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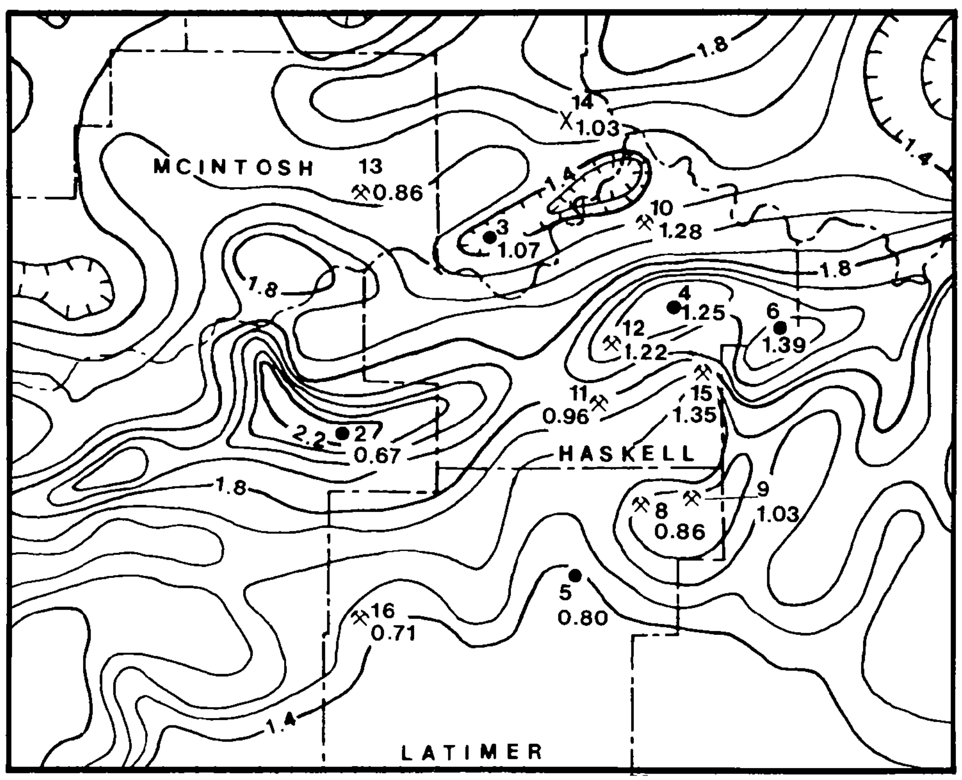
The Relationship Between Coal Rank and Present Geothermal Gradient in the Arkoma Basin, Oklahoma

Brian J. Cardott, LeRoy A. Hemish,
Charles R. Johnson, Kenneth V. Luza



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THE RELATIONSHIP BETWEEN COAL RANK AND PRESENT GEOTHERMAL GRADIENT IN THE ARKOMA BASIN, OKLAHOMA

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Oklahoma Geological Survey
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Norman, Oklahoma

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ABSTRACT

The Arkoma Basin, Oklahoma, is composed of a series of anticlines and synclines in Pennsylvanian clastic rocks, broken by thrust and (or) growth faults near the center of the basin. The Desmoinesian Series, Pennsylvanian System, contains the major coal-bearing strata in the Arkoma Basin.

Vitrinite-reflectance techniques were used to determine if there is a relationship between present geothermal gradient and coal rank. Three coal seams from high geothermal-gradient areas were compared with the same coal seams, respectively, from low geothermal-gradient areas. The three coal seams selected for study were the Hartshorne, McAlester (Stigler), and Secor. Samples were obtained from three core holes that were drilled in the high geothermal-gradient areas in Pittsburg and Haskell Counties, and three core holes that were drilled in the low geothermal-gradient areas in Latimer and Muskogee Counties. The following three combinations were selected: (1) a north-south orientation with low geothermal gradient to the north (Secor coal), (2) an east-west orientation with low geothermal gradient to the west (McAlester-Stigler coal), and (3) a northeast-southwest orientation with a low geothermal gradient to the southwest (Hartshorne coal). Nine additional coal samples were collected from active coal mines and one from an outcrop to supplement the core samples.

The vitrinite-reflectance data indicate the present geothermal gradient did not produce the coal rank in the Arkoma Basin of Oklahoma. The coal rank is believed to have developed during the late Paleozoic, possibly in connection with the Ouachita orogeny. The coal isocarb maps suggest that the present geothermal-gradient pattern reflects the paleogeothermal gradient that produced the coal rank. Perhaps the intense folding and faulting associated with the Ouachita orogeny combined to transmit heat from the basement along an east-west thermal-anomaly zone through Haskell and Pittsburg Counties, Oklahoma.

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PART I. - INTRODUCTION

Kenneth V. Luza, LeRoy A. Hemish, Brian J. Cardott,
and Charles R. Johnson

In connection with activities performed under contract DE-AS07-80ID 12172 to evaluate the geothermal resources of Oklahoma, a number of peripheral investigations were conducted. These are summarized in Prater and others (1981), Harrison and Luza (1982), Harrison and others (1983), and Luza and others (1984). During 1983-85, two additional studies were made. Both are important for a better understanding of the geothermal potential of Oklahoma and are subjects of topical reports. This report concerns the program to gain a better understanding of the geologic controls on geothermal anomalies in the Arkoma Basin, Oklahoma.

The geothermal-gradient map of Oklahoma delineates a range in the present geothermal gradient of 1.1 to 2.3°F/100 feet (Cheung, 1978). The highest gradient trend occurs from the east-northeast toward the west-southwest through Haskell and Pittsburg Counties in the Arkoma Basin (figs. 1, 10).

The Arkoma Basin comprises a series of anticlines and synclines in Pennsylvanian clastic rocks, broken by thrust and (or) growth faults near the center of the basin. The Desmoinesian Series, Pennsylvanian System, contains the major coal-bearing strata in the Arkoma Basin.

In order to obtain coal samples for evaluation, the Oklahoma Geological Survey (OGS) undertook a drilling project using the OGS drill rig and crew. The project was designed to recover pairs of cores from three selected coal beds in both high and low geothermal-gradient zones. The site selections were made by superimposing the contour lines shown on the geothermal-gradient map of

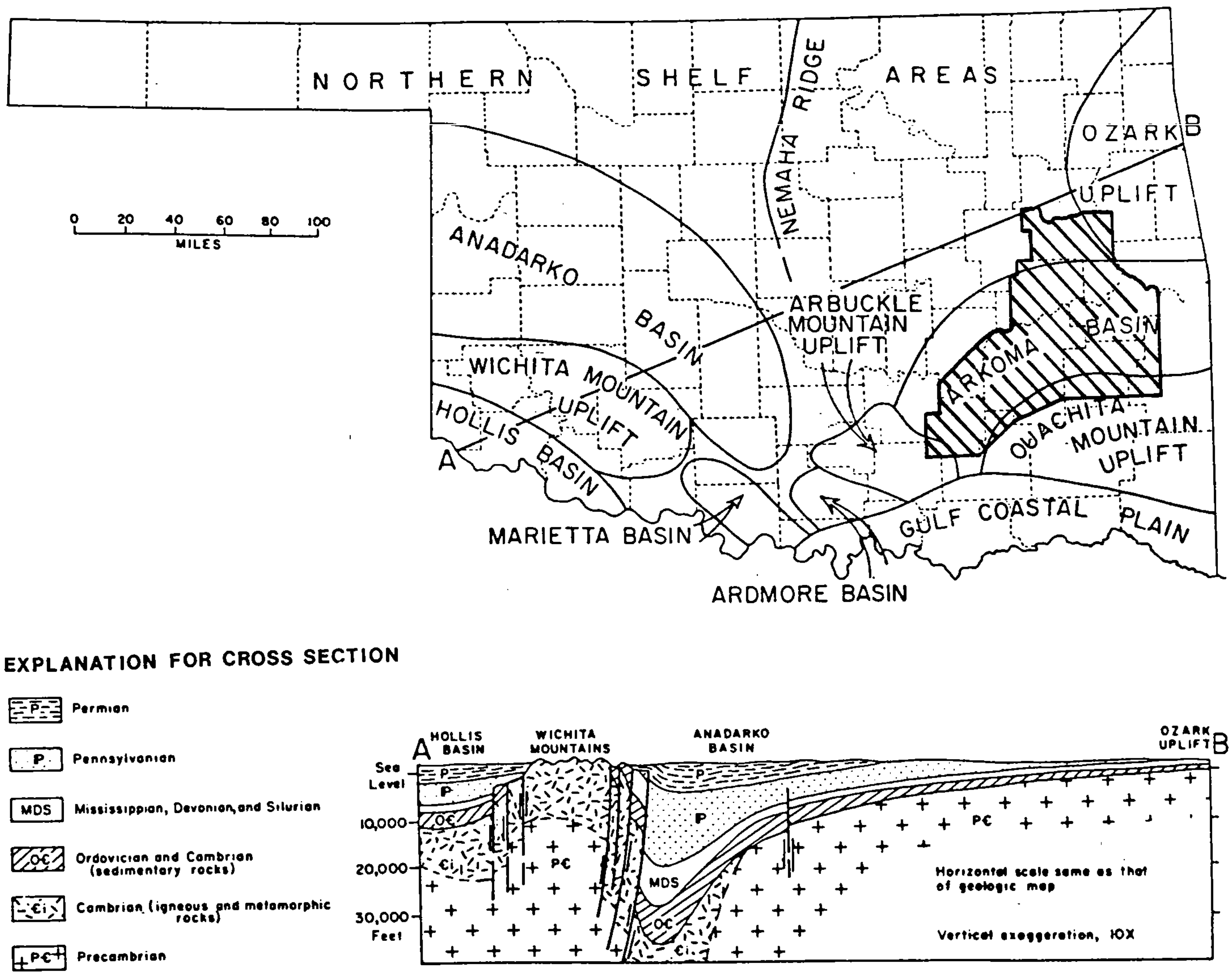

Figure 1. Map and cross section showing major geologic and tectonic provinces of Oklahoma and location of the study area.

eastern Oklahoma by Cheung (1978) on coal maps by Friedman (1982) and Hemish (report on the coal geology of McIntosh and Muskogee Counties, in preparation). The following requirements were considered essential: (1) one sample of each coal bed had to be from a high geothermal-gradient area, and a matching sample of the same coal bed had to be from a low geothermal-gradient area; (2) the core holes had to be in close proximity to the outcrop line of the selected coal beds to maximize efficient use of time and money; and (3) the selected site had to be accessible to the drill rig and other equipment.

The objective of this study was to determine if a relationship between present geothermal gradient and coal rank could be established by studying the variation of coal rank of the same coal bed in different parts of the basin or in the adjacent shelf area. Furthermore, the study could possibly provide insight into understanding the present geothermal-gradient anomalies.

This report is divided into four parts. Part II provides a detailed discussion of the geology and pre-Desmoinesian stratigraphy of the Arkoma Basin in Oklahoma. A detailed cross section was prepared to show if there is a correlation between subsurface structure and stratigraphy, and the present geothermal gradient in the basin (pl. 1).

Geophysical logs in oil and gas boreholes drilled in Townships 4 to 15 North and Ranges 17 to 19 East were used to construct an approximate north-south cross section across the Arkoma Basin. The criteria used in the selection of key logs included the following: (1) total depth, (2) number of formations penetrated by a well, (3) total interval logged, (4) quality of the log, (5) availability of sample descriptions, and (6) evidence of faulting. A total of 38 logs met these criteria and were selected for the preparation of a detailed large-scale cross section. Scale limitations permitted the use of only 17 logs on plate 1. Temperature-gradient information for the townships and ranges used in the cross section was enlarged and positioned above the cross section.

Parts III and IV are directed toward the evaluation of geothermal gradient on coal rank in the Arkoma Basin in Oklahoma. To gain a better understanding of geologic controls on the geothermal anomalies, vitrinite-reflectance studies of the same coal seams in the high-anomaly areas and in areas with low geothermal gradients were conducted. Part III provides a brief review of the geologic setting of the coal-bearing strata in the Arkoma Basin. Six core holes, which range in depth from 40 to 277 feet, were drilled by the Oklahoma Geological Survey in the Arkoma Basin and the adjacent shelf areas. Three core holes were drilled in the high geothermal-gradient areas of Pittsburg and Haskell Counties, and three core holes were drilled in the low geothermal-gradient areas (fig. 10). The core-description data and data from other sources were used to construct two cross sections (pl. 2). The cross sections show the relationships of the various stratigraphic units encountered in the upper part of the basin. Furthermore, the cross sections were used to demonstrate that the three coal samples cored in the low geothermal-gradient areas correlated with the three coal samples cored in the high geothermal-gradient areas.

In the final section, Part IV, coal samples were analyzed for vitrinite reflectance. The mean maximum vitrinite-reflectance data for each coal sample can be used to determine coal rank. Initially, three pairs of coals were chosen for study. Each coal pair consisted of one core sample from a high geothermal-gradient area and a matching core sample of the same coal seam from a low geothermal-gradient area. The three coal seams chosen were the Secor, McAlester (Stigler), and Hartshorne. The following three combinations were selected: (1) a north-south orientation with low geothermal gradient to the north (Secor coal), (2) an east-west orientation with low geothermal gradient to the west (McAlester-Stigler coal), and (3) a northeast-southwest orientation with a low geothermal gradient to the southwest (Hartshorne coal). Nine additional coal samples were collected from active coal mines and one from an outcrop to supplement the coals from the core samples; these consisted of six samples of the McAlester (Stigler) coal and four samples of the Hartshorne coal. The vitrinite-reflectance data were used to determine what, if any, relationship exists between the present geothermal gradient and coal rank.

PART II. - GEOLOGY AND PRE-DESMOINESIAN STRATIGRAPHY OF THE ARKOMA BASIN, OKLAHOMA

Charles R. Johnson

Introduction

The Arkoma Basin, located in east-central Oklahoma and west-central Arkansas, is an elongate, asymmetrical, east-west-trending structural and depositional basin encompassing an area of more than 13,000 square miles (fig. 2). It is bounded on the north by the Ozark dome and on the northwest by the Central Oklahoma platform. The Hunton (Seminole) arch forms the western boundary, the Arbuckle uplift the southwestern boundary and the Choctaw Fault the southern boundary. The basin, formed during the late Paleozoic Ouachita Orogeny, was part of the larger Ouachita geosyncline and is one of seven similar foreland basins found along the fronts of the Ouachita and Appalachian orogenic belts (Branan, 1968).

The Arkoma Basin contains more than 25,000 feet of pre-Missourian Pennsylvanian sedimentary rocks (fig. 3), with the greatest percentage found in the Atokan Series (Flawn and others, 1961). Both compressional and tensional forces were exerted on the area, creating a complex structural configuration in which surface and pre-Atokan subsurface structures are unrelated (Branan, 1968). A detailed account of the geologic history and pre-Desmoinesian stratigraphy of the Arkoma Basin is not the purpose of this paper, but a synopsis is included to show the correlation between the subsurface structure and stratigraphy and the present geothermal gradient (pl. 1).

