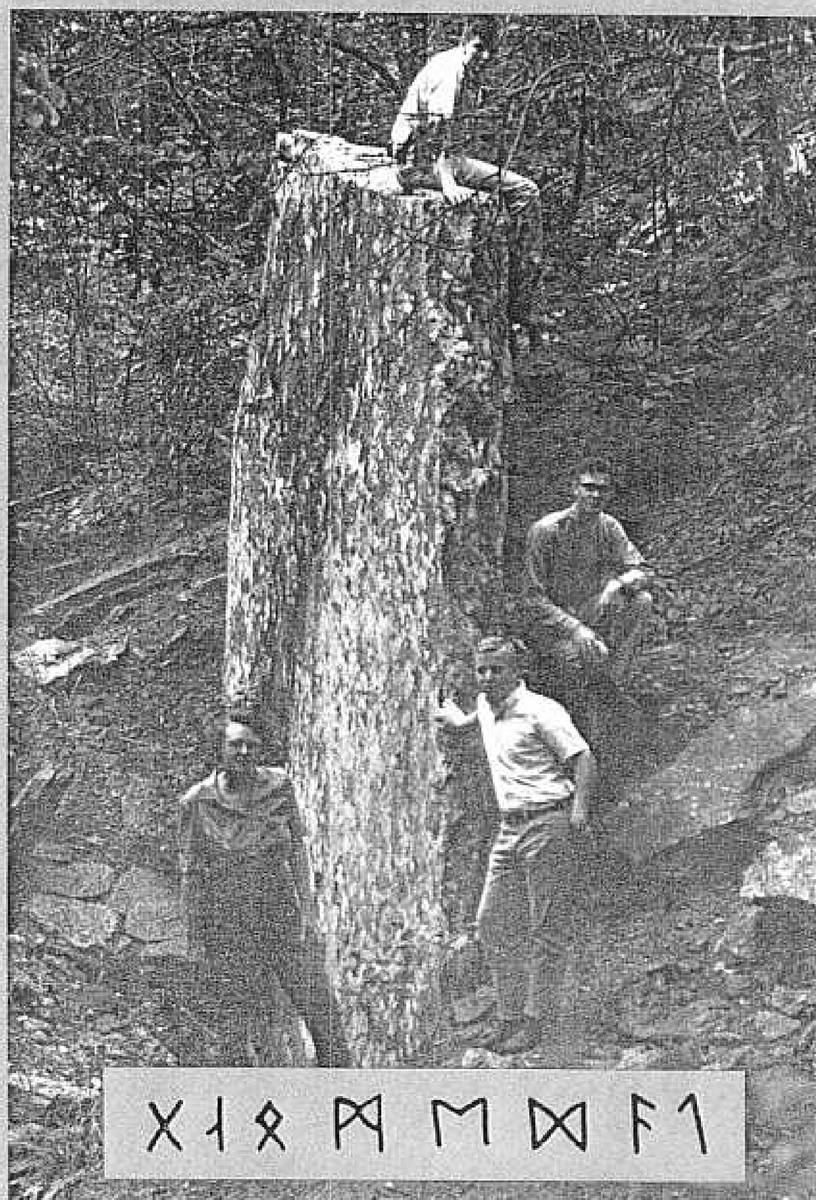
Monrad suggests that the "inscription was cut in the 16th, 17th, or 18th century by a not wholly unlearned man with good knowledge of the eldest runes, as the interest for antiquity had a flowering in the last two mentioned centuries here in Scandinavia" (McRill, 1966, p. 125–126). The first French expeditions came into the Arkansas River Valley about 1718–1720; some of these early colonists were German. Captain Jean Bossu of the French Marines reported (English translation published in 1771) "two German villages...under the supervision of a Swedish captain, Mr. Arntsbourg" (McRill, 1966, p. 127) on the Arkansas River. Furthermore, the idea that the Heavener runestone may be relatively modern is supported by the word *poteau*, the French word for "post." "Could it be that the huge 'post' was carved by Germans in a party under the direction of their learned Swedish captain, describing the valley below and marking their visit to the mountain?" (McRill, 1966, p. 123–124).

The third interpretation of the Heavener runestone is based on the work of Alf Monge, a former U.S. Army cryptographer who was born in Norway (Monge and Landsverk, 1967; Landsverk, 1970). Monge interpreted the runic inscriptions not as letters, but as numbers that were "hidden" in a runic code. He believed the numbers represented a date from the Roman Catholic perpetual calendar, which was in wide use prior to about 1500 A.D., when calendars were first printed annually. Using an auxiliary table known as the "Easter Table," Monge and Landsverk (1967) deduced the date that the Heavener inscription was carved: November 11, 1012 A.D.

The plausibility of such a solution of the runic cryptograph is supported by six other inscriptions found in Oklahoma (Pohl, 1972): Heavener no. 2 (1015 A.D.), Poteau (1017 A.D.), Heavener no. 3 (1022/23 A.D.), Tulsa (1022 A.D.), and Shawnee (1024 A.D.). Landsverk (1970, p. 34) suggests that some of these "dated inscriptions... are so similar in construction that they are most certainly the work of the same runemaster."

Wycoff (1973) (present State Archaeologist) reviewed evidence for the antiquity of the six runestones found in Oklahoma (including the Heavener no. 1 runestone). He suggests that two were probably carved by prehistoric or early historic Native Americans. Based on the character of the inscriptions and hardness of the stone into which they were carved, Wycoff (1973) believes two others were probably cut about ten years before they were found. Another was not present in the 1920s, as reported by a man who grew up near where it was found. Therefore, using other Oklahoma runestones to support the view that the Heavener runestone was carved by Vikings is inadequate. In addition, Wycoff cites several reports that criticize the methodology of the Monge-Landsverk cryptological approach and states that the only people who use it are "those people promoting the cause for Viking explorations in the interior of the United States.... They accept its results because the results match their beliefs" (Wycoff, 1973, p. 28).

Wycoff admits that there is no evidence against a Viking origin for the Heavener runestone, but suggests that it was carved in the 1800s. Fort Smith, 35 miles to the north, was an active trading center and military post visited by people with a European education that "included the study of runic alphabets" (Wycoff, 1973, p. 31). In the 1890s, a resort near Heavener catered to wealthy German and Dutch families. It is possible that the Heavener runestone was carved during an outing and climb of the hill just east of Heavener.



Photograph of the Heavener runestone taken in early 1960s before protective housing was built around it. Runic inscription (shown on inset) is just barely visible in the photo, above and to right of Gloria Farley. Mark Farley on top, Scott Farley behind, and Jim Johnson in front of runestone. (Photograph courtesy of Fran Johnson, The Heavener Ledger, *Heavener, Oklahoma.)*

