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GEOLOGIC OVERVIEW
COAL AND COALBED METHANE RESOURCES
OF THE ARKOMA BASIN,
ARKANSAS AND OKLAHOMA

DRAFT

BY

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ACKNOWLEDGMENTS

TRW gratefully acknowledges the assistance of those organizations and persons who provided information, data, and advice during the preparation of this report. Among these, special thanks are due to Fred E. Galliers (Mustang Production Company), Charles W. Cargile (Consulting Geologist), S. A. Freedman (Oklahoma State Geological Survey), Walter H. Fertl (Dresser Atlas), Anthony T. Iannacchione (U.S. Bureau of Mines), Robert C. Brown (U.S. Bureau of Land Management), Boyd R. Haley (U.S. Geological Survey), and William V. Bush (Arkansas Geological Commission).

In addition, the cooperation of Mustang Production Company, Arkla Exploration Company, American Association of Petroleum Geologists, McGraw-Hill Publications, Oklahoma State Geological Survey, the Arkansas Geological Commission, U.S. Bureau of Land Management, U.S. Bureau of Mines and U.S. Geological Survey in permitting the reproduction of various figures, tables, and textual data is greatly appreciated.

1. SUMMARY

This geologic basin report provides a data base for determining the coalbed methane resource and directing the Methane Recovery from Coalbeds Project (MRCP) resource delineation efforts in the Arkoma Basin. An initial target area of approximately 5,300 square miles had been previously selected by the MRCP as having the highest probability of early commercialization. The information gathered in conjunction with this report and initial field testing provided the basis for redefining that area and for recommending project coring and testing efforts in the newly defined target areas.

The Arkoma Basin encompasses an area of approximately 13,488 square miles in the south-central United States, covering the east-central part of Oklahoma and west-central part of Arkansas. The southern part of the coal region is in the Arkansas Valley section of the Interior Highlands physiographic province. This province has been divided into the Arkansas Hill and Valley belt and the McAlester Marginal Hills belt which contains resistant sandstone capped synclinal hills and mountains 300 to 2,000 feet above wide hilly plains. Because of its central location and proximity to interstate pipelines, the Arkoma Basin is an attractive potential gas resource area.

The Arkoma is an elongated, linear east-west trending sedimentary basin. Except for large-scale faulting and folding in the trough portion of the basin, the shelf and subshelf are only gently disturbed. Deepest coal-bearing portions of the basin occur in a broad area centered around southern Pittsburg, central Latimer, southern Haskell, central and northern Le Flore counties, Oklahoma and west central Sebastian County, Arkansas.

The Arkoma Basin contains extensive bituminous coal reserves and some semi-anthracite reserves in Pennsylvanian age rocks. The Oklahoma Geological Survey and the U.S. Geological Survey have estimated that the total coal resource of the Arkoma basin might be 7.89 billion tons. More than 10 individual coal seams have been identified in this area, 8 of which have been mined or are being mined presently. The majority of the major coalbeds are continuous but do not maintain constant thickness. Individual beds range from a few inches to 7 feet in thickness. The coalbeds outcrop

along the periphery of the synclines and dip steeply (up to 90°) toward the axis. Lower (Atokan) and Upper (Missourian) Pennsylvanian coals are thin and discontinuous, whereas the middle Pennsylvanian (Desmoinesian) coals are thick, generally continuous, and provide the basin's major proven reserves. The thin Lower Pennsylvanian coals have not been studied in as much detail. These Atoka coals are geographically located in Le Flore County, Oklahoma and Sebastian County, Arkansas. The greatest cumulative thickness of coal presumably occurs in the Canaval synclines, Le Flore County, Oklahoma. The maximum overburden over the Hartshorne coals is believed to be about 6,000 feet in the Cavanal syncline.

The Hartshorne, the McAlester (Stigler) and the Secor coalbeds are the most extensive and uniformly thick coals in the Arkoma Basin; estimated coal reserves are over 7.4 billion tons, constituting 93 percent of the basin's total coal resource.

Arkoma Basin coals have been mined by both underground and surface methods. Mining activities are located near the perimeters of the synclines where the coal is exposed or shallow.

The potential methane resource from selected coalbeds in the Arkoma Basin can be estimated from desorption data generated by the U.S. Bureau of Mines (USBM) and field tests performed under the MRCP.

The Hartshorne coals in Oklahoma have been the most frequently sampled coalbeds. Estimated gas content of the Hartshorne ranges from 73 to 570 cubic feet per ton. Other measured values are 200-211 cubic feet per ton for the Booch coals and 131 cubic feet per ton for the McAlester coal. The latter two estimates are from coals located in the subshelf part of the basin where the coals are thinner and not as well developed.

MRCP data on the methane gas content of Arkoma Basin coals is presently limited to coring and well testing in Pittsburg, Haskell and Le Flore Counties, Oklahoma. In Pittsburg County, the Upper Hartshorne, Upper Booch and McAlester coals were cored in two wells between the depths of 1,905 and 3,650 feet and samples were desorbed for approximately five months using the USBM's direct method. Total gas contents ranged between 73 and 211 cubic feet per ton. In Le Flore County, Oklahoma, the Upper Hartshorne was sampled at a depth of 192 feet and found to contain 310

cubic feet per ton. Desorption tests are still in progress for the Upper Booch and Upper Hartshorne coal cores. Variability in gas content cannot always be directly related to coalbed depth, inasmuch as some of the gassier coals were from shallower horizons--the opposite of what might have been expected--but is related to other geologic controls on the gas content, analytical errors, or to the method used in determining the "remaining" gas content.

Methane liberated from mines during operation also provides an indication of the potential methane resource in an area. The correlation between the amount of gas emitted from coal mines and that predicted to be there by desorption testing is not obvious. Experience in the Arkoma Basin at the Howe mine in Le Flore County, Oklahoma shows that about seven times more gas is liberated from a mature mining operation than what was measured by desorption testing.

Based on the limited data available, ranges for the maximum and minimum expected in-place gas resource have been made for all the major coalbeds. The Hartshorne coals are anticipated to have a minimum of about 5.4 billion short tons and a maximum of nearly 2.45 trillion cubic feet in-place gas. The McAlester (Stigler) Coal, likewise, is estimated to contain a maximum of 0.69 trillion cubic feet of gas. The minimum in-place gas resource for the Hartshorne and McAlester coals totals about 1.4 trillion cubic feet.

It is reasonable to assume that the methane contained in the deeper parts of the various major synclines may add significantly to this figure. The gas content of the coals in the Arkoma Basin is generally higher towards the east. Several target areas totalling approximately 3,600 square miles have been identified using a developed exploration rationale. These areas hold the greatest probability for early commercialization of gas and were recommended for additional testing. The main target area is located in the deepest portion of the Cavanal syncline in Le Flore County, Oklahoma. Another main target area is located in the Lehigh syncline in Coal and Atkoa Counties, Oklahoma. An alternate target would be the

Cavanal syncline area in the western part of Sebastian County, Arkansas. These areas contained reasonably thick coal sections at considerable depths.

It is recommended that a minimum of three Type I test wells be planned for these chosen target areas. In addition, at least one Type III well test should be conducted in the Kiowa syncline, Pittsburg County, Oklahoma to test the deep McAlester (Stigler) and Hartshorne coals. Once these target areas have been adequately tested, an evaluation of the resource data should be made to determine the requirements for, or value of, additional Type I testing in the Arkoma Basin. Type III testing should be planned for the purpose of gathering specific reservoir and production data from these coalbeds.

2. INTRODUCTION

Methane, the major component of natural gas, is generated during the natural process of coal formation and frequently is trapped in the coal and associated strata. The total magnitude of the U.S. coal-associated methane resource has been estimated as much as 700 trillion cubic feet. Given current and conservatively projected economic and technological factors, the recovery of some 300 trillion cubic feet of this natural gas resource appears to be feasible.

The objective of this report is to provide a data base on what is presently known about the coalbed methane resource in the Arkoma Basin of Arkansas and Oklahoma. Various sections of the report detail the basin's general geographical, cultural and geological setting and give an overview of its coal resources and associated coalbed methane gas. This analysis was performed under the Department of Energy's Methane Recovery from Coalbeds Project (MRCP). The MRCP consists of a planned sequence of resource characterization, research and development, and technology systems tests, designed to evaluate and test the technical and economical extraction and utilization of gas associated with coalbeds. Resource delineation of the methane content of the nation's coalbeds has been done on a very limited basis, mostly in conjunction with active mining. Previous work includes only a very small percentage of the coal resource and does not provide the knowledge needed to locate recovery and utilization projects in the coalbeds with the greatest potential for methane production.

A primary target area of approximately 5,300 square miles of the Arkoma Basin has been selected out of the 90,700 square miles of the Western Interior Coal Region as having the probability of early commercialization. The target area has been selected on the basis of the following general criteria:

- Physical and chemical characteristics of coal
- Seam depth (greater than 700 feet)
- Total effective coal thickness (greater than or equal to 30 feet)
- Individual seam thickness (greater than or equal to 5 feet)
- Areal extent of the seams.

The information gathered in conjunction with this report provides the basis for redefining the Arkoma target area and for recommending additional coring and well testing efforts in the newly defined targets.

The Arkoma Basin's geographic/physiographic, cultural and geologic setting is presented in Sections 3.1 through 3.3. Section 3.3 (Geology) includes discussions of the geologic history, structural framework and basin stratigraphy. Appropriate maps are included with these discussions.

The coal resources of the Arkoma Basin are reviewed in Section 4. Coal type (rank and quality), areal extent, stratigraphic position and chemical characteristics are discussed. Subsections discuss individual coal seams in more detail and provide correlations across state boundaries.

Section 5 deals with the basin's potential methane resource and presents tables and figures summarizing pertinent data. This section includes a discussion of three Type I well tests in Pittsburg and Haskell Counties, Oklahoma, and one shallow hole test in Le Flore County, Oklahoma. Data on the isotopic and chemical analysis of natural gases from the Hartshorne Formation is presented and related to the geologic environment in the Arkoma Basin. Conclusions and recommendations, made in Section 6, include a redefinition of the areas with highest probability of early commercialization, a suggested testing program, and an estimation of coalbed gas resource volume.

Cited references are presented in Section 7. Supporting information such as maps, map indices and publication lists are provided in the appendices.

3. BASIN SETTING

3.1 GEOGRAPHY/PHYSIOGRAPHY

The Arkoma Basin has been referred to as the "Arkansas-Oklahoma Coal Basin", and is known in Arkansas as the "Arkansas Valley Basin", and in Oklahoma as the "McAlester Basin" (Figure 3-1).

3.1.1 Location

The Arkoma Basin extends for approximately 250 miles in an east-west direction and is situated in east-central Oklahoma and west-central Arkansas. This long, arcuate trough is 20-50 miles wide from north to south and is bounded along the southern side by the very complex Ouachita overthrust belt. The deepest part of this basin is adjacent to the Ouachita Mountains system where the sedimentary column is estimated to be 30,000 feet thick. In central Arkansas the Arkoma Basin plunges beneath the overlapping Tertiary and Cretaceous strata of the Mississippi Embayment, where its nature becomes obscure. The basin is bounded on the north by the Boston Mountains and the Ozark dome and its northwest boundary is the Central Oklahoma platform; and on the west is the Seminole uplift or Hunton arch (Figure 3-1). The basin terminates abruptly on the southwest against the Tishomingo anticline in Atoka County, Oklahoma northeast of the Arbuckle Mountains. An estimated 40,000 cubic miles of sediment fills this basin (Branan, 1968).

For purposes of this report, the Arkoma coal basin's areal extent is defined by the cross-hatched region in Figure 3-2. This area is underlain by known Pennsylvanian age coalbeds in the subshelf and trough portion of the basin and encompasses an area of approximately 5,300 square miles.

3.1.2 Physiography

The Arkoma Basin is located between two major physiographic provinces: the Ouachita Province and the Ozark Plateaus, and is a subset of the Ouachita Province (Figure 3-3). Both of these major provinces resemble the Appalachian Provinces and Interior Low Plateaus in many ways. The east-west trending Ouachita Mountains are fold mountains of thick Paleozoic

formations. The Ozark Plateaus lie north of the basin, forming a broad upwarp which exposes lower Paleozoic formations similar to those of the Cincinnati Arch.

Mesas, buttes, cuestas, recent fault-line scarps, anticlinal ridges and synclinal valleys are the most common erosional forms in the eastern Arkansas part of the basin. Large amounts of alluvium deposited by the Arkansas River cover the valley floor. Terraces are the prevalent depositional form in this area (Merewether and Haley, 1969). The Arkoma Basin in its western and central portions has reverse topography with anticlines forming valleys and synclines forming flat-topped mountains. The alternating sandstones and shales in the Arkansas Valley Section are Pennsylvanian in age. This country is hilly owing to the dissecting action of streams upon bedrock differing in erosional resistance. Most of the landscape is characterized by long, sinuous, nearly parallel hogbacks that generally coincide with the outcrops of resistant sandstone members. The slopes of the synclinal mountains and sandstone ridges are commonly very steep. Between the hogbacks are wide anticlinal valleys underlain mostly by shale. Dip of the strata determines the spacing between hogbacks, their steepness, valley width, and the areal extent of the synclinal mesas and mountains (Craney, 1978). The basin's boundary with the Ouachita Mountains to the south is the structural boundary of the Choctaw Fault. The fault separates the linear Ouachita ridges, comprised of steeply folded and faulted beds, from the broad hills and mountains of the southern Arkoma basin.

Folding is present everywhere in eastern Oklahoma and increases to the south, resulting in sandstone capped, isolated synclinal mountains which rise to 2,000 feet above the wide hilly plains. Relief increases towards the east, reaching a maximum on either side of the Arkansas-Oklahoma state line. In the western portion of the basin the relief is about 350 feet, whereas near the eastern boundary of the basin the relief is about 600 feet. Folding decreases in eastern Oklahoma northward to less prominent east-west monoclinal ridges with smooth continuous uplands and distinct scarps that are commonly precipitous (Figure 3-1). This southern portion has been classified as the McAlester Marginal Hills Belt by Curtis and Ham (1972) (Figure 3-4). Folding continues to decline northward resulting in

broad, gently rolling lowlands of shale lying between sandstone ridges and hills that rise less than 300 feet above the plains. Curtis and Ham (1972) have classified this northern portion of the Arkoma Basin as the Arkansas Hill and Valley Belt. The boundary separating the Arkansas Hill and Valley Belt from the McAlester Marginal Hills Belt trends east-west near the center of the Panama Quadrangle, Oklahoma.

3.2 CULTURAL FEATURES

The Arkoma Basin is an attractive potential coalbed gas resource area owing to its central location in the midcontinent region and the availability of pipelines. This area has great mineral wealth, ample agricultural lands and some light manufacturing. The climate is continental in nature which is modified by weather systems in the Gulf of Mexico. Winters are short in the western part of the basin, and extremely cold weather is seldom experienced. Ice storms are frequent in the winter. The summers are long with periods of high day temperatures, but these temperatures in the western part of the basin are invariably coincidental with a dry atmosphere. Rainy season occurs in spring and early summer. Humidity increases towards the east. Most agricultural activities take place in the valleys. Large areas of upland are covered by forests. There are a few small areas of natural prairie in Oklahoma, and much of the forest has been removed in the lowlands to supply the demand for tillable ground.

Parts of the entire Arkoma Basin were surveyed from the perspective of cultural activities, land use and natural resources which would have an impact on the development of the gas resource. A series of maps was produced displaying the extent of federal land holdings, utility systems and communication sites and mining history.

3.2.1 Base Map

Standard U.S. Geological Survey maps of the states of Arkansas and Oklahoma (scale 1:500,000) were used to produce the base map for the study. Coalbed gas information is displayed in a manner suitable to the preservation of all data recorded on the base map. Indexes showing topographic maps for both the 6° (scale 1:100,000) and 2° (scale 1:250,000) quadrangle units are included as Enclosures A-1 and A-2 (Appendix A). The complete basin has been topographically mapped in 15-minute quadrangle

units, and much of it in 7.5 minute quadrangle units. Indexes to the available topographic and geologic maps for Oklahoma and Arkansas are included (Enclosures A-3 through A-6, Appendix A, and Enclosures B-1 and B-2, Appendix B).

3.2.2 Political Boundaries

A large percentage of the Arkoma Basin population lives on farms and in small trading communities. With a long history of commercial coal mining and natural gas production in the basin, there should be no major political or social issues in the development of methane resources from the coalbeds. State, county, township and section boundaries along with major centers of urban populations have been highlighted on the appropriate maps.

Reference is made in the coal literature to "districts" in the Arkoma Basin. Informal districts were developed to distinguish the different underground mining areas. Some of the districts referred to are:

- McAlester District - Oklahoma
- Lehigh District - Oklahoma
- Howe-Wilburton District - Oklahoma
- Quinton-Scipio District - Oklahoma
- West District - Arkansas
- East District - Arkansas

3.2.3 Transportation Systems

Access to the potential methane resource and delivery of gas from the basin to market is facilitated by the maze of highways, railroads and pipelines which crosscut the region. Transportation systems and population centers such as Dallas, Fort Worth, Amarillo, Oklahoma City, Tulsa, Shreveport, Fort Smith, Little Rock, and Memphis are shown on the 6° topographic quadrangles in Appendix A (Enclosures A-5 and A-6).

3.2.4 Utility Systems

The U.S. Bureau of Land Management has produced a utility system and communications site map for the Oklahoma portion of the Arkoma Basin showing oil and natural gas pipelines including pumping and compression

stations, major electrical transmission lines, telephone transmission lines and stations, and water supply lines for major cities (Figure 3-5).

3.2.5 Federal Lands

Federal lands are shown on Enclosure A-7. This map was prepared by the U.S. Bureau of Land Management for a study on possible coal mining developments in southeastern Oklahoma.

Mining development is influenced by the availability of leases for the coal. The U.S. Government owns the coal leases of large tracts of land in the Arkoma Basin. The federal coal lease boundaries are shown in Enclosure A-9. The Bureau of Land Management through the Oklahoma Project Office (200 N.W. 5th, Room 548, Oklahoma City, Oklahoma 73102) manages the coal leases, and evaluates formal bids offered by private operators for the leases. Leases in areas under federal coal lease are difficult to obtain, and therefore the federal coal lands have not been developed, except in some areas operating under existing leases. A private coal operator new to the area therefore would be somewhat restricted to the non-federal areas unless arrangements were made with a company presently holding a federal lease. These virgin coal deposits could hold promise for the development of coalbed methane resources in the Arkoma Basin.

3.2.6 Water

Presently, there are ongoing water resource efforts in Arkansas and Oklahoma in which the U.S. Geological Survey is a major participant. The kinds of water information available from the USGS consist of professional papers, water-supply papers, circulars, hydrologic investigations atlases, hydrologic unit maps, open-file reports and water-resources investigations. Complete listings of USGS geologic and water supplies reports on a state basis are available from the USGS. In addition, publications and open-file reports of the Arkansas Geological Commission, Oklahoma State Geological Survey, Oklahoma Water Resources Board and the U.S. Bureau of Land Management can be obtained from these agencies.

The ongoing water-resource investigations are summarized in the water-resources investigation indexes (Enclosures C-1 and C-2, Appendix C).

3.2.6.1 Climatic and Hydrologic Variations

Annual precipitation ranges from about 38 inches in the western part to 56 inches in the eastern portion of the Arkoma Basin (Figure 3-6). The volume of average annual surface-water runoff ranges from about 7 inches (western Arkoma) to about 20 inches (eastern Arkoma) (Figure 3-6). Stream flow is lowest in late summer and fall (August), whereas the highest stream flow occurs in early spring. The basin is drained by the south Canadian, Arkansas and Poteau rivers which flow to the east, and by the Muddy Boggy and Clear Boggy creeks which flow south to the Red River. Major reservoirs are the Eufaula and Robert S. Kerr in Oklahoma and Lake Dardanelle in Arkansas. The Arkansas River is navigable to Tulsa, Oklahoma. There have been no established acid mine drainage problems in the basin.

3.2.6.2 Basin Hydrology

Groundwater laws in Oklahoma are both appropriation and riparian, whereas in Arkansas they are riparian. Doctrines recognized are appropriation in Oklahoma and common-law riparian in Arkansas (Geraghty, et al, 1973).

The basin is for the most part underlain by aquifers that will yield less than 50 gal/min to wells. Exceptions are the high yield alluvium deposits located in the major river valleys.

Dissolved solids content of the surface water ranges from 120 to more than 350 ppm. The Interstate Oil Compact Commission study dealing with the impact of oil and gas production in Arkansas and Oklahoma on saline pollution of major fresh water aquifers adds little usable information except that such operations do not contaminate fresh water aquifers (IOC, 1978). There is inadequate information on the depth to saline groundwater in the eastern part of the basin in Arkansas, but it is generally less than 500 feet for the western and central part of the basin.

3.2.7 Resource Development

The Arkoma Basin is rich both in coal and natural gas. As might be expected, the geographic distribution of the coal and methane in coalbeds resource data are influenced more by local economics than by the actual concentration of total coal deposits. The most accessible coal and gas deposits commonly have been mapped and defined in preference to potentially

larger, riskier deposits (Enclosure A-8.) For example, in areas where strippable coalbeds in the basin are available, minable coal at greater depth may be mapped, if at all, only in very gross detail. The only detailed coalbed mapping is found within short distances of outcrops of minable coal and represents only a small fraction of the total resource. Usually only stratigraphic relationships of the coalbeds were evaluated, with very little care given to geologic structures and the tectonic stresses which modified their character. In cases where structural patterns cause minability problems such as roof collapse (especially true in Le Flore County, Oklahoma), there was little economic incentive to take an analytic approach; the tendency was simply to mine around or away from the problem areas.

Underground mines operating in the Hartshorne coalbed have had a long history of high methane emissions. Recently, two mines (Howe Mine, Le Flore County, Oklahoma, and Choctaw Mine, Haskell County, Oklahoma) closed down completely or suspended mining due to a combination of high methane emissions and roof control problems (Iannacchione and Puglio, 1979).

A short historical introduction to previous geologic investigations is given in this section. Brief descriptions of coal and natural gas developments also are included to provide background information on why and where certain extraction operations occurred first in the basin. Special attention is paid to the mined-out areas.

3.2.7.1 Previous Investigations

Historically, the early geologic studies in the Arkoma Basin are best summarized by listing the published works from 1819 to 1929. Data from these publications (see Section 7) has been used extensively and repeatedly in subsequent reports.

All the formations that crop out in Haskell County were first studied in other parts of Oklahoma. Thomas Nuttall (1821) in 1818 made several trips across the general region geology. Jules Marcou (1855) visited the region in 1852 as geologist for the Pacific Railroad Expedition, and he probably saw parts of Haskell County. What seems to be the earliest published reference to botany and coal in Haskell County, at least among the official documents, is by Whipple (1855).

Taff (1899) reported on the McAlester-Lehigh coal field, introducing formal names for the mappable units he studied. Taff later reported (1906) on the progress of coal work in Indian Territory. In a description of coal fields in Oklahoma, Shannon (1926) included part of the area in his report.

The first detailed mapping in the region was carried on by the U.S. Geological Survey during 1930-1934 (Hendricks, et al, 1939).

3.2.7.2 Mining History

Coal mining activites in Arkansas began on a significant scale about 1870 with the extension of several railroads through the coal fields between 1870 and 1888. Extensive mining operations began in 1888 with Huntington, Hackett, Jenny Lind, Paris, Charleston, Scranton and other localities in the Arkoma Basin being the centers of expansion (Enclosure A-5, Appendix A).

Coal was first mined on a commercial scale in the McAlester district, Oklahoma, in 1872, whereas coal has been produced commercially in the Howe-Wilberton district since 1890. About half the coal produced in the McAlester district has come from the McAlester bed, and about 40 percent from the Lower Hartshorne bed (Figure 3-7). Most of the remaining 10 percent has come from the Upper Hartshorne and Secor (Boggy Formation) beds, as only a few small mines have been worked in the other beds (Hendricks, et al, 1939). There are no active underground mines at present in the McAlester district.

Total coal production in the Howe-Wilburton district can only be estimated because, prior to 1907, when Oklahoma became a state, production records of the Indian Territory were not kept by districts, and since that time available records have been prepared by counties. Coal production in the Howe-Wilburton district comes from Latimer and Le Flore Counties, and there is also some production in the parts of these two counties lying outside the Howe-Wilburton district. Hendricks, et al, (1939) estimated that 19,000,000 tons of coal had been produced in this district prior to 1931. Most of the mining has been done in the Upper and Lower Hartshorne beds near Wilburton, in the Lower Hartshorne near Red Oak and Howe, and the Cavanal (Savanna Formation) beds northeast of Wister, Oklahoma.

New strip mines have been opened in recent years as well as some deep mines in the basin. Known mined-out areas in the Arkoma Basin are presented in Enclosure A-9 (Appendix A).

3.2.7.3 Natural Gas

Surface exploration for coal seams in the Arkoma Basin provided maps which showed closed anticlines and encouraged prospectors to drill for oil and gas (Branan, 1968). Except for oil in the extreme western portion of the region, the Arkoma Basin is essentially a nonassociated dry gas province.

Natural gas first was discovered in the Arkoma Basin in March 1902 at Mansfield, Sebastian County, Arkansas (Figure 3-8). The discovery well was drilled on a large surface feature known as the Hartford anticline, and this small field still is producing. The productive zones are lenticular sandstone bodies in the Atoka Formation at approximately 2,000 feet. Although the productivity of the wells at Mansfield was small, they proved the presence of hydrocarbons in the basin.

In the early 1900s the obvious surface anticlines in the basin were drilled. Hydrocarbons were found in many of these features in the thick basal Desmoinesian (Hartshorne Sandstone) and in the Upper Atoka Sandstone beds. Depths to productive beds in these fields range from 500 to 3,500 feet and most fields still are producing or are being used for gas storage.

Several of the early shallow fields, notably Poteau-Gilmore in Le Flore County, Oklahoma, and the Kinta-Quinton-Featherston trend in Haskell and Pittsburg Counties, Oklahoma (Figure 3-8), have yielded large quantities of natural gas despite the low pressures and shallow depths. A conservative estimate of the combined gas recovery to date from these two fields is more than 160 billion cubic feet.

The first significant deep gas in the basin was discovered in 1930 at Cartersville in western Le Flore County, Oklahoma. This well produced from the basal Atoka (Spiro) Sandstone.

Development in the basin was slow in the early 1950s, but was accelerated from 1955 to 1959. During this period many of the shelf-area fields were discovered. As previously mentioned, the deep potential of the basin became apparent with the discovery by Midwest Oil Corporation and

Frankfort Oil Corporation of gas in the Red Oak and Spiro sands in the No. 1 Orr at Red Oak, Latimer County, Oklahoma. This marked the beginning of the present era of deep drilling.

Presently, commercial quantities of natural gas have been produced from the lower part of the McAlester Formation, the Hartshorne Sandstone, the Atoka Formation, the Morrow Series, the Penters Chert (Lower or Middle Devonian), and the St. Clair Limestone (Silurian) in Arkansas.

Possible source rocks in the Arkoma Basin are the Hartshorne coalbed, the marine Atoka Shales below it, and the carbonaceous McAlester Shales above the Hartshorne Formation. The Hartshorne Formation is composed of coalbeds, sandstones, and shale. The Hartshorne coalbed is considered to be one of the gassiest coalbeds in the United States; it has an estimated methane content of between 1.1 and 1.5 Tcf within a relatively small area and has a long history of high methane emissions from underground workings (Iannacchione and Puglio, 1979). Closely associated with this coalbed is the Hartshorne Sandstone, which has produced natural gas from three small gasfields (Quiton, Poteau-Gilmore and Camaron) for approximately 65 years (Figure 3-8).

3.3 GENERAL GEOLOGY

The Arkoma Basin is one of seven similar basins which lie along the fronts of the Ouachita and Appalachian mountain systems. Extending eastward from West Texas they are the Marfa, Val Verde, Kerr, and Fort Worth Basins in Texas, the Arkoma Basin in Oklahoma and Arkansas, and the Black Warrior Basin at the intersection of the Appalachian and Ouachita mountain systems in northern Mississippi and northwestern Alabama. The Appalachian Basin extends northeastward into New York State.

These basins are closely related, both stratigraphically and tectonically, and all were part of the gigantic Ouachita geosyncline of the eastern and southeastern United States (Branan, 1968).

3.3.1 Geologic History

3.3.1.1 Pre-Pennsylvanian History

An ancient Oklahoma embayment was the predominant sedimentary feature of Oklahoma and Arkansas until the post-Hunton (Devonian) orogeny changed

sedimentary patterns. Two shallow basins occupied the Arkansas Valley region during Ordovician time, one being generally east and the other west of the Pope-Conway County area (Figure 3-1) (Caplan, 1957, p. 5). Both basins persisted into Atoka time (Table 3-1). Formations older than Mississippian in the Arkoma area thicken southwestward into the Oklahoma embayment. Above this unconformity these deposits thicken toward the south-southeast into the Ouachita geosyncline.

At the beginning of Mississippian time a large part of what now is the trough of the Arkoma Basin was a high area. This is evidenced by the presence of the Silurian-Devonian limestone of the Hunton Group on the basin shelf, whereas in much of the trough area the Hunton is either thinner than on the shelf or absent by truncation below Mississippian strata (Table 3-1) (Branan, 1968).

The elevated arch began to subside during Mississippian time; maximum subsidence was in the Early and Middle Pennsylvanian--in the Atokan (Pottsville) and the early Desmoinesian.

3.3.1.2 Pennsylvanian Sediments

Pennsylvanian age strata were deposited in deltaic fashion in a rapidly subsiding environment. These clastic sediments probably were derived primarily from the eroding highlands located on the northeast, north, and northwest sides of the basin. Paleocurrent azimuths in the deeper Atoka strata show that the direction of flow was southward (Briggs and Cline, 1967).

Sedimentation continued until late Pennsylvanian time, when the Arbuckle orogeny of southern Oklahoma took place (Figure 3-1). This late Pennsylvanian orogeny uplifted the Tishomingo anticline in south-central Oklahoma, thereby separating the Arkoma depression from the Fort Worth Basin south of the uplift. During early Permian time the violent Ouachita orogeny occurred.

The Ouachita Mountains area south of the basin was an incipient uplift from the late Atokan time until the major Permian orogeny. During this period it had an effect on the sedimentary patterns of the middle and late Pennsylvanian strata, but little effect on the structural framework of the basin.

Pulsations of the Ouachita uplift began in late Atokan time and continued throughout Pennsylvanian time. These pulsations which preceded the major early Permian orogeny had a dramatic effect on Pennsylvanian sedimentary patterns over the entire mid-continent region of the United States (Branan, 1968).

During the Desmoinesian Epoch of middle Pennsylvanian time, access to the open sea on the southeast was cut off periodically by Ouachita pulsating uplifts.

3.3.1.3 Post Pennsylvanian History

The Permian movement was intense and modified the entire province. In the Arkoma Basin this great force from the south caused compaction of sediments, crustal shortening through folding, and thrust faulting (Branan, 1968). At nearly the same period the Ozark dome was re-elevated, causing beds to be tilted away and block faulting to occur in that area.

The entire Arkoma Basin was tilted westward subsequent to the Ouachita folding, presumably by the later Appalachian movements (Branan, 1968). There also were movements in late Permian time and during the Cretaceous Laramide orogeny which had a minor influence on the basin. Movements still occur today in the Ouachita Mountains, as evidenced by earthquakes.

From Mesozoic to Cenozoic time, heat was introduced into the Arkoma Basin from igneous intrusions in the eastern Ouachita Mountains and the adjacent areas of the Mississippi Embayment (Craney, 1978). It is believed that this igneous influence resulted in the eastward increase of the rank of the Arkoma Basin coals.

The combined forces over geologic time have left the Arkoma Basin a crumpled, faulted complex. Figure 3-9 shows the distribution of surface folds in the basin.

3.3.2 Structural Framework

Rocks and coalbeds in the Arkoma Basin have been highly deformed by a combination of forces. As shown in Figure 3-10, the Pre-Cambrian/Cambrian basement rocks have been depressed to depths greater than 25,000 feet in parts of the basin. Influence of the Ozark uplift and the Ouachita orogenic province has caused the Arkoma Basin to possess many unique

structural conditions. This has given rise to the unique physiography where the synclines form the mountains and the anticlines are expressed as valleys.

3.3.2.1 Tectonic Provinces

In order to explain the tectonics, Branan (1968) divided the Arkoma Basin into three structural provinces, ranked in order of Ouachita deformation (Figure 3-1).

Zone 1 is at the forefront of the Ouachita Mountains in the trough area. Steep dips are common. The rocks are folded into a series of long, narrow anticlines, generally overthrust on the north.

Zone 2 is an area of elongate and domal features, with little or no evidence of thrusting. This is known as the subshelf area.

Zone 3 is the basin shelf area where the Ouachita influence was slight, and only gentle folds are found. In Zone 3 in Oklahoma the outcropping beds are middle and upper Pennsylvanian. These rock units thicken southeastward; however, they have been elevated by the Ouachita force and now dip northwestward.

3.3.2.2 Folds

There are two basic structural patterns affecting the area of interest in the basin: (1) folding and northward overthrusting, and (2) block faulting. The stability of the Ozark Plateau on the north during basin subsidence caused tensional forces to develop which resulted in the evolution of major block faulting in the basin (Figure 3-11). Evidence indicates that some of these faults were growing contemporaneously with deposition of the lower Pennsylvanian beds.

Early Permian (Ouachita) mountain building on the south compressed the basin sediments into a series of long, narrow, east-west anticlinal and synclinal folds. Overthrusting along anticlinal axes near the mountain front is common. Some of the folds have surface expressions extending 75 miles or more (Figure 3-1). Disney (1960) reported that the anticlines occupy approximately 35 percent of the total basin area. The synclines being wider account for approximately 65 percent of the basin area.

Indications are that these superficial folds diminish with depth. A high anticline on the surface may not be expressed as an anticline in the subsurface below the Atoka.

These features are much more complex than simple anticlines. In many cases low-angle sole thrusts in the Atoka section break into imbricate thrusts as they rise to the surface, causing much repetition of section (Figure 3-11). This has created the unique situation, in parts of the basin, in which the shallower beds and surface rocks were folded and thrusted, whereas the deeper beds are only block faulted.

There were unusual structural developments as Ouachita tectonic pressures were applied to the zones of major down-to-the-basin block faulting. When the force came from the south, the faces of these large block faults became buttresses which, in some cases, caused the thicker section of the Atoka Formation on the south side of the fault to be shoved and thrust upward. The final effect is an anticline on the surface that is actually on the downthrown side of a major block fault in the deeper beds (Branan, 1968).

3.3.2.3 Faults

Many types of fault systems are found in the basin. An understanding of the nature of the faulting in a particular area of the basin might be of great value in developing a coalbed methane reservoir. Block faulting took place as the basin was subsiding in Pennsylvanian time and was being filled with Atoka sediments. As a result, deep in the basin, major zones of faulting are commonly obscure or absent on the surface, because enough Atoka age shale was deposited on the downthrown side to compensate for the throw.