For a more detailed account of the Arkoma Basin, the reader is referred to Bercutt (1959), Huffman (1959), Disney (1960), Branan (1961, 1968), Branson (1961, 1962), Diggs (1961), Flawn and others (1961), Lyons (1961), Scull (1961), Swanson and others (1961), Frezon (1962), Amsden (1980), Haley (1982), and Sutherland and Manger (1984).

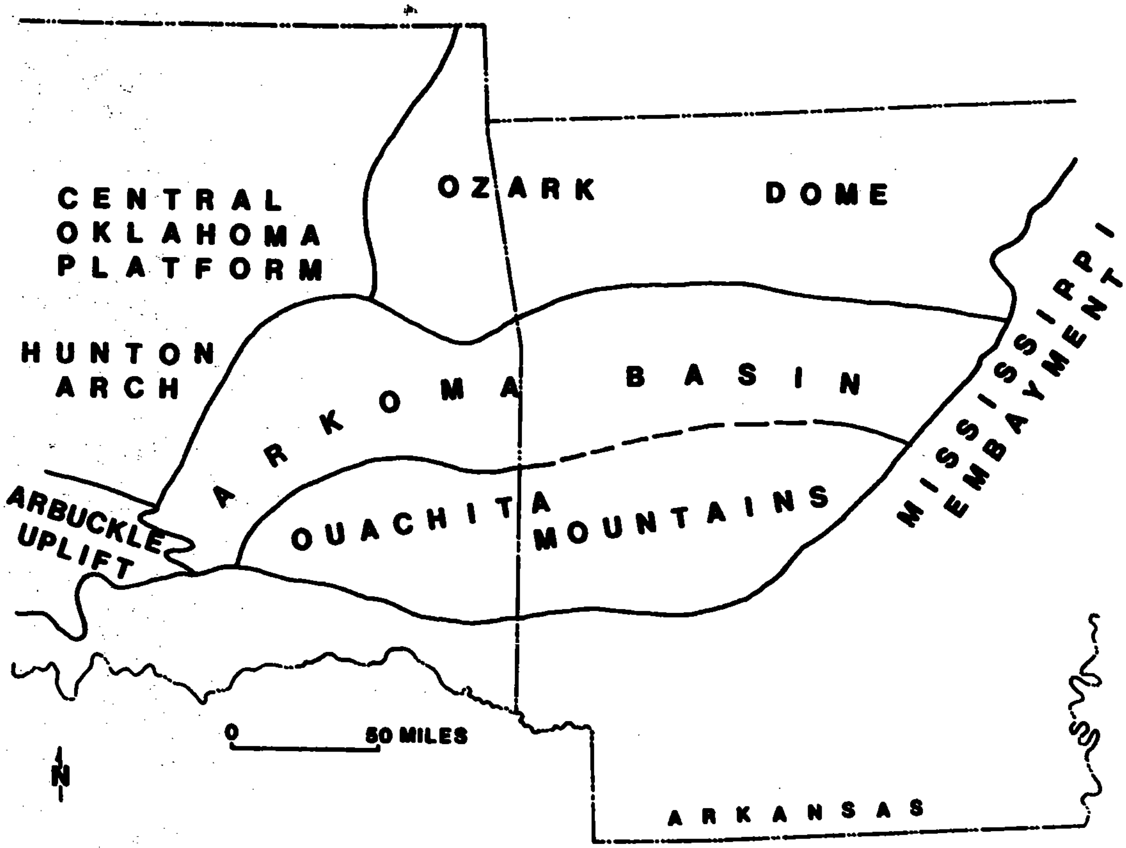

Figure 2. Map showing Arkoma Basin and surrounding tectonic features. Modified from Branan (1968).

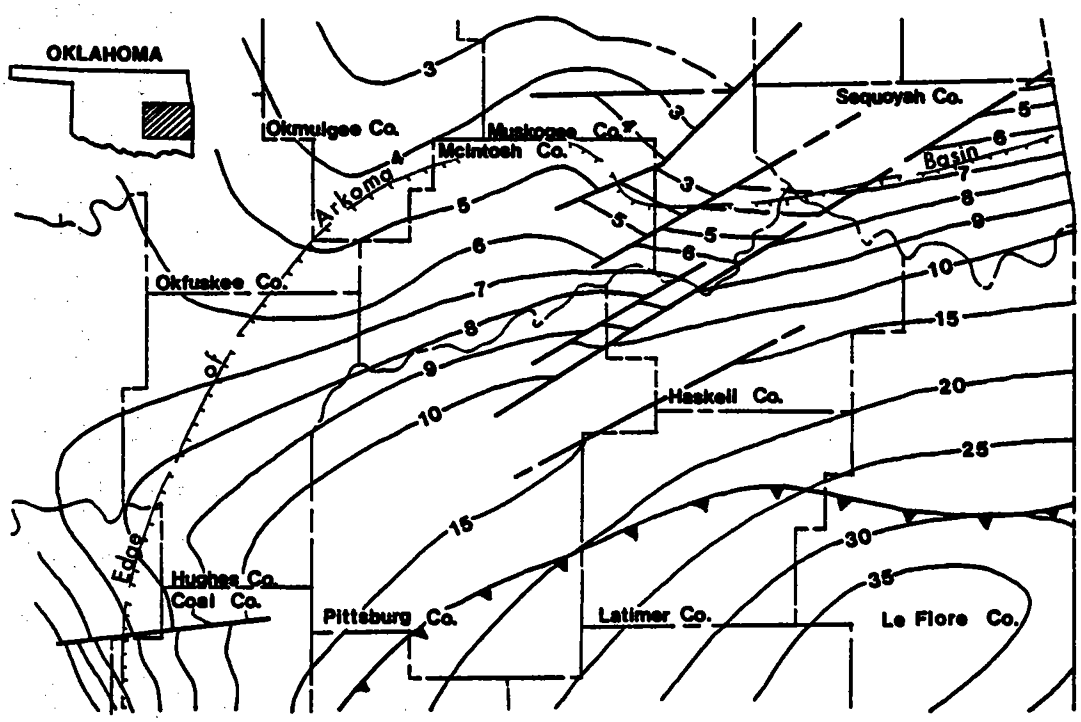

Figure 3. Map showing depth to basement in Arkoma Basin. Contours in thousands of feet below sea level. Modified from Lidiak (1982).

Geology

Phanerozoic deposition began with the transgression of Late Cambrian seas over an eroded Precambrian surface of low relief, followed by shallow-marine-shelf conditions that persisted until the post-Hunton (Devonian) uplift (fig. 4A). The area was structurally stable except for slow subsidence and southwesterly tilting, with the Oklahoma embayment the primary sedimentary feature (Branan, 1968). Deposition kept pace with subsidence, as evidenced by the absence of a deep-water facies in the sedimentary record. Following deposition of the Hunton Group, the area was uplifted, possibly in relation to the Acadian Orogeny (Disney, 1960).

Marine conditions returned to the Arkoma Basin in Late Devonian through Late Mississippian time, marking a change in the sedimentary pattern owing to influence from the Ouachita Geosyncline (Branan, 1968). Early, rapid movement of the Ouachita Geosyncline began in the Mississippian, with subsidence to the south resulting in shelf conditions in the Arkoma Basin and foredeep conditions in the Ouachita Mountain area (Disney, 1960). With the beginning of subsidence, down-to-the-basin tensional faults began to form, subsequently denoting a facies change from shelf to foredeep conditions during Mississippian and Early Pennsylvanian (Morrowan) time (Haley, 1982). During Morrowan time, the area continued to subside and tilt to the south, and marine-shelf conditions persisted (fig. 4B).

Maximum subsidence in the Arkoma Basin occurred during Early Pennsylvanian (Atokan) time, accompanied by extensive basinwide block faulting (Branan, 1968) (fig. 4C). Deltas began prograding southward from the uplifted Ozark region during early Atokan time, while prodeltaic foredeep conditions existed along the southern margin. Complete southward progradation of the deltaic environment was not accomplished until late Atokan time (Haley, 1982). Uplift

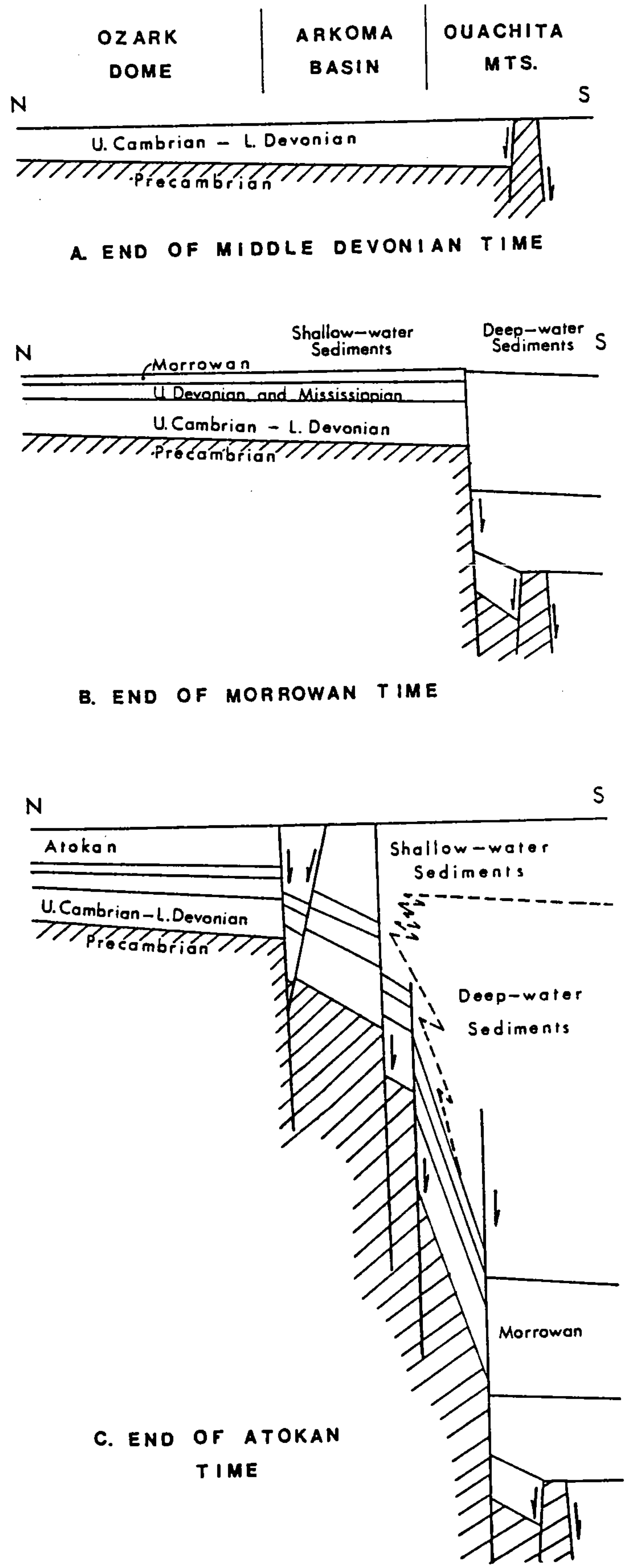

Figure 4. Generalized cross sections of Arkoma Basin and vicinity showing basin development through Atokan time. Not to scale. Modified from Haley (1982).

related to the early stages of the Ouachita Orogeny began in late Atokan time, affecting sedimentary patterns more than the structural framework of the basin. By early Desmoinesian time, these movements had changed the physical character of the basin such that thin coal seams are found in the sedimentary record for the first time.

Subsidence and block faulting continued into early Desmoinesian time, but pulses in the Ouachita uplift restricted access to southeastern seas, thus forming the vast coal deposits found in the Midcontinent region (Branan, 1968). Desmoinesian deposits in the Ouachita Mountains to the south are absent, and limits of the basin were close to the current limits. Deposition was cyclical, especially on the northern shelf, with each marine transgression from the west followed by deltaic conditions, the development of coal swamps, and a return to marine conditions.

Sedimentation continued in the Arkoma Basin until the Late Pennsylvanian Arbuckle Orogeny separated the Fort Worth Basin from the Arkoma Basin. However, rocks younger than Desmoinesian are absent over a large part of the basin. This could possibly indicate that the area has been above sea level since late Desmoinesian time (Haley, 1982).

Two structural patterns are found in the Arkoma Basin: (1) block faulting and (2) folding and northward overthrusting. Tensional forces, developed as the basin subsided and the Ozark Dome remained stable, created east-west-trending down-to-the-basin normal faults, predominantly Atokan in age and increasing in magnitude southward. Enough Atokan shale was deposited on the downthrown side of these faults to compensate for the throw, resulting in the absence of the structures at the surface.

Compressional forces resulting from the Ouachita Uplift (Late Pennsylvanian-Early Permian) to the south produced long, narrow folds and thrust faults that diminish with depth. Imbricate thrusting in the Atoka section causes much repetition of section and has created a complex structural configuration in which post-Morrowan beds are thrusted and folded, whereas pre-Atokan beds are only block faulted (fig. 5). An unusual structural development in the basin is the presence of surface anticlines on the downthrown side of major subsurface faults. These structures served as buttresses during the compressional phase and caused the thicker Atoka section on the south side of block faults to be shoved and thrust upward.

Pre-Desmoinesian Stratigraphy

Precambrian.--Precambrian rocks do not crop out in the Arkoma Basin, and wells penetrating basement are few and restricted to the northern shelf area. Where the basement is intersected by deep wells, rhyolite porphyry and granite were encountered (fig. 6). A prominent -100 mGal gravity minimum suggests that the basement in the Arkoma Basin is composed of low- or moderate-density material, consistent with the findings along the northern shelf.