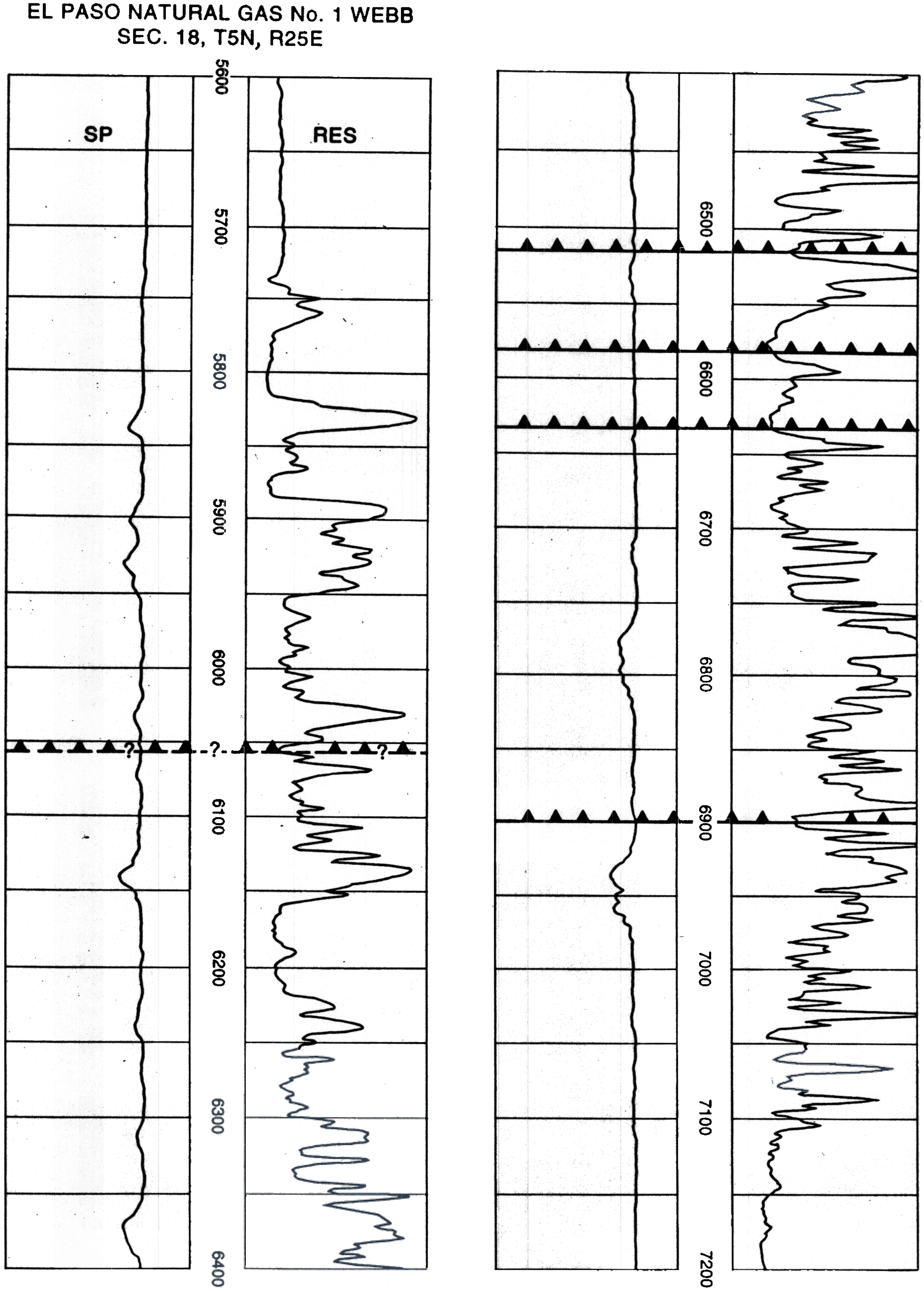


Figure 65. Part of El Paso Natural Gas No. 1 Webb well log showing multiple repetition of beds and interpreted positions of thrust faults.

The outermost curved ridge is formed by the Hartshorne Formation. From this viewpoint, our next stop, the "Heavener road cut" (Stop 18) can be seen. In addition, the strip pit of the Pine Mountain Coal Mine and the reclaimed land adjacent to the pit can be seen.

The Heavener anticline is slightly asymmetric—the sandstones of Glendale and Potts Mountain dip slightly more on the south flank than on the north flank. The sandstone of Horseshoe Ridge is too close to the axis of the Pine Mountain syncline (~2 mi south of the axis of the Heavener anticline) to be useful for determining asymmetry. A brief inspection of two seismic lines across the anticline indicates that the subsurface Spiro sandstone is not folded in a manner similar to that of the strata on the surface.

Several wells have drilled the core of the Heavener anticline (listed in Hemish and Suneson, 1993); the most important for determining the subsurface structure is the El Paso Natural Gas No. 1 Webb (NW¼NE¼ sec. 18, T. 5 N., R. 25 E.). The interval between ~5,700 ft and 7,100 ft shows multiple repetitions of beds (Fig. 65), which suggests thrusting. Tectonic thickening in this interval, evidence for thrust faults elsewhere in the well, and the apparent absence of any major thrust faults at the surface led Hemish and Suneson (1993) to interpret a duplex structure within the Atoka Formation beneath the surface expression of the anticline. They suggest the asymmetry is caused by a south-directed back thrust that is exposed locally at the surface.

		Retrace route to Seventh Street (north-south section-line road).
14.3	~1.2	Turn left (south) on Seventh Street.
15.0	0.7	Turn right (west) on C Street. Enter Heavener, Oklahoma.

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.

15.5	0.5	Turn left (south) on Main Street.
15.55	0.05	Turn right (west) and cross Kansas City Southern railroad tracks.
15.6	0.05	Intersection with U.S. 59/270. Turn left (south).
16.6	1.0	Leave Heavener 7.5′ quadrangle, enter Hontubby 7.5′ quadrangle. Road to Pine Mountain Coal Mine on right.

PINE MOUNTAIN COAL MINE

The Pine Mountain Mine has been operated by the Farrel-Cooper Mining Co. since 1990. The Lower Hartshorne coal is mined here by stripping methods (Fig. 66A,

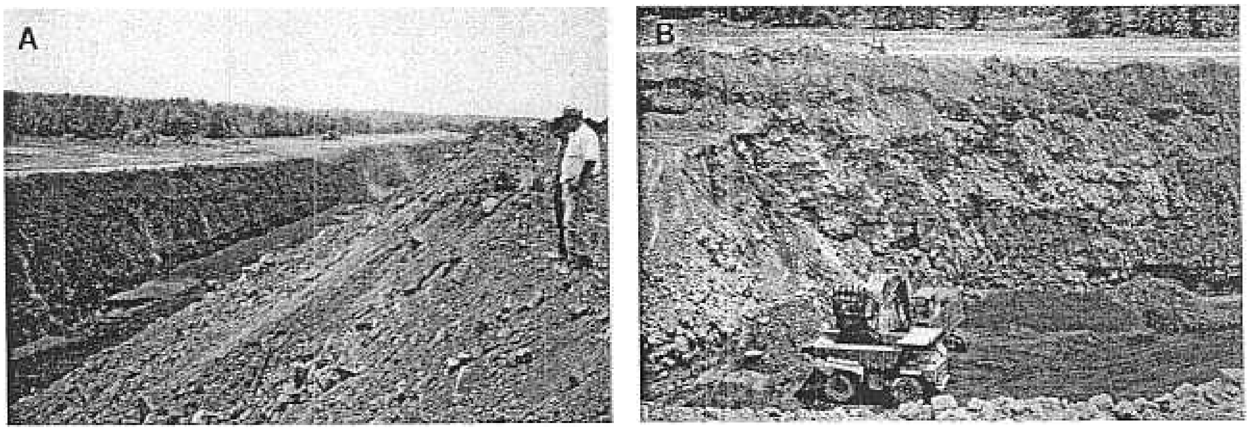


Figure 66. *A*—View of cut and 70-ft highwall in the Pine Mountain Mine. Mine development is progressing toward the treed area. LeRoy Hemish and Bob Cooper (white shirt), Vice President of Farrell-Cooper Mining Co., are standing on spoils that are used for recontouring in Farrell-Cooper's ongoing reclamation program. *B*—Heavy equipment used to load and haul blasted overburden from top of the Lower Hartshorne coal in the Pine Mountain Mine. Overburden consists of sandstones, siltstones, and shales. Casts of tree trunks standing in growth position are common in the unit overlying the coal bed, but none are visible in this photograph.

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 century, about 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 country. 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 McConnel, which was the largest mining interest in the Indian Territory at that time. Production records have been kept by counties only 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.

From Suneson and Hemish (1994, p. 90).

Howe Mine

Irani and others (1972) reported that the low-volatile-bituminous Lower Hartshorne coal (averaging 39 in. thick and 350 ft deep) in the Howe Coal Co. Howe No. 1 mine in Le Flore County (NW¼ sec. 7, T. 5 N., R. 26 E.; operating 1967–71) emitted an average of 1.6 million cubic feet of gas per day (MMCFGPD) in 1971 (an average of 2,191 cubic feet per short ton [CF/ton]). Kissell (1972) described a U.S. Bureau of Mines study of coal-bed permeability and methane-sorption capacity from the Pittsburgh coal (West Virginia), the Pocahontas No. 3 coal (Virginia and West Virginia), and the Hartshorne coal (Oklahoma; Howe No. 1 mine). The gas pressure in the Hartshorne coal increased with horizontal-hole distance to a maximum of 138 PSIG (gauge pressure) at 110 ft (hole 11), with a range of 25–95 PSIG at a distance of 50 ft. The permeability of the Hartshorne coal ranged from 0.08 to 1 md (assuming the sorption capacity to be 0.5). The overburden (thickness of the sedimentary deposit from the surface) was 285 and 700 ft. Kissell (p. 18) concluded that "the values of permeability shown...are for coalbeds that have already been influenced by the mining process and that the permeability of the virgin coalbed was much lower." The Hartshorne coal in Haskell and Le Flore Counties was described as friable and highly fractured, with closely spaced cleats (the numerical value was not indicated). Iannacchione and Puglio (1979, p. 9) concluded that "the friability of the Hartshorne coalbed is due to close spacing of cleat and the frequent occurrence of shear fractures with dips of 45° to 55° within the coalbed." McCulloch and others (1975) reported that friable coals emit more gas during desorption than do blocky coals.

Kissell and others (1973) compared the average gas-emission data from Irani and others (1972) from the Hartshorne coal in the Howe No. 1 mine (2,191 CF/ton) with the gas content of nearby exploration coal-core samples determined by the direct method. The amount of methane from the Hartshorne coal within 1 mi of the Howe mine was 11.1 cm^3/g (355 CF/ton) measured by the direct method (see Diamond and Levine, 1981; Mavor and others, 1995), 10.5 cm^3/g (336 CF/ton) determined by the indirect method, and 11.8 cm^3/g (378 CF/ton) calculated from adsorption data (Kim, 1977). Of seven coals studied by Kissell and others (1973), the ratio (mine emission/direct amount) varied between 6 and 9, with higher emissions from older mines than from newer mines.

Iannacchione and others (1983) reported that the gas production from a five-hole vertical methane-drainage project totaled 5 MMCFG and 101,000 gallons of water from 500–600 ft deep in the Howe mine over a 3-year period.

From Andrews and others (1998, p. 41-42).