Later Permian uplift on the south, and consequent folding and overthrusting of the beds in the basin produced some complex structural situations.

Near the forefront of the mountains is a system of block faulting, or high-angle thrusting, in the deeper and older strata (Figure 3-11). These faults are upthrown on the south, and were probably created by Ouachita pressure. The faults appear to be unrelated to the system of major

down-to-the-basin faults previously described. This system of faulting can be observed in the Wilburton Field in Latimer County, Oklahoma (Figure 3-8).

Throws on the faults in the Cartersville-Kinta-Red Oak area range from 3,000 to 6,000 feet. The throw is generally down to the south, or basinward. However, there are notable exceptions where the throw is reversed. The faults downthrown on the north generally are not of the magnitude of the large down-to-the-basin faults (Figure 3-11).

3.3.3 Stratigraphy

Stratigraphic relationships are important in order to reconstruct the geological depositional environments of the coal and associated sediments. Table 3-1 presents the general geologic section for oil and gas producing areas in eastern Oklahoma. Branan (1968) prepared a nomenclature chart for both the McAlester and the Arkansas Valley regions which is presented in Table 3-2. The stratigraphic terminology is different in Arkansas and Oklahoma, and the adoption of a single set of names for the numerous formations and members by industry and government is improbable. This conflict in terminology has arisen between surface geology and subsurface geology interpretations of the depositional patterns in the basin. Beds above and below the Atoka correlate well across the basin, and although different names are used, the rocks are essentially alike lithologically (Branan, 1968).

The number of sandstone beds in the Atokan series increases from west to east in the basin. The Atokan section is composed of predominantly dark-gray shale with a few sandstone beds in the western part of the basin and many sandstone and siliceous shale beds in the eastern end of the basin. This regional lithofacies change causes many correlation problems.

The names of the lenticular bodies are different in each producing field in Arkansas, and no attempt has been made by Branan (1968) in Table 3-2 to list all of the local names used to identify Atoka sandstone bodies in the Arkansas gas fields. The Fort Smith Geological Society has published a correlation chart for the Arkansas side in which general sandstone series are recognized; however, correlation of certain individual units is

questionable (Bacho, 1961). The difficulties are compounded as stratigraphic correlations are attempted from north to south.

The Atoka series thickens so markedly on the south in parts of the basin that it becomes impossible to correlate updip sandstone beds with those within the thicker Atoka units (Branan, 1968). As the formation thickens, sandstone bodies become more numerous.

Branan (1968) reported that there are about 25 gas-productive zones in the Arkoma Basin ranging in age from early Desmoinesian (Pennsylvanian) to Simpson (Ordovician), and there have been encouraging shows from the Cambria-Ordovician Arbuckle below the Simpson (Table 3-1). As mentioned before, some of the productive zones are associated with coalbeds. Arkansas has more productive zones than Oklahoma because of the increase in the number of sandstone bodies in the Atoka on the Arkansas side.

3.3.3.1 McAlester Region

The coal-bearing strata of middle and late Pennsylvanian age in eastern Oklahoma occur in an area of 14,500 square miles. At least 24 coals have been recognized as Desmoinesian and early Missourian (Pennsylvanian) in eastern Oklahoma. This area is located in the southern part of the Western region of the Interior coal province of the United States (Campbell, 1917). Some 8,000 square miles in Oklahoma are known to contain coalbeds 1 to 7 feet thick that are of commercial value at the present time, have been in the past 100 years, or may be in the future (Figure 3-12). The rocks of the McAlester region are chiefly of Pennsylvanian age, with some tentatively classified as Quaternary (Hendricks, et al, 1939). The rocks tentatively referred to as being Quaternary consist of sand and gravel that cover stream terraces.

The Pennsylvanian rocks in the basin contain these valuable coalbeds and have been subdivided into the following formations, listed in order of age, with the oldest first: Atoka Formation, Hartshorne Sandstone, McAlester Shale, Savanna Sandstone, Boggy Shale, Thurman Sandstone, Stuart Shale and Senora Formation (Figure 3-12). Each of these formations consists of alternating sandstone and shale, and all except the Atoka and Thurman include beds of commercially exploitable coal. The shales and sandstones at some horizons are of continental origin, and those at others

are marine. Some continental beds grade laterally into marine beds. All of these formations were deposited in a shallow water environment. No marked unconformity in the Pennsylvanian rocks can be recognized at any one horizon over the entire basin, but locally between the Savanna and McAlester formations there is an unconformity that probably extends over the entire area without being recognizable at all places. Minor breaks within the formations are indicated by considerable irregularity in the bedding of the rocks (Hendricks, et al, 1939).

The Quaternary age Gerty Sand consists of unconsolidated sand, gravel and clay up to 50 feet thick and derived from a western source of Cretaceous age. These sediments are widely distributed over the north half of the McAlester district and are found along the former course of the Canadian River in parts of the Lehigh District and the Howe-Wilburton District. Other terrace deposits of the same age as the Gerty Sand have an eastern source in the Ouachita Mountains. Alluvium of recent age forms mainly the floors of the larger valleys and consists of an ash-gray silt.

The bituminous coals in the Pennsylvanian rocks are low volatile in northern Le Flore County; medium volatile in northern Le Flore, Sequoyah, and most of Haskell Counties; high volatile A and B in parts of Haskell County and in the remaining coal-bearing counties, and high-volatile C in Craig, Nowata, Pittsburg and Rogers Counties (these are in coal groups 1-5, Class II, American Society for Testing and Materials Standard D388-66).

The coalbeds in the northeast Oklahoma shelf area are 0.8 to 5.0 feet thick, dip westward from less than 1° to 2°, and contain more than 3 percent sulfur by weight with the exception of the Croweburg coal. The coalbeds in the McAlester Region are 1 to 7 feet thick and occur in eroded anticlines and synclines that plunge southwestward. The coals crop out mostly around the sides of these folded and faulted structures, and their dip ranges from nearly vertical to 3° (Enclosure A-8, Appendix A). Although coal with steep dips (up to 65°) was mined in the past, in recent years mines were developed in beds dipping 3° or less. As a result of the recent energy shortage, four new surface mines have been developed in steeply dipping coalbeds in the McAlester region. Classical stratigraphic descriptions are presented for the McAlester region part of the Arkoma Basin.

Atokan Series

Atoka Formation: The Atoka Formation was named after the town of Atoka, Atoka County, Oklahoma and described by Taff and Adams (1900). The formation consists mainly of gray-to-black sandy shale with thick sandstone units interbedded at widely-spaced intervals. Maximum thickness is probably greater than 9,000 feet thick. The shale units are brown to black, micaceous, and contain lenses and nodules of siderite. Knechtel (1949) stated that these shale units in the Atoka Formation are more silty and less clayey than those of the younger, overlying Pennsylvanian formations. The contact between the Atoka Formation and the overlying Hartshorne Sandstone needs better definition, but is thought to be at the base of the massive Lower Hartshorne Sandstone by Oaks and Knechtel (1948), which is some 42 feet above the thin laterally discontinuous sandstone used by Hendricks. This problem is discussed in Section 4.

Desmoinesian Series

Hartshorne Formation: Taff (1899) renamed the "Tobucksy" Sandstone of Chance (1890) as the Hartshorne after the town of Hartshorne, Pittsburg County, Oklahoma. The Hartshorne Sandstone is the basal unit of the Desmoinesian series. This formation is conformably underlain by the Atoka Formation and overlain conformably by the McAlester Formation, and is a clastic unit containing no pure carbonate rocks.

McAlester Formation: Taff (1899) described the McAlester Formation which conformably overlies the Hartshorne Formation and is named after McAlester, Pittsburg County, Oklahoma. The contact is normally placed at the top of the Hartshorne coal (Figure 3-12). The formation consists mostly of gray shale and siltstones. The Booch sandstones are named after the Booch farm, Morris field, Okmulgee County, Oklahoma (Jordan, 1957) and are stratigraphically equal to the Warner, Cameron and Tamaha sandstones.

Savanna Formation: The Savanna Sandstone was named by Taff in 1899 from exposures near the town of Savanna, Pittsburg County, Oklahoma. The formation consists of gray shale units with interbedded black carbonaceous shales and fine-grained, silty to coarse-grained sandstones of variable thickness. The lower boundary is at the base of the lowermost sandstone. The Savanna Sandstone overlies the McAlester Formation with an irregular

contact, although at some places the transition from one formation to another appears to be gradational (Hendricks, et al, 1939). In the northeast part of the McAlester basin the Savanna Formation changes facies into the Spaniard Limestone (Knechtel, 1949). The lower boundary of the Savanna Formation has been placed by Knechtel (1949) at the base of the Spaniard Limestone in the northeastern shelf area (Figure 3-1). The upper boundary of the Savanna Formation is at the base of the Bluejacket Sandstone member of the overlying Boggy Formation.

Boggy Formation: Taff (1899) named the Boggy Formation after the shale exposures along North Boggy Creek in Atoka and Pittsburg counties, Oklahoma. Miser (1954) redefined the lower boundary of the formation to be the base of the Bluejacket Sandstone. The Boggy Shale, as it is commonly called, consists of alternating gray shales and sandstones.

The Thurman Sandstone member ranges from 250 to 335 feet thick in the Lehigh and Quinton-Scipio Districts. A basal bed of chert-pebble conglomerate is rather widespread (Dane, et al, 1938). The basal conglomerate rests with a sharp contact and local erosional irregularity on the underlying Boggy Shale.

Taff (1901) named the Stuart Shale member after the town of Stuart in Hughes County, Oklahoma. The Stuart Shale consists of dark laminated shales, which sometimes carry ferruginous or calcareous nodules and concretionary beds.

Senora Formation: Taff (1901) named the formation after the old post office of Senora in Okmulgee County, Oklahoma. It exists only as a thin formation in the Quinton-Scipio District and consists of sandstone with some shale beds.

3.3.3.2 Arkansas Valley Region

Of the 19 or 20 coalbeds in the Arkansas Valley investigated by state and federal agencies, only four have been considered to be of economic importance by the U.S. Geological Survey. These are the lower Hartshorne, upper Hartshorne, Charleston, and Paris coalbeds (Figure 3-13).

The stratigraphic boundaries of the post-Atoka rocks established by Hendricks and Parks (1950, p. 69) are used in this report. The stratigraphic nomenclature of these rocks as reported in Hendricks and Parks

(1950) was modified by Merewether and Haley (1961), who adopted Miser's (1954) terminology for equivalent rocks in Oklahoma of the McAlester Formation, Savanna Formation, and Boggy Formation, and Oakes' (1953) classification of the Krebs Group, which includes the Hartshorne Sandstone and the McAlester, Savanna, and Boggy formations. Haley (1961a) moves the base of the Boggy Formation stratigraphically upward, thereby conforming to the definition established by Miser (1954). The formations as described here for the Arkansas Valley with the exception of the Hartshorne Sandstone are stratigraphically equivalent to the formations in the type areas in Oklahoma (Haley and Hendricks, 1972). The stratigraphic nomenclature and boundaries of Atoka rocks introduced in this section conform, in general, to those used elsewhere in Arkansas.

Rocks of the Pennsylvanian and Quaternary systems are exposed or have been penetrated by wells drilled for gas in the Arkansas Valley. The Pennsylvanian rocks are, from oldest to youngest, the Atoka Series, and the Krebs Group. The Quaternary rocks are stream and river terrace deposits of Pleistocene age (Hendricks and Parks, 1950), and stream and river alluvium of recent age. The Hartshorne Sandstone in the western part of the Arkansas Valley is equivalent to the lowermost sandstone in the Hartshorne Sandstone in Oklahoma. Hendricks and Parks (1950, p. 69) state: "Hendricks traced the formation boundaries eastward from their type localities in Oklahoma to the Arkansas-Oklahoma state line, and from there into Arkansas". The boundaries were traced from the Fort Smith District, Arkansas (Hendricks and Parks, 1950), eastward to the Delaware Quadrangle by B. R. Haley (Enclosure B-1, Appendix B).

The Lower Hartshorne coal is the most productive and extensive coalbed in Arkansas. Underlying 1320 square miles, it is greater than 14 inches thick over an area of about 740 square miles. In Sebastian County it reaches 8 feet thick locally. Rank ranges from low volatile bituminous in the western part of the Arkansas Valley coal fields to semi-anthracite in the eastern part. The Upper Hartshorne coal is low volatile bituminous in rank and underlies about 28 square miles of the southwestern Arkansas Valley. It is approximately 14 inches thick over an area of about 16 square miles and reaches a maximum of 34 inches in thickness.

The Charleston coalbed underlies an area of about 120 square miles and has been mined by many strip operations in both the East and West Districts of Arkansas. Maximum thickness is about 23 inches, and it is 14 inches thick over 52 square miles. In the western part of the Arkansas Valley, the coal is low volatile bituminous in rank, whereas in the eastern part it is semi-anthracite.

The Paris coal underlies three small areas that total 18 square miles and ranges from 14 to 32 inches in thickness. The Paris coal has been mined (surface and subsurface) in the Charleston coal field.

Stratigraphic descriptions along with subsurface interpretations are presented for the Arkansas Valley region of the Arkoma Basin.

Atokan Series

Atoka Formation: Henbest (1953) described the contact between the Atoka Formation and the Morrow Series and named the basal sandstone of the Atoka the Greenland Sandstone member of the Atoka Formation. According to Henbest, the Greenland Sandstone member consists of silty, ripple-marked, flaggy sandstone with shaley partings, and, locally, interfingering marine quartz-gravel conglomerate.

This unit of sandstone or a lithologically similar unit is at the base of the Atoka Formation throughout most of northwestern Arkansas. In the Arkansas Valley region the contact between the Atoka Formation and the Morrow is not exposed but has been penetrated by wells drilled for gas or oil (Haley and Hendricks, 1972). In preparing a stratigraphic log of the rock cuttings from any one of these wells, the contact is placed at the base of the first sandstone unit overlying a unit of rocks similar to those of the Morrow (shale and limey sandstone, sandy limestone, and limestone). The lithologic character of this basal sandstone unit of the Atoka Formation, as identified from the well cuttings in the Arkansas Valley region and in the Delaware quadrangle, is similar to those of the Greenland Sandstone member as described by Henbest. However, the regional decrease in amount of carbonate and increase in amount of sand in the rocks of the upper part of the Morrow Series make them increasingly similar to the rocks

in the lower part of the Atoka Formation south and east of Washington County, Arkansas and thus the two are not easily separated, south, southeast and east of the Delaware quadrangle.

Hendricks and Parks (1950, p. 73) reported a minor unconformity between the Atoka Formation and the overlying Hartshorne Sandstone. The basal sandstone bed of the Hartshorne Sandstone overlies the uppermost bed (generally dark-gray shale or silty shale) of the Atoka Formation with a channel-type relationship which Hendricks and Parks (1950) have interpreted as a minor unconformity. The stratigraphic sections show a convergence of the base of the Hartshorne Sandstone and the top of the youngest sandstone of the Atoka in the western Arkansas Valley.

Desmoinesian Series

Hartshorne Sandstone: The Hartshorne Sandstone of Hendricks and Parks (1950, p. 73) is equivalent to the lowermost sandstone in the Hartshorne Sandstone underlying the Lower Hartshorne coalbed in the type area near Hartshorne, Oklahoma. The minor unconformity between the Hartshorne Sandstone and the Atoka Formation is considered to be present in the Arkansas Valley region. The Hartshorne Sandstone is conformably overlain by the McAlester Formation.

The Hartshorne Sandstone is one of the most persistent sandstone units in Arkansas. As a sandstone unit, it has several lithologic characteristics which tend to set it apart from most of the sandstone units in the overlying McAlester Formation or in the underlying Atoka Formation. In general, the Hartshorne Sandstone is lighter in color (grayish-white to light-gray), coarser in grain size (very fine to medium), less silty or clayey, and more widespread. Pebbles of shale and siltstone are present near the base of some sandstone beds (Haley and Hendricks, 1972).

McAlester Formation: The McAlester conformably overlies the Hartshorne Sandstone and is overlain by the Savanna Formation with a contact that, according to Hendricks and Parks (1950, p. 76), represents a minor unconformity. Haley (1961, p. 7) reported that the McAlester and Savanna Formations in the vicinity of Paris, Arkansas have an interfingering relationship. Merewether and Haley (1969) stated that the formations interfinger in the vicinity of Clarksville, Arkansas. In the southeastern

part of the Van Buren quadrangle where the basal sandstone of the Savanna is in channel cuts in shale of the McAlester, the contact appears unconformable.

The McAlester Formation is mostly shale with a minor amount of siltstone and sandstone. The shale is dark gray, nonsilty, and fissile bedded for the most part. Pyrite and ironstone concretions are common in all the shale.

Savanna Formation: The sandstone in the Savanna is finer grained, siltier, and more argillaceous than the sandstone in the McAlester, Hartshorne, or Atoka. In some places, the sandstone and siltstone weather yellowish or greenish brown, whereas the sandstone and siltstone in the other three formations generally weather light gray or grayish white. Thin coalbeds are common in the lower part of the formation. The Charleston coalbed is near the base of the formation, and the Paris coalbed is in the upper part of the formation.

The lower part of the Savanna Formation interfingers with the upper part of the McAlester Formation in the eastern part of the Paris quadrangle (Haley, 1961a, p. 7). The same relation between the two formations exists in the Scranton and New Blaine quadrangles. The shale is mostly dark gray, micaceous, and slightly silty to silty. Some of the shale is light to medium gray and, from the appearance of the rock samples from shallow exploration wells, is nonbedded; thus, it could be either claystone or underclay. Ironstone concretions are common in the shale, and pyrite is present in some places.

Boggy Formation: There are a few remnants of the Boggy Formation in the Arkansas Valley region located in Logan County, Arkansas. Part of the basal sandstone unit caps Short and Little Short Mountains.

Figure 3-14 illustrates the relation between general structure and stratigraphy for the Greenwood quadrangle in the western part of the Arkansas Valley region.

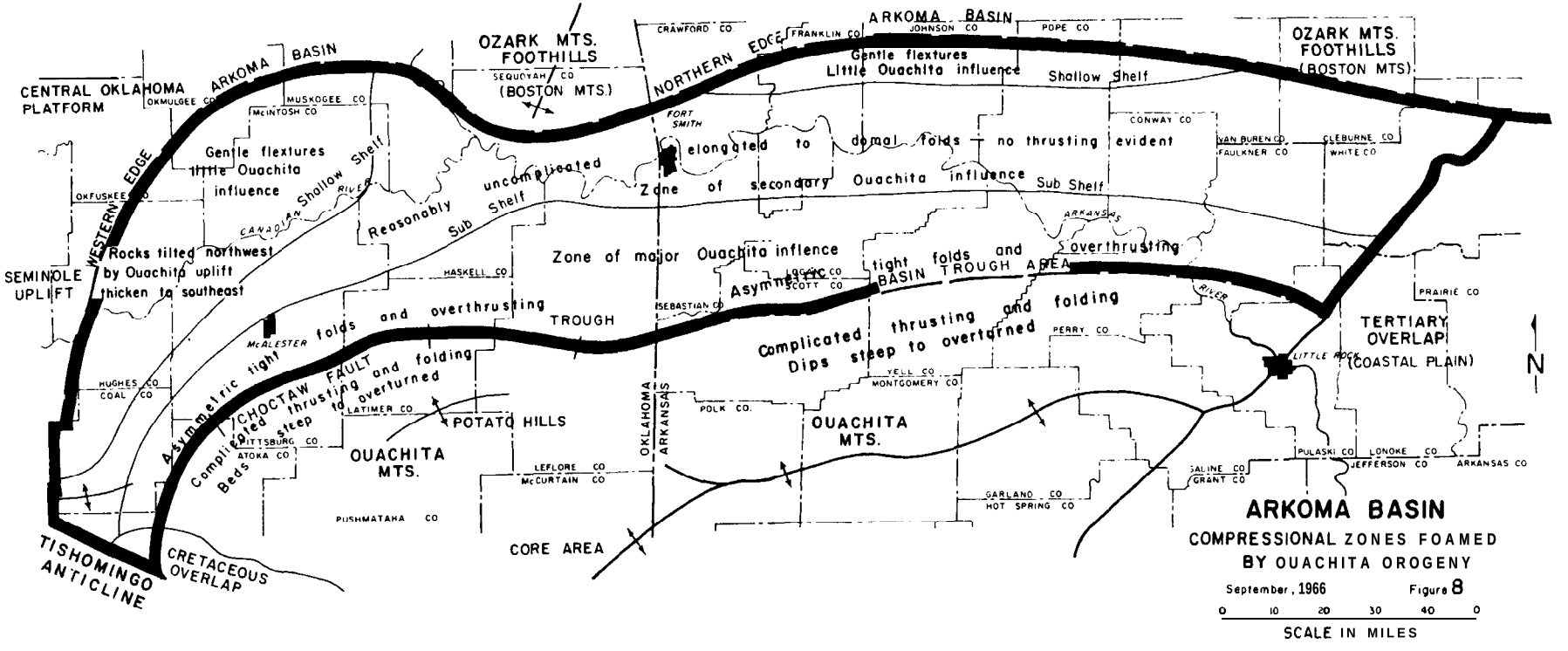


Figure 3-I Regional Setting of the Arkoma Basin (From **Branan**, 1968) (Courtesy of AAPG)

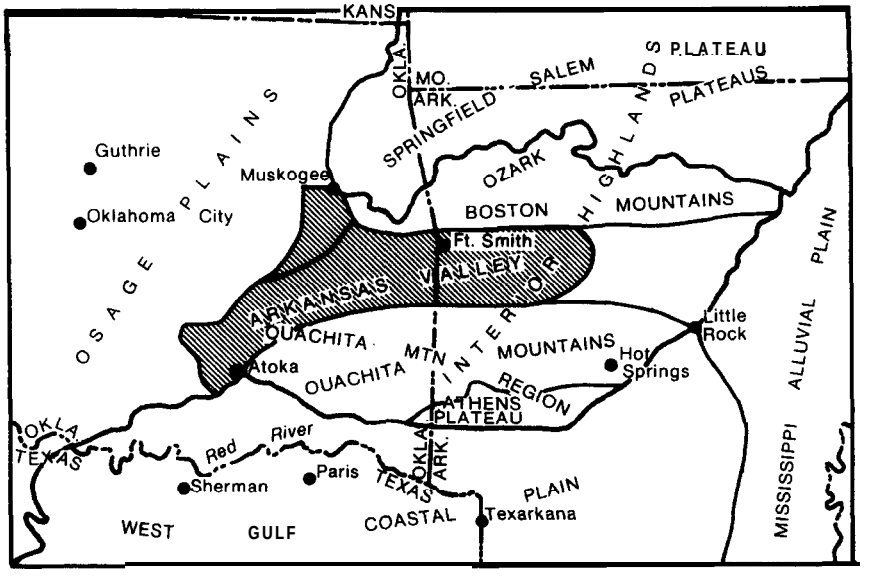
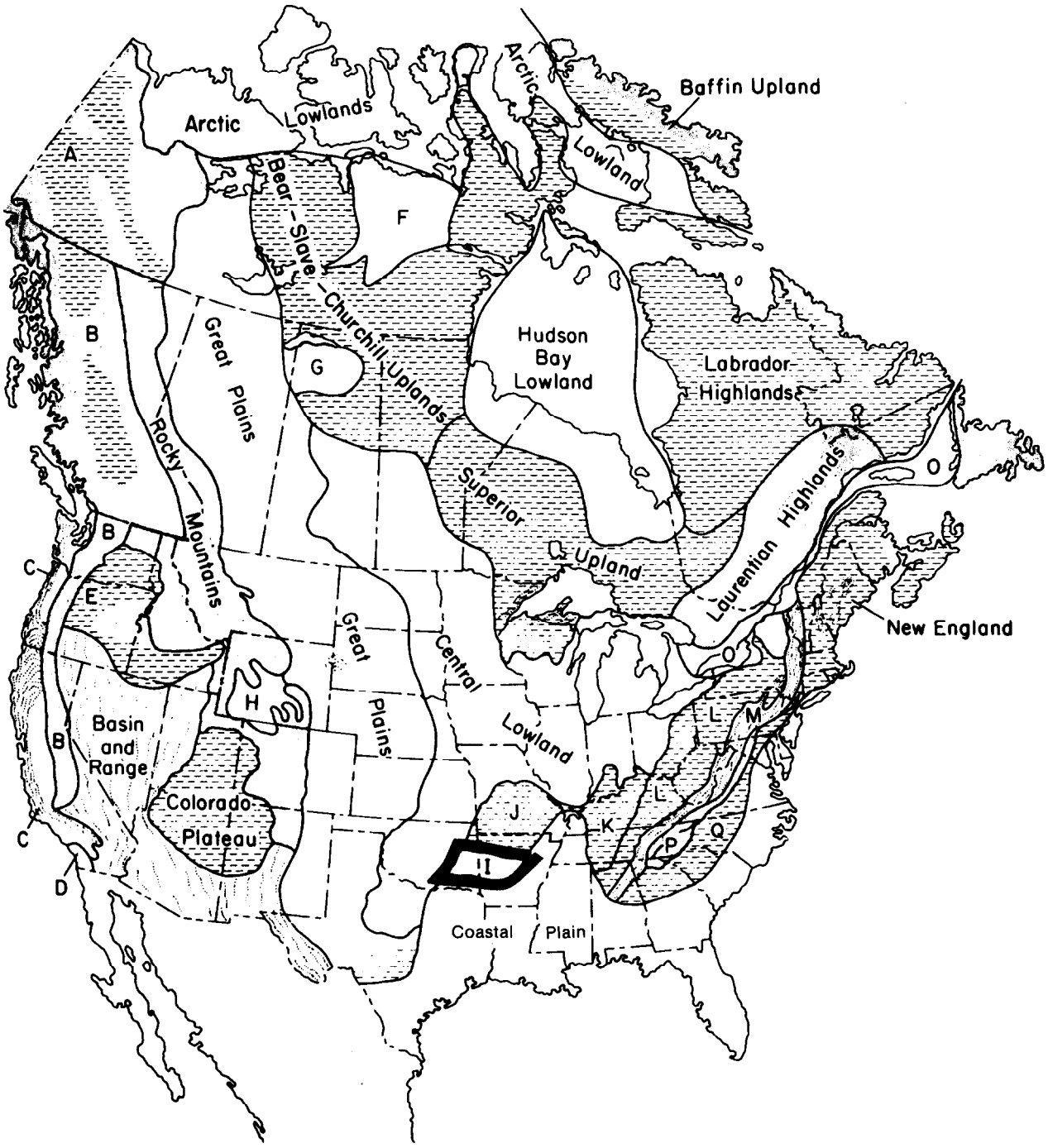


Figure 3-2 Map Showing Location of the Arkansas-Oklahoma Coal Basin (Shaded Area) and Physiographic Provinces (After Hendricks, et al, 1936, p. 1342) (Courtesy of AAPG)



Mountain

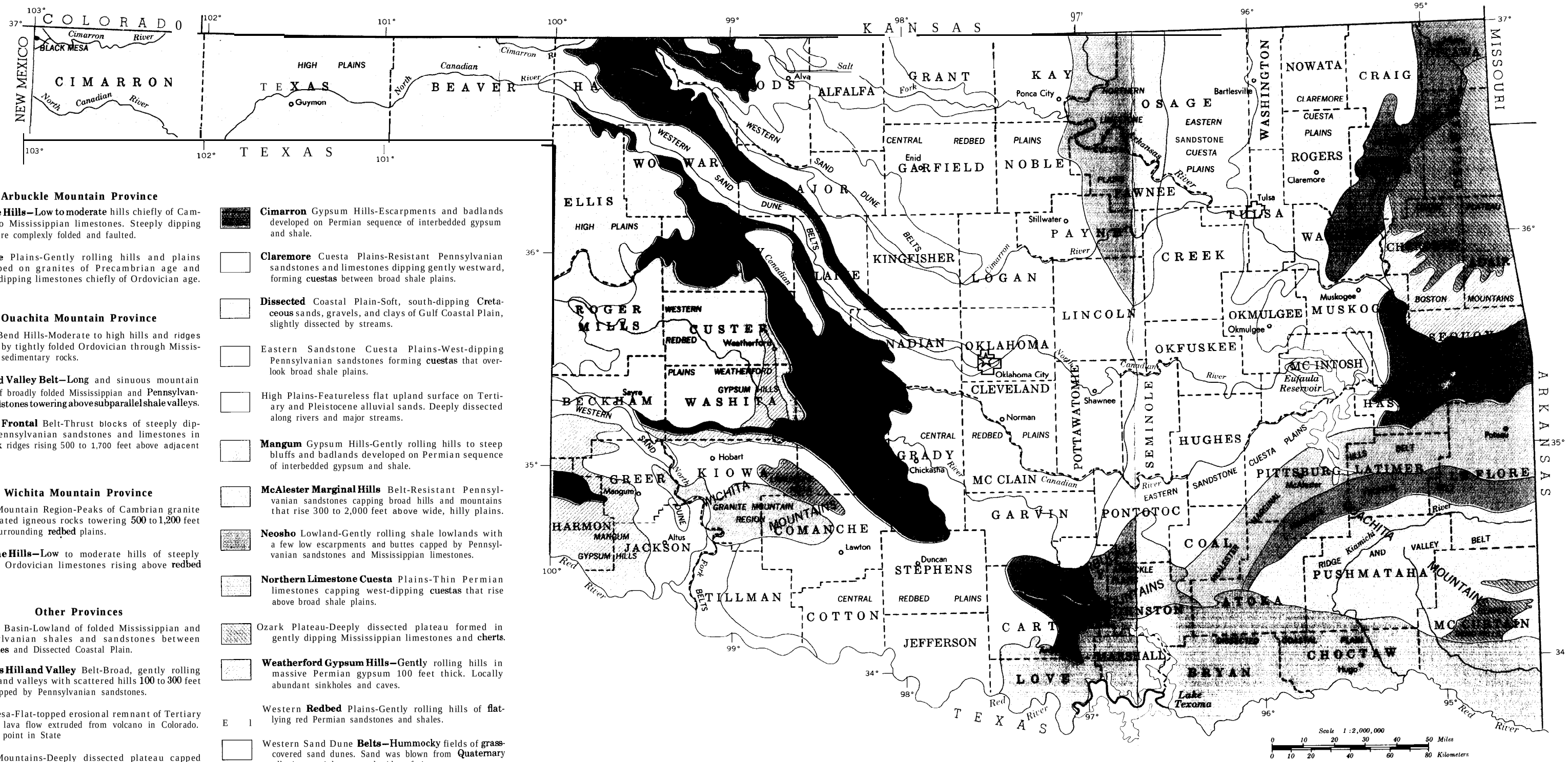
Plateaus

Plains

A Canada West of Mackenzie River
B Pacific Mountain System; includes
C Pacific Border
D Lower California
E Columbia -Snake River Plateau
F Thelon Plains ond Back River Lowland
G Athobasco Plain
I-I Wyoming Basin
I Ouachita

J Ozark Plateaus
K Interior Low Plateaus
L Appalachian Plateaus
M Valley and Ridge
N Adirondack
0 St. Lawrence Lowland
P Blue Ridge
Q Piedmont Plateau

Figure 3-3 Physiographic Regions of the United States and Canada and Their Dominant Landforms (From Natural Regions of the United States and Canada, by C. B. Hunt, W. H. Freeman and Company, Copyright 1974) (Courtesy of Publisher, June 1979).



GEOMORPHIC PROVINCES OF OKLAHOMA

By
NEVILLE M. CURTIS, JR., AND WILLIAM E. HAM

(Updated 1979)

Arbuckle Mountain Province

Arbuckle Hills—Low to moderate hills chiefly of Cambrian to Mississippian limestones. Steeply dipping strata are complexly folded and faulted.

1 **Arbuckle** Plains-Gently rolling hills and plains developed on granites of Precambrian age and gently dipping limestones chiefly of Ordovician age.

Ouachita Mountain Province

Beavers Bend Hills-Moderate to high hills and ridges formed by tightly folded Ordovician through Mississippian sedimentary rocks.

1 **Ridge and Valley Belt—Long** and sinuous mountain ridges of broadly folded Mississippian and **Pennsylvanian sandstones towering above subparallel shale valleys.**

1 **Hogback Frontal** Belt-Thrust blocks of steeply dipping Pennsylvanian sandstones and limestones in **hogback** ridges rising 500 to 1,700 feet above adjacent valleys.

Wichita Mountain Province

1 Granite Mountain Region-Peaks of Cambrian granite and related igneous rocks towering 500 to 1,200 feet above surrounding **redbed** plains.

Limestone Hills—Low to moderate hills of steeply dipping Ordovician limestones rising above **redbed** plains.

Other Provinces

Ardmore Basin-Lowland of folded Mississippian and Pennsylvanian shales and sandstones between **Arbuckles** and Dissected Coastal Plain.

Arkansas Hill and Valley Belt-Broad, gently rolling plains and valleys with scattered hills 100 to 300 feet high capped by Pennsylvanian sandstones.

7 **Black** Mesa-Flat-topped erosional remnant of Tertiary basaltic lava flow extruded from volcano in Colorado. Highest point in State

1 Boston Mountains-Deeply dissected plateau capped by gently dipping Pennsylvanian sandstones.

1 **Central Redbed** Plains-Red Permian shales and sandstones forming gently rolling hills and broad, flat plains.

Cimarron Gypsum Hills-Escarpments and badlands developed on Permian sequence of interbedded gypsum and shale.

Claremore Cuesta Plains-Resistant Pennsylvanian sandstones and limestones dipping gently westward, forming **cuestas** between broad shale plains.

Dissected Coastal Plain-Soft, south-dipping **Cretaceous** sands, gravels, and clays of Gulf Coastal Plain, slightly dissected by streams.

Eastern Sandstone Cuesta Plains-West-dipping Pennsylvanian sandstones forming **cuestas** that overlook broad shale plains.

High Plains-Featureless flat upland surface on Tertiary and Pleistocene alluvial sands. Deeply dissected along rivers and major streams.

Mangum Gypsum Hills-Gently rolling hills to steep bluffs and badlands developed on Permian sequence of interbedded gypsum and shale.

McAlester Marginal Hills Belt-Resistant Pennsylvanian sandstones capping broad hills and mountains that rise 300 to 2,000 feet above wide, hilly plains.

Neosho Lowland-Gently rolling shale lowlands with a few low escarpments and buttes capped by Pennsylvanian sandstones and Mississippian limestones.

Northern Limestone Cuesta Plains-Thin Permian limestones capping west-dipping **cuestas** that rise above broad shale plains.

Ozark Plateau-Deeply dissected plateau formed in gently dipping Mississippian limestones and **cherts.**

Weatherford Gypsum Hills—Gently rolling hills in massive Permian gypsum 100 feet thick. Locally abundant sinkholes and caves.