Upper Cambrian to Lower Devonian.--This interval--which includes, in ascending order, the Timbered Hills Group, Arbuckle Group, Simpson Group, Viola Group, Sylvan Shale, and Hunton Group--consists of a basal transgressive sandstone followed by a predominance of carbonates (fig. 6). The section is composed mostly of dolomite with some limestone, containing oolites, oolitic chert and chert. Some sandstone and a few thin shale beds are also present. The thickness increases southward across the basin, ranging from more than 2,500 feet on the north to more than 5,000 feet on the south. The depositional environment was primarily a shallow-water-marine shelf, thickening to the southwest, which was structurally stable except for slow subsidence and westerly tilting. Unconformities produced during this interval are widespread, and represent slight bowing and tilting more

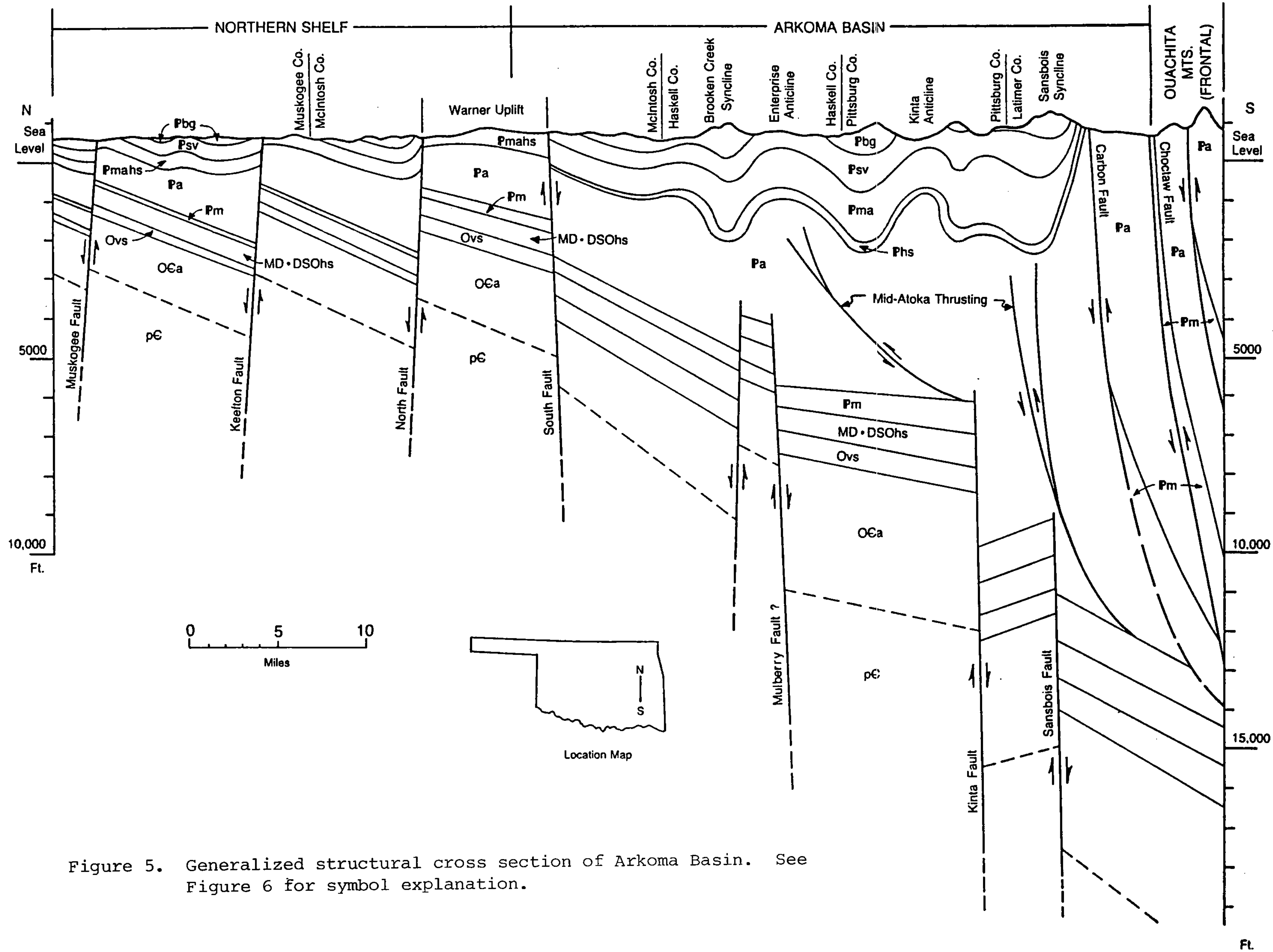

Figure 5. Generalized structural cross section of Arkoma Basin. See Figure 6 for symbol explanation.

	SERIES		FORMATION	
PENNSYLVANIAN	Desmoinesian	Krebs Gp.	Boggy Fm.	Pbg
			Savanna Fm.	Psv
			McAlester Fm.	Pma
			Hartshorne Fm. — Upper / Lower	Phs
	Atokan		Atoka Fm.	Pa
	Morrowan		Wapanucka Ls. Limestone Gap Sh. Union Valley Ls. Cromwell ss.	Pm
MISSISSIPPIAN	Chesterian		Goddard Fm.	MD
	Meramecian		Delaware Creek Sh. (="Caney")	
	Osagean			
	Kinderhookian		Welden Ls.	
DEVONIAN	Upper		Woodford Sh.	
	Lower	Hunton Gp.	Frisco Ls. Bois d'Arc Ls. Haragan Ls.	DSOhs
SILURIAN	Niagaran		Henryhouse Fm.	
	Alexandrian		Chimneyhill Subgroup	
ORDOVICIAN	Upper		Sylvan Sh.	
		Viola Gp.	Welling Fm. Viola Springs Fm.	Ovs
	Middle	Simpson Gp.	Bromide Fm. Tulip Creek Fm. McLish Fm. Oil Creek Fm. Joins Fm.	
	Lower	Arbuckle Gp.	West Spring Creek Fm. Kindblade Fm. Cool Creek Fm. McKenzie Hill Fm. Butterly Dol.	O€a
CAMBRIAN	Upper		Signal Mountain Ls. Royer Dol. Fort Sill Ls.	
		Timbered Hills Gp.	Honey Creek Ls. Reagan Ss.	
PRECAMBRIAN			Granite & Rhyolite	p€

Figure 6. Stratigraphic chart for Arkoma Basin.

than significant structural events (Haley, 1982). This interval was climaxed by the post-Hunton (Devonian) uplift which affected a major part of the entire continent and changed sedimentary patterns in the area.

Upper Devonian through Mississippian.--This interval includes, in ascending order, the Woodford Shale, Welden Limestone, Delaware Creek ("Caney") Shale and Goddard Formation (fig. 6) and represents initial deposition in the Ouachita geosyncline in the Arkoma Basin (Branan, 1968). Following the mid-Devonian emergence of the area, marine conditions returned, depositing about equal percentages of limestone (some cherty) and shale. Sandstone and siltstone are found along the northern edge of the basin. Limestone changes southward to silty limestone, limy siltstone, and shale (Haley, 1982). Shallow-marine-shelf conditions existed in the Arkoma Basin, with a deep-water environment to the south in the present Ouachita Mountain area. The thickness increases southward from less than 400 feet on the shelf to possibly more than 1,000 feet in the southern part of the basin. In the Ouachita Mountain area, equivalent strata reach a thickness greater than 5,000 feet. A disconformity separates the Upper Mississippian rocks from the overlying Pennsylvanian strata.

Pennsylvanian Morrowan Series.--Rocks of this series--which includes, in ascending order, the Cromwell sandstone, Union Valley Limestone, Limestone Gap Shale and Wapanucka Limestone (fig. 6)--contain nearly equal percentages of sandstone, shale, and limestone deposited in a shallow-marine environment (Haley, 1982). Conditions were still relatively stable, but sand made up an important percentage of the sediments for the first time. The thickness increases southward from less than 300 feet on the north to approximately 1,000 feet along the southern margin of the basin. In the Ouachita Mountains to the south, equivalent rocks increase in shale percentage and thickness, and represent a facies change to a deep-marine environment. These changes are attributed to the growth-fault system begun in Mississippian time. One fault scarp at least 2,300 feet high must have exposed lower Paleozoic rocks along the southern margin of the basin, as evidenced by the presence of exotic rock fragments in Morrowan shale (Haley, 1982). An unconformity separates this series from the overlying Atokan Series.

Pennsylvanian Atokan Series.--This series, composed entirely of the Atoka Formation (fig. 6), is made up primarily of shale (approximately 70 percent), with lenses and tongues of sandstone and siltstone, and a few coal beds making up the remaining percentages. Subsidence in the basin reached a maximum, introducing a deep-water environment along the southern margin of the basin for the first time. Deltas prograded southward from the uplifted Ozark region, finally reaching the south margin in late Atokan time. The thickness increases dramatically into the basin, from more than 1,500 feet on the northern edge to more than 10,000 feet along the southern edge. Excluding the basal sandstone, correlation between sandstones in the basin and on the shelf is nearly impossible. The presence of thin coal seams by late Atokan time indicates that the Arkoma Basin was becoming full of sediments and marks a return to shallow-water deposition in the basin.

PART III. - DESMOINESIAN STRATIGRAPHY AND COAL GEOLOGY

LeRoy A. Hemish

Introduction

The purpose of this part of the report is to review briefly the geologic setting of the coal-bearing strata in the study area and to present data concerning the quality of the coal beds sampled. A detailed study of the coal geology of the area was not the primary purpose of the work done during the investigation; however, a frame of reference must be established for the benefit of the reader. For more detailed descriptions of the character, distribution, thickness and depths of the coal beds in various parts of the study area, the reader is referred to works by Wilson and Newell (1937), Dane and others (1938), Hendricks and others (1939), Oakes and Knechtel (1948), Trumbull (1957), Vanderpool (1960), Friedman (1974, 1982), and Oakes (1977).

The area covered in this investigation includes most of Haskell and Muskogee Counties and parts of Latimer, McIntosh, and Pittsburg Counties, all within the coal belt of eastern Oklahoma (fig. 7). The coal belt (Friedman, 1974) is divided into two general regions: the northwestern area, usually called the shelf or platform area, and the southern area, usually called the Arkoma Basin area (fig. 7). The Arkoma Basin was named by Branson (1956). Other names for the Arkoma Basin are McAlester Basin (Oklahoma portion only), Arkansas Valley Basin, and Arkansas-Oklahoma Coal Basin (Jordan, 1959).

The shelf area borders the Ozark Uplift on the north and west. Rocks generally dip away from the Ozark Dome at angles of 1° or less. The regional dip of 25 to 50 feet per mile is interrupted by a series of northeast-southwest-trending folds and faults in the shelf area (Huffman, 1958). The sedimentary rocks that fill the basin are thousands of feet thick in the

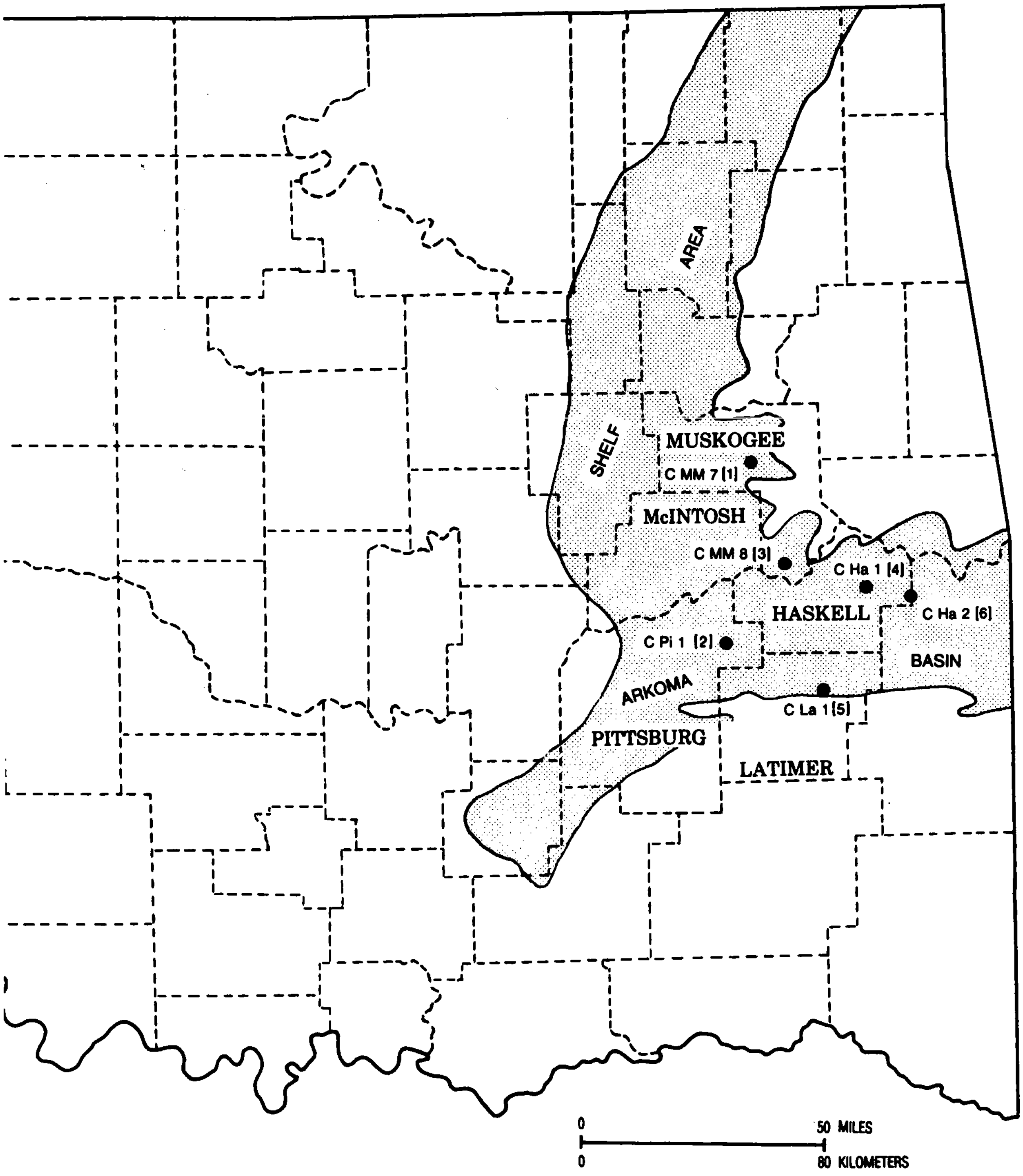

Figure 7. Map of eastern Oklahoma showing the coal belt (stippled pattern) and the locations of Oklahoma Geological Survey core-holes (solid circles). Core-holes logs are identified by the letter C, county abbreviations, and numbers; sample-identification numbers from table 2 are shown in parentheses.

central part of the basin. These units thin northward, and convergences of hundreds of feet within a few miles are common. Figure 8 shows the relationship of the Arkoma Basin to the shelf area.

Stratigraphy

The rocks exposed in the study area all belong to the Desmoinesian Series, Pennsylvanian System. The Desmoinesian Series rests comformably on the underlying Atokan Series, also Pennsylvanian. This part of the report is concerned only with some of the rocks in the Krebs Group of the Desmoinesian Series--specifically, the Hartshorne Formation, the McAlester Formation, the Savanna Formation, and the Boggy Formation (fig. 6).

Hartshorne Formation.--The oldest of the coal-bearing rocks discussed herein is the Hartshorne Formation. It is conformable with the Atoka Formation, below, and the McAlester Formation, above (Oakes, 1977). The generalized stratigraphic column (pl. 2) shows the section of rocks containing the coal beds studied in the present investigation.

The Hartshorne Formation is dominantly sandstone, usually brown to gray, thin bedded and locally shaly. In places, the upper beds are thick and massive, while the lower beds generally grade into shale toward the base. The maximum thickness of the Hartshorne Formation is estimated to be about 316 feet (Friedman, 1974).