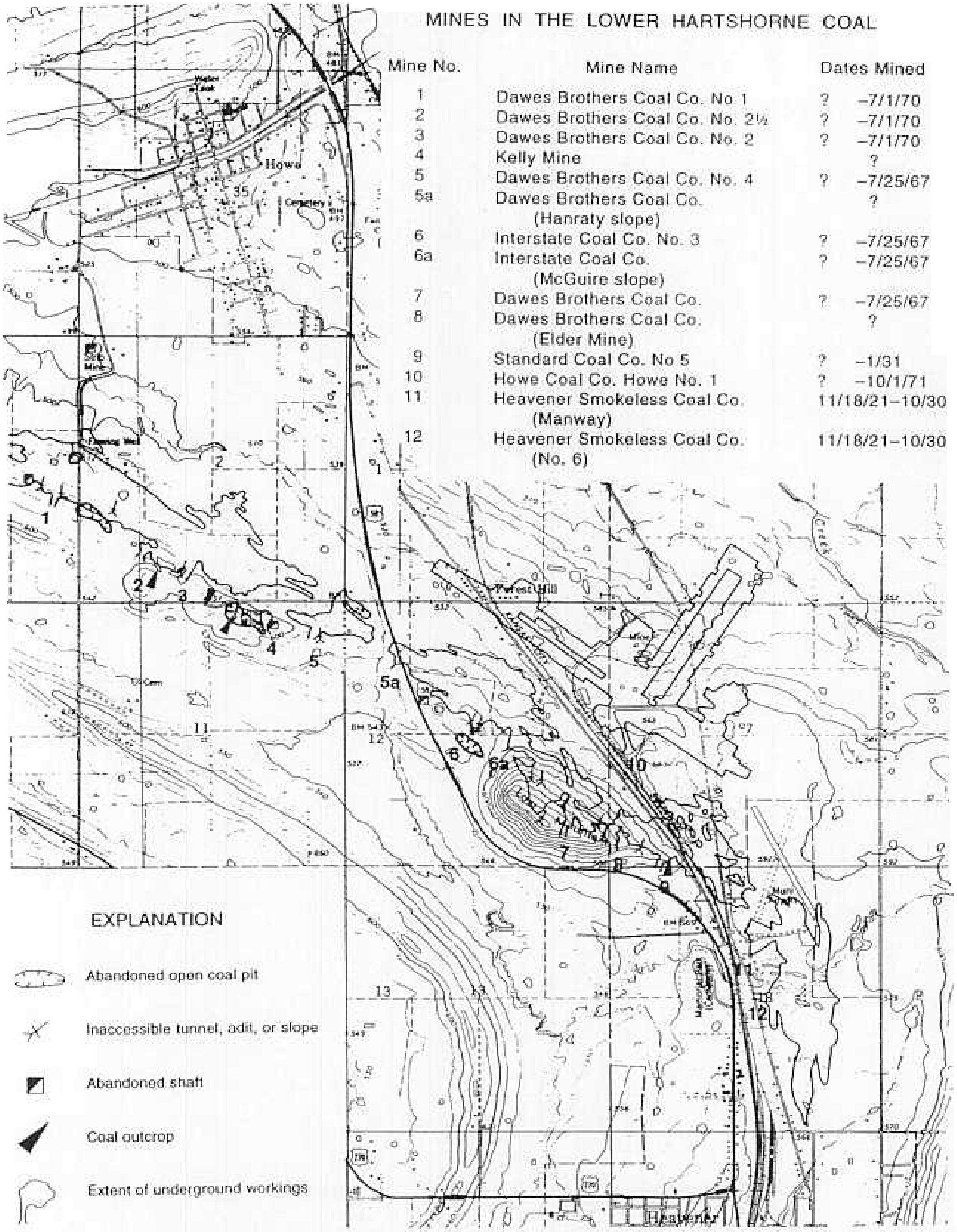
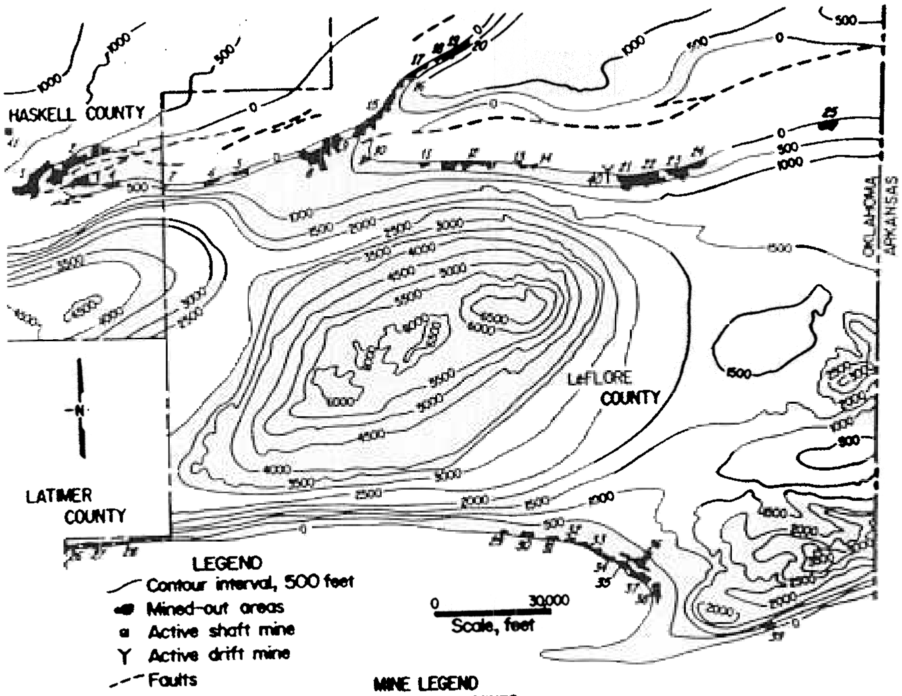


Figure 60. Locations of shafts, adits, and abandoned underground mine workings in the Lost Mountain area, north of Heavener (modified from Donica, 1978, pl. 1).

From Suneson and Hemish (1994, page 92).



MINE LEGEND

INACTIVE DEEP MINES

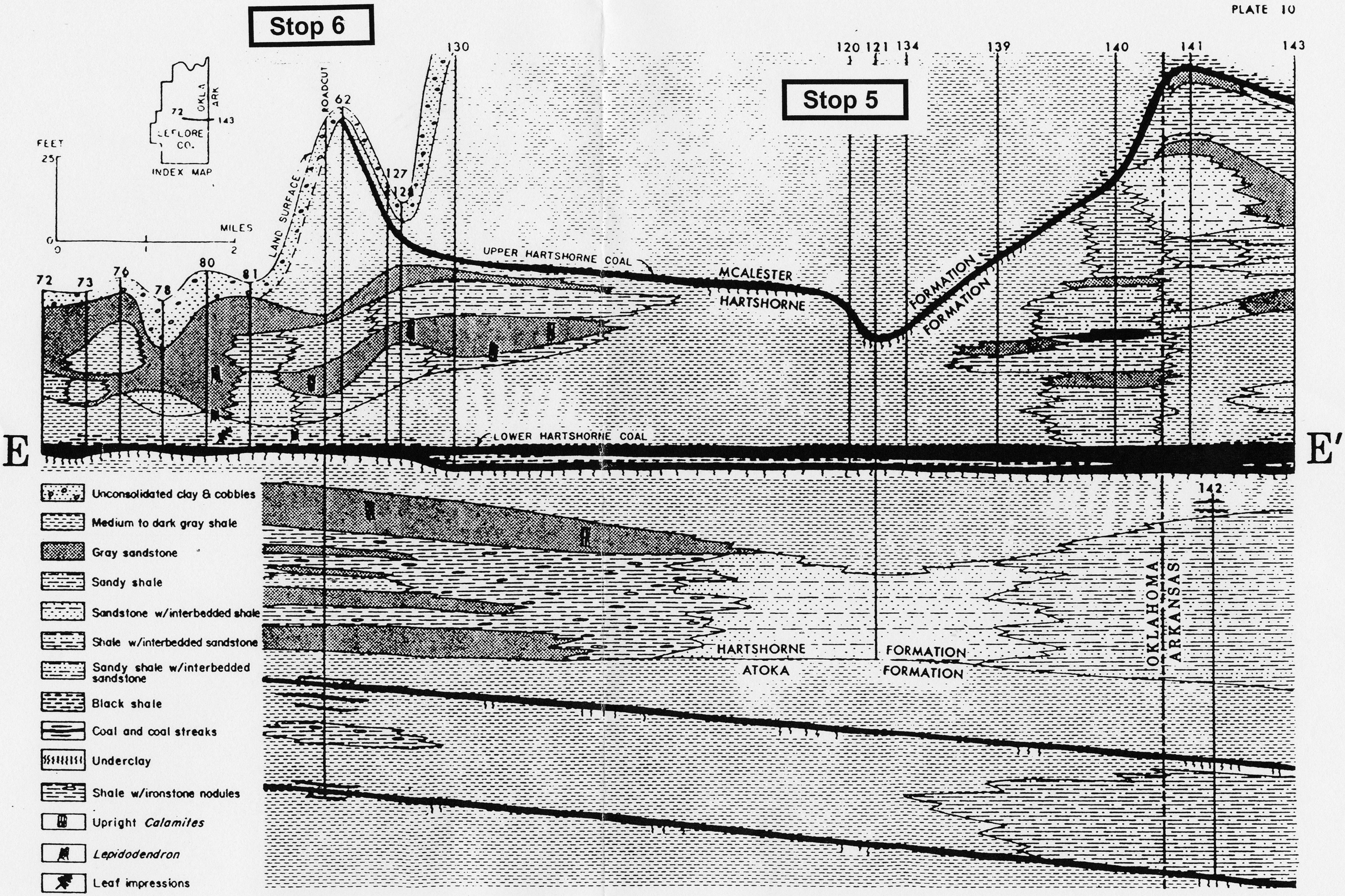
1 Lone Star Steel, McCurtain mine
2 Evans Coal Co., No. 3, 7, 9, 11, and 14 mines
3 Evans Coal Co., No. 2 mine
4 Panther Coal Co., No. 1 and 2 mines
5 Milton Coal Co.
6 Reese Coal Co.
7 John Jones No. 1 and 2 mines
8 Lone Star Steel
9 Keener Coal Co.
10 Howe Coal Co., Bokoshe No. 1 mine
11 Heatherington Brothers Coal Co.
12 Keener Coal Co., No. 10, 11, 12, 14, 15, 16, 17, 18, and 19 mines
13 Panama Coal Co., No. 2 mine
14 Ozark Coal and Railway
15 Black Diamond Coal Co., No. 6 mine
16 Bokoshe Smokeless Coal Co., Old Oliver No. 1 mine
17 Brentetschies Coal Co.
18 Unknown
19 Bokoshe Coal Co., No. 8, 8 1/2, 9, 10, 14, 15 1/2, and 16 mines
20 Davis and Swindle No. 1 mine
21 Covington Coal Co., No. 1 and 12 mines
22 Superior Smokeless Coal Co., No. 29 mine
23 Acme Semi-Anthracite No. 12 mine
24 Williams Coal Co., No. 1 mine
25 Reeves Coal Co.
26 W. J. Gough Coal Co.
27 Texas Coal Co., No. 2 and 4 mines
28 LeBosquet Coal and Mining Co., No. 1 and 2 mines
29 Lincoln Power Co., No. 4 mine
30 Poteau Valley Coal Co., No. 3 mine
31 Martin Coal and Coke Co., No. 7 and 9 mines
32 Martin Coal and Coke Co., No. 8 mine
33 Degnan and McConnell Coal and Coke Co., No. 1 and 2 mines
34 Dawes Brothers Coal Co., No. 4 mine
35 Interstate Coal Co., No. 4 and 5 mines
36 Howe mine
37 Standard Coal Mining Co.
38 Heavener Smokeless Coal Co.
39 Choctaw Coal and Mining Co.