E 1 Western **Redbed** Plains-Gently rolling hills of **flat-lying** red Permian sandstones and shales.

Western Sand Dune **Belts—Hummocky** fields of **grass-covered** sand dunes. Sand was blown from **Quaternary** alluvium mainly on north sides of rivers.

Western Sandstone Hills—Soft, flat-lying red Permian sandstones forming gently rolling hills cut by steep-walled canyons.

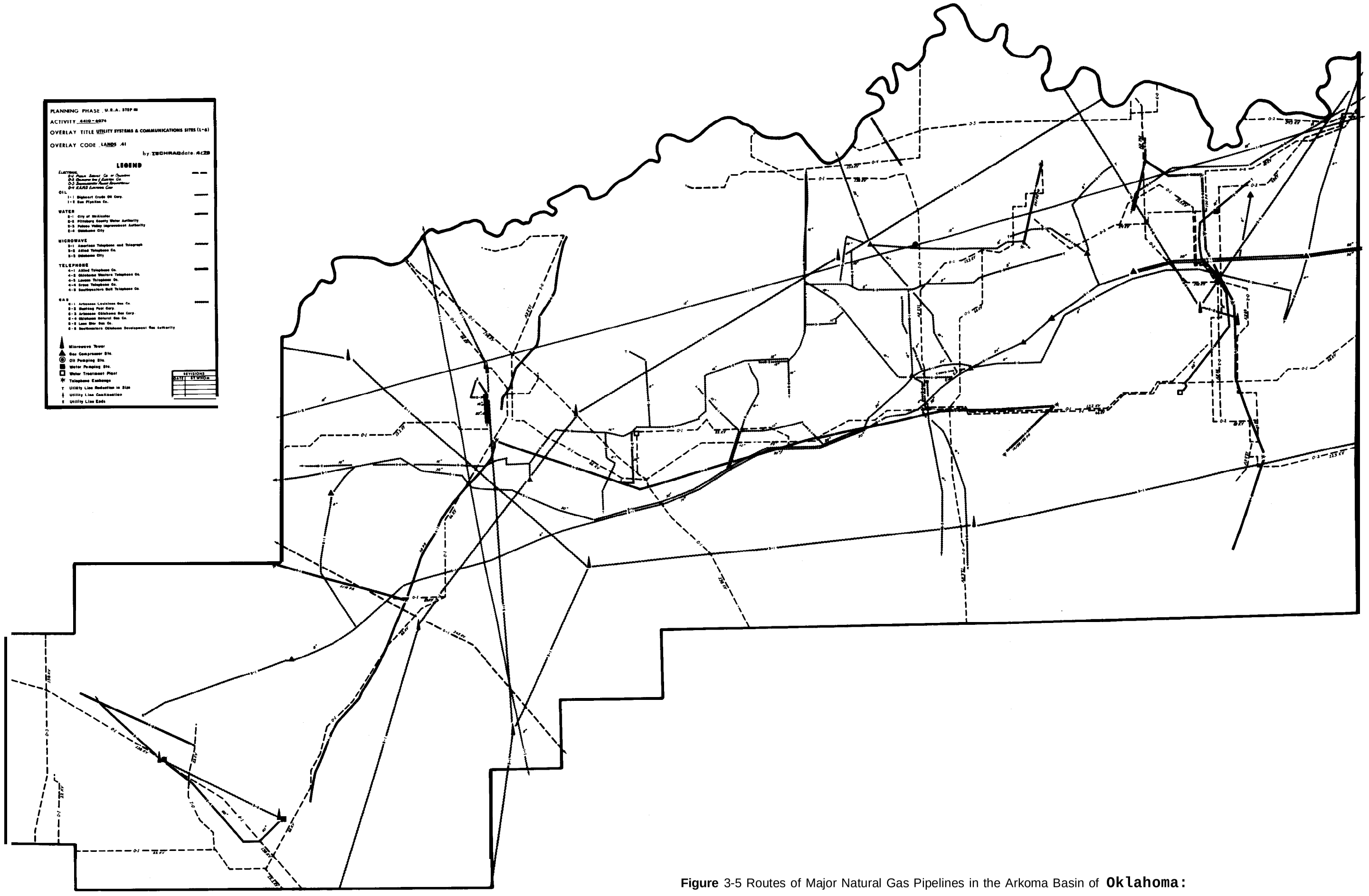
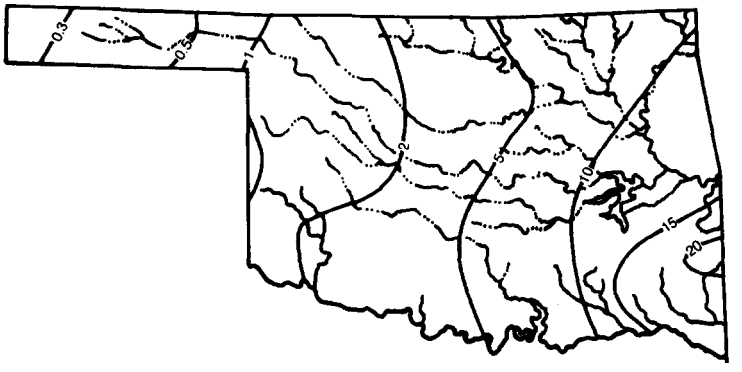
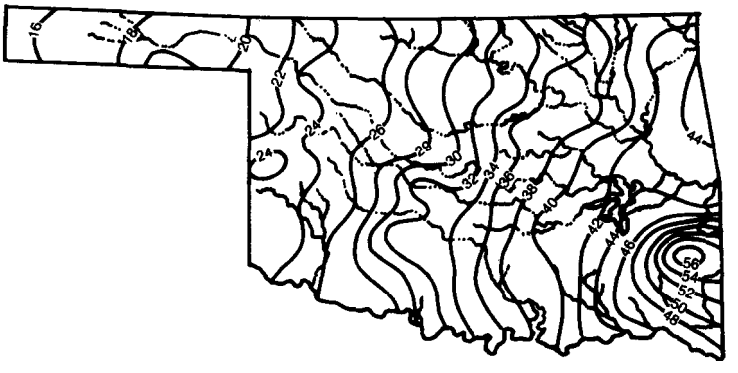


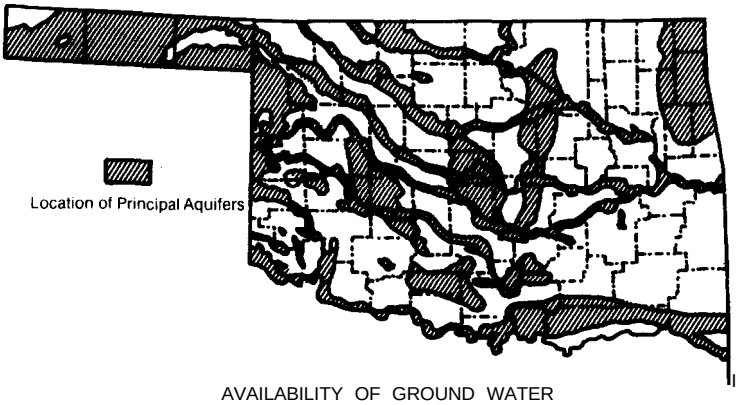
Figure 3-5 Routes of Major Natural Gas Pipelines in the Arkoma Basin of **Oklahoma:**



AVERAGE ANNUAL RUNOFF, IN INCHES



AVERAGE ANNUAL PRECIPITATION, IN INCHES
(Data from National Weather Service-NOAA)



AVAILABILITY OF GROUND WATER

Figure 3-6 Variation in the Annual Precipitation, Average Annual Runoff and the Availability of Ground Water.

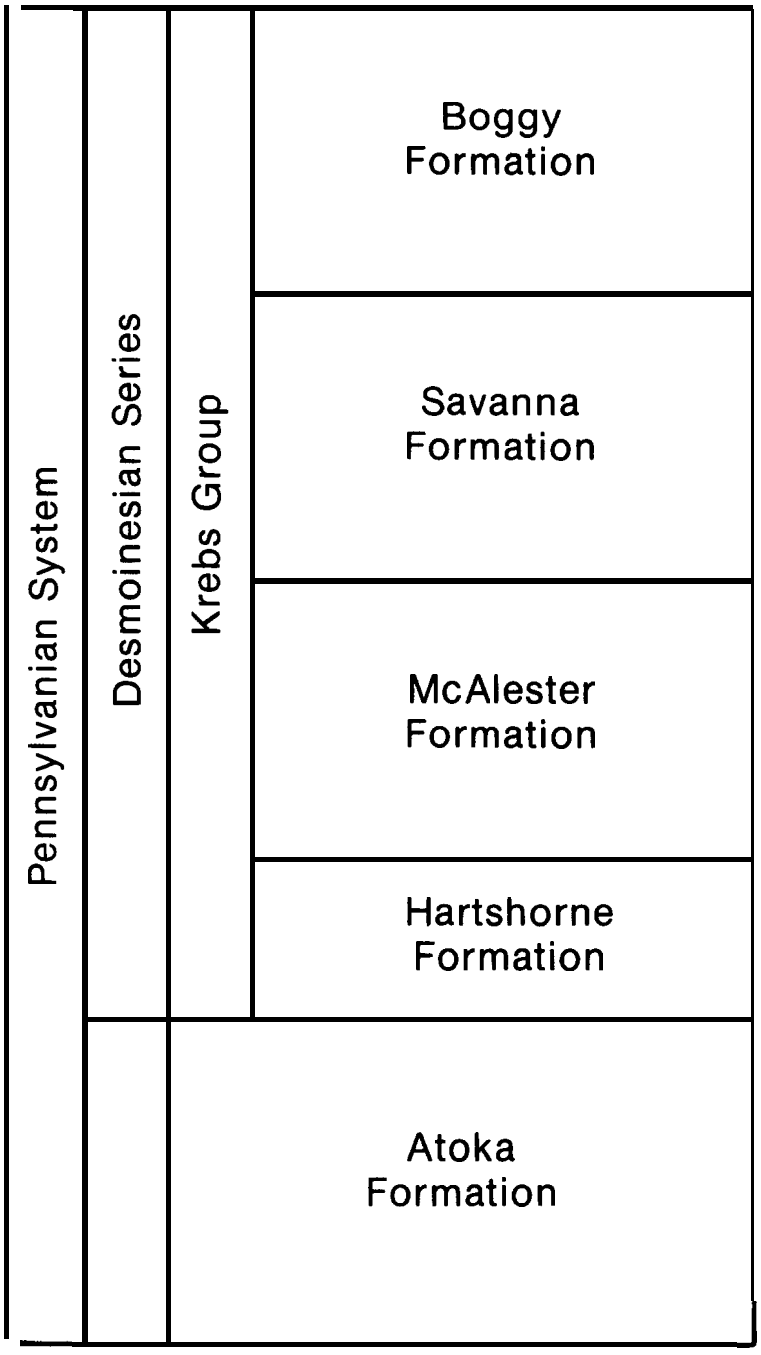


Figure 3-7 Generalized Stratigraphic Column of Exposed Rocks in the Arkoma Basin (lannacchione and Puglio, 1979).

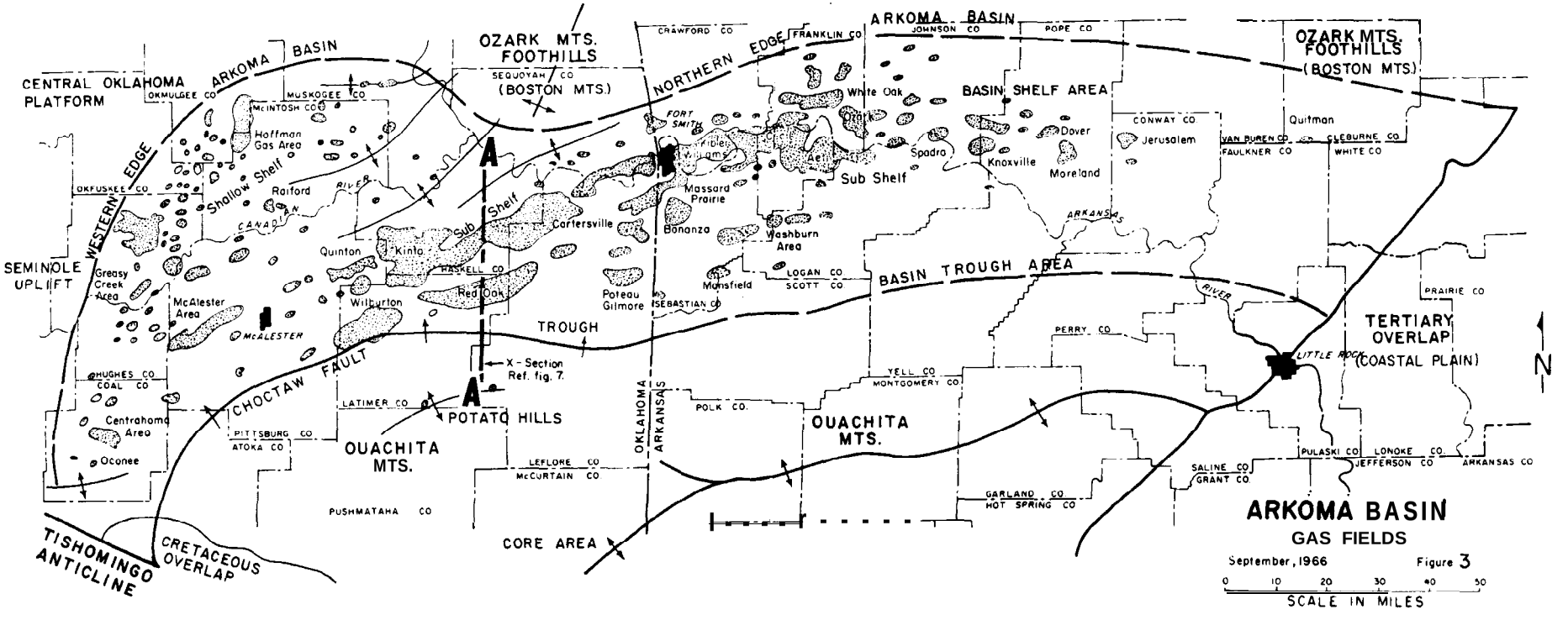


Figure 3-6 Arkoma Basin Gas Fields (From **Branan**, 1968, Courtesy of AAPG).

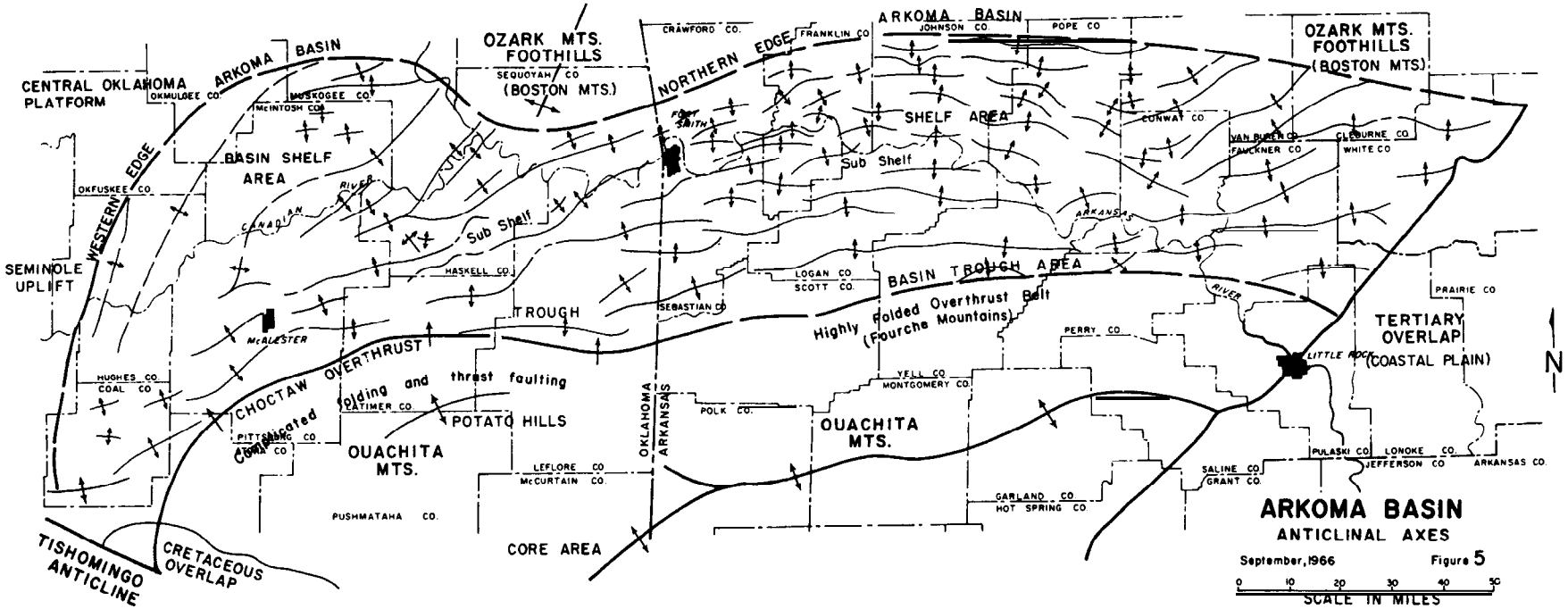


Figure 3-9 Major Structural Features of the Arkoma Basin (After **Branan,** 1968, Scull, et al, 1959) (Courtesy of AAPG, Dallas Geological **Soc.** and Ardmore Geological **Soc.**)

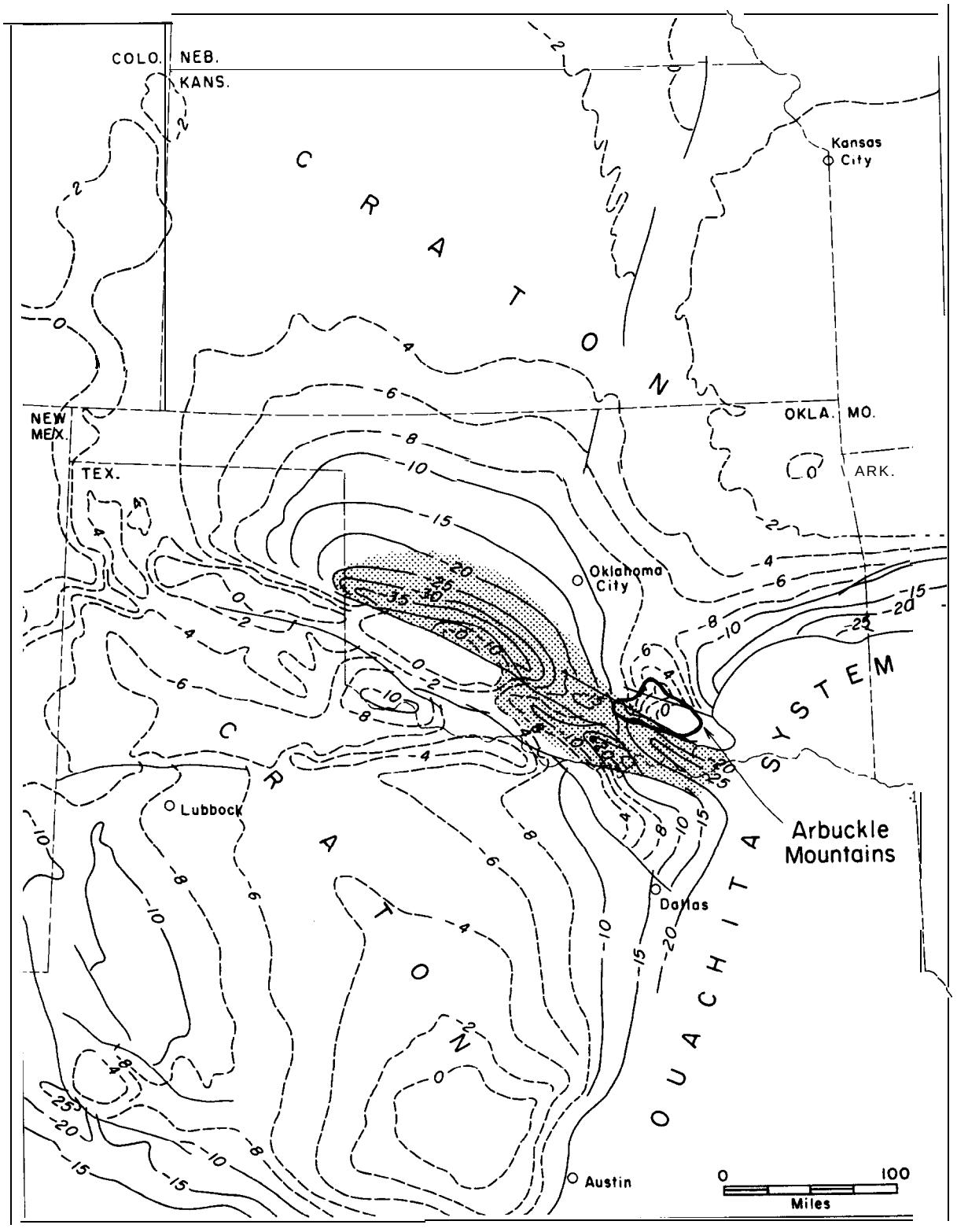


Figure 3-10 Basement Map Showing the Regional Setting of the Arkoma Basin. Configuration of the Basement Surface is Given by Contours Drawn on **2000-Foot** (Dashed) and **5000-Foot** (Solid) Intervals. Age of the Precambrian Rocks Range From 1000 to 4000 **m.y.** (Ham, 1969).

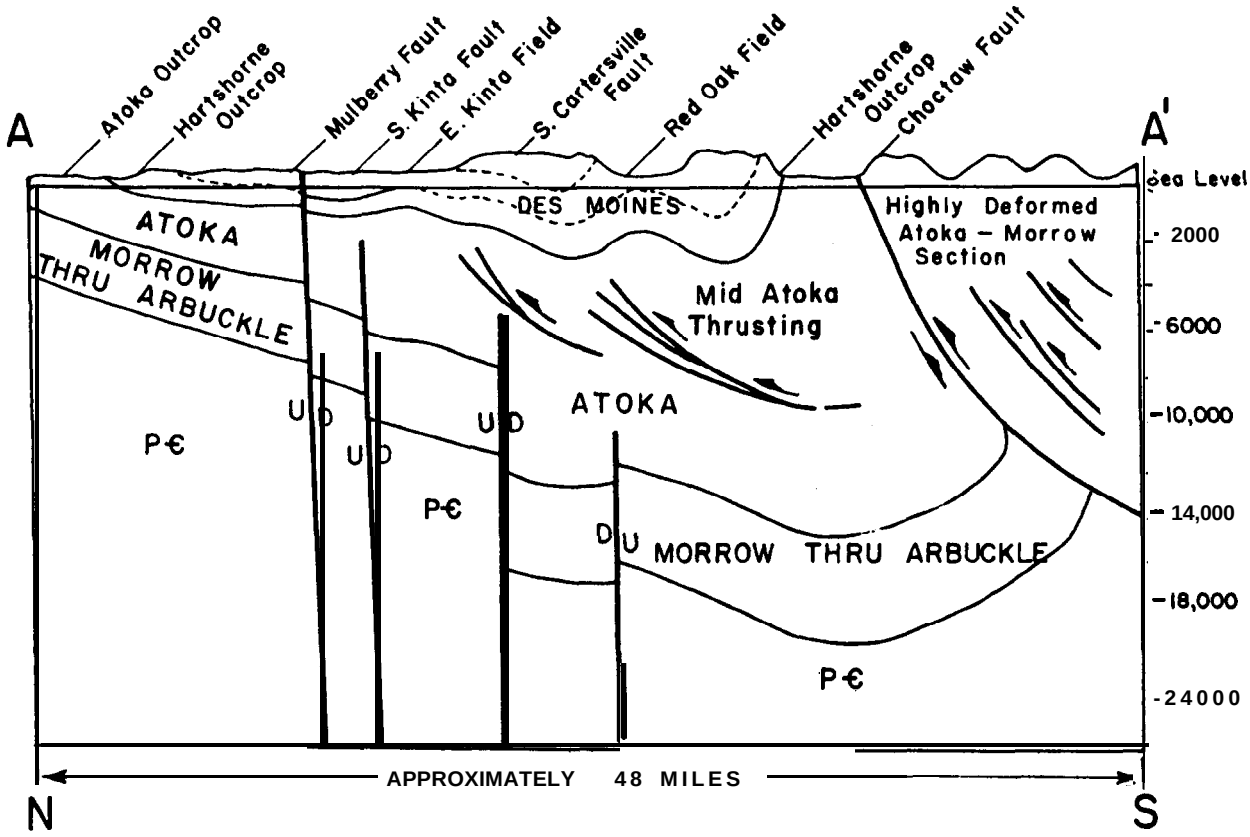


Figure 3-11 North-South Cross Section (See Figure 3-8) Showing General Structural Relationships in the Basin (From Branan, 1968) (Courtesy of AAPG).

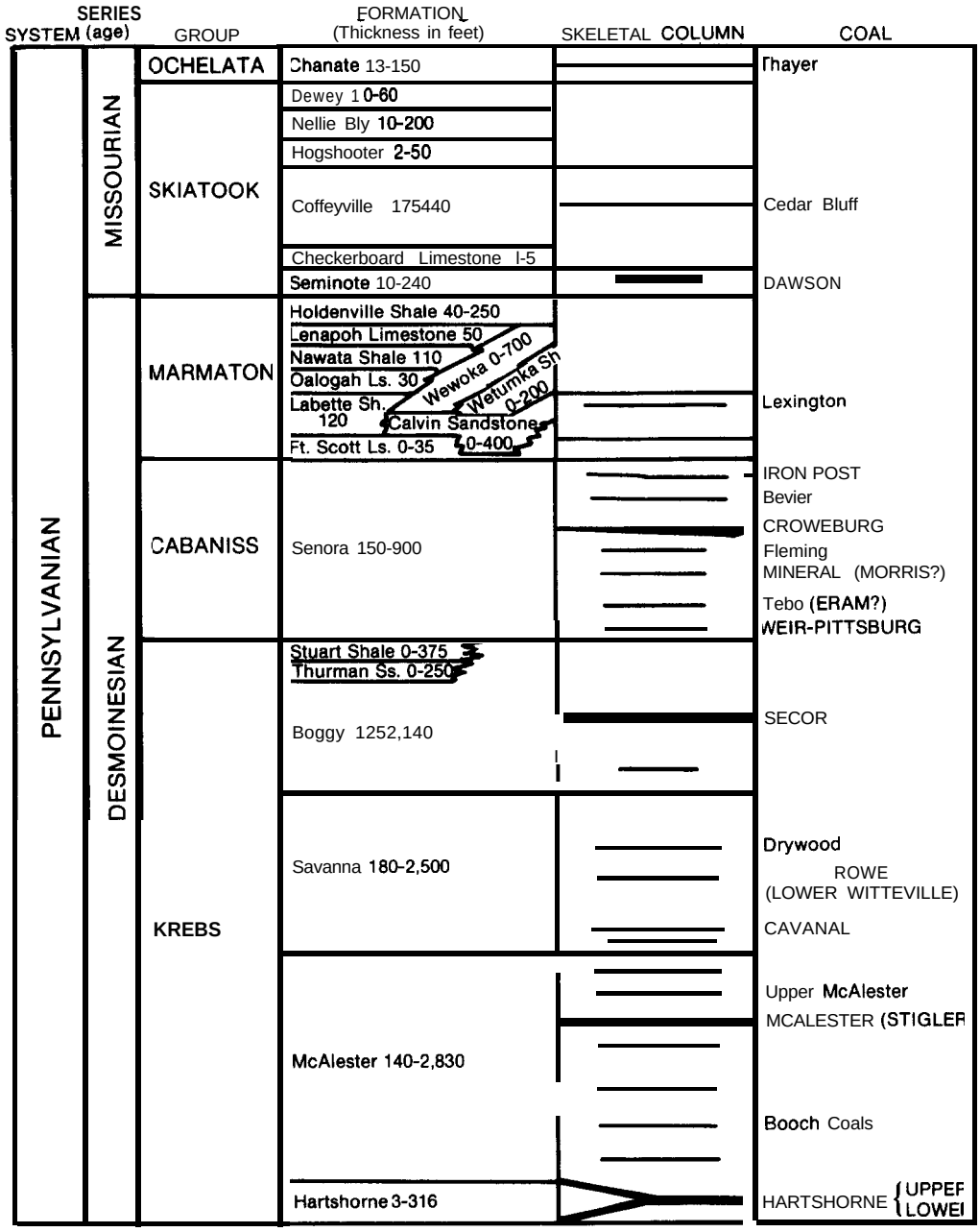


Figure 3-12 Generalized Geologic Column Showing the Sequence of Coalbeds of Pennsylvanian Age in Oklahoma (Friedman, 1977).

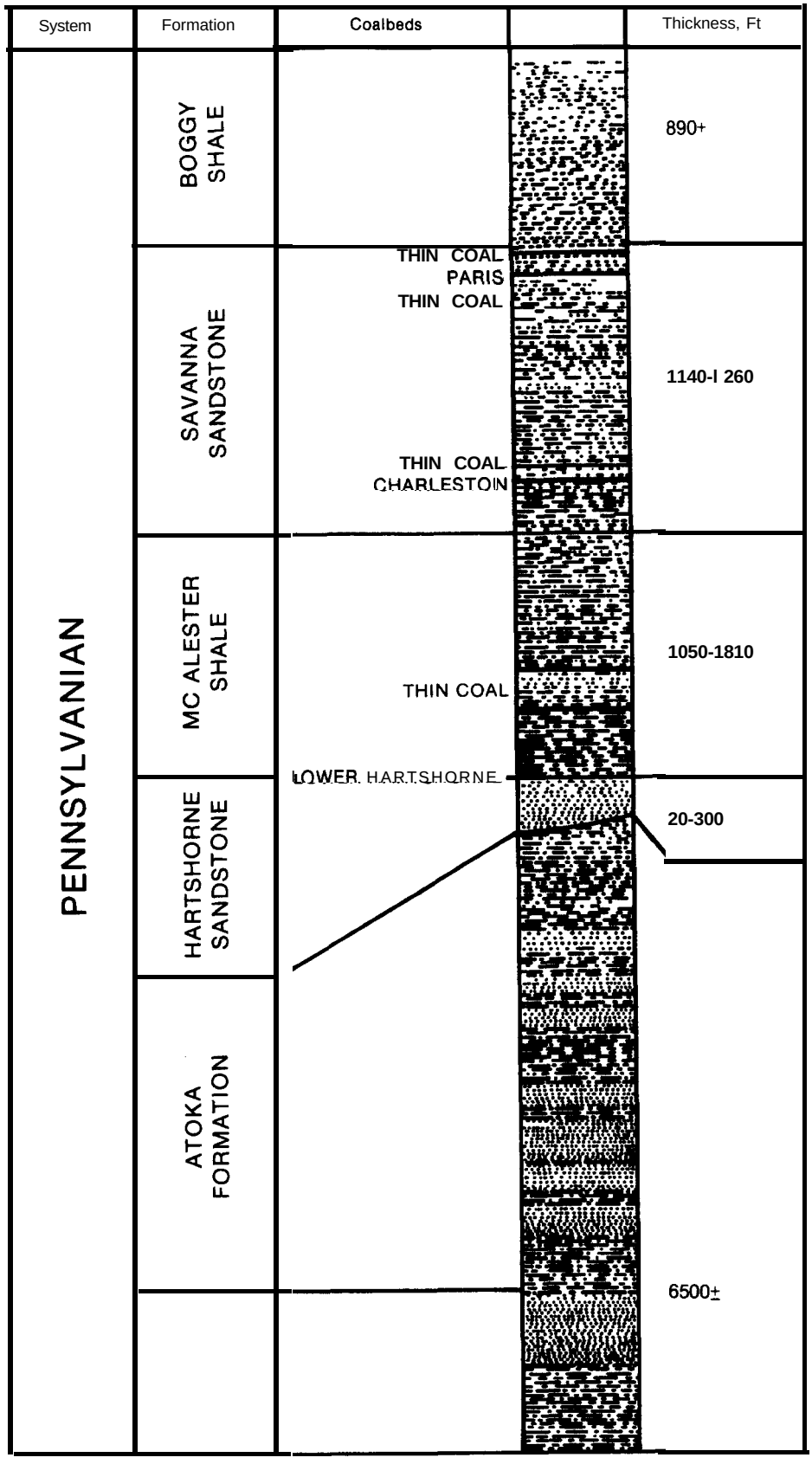
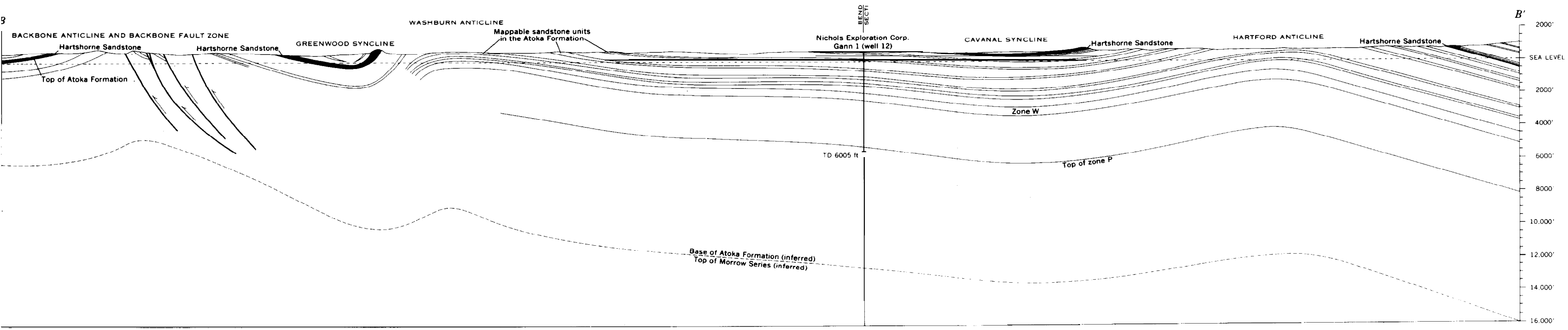


Figure 3-13 Generalized Geologic Column Showing the Sequence of Coalbeds of Pennsylvanian Age in Arkansas (Keystone, 1979) (Courtesy of McGraw-Hill Publishing Co.).