Two coal beds, known as the Upper and Lower Hartshorne coals, are associated with the Hartshorne Sandstone. In the northeastern part of the area of investigation, the two coals are represented by one seam composed of upper and lower parts separated by a 2-inch-thick carbonaceous shale parting (see core-hole log C Ha 2, No. 6 in Appendix). In the southwestern part of the area, the Lower Hartshorne coal bed is separated from the upper bed by more

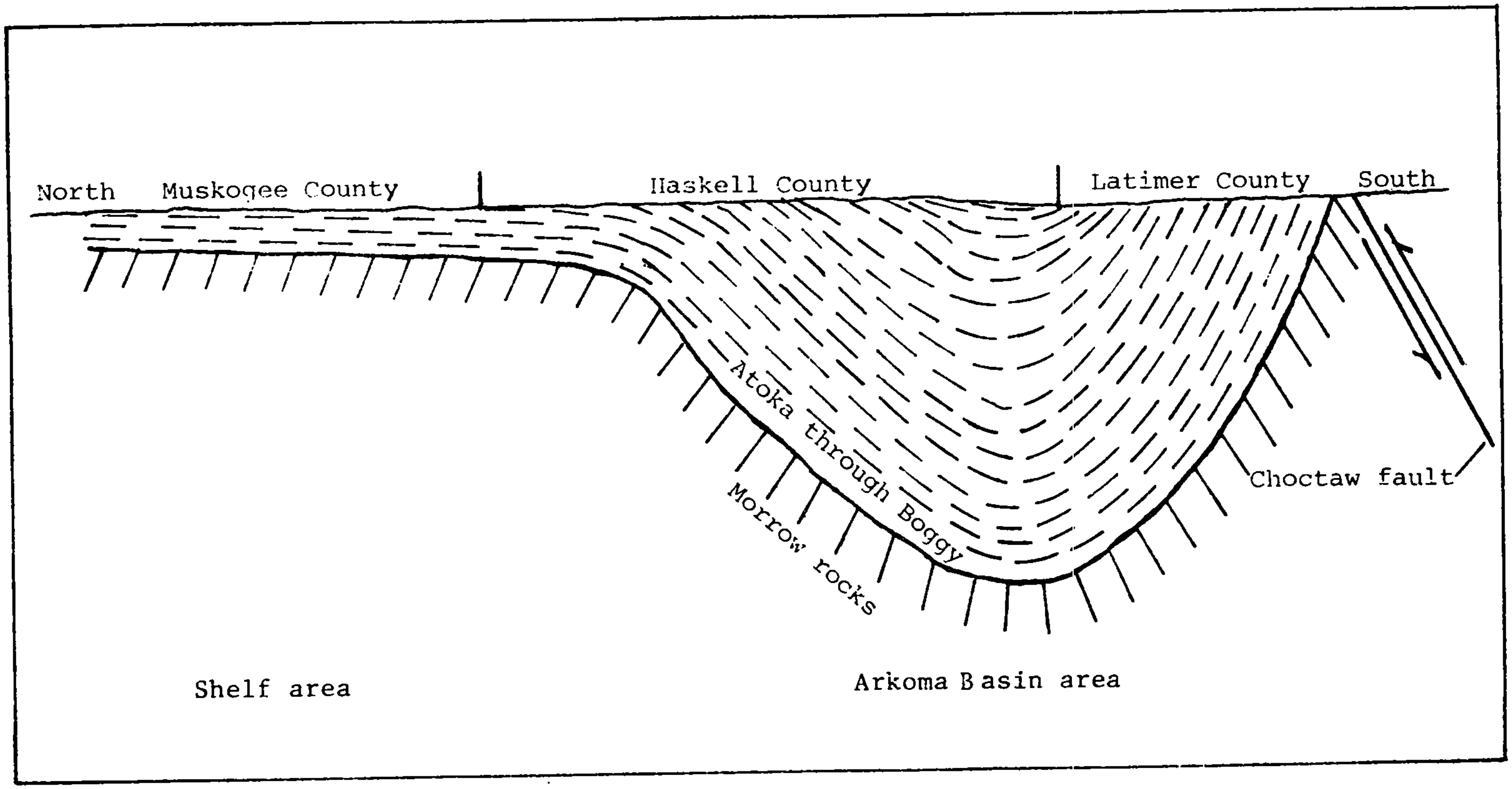

Figure 8. North-south diagram showing relation of shelf area to Arkoma Basin. Not to scale. Rocks shown are of Early Pennsylvanian age. Modified from Oakes and Knetchel (1948).

than 100 feet of sandstone and shaly strata. The log of core hole C La 1, no. 5 (fig. 7 and Appendix) shows that a grayish-black carbonaceous shale is present at the stratigraphic position generally occupied by the Upper Hartshorne coal bed. Figure 9 shows the relationship of the Upper and Lower Hartshorne coals in the study area. The top of the Upper Hartshorne coal marks the boundary between the Hartshorne Formation and the overlying McAlester Formation in the area of the present investigation.

McAlester Formation.--The McAlester Formation consists predominantly of silty shale and clay shale. Several sandstone beds occur at widely spaced intervals within the formation. Wilson (1935) formally named these sandstone units and the lowest shale unit. From the base upward, the units are McCurtain Shale, Warner Sandstone, Lequire Sandstone, Cameron Sandstone, Tamaha Sandstone, and Keota Sandstone.

The McAlester Formation also includes a few thin, discontinuous limestone beds and several coal beds (pl. 2). Most of the coal beds have not been named, and are thin and discontinuous. The named beds include the McAlester, the Upper McAlester, the Stigler, and the Stigler rider. Friedman (1982) equated the Stigler with the McAlester and the Stigler rider with the Upper McAlester.

The McAlester Formation is variable in thickness. Its maximum estimated thickness (in the Arkoma Basin) is more than 2,800 feet (Friedman, 1974). In the northern part of the area of present investigation (T. 15 N.) Oakes estimated its thickness to be about 150 feet; the top of the McAlester Formation is the base of the Spaniard Limestone, the basal member of the overlying Savanna Formation (Oakes, 1977).

Savanna Formation.--In the Arkoma Basin, the Savanna Formation consists mostly of sandstone and shale, a few thin, discontinuous limestone beds, and several thin coal beds. It thins northward, and on the shelf area in Muskogee

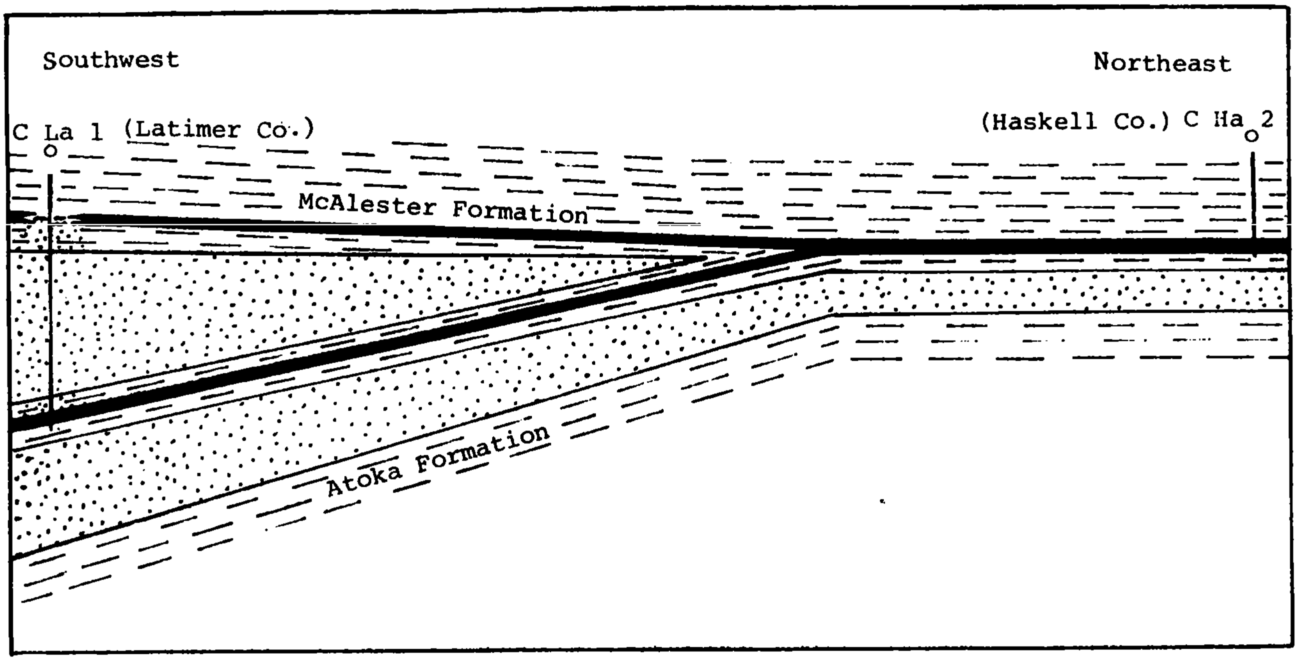

Figure 9. Schematic diagram showing Hartshorne Formation in the study area and the relationship of the Upper and Lower Hartshorne coals (shown in black). Logs of core holes C Ha 2 (no. 6) and C La 1 (no. 5) are given in appendix. Modified from Oakes and Knetchel (1948).

County it contains three named limestones and one coal bed that is sufficiently thick for mining (Rowe coal). In T. 15 N., Muskogee County, the Savanna Formation is about 170 feet thick (Oakes, 1977). In the Arkoma Basin, its estimated maximum thickness is 2,500 feet (Friedman, 1974). The top of the Savanna Formation is the base of the Bluejacket Sandstone, the basal member of the overlying Boggy Formation.

Boggy Formation.--The Bluejacket Sandstone is generally a fine-grained, silty, cross-bedded sandstone that weathers yellowish brown to reddish brown. Its thickness varies considerably, from as thick as 150 feet in the Arkoma Basin (Oakes and Knechtel, 1948) to as thin as 10 feet in T. 15 N., in the Muskogee area (Bell, 1959).

A shale unit ranging from 4 to 20 feet thick overlies the Bluejacket Sandstone. The shale unit contains coal beds that locally occur at more than one zone. The name Secor has been applied to the most prominent coal seam lying above the Bluejacket Sandstone (Oakes, 1977); (see logs of core holes C MM 7, no. 1 and C Pi 1, no. 2 in Appendix).

A 10-foot-thick, fine-grained, reddish-brown sandstone overlies the shale unit that contains the Secor coal. The sandstone was named Crekola in Muskogee County by Wilson (1935). Positive correlations with sandstone units occuring in similar stratigraphic positions in surrounding areas have not been made.

About 80 feet of Boggy rocks overlying the Secor coal was logged in core hole C Pi 1, no. 2 (Appendix) in Pittsburg County. These rocks consist of shale, sandstone, a thin unnamed limestone, and a 10-inch-thick unnamed coal. No younger rocks (other than unconsolidated Quaternary materials) were encountered during the coring project in the area of investigation.

The Boggy Formation is the youngest formation in the Krebs Group. Rocks above the units discussed (lower part of the Boggy Formation) are of no concern in the present investigation.

Chemical Properties and Coal Classification

Chemical analyses of the various coal beds sampled from the cores were performed by the laboratories of the Oklahoma Geological Survey according to standard procedures of the American Society for Testing and Materials (1984). Table 1 shows the analyses of the coal samples and the rank of the coal.

The rank of coal was determined according to the standard classification of the American Society for Testing and Materials (1984, p. 242-246), using the appropriate Parr formula (Mm-free basis) which is reproduced below.

Moist, Mm-free Btu = (Btu - 50S)/[100 - (1.08A + 0.55S)] x 100, where:

Mm = mineral matter,

Btu = British thermal units per pound (calorific value),

A = percentage of ash, and

S = percentage of sulfur.

Two of the coal beds sampled were classified as medium-volatile bituminous in rank (Hartshorne and McAlester (Stigler), in the eastern part of the area of investigation). The other four samples were classified as high-volatile A bituminous in rank.

Summary

Two cross sections were constructed to show the relationships of the various stratigraphic units encountered during the study (see pl. 2). The primary purpose of preparing the cross sections was to demonstrate that the three coal samples cored in the high geothermal-gradient areas (fig. 10) are

Table 1. Analyses of coals cored by Oklahoma Geological Survey
(Samples collected in 1984 by L. A. Hemish and tested in 1984 by the OGS Chemistry Laboratory)

Sample number[a]	Map number[b] (Fig. 7)	Coal bed	Sample condition	Proximate analysis (percent)				Sulfur (percent)	Btu/lb	Free swelling index	Rank[c]
				Moisture	Volatile matter	Fixed carbon	Ash				
84-C-20-H 84-C-21-H 84-C-22-H	C Ha 2 (no. 6)	Hartshorne	As received	2.1	20.0	67.6	10.3	3.6	13,476	9.0	mvb
84-C-23-H 84-C-24-H	C La 1 (no. 5)	Lower Hartshorne	As received	4.6	34.5	52.1	8.8	2.0	12,862	7.5	hvAb
84-C-08-H	C MM 7 (no. 1)	Secor	As received	3.0	33.8	57.5	5.7	0.7	13,899	8.5	hvAb
84-C-29-H 84-C-30-H 84-C-31-H	C Pi 1 (no. 2)	Secor	As received	1.6	38.9	48.9	10.6	4.9	13,133	7.5	hvAb
84-C-10-H 84-C-11-H	C MM 8 (no. 3)	McAlester (Stigler)	As received	1.0	29.1	61.8	8.1	1.6	14,066	9.0	hvAb
84-C-17-H 84-C-18-H 84-C-19-H	C Ha 1 (no. 4)	McAlester (Stigler)	As received	1.9	25.0	67.9	5.2	1.1	14,471	9.0	mvb

[a]For analyses with multiple sample numbers, determinations are from composite weighted averages.

[b]Data-point number on map (sample site) corresponds to measured section number, Appendix, this report.

[c]hvAb, high-volatile A bituminous; mvb, medium-volatile bituminous.