ACTIVE DEEP MINES

40 Evans Coal Co., Experimental No. 1 mine
41 Kerr-McGee Coal Co., Choctaw mine

FIGURE 2. - Mined-out-area map and overburden map of the Hartshorne coalbed.

From Iannacchione and Puglio (1979, p. 3).



Cross Section E-E′, stratigraphic relations of coals and sandstones in the Hartshorne and Atoka Formations.

Donica, D.R., 1978, The geology of the Hartshorne coals (Desmoinesian) in parts of the Heavener 15' quadrangle, Le Flore County, Oklahoma: Norman, University of Oklahoma, unpublished M.S. thesis, 128 p.

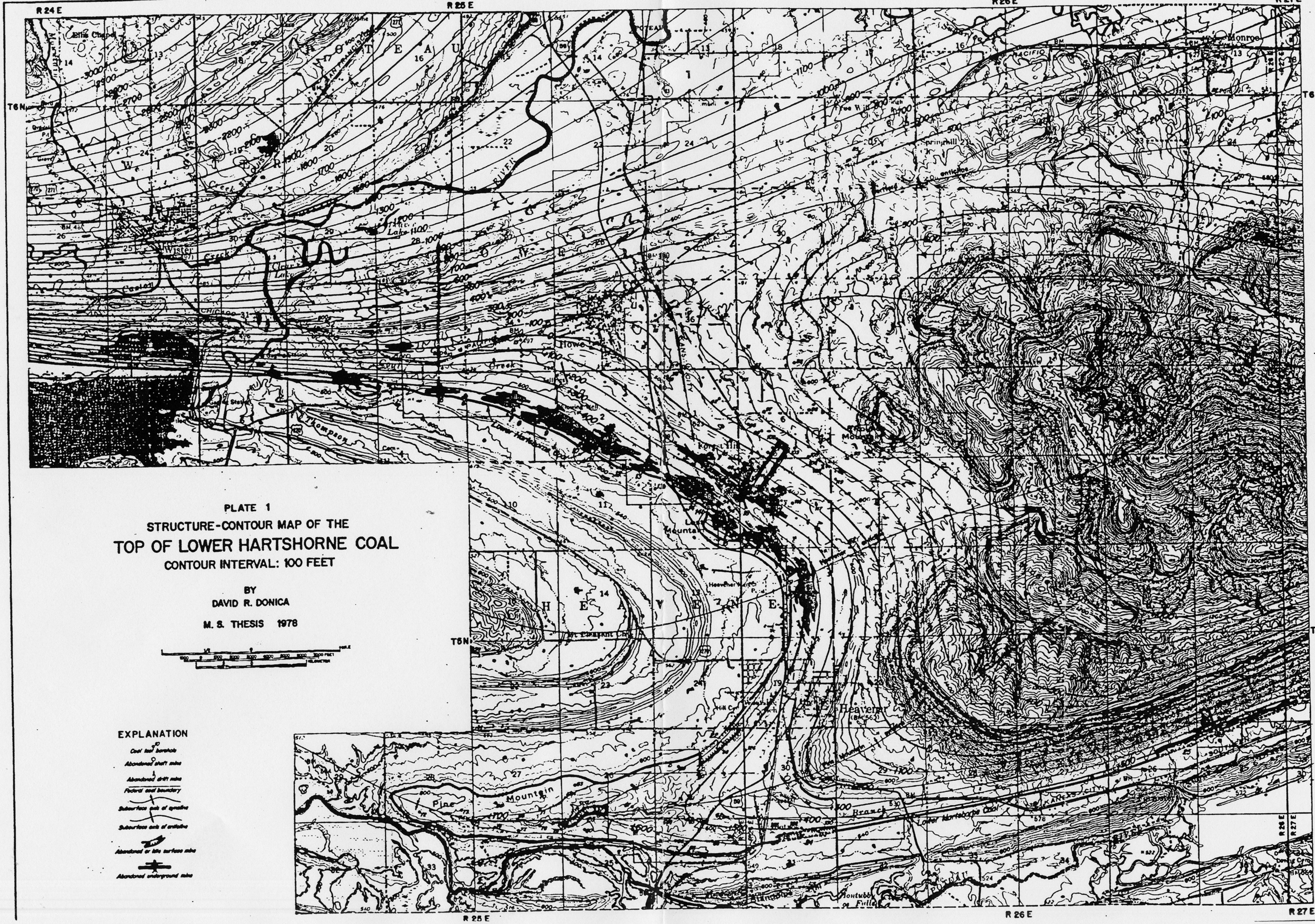


PLATE 1

STRUCTURE-CONTOUR MAP OF THE

TOP OF LOWER HARTSHORNE COAL

CONTOUR INTERVAL: 100 FEET

BY

DAVID R. DONICA

M. S. THESIS 1978

Stop 5. Farrell-Cooper Mining Company Heavener East No. 1 Mine

Location: Section 26, T.5N., R.27E., Le Flore County, Oklahoma.

Introduction: The emphasis of this stop will be to view an active surface auger coal mine and reclamation, visualize the thickness of the coal and overburden, and collect coal samples from the coal storage pad.

Lower Hartshorne coal (Hartshorne Formation; Desmoinesian; Middle Pennsylvanian)
- ~6.75 ft thick (upper 53 in. coal, 20 in. shale parting, lower 8 in. coal)
- dip ~17°, N19°W
- Mining 300–500 ft into a 100 ft highwall with a 48 in. diameter auger.
- Holes are drilled 40 in. apart. A hole is drilled a distance of 3 ft at the top of the coal to vent gas.