Quaternary deposits not shown

STRUCTURAL SECTIONS IN GREENWOOD QUADRANGLE, SEBASTIAN COUNTY, ARKANSAS, AND LE FLORE COUNTY, OKLAHOMA

SCALE 1:48 000

1 ½ 0 1 2 3 MILES

1 .5 0 1 2 3 KILOMETERS

DATUM IS MEAN SEA LEVEL

Zones
W — 400 Feet of Sandstone and Siltstone with a Small Amount of Shale
P — Coarse-grained Sandstone with Limey Streaks

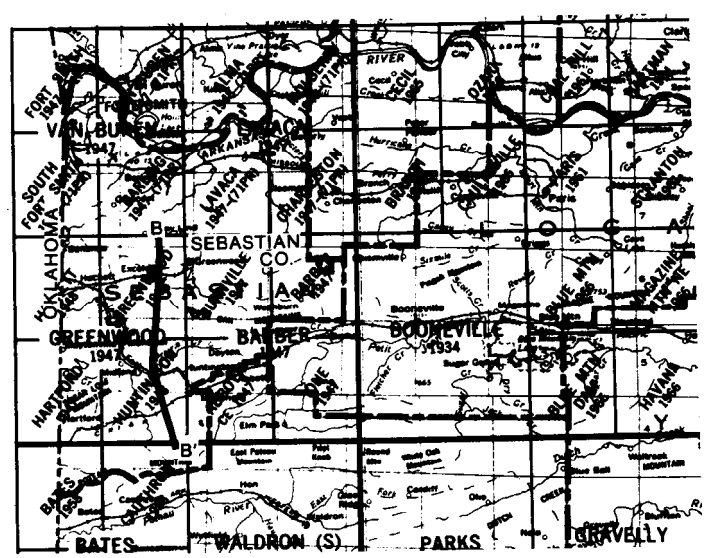


Figure 3-14 Stratigraphic and Structural North/South Cross Section Approximately 8 Miles East of the Arkansas-Oklahoma State Line in the Greenwood Quadrangle, Sebastian County, Arkansas (Haley and Hendricks, 1968) Quaternary Deposits Not Shown.

Table 3-1 General Geologic Section of Oklahoma Oil and Gas Producing Areas (Prepared by R. H. Dott, Director, Oklahoma Geological Survey, 1945).

System	Series	Group or Formation			Description
Cretaceous	U. Cretaceous			Colorado gp.	Clay, Some Limestone.
				Dakota-Woodbine sss.	Sandstone
	L. Cretaceous			Washita gp.	Clays, Some ls. in Southeast Okla., Cheyenne ss. and Kiowa sh. in Cimarron Co.
				Fredericksburg gp.	Represented by Goodland ls., Southeast Okla.
				Trinity gp.	Sandstone, Southeastern Okla. Madill sd., Madill Pool, Marshall County.
Triassic				Morrison fm. Exeter ss	Variegated sh. and marl: Some ss Jurassic Present Only in Panhandle.
Triassic				Dockum gp.	Red Beds Present Only in Panhandle.
Permian	? Quadalupian			Quartermaster fm.	Red Shale and Sandstone.
				Cloud Chief fm.	Red Shale, Local Lenses Gypsum and Limestone.
		Whitehorse		Rush Springs ss.	Massive Sandstone.
				Marlow fm.	Shale, Some ss, Thin Gypsums. Contains Verden Sandy Dolomite.
	Leonardian			El Reno gp.	Duncan-Chickasha, Grating Northward Into Flowerpot, sh., Illalene gyp., and Dog Creek Shale.
				Hennessey sh. Garber ss. Wellington fm.	Shale and ss., Probably Contains Chickasha Gas Sand, and Other Horizons in Southwestern Oklahoma.
	Wolfcampian	Pontotoc		Stratford fm.	Equivalent to Stillwater fm. of North-Central Oklahoma, Contains Hoy, Hotson, and Other Sds., in North-Central Okla.: Gas-Bearing Dolomite and ls. in Texas Co., and Probably Producing Horizons in Southwestern Okla.
				Vanoss fm.	Sandstone, Shale, Limestone, Conglomerate: Produces in Ardmore Basin, Cement, and Elsewhere in Southwestern Okla.: Refered to as "Pontotoc"; Contains Smith and Brown sds. of Itainola Pool, Stephens Co.
	Virgilian			Pawhuska fm.	Shale and ls., Some ss.
				Elgin ss.	Sandstone and sh. ss. at Base = Carmichael sd., Higher sss. = Hoover sds. of North-Central Okla.
				Nelagoney-Vamoosa	Sandstone and sh. Bigheart and Fourmile sss. at Base = Tonkawa-Stalnaker sds. in North-Central Okla.: Lovell ls. About Middle; Wynona ss = Endicott sd. Above Middle: Oread ls. at Top.
	Missourian	Hoxbar-Canyon (Ardmore Basin)	Ochelata Group	Wildhorse ls.	Dolomitic ls. = "Avant" ls. of Some Geologist; Above Perry Gas sd. in North-Central Okla. Sandstone and Shale Southward.
				Shale	Calcareous sh.
				Okesa ss.	Calcareous ss.
				Wann fm.	Shale and Lenticular sss., Contains Perry Gas sd.
				Avant ls.	Limestone, Somewhat Dolomitic = Oil City Lime in Southern Osage Co.
				Chanute sh.	Shale and Sandstone, Including Cottage Grove ss. = So-Called "Layton" sd. of Osage Co. (not the Laten sd. of Creek Co.), = "Musselem" (Musselem) and Peoples sds. of Osage Co. (not Musselem sd. of Oilton Pool, Creek Co.).
			Skintook Group	Dewey ls.	Probably Equivalent to Belle City Limestone in Central Oklahoma.
			Francis fm	Nellie Bly fm.	Shale and Variable Sandstones: Thins Westward in Subsurface.
				Hogshooter ls.	Limestone, Layton Lime of Creek County.
				Coffeyville fm.	Shale and Sandstone Dodds Creek ss. = Layton Sand (of Creek County) at Top: Checkerboard Limestone at Base.
				Seminole fm.	Two Sandstones and Middle Shale Containing Dawson Coal. Equivalent to Upper and Lower Cleveland Sands, Jones and Dillard Sands.
			H'ville	Lenapah ls.	Limestone and Shale Overlayed by Memorial Shale of Des Moines Aged, Near Tulsa.
				Nowata Shale	Shale, Some Sandstone, Contains Wayside Sand.
Pennsylvanian	Desmoinesian	Deese Formation (Ardmore Basin)	Wewoka	Oologah fm.	Limestone the "Big Lime": Splits Into Pawnee Limestone, Bandera Shale, and Altamont Limestone ls. Northern Rogers and Nowata Counties.
				Labette sh.	Shale, Contains Sandstone Equivalent to Peru Sand.
			Wetumka	Ft. Scott ls.	Limestone Oswego Lime of North-Central Oklahoma: Oolitic Phase in Cushing Field, etc., Called Wheeler "sd."
			Cherokee	Upper Calvin Middle Clavin Lower Calvin	Sandstone, Upper Calvin = Pure Sand. Shale, Contains Thin lss. Lower ls. Probably = Verdigris Limestone. Lower Calvin Is Sandstone: Senora Formation Is Shale and Sandstone. Skinner Sand Probably = L. Calvin and Sandstone of Senora. Zone also Includes Allen Sand.
				Senora fm.	
				Stuart Shale	Pink Lime of Subsurface Probably in Stuart Shale.
				Thurman ss.	Red Fork-Burbank-Earlsboro sd. Zone Probably Included in Thurman and Upper Boggy. Bartlesville-Glenn-Salt sds. (= Bluejacket ss.) in Lower Boggy. Inola Lime is Between Bartsville and Red Fork sds.
				Boggy fm.	
				Savanna fm.	Shale, ss. and Few Thin lss., Including the "Brown Limes" (Sam Creek and Spaniard).
		U. Dornick Hills fm		McAlester fm.	Shale and Sandstone. One or Another ss, and In Some Places the Underlying Hartshorne ss have Been Correlated With Booch (Taneha) sd.
				Hartshorne ss.	Sandstone, Some Shale, Contains Hartshorne Coals. Produces Gas in Eastern Oklahoma.
				Atoka fm.	Thick Succession of Shale and Sandstone: Contains in Lower Part the Following: Timber Ridge, Muskogee, and Boynton sds. in Muskogee Co.: Butcher (= Boynton), and Dilerease-Deaner, in Central Oklahoma; Other Horizons Produce Gas in Le Flore, Sequoyah, Haskell, and Pittsburg Counties.
	Morrowan			Wapanucka fm Union Valley fm.	Wapanueka fm. Contains ls., Sandy In Relatively Pure; Shale, and Sandstone. Union Valley fm. Contains ss. With ls. at Top, and is Correlated With Primrose ss of Ardmore Basin and Hale fm. of Ozark Area. Both Wapanueka and Union Valley fms. Produce Oil in East-Central Oklahoma. Lyons Lime and Sand of Okmulgee Dist., Cromwell, Quinn, Smith, and Sykes sds. of Seminole, Hughes, and Okfuskee Counties are of Morrowan Age. Probably = Union Valley fm. Lower Dornick Hills fm. Represents Morrowan Series in Ardmore Basin.
	Springeran				Dark Grey to Black Shale Called "Pennsylvanian Caney." Contains Several sss. in Ardmore Basin, Productive in Some Oil Fields in Southern Oklahoma. Outcrop Names From Base Upwards: Rod Club, Overbrook, and Lake Ardmore sss. Black sh. Between Rod Club ss. and Top of Mississippian Caney.
Mississippian	Chesterian	Caney sh. ?		Pitkin ls.	Fine-Grained, Drab ls. Present Only In Northeastern Oklahoma; Produces Locally.
	? Meramecian			Fayetteville sh.	Black Shale. Caney Contains Black, Grandular, ls. ("False Stayes") in Lower Part Locally in Central Oklahoma.
	Osaglan ("Boone")	Mayes = Sycamore ls.		Mayes ls. (Mississippi Lime)	"Mississippi Lime" (White, Cherty ls.) In Northern Okla. in Lincoln Co. Grades Into Seminole Mayes" (Black, Grandular ls.), Probably = Sycamore ls. Bed of Glauconite at Base of Mayes. Burgess sv. in Northeastern Oklahoma Lies at Contact of Basal Pennsylvanian (Cherokee) and Weathered Surfaced of "Mississippi Lime"; Exact Age of Overlying Beds Varies.
	Kinderhooklan	? Woodford sh.		Chatanooga sh.	Black Shale; Woodford Is Cherty in Vinicity of Arbuckle Mts. and Subsurface of Central and Southern Okla. Chattanooga Black Shale in Northern and Northeastern Okla., has at Base the Lenticular Sylamore ss. = Misemer sd.
Devonian		Hunton gp		Frisco ls. Bois d' Arc ls. Harakan Snarl	Limestone, Cherty in Part; Marly. Considerable Production Especially at West Edmond and Elsewhere in Central and South-Central Oklahoma. Subdivided in Arbuckle Mts.
Silurian				Henryhouse sh. Chimneyhill ls.	
Ordovician	Cincinnatian			Sylvan Shale	Grey, Grey Shale, Green in Upper, Part: Black in Middle Part Locally; Locally Dolomitic in Lower Part in Southern Oklahoma.
			Viola ls.	Fernvale ls.	White, Crystalline Limestone; Called "Buttermilk Lime." Most Widely Used Datum for Subsurface Structure Mapping
	Mohawkian			Trenton ls.	Fine-Grained, Dolomitic ls. Produces Oil in Many Areas: "Arst" or "Seminole Wilcox" Sand Probably Belongs in Trenton.
	Chanyan		Simpson Group	Bromida fm. Tulip Cr. fm. McLish fm. Oil Creek fm. Joins fm.	Ss., ls., Dolomite, and Green Shale; Contains Wilcox sd. Which Probably Represents Different Formations in Different Areas. Contains "Lower Simpson" sds. at Oklahoma City, etc. Hominy or Burgen, Tyner, and Wilcox in Northern Oklahoma Probably Belongs in Tulip Cr. and Bromide fms. "Tucker" sd of Cushing Field = Wilcox. Wilcox sd. Gives Largest Area-Yields of State's Producing Formations.
	Beekmantownian			Arbuckle Group	Known as "Siliceous Lime": Porous Dolomite In Top of Arbuckle has Been Turkey Mt. "sd." Considerable Oil Production in Northern Oklahoma; Discovery Horizon at Oklahoma City.
Cambrian	U. Cambarian			Timbered Hills gp.	Contains Arkosic Reagan ss. at Base, and Honey Creek fm. No Known Oil Production in Oklahoma.
Pre-Cambrian					Granite etc.

Table 3-2 Correlation Chart, Arkomas Basin (**Branan**, 1968) (Courtesy of AAPG).

System	*Series (Group)*	*Oklahoma*	*Arkansas*
Pennsylvanian	Desmoinesian (Krebbs)	Boggy Shale Savanna Sandstone McAlester Shale[1] Hartshorne Sandstone[1]	Boggy Shale Savanna Sandstone McAlester Shale Hartshorne Sandstone
	Atokan	Webbers Falls Sand Gilcrease Sands' Fanshawe Sand[1] Red Oak Sand[1] Basal Atoka-Spiro Sand[1]	Carpenter "A" Sand[1] Upper Alma Sand[1] Middle Alma Sand[1] Lower Alma Sand[1] Carpenter "B" Sand[1] Morris-Tackett Sand[1] Self-Areci Sand[1] Freiburg-Henson-Pearson Sand[1] Casey-Vernon-Hudson Sand[1] Cecil Series[1]: Dunn "A"-Sells-McGuire Sand; Ralph Barton Sand; Dunn "B" Sand; Dunn "C"-Dawson "A" Sand; Paul Barton-Dawson "B" Sand; Cecil Spiro-Hamm Sand Spiro-Orr-Kelly-Barton Sand'
	Morrowan	Wapanucka Limestone' Union Valley Formation Cromwell Sand[1] Jefferson Sand	Bloyd Shale[1] Kessler Limestone Member Brentwood Limestone Member (Cline) Hale Formation[1] Prairie Grove Member Cure Hill Member
Mississippian		Pitkin Limestone Caney Shale Ada Mayes Member Welden Limestone	Pitkin Limestone Fayetteville Shale Wedington Sandstone Member' Batavillc Sandstone Moorefield Formation Boone Formation'
		Woodford Shale Miner Sand	Chattanooga Shale Sylamore Sandstone Member
Sil.-Dev.	(Hunton)[1]	Haragan shale Chimneyhill Limestone	Penters Chert[1] Lafferty Limestone St. Clair Limestone[1] Brassfield Limestone
Ordovician		Sylvan Shale	Cason Shale
		Fernvale Limestone Viola Limestone[1] 2nd Wilcox Sand	Fernvale Limestone Kimmswick Limestone
	(Simpson)	McLish Formation[1] Oil Creek Formation Joins Formation	Plattin Limestone Joachim Dolomite St. Peter Sandstone Everton Formation
Cambrian	(Arbuckle)	Dolomite	Powell Dolomite Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Eminence Dolomite Potosi Dolomite Derby Dolomite Davis Formation Bonneterre Dolomite
		Reagan Sandstone	Lamotte Sandstone
Pre-C		Granite	Granite

4. COAL RESOURCES

4.1 STRATIGRAPHIC CHARACTER

Accurate coalbed correlation is an essential prerequisite to the determination of coal resources and reserves, especially those beds which are particularly gassy. The bituminous coals of Arkoma Basin are shown in sequence in generalized geologic columns (Figures 3-12 and 3-13). Although some minor coals have been noted or described in the geologic literature, they are not shown in the geologic column, having been omitted from the present coalbed methane investigation because of insufficient information. Figure 4-l provides a generalized geologic column showing coals and major key beds in part of the Arkoma Basin, eastern Oklahoma. A generalized correlation of the Pennsylvanian age formations of the Lehigh District in the western part of the Arkoma Basin with those in Arkansas is shown in Figure 4-2 (after Hendricks, et al, 1939, Plate 33).

Friedman (1974) noted that there are certain stratigraphic sequences and correlation uncertainties in the McAlester region of the Arkoma Basin, such as the four coals present in the McAlester Formation above the Hartshorne coal and beneath the McAlester, Stigler, coal. The McAlester coal appears to correlate with the Stigler coal. The upper McAlester coal appears to correlate with a "rider" coal above the Stigler. At least one additional coal is present above this rider coal in the McAlester Formation in Le Flore County.

As many as four coals are present in the "Cavanal coal zone" in the lower part of the Savanna Formation in Le Flore County. A previously undetected coal occurs about midway between the Secor (Upper Witteville) coal and the Lower Witteville coal in Cavanal Mountain, Le Flore County. This coal may be the one that is present 30-45 feet below the Secor in Pittsburg County in places where the Lower Witteville cannot be identified (Friedman, 1974).

An unnamed coal lies some 30-50 feet above the Secor coal in Pittsburg County, and it may or may not be equivalent to the Mayberry coal in Cavanal Mountain in Le Flore County. Another unnamed coal lies at least 100 feet stratigraphically above this "rider" of the Secor coal, and if it is in the

Boggy Formation it cannot be equivalent to the Weir-Pittsburg coal of the Northeast Oklahana shelf area (Figure 4-l).

Coalbeds are the most continuous lithotypes known and can be effectively used as key beds in lithostratigraphic correlation. Thus, Friedman's first comprehensive generalized geologic column showing coalbeds in the coal fields of Oklahoma (Figure 3-12) is preliminary and will be changed as additional facts come to light from deep drilling and resource characterization studies of the coalbed methane resources which are in progress (see Section 5.2).

Strictly speaking, the Hartshorne Sandstone forms the base of the commercial coal-bearing portion of the Pennsylvanian rock sequence in the coal basin. Coalbeds are present in the Atoka Formation of Arkansas (Haley and Hendricks, 1972). The uppermost known coal occurs in the basal portion of the Boggy Shale in the McAlester District, to the northeast, but in the Lehigh District no beds of coal are known to occur in rocks younger than the McAlester Shale.

Available information concerning these stratigraphic units varies significantly and is reflected in the following discussion. This is due to the deltaic environment in which the coal was deposited.

4.1.1 Atoka Coals

All coalbeds in the Atoka Formation are generally thin, poor quality, and of local extent (Haley, 1966, p. 11). Three coalbeds, two feet, one foot, and one foot thick were penetrated by the Hambee Well No. 1, T.8N., R.26W, Sec. 13, Logan County, Arkansas at depths of 1,800 feet, 2,305 feet, and 2,977 feet, respectively. The two-foot thick bed is an exception inasmuch as the Atoka Coals encountered are generally less than 15 inches thick. Haley (1966, p. 11) reported that a coalbed near the top of zone W (Figure 3-14) is thought to extend eastward from the Barber quadrangle in Sebastian County, Arkansas for more than 30 miles beyond the quadrangle. Sulfur content ranges from 0.6 to 5.7 percent in Logan, Johnston and Pope Counties, Arkansas. (Haley, 1977).

Donica (1976, p. 15) reported that two thin coals, each 6 inches thick, occur 10 feet and 40 feet, respectively, below the top of the Atoka Formation in parts of Le Flore County, Oklahoma (Figure 4-3). The exact

stratigraphic position of these coals is undecided (Hendricks, et al, 1939; Friedman, 1978a).

4.1.2 Hartshorne Coals

At the southern edge of the coal region in Oklahoma the Hartshorne coal commonly is split into two beds by shale and sandstone 5 to 100 feet thick (Friedman, 1974). These beds are known as the Upper and Lower Hartshorne coals, and they have been mined extensively. Oakes and Knechtel (1948, p. 22) and Knechtel (1949, p. 16) recognized a convergence between the Upper and Lower Hartshorne coals and redefined the Hartshorne Formation to include both coals. Until this redefinition the Upper Hartshorne coal had been placed in the overlying McAlester Formation (Figure 4-4). Merewether and Haley (1969, P.C. 19) reported that the thickness of the split in Johnson County, Arkansas, ranges from 1 inch to about 20 feet and is less than 12 inches in much of this coal-bearing area. The split apparently changes rapidly and without uniformity in either rate or direction of thickening. In the Greenwood quadrangle (Sebastian County, Arkansas) the Upper Hartshorne is present only in the southern part of the quadrangle. The interval between the Upper and Lower coals is from 60-90 feet (Haley and Hendricks, 1968, p. All). Northward, in the middle of the Arkoma basin, the Hartshorne coal "undivided" is a single bed containing a persistent black-shale parting about l-inch thick. In parts of the basin three coals occur within the Hartshorne Formation. This third unit is known as the Middle Hartshorne coal and is laterally discontinuous in Le Flore County, Oklahoma where it is present (Figure 4-5). In the McAlester District the Hartshorne coal can exist as three separate beds as interpreted from geophysical well logs. Recent core drilling has indicated significant underground coal resources in the Hartshorne coal in areas where it is 3 to 5 feet thick and of low- or medium-volatile rank. The Hartshorne has the qualities of a good coking coal with a high free-swelling index. In the vicinity of the Arkansas River in northern Le Flore County, it is essentially noncaking. The Hartshorne coalbed contains 0.5 to 6.0 percent sulfur and averages 1.8 percent (raw). This coal requires cleaning for use in coke manufacture and metallurgical processes.

The Lower Hartshorne Coal is 0.7 to 7.0 feet thick and occurs about 60 feet above the base of the Hartshorne Formation within a gray shale

interval which separates the Upper and Lower Hartshorne Sandstone units. It has been mined recently in Le Flore County in underground mines, where it is 3.0 to 3.7 feet thick. This bed is the thickest, most extensive, and most economically important coal in the basin. The bed is underlain by a thin underclay. The Lower Hartshorne coalbed contains 0.4 to 5.1 percent sulfur and averages 1.0 percent (raw) in Oklahana. The range in sulfur content in Arkansas is from 0.4 to 4.6 percent. An isopachous map of the Lower Hartshorne coalbed is presented in Figure 4-6. The Lower Hartshorne coalbed contains one to four irregular shale partings which persist locally (Figure 4-7). The partings consist mainly of black carbonaceous shale and range in thickness from 1/32 to 1/4 inches.

The Upper Hartshorne coal has been extensively mined from slopes and drifts in Haskett, Latimer, and Le Flore Counties. It is 2 to 4 feet thick and is low or medium volatile in rank on the east side of the Arkoma Basin and high volatile on the west side. The Upper coalbed is relatively free of shale and bone partings. It contains 0.8 to 2.6 percent sulfur and averages 1.6 percent (Friedman, 1974).

4.1.3 McAlester Coals

The McAlester coal was extensively mined in the past by underground methods at McAlester in central Pittsburg County and in southeastern Coal County, where it had been called the Lower McAlester (Friedman, 1974). Significant resources of this coal remain in these areas and are amenable to underground mining. The McAlester coalbed is 1.5 to 5.0 feet thick and mostly high volatile in rank. It is not mined at present but is suitable for use in electric-power generation, for blending with higher rank coal for coke manufacture, and for gasification and liquefaction. The McAlester coalbed contains 0.8 to 4.8 percent sulfur and averages 2.1 percent.

A correlative of the McAlester coal, the Stigler coal, has been mined by surface methods in Haskell, Le Flore, Muskogee, and Sequoyah Counties, Oklahoma. Hendricks' (1937) suggestion that the coal above the Lower McAlester coal may be correlative with the Stigler coal of northern Le Flore and Haskell Counties has not yet been determined (Donica, 1978, p. 23). The Stigler coal may correlate with the Lower McAlester coal, and the upper coal, named tentatively by Hendricks in 1939 as being the Stigler, may be more appropriately named the Stigler rider coal (personal

communication, S. A. Friedman, 1979) (Figure 4-2 and 4-8). Hendricks (1939) reported that four thin coalbeds (1 foot or less in thickness) are present at least locally between the Stigler (?, upper coal) and the top of the McAlester Shale in Le Flore County (see Donica, 1978, p. 24). In the McAlester District numerous thin coalbeds are present a short distance above the McAlester coal, and some of these beds are present over considerable areas (Hendricks, 1939, p. 15). Craney (1978, p. 29) reported that in the Panama quadrangle, the McCurtain Shale contains three unnamed thin coals underlain by sandstones.

There are several unnamed coalbeds in the McAlester Formation in the Arkansas Valley region (Haley, 1968). Haley and Hendricks (1968. p. All) reported that in the Greenwood quadrangle, Sebastian County, Arkansas and eastern Le Flore County, Oklahoma the Stigler coal was near the top of the McAlester Formation and the McAlester coalbed was near the middle. Haley and Hendricks misinterpreted the upper coal as being the Stigler and it is probably the Stigler Rider coal (see Friedman, 1974, p. 28).

The McAlester coalbed contains in the McAlester District more partings and bands of impurities than the Lower and Upper Hartshorne beds--as many as seven partings have been recorded (Hendricks, 1937, p. 57). Partings consist of pyrite (Figure 4-9).

Of low- and medium-volatile rank, the Stigler coal is used in coke manufacture. The Stigler coal contains 0.4 to 5.2 percent sulfur and averages 1.5 percent in Oklahoma.

4.1.4 Savanna Coals

There are numerous local coalbeds in the Savanna Sandstone, but only two could be of importance in coalbed methane determinations.

The Cavanal coal, named after Cavanal Station in Le Flore County, Oklahoma, is 1.2 to 3.5 feet thick, has a high (+100) Hardgrove grindability index, and is mostly medium volatile and in part high volatile in rank (Figure 4-10). It is overlain by 20 to 50 feet of shale and sandstone, at the top of which another, thinner coal is present at some places (Friedman, 1974). The Cavanal coal contains 2.1 to 4.8 percent sulfur and averages 3.3 percent.

Dane, et al, (1938) did not report the existence of the Cavanal coal in the Quinton-Scipio District. The Cavanal coal is present in the Howe-Wilburton District. Donica (1978, p. 27) reported an Upper Cavanal coal lying 20 to 50 feet above the Cavanal coal in the Heavener area, Oklahoma. Hendricks (1937, p. 62) reported a coalbed about 2 feet thick which is younger than the Cavanal coal just south of Krebs in the McAlester District.

The Lower Witteville coal is high-ash, high-sulfur, medium-volatile coal; the Lower Witteville is present in Cavanal Mountain, Le Flore County, where it has been mined underground. It is 3 to 4 feet thick with one or more clay-stone partings, and the underlying shale contains numerous coal stringers (Figure 4-10). The Lower Witteville coal contains 4.4 percent sulfur (Friedman, 1974).

The Rowe coal is a high-volatile coal of the Northeast Oklahoma shelf area (Figure 3-l); the Rowe is believed a correlative of the Lower Witteville. The Rowe coalbed is 1.0 to 2.5 feet thick in Craig, Mayes, Muskogee, Rogers, and Wagoner Counties. The Rowe coal may be suitable for gasification and liquefaction although it had been considered of only marginal value owing to its high sulfur and ash content and its dull appearance. The Rowe coal contains more than 13,000 Btu in mine-run condition. The sulfur content is 2.8 to 3.4 percent and averages 3.1 percent (mine run) (Friedman, 1974).

The Savanna coalbeds in Arkansas are poorly developed, but only the Charleston and the Paris are sufficiently thick and extensive to be of any economic importance. The coalbed mined as the Charleston coal probably is a single continuous bed in Arkansas, but like most of the coalbeds in the Savanna it is probably lenticular and of local extent (Haley and Hendricks, 1972, p. 428).

The Charleston coal is near the base of the Savanna (possibly correlative to the Cavanal) and is not known to be more than 2 feet thick. Sulfur content ranges from 0.9 to 3.8 percent.

The Paris coalbed is the thickest and most extensive coalbed in the Savanna Formation in Arkansas. In the Paris quadrangle it ranges in thickness from 19 to 32 inches, and is covered by less than 250 feet of

overburden (Haley, 1961a). There is a thin coal rider above the Paris coal, approximately 50 feet above the Paris in Sebastian County, which ranges in thickness from 4 to 9 inches. Sulfur content ranges from 0.6 to 3.3 percent (Haley, 1977).

4.1.5 Boggy Coals

Various coals exist in the Boggy Formation which lie above and below the Secor and are very lenticular. No Boggy coals are known to exist in the Arkansas Valley region.

The Secor coal is 1.5 to 4.3 feet thick in places where it has been mined. It is a medium-volatile bituminous coal in Le Flore County and a high-volatile coal in Haskell, Pittsburg, Muskogee, and McIntosh Counties. This coalbed commonly contains one or two shale partings and is high in ash and sulfur content. Hendricks (1937, p. 63) measured sections of the Secor coal in the McAlester District. The Secor is well developed in the Quinton-Scipio District (Dane, et al, 1938, p. 196). In places where it is of high-volatile rank, the Secor coal probably is suitable for use in gasification and liquefaction processes (Friedman, 1974).

Recent exploratory drilling indicates that in Pittsburg County the Secor, 3 feet thick, can be mined by surface and underground methods and that additional recoverable reserves in Le Flore County are amenable to underground mining. The coal contains 3.5 to 6.6 percent sulfur and averages 4.9 percent (raw).

4.1.6 Senora Coals

No Senora Coals are known to exist in the Arkoma Basin as defined by Figure 3-2. Although the Eram, Morris and Croweburg coals abut up to the northwestern edge of the subshelf portion of the basin in Okmulgee and Hughes Counties, Oklahana, they have been excluded from this discussion owing to the lack of burial depth and evidence of a gassy nature.

4.2 COAL QUALITY

This section reviews both published and unpublished data on the chemistry, petrography, rank and continuity of major coalbeds in the Arkoma Basin. Additional relevant data, such as overburden thickness, have been incorporated. Analyses show that coals of the Arkoma Basin generally

fall within the following range of values, although some compositions are known to be both higher and lower.

Moisture (%)	1.0-7.0
Ash (%)	4-11
Sulfur (%)	1-5
Btu/lb	11,500-15,000

4.2.1 Chemical Character

The elemental composition of coal is an important analytical consideration. Sane elements are associated with the organic portion of the coal, others with the inorganic portion, and a few show affinities for both.

Friedman (1974, p. 17) integrated data from more than 600 logs of boreholes drilled for coal during the past 20 years with sane 200 proximate, sulfur, Btu, and ash-fusion analyses provided by private parties involved in coal mining and/or exploration. In addition, analyses which appeared in various publications were incorporated. Most of the analyses from the literature were performed by the U.S. Bureau of Mines and some were performed by the University of Oklahoma (Friedman, 1974). The average analyses of the Krebs Group of coals in eastern Oklahoma are presented in Table 4-l. Similar results for the Arkansas Valley are given in Table 4-2 (Haley, 1977).

4.2.1.1 Sulfur Content

Next in importance to the quantity and location of the coal resources is their sulfur content, which has always been a valid factor for determining certain end uses of coal, such as cement and coke manufacture. Recently the sulfur content of fuels, including coal, also has become an important social, political, and economic factor (Friedman, 1974, p. 23).

The sulfur content of most of the coal resources in the Arkana Basin area is low in comparison to those resources of the Northeast Oklahoma shelf area. For example, the original and remaining coal resources of Haskell, Pittsburg, Latimer, Le Flore, and Sequoyah Counties in the Arkoma Basin average less than 2 percent sulfur. Exceptions are Atoka and Coal Counties, whose coal resources average 4.1 and 5.0 percent sulfur, respectively. Coal resources of the counties in the shelf area (Figure 3-l) average more than 3.0 percent. An exception to this is the Croweburg

coal (Henryetta coal) in Okmulgee, Okfuskee, and Rogers Counties. Here, the Croweburg averages 2.2, 2.3, and 0.8 percent sulfur, respectively (Figure 4-l).

The sulfur content of coal is influenced by the depositional origin of the coal as well as by the diagenetic and postdiagenetic changes affecting the coalbeds. In addition, deep-lying bituminous coalbeds tend to contain less sulfur than shallow-lying coalbeds. Friedman (1974, p. 23) stated that the low- and medium-volatile coals of Le Flore and Haskell Counties tend to contain less sulfur than the high-volatile coals of the Northeast Oklahoma shelf area, with two exceptions: the Secor coal of the Arkoma basin is high in sulfur content, and the Croweburg coal of the shelf is low in sulfur content. Variations in the percent sulfur for different coalbeds on an average county basis is given in Tables 4-l and 4-2.

4.2.1.2 Petrographic Characterization

Megascopic petrographic analysis is performed as part of a preliminary effort by the Oklahoma Geological Survey to determine the petrographic character of the Arkoma Basin coals (Friednan, 1978b).

The organic portion of the coal is made up of distinctly different components, some recognizable as plant remains, others not. These components are categorized into basic groups called macerals. The basic macerals are vitrinite (wood), exinite (spores) and inertinite (charcoal) and are usually layered throughout the coalbed. This layering reflects the initial horizontal accumulation of the original peat materials and gives coal its characteristic bright and dull banding.

The average Oklahoma coal contains sparse (15 percent) to moderate (15 to 30 percent) and thin (1/2 to 2 mm (1/50 to 1/2 in)) bands of vitrain and moderately bright attritus. The daninance of moderately bright attritus and thin bands of vitrain suggests microscopic (1/2 mm (1/50)) vitrinite might be abundant in Oklahoma coals (Table 4-3) (Friedman, 1978b). Examination of lateral and vertical petrographic variations of the coalbed character probably will be made in the future. Petrographic analysis will help identify the primary environment of coal deposition and might have value in relating initial amounts of methane in the coal with the environment of deposition.

4.2.1.3 Btu Content

In coalbed methane studies, the Btu content of the coalbed is extremely important in the evaluation of the resource and variations in Btu content for various coalbeds on a county basis. These analyses are given in Tables 4-l and 4-2. It is interesting to note that the carbon/oxygen (C/O) atom density ratio in coal is related to the Btu content, as indicated in Figure 4-11, and a C/O well logging tool would be useful in evaluating coals.

4.2.2 Rank

The fact that coal rank increases with depth has been known for quite some time in many basins and can be observed using different rank parameters obtained from core samples selected at different depths. The basic assumption, however, is that the stratigraphic column tested is essentially the same as the stratigraphic column at the time the rocks were most deeply buried, and that subsequently they have not been markedly disturbed. Thus, if the rocks have been subsequently faulted or folded, as they are in the Arkana Basin, the relationship of rank versus depth of burial may not apply.

The results of chemical analyses are such that rank in the Arkoma Basin increases from west to east. These coals cover a wide range in rank from high-volatile bituminous B to semi-anthracite (Figure 4-12). There is a progressive increase in rank from high-volatile in the western part of the basin to semi-anthracite in Johnson, Logan and Pope Counties, Arkansas.

4.2.2.1 Isocarb Results

The fixed-carbon percentage is determined on a dry, mineral-matter-free (mmf) basis from the chemical (proximate) analysis. The proximate analysis normally includes the moisture, ash, fixed-carbon, and volatile matter percentages of the coal.

Hendricks, et al, (1939, p. 296) prepared an isocarb map based on analyses of the coals ranging in age from the Lower Hartshorne to the Croweburg (Henryetta) and covering both the McAlester and Arkansas Valley regions as shown in Figure 4-13. Most of the figures for fixed carbon used in the preparation of the map represent an average of several analyses. In

general there is an increase in fixed carbon in the coals from west to east across the Arkoma Basin. The carbon ratios increase from 51.2 percent near Atoka, Oklahoma to 88.4 percent near Russellville, Arkansas. The Lower Hartshorne coal, however, does not have an apparent increase in fixed carbon over the Lower Witteville coal although it is 4,800 feet stratigraphically lower (Hendricks, 1935, p. 944-945).