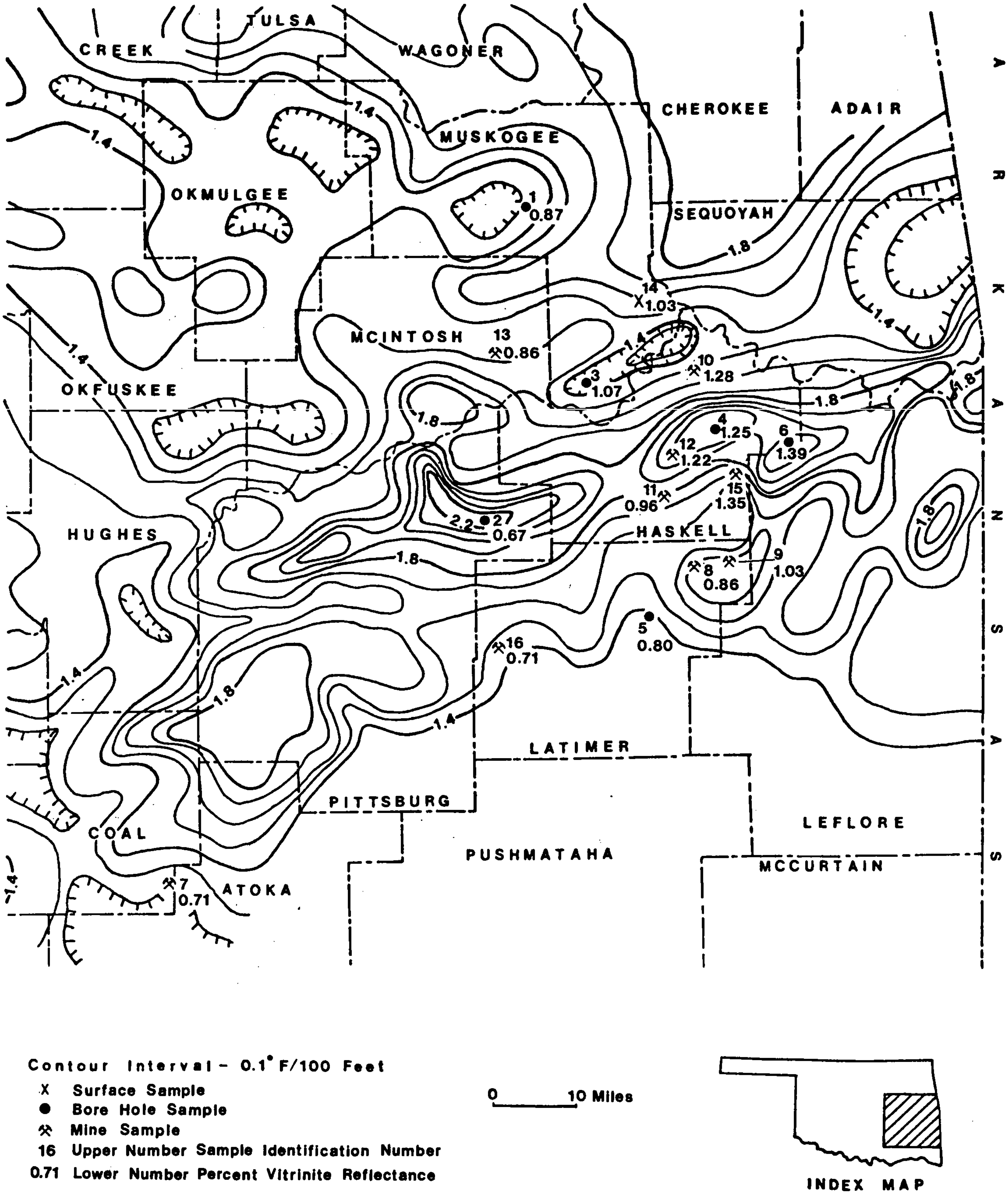

Figure 10. Geothermal-gradient map of eastern Oklahoma, showing location of coal samples and vitrinite-reflectance data (modified from Cheung, 1978).

correlatable with the three coal samples cored in the low geothermal-gradient areas (fig. 10). The three coal beds sampled include the Hartshorne coal (Hartshorne Formation), the McAlester (Stigler) coal (McAlester Formation), and the Secor coal (Boggy Formation). Data from sources other than the coring project were incorporated into the cross sections to enhance the presentation.

PART IV. - PRESENT GEOTHERMAL GRADIENT AND COAL RANK IN THE ARKOMA BASIN, OKLAHOMA

Brian J. Cardott

Introduction

The geothermal-gradient map of eastern Oklahoma delineates a range in the present geothermal gradient in the Arkoma Basin of 1.3° to 2.3°F/100 feet (Cheung, 1978). A high-gradient trend occurs from east-northeast to west-southwest through Haskell and Pittsburg Counties, Oklahoma (figure 10).

The surface rocks of any geologic province record and date the last heating event since deposition of the sediment. The Geologic Map of Oklahoma (Miser, 1954) indicates that the surface rocks in the Arkoma Basin are of the Desmoinesian Series, Pennsylvanian System. This series contains the major coal-bearing rocks of the Arkoma Basin.

The objective of this section is to determine if there is a relationship between the present geothermal gradient and coal rank. This can be realized through a comparison of rank on the same coal seam from areas of contrasting geothermal gradients. Of related concern are the following:

(1) What was the source of the heat that produced the coal rank?

(2) When was the coalification completed?

(3) Does the present geothermal-gradient pattern follow a remnant gradient trend that relates to coal rank?

(4) What is the reason for the geothermal-gradient pattern present today?

Data Acquisition

Initially, three coal seams were selected for coring, consisting of one sample from a high geothermal-gradient zone and a matching sample of the same coal seam from a low geothermal-gradient zone. The three coal seams selected are the Secor coal (Boggy Formation), McAlester (Stigler) coal (McAlester Formation), and Hartshorne coal (Hartshorne Formation). In this report the Stigler coal is correlated with the McAlester coal in accordance with Friedman (1978). Figure 10 gives the location of the six samples as identification numbers (ID) 1 through 6. Table 2 provides sampling information. Figure 11 provides a generalized geologic column of the Desmoinesian Series in part of the Arkoma Basin, eastern Oklahoma.

Three orientations were selected relative to the trend of the high geothermal-gradient zone:

(1) north/south orientation with low geothermal-gradient zone to the north (Secor coal pair, ID 1, 2);

(2) east/west orientation with low geothermal-gradient zone to the west (McAlester [Stigler] coal pair, ID 3, 4);

(3) northeast/southwest orientation with low geothermal-gradient zone to the southwest (Hartshorne coal pair, ID 5, 6).

The coal core samples were crushed to minus one-half inch and split in half to provide material for chemical and petrographic analysis. One split was crushed to minus sixty mesh (less than 0.25 mm) for chemical analysis. The other split was crushed to minus twenty mesh (less than 0.84 mm) for petrographic analysis. The minus-twenty-mesh fraction was prepared into crushed-particle pellets and polished to 0.05 microns following ASTM D 2797 (ASTM, 1984). Mean maximum vitrinite reflectance in oil immersion ($\%R_o$) was determined on the coal samples following ASTM D 2798 (ASTM, 1984). Ten additional coal samples were collected from active coal mines or outcrop to supplement the coal core data. Figure 10 and table 2 give the locations and sampling information for identification numbers 7 through 16. These consist of six samples of the McAlester (Stigler) coal and four samples of the Hartshorne coal. Whole-seam channel samples were collected from each. These coal samples

Table 2. Sample information, vitrinite-reflectance data (R_o), and present geothermal gradient

ID no.	OPL no.(s)	Other ID	Location	Coal seam	Seam thickness (inches)[a]	Sample type	R_o(%)[b]	Rank[c]	Present geothermal gradient (°F/100 ft)
1	429	C-MM-7	4-13N-18E	Secor	7	core	0.87	hvAb	1.3
2	463-465	C-Pi-1	11- 7N-17E	Secor	27½	core	0.67	hvBb	2.3
3	444-445	C-MM-8	22-10N-19E	McAlester	22	core	1.07	hvAb	1.4
4	451-453	C-Ha-1	20- 9N-22E	McAlester	27	core	1.25	mvb	2.1
5	457-458	C-La-1	12- 5N-20E	L. Hartshorne	22	core	0.80	hvAb	1.4
6	454-456	C-Ha-2	36- 9N-23E	Hartshorne	27	core	1.39	mvb	2.1
7	494	---	16- 1N-11E	McAlester	12/36	mine	0.71	hvAb	1.4
8	499	---	11- 6N-21E	McAlester	12/24	mine	0.86	hvAb	1.7
9	503	---	3- 6N-22E	McAlester	10/21	mine	1.03	hvAb	1.7
10	506	---	13-10N-21E	McAlester	12/24	mine	1.28	mvb	1.5
11	509	---	29- 8N-21E	McAlester	8/17	mine	0.96	hvAb	1.8
12	513	---	33- 9N-21E	L. Hartshorne	7	mine	1.22	mvb	2.1
13	323-324	---	36-11N-17E	McAlester	18	mine	0.86	hvAb	1.5
14	319	---	35-12N-20E	Hartshorne	9	outcrop	1.03	hvAb	1.6
15	351	---	14- 8N-22E	U. Hartshorne	27	mine	1.35	mvb	1.7
16	419-420	---	25- 5N-17E	L. Hartshorne	28	mine	0.71	hvAb	1.5

[a] Where two numbers are given, the first number indicates the thickness of the upper bench that was analyzed for vitrinite reflectance. The second number indicates the total seam thickness.

[b] Vitrinite reflectance in oil immersion.

[c] hvBb = high volatile B bituminous; hvAb = high volatile A bituminous; mvb = medium volatile bituminous.

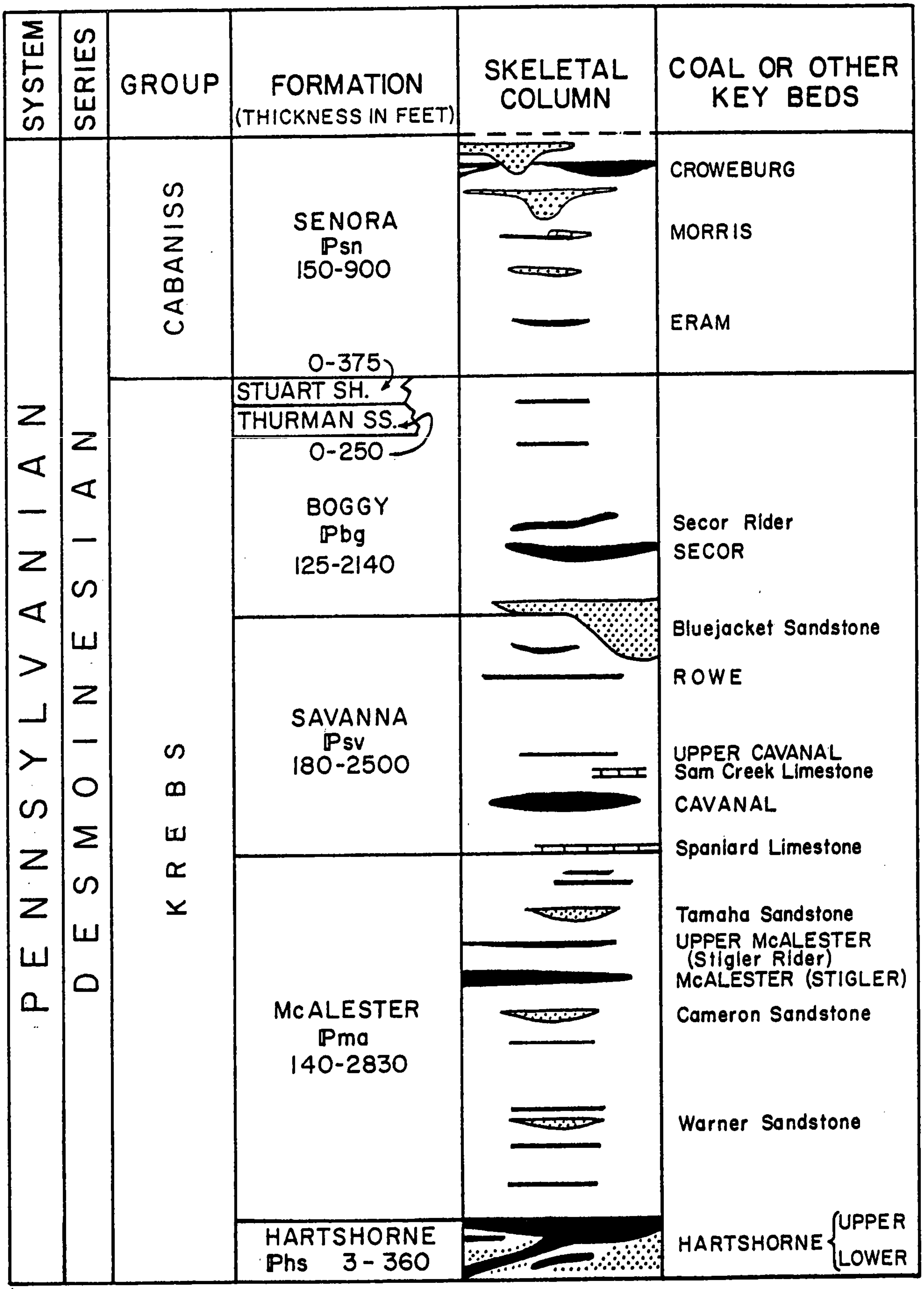

Figure 11. Generalized geologic column showing coals and other key beds of Desmoinesian age in part of the Arkoma Basin, eastern Oklahoma (modified from Friedman, 1978).

were processed identical to the coal core samples. Only the upper bench was analyzed for vitrinite reflectance for some of these samples (ID 7-11).

Discussion of Results

Table 2 summarizes the mean maximum vitrinite-reflectance data for each coal sample, assigns the rank following Davis (1984), and provides the approximate present geothermal gradient from the geothermal-gradient map of Oklahoma (Cheung, 1978).

Concerning the six paired coal cores (ID 1-6), the high geothermal-gradient zones contain the higher rank coal for the McAlester and Hartshorne coal pairs, while the high geothermal-gradient zone of the Secor coal contains the lower rank coal. Therefore, two of the three coal core pairs appear to have a direct relationship between geothermal gradient and coal rank.

Table 3 compares the present geothermal gradient with coal rank for all of the coal samples. The additional coal samples (ID 7-16) indicate that there is not a corresponding increase in coal rank with an increase in geothermal gradient. There is a wide range in rank for coals with the same geothermal gradient (ID 7, 3; 13, 10; 12, 6), even in the same contour interval (ID 8, 9). The apparent relationship between present geothermal gradient and coal rank (ID 3-6) is due to the thermal overprint of increasing coal rank toward the east.

Relationship between present geothermal gradient and coal rank.--It has already been established that coal rank in the Arkoma Basin of Oklahoma was not produced by the present geothermal gradient. What remains to be explained is the source and timing of establishing the coal rank, any relationship between coal rank and a paleogeothermal gradient that may have a remnant today, and the reason for the present geothermal-gradient anomalies.

Table 3. Comparison between present geothermal gradient and coal rank

ID no.	Present geothermal gradient (°F/100 ft)	R_o(%)
	Secor coal	
1	1.3	0.87
2	2.3	0.67
	McAlester (Stigler) coal	
7	1.4	0.71
3	1.4	1.07
13	1.5	0.86
10	1.5	1.28
8	1.7	0.86
9	1.7	1.03
11	1.8	0.96
4	2.1	1.25
	Hartshorne coal	
5	1.4	0.80
16	1.5	0.71
14	1.6	1.03
15	1.7	1.35
12	2.1	1.22
6	2.1	1.39

Source and timing.--The time constraint for the emplacement of coal rank ranges from the time of peat deposition in Desmoinesian time to the present. Coal rank could have developed during any segment of that time period or could have taken the entire length of time. Certain lines of evidence limit us to a segment of time.

One line of evidence comes from the source of heating. It has long been known from isocarb data that the coal rank in the Arkoma Basin ranges from high-volatile bituminous in Oklahoma to semianthracite in Arkansas, increasing from west to east (Fuller, 1920; Hendricks, 1935; Hendricks and others, 1939; Wilson, 1961, 1971; Burgess, 1974; Damberger, 1974). It has been shown that the source of heat is localized in the eastern Arkoma Basin in Arkansas with regional heating effects that extend into Oklahoma. This observation is important to discount the development of the Ouachita Mountains to the south as the source of heat.