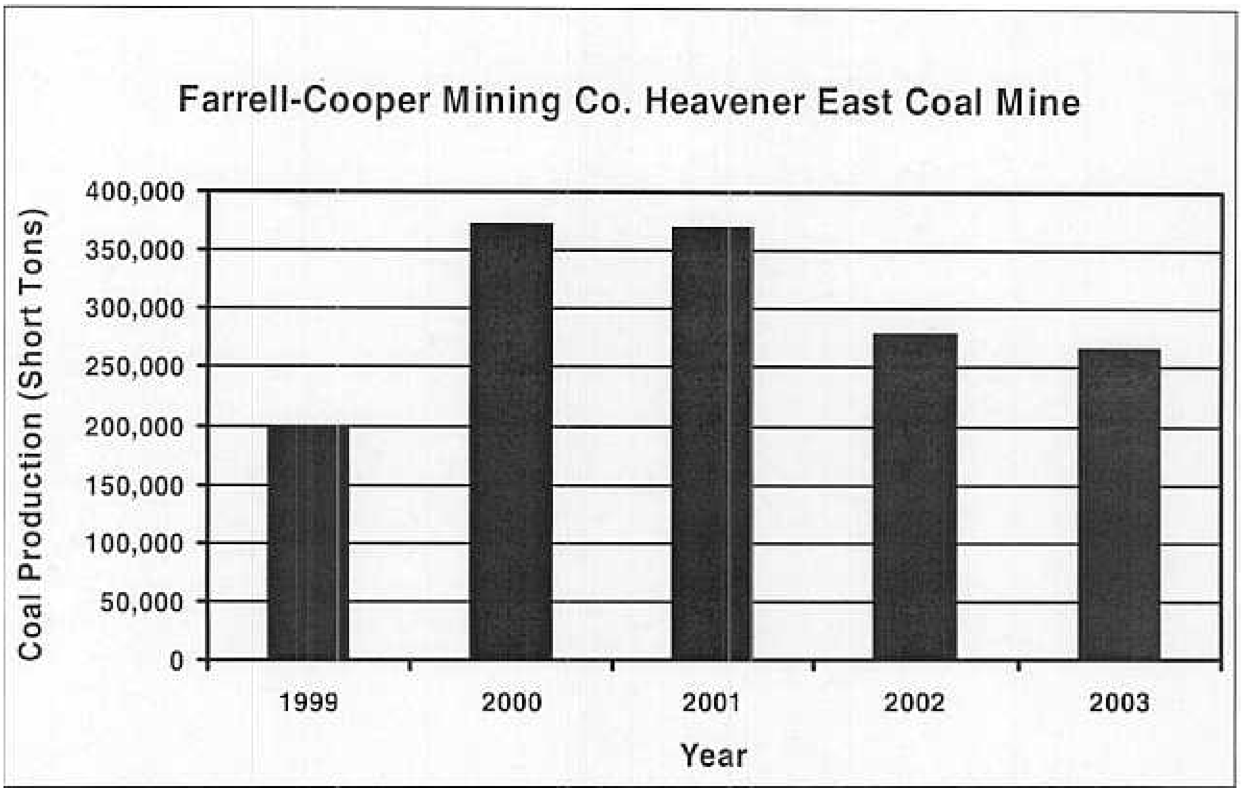
Upper Hartshorne coal (top of Hartshorne Formation) is in the highwall (~62 ft above the Lower Hartshorne coal; ~2.1 ft thick).

Petrographic coal rank: medium volatile bituminous [vitrinite reflectance (Rmax) = 1.38%].

Chemical analyses (as-received basis) of Lower Hartshorne coal:

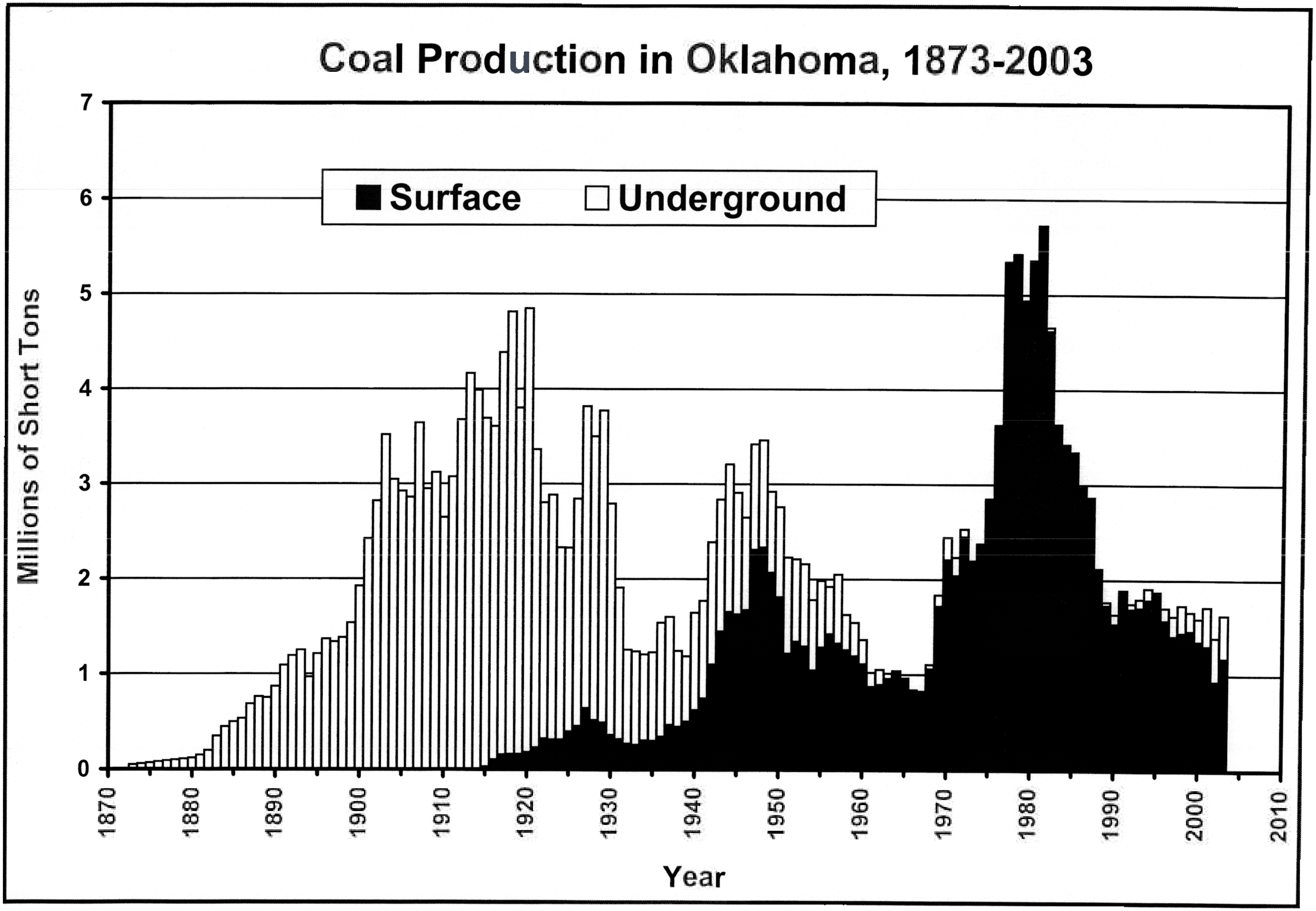
Moisture	4.08%
Ash	8.90%
Volatile Matter	21.04% [24.18% dmmf; medium volatile bituminous]
Fixed Carbon	65.98% [75.82% dmmf; medium volatile bituminous]
B.T.U./LB.	13,454 [14,924 moist, mmf]
Sulfur	1.11%

The coal mine opened in April 1999. Year 2003 production was 265,959 short tons (16.3% of Oklahoma coal production; total Oklahoma coal production in 2003 was 1,631,073 short tons from 11 mines).



From 1873–2003, 284,347,034 short tons of coal were produced in Oklahoma (see graph on next page). Coal was mined in Oklahoma strictly by underground methods until 1915. Peak annual coal production was 5.73 million short tons in 1981, with smaller production peaks during and immediately following World War I (4.85 million short tons in 1920) and World War II (3.46 million short tons in 1948). Five coal-fired utility electric power plants were built in Oklahoma from 1978–1982.

Much of the coal mined in eastern Oklahoma is shipped by truck to the Applied Energy Services (AES) Shady Point coal-fired cogeneration facility near Panama, Oklahoma (Le Flore County; SE¼ Section 3, Township 8 North, Range 25 East). Commercial operation of the plant began on January 15, 1991. The plant supplies electricity to Oklahoma Gas and Electric Company and food-grade carbon dioxide to Tyson Foods. The plant has four coal-fired circulating fluidized-bed (CFB) steam boilers and two turbine generators with a net electrical output of approximately 320 megawatts per hour (enough electricity for about 230,000 homes). The CFB technology offers low sulfur dioxide and nitrogen oxides emissions while burning Oklahoma high sulfur coal, and is a highly efficient combustion process at a low firing temperature. In the process of burning coal, there is a combustion gas reaction with limestone for sulfur dioxide capture. The plant uses about 3,000 tons of coal per day, and 1,000 tons of limestone per day.


Coal Production in Oklahoma, 1873-2003
Surface
Underground
Millions of Short Tons
0
1
2
3
4
5
6
7
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

Stop 6. U.S. Highway 59 roadcut (northwest side of road). Le Flore County, SW¼ NW¼ SE¼ NW¼ Section 36, T.5N., R.25E.

Emphasis:
Examine cleat direction and spacing in Lower Hartshorne coal; contrast coal thickness and interval above coal with Stop 5.

Lower Hartshorne coal (Hartshorne Formation; Desmoinesian; Middle Pennsylvanian) is 1.9 ft thick; coal dip 7°, N6°E
Face cleat: N6°W
Butt cleat: S85°E

Petrographic rank: medium volatile bituminous [vitrinite reflectance (Rmax): 1.27%]

Text from Suneson, 1998, p. 58-61.