Fuller (1920) presented data showing the relationship of fixed carbon to structural deformation. Table 4-5 illustrates that folding of the rocks in the Arkoma Basin resulted in more fixed carbon than was produced by faulting and also shows comparisons of the fixed carbon in the coals within the folded structures. The coals in the anticlines have a higher percentage of fixed carbon than those in the adjacent synclines (Craney, 1978). The fixed carbon content of the coals in the basin probably is related to structural defonnation.

Examination of detailed isocarb maps of the Hartshorne coals reveals some regional trends. The Lower Hartshorne coal in the Heavener area is low- and medium-volatile bituminous in rank (Figure 4-14) (Donica, 1978). The boundary between the two ranks (78 percent isocarb contour) is accentuated on the isocarb map and trends east-west through the area.

The fixed-carbon percentage (mmf) ranges from 70 to 84 percent in the Heavener area, and fairly constantly decreases from the northeast to the south (Donica, 1978, p. 58).

4.2.3 Compositional Variability

An important aspect of the chemical, physical and mechanical properties of coal in the Arkoma basin is their variability.

A vertical variation in the fixed carbon between the Lower Hartshorne and Upper Hartshorne coal is presented in Figure 4-15. Lateral variations are shown for the ash sulfur free-swelling index and in the Lower Hartshorne coal (Figure 4-16). Generalized variation in the overburden thickness above the Hartshorne coal is given in Figure 4-17. Overburden varies from zero at the outcrop to nearly 7,000 feet (Iannacchione and Puglio, 1979, Figure 11, p.12).

4.3 FRACTURE CHARACTERISTICS

The structural characters of the coals in the Arkoma Basin, such as fracture or cleat (joint) density and orientation have been investigated on a basin-wide scale. The U.S. Bureau of Mines has demonstrated that the amount of gas flowing through a coalbed is controlled by the orientation of natural fractures (cleats) within the coal.

It should be noted that coal cleats do not always show the same directions through a vertical sequence. That is to say, the orientation of the butt and face cleats in the Secor coal could be different from those directions in the Hartshorne coalbed. These variations can be attributed to the competency of the coalbed and the host rocks.

Iannacchione and Puglio (1979) reported on cleat directions that were measured at strip mines and surface exposures of coal in Le Flore County, Oklahoma (Figure 4-18). Cleat data were then analyzed by them using a method devised by Diamond, et al, (1976). Results of these analyses show that the direction of face cleat varies from N 32° W to N 17° W, which is perpendicular to structural trends in the area of Le Flore County. Butt cleat directions vary from N 52° E to N 77° E and are generally parallel to structural trends in the area. The friability of the Hartshorne coalbed is due to close spacing of cleats and the frequent occurrence of shear fractures with dips of 45° to 55° within the coalbed. Directional permeability characteristics of ccalbeds are generally dependent on the orientation of these cleat fractures.

At the Howe Coal Company mine, the Lower Hartshorne coalbed, located 6 miles south of Poteau, Le Flore County, Oklahoma, on the southern border of the Arkoma coal basin, the strike of the butt cleat is N 74° E, subparallel to the local axial trend (McCulloch, et al, 1974). The strike of the nonsystematic rock joints in this area is N 72° E, also subparallel to the regional trend. The face cleat in the coal and the systematic rock joint both strike N 15° W, which is subperpendicular to the trend and, therefore, parallel to the axis of compression. These details are illustrated in Figure 4-19.

The face cleats tend to be perpendicular to the axial trend of the folds and probably formed as extension fractures. The butt cleats tend to

be parallel to the axial trend and formed after compression forces were released.

Cleats in the McAlester (Stigler) coal are so closely spaced (1/8 inch to 1/2 inch) that they contribute to the friability and high Hardgrove grindability index of the coal at the Garland Coal and Mining Company Stigler No. 9 strip mine (R. 21 E., T. 9 N., Sec. 4), Haskell County, Oklahoma.

The cleat directions in the Croweburg coal (on the shelf) measured by Friedman (1978a) at pit 3 of P&K Company, Ltd., near Henryetta, Okmulgee County, Oklahoma are N 32° E and N 45° W.

Prominent cleat directions in the Secor coal at the Burdett mine 5 miles east of Checotak, McIntosh County, Oklahoma were determined by Friedman (1978a) to be N 45° W and N 40° E.

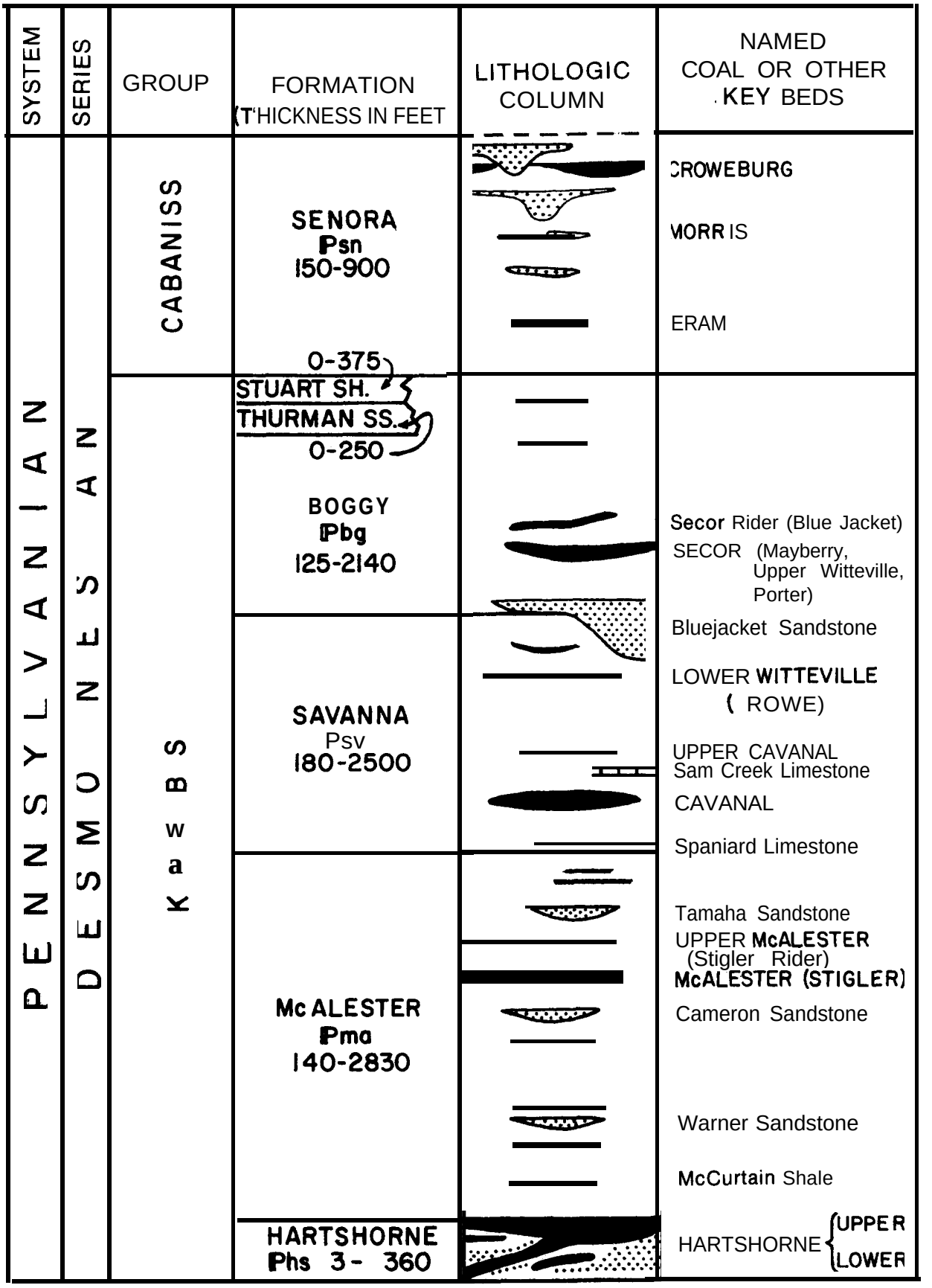


Figure 4-1 Generalized Geologic Columns Showing Coals and Major Key Lithological Beds in Part of the Arkoma Basin, Eastern Oklahoma (Friedman, 1978a).

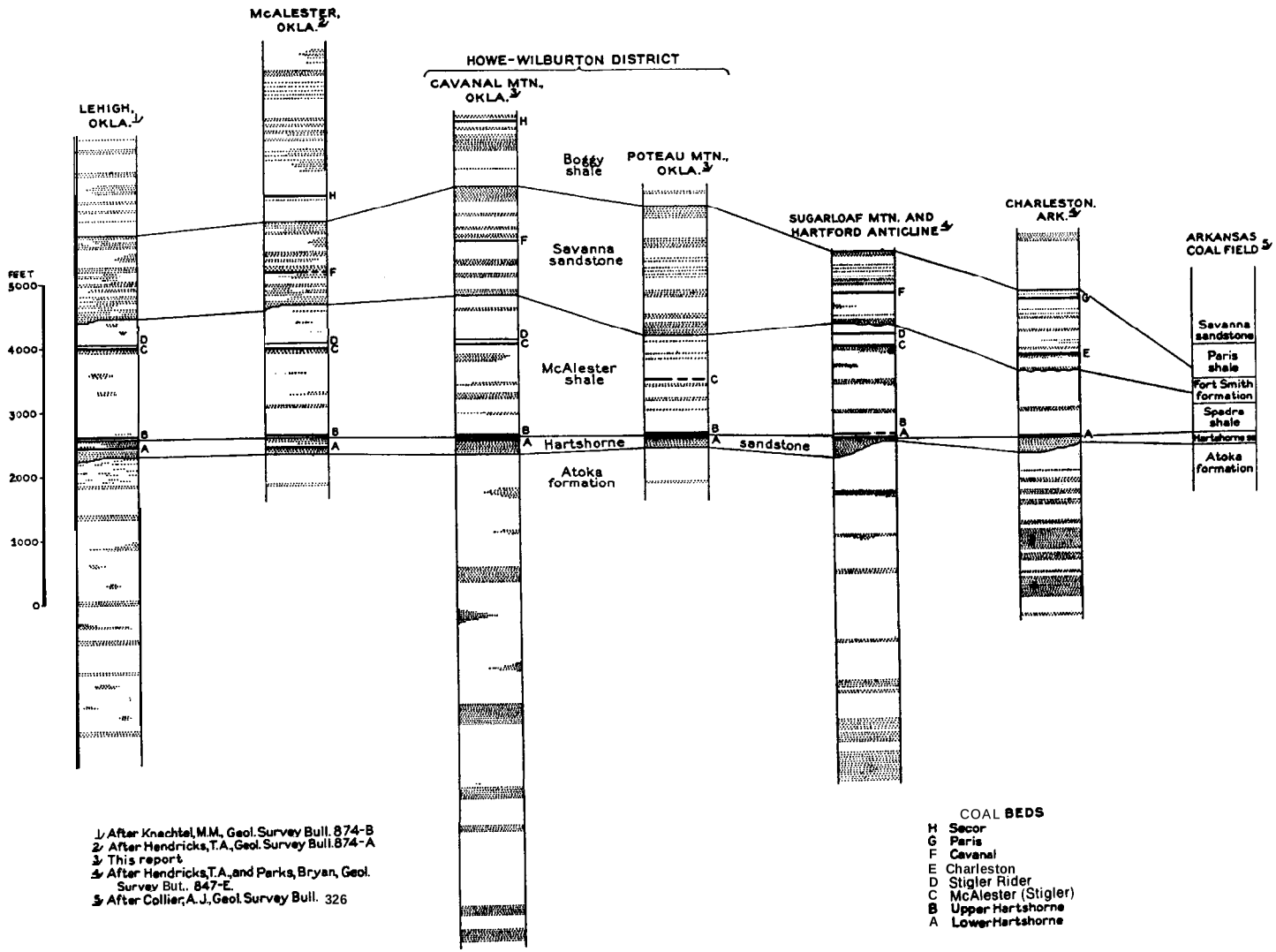


Figure 4-2 A Generalized Correlation of Pennsylvanian Formations in the Howe-Wilburton District With Those of the **McAlester** and Lehigh Districts, Oklahoma, and the Arkansas Districts (After Hendricks, 1939).

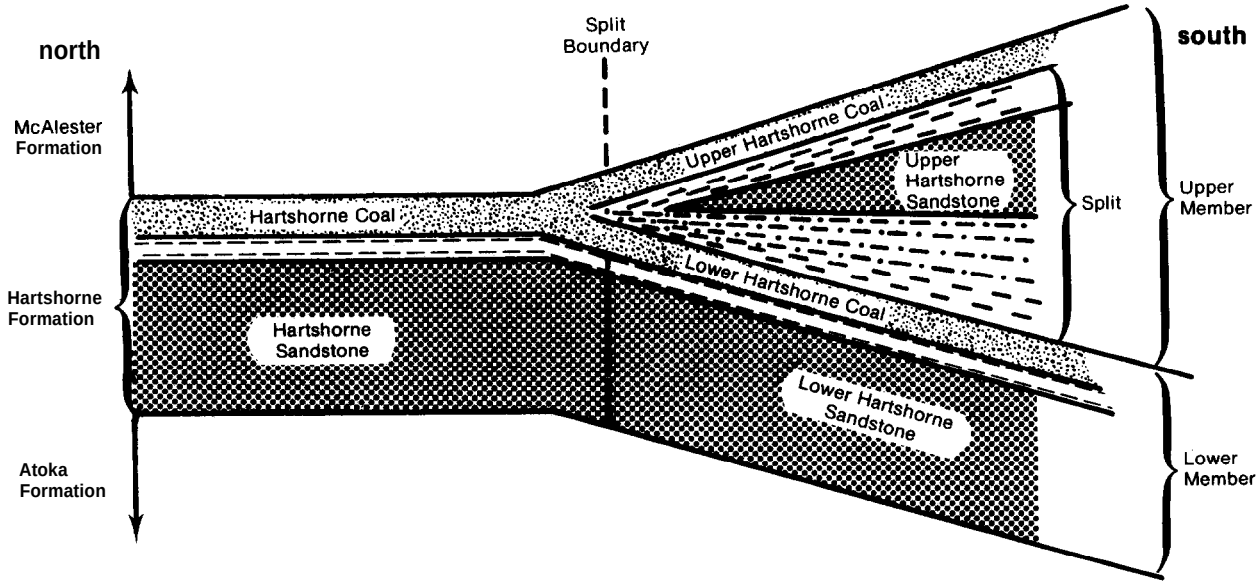


Figure 4-4 Diagram Showing the Definition of the Hartshorne Formation in this Study (Modified from Oakes and Knechtel, 1948, in Trumbull, 1957).

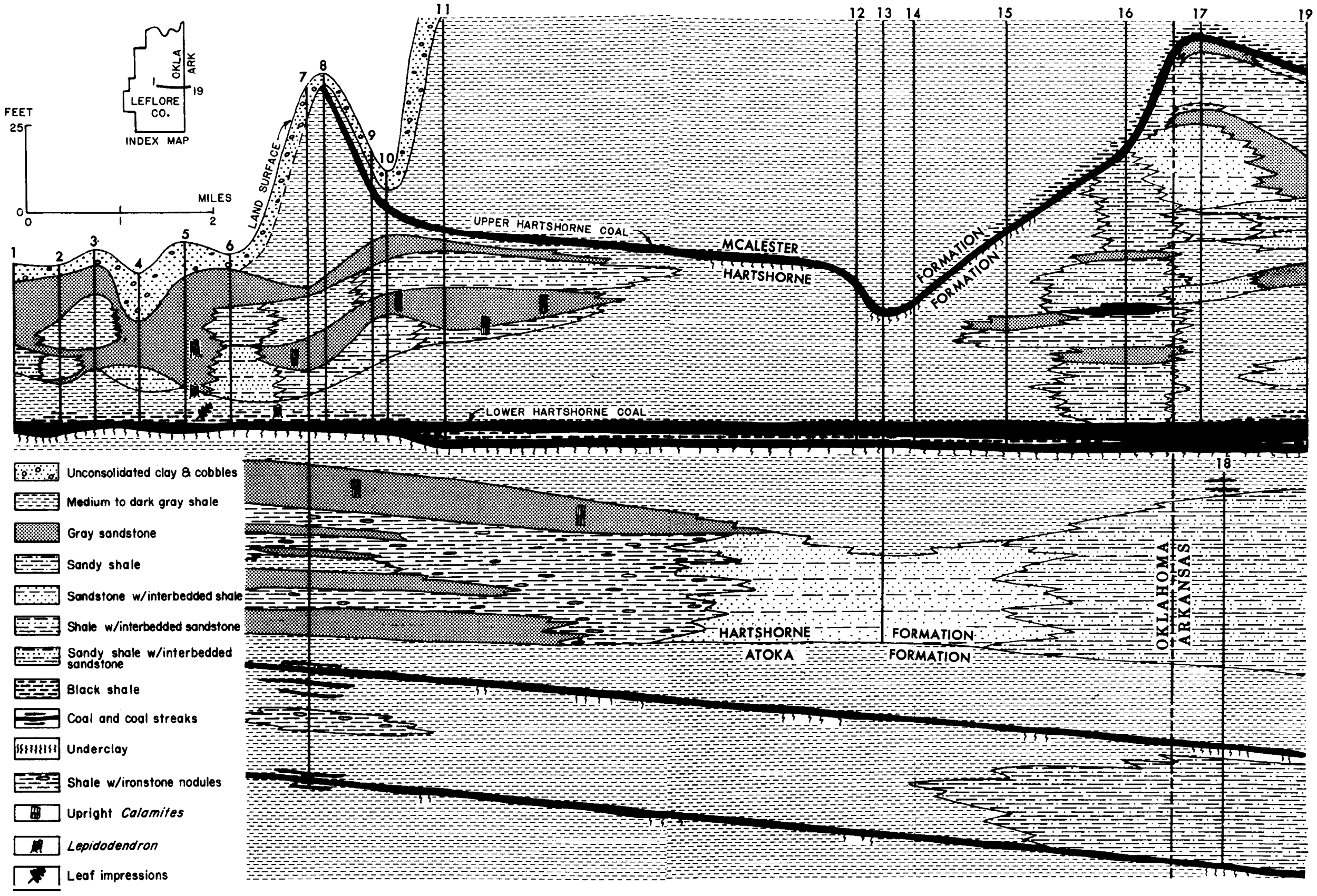


Figure 4-3 Cross Section Showing Stratigraphic Relations of Coals and Sandstones in the Hartshorne and Atoka Formations, Le Flore County, Oklahoma and Sebastian County, Arkansas (After Friedman, 1978a).

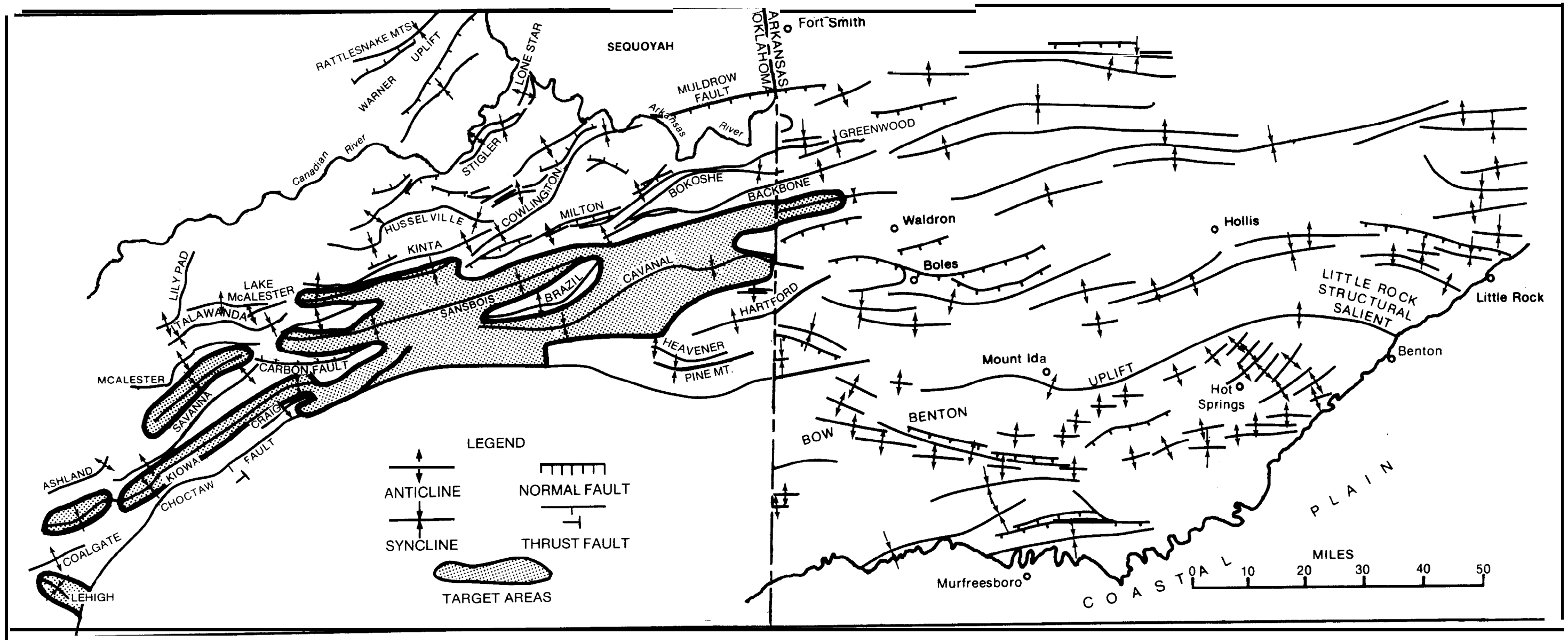
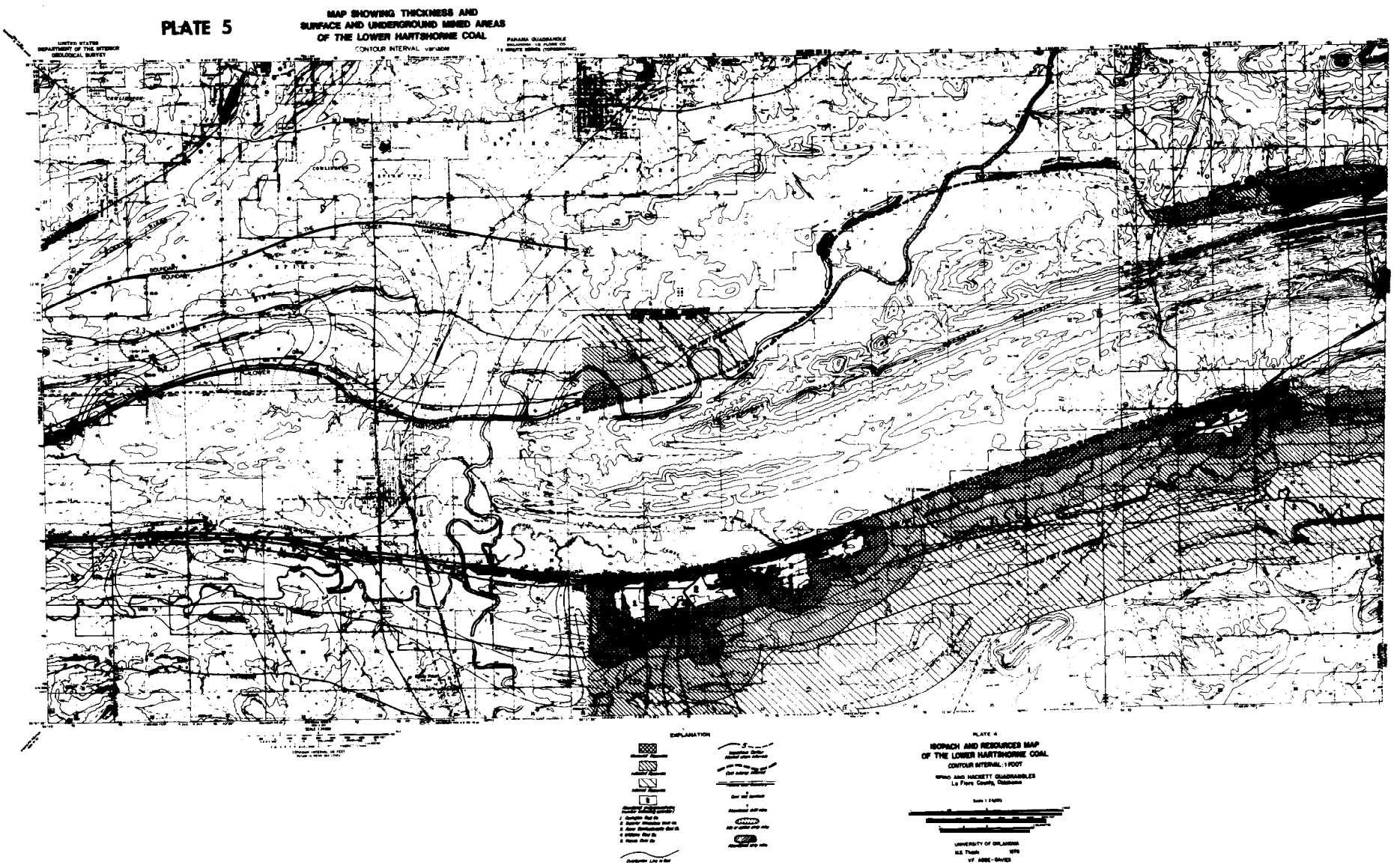


Figure 6-1. Redefined Target Areas in the Arkoma Basin.



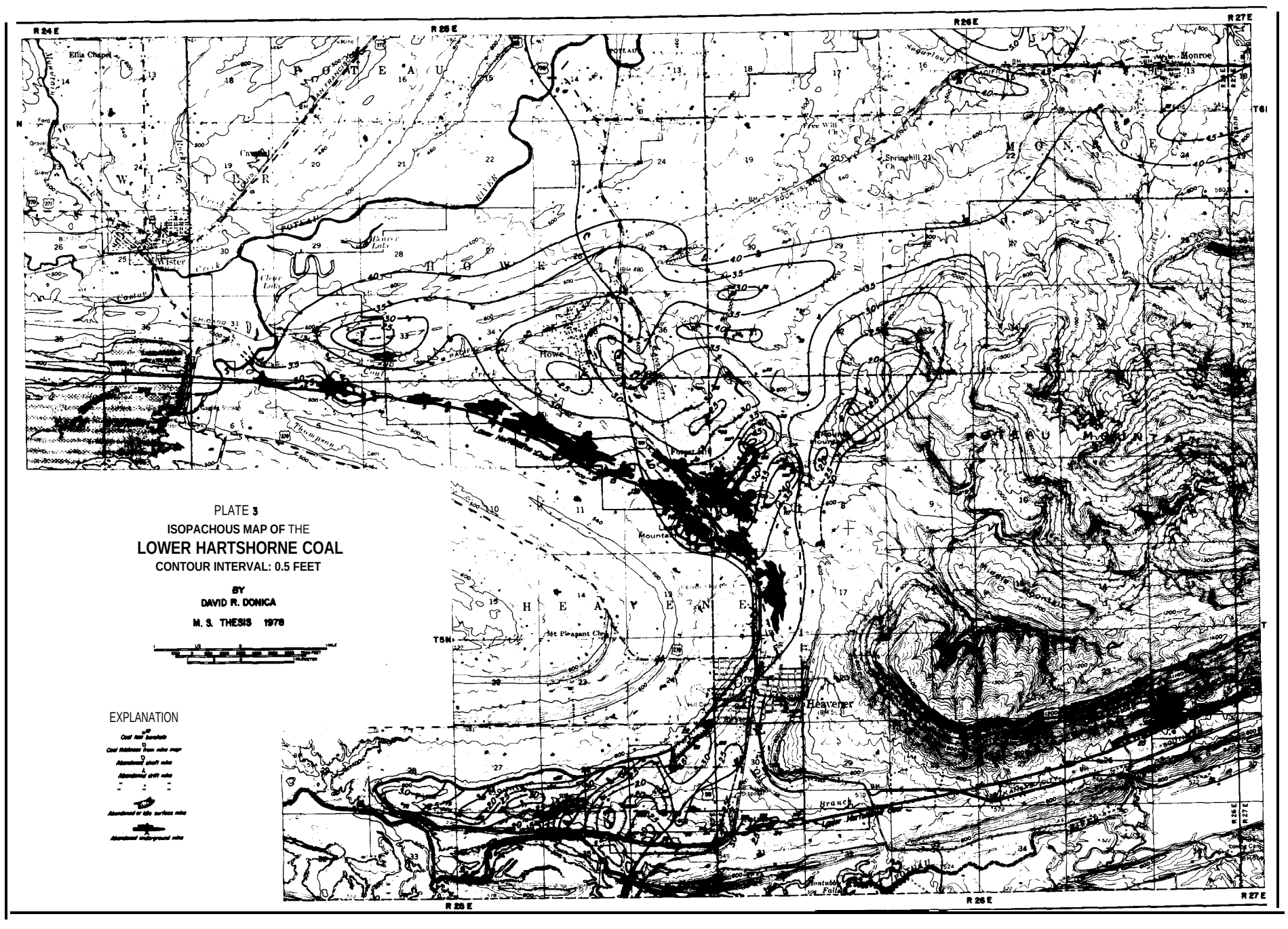


Figure 4-6 Isopachous Map of the Lower Hartshorne Coal (Agbe-Davis, 1876; Donica, 1876).

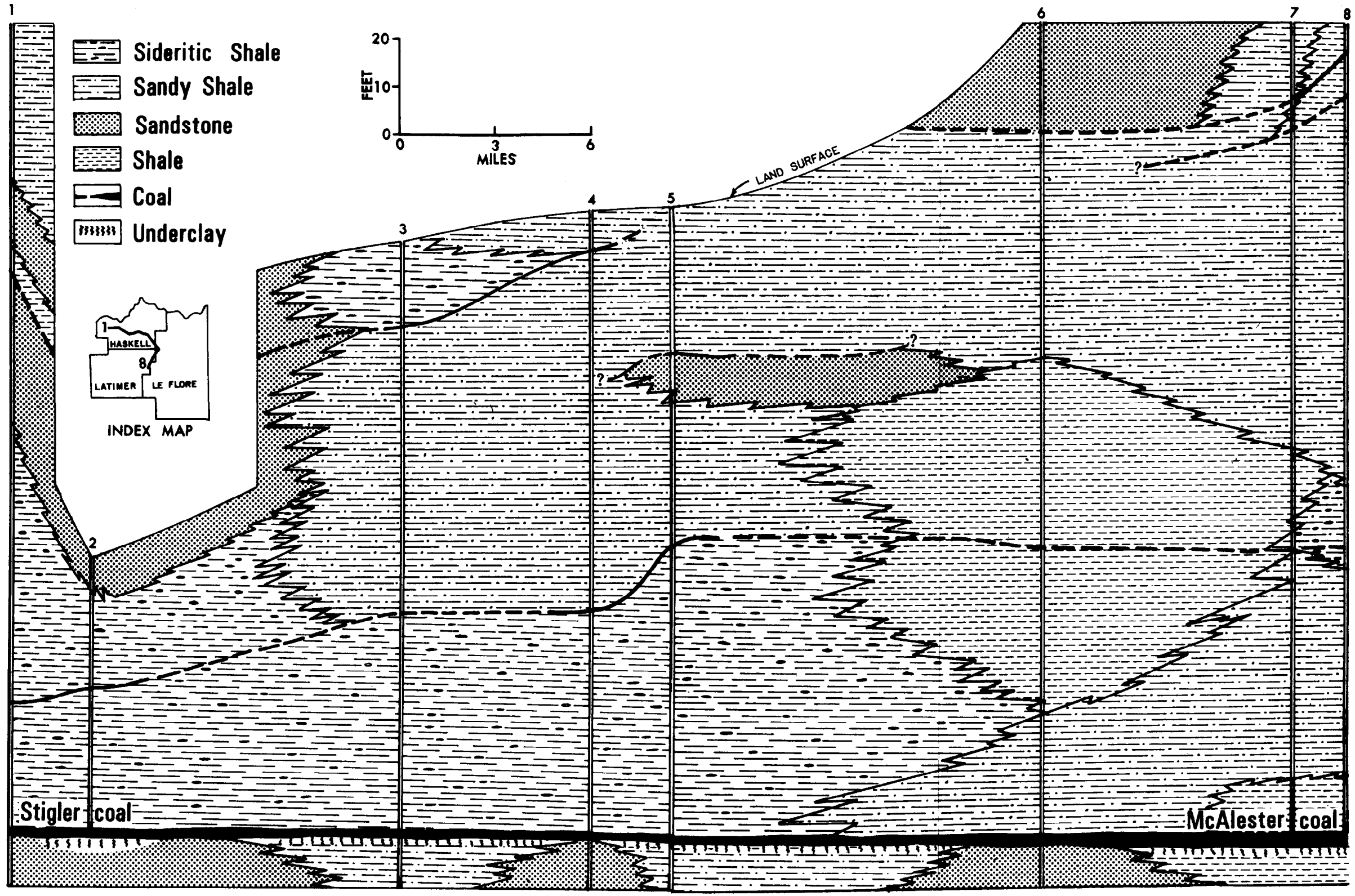


Figure 4-8 Stratigraphic Cross Section Showing Correlation of theStigler Coal With the McAlester Coal and of the Stigler Rider Coal With the Upper McAlester Coal (Friedman, 1978a,).

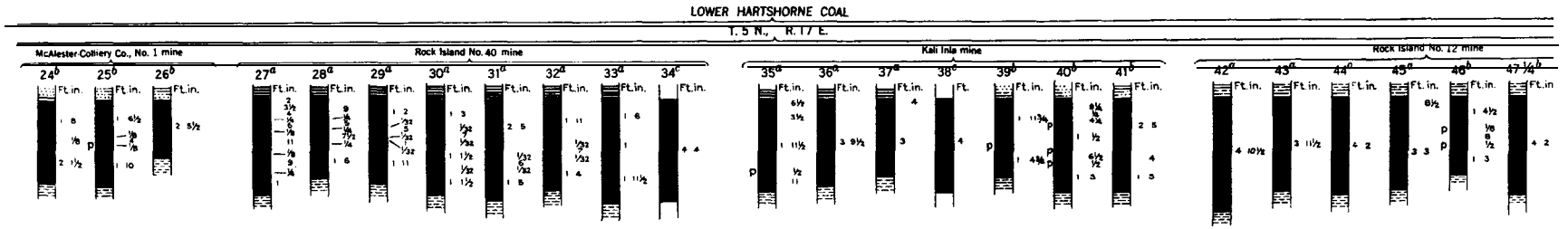


Figure 4-7 Examples of Variations in the Partings of the Lower Hartshorne Coal in Pittsburg County, Oklahoma (After Hendricks, 1937).