The development of high-volatile bituminous rank requires a temperature of greater than 150°F (Staplin, 1982). This would require either a minimum depth of burial of 4,500 feet (average geothermal gradient of 1.8°F/100 feet and assumed near-surface temperature of 70°F) or a high heat flow from a thermal anomaly. Higher temperatures approaching 350°F are required to produce a coal of semianthracite rank (Staplin, 1982). This would require an unrealistic increase in overburden from west to east in the Arkoma Basin. Haley (1982) suggests that Pennsylvanian rocks younger than Desmoinesian never were deposited in the Arkoma Basin, as the region has been above sea level since that time. Therefore, high heat flow from a thermal anomaly in Arkansas is more likely to be the cause of heating.

Damberger (1974, p. 67) alludes to a geothermal anomaly having developed after the Late Pennsylvanian Epoch:

> In the Arkoma Basin, rank increases to semianthracitic rather rapidly to the east from the Oklahoma-Arkansas boundary. The coals are of about the same age throughout the area, and no significant change of thickness, which might help explain the rank changes, has been observed in west-east direction in the Pennsylvanian Period. Rapid change in rank parallel to the structural grain suggests the development of a geothermal anomaly in this area some time after the late Pennsylvanian Period. Igneous intrusions of Mesozoic to Cenozoic age and still-active hot springs in the eastern Ouachita Mountains and the adjacent areas of the Mississippi Embayment can be cited in support of this interpretation.

Some have taken this to mean that the timing of heating in the Arkoma Basin is attributed to Mesozoic igneous intrusion, particularly during the Cretaceous (Reike and Kirr, 1984, p. 137, cited from Craney, 1978). Scull (1958) and Stone and Sterling (1964, fig. 2) documented the locations and ages of various igneous activity in Arkansas, most of which occurred in the eastern Ouachita Mountain region during the Mesozoic Era. Houseknecht and Matthews (1985) indicated that the Mesozoic intrusive overprint dies out within 50 km (31 mi) of the intrusive region (fig. 12). Haley (1984, personal communication) has indicated that medium-volatile and low-volatile bituminous rank coals occur between the igneous region and the semianthracite rank coals in Arkansas. Stone (1984, personal communication) has concurred that the coal rank present in the Arkoma Basin was not produced by Mesozoic igneous activity, but probably was established earlier, during the late Paleozoic. Desborough and others (1985) used zircon fission-track dating to determine that the thermal alteration occurred during Early Permian time in the Ouachita region and the Arkansas River Valley (Arkoma Basin). They state that "our data show that a regional high heat-flow (175°-200°C) event occurred in Arkansas during late Paleozoic time and contrasts with localized thermal effects of Cretaceous plutons." Denison and others (1977) and Denison (1982) indicate that the most recent period of metamorphic activity in the Ouachita fold belt occurred from about 320 to 250 million years ago. The Ouachita Orogeny began in

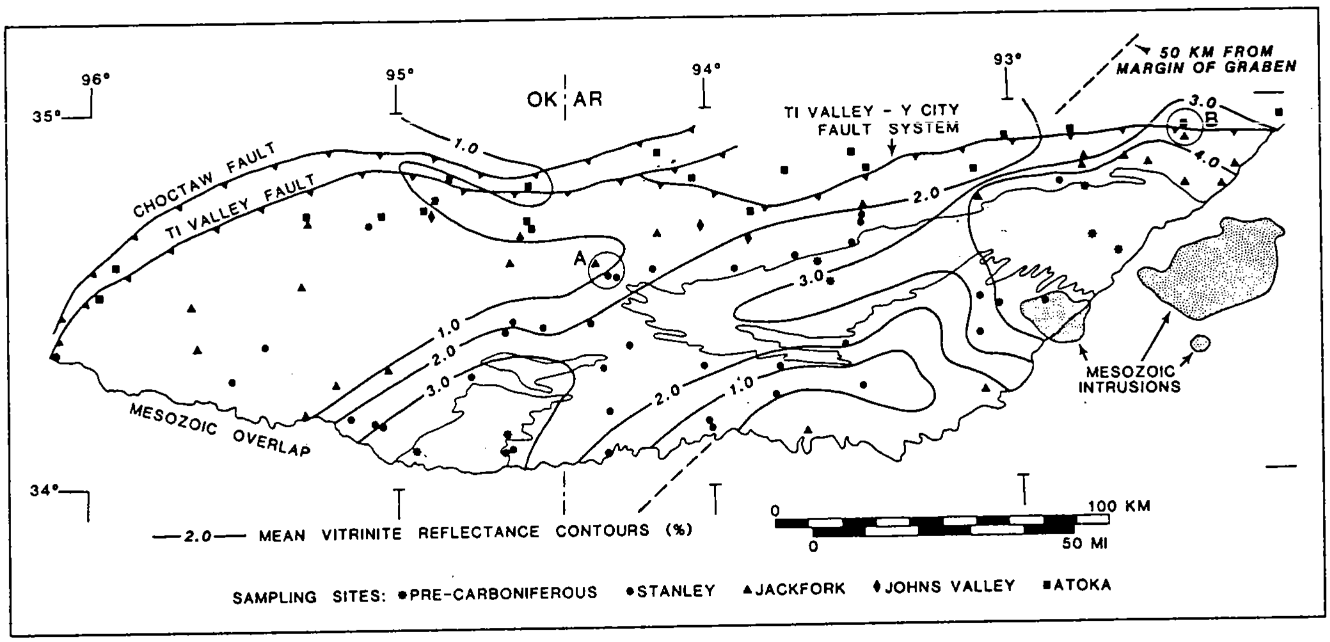

Figure 12. Thermal-maturity map of exposed strata in Ouachita Mountains showing 50-km (31-mi) zone of anomalously high thermal maturities associated with Mesozoic rifting (from Houseknecht and Matthews, 1985).

Mississippian time and culminated during Early Permian time (Branan, 1968; Fay and others, 1979). The exact nature of the high heat source has not been determined.

Coal rank and paleogeothermal-gradient remnant.--Several versions of an isocarb map on coals in the Arkoma Basin have been developed (Fuller, 1920; Hendricks, 1935; Wilson, 1961, 1971; Burgess, 1974; Damberger, 1974; Friedman, in preparation; figs. 13-16). Most of these maps show the isocarb contours cutting obliquely across present geothermal-gradient contours. A slight deviation in the contours occurs along the high geothermal-gradient zone through Haskell and Pittsburg Counties, Oklahoma. Burgess (1974) used coal fixed-carbon data in conjunction with kerogen-color data from shales to produce an isocarb map that clearly has high rank lobes that parallel the high geothermal-gradient zone (fig. 16).

Although no overwhelming evidence supports the claim, coal isocarb mapping suggests that the present geothermal-gradient pattern reflects the paleo-geothermal gradient that produced the coal rank. This does not mean that the coal rank was produced directly from the present geothermal gradient.

Present geothermal-gradient pattern.--Fourier's Law relates geothermal gradient to heat flow and thermal conductivity of lithologies (Turcotte and Schubert, 1982). In addition, geothermal gradient depends on subsurface water movement (Blatt, 1982; Isprapilov and Abdurakhmanov, 1984). Therefore, variations in heat flux from the Precambrian basement rocks in the Arkoma Basin and variations in thermal conductivities of a wide range in lithologies and thicknesses and water movement may have caused the pattern of the present geothermal anomaly.

Denison (1981), Lidiak (1982), and Denison and others (1984) describe the structural framework, basement-rock types, and regional geophysics in and

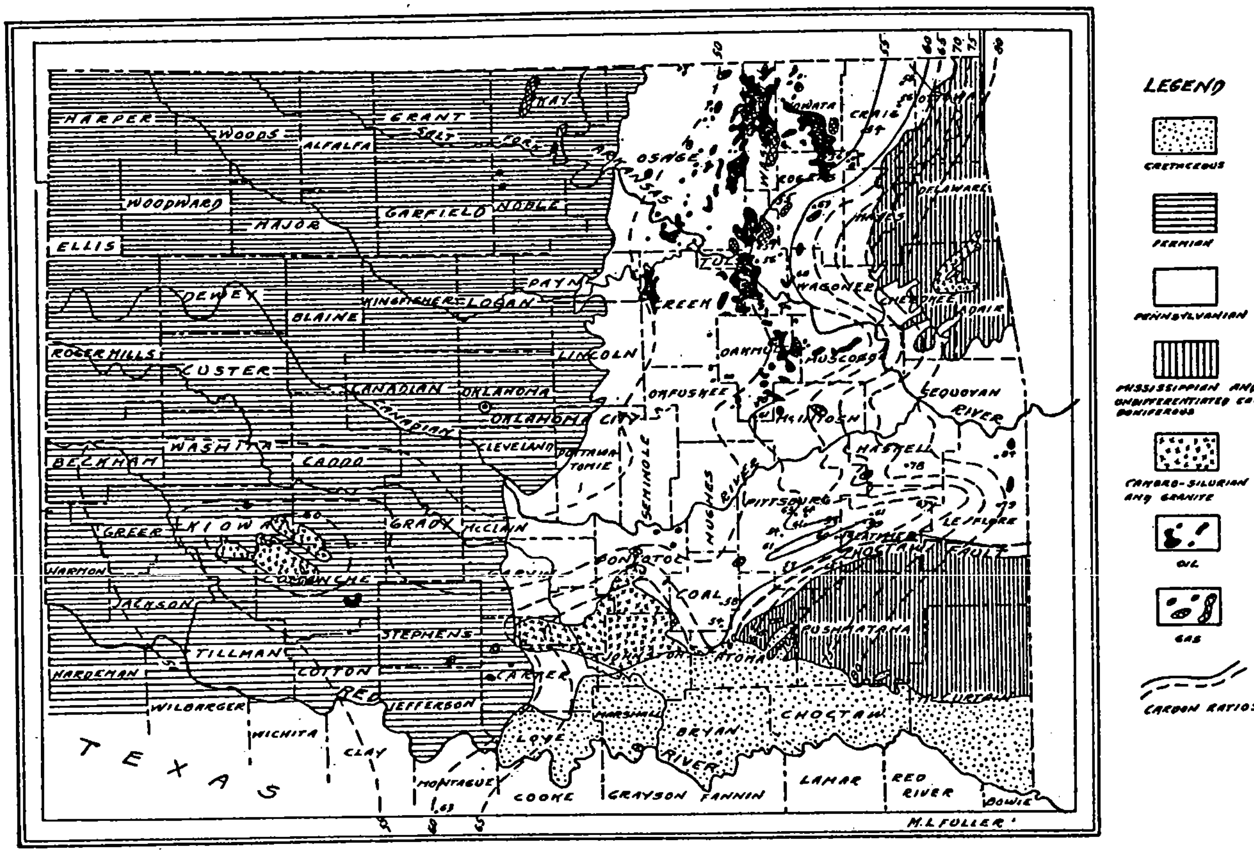

Figure 13. Map of lines of equal fixed-carbon percentages as determined on a pure-coal basis in Oklahoma (from Fuller, 1920).

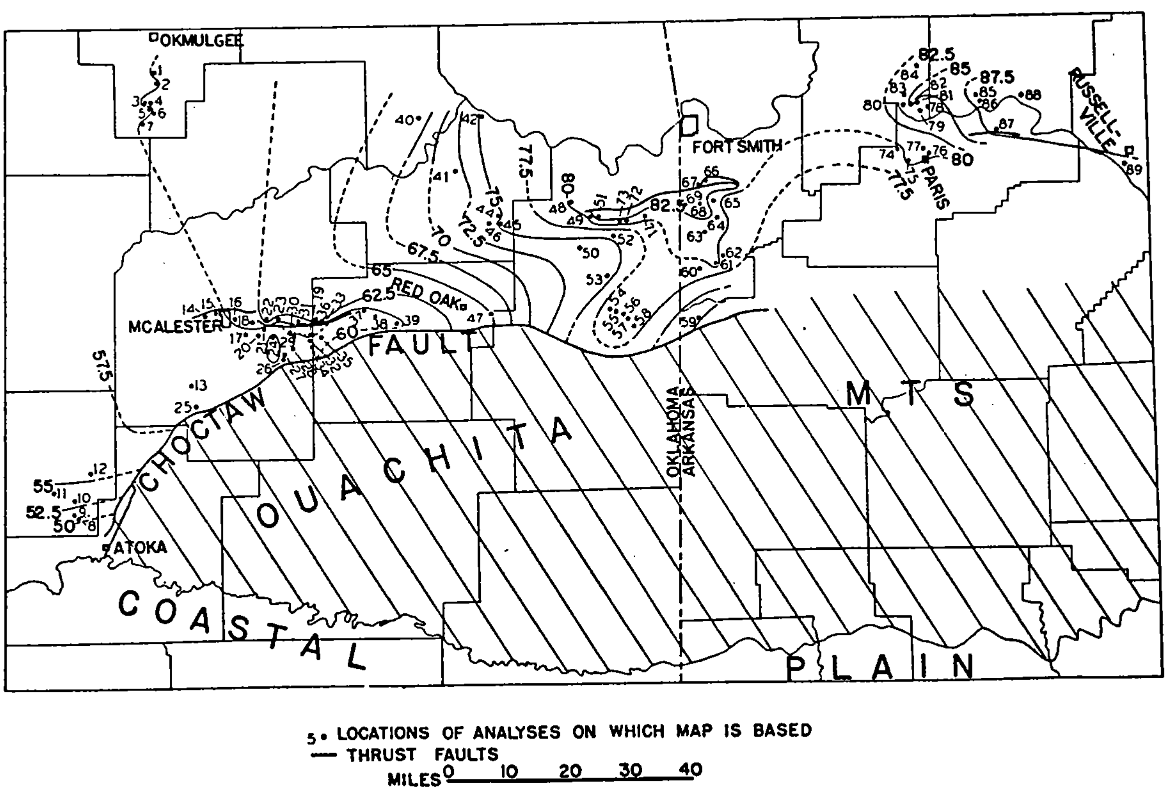

Figure 14. Isocarb map of part of Arkoma Basin (from Hendricks, 1935).