STOP 15

Heavener Road Cut Measured Section

Directions: From the intersection of U.S. Highways 59 and 270 just north of Heavener, Oklahoma, drive 2.7 mi south on U.S. Highway 59/270 to large road cut on both sides of road. Measured section is on west side.

Map reference: Mazengarb and Hemish (1993).

Geologic reference: Donica (1978, p. 125–128); Suneson and Hemish (1994, p. 100–102).

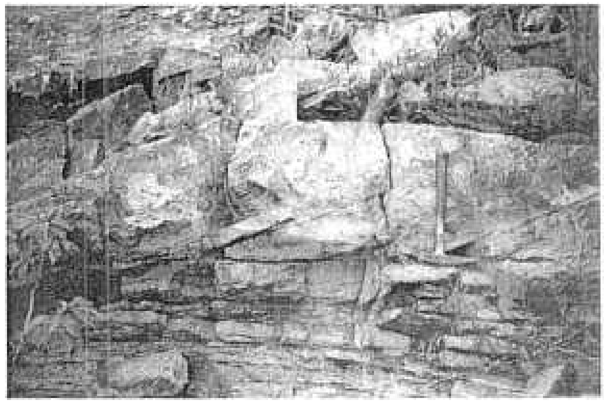


Figure 59. Large-scale tabular cross-stratification in unit 3, Quarry Isle section, indicating deposition under high-energy conditions. The association of such deposits with distributary-mouth-bar sediments suggests that this is a storm deposit. Stratigraphic top is toward top of photograph. Geologic hammer for scale.

This outcrop of the Hartshorne Formation (Fig. 60) probably has been visited by more geologists than all the other Hartshorne outcrops in the State combined. Although truly spectacular and an excellent example of delta-plain sediments (Fig. 61), it is atypical of most exposed Hartshorne strata in the southern part of the Arkoma basin. As discussed at previous stops, most of the Hartshorne consists of delta-front sandstone, siltstone, and shale. This outcrop, perhaps more than any other in Oklahoma, probably has caused geologists to think of the Hartshorne Formation in terms of a delta model.

The following description of this outcrop is modified slightly from Suneson and Hemish (1994, p. 100–102), which, in turn, was based on a detailed study of the outcrop by Donica (1978).

The Atoka and Hartshorne Formations at the Heavener road cut were described in detail by Donica (1978). He placed the contact between the two formations at the base of the lowest sandstone (Fig. 60). This sandstone is 10–40 ft above two thin (0.5-ft-thick) coal beds. Hendricks' (1939, p. 267) measured section of the Hartshorne Formation at Petry's Cut along the railroad 0.9 mi to the east showed the Atoka-Hartshorne contact at the base of a 1.5-ft-thick sandstone that is directly below the lower of the two thin coals at Petry's Cut. Donica (1978, p. 16) suggested that the sandstone used by Hendricks (1939) to mark the base of the Hartshorne is discontinuous and is not the more extensive Hartshorne sandstone that typically is used to mark the base of the Hartshorne. An equally likely explanation is that Hendricks (1939, p. 264) believed that the Atoka Formation did not contain any coal beds; therefore, he placed the two thin coals in the Hartshorne Formation. Briggs and others (1975, p. 93) briefly described the strata at the Heavener road cut and apparently included the entire exposed sequence in the Hartshorne Formation.

The strata exposed in the Heavener road cut (Fig. 61) were deposited in interdistributary marshes and swamps in a delta-plain environment (Donica, 1978; Briggs and others, 1975). Coal beds represent periods of peat accumulation with little or no sediment influx; shale intervals represent periods of slightly greater clastic sedimentation; and the sandstones are overbank and/or crevasse-splay deposits that probably represent periods of flooding. Unlike the Hartshorne exposure at Stop 10B, the Heavener road cut exposes no fluvial-channel deposits. The "alluvial channel" in the lower Hartshorne Formation shown by McDaniel (1961, fig. 8) may refer to the "channel sandstone" pictured by Hendricks (1939, pl. 29A); however, the sandstone pictured by Hendricks (1939) is in the upper part of the Hartshorne. Similar, but thicker, channels in the upper part of the Hartshorne Formation near Heavener are on Lost Mountain (SE¼ sec. 12, T. 5 N., R. 25 E.) and on the hill in the NE¼ sec. 5, T. 5 N., R. 25 E. (L. A. Hemish, unpublished field observations).

A reexamination of the Atoka Formation at the Heavener Road Cut section by R. Andrews and me for this field trip allows some additional interpretations to be made. Units 1 through 5 and 6 through 10 (Fig. 60) appear to represent two fining-upward transgressive sequences. The lower parts of both sequences are laminated sandy siltstones; these grade upward into black organic-rich shales with abundant siderite nodules, which are overlain by zones with abundant coal. Our interpretation of these sequences is that the lower part of each was deposited in a delta-margin environment, possibly at the outer fringe of an interdistributary bay. The sandy siltstones may be distal crevasse-splay deposits. These are overlain by lagoonal shales, which, in turn, are overlain by and/or interbedded with probable marsh deposits (coals). As correctly interpreted by Donica (1978), the overlying units are upper-delta-plain bay-fill shales and crevasse-splay sandstones or possibly flood-plain deposits.

Figure 62 is part of the electric log from the Mobil No. 1 Ann Lyons well, drilled ~7.1 mi north-northeast of the Heavener Road Cut section. A comparison of the measured section (Fig. 60) and the log (Fig. 62) shows several similarities. In both, the Lower Hartshorne coal is underlain by shale; the thin coal beds in the shale strongly suggest that the unit (unit 24 in Fig. 60) represents lagoonal–bay-fill sediments. Below the shale is a series of delta-plain (probably lagoonal, bay-fill, and crevasse-splay) shale and sandstone units (units 13–23) that range from about 0.5 to 13 ft thick; these are represented on the log in the interval from about 1,102 to 1,158 ft. The highly irregular gamma-ray log is characteristic of such delta-plain deposits. The log suggests that one or two slightly fining-upward delta-plain sequences constitute the lower part of the Hartshorne in this area, but this is not obvious at the outcrop.

Some significant differences are apparent between the outcrop (Fig. 60) and log (Fig. 62). The Atoka For-

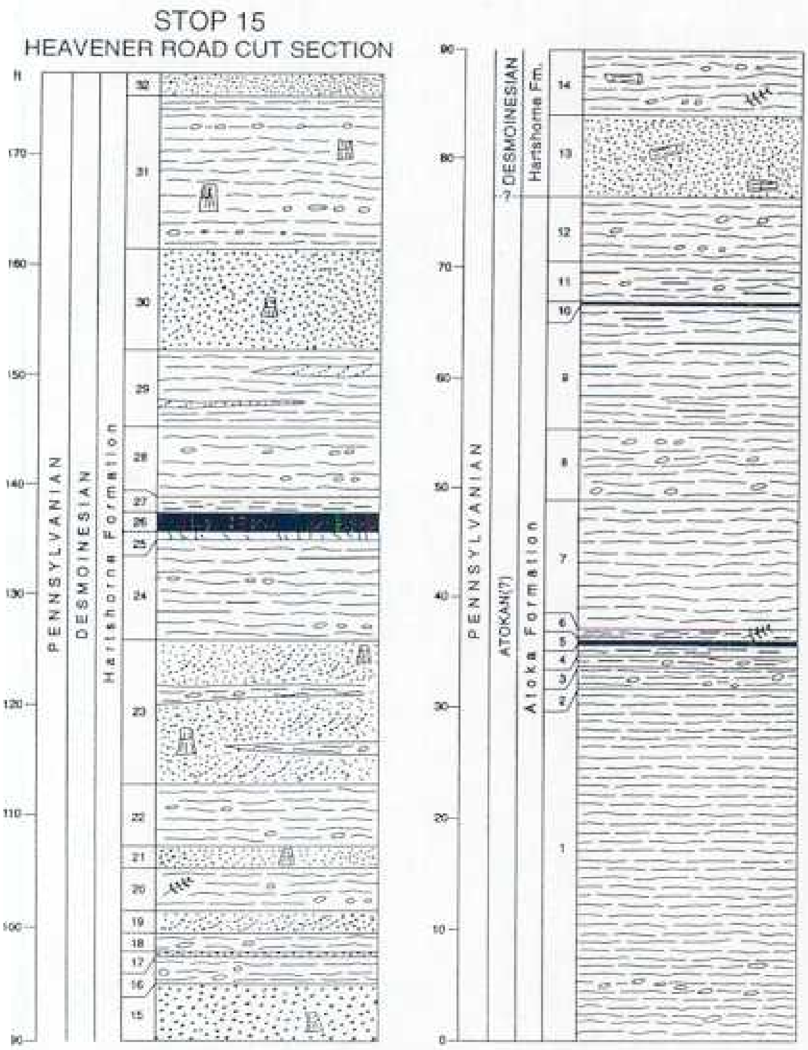


Figure 60. Graphic columnar section of the upper part of the Atoka Formation and the lower part of the Hartshorne Formation exposed at Stop 15 (Heavener Road Cut section). Note the presence of several thin coal beds in the Atoka Formation and upright (growth position) *Calamites* in the Hartshorne Formation. Such features are diagnostic of a delta-plain environment. (From Suneson and Hemish, 1994, fig. 67.)