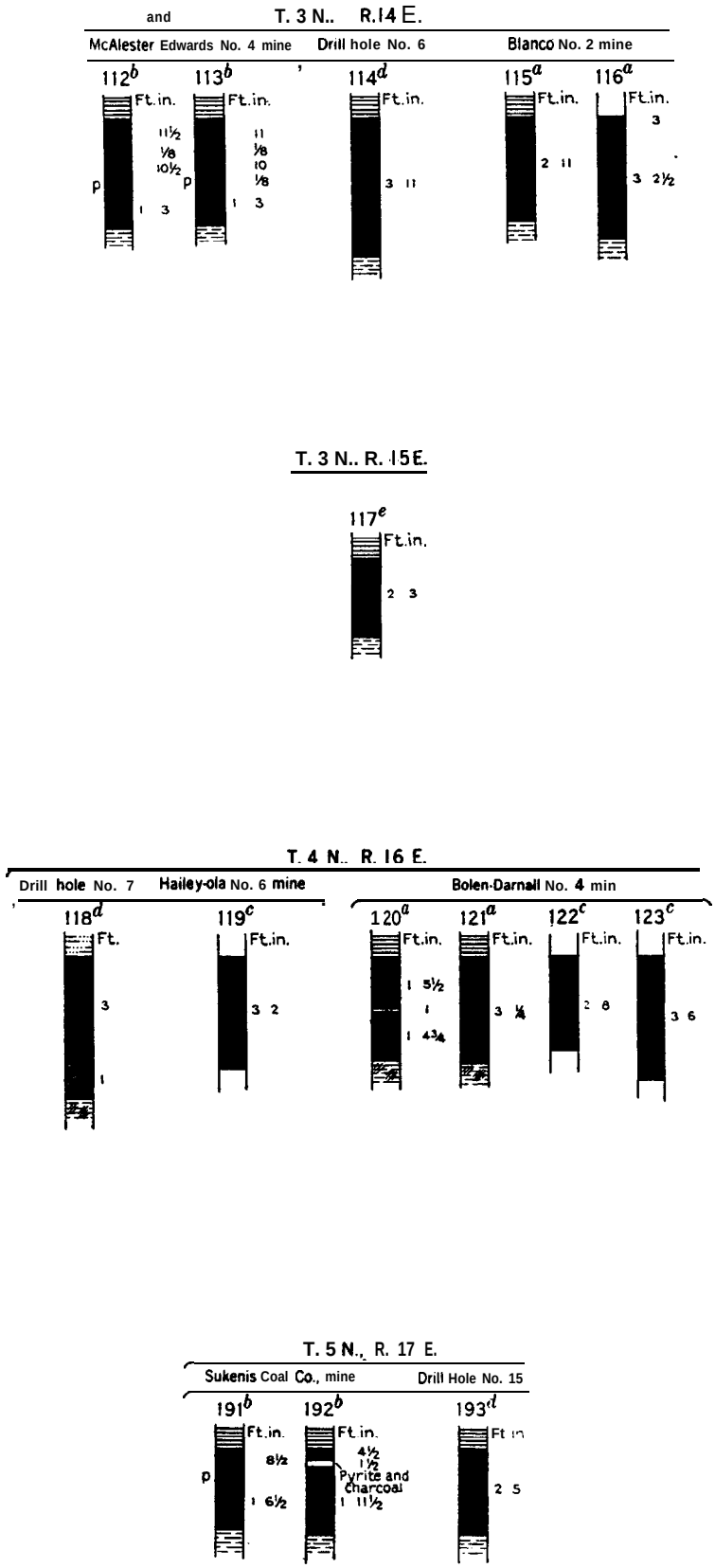
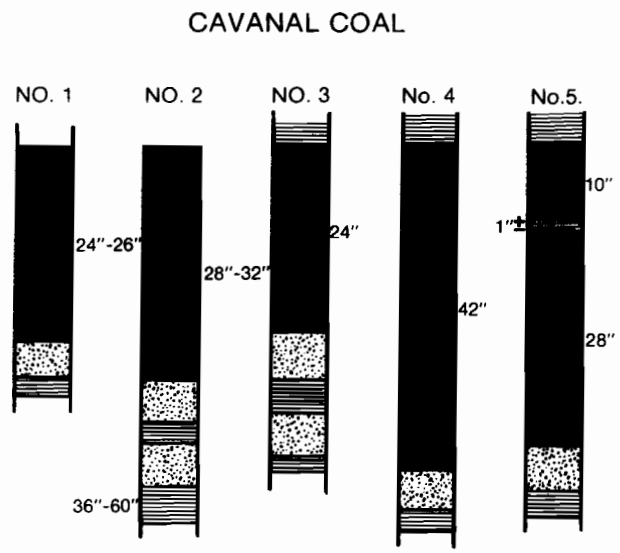


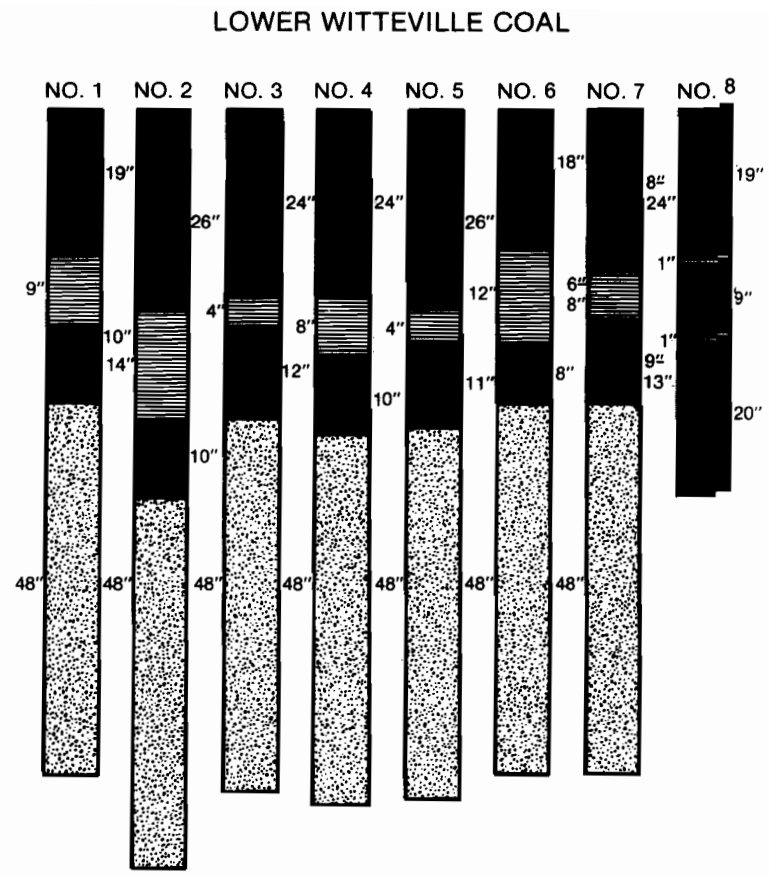
Figure 4-9 Measured Sections of the McAlester Coal in the McAlester District (After Hendricks, 1937).



THICKNESS OF COAL SHOWN ON RIGHT OF SECTION.
" " OTHER MATERIAL LEFT " "

VERTICAL SCALE 1 INCH - 2 FEET

NO. 1 McKENNA-TERRY COAL CO., POTEAU, LeFLORE COUNTY
NO. 2 TARBY COAL CO., N.W. OF POTEAU, LeFLORE COUNTY
NO. 3, NO. 4, NO. 5 } VARIATIONS IN THICKNESS AND CHARACTER OF THIS COAL



THICKNESS OF COAL SHOWN TO RIGHT OF SECTION
" " OTHER MATERIAL LEFT " "

VERTICAL SCALE 1INCH - 2 FEET

NO. 1 NORTH OF QUINTON - N.E.¼, N.W.¼ SEC.25, T.8N, R.18E
NO. 2 NORTH-EAST QUINTON - NEAR CENTER SEC.30, T.8N, R.19E
NO. 3 NORTH-EAST QUINTON - N.E.¼, S.W.¼, SEC.8, T.8N, R.19E
NO. 4 NORTH-WEST QUINTON - N.E.¼, N.E.¼, SEC.15, T.8N, R.18E
NO. 5 NORTH QUINTON -N.E.¼, N.W.¼, SEC.24, T.8N, R.18E.
NO. 6 NORTH-WEST QUINTON - S.E.¼, S.E.¼, SEC.27, T.8N, R18E
NO. 7 AVERAGE SECTION NORTH OF FEATHERSTON
NO. 8 LOWER WITTEVILLE, MINE NO. 1, SEQUOYAH COAL & MINING CO

Figure 4-10 Measured Sections in the Cavanal and Lower Witteville Coals in the Arkoma Basin.

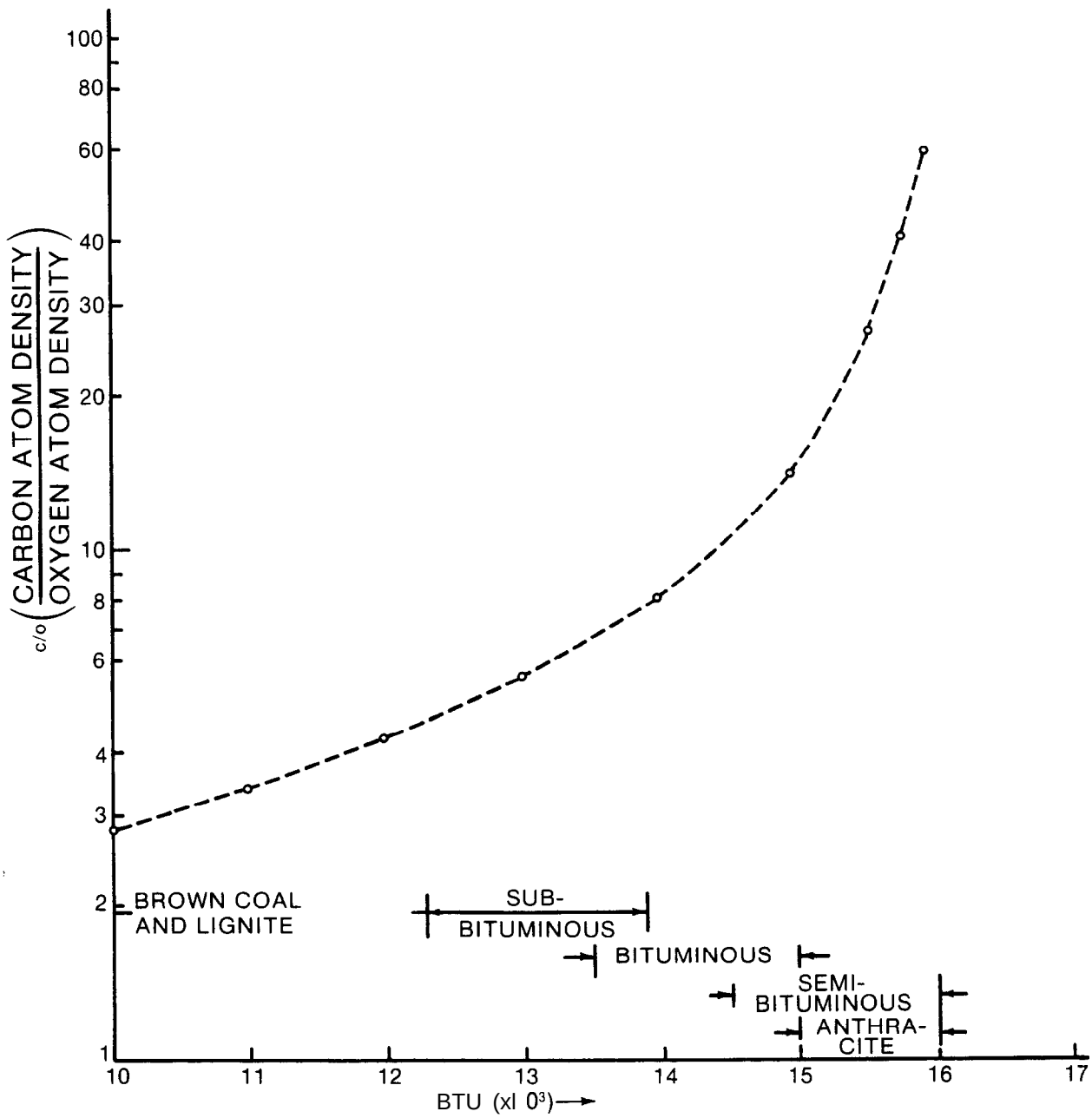
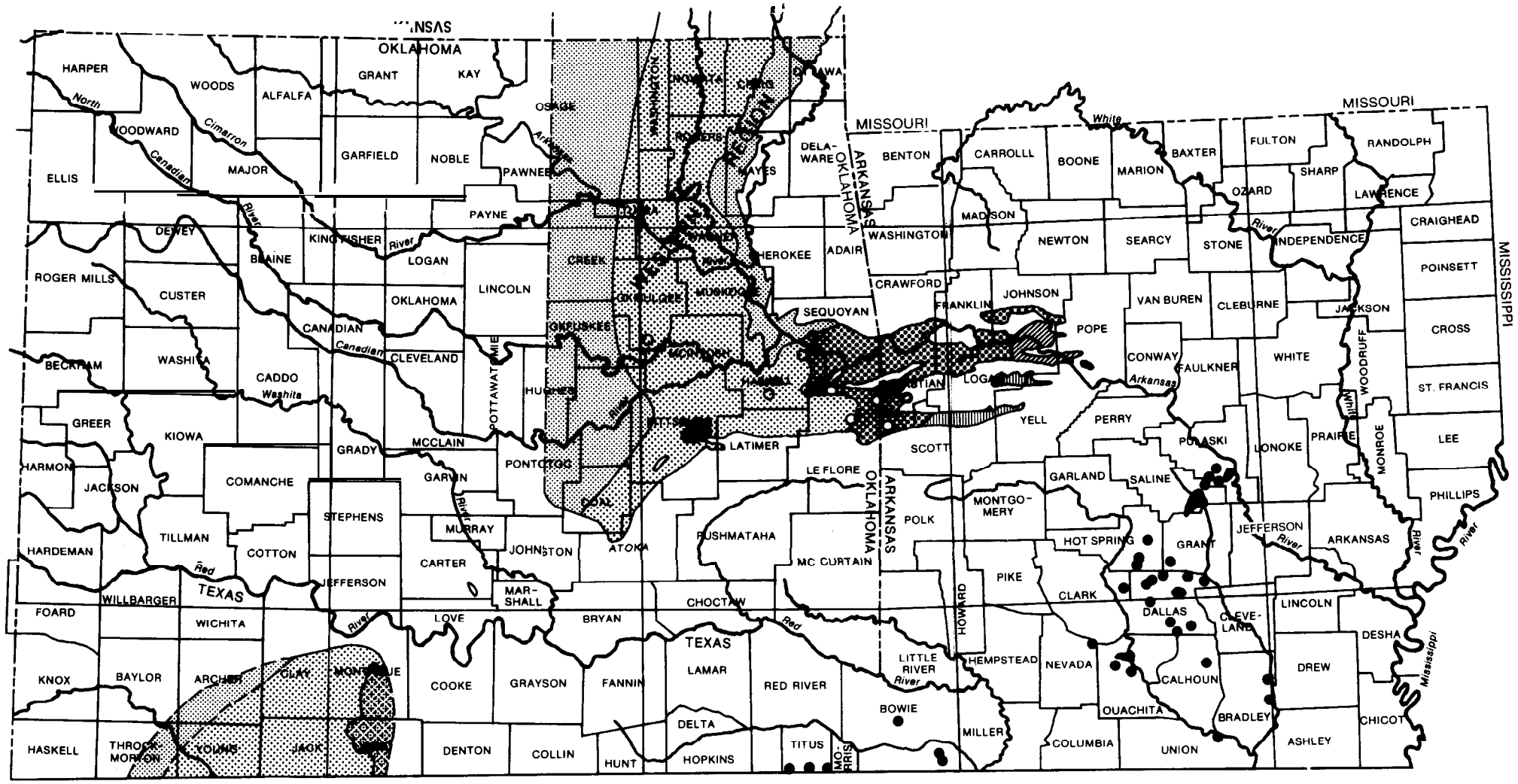


Figure 4-11 General Relations Between C/O Ratio and Btu Content of Coals (U.S. Patent 3,849,646).



LEGEND

- Anthracite, Semianthracite, and Meta-Anthracite
- Low-Volatile Bituminous Coal
- Medium- and High-Volatile Bituminous Coal
- Lignite and Brown Coal
- Coking Coal (Coal Coked at the Present Time, or Coal That Has Been Coked in the Past)

Deep color represents areas known to contain coal beds that are of commercial value at the present time or that may be of value in the future. In general the minimum thicknesses included are 14 inches for anthracite and bituminous coal, and 30 inches for subbituminous coal and lignite.

Light color represents areas of doubtful value for coal. These may be divided into three classes — (1) areas containing thin or irregular beds, which generally have little or no value, but which locally may be thick enough to mine, (2) areas in which the coal is poor in quality, and (3) areas where information on the thickness and qualify of coal beds is meager or lacking.

Light color and stippling denote that the coal-bearing formations are under cover which may range from a few hundred to several thousand feet.

Figure 4-12 Map Showing the General Rank of the Pennsylvanian Coals in the Arkoma Basin (After Trumbull, 1960).

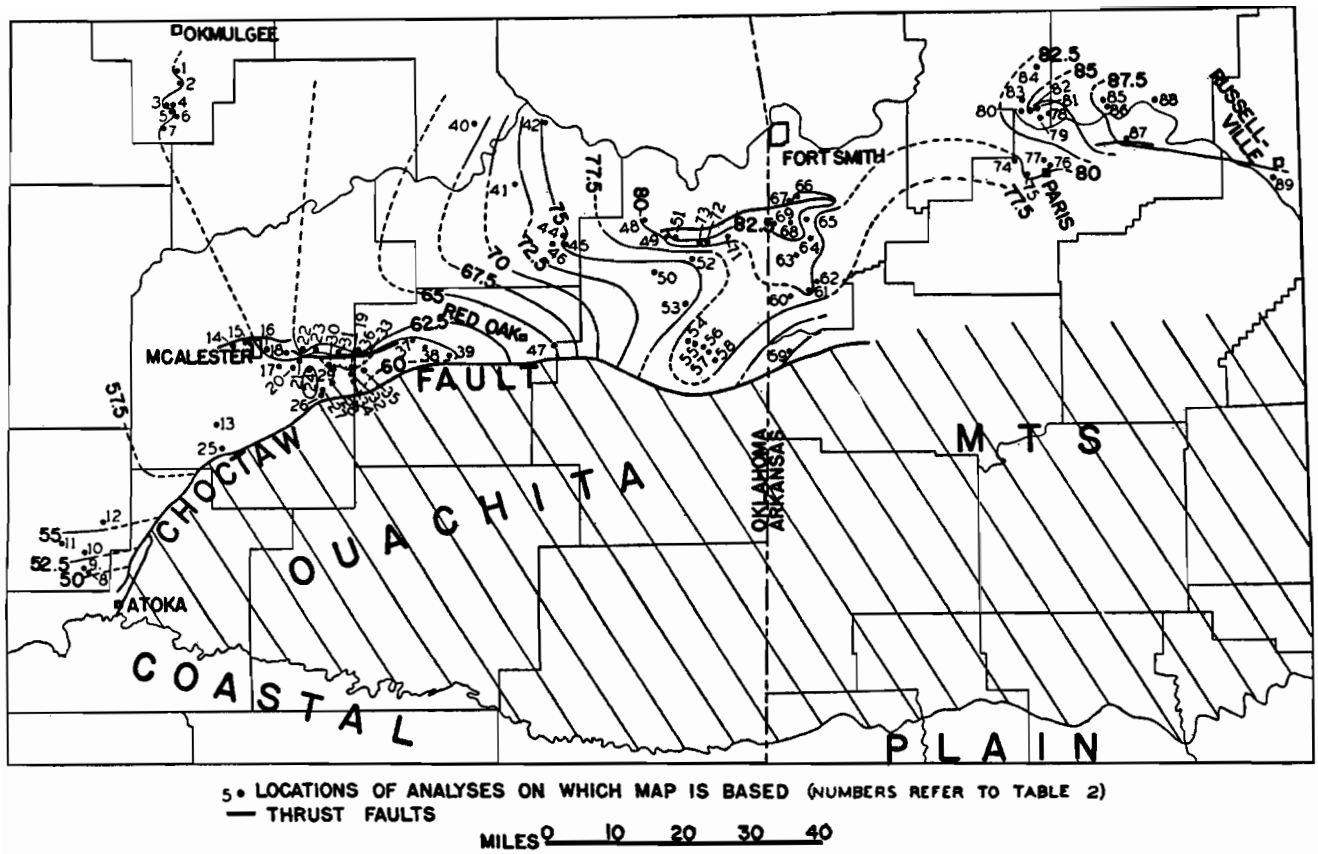
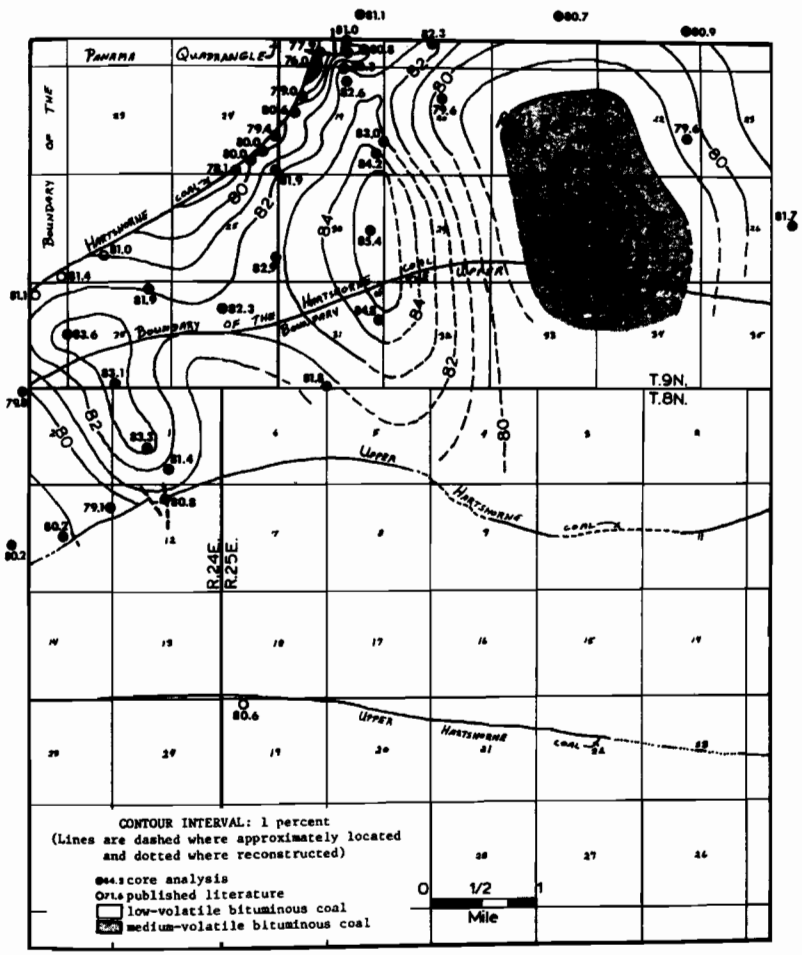
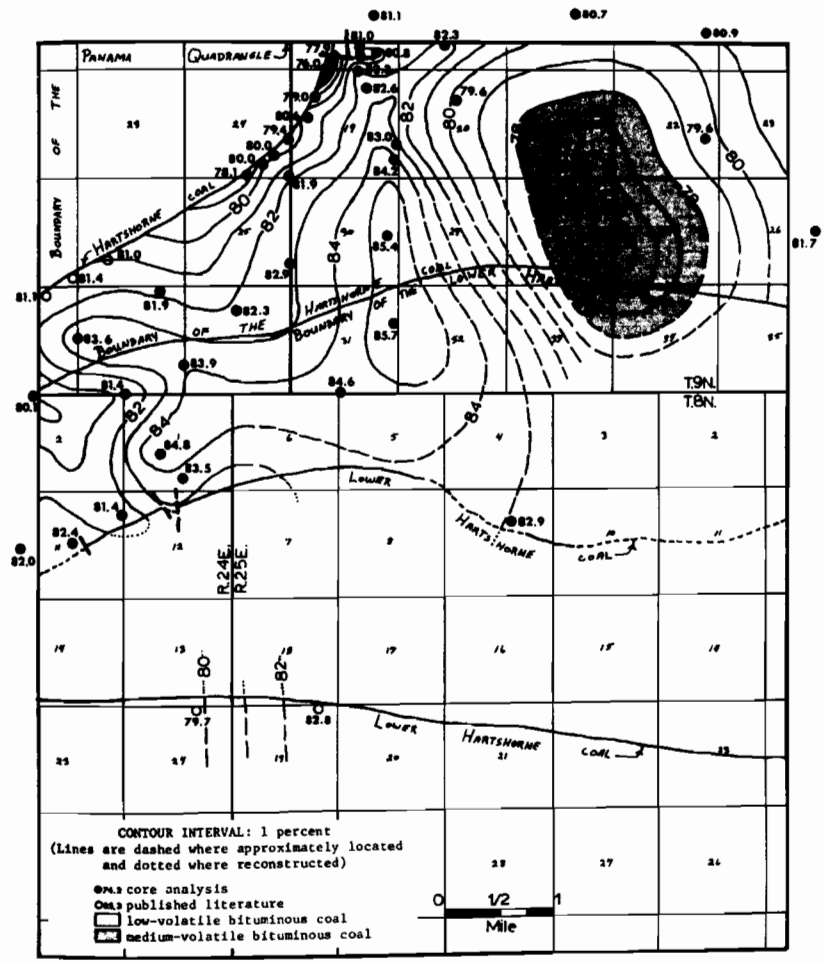


Figure 4-13 Isocarb Values in the Arkoma Basin (After Hendricks, et al, 1939).



Upper Hartshorne



Lower Hartshorne

Figure 4-15 Variation in the Isocarb Values Between the Upper and Lower Hartshorne Coals in the Panama Quadrangle, Le Flore County, Oklahoma (After Craney, 1978).

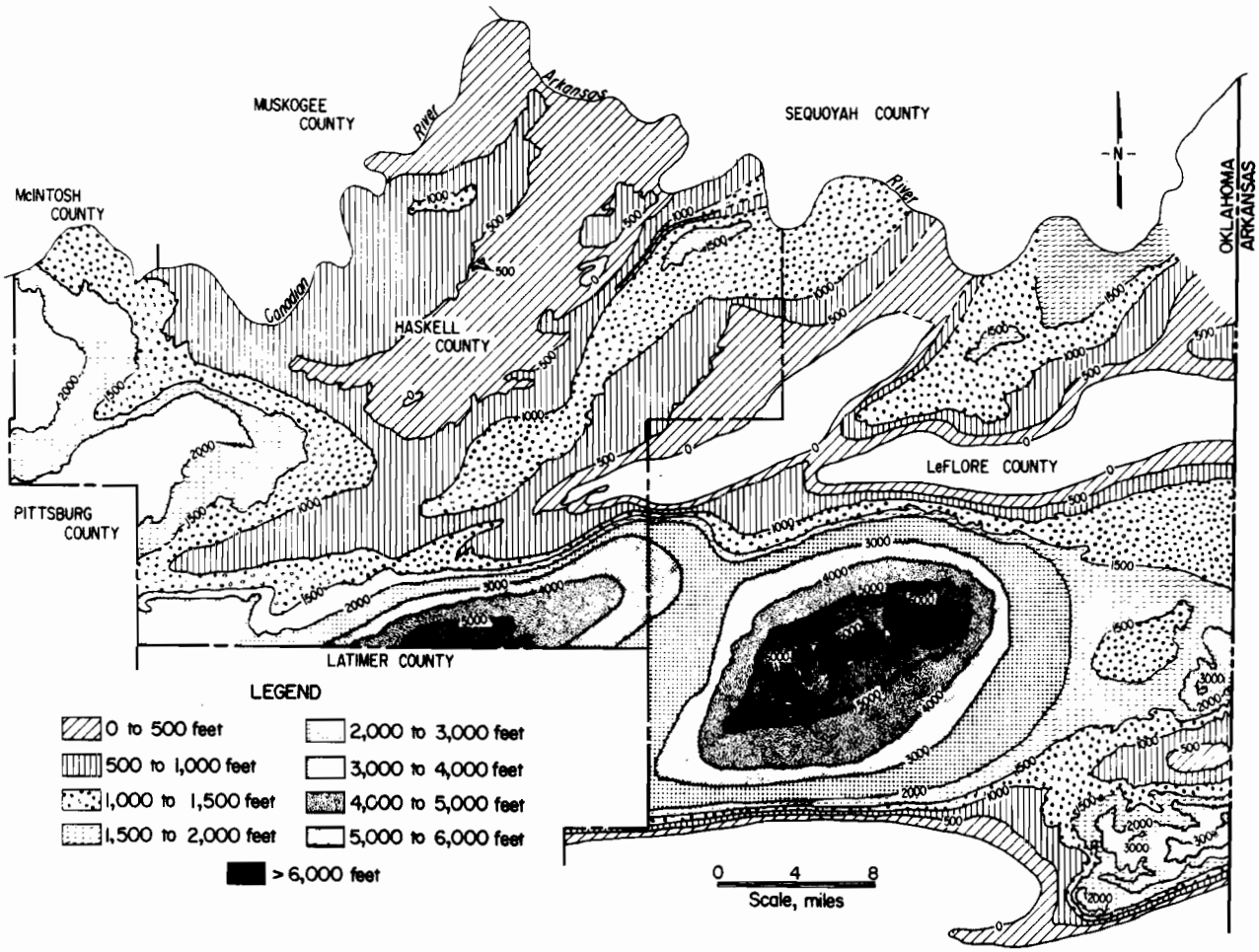


Figure 4-17 Overburden Above the Hartshorne Coal, Haskell and Le Flore Counties, Oklahoma, (After Innacchione and Puglio, 1979).