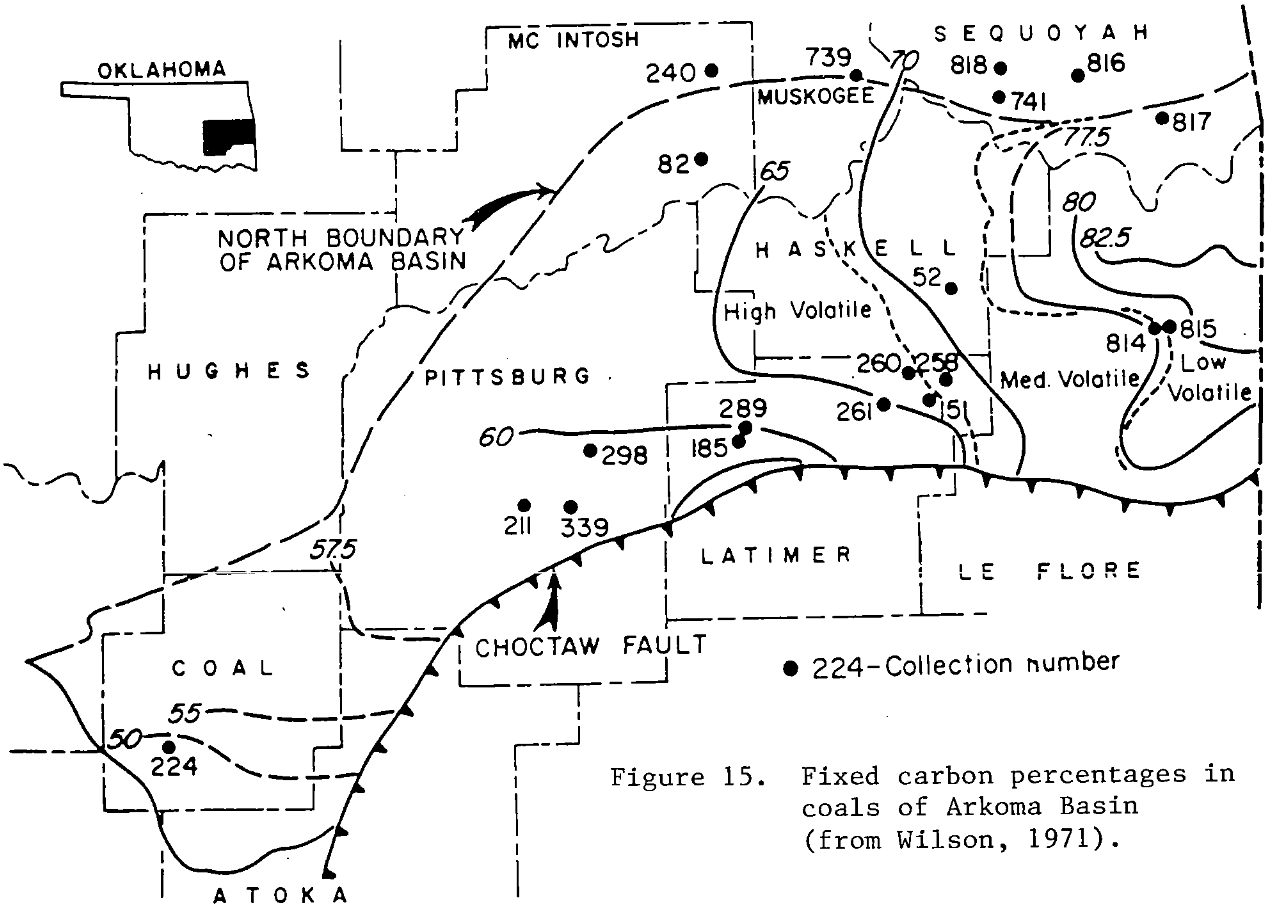

Figure 15. Fixed carbon percentages in coals of Arkoma Basin (from Wilson, 1971).

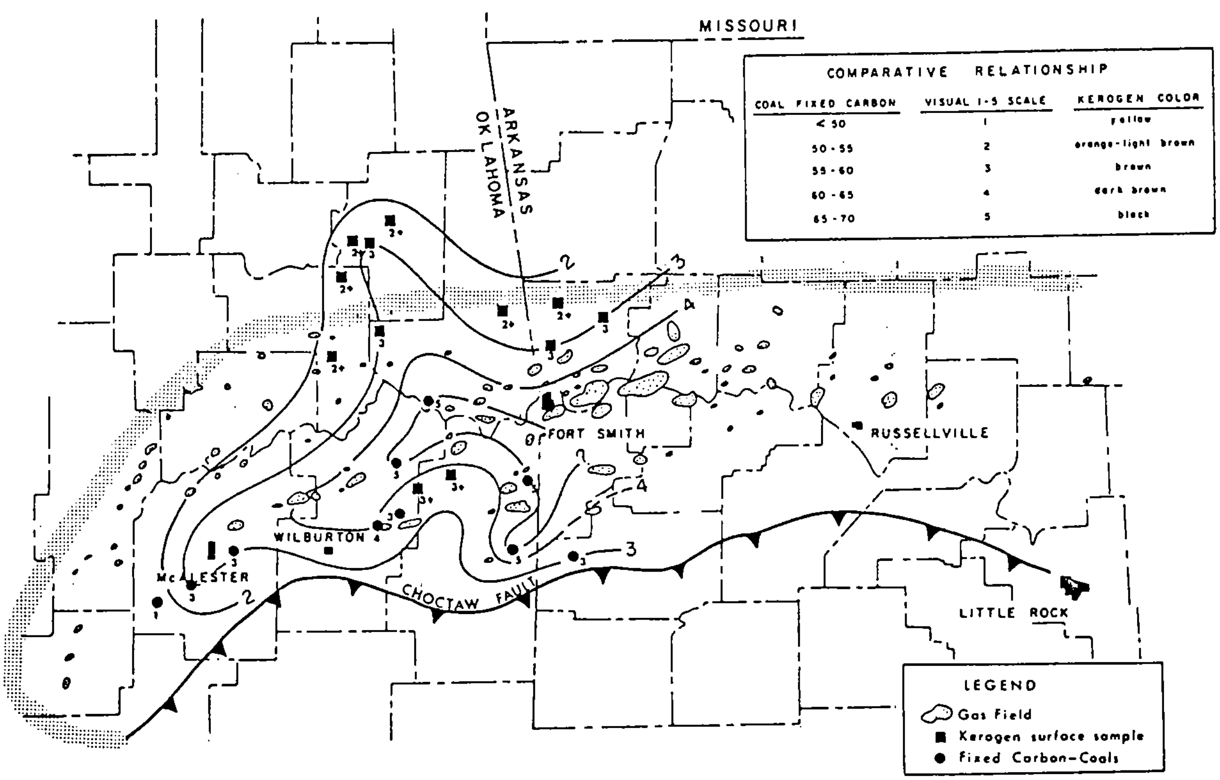

Figure 16. Arkoma Basin thermal-alteration isocarb map, interpreted from kerogen and coal fixed-carbon data (from Burgess, 1974).

around the northern border of the Arkoma Basin. This area is described as a granite-rhyolite complex of unknown origin. Compositionally, there does not exist a pattern in the basement-rock types that parallels the present high geothermal-gradient zone through Haskell and Pittsburg Counties, Oklahoma. Southeast of this zone a Precambrian granite of the Central Oklahoma Granite Group has converted rhyolite of the Precambrian Washington Volcanic Group to metarhyolite (Denison, 1981). There is insufficient evidence to further relate variations in the composition of the basement rocks to the present geothermal-gradient pattern.

A structure map of the Precambrian surface (Denison, 1981) and the north-south cross section through the Arkoma Basin (pl. 1) illustrate a zone of faulting parallel to the high geothermal-gradient zone. Branan (1968) and Houseknecht and others (1985) describe syndepositional normal faults parallel to the Ouachita orogenic belt that formed during the Atokan. The normal faults penetrate the basement rocks. Northward-thrust faults and east-trending anticlines and synclines have affected the post-Morrowan section, with increasing intensity toward the Ouachita orogenic belt (Lidiak, 1982). The high geothermal-gradient zone through Haskell and Pittsburg Counties comprises anticlines and synclines near the surface, thrust faults in the Atoka section, and normal faults from basement rocks to the Atoka Formation (pl. 1). The variety of faults most likely has had a major influence in providing both a conduit for vertical and lateral heat transfer and in placing rocks of different thermal conductivities side by side. Isprapilov and Abdurakhmanov (1984) discussed the formation of thermal-anomaly zones along faults.

In summary, structural complexities in the Arkoma Basin, particularly close to the Ouachita front, have combined to transmit heat from the basement along an east-west thermal-anomaly zone through Haskell and Pittsburg Counties, Oklahoma.

Conclusions

1. The present geothermal gradient did not produce the coal rank in the Arkoma Basin of Oklahoma.

2. High heat flow from a thermal anomaly in Arkansas is the source of heating that produced the coal rank. The nature of the high heat source has not been determined.

3. Coal rank is believed to have developed during the late Paleozoic, possibly in connection with the Ouachita Orogeny, which culminated in the Permian.

4. Coal isocarb mapping suggests that the present geothermal-gradient pattern reflects the paleogeothermal gradient that produced the coal rank.

5. Intense folding and faulting, particularly close to the Ouachita front, have combined to transmit heat from the basement along an east-west thermal-anomaly zone through Haskell and Pittsburg Counties, Oklahoma.

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APPENDIX

LOGS OF CORE HOLES DRILLED BY THE OKLAHOMA GEOLOGICAL SURVEY

(Core-hole logs are identified by the letter C, county abbreviations, and numbers; sample-identification numbers from table 2 are shown in parentheses)

C MM 7 (no. 1)

NE¼NE¼NE¼SE¼NE¼ sec. 4, T. 13 N., R. 18 E., Muskogee County. Well cored by Oklahoma Geological Survey; lithological descriptions by LeRoy A. Hemish. Drilled 1,370 feet from N. line and 50 feet from E. line. (Surface elevation, estimated from topographic map, 611 feet.)

	Depth to unit top (feet)	Thickness of unit (feet)
Sand, grayish-brown, very fine-grained, silty; contains organic material	0.0	1.6
Sand, moderate-reddish-brown, very fine-grained, silty, clayey	1.6	0.9
Sand, moderate-yellowish-brown, very fine-grained, clayey; contains brownish-black fragments of iron oxide concretions	2.5	8.0
Krebs Group		
Boggy Formation		
Shale, very light-gray, with dark-yellowish-orange streaks	10.5	0.5
Shale, light-olive-gray, with dark-yellowish-orange streaks; becomes olive gray in lower 10 inches of unit	11.0	3.0
Sandstone, light-olive-gray, with light-brown and grayish-black bands, very fine-grained, micaceous, cross-laminated, wavy-bedded; bedding distorted in part; abundant black carbonized plant debris on stratification surfaces (Crekola Sandstone)	14.0	1.6

Sandstone, light-gray, with grayish-black bands, micaceous, very fine-grained, cross-laminated, wavy-bedded; bedding highly distorted in part; includes abundant black carbonized plant debris on stratification surfaces (Crekola Sandstone)	15.6	18.2
Shale, medium-gray, silty; includes coalified plant material on stratification surfaces	33.8	0.2
Coal, black, bright, friable; minor pyrite on cleat surfaces (Secor coal)	34.0	0.6
Siltstone, medium-gray, shaly; includes a ¼-inch-thick layer of grayish-black, highly carbonaceous shale at top of unit as well as black, carbonized plant fragments distributed throughout	34.6	0.3
Underclay, medium-gray, silty; contains black carbonized plant fragments; slickensides common	34.9	1.3
Shale, medium-gray, silty; contains black, carbonized plant fragments.	36.2	2.5
Sandstone, medium-light-gray, with dark-gray bands, fine- to very fine-grained, micaceous, cross-stratified; black; macerated plant debris abundant on stratification surfaces (Bluejacket Sandstone)	38.7	1.3
Total Depth		40.0

C MM 8 (no. 3)

NW¼NE¼SE¼SW¼NE¼ sec. 22, T. 10 N., R. 19 E., Muskogee County. Well cored by Oklahoma Geological Survey; lithological descriptions by LeRoy A. Hemish. Hole drilled in pasture NW of buildings 40 feet directly east from pond. (Surface elevation, estimated from topographic map, 570 feet.)

	Depth to unit top (feet)	Thickness of unit (feet)
Sand, dark-yellowish-brown, silty; contains organic material	0.0	1.0
Krebs Group		
McAlester Formation		
Shale, dark-gray, with moderate-reddish-brown iron oxide deposits on stratification surfaces, silty; includes some moderate-reddish-brown ironstone concretions	1.0	12.5
Shale, medium-light-gray, calcareous	13.5	2.3
Sandstone, medium-light-gray, very fine-grained, noncalcareous	15.8	0.8
Shale, medium-dark-gray, silty, fissile; includes some hard, thin, light-gray sandstone layers at 23.5 and 24.5 feet	16.6	12.4
Shale, dark-gray, silty, fissile, pyritic; includes black carbonized plant fragments on stratification surfaces	29.0	15.8
Shale, dark-gray, silty, fissile, interbedded with thin stringers of light-gray, very fine-grained sandstone and siltstone; includes some minor pyrite	44.8	9.7
Sandstone, medium-gray, with black flecks, very fine-grained, well-indurated, interbedded with dark-gray, silty shale and siltstone, noncalcareous (Keota Sandstone)	54.5	3.5

Sandstone, medium-gray, with very light-gray bands, very fine-grained, silty, bedding contorted, bioturbation features abundant, noncalcareous (Keota Sandstone)	58.0	1.3
Siltstone, medium-gray, with minor light-gray stringers of very fine-grained sandstone, thin-bedded, shaly	59.3	0.7
Shale, dark-gray, with light-gray streaks, sandy, silty, bioturbated	60.0	2.3
Shale, dark-gray, silty; contains scattered calcareous brachiopod shell fragments	62.3	2.0
Sandstone, light-gray, very fine-grained, highly calcareous, shaly.	64.3	0.1
Shale, medium-dark-gray, with brownish-gray sandstone-filled burrows, silty; grades into underlying unit.	64.4	1.0
Sandstone, medium-light-gray to light-gray, very fine-grained, silty, highly bioturbated, noncalcareous	65.4	1.5
Shale, medium-gray, with light-gray streaks, silty, sandy. . .	66.9	0.4
Shale, dark-gray	67.3	0.2
Siltstone, medium-dark-gray, sandy, becomes shaly downward, bioturbated, noncalcareous	67.5	3.7
Shale, medium-dark-gray, silty, intricately interbedded with light-gray, very fine-grained sandstone, noncalcareous; wavy bedded, crossbedded; bioturbation and flow features common in the sandstone; unit consists of about 25 percent sandstone in upper part and less than 10 percent sandstone in lower part	71.2	6.3

Shale, medium-dark-gray, silty; includes some very thin stringers of very fine-grained sandstone; extensively bioturbated, with very fine-grained sandstone fillings in burrows; includes a 3/16-inch-thick grayish-black carbonaceous shale layer at 88.3 feet	77.5	14.5
Shale, dark-gray, silty; contains minor very fine-grained sandstone laminae and burrow fillings in upper 6 feet of unit.	92.0	8.0
Shale, dark-gray, silty, hard; includes some minor pyrite and layers of brownish-gray, silty ironstone	100.0	26.0
Shale, dark-gray, silty; includes thin laminae of very fine-grained sandstone; bioturbated in part; grades into underlying unit	126.0	2.7
Siltstone, dark-gray, shaly; includes abundant very fine-grained sandstone in thin laminae and burrow fillings, hard; contains some black carbonized plant compressions	128.7	5.1
Shale, dark-gray, silty, hard; includes thin laminae of very fine-grained sandstone and siltstone; bioturbated in part; contains black carbonized plant material and layers of brownish-gray, silty ironstone up to 2 inches thick; includes scattered brachiopods from 165 to 168 feet	133.8	55.0
Coal, black, bright, moderately friable; contains thin lenses of pyrite and white calcite on cleat surfaces (unnamed coal)	188.8	0.3