Figure 61. Northwest side of Heavener road cut, Stop 15. Dark-colored strata on left were identified by Donica (1978) as mostly shale in the Atoka Formation, but they appear to include a significant amount of sandy siltstone (R. Andrews' and the author's observations); lighter colored strata above are in lower part of Hartshorne Formation. Upper Hartshorne sandstone exposed at top of road cut, underlain by conspicuous black band of Lower Hartshorne coal. (From Suneson and Hemish, 1994, fig. 68.)

mation at the Heavener Road Cut section consists of a thick seqence of bay-fill shale and minor coal. This is the only outcrop of the upper part of the Atoka Formation in the southern part of the Arkoma basin that is not made up of marine, prodelta, or distal-delta-fringe strata. The marine shale and shoreface-transition strata interpreted on the log of the No. 1 Ann Lyons well are typical of most Atoka–basal Hartshorne strata in the Arkoma basin. Also, the strata above the Lower Hartshorne coal on the log are sandstone and probably fill a channel, whereas those above the coal in the outcrop are interbedded shale and sandstone. These differences are probably due to the distance between the measured section and the well.

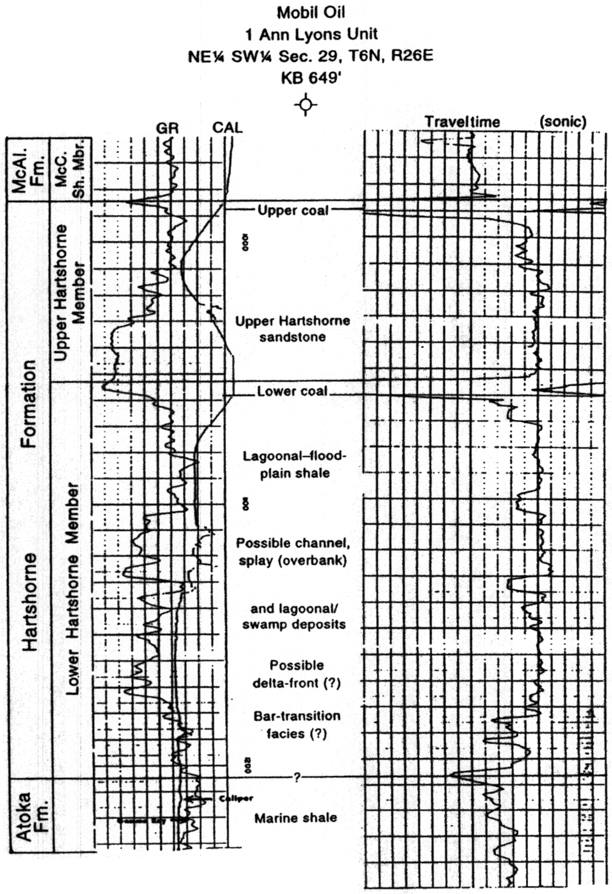


Figure 62. Part of log from the Mobil No. 1 Ann Lyons well. Log pattern of upper and middle parts of Lower Hartshorne Member is characteristic of delta-plain deposits (R. Andrews, personal communication, 1998). Lower part of Hartshorne Formation (bar transition) and upper part of Atoka Formation (marine) on log are different from those exposed at Stop 15. *GR* = gamma ray, *CAL* = caliper.

Measured Section, Stop 15

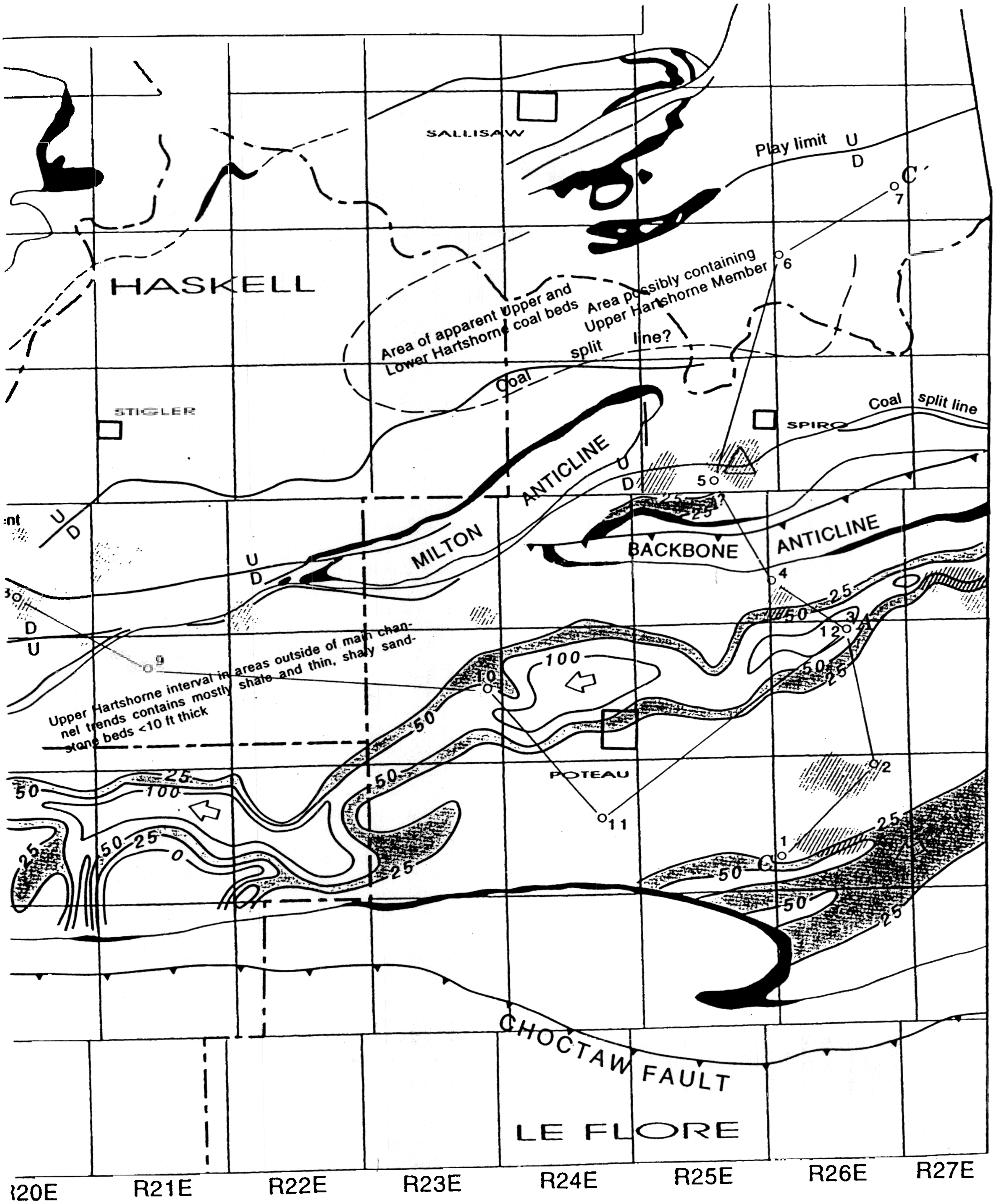
Upper Part of Atoka Formation and Hartshorne Formation