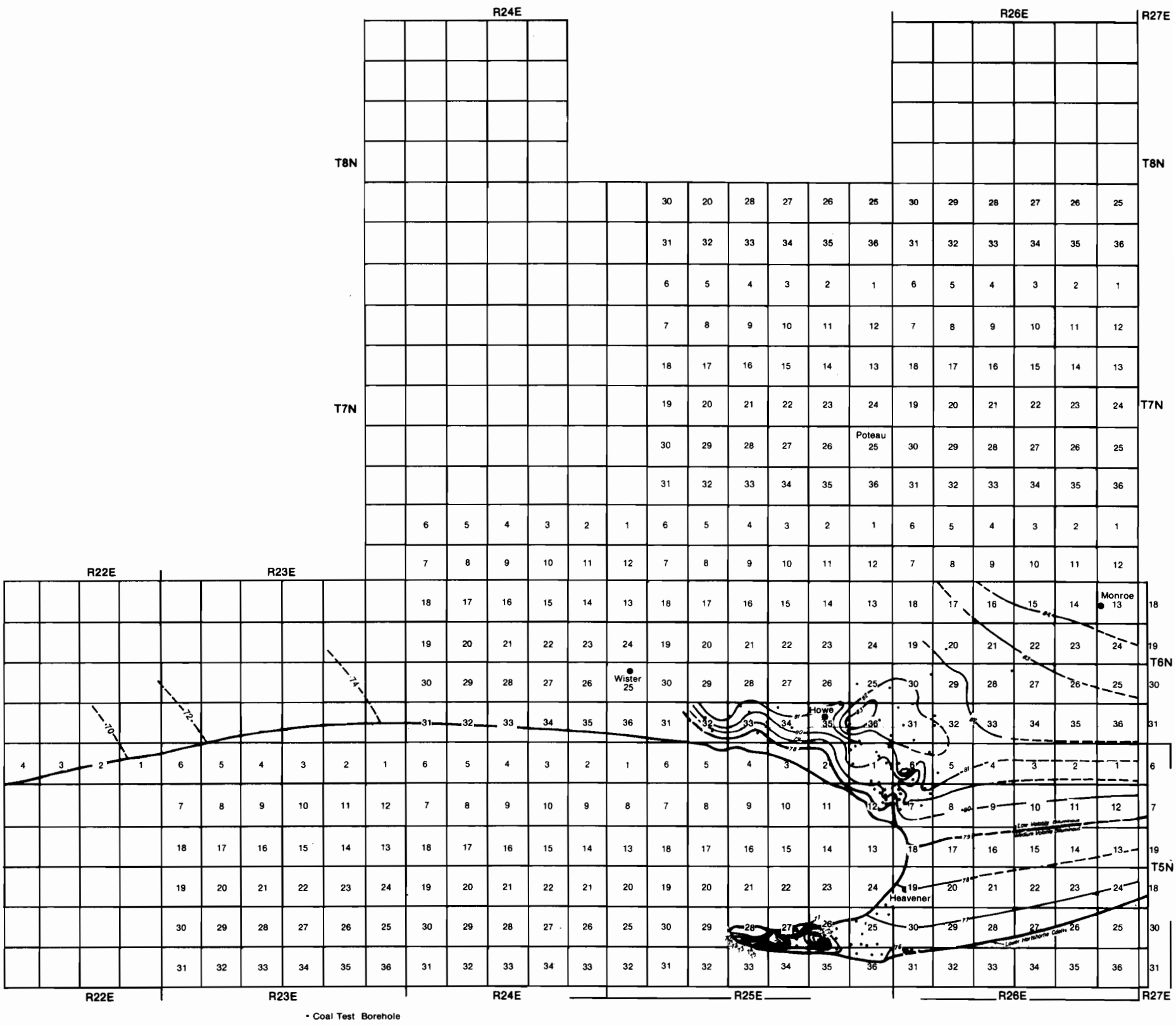
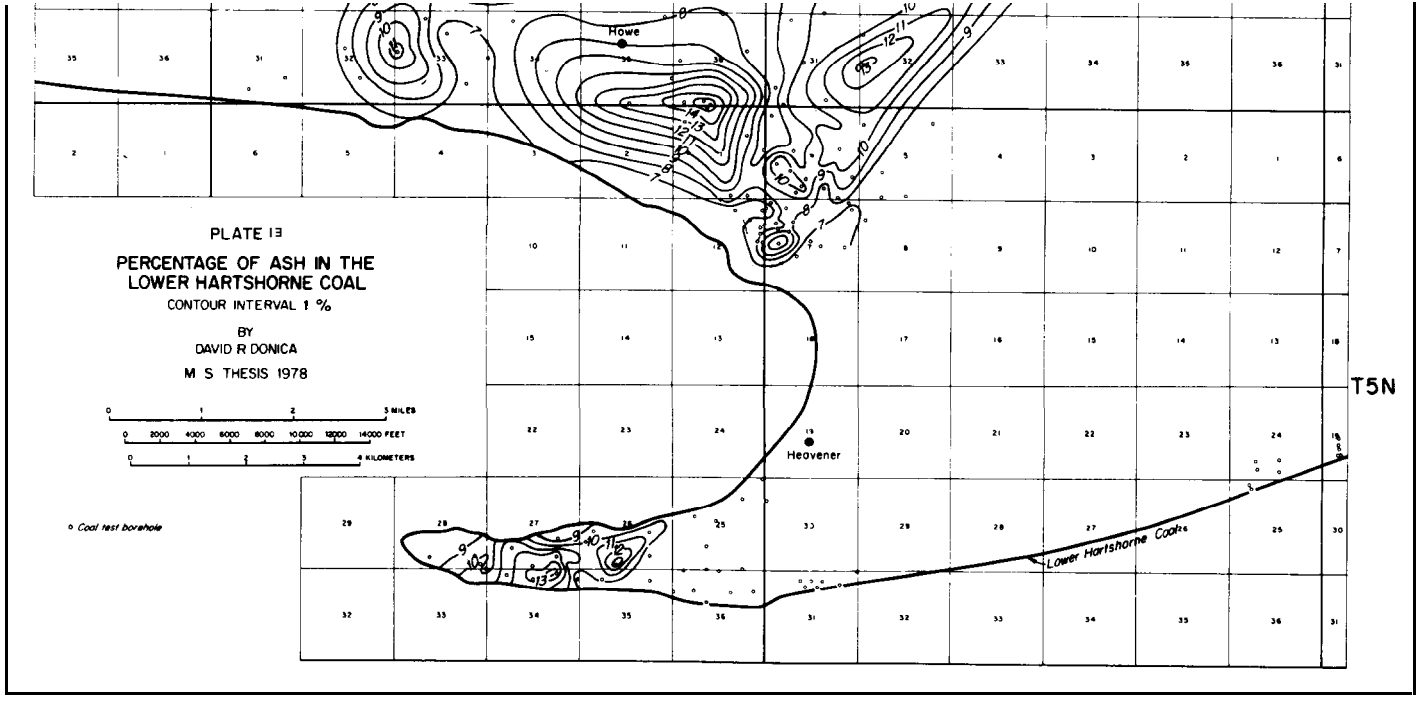
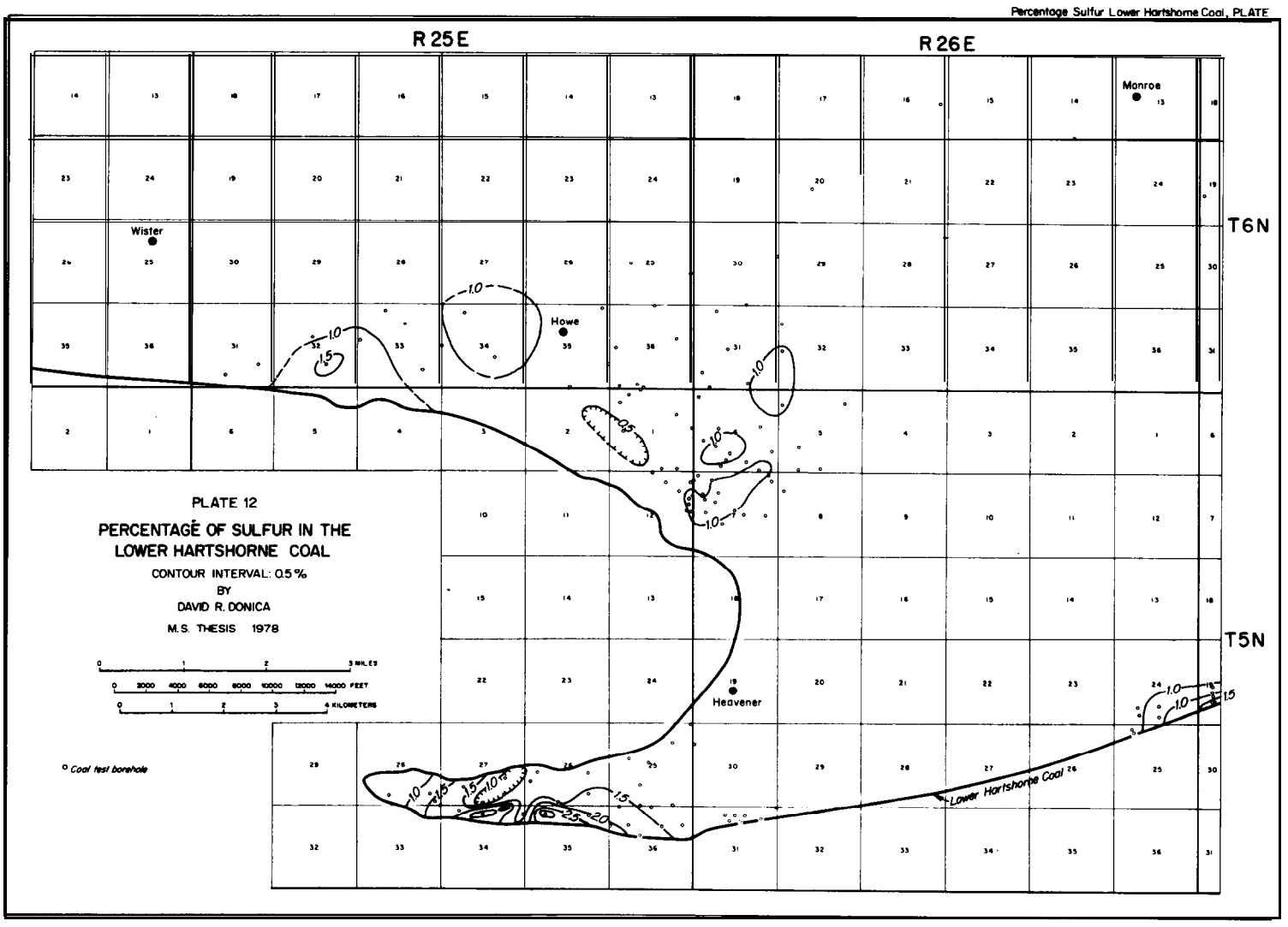


Figure 4-14 Map Showing Detailed Variations in the Fixed-Carbon Percentages of the Lower Hartshorne Coal in the Panama and Heavener Quadrangles in Le Flore County, Oklahoma (After Donica, 1978 and Craney, 1978).





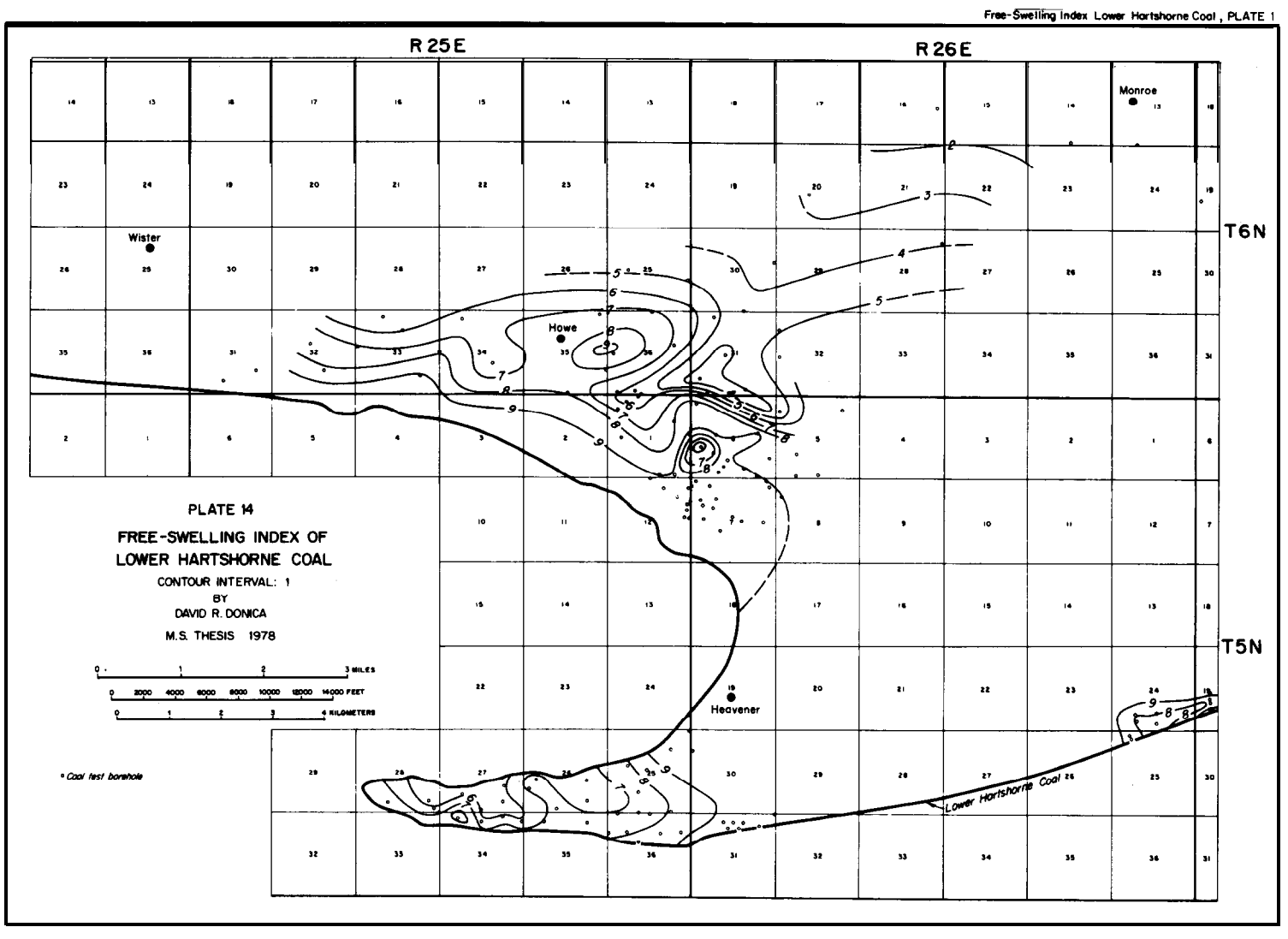


Figure 4-16 Variations in the Percentage of Ash and Sulfur, and the Free-Swelling Index of the Lower Hartshorne Coal in the Heavener 15' Quadrangle, LeFlore County, Oklahoma (After Donica, 1978).

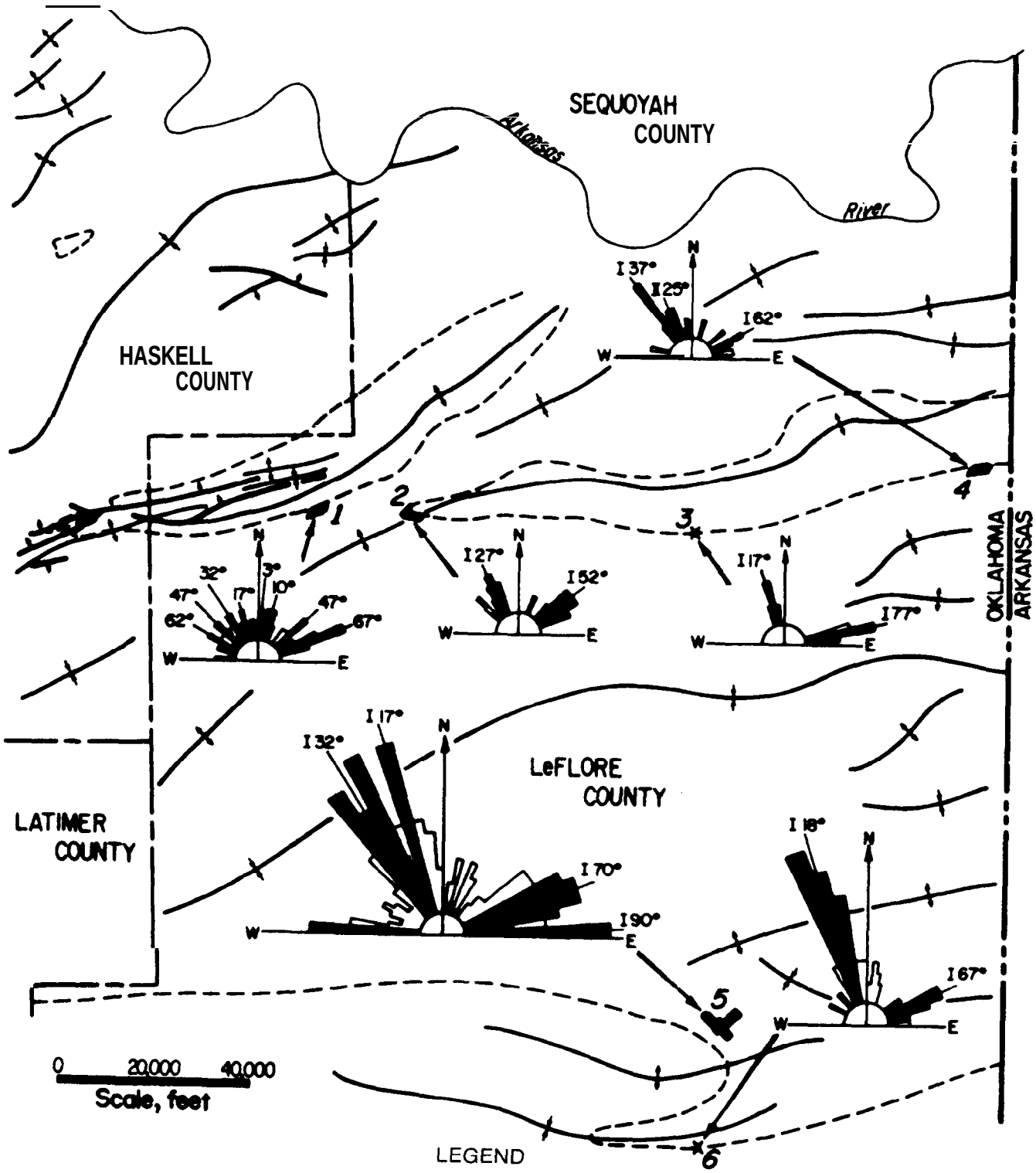


Figure 4-18 Coal Cleat Orientations of the Hartshorne Coalbed in Le Flore County, Oklahoma (After Innaccnione and Puglio, 1979).

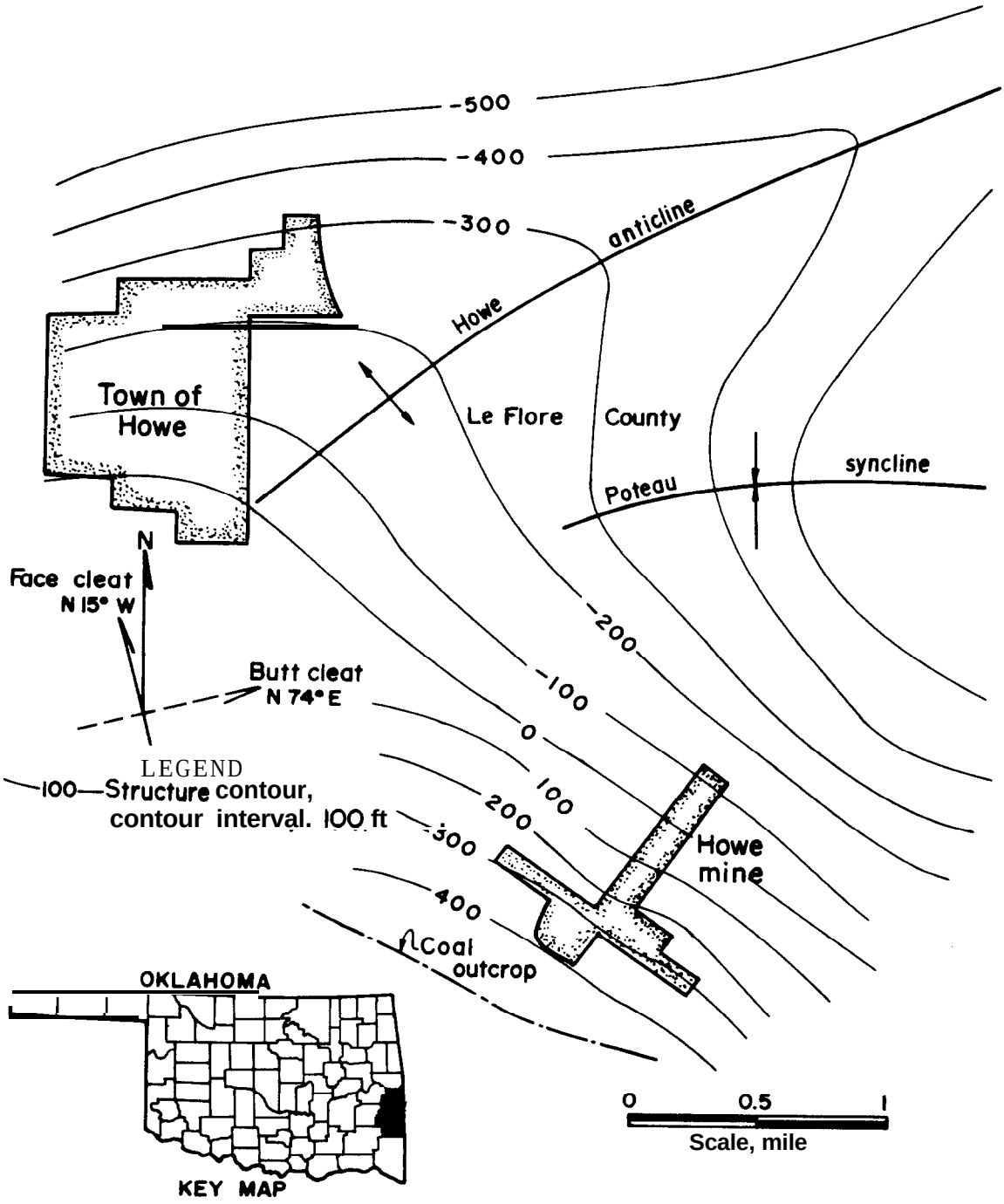


Figure 4-19 Structure of the Lower Hartshorne Coalbed (After McCulloch, et al, 1974).

Table 4-1 Average Analyses on a County Basis of Coals in Eastern Oklahoma (After Friedman, 1974).

County	Coal bed	Typical Proximate Analyses (As Received, Percent)				Sulfur (Percent)	Btu	Ash Softening Temp.(° F)	No. of Anal.	Data
		Moisture	Volatile	Fixed	Ash					
Haskell	Hartshorne	3.1	22.0	68.2	6.7	0.9	13,960	2,200	23	Pre-1953
Haskell	Hartshorne	Dry	22.3	69.1	8.6	1.8	14,346	—	64	1958-1968
Le Flore	Hartshorne	2.4	20.6	71.4	5.6	1.0	14,190	2,250	5	Pre-1953
Sequoyah	Hartshorne	5.3	16.8	72.4	5.5	1.7	13,980	2,170	1	Pre-1953
Coal	Lower Hartshorne	5.9	35.7	50.5	7.9	1.4	13,782	—	1	1915
Haskell	Lower Hartshorne	0.2	21.3	72.1	6.4	0.8	14,233	—	1	1965
Latimer	Lower Hartshorne	4.7	35.9	53.5	5.6	1.4	13,450	2,030	21	Pre-1953
Le Flore	Lower Hartshorne	2.9	17.8	72.3	7.1	0.8	14,000	2,100	23	Pre-1953
Le Flore	Lower Hartshorne	Dry	17.3	73.5	9.1	0.8	—	—	47	1957-1968
Pittsburg	Lower Hartshorne	3.6	37.2	52.8	6.5	1.5	13,490	2,080	39	Pre-1953
Haskell	Upper Hartshorne	0.04	21.0	71.9	7.0	1.3	13,969	—	1	1965
Latimer	Upper Hattshorne	3.4	37.1	55.0	5.3	1.0	13,590	2.190	11	Pre-1953
Le Flore	Upper Hartshorne	2.5	21.3	66.3	10.1	4.1	13,702	2,340	2	Pre-1953
Pittsburg	Upper McAlester	2.3	38.9	50.4	8.3	4.1	13,327	—	1	—
Pittsburg	Upper Hartshorne	4.5	35.4	53.7	6.5	1.5	13,230	2,000	6	Pre-1953
Coal	McAlester	6.8	38.6	44.3	10.4	3.6	11,590	2,180	23	Pm-1953
Latimer	McAlester	2.5	31.6	54.2	11.7	3.2	—	—	1	Pre-1953
Pittsburg	McAlester	3.3	36.1	55.1	5.6	0.9	13,640	2,210	59	Pre-1953;
Haskel l	Stigler	3.1	25.4	67.3	4.2	1.2	14,430	2,180	13	Pre-1953
Haskell	Stigler	5.0	27.4	63.2	4.4	1.1	13,869	—	3	1972
Muskogee	Stigler	2.3	30.5	60.6	6.6	3.7	14,110	2,340	1	Pre-1953
Le Flore	Cavanal	2.3	22.0	66.3	9.4	3.4	13,840	2,410	4	Pre-1953
Le Flore	Cavanal	2.0	20.9	66.2	10.9	4.7	13,580	—	1	1969
Le Flore	Lower Witteville	1.7	22.1	63.0	13.3	4.3	13,180	—	5	Pre-1953
Rogers	Rowe	1.9	35.6	54.6	7.9	2.8	13,995	—	3	1971
Rogers	Rowe	0.7	38.3	47.9	13.2	3.4	13,348	—	1	1973
Le Flore	Secor	2.4	18.3	56.7	22.6	4.1	11,711	—	1	1972
Pittsburg	Secor	2.5	37.2	48.4	11.8	5.4	12,880	2,240	3	Pre-1953
Pittsburg	Secor	3.0	34.5	46.2	16.5	5.9	11,065	—	2	1973
Okmulgee	Croweburg	7.1	34.5	52.8	5.6	1.6	12,910	2,020	25	1973
Rogers	Croweburg	7.1	34.7	51.9	6.3	2.0	12,780	2,280	17	1973
Rogers	Croweburg	Dry	33.3	59.7	7.0	0.4	12,690	—	1	1965

Table 4-2 Average Analysis of Arkansas Coals on an As-Received Basis (Keystone, 1979; Haley, 1977).

County	Coal Seam	No. of Samples	% Moisture	% Vol. Matter	% Fixed Carbon	% Ash	% Sulfur
Johnson	Lower Hartshorne	30	2.5	12.6	75.4	9.6	2.6
Logan	Lower Hartshorne	6	3.6	14.4	78.1	9.5	1.35
Pope	Lower Hartshorne	6	2.1	12.3	75.1	10.6	2.4
Scott	Lower Hartshorne	19	4.05	23.6	67.4	10.5	1.3
Sebastian	Lower Hartshorne	72	2.4	17.5	72.8	7.3	1.1
Franklin	Charleston	12	2.1	19.4	76.1	5.7	3.5
Sebastian	Charleston	2	3.8	16.3	77.3	4.5	2.2
Franklin	Paris	3	1.0	20.5	76.1	4.7	2.4
Logan	Paris	63	1.8	68.9	11.5	11.5	2.0

Table 4-3 Characterization of Vitrain and Attritus in Bituminous Coalbeds of Oklahoma (Friedman, 1978b).

Formation		Average Quantity[1] and Thickness[2] of Vitrain	Average Luster of Attritus
Senora	Croweburg	Moderately, Thin	Moderately Bright
	Morris	Sparse, Thin	Moderately Bright
	Eram	Moderate, Thin	Bright
	Weir-Pittsburg	Moderate, Thin	Moderately Bright
Boggy	Secor	Sparse, Thin	Moderately Bright
Savanna	Lower-Witteville	Moderate, Medium	Moderately Bright
	Rowe	Moderate, Medium	Moderately Bright
	Cavanal	Moderate, Thin	Moderately Bright
McAlester		Moderate, Thin	Moderately Bright
Hartshorne	Upper Hartshorne	Sparse, Thin	Moderately Bright
	Lower Hartshorne	Sparse, Thin	Bright
	Hartshorne	Sparse, Thin	Moderately Bright

[1]Sparse, 15 Percent: Moderate, 15 to 30 Percent: Abundant, 30 to 60 Percent
[2]Thin Banks, 1/2 to 2 mm, Medium Bands, 2 to 5 mm; Thick Bands > 5 mm.
(Modified from Schopf)

Table 4-4 Classification of Coals by Rank.

Class	Group	Fixed Carbon Limits, per cent (Dry, Mineral-Matter-Free Basis)		Volatile Matter Limits, per cent (Dry, Mineral-Matter-Free Basis)		Calorific Value Limits, Btu per pound (Moist,[b] Mineral-Matter-Free Basis)		Agglomerating Character
		Equal or Greater Than	Less Than	Greater Than	Equal or Less Than	Equal or Greater Than	Less Than	
I. Anthracitic	1. Meta-anthracite	98	. .		2		.	...
	2. Anthracite	92	98	2	8			...
	3. Semianthracite	86	92	8	14		.	Nonagglomerating[e]
II. Bituminous	1. Low volatile bituminous coal	78	86	14	22			Commonly agglomerating[e]
	2. Medium volatile bituminous coal	69	78	22	31	...	...	
	3. High volatile A bituminous coal	.	69	31	...	14 000[d]	...	
	4. High volatile B bituminous coal		...	...	. .	13 000[d]	14 000	
	5. High volatile C bituminous coal				.	11 500	13 000	
						10 500	11 500	Agglomerating
III. Subbituminous	1. Subbituminous A coal	..	. .	...	..	10 500	11 500	Nonagglomerating
	2. Subbituminous B coal	..	.	.		9 500	10 500	...
	3. Subbituminous C coal	.	. .		. .	8 300	9 500	...
IV. Lignitic	1. Lignite A	...	.	.	.	6 300	8 300	...
	2. Lignite B	.	. .	...	. .		6 300	...

[a] This classification does not include a few coals, principally nonbanded varieties, which have unusual physical and chemical properties and which come within the limits of fixed carbon or calorific value of the high-volatile bituminous and subbituminous ranks. All of these coals either contain less than 48 percent dry, mineral-matter-free fixed carbon or have more than 15,500 moist, mineral-matter-free British thermal units per pound.

[b] Moist refers to coal containing its natural inherent moisture but not including visible water on the surface of the coal.

[c] If agglomerating, classify in low-volatile group of the bituminous class.

[d] Coals having 69 percent or more fixed carbon on the dry, mineral-matter-free basis shall be classified according to fixed carbon, regardless of calorific value.

[e] It is recognized that there may be nonagglomerating varieties in these groups of the bituminous class, and there are notable exceptions in the high volatile C bituminous group.

Table 4-5 Relationship of Fixed-Carbon to Fault and Fold Structures and to Adjacent Structures in the Arkoma Basin (After Fuller, 1920; Wilson, 1961).

Group	Local	Ratio	Adjacent Structures
	Edwards	55	Choctaw Fault
I	Pittsburg	57	Choctaw Fault
	Savanna	61	Savanna Anticline
	Wilburton	59	Near Choctaw Fault
II	Lutie	61	Near Choctaw Fault
	Hughes	63	Cavanal Syncline

Locality	Adaiacent Structure	Fixed C-%
Savanna	Savanna Anticline	61
Chambers	Krebs Syncline	54
Craig	Flank of Anticline	65
Dow & Coleman	Kiowa syncline	61
McAlester	McAlester Anticline	63
So. McAlester	Krebs Syncline	59
Coalgate	Coalgate Anticline	58
Lehigh	Lehigh Syncline	54

5. POTENTIAL METHANE RESOURCE

5.1 PREVIOUS STUDIES/ANALYSES

Previous studies involving the determination of methane gas in coal in the Arkoma Basin were performed by the U.S. Bureau of Mines and consist of specific degasification and desorption tests.

5.1.1 Degasification Test Data (USBM)

Gas emission data exist for two mine locations in Oklahoma: Choctaw Coal Facility, Kerr-McGee Coal Corporation, Haskell County, has an average methane emission per day of 0.4 million cubic feet, whereas the Howe No. 1 mine, Howe Coal Company, Le Flore County emits 1.6 million cubic feet/day. Both emissions are from the Hartshorne coal.

In Figure 5-1, cubic feet of methane emitted per ton of coal mined is plotted versus the methane content of the sample for several mines. The resulting correlation is good for mines that are large and deep, have a sustained coal production of at least several thousand tons a day, and have been in operation for a number of years. New mines emit less methane per ton of coal mined than older mines with extensive old working and gob areas that still bleed gas. Hence, an estimate using Figure 5-l may be too high for a new mine, but after the mine has been worked for some time, the emission will approach the relationship shown in Figure 5-l (McCulloch, et al, 1975). The Howe mine in Le Flore County, Oklahoma is the only representative mine from the Arkoma Basin on the graph.

5.1.2 Desorption Test Data (USBM)

A total of 16 Hartshorne coal samples have been desorbed by the USBM from Haskell and Le Flore Counties, Oklahoma. The data set has not been published by USBM. Figure 5-2 shows the location of counties in which methane desorption data are available.

5.1.3 Relationship Between Methane and Depth, Hartshorne Coalbed

Methane content of the Hartshorne coalbed increases with depth, but at a decreasing logarithmic rate so that the maximum content probably will not exceed approximately 700 ft^3/ton at 3,000 feet of overburden. According to Figure 5-3 (Iannacchione and Puglio, 1979), gas content values in cubic

feet per ton range from approximately 160 at 200 feet buried depth to a value of 576 at 1,600 feet. The distribution of methane in the Hartshorne coalbed in Haskell and Le Flore Counties, Oklahoma is given in Table 5-1.

5.2 ARKOMA BASIN MRCP WELL TEST DATA

Methane Recovery from Coalbeds Project data on the methane gas content of Arkoma Basin coals are presently limited to coring and well testing in Pittsburg, Haskell and Le Flore Counties of Oklahoma (Figure 5-4).

5.2.1 Test Well Location

In Pittsburg County two wells were cored in cooperation with private industry:

- o Brown Estate Well Number l-2, Arkla Exploration Company
- o Barringer Well Number l-11, Mustang Production Company

In Haskell County one well was cored in cooperation with private industry:

- o Day Well Number 1-14, Mustang Production Company.

In Le Flore County one well was cored in the Rock Island area near the Arkansas-Oklahoma State line in cooperation with the U.S. Bureau of Land Management, Oklahoma City, Oklahoma:

- o DH-A17 Well, USBM/USBR

5.2.2 Testing Operations and Results

The MRCP desorption test results are presented in Table 5-2. Using weighted average values for gas content measured in the Brown Estate Numbet l-2 well (T. 6 N., R. 13 E., Sec. 2), the gas-in-place is estimated at 1.4 Bcf/640 acres. Using maximum permeability of 1.0 md and maximum relative permeability curve and minimal permeability of 0.1 md and minimum relative permeability curve, a range of discounted gas deliverability of 40,000 Mcf and 3500 Mcf, was calculated.

A DST was run on the Hartshorne coal in the Brown Estate well. The test was conducted over the interval 2,700 to 2,740 feet and showed flow of 9.0 barrels of water per day at a shut-in pressure of 716 psig. The average permeability calculated over the interval was 4.5 md. Table 5-3 is a summary of the bottom hole pressure and time data for the successful mechanical test.

In the Barringer well Number 1-11 (T. 4 N., R. 15 E., Sec. 11) three zones were conventionally cored. Only one coal core was successfully recovered from the Upper Booch coal. No DST were run in the wells. Future hydraulic fracturing stimulation tests are planned for the well in 1980. Well flow tests planned are pre-fracture and post-fracture flow tests. These tests will be conducted on the Hartshorne coal (4,628-4,632 feet) and the McAlester coal (3,212-3,218 feet).

No coal cores were obtained from the Day Well Number 1-14 (T. 7 N., R. 20 E., Sec. 14).

The DH-A17 well (T. 8 N., R. 26 E., Sec. 14) penetrated a total of 2.9 feet of Hartshorne coal. Initial desorption results indicate that the Hartshorne coalbed at this location contains a moderate amount of gas (Table 5-2).

5.3 ESTIMATED RESOURCE VOLUME

The very limited data available on the methane content of the different coalbeds in the Arkoma Basin make it difficult to construct an accurate resource estimate. However, based on the limited data in Tables 5-2 and 5-4, it is possible to present reasonable ranges for the maximum and minimum expected in-place gas resource of the coals in the Arkoma Basin. These estimates have been made on a county base and on a bed basis for the Arkoma Basin.

5.3.1 USBM Studies

Iannacchione and Puglio (1979) calculated the total volume of methane contained within the Upper and Lower Hartshorne coals for an area within Haskell and Le Flore Counties, Oklahoma. Table 5-4 presents the methane gas content versus the overburden for the Hartshorne undivided, Upper Hartshorne and the Lower Hartshorne. The methane content of these coals within their study area as shown in Figure 5-5 was calculated to be between 1.1 and 1.5 trillion cubic feet of gas. This estimate was based on a reserve of 2,330 to 3,120 million short tons of coal in place (Table 5-5). The estimate of total coal in place was made using over 900 coal data points. The distribution of methane gas in the Hartshorne coals with depth for Haskell and Le Flore Counties is given in Figure 5-3.

5.3.2 Volumetric Assessment

The volumetric assessment of the coalbed methane resource in the Arkoma Basin is based on Friedman's 1974 study for the Ozarks Regional Commission which provides the data for the bituminous coal resources and recoverable reserves of Oklahoma. The coal resource data for Arkansas is from Haley's 1977 study. The purpose of these coal investigation studies was to obtain, evaluate, and provide basic information pertaining to the extent, thickness, depth of burial and quality of the coals. The coal resources for Oklahoma include those that are greater than 3,000 feet deep, and coalbeds greater than 12 inches thick, whereas the Arkansas data were not specified. Both data sets did not separate out the shallow (strippable) coals from the deep (nonstrippable) coals.

5.3.2.1 Previous Coalbed Resource Investigations

The most recent comprehensive coal investigation in Oklahoma was completed in 1952 by Trumbull (1957). He reported 3.25 billion short tons of remaining bituminous coal resources in Oklahoma from an estimated 3.67 billion short tons of original resources.

The coal resource is broken down by rank. Trumbull (1957) reported that of the remaining reserves in Oklahoma:

- 65 percent was high-volatile-bituminous
- 13 percent was medium-volatile-bituminous
- 22 percent was low-volatile-bituminous

5.3.2.2 Arkoma Basin Coal Resource Data Base

For Oklahoma, Friedman plotted coal datum points on base maps compiled from 7.5-minute topographic-quadrangle maps at a scale of 1:24,000, on county road maps and geologic maps at a scale of 1:63,680. These datum points are located by 1/4 section, township, and range, within a geographic accuracy of about 50-100 feet. The datum points were obtained by Friedman from available sources excluding geophysical well logs. Arcs or circles were drawn around all datum points, in the manner previously described, delineating the measured, indicated, and inferred, resources and reserves. Although coal deposits were judged by Friedman to exist in geologic continuity with adjacent resources, these deposits have not been included in the tonnage figures of resources if they were more than 2 miles from a

datum point. This has been done to adhere as closely as possible to the criteria established by the U.S. Geological Survey, which have been used conservatively by Trumbull (1957) in maintaining the standard method of determining coal resources and reserves (Friedman, 1974).

5.3.3.3 Arkoma Basin Coalbed Methane Resource Base

Table 5-6 presents the minimum in-place gas resource of 1.58 Tcf based on a minimum average methane content of 200 cubic feet/ton. The following coalbeds were included:

- Lower Hartshorne
- Upper Hartshorne
- Hartshorne Undivided
- McAlester (Stigler)
- McAlester (Stigler) Rider
- Charleston
- Cavanal
- Paris
- Lower Wittevi1le
- Secor

It is reasonable to assume that the methane resource contained in these coalbeds should be much higher, inasmuch as no depth scaling for the gas content was made in this study such as that done for the USBM study (Iannacchione and Puglio, 1979) (see 5.3.1). An average gas content of 450 cubic feet/ton would give a methane gas resource of about 3.55 Tcf. The methane gas resource on a bed basis is presented in Table 5-7. Additional drilling in the Arkoma Basin also has delineated areas which contain more coal than previously thought, as in the case of the Day well in Haskell County, Oklahoma. These new reserves have not been included in the present evaluation.

The coalbeds are listed in rank order of the magnitude of the methane gas resource for the Arkoma Basin.

	200 cf/ton	450 cf/ton
o Lower Hartshorne	0.636 Tcf	1.431 Tcf
o Hartshorne Undivided	0.314 Tcf	0.707 Tcf
o McAlester (Stigler)	0.306 Tcf	0.688 Tcf
o Upper Hartshorne	0.138 Tcf	0.311 Tcf

5.4 GAS COMPOSITION

Iannacchione and Puglio (1979) estimated that the Hartshorne coalbed in Haskell and Le Flore Counties, Oklahoma contains between 1.1 and 1.5 Tcf of gas. In the same area, the Hartshorne Sandstone produces natural gas from the Quinton, Poteau-Gilmore, and Camaron gas fields (Figure 3-8). These small gas fields are producing from combination traps (structural and stratigraphic). Gas samples were collected from nine producing wells in the three Oklahoma gas fields, from several gas drainage holes in the Hartshorne coalbed, and from two Hartshorne coal cores (Iannacchione and Puglio, 1980). The δC^{13} value of the methane, ranging from -34 to -44 per mil, and the amount of ethane, propane, and butane were found to be dependent on the rank of the coal associated with each gas field. Coalbed gas sampled from a mine near the Quinton field contained more methane and less ethane, propane, and butane than natural gas from the Quinton field. This may be due to the high sorption properties of coal. The heavier hydrocarbon gases remain adsorbed on the surface of the coalbed micropore structures, with higher proportions of methane released into coalbed macropore structures. Data collected so far indicate that the gas from the Poteau-Gilmore and Camaron fields is derived, at least partially, from associated coalbeds, while the gas from the Quinton field may have another origin. Gas sample analysis from the Hartshorne Formation shows gas com-Position variation in the western part of the Arkoma Basin (Moore, 1977). The Btu content of the Hartshorne gas ranges from 993 to 1062 (Table 5-8).

5.4.1 Chemical Analysis

An analysis of the composition of gases by Iannacchione and Puglio from the Hartshorne coalbed and sandstone has given some insight into the generation, migration, and retention of gas within the Hartshorne Formation. Samples were collected from nine production wells (C-1, 2, 3; PG-1, 2, 3; Q-1,2, 3) in the Hartshorne Sandstone, eight horizontal degasification holes (HC-1 to 8) in the Choctaw mine (Hartshorne coalbed), and two coal cores collected from the Hartshorne coalbed (HC-9 and HC-10, south of Poteau-Gilmore gas field). Isotopic and chemical data showed variations in the composition of the gases. Carbon isotope values given in δC^{13} per mil express parts per thousand deviation from PDB standard

(Table 5-9). Compositions differ with changing rank of the associated coalbeds, different sorption properties of the respective reservoir rocks, and the type of source material from which the gases were generated (Iannacchione and Puglio, 1980).

5.4.1.1 Relation of Gas Composition to Coalbed Rank

Both the δC^{13} value of the methane and the amount of heavier hydrocarbons (ethane, propane, and butane) from gas produced from the nine gas wells sampled in the three different gas fields are correlated to the rank of the coal associated with these gas fields.

Chemical analysis of coalbed gas also shows a slight increase in the percentage of methane with increasing rank (Table 5-10).

Recent work has shown that the composition of gas generated is generally dependent upon the degree of thermal maturation of the organic matter in the associated sedimentary rocks (Rice, 1975; Stahl, 1975). Different proportions of methane, ethane, propane, and butane are generated at different stages of metamorphism. An excellent indicator of the degree of thermal maturation is rank of coal. With increasing rank (metamorphism) of the coal associated with gas reservoir rocks, the methane becomes isotopically heavier. Percentages of methane and associated heavier hydrocarbons generated are also affected by this increased metamorphism.

The δC^{13} content of the methane from coalbed gas was determined only at one location (HC-1 to 8, T. 8 N., R. 21 E. south of Stigler, Haskell County, Oklahoma), where the Hartshorne coalbed is a medium-volatile bituminous coal. The δC^{13} content of this coalbed gas is similar to the δC^{13} content of the natural gas from the nearby Quinton gas field, where the associated Hartshorne coalbed is high-volatile A to medium-volatile bituminous rank. Therefore, rank of the coal, which reflects the temperature and pressure history of the Hartshorne Formation, can give some insight into the expected thermal and chemical composition of the gases generated from associated rocks. Iannacchione and Puglio's data are summarized in Figure 5-6.

5.4.1.2 Evidence of Coalbed Gas Fractionation

There is some evidence that physical fractionation of coalbed gas occurs after prolonged production from the coalbed reservoir. Physical

fractionation refers to the process of separating different hydrocarbon gases according to their differences in physical properties of weight and size. Eight coalbed gas samples were collected from a horizontal degasification system in the Hartshorne coal.

Seven samples (HC-1 to 7, Table 5-10) were collected from production holes drilled 3 to 14 months before sampling. The maximum percentage Of hydrocarbons from these samples was 97.8 pct methane, 0.86 pct ethane, 0.0016 pct propane, and 0.0005 pct butane. The eighth sample (HC-8) was collected from a horizontal hole drilled 31 months before sampling. This sample contained 94 pct methane, 4.2 pct ethane, 0.0045 pct propane, and 0.0049 pct butane. All holes were drilled in the same general area; however, the oldest hole (HC-8) has less methane and more ethane, propane, and butane (Iannacchione and Puglio, 1980).

It appears that coalbed gas does fractionate with lowering of reservoir pressure and time. This drop in pressure with time weakens the physical bonds of the adsorbed gas, allowing the gas to desorb and migrate.

5.4.2 Relation of Gas Composition to Geology

Closely associated with this coalbed is the Hartshorne Sandstone, which has produced natural gas from three small gas fields for approximately 65 years.

Natural gas has accumulated in commercial quantities in the Hartshorne Sandstone in at least three fields within Haskell and Le Flore Counties (Figure 3-8). These small gas fields are located along the axes of anticlines, where the Hartshorne Sandstone is locally thickly developed. This indicates a combination of structural and stratigraphic trapping mechanisms were operative. Production from all three gas fields began between 1910 and 1915. Average depths to reservoir of all three fields are approximately 1,500 feet, with initial bottom hole pressures ranging from 205 to 600 psi (Dane, et al, 1938). The range of initial production rates is from 250 to 16,000 Mcfd.

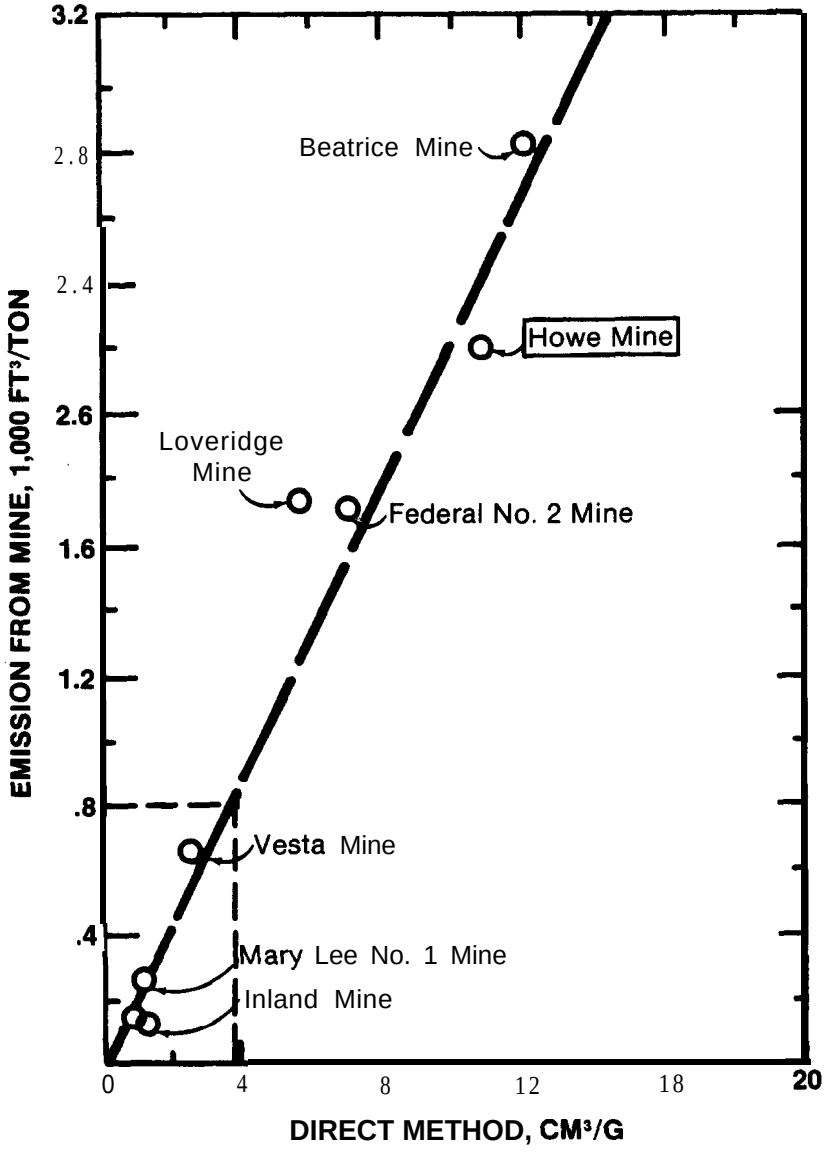


Figure51 Gas Content of Coal Versus Actual Mine Emission (After Kissell, et al, 1973).

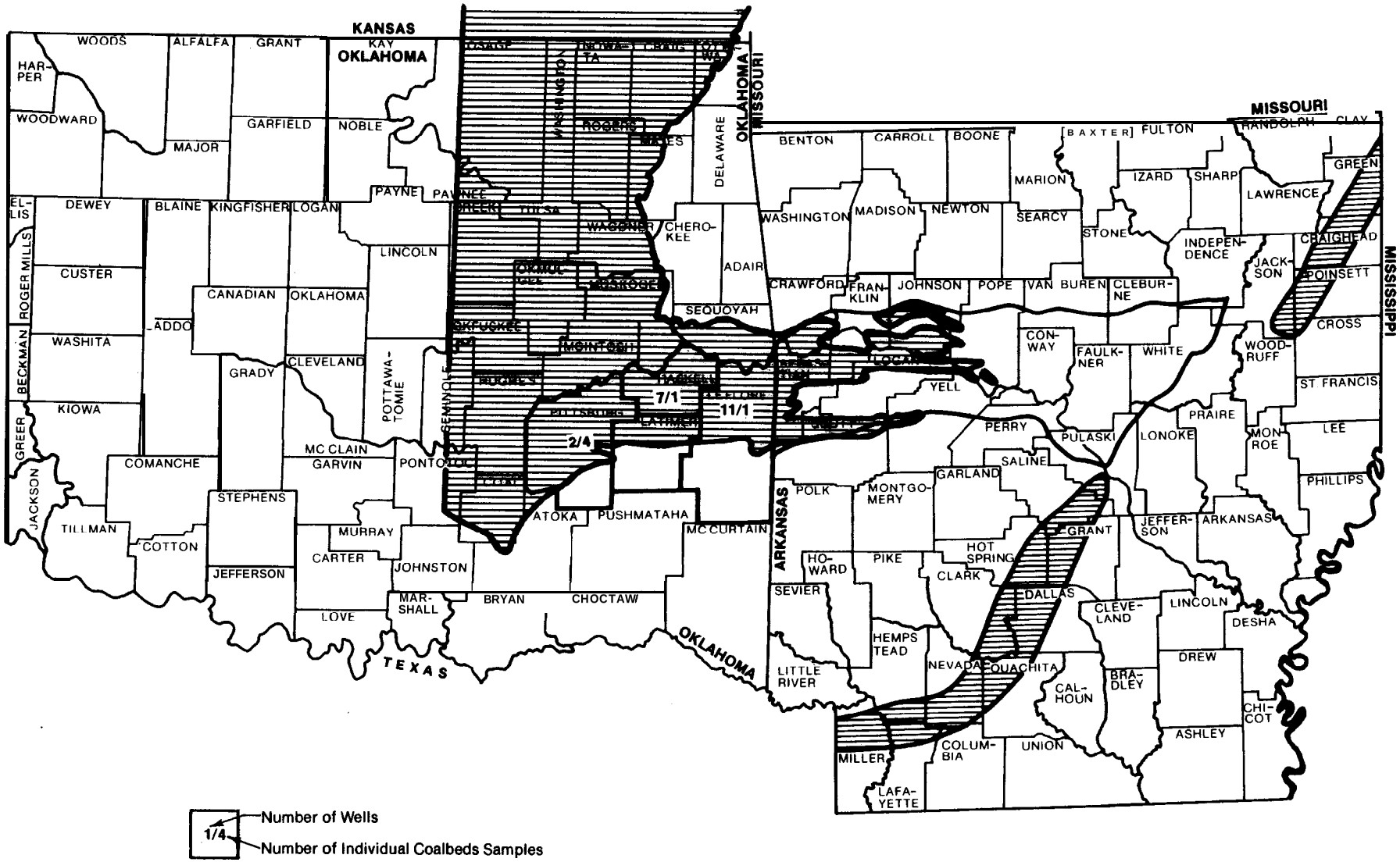


Figure 5-2 Arkoma Basin Map Locating Counties in Which **Methane Desorption Data are Available.**

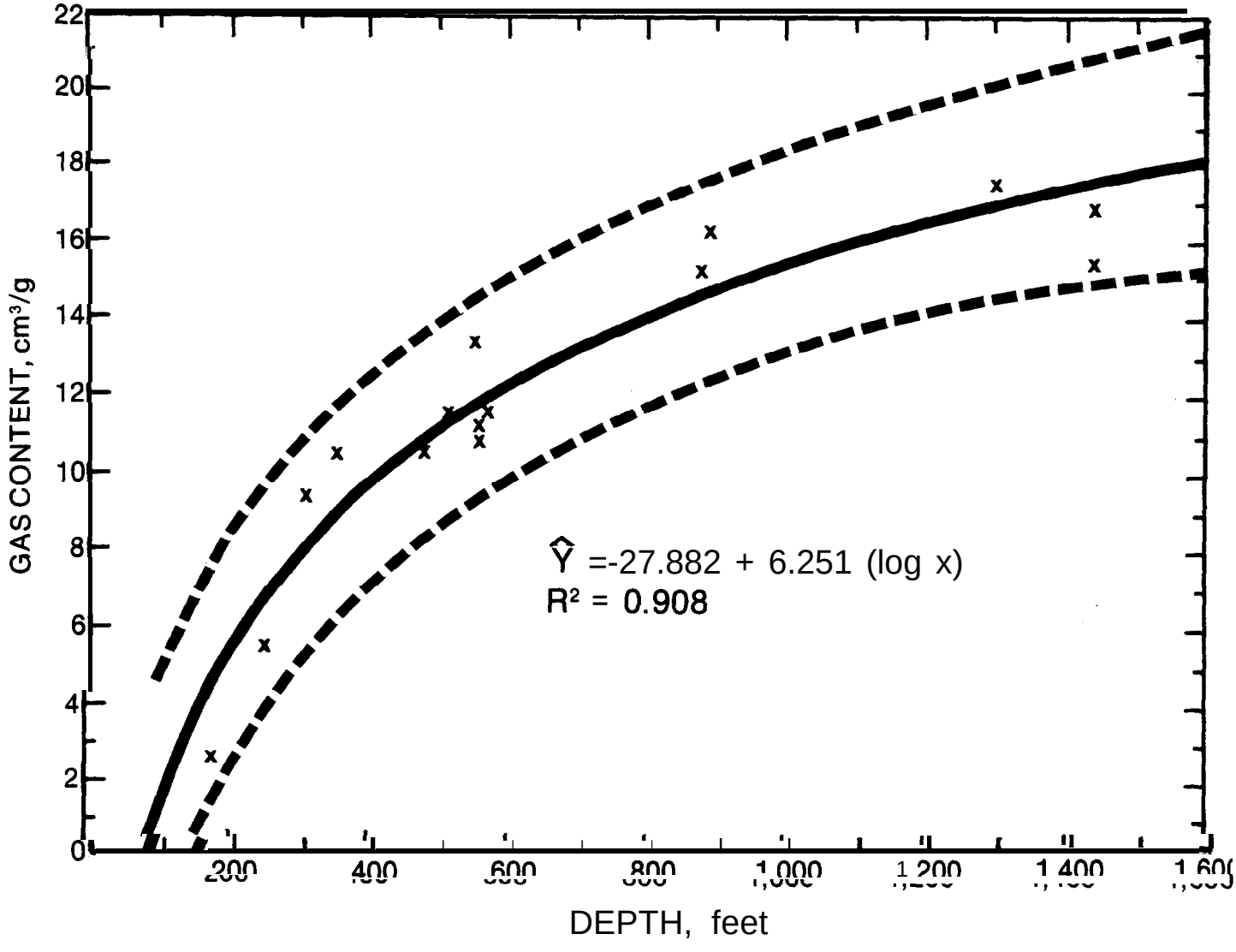
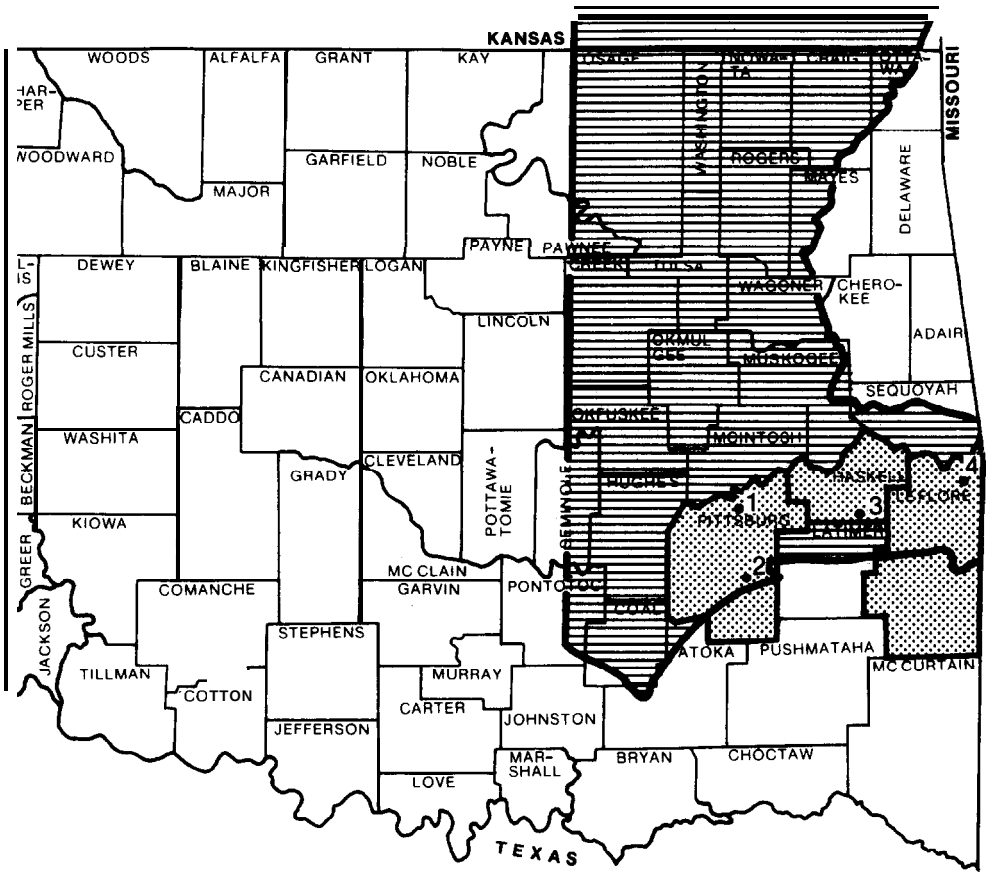


Figure 5-3 Graph Showing Changes in Gas Content of the Hartshorne Coalbed with Changes in Depth (lannacchione and Puglio, 1979, p. 10).



1 – Brown Estate Number l-2
2 – Barringer Number l-11
3 – Day Number 1-14
4 – DH-A17

Figure 5-4 MRCP Well Locations in the Arkoma Basin.

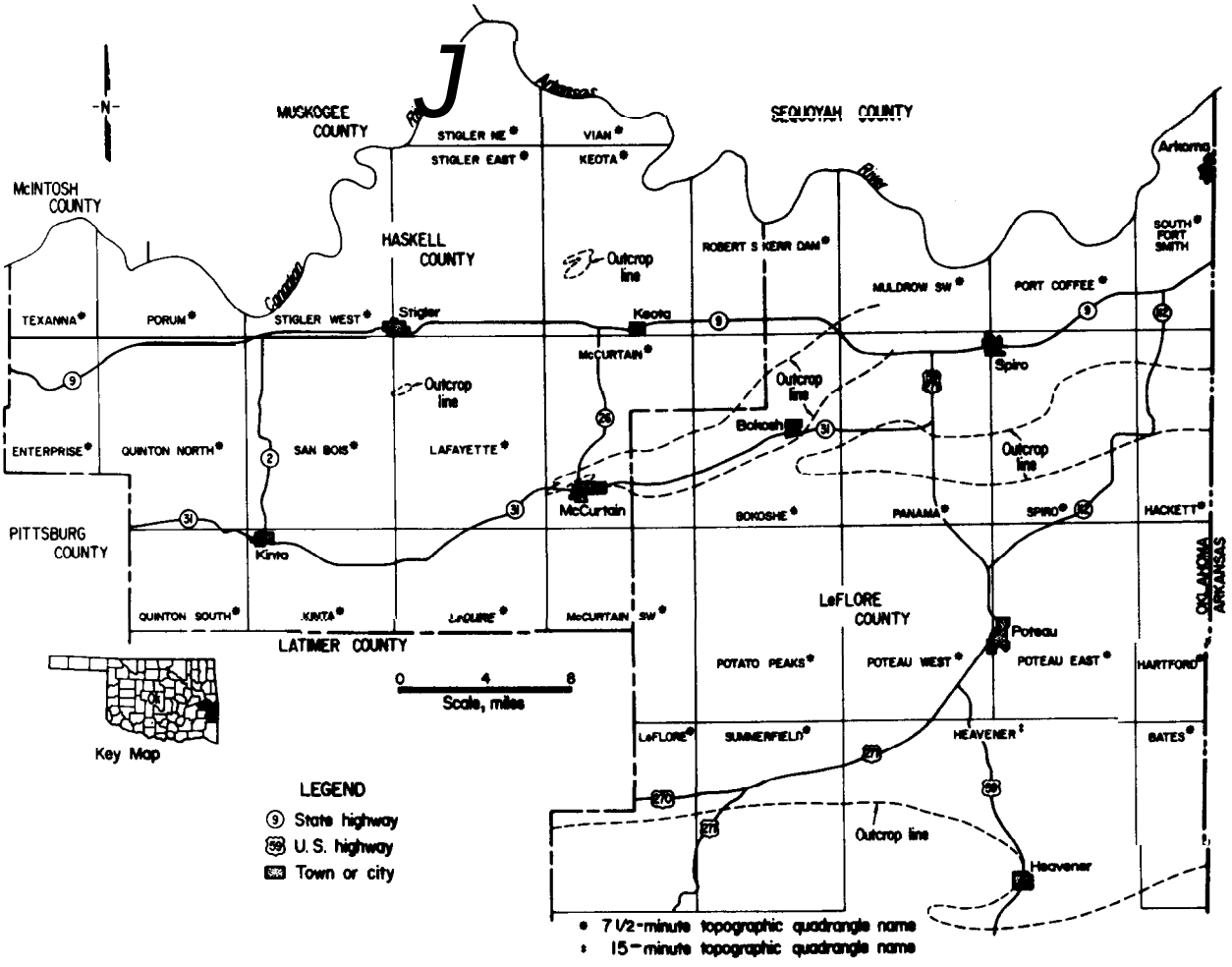


Figure 5-5 Location Map of Study Area Showing Topographic Quadrangles, Towns, and Major Roads (After Iannacchione and Puglio, 1980).

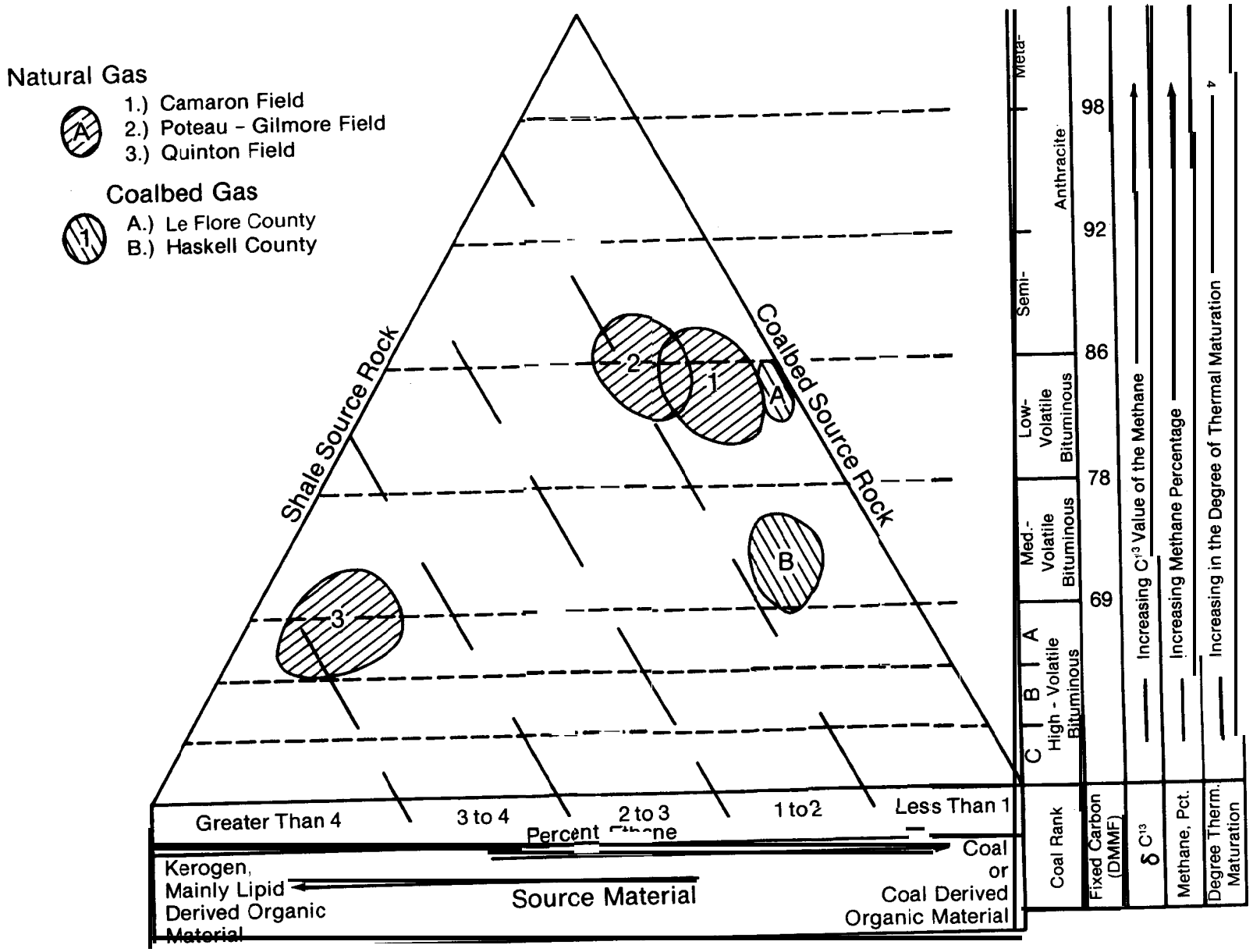


Figure 5-6 Gas Source Diagram Showing the Relation of Natural Gas and Coalbed Gas With Respect to the Gas Origin in the Arkoma Basin (Iannacchione and Puglio, 1980).

Table 5-l Distribution of Methane in the Hartshorne Coalbed (After lannacchione and Puglio, 1979).

	Metha	e Distribution,	Percent	
Overburden, Feet	Undivided Hartshorne	Upper Hartshorne	Lower Hartshorne	Total
0 - 500	8	15	9	9
500 - 1,000	31	28	23	27
1,000 - 1,500	38	24	24	31
1,500 - 2,000	18	14	22	19
2.000 - 3.000	6	19	22	4

Table 5-2 MRCP Methane Data From Coals Sampled in the Arkoma Basin of Oklahoma.

Coalbed	Thickness	Depth	Lost Gas cc/g	Desorbed Gas cc/g	Remaining Gas cc/g	Total Gas cc/g	Content ft^3/ton	Well
McAlester Coal (?)	2.0(?)	1905	1.407	2.683	Nil	4.09	131	Brown Estate Number 1-2
Booch Coal(?)	1.0(?)	2130	3.514	3.087	Nil	6.60	211	Brown Estate Number 1-2
Upper Hartshorne Coal	4.0(?)	2733	0.630	1.639	Nil	2.27	73	Brown Estate Number 1-2
Upper Booch Coal	1.0	3650	0.76	5.60	0.9	7.25	232	Barringer Number 1-11
Upper Hartshorne Coal	2.9	192	0.08	8.37	1.2	9.65	309	DH-A17

Table 5-3 Drill Stem Test Data, Upper Hartshorne Coal, Arkla Well, Brown Estate Number 1-2, Pittsburg County, Oklahoma.

Depth Internal: 2700 - 2740 Feet

Bottom Hole Temperature: 102° F

Description	Pressure (PSI)	Time (Minutes\
Initial Hydrostatic Mud	1437.9	
Initial Flow (1)	350.6	
Initial Flow (2)	361.0	6
Initial Shut-In	700.8	90
Final Flow (1)	370.5	
Final Flow (2)	377.1	31
Final Shut-In	678.1	120
Final Hydrostatic Mud	1616.1	

Table 5-4 Methane Content Versus Overburden, Haskell and Le Flore Counties, Oklahoma (Iannacchione and Puglio, 1979).

	Average Methane Content		Estimated Methane Content, Ft^3		
Overburden, Feet	Cc/g	Ft^3/Ton	Undivided Hartshorne	Upper Hartshorne	Lower Hartshorne
0 - 500	6.6	211	Min 32×10^9 Max 47×10^9	Min 26×10^9 Max 37×10^9	Min 37×10^9 Max 50×10^9
500 - 1,000	13.5	432	Min 159×10^9 Max 210×10^9	Min 47×10^9 Max 71×10^9	Min 99×10^9 Max 125×10^9
1,000 - 1,500	16.7	534	Min 195×10^9 Max 253×10^9	Min 40×10^9 Max 64×10^9	Min 106×10^9 Max 135×10^9
1,500 - 2,000	18.8	602	Min 95×10^9 Max 123×10^9	Min 23×10^9 Max 36×10^9	Min 96×10^9 Max 119×10^9
2,000 - 3,000	21.0	672	Min 33×10^9 Max 41×10^9	Min 32×10^9 Max 51×10^9	Min 95×10^9 Max 119×10^9

Table 5-5 Total Hartshorne Coal in-Place, Haskell and Le Flore Counties, Oklahoma (lannacchione and Puglio, 1979).

Overburden. Feet	Hartshorne (Undivided)	Millions of Short Tons		Percent of Total Coal
		Upper Hartshorne	Lower Hartshorne	
0 - 500	Min 149 Max 221	Min 122 Max 178	Min 174 Max 238	19
500 - 1,000	Min 368 Max 487	Min 108 Max 165	Min 228 Max 290	29
1,000 - 1,500	Min 365 Max 475	Min 76 Max 120	Min 198 Max 252	27
1,500 - 2,000	Min 158 Max 204	Min 37 Max 60	Min 160 Max 198	15
2,000 - 3,000	Max 49 Max 61	Min 48 Max 75	Min 141 Max 176	10
Total	Min 1,089 Max 1.448	Min 391 Max 598	Min 901 Max 1.154	100

Table 5-6 Total Remaining Bituminous Coal and Coalbed Methane on a County Basis, Arkoma Basin, in Arkansas and Oklahoma.

County	State	Remaining Coal 1,000 Short Tons	Average Gas Content BCF 200 cf/ton (6.25 cc/g)	Average Gas Content BCF 450 cf/ton (14 cc/g)
Atoka	Oklahoma[1]	29,619	5.92	13.33
Coal		292,875	58.58	131.79
Haskell		1,513,681	302.74	681.16
Hughes		Not Known	—	—
Latimer		841,968	168.39	378.89
LeFlore		1,973,362	394.67	888.01
Muskogee		61,199	12.24	27.53
Pittsburg		1,383,832	276.77	622.72
Sequoyah		27,146	5.43	12.22
Subtotal	Oklahoma	6,123,682	1,224.74	2,755.65
Crawford	Arkansas[2]	289,900	57.98	130.46
Franklin		212,400	42.48	95.58
Johnson		59,400	11.88	26.73
Logan		41,400	8.28	18.63
Scott		104,200	20.84	46.89
Sebastian		1,063,000	212.60	478.35
Subtotal	Arkansas	1,770,300	354.06	796.29
Total	Arkoma Basin	7,893,982	1,578.80	3,552.29

[1]As of January 1, 1974.
[2]As of January 1, 1977.

Table 5-8 Gas Sample Analysis From the Hartshorne Formation (Moore, 1977).

STATE	OKLAHOMA		OKLAHOMA		OKLAHOMA		
COUNTY	COAL		PITTSBURG		PITTSBURG		
FIELD	ASHLAND S		ASHLAND