Underclay, medium-gray to medium-dark-gray; silty in lower part; contains black coalified plant roots and white calcite veinlets; slickensides common; grades into underlying unit	189.1	1.1
Shale, dark-gray, with very light-gray laminae of very fine-grained sandstone, highly silty; bioturbation, scour, and soft-sediment deformation features abundant	190.2	4.4
Siltstone, dark-gray, with very light-gray laminae of very fine-grained sandstone, shaly in part, micaceous; bioturbation, scour, and soft-sediment deformation features abundant; grades into underlying unit	194.6	9.2
Shale, dark-gray, silty; includes minor very thin laminae of very fine-grained sandstone	203.8	11.0
Sandstone, medium-dark-gray, very fine-grained, silty and shaly, very thin-bedded, basal contact sharp and disconformable (Tamaha Sandstone)	214.8	0.2
Shale, dark-gray, silty, hard; includes thin laminae of very fine-grained light-gray sandstone and siltstone; extensively bioturbated; contains layers of brownish-gray, silty ironstone up to 1 inch in thickness	215.0	9.4
Shale, dark-gray, silty, hard; contains brownish-gray, silty ironstone lenses up to 1¾ inches in thickness; includes minor bioturbation features; grades into underlying unit .	224.4	16.6
Shale, dark-gray, less silty and softer than overlying unit	241.0	29.0
Shale, dark-gray; contains small, sparsely distributed calcareous brachiopods	270.0	0.8

Shale, black, highly calcareous, fossiliferous; contains a high concentration of white fossil hash consisting mostly of brachiopod shells in lower 1 inch	270.8	0.5
Shale, dark-gray, silty; contains abundant carbonized plant material	271.3	0.2
Coal, black, bright; includes a ¼-inch-thick carbonaceous shale parting 1 inch from top of unit (unnamed coal) . .	271.5	0.3
Underclay, medium-dark-gray, shaly; contains abundant black carbonized plant fragments and minor coal streaks in lower part of unit	271.8	1.3
Coal, black, bright, finely cleated (Stigler coal)	273.1	1.8
Underclay, medium-dark-gray; contains black carbonized plant fragments; slickensided surfaces common	274.9	2.1
Total Depth		277.0

C Ha 1 (no. 4)

NE¼NE¼NW¼NE¼NE¼ sec. 20, T. 9 N., R. 22 E., Haskell County, Oklahoma. Well cored by Oklahoma Geological Survey; lithological descriptions by LeRoy A. Hemish. Hole drilled in pasture 40 feet south of center of gravel road and 75 feet east from center of driveway. (Surface elevation, estimated from topographic map, 587 feet.)

	Depth to unit top (feet)	Thickness of unit (feet)
Sand, dark-yellowish-brown, very fine, silty; contains organic material	0.0	1.0
Sand, moderate-yellowish-brown to light-brown, very fine, silty, clayey	1.0	3.5
Sand, moderate-reddish-orange, fine-grained, silty; clasts are well rounded; gravelly at base of unit	4.5	4.0
Krebs Group		
McAlester Formation		
Sandstone, moderate-reddish-brown to dark-yellowish-brown, very fine-grained, noncalcareous, well-indurated; includes some soft grayish-orange to very pale-orange shale layers (Tamaha Sandstone)	8.5	1.5
Sandstone, moderate-olive-brown, very fine-grained, noncalcareous, well-indurated; color change to moderate reddish brown 11 to 12 feet.	10.0	2.5

Shale, light-olive-gray, interbedded with olive-gray, very fine-grained sandstone layers from 2 to 3 inches in thickness	12.5	0.9
Sandstone, olive-gray and moderate-reddish-orange, very fine-grained, well-indurated	13.4	2.0
Shale, grayish-orange, soft; color change to olive gray at 16 feet and to medium dark gray at 17 feet, with some moderately hard silty stringers	15.4	2.6
Shale, medium-dark-gray to dark-gray, silty, moderately hard and brittle, noncalcareous; softer below 26 feet; sideritic concretions from 26.3 to 26.6 feet, 29.7 to 29.8 feet, 32.8 to 33.0 feet, and numerous concretionary layers from 33.5 to 35.0 feet and 54.5 to 61.2 feet	18.0	44.9
Shale, grayish-black, brittle, highly carbonaceous	62.9	0.4
Shale, dark-gray; contains sparsely distributed, black carbonized plant fragments	63.3	5.0
Shale, dark-gray, silty; includes thin laminae and burrows filled with light-gray siltstone and very fine-grained sandstone; also includes silty brownish-gray sideritic concretions ranging from ¼ to 1 inch in thickness as well as sparsely distributed, black carbonized plant fragments and calcareous shell fragments	68.3	16.8
Shale, grayish-black, silty, hard, noncalcareous; includes several silty brownish-gray sideritic concretions ranging from ½ to 1½ inches in thickness	85.1	17.5

Coal, black, bright, finely cleated, friable; white calcite on cleat surfaces and minor pyrite on stratification surfaces (Stigler coal)	102.6	2.3
Shale, grayish-black, very highly carbonaceous; includes thin, contorted laminae of coal and streaks of white calcite in lower 3 inches of unit.	104.9	0.5
Sandstone, light-gray, with very light-gray bands, very fine-grained, noncalcareous, carbonacaeous in upper 3 inches, bedding contorted and disturbed, bioturbation features abundant, cross-laminated in part (Cameron Sandstone)	105.4	2.9
Total Depth		108.3

C Ha 2 (no. 6)

NW¼NW¼NW¼NW¼NW¼ sec. 36, T. 9 N., R. 23 E., Haskell County, Oklahoma. Well cored by Oklahoma Geological Survey; lithological descriptions by LeRoy A. Hemish. Drilled 100 feet S. of N. line and 100 feet E. of W. line. (Surface elevation, estimated from topographic map, 562 feet.)

	Depth to unit top (feet)	Thickness of unit (feet)
Silt, grayish-brown, clayey; contains organic material (topsoil)	0.0	1.4
Clay, light-brown, feels gritty; contains gravel-size concretionary fragments	1.4	1.1
Clay, dark-yellowish-orange to pale-yellowish-brown, feels gritty; contains sand and gravel-size concretionary fragments	2.5	9.0
Gravel, dusky-yellowish-brown, clayey, sandy; contains subangular clasts of ironstone and sandstone	11.5	0.5
Krebs Group		
McAlester Formation		
Shale, olive-gray to olive-black with some grayish-orange iron oxide staining on fracture surfaces, noncalcareous	12.0	5.5
Shale, dark-gray, silty, noncalcareous; stained moderate reddish brown in part along fracture surfaces; uniform in character	17.5	67.0
Ironstone, moderate-reddish-brown, very hard	84.5	0.8

Shale, dark-gray, silty, noncalcareous; includes hard, dark-reddish-brown to moderate-reddish-brown ironstone concretions ranging from 1 to 2 inches in thickness	85.3	19.7
Shale, dark-gray, silty, moderately hard, noncalcareous; contains a few small pyrite nodules up to ¼ inch in diameter and numerous brownish-gray siderite concretions ranging from 1/16 to 1½ inches in thickness; also includes thin, white calcite deposits occurring in layers and as veinlets; includes scattered lens-shaped, siltstone-filled burrows in lower part	105.0	28.2
Hartshorne Formation		
Shale, grayish-black, carbonaceous, pyritic in upper 1 inch; includes a ¼-inch-thick coal layer near base of unit	133.2	0.8
Coal, black, bright, moderately friable; contains white calcite on cleat surfaces and minor pyrite in nodular form; includes a 2-inch-thick, grayish-black, highly carbonaceous shale parting in the interval from 22 to 24 inches below top of unit (Hartshorne coal) . . .	134.0	2.4
Underclay, brownish-gray to medium-gray, carbonaceous and coaly in upper 1 inch.	136.4	1.6
Total Depth		138.0

C La 1 (no. 5)

NE¼SW¼NW¼NW¼NE¼ sec. 12, T. 5 N., R. 20 E., Latimer County, Oklahoma. Well cored by Oklahoma Geological Survey; lithological descriptions by LeRoy A. Hemish. Drilled 50 feet N. from edge of gravel road. (Surface elevation, estimated from topographic map, 590 feet.)

	Depth to unit top (feet)	Thickness of unit (feet)
Sand, dark-yellowish-brown, very fine-grained; contains organic material	0.0	1.0
Sand, dark-yellowish-orange, very fine-grained, clayey; contains gravel-size, dusky-brown concretion fragments and subangular clasts of moderate-reddish-brown sandstone	1.0	5.7
Sand, as above, but becoming dark-yellowish-brown	6.7	3.8
Krebs Group		
McAlester Formation		
Shale, light-olive-gray, weathered	10.5	1.5
Shale, olive-gray to dark-gray, with moderate-brown staining along fracture surfaces	12.0	9.0
Shale, dark-gray, noncalcareous; includes dark-reddish-brown siderite concretions	21.0	5.5

Shale, dark-gray, pyritic, moderately hard; contains abundant sideritic concretions about 2 inches in thickness, some of which are cut by calcite-filled veinlets; also includes beds of soft, grayish-black carbonaceous shale ranging from 1 to 2 inches in thickness from 26.5 to 28.5 feet	26.5	17.2
Hartshorne Formation		
Shale, grayish-black, carbonaceous, soft, interbedded with harder dark-gray shale	43.7	1.5
Sandstone, medium-gray to light-olive-gray, very fine-grained, silty, shaly in part; contains well-preserved carbonized and pyritic plant remains, including abundant seed-fern compressions	45.2	5.8
Shale, medium-dark-gray, silty, interbedded with very fine-grained sandstone and siltstone; contains black, carbonized plant fossils	51.0	5.2
Shale, medium-dark-gray; contains black, carbonized plant fragments	56.2	4.6
Shale, medium-dark-gray, with light-gray bands, highly silty; contains abundant layers of very fine-grained sandstone from 1/64 to 4 inches thick; includes black, carbonized plant fragments, pyrite, and minor streaks of coal	60.8	16.2

Sandstone, medium-gray, with light-gray bands, very fine-grained, silty, shaly, wavy-bedded and crossbedded in part; contains plant fossils, streaks and flecks of black, carbonized plant material as well as minor coal inclusions; includes some pyrite, rare ½-inch-thick layers of intraformational conglomerate, burrows filled with medium-grained sandstone, and sandy concretionary lenses up to 4 inches in thickness	77.0	24.4
Sandstone, very light-gray to white, with medium-dark-gray bands ranging from 1/64 to 4 inches in thickness, very fine- to fine-grained, micaceous, crossbedded; sedimentary structures such as scour and fill, plume, soft-sediment deformation, and cross-lamination features abundant; black macerated plant materials common on stratification surfaces; contains discoidal sideritic concretions about 2 to 3 inches in diameter	101.4	27.8
Sandstone, very light-gray, fine-grained, massive, noncalcareous	129.2	1.3

Sandstone, very light-gray, with dark-gray laminae spaced about 1 inch apart, fine-grained, micaceous, noncalcareous; contains black, macerated plant material; fractured; includes some 1- to 3-inch-thick dark-gray shaly sandstone layers below 52 feet; sedimentary structures such as scour and fill, plume, soft-sediment deformation, and cross-lamination features abundant; includes some sandy, sideritic concretions averaging about 1 inch in thickness; contact with underlying unit sharp	130.5	34.8
Coal, black, bright, banded, moderately friable; contains veinlets and small nodules of pyrite (Lower Hartshorne coal)	165.3	1.8
Underclay, dark-gray to grayish-black, shaly, highly carbonaceous; plant compressions abundant	167.1	1.2
Total Depth		168.3

C Pi 1 (no. 2)

SE¼SE¼NE¼SW¼SW¼ sec. 11, T. 7 N., R. 17 E., Pittsburg County, Oklahoma. Well cored by Oklahoma Geological Survey; lithological descriptions by LeRoy A. Hemish. Drilled on bench made for gas-well drill site 700 feet from S. line and 1,500 feet from W. line. (Surface elevation, estimated from topographic map, 840 feet.)

	Depth to unit top (feet)	Thickness of unit (feet)
Krebs Group		
Boggy Formation		
Shale, olive-gray to dark-gray, some moderate reddish-brown iron oxide staining along fractures, noncalcareous; includes some grayish-brown clay-ironstone concretions about 1 to 2 inches in thickness	0.0	10.0
Shale, dark-gray, with minor moderate-reddish-brown staining; includes some grayish-brown and moderate-reddish-brown clay-ironstone concretions; noncalcareous . .	10.0	8.0
Shale, dark-gray to grayish-black; contains minor crusts of calcite on stratification surfaces and calcareous brachiopods; includes highly calcareous, light-gray concretions ranging from 1 to 2 inches in thickness . . .	18.0	25.0
Limestone, grayish-black, highly shaly; contains abundant brachiopods	43.0	0.3
Shale, grayish-black, with medium-gray bands, carbonaceous; contains abundant pyrite, some occurring as pyritized brachiopod shells; black, carbonized plant compressions common on stratification surfaces.	43.3	5.7

Shale, black, highly carbonaceous	49.0	0.2
Coal, black, bright, moderately friable; includes pyrite occurring as crusts on cleat surfaces and stratification surfaces (unnamed coal)	49.2	0.8
Underclay, medium-dark-gray; contains abundant black, carbonized plant fragments	50.0	1.3
Siltstone, medium-gray, shaly, noncalcareous; includes some very fine-grained sandstone	51.3	0.9
Sandstone, light-gray, with medium-dark-gray bands, micaceous, noncalcareous, ripple-marked and cross-bedded, fine-grained to very fine-grained; shaly in part, with shale laminae increasing in abundance downward; black, macerated plant materials abundant on stratification surfaces	52.2	8.2
Sandstone, very light-gray, with abundant dark-gray laminae, shaly, very fine-grained, micaceous, non-calcareous; includes some layers of pyritic coal about 1/64 inch thick and abundant black, macerated plant materials on stratification surfaces; fines downward	60.4	10.4
Siltstone, medium-dark-gray, with light-brownish-gray bands, shaly; grades into underlying unit	70.8	2.5
Shale, dark-gray, with light-brownish-gray bands, silty . . .	73.3	3.5
Shale, grayish-black, carbonaceous	76.8	2.2
Shale, grayish-black, carbonaceous; contains small calcareous brachiopod shells	79.0	1.5
Shale, black, hard, coaly; includes abundant laminae of pyrite	80.5	0.2

Coal, black, bright, moderately friable; contains pyritic nodules and laminae; includes a 7½-inch-thick black, carbonaceous, coaly shale parting in the interval from 19 inches to 26½ inches from top of unit (Secor coal)	80.7	2.9
Underclay, medium-dark-gray, pyritic in upper 1 inch	83.6	0.4
Total Depth		84.0