Heavener Road Cut Section

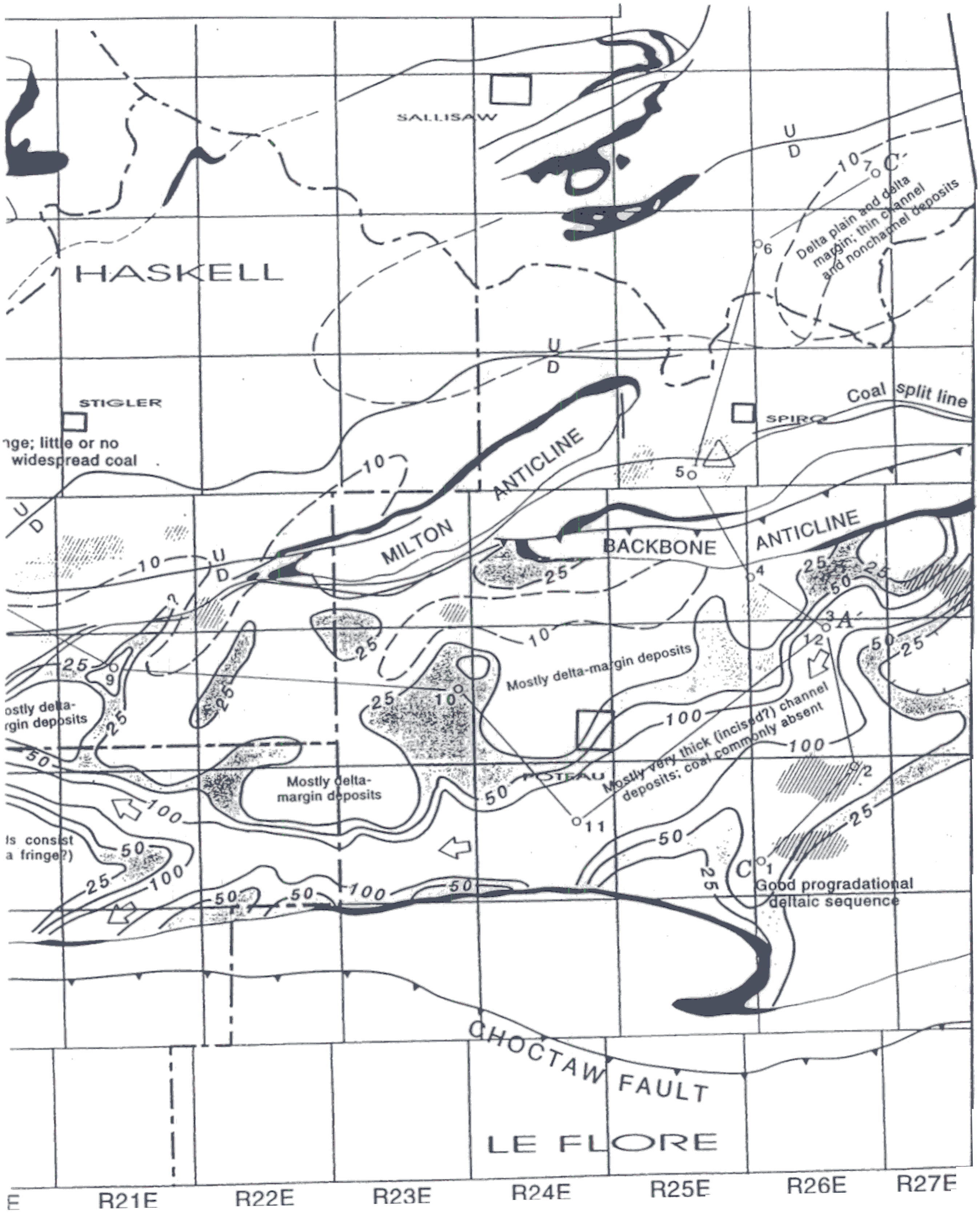
Location: NW¼SE¼NW¼ sec. 36, T. 5 N., R. 25 E. (Hontubby 7.5' quadrangle). Road cut along U.S. Highway 59/270 about 1.5 mi south of Heavener. Le Flore County, Oklahoma. Section measured by David R. Donica. The following description is modified from Donica (1978).

	Thickness (feet)
KREBS GROUP:	
HARTSHORNE FORMATION:	
32. Sandstone, gray, weathers buff (top of section).	2.0
31. Shale, interlaminated gray and brown, containing siderite nodules and upright *Calamites*.	4.0
30. Sandstone, gray, fine-grained, containing upright *Calamites*.	9.0
29. Shale, gray, interbedded with cross-bedded sandstone.	6.8
28. Shale, gray, thinly laminated, containing siderite nodules.	6.8
27. Shale, black, carbonaceous.	1.2
26. Coal (Lower Hartshorne).	1.9
25. Underclay, rooted.	0.5
24. Shale, gray, fissile, containing siderite nodules and streaks of coal.	9.4
23. Sandstone, gray, cross-bedded, containing upright *Calamites*, interbedded with gray shale containing siderite nodules.	12.8
22. Shale, gray, containing siderite nodules.	5.8
21. Sandstone, gray, fine-grained, containing upright *Calamites*, one of which is 1.8 ft tall. The sandstone is variable in thickness.	
20. Shale, gray, finely laminated, with siderite nodules containing plant impressions.	4.2
19. Sandstone, gray, fine-grained, cross-bedded.	1.9
18. Shale, gray, thinly laminated, containing siderite nodules.	1.6

17. Sandstone, gray, very fine grained, cross-bedded. ...	0.5
16. Shale, gray, thinly laminated, containing siderite nodules.	2.5
15. Sandstone, gray, very fine grained, containing upright *Calamites*.	5.2
14. Shale, gray, finely laminated, with siderite nodules containing *Calamites* and numerous leaf impressions.	5.7
13. Sandstone, gray, fine-grained, containing *Calamites*.	7.5
ATOKA FORMATION:	
12. Shale, gray, thinly laminated, containing siderite nodules.	5.7
11. Shale, carbonaceous, containing thin coal streaks and siderite nodules.	3.7
10. Coal.	0.5
9. Shale, black, carbonaceous, with numerous coal streaks.	11.3
8. Shale, gray, containing siderite nodules.	6.5
7. Shale, gray.	11.5
6. Shale, sideritic, overlying shale, black, carbonaceous, containing thin coal streaks and numerous plant impressions.	1.2
5. Coal.	0.5
4. Shale, black, with coal streaks.	0.9
3. Shale, black, containing siderite nodules.	0.9
2. Shale, gray, containing siderite nodules.	2.0
1. Shale, gray, thinly laminated, with interbedded sideritic shale (base of section).	31.8
Total thickness of section	177.5



Part of gross-sandstone isopach map, upper member of Hartshorne Formation. Modified from Andrews and others (1998, plate 2).



Part o g oss-s tone isopach m lower membe of H rtshorne
ormatio Modified from Andrews n others 199 plate 1

References Cited

Ammosov, I. and Eremin, I.V., 1960, Fracturing in coal (Translated from Russian, 1963): IZDAT Publishers, Office of Technical Services, Washington, DC, 109 p.

Andrews, R.D., B.J. Cardott, and T. Storm, 1998, The Hartshorne play in southeastern Oklahoma: regional and detailed sandstone reservoir analysis and coalbed-methane resources: OGS Special Publication 98-7, 90 p.

Cardott, B.J., 2002, Introduction to coal geology of Oklahoma, *in* B.J. Cardott, compiler, Fourth annual Oklahoma coalbed-methane workshop: OGS Open-File Report 9-2002, p. 34-55.

Close, J.C., 1993, Natural fractures in coal: in Law, B.E. and Rice, D.D., Eds., Hydrocarbons from coal: Tulsa, OK, AAPG Studies in Geology, #38, p. 119-132.

Donica, D.R., 1978, The geology of the Hartshorne coals (Desmoinesian) in parts of the Heavener 15' quadrangle Le Flore County, Oklahoma: Norman, University of Oklahoma, unpublished M.S. thesis, 128 p.

Friedman, S.A., field trip leader, 1991, Fracture and structure of principal coal beds related to coal mining and coalbed methane, Arkoma basin, eastern Oklahoma: AAPG EMD trip 2, AAPG annual convention, Dallas, Texas.

Friedman, S.A., and R.J. Woods, 1982, Map showing potentially strippable coal beds in eastern Oklahoma: Oklahoma Geological Survey Map GM-23, scale 1:125,000, 4 sheets.

Fugate, F.L., and R.B. Fugate, 1991, Roadside history of Oklahoma: Missoula, Montana, Mountain Press Publishing Company, 456 p.

Hemish, L.A., 1999, Hartshorne coal bed, Latimer County – thickest known coal in Oklahoma: OGS Oklahoma Geology Notes, v. 59, p. 34, 78.

Hendricks, T.A., 1937, Geology and fuel resources of the southern part of the Oklahoma coal field; part 1, the McAlester district, Pittsburg, Atoka, and Latimer Counties: U.S. Geological Survey, Bulletin 874-A, 90 p.

Hendricks, T.A., 1939, Geology and fuel resources of the southern part of the Oklahoma coal field; part 4, the Howe-Wilburton district, Latimer and Le Flore Counties: U.S. Geological Survey, Bulletin 874-D, p. 255-300.

Iannacchione, A.T., and D.G. Puglio, 1979, Methane content and geology of the Hartshorne coalbed in Haskell and Le Flore Counties, Oklahoma: U.S. Bureau of Mines Report of Investigations 8407, 14 p.

Joubert. J.I., Grein, C.T., and Bienstock, D., 1974, Effect of moisture on the methane capacity of American coals: Fuel, v. 53, p. 186-191.

Law, B.E., 1993, The relationship between coal rank and cleat spacing: Implications for the prediction of permeability in coal: Proceedings of the 1993 International Coalbed Methane Symposium, The University of Alabama, Tuscaloosa, May 17-21, 1993, p. 435-441.

Pollard, D.D. and Aydin, A., 1988, Progress in understanding jointing over the past century: GSA Bulletin, v. 100, no. 8, p. 1181-1204.

Suneson, N.H., 1998, Geology of the Hartshorne Formation, Arkoma basin, Oklahoma: OGS Guidebook 31, 74 p.

Suneson, N.H., and L.A. Hemish, eds., 1994, Geology and resources of the eastern Ouachita Mountains frontal belt and southeastern Arkoma basin, Oklahoma: OGS Guidebook 29, 294 p.

Tremain, C.M., Laubach, S.E., Whitehead III, N.H., 1991, Coal fracture (cleat) patterns in Upper Cretaceous Fruitland Formation, San Juan Basin, Colorado and New Mexico: Implications for coalbed methane exploration and development, in Ayers, W.B., Jr. et al., Geologic and hydrologic controls on the occurrence and producibility of CBM, Fruitland Fm., SJB:GRI, Chicago, Topical Report GRI-91/0072, p. 97-117

Wilson, L.R., 1970, Palynology of Oklahoma's ten-foot coal seam: Oklahoma Geological Survey Oklahoma Geology Notes, v. 30, p. 62-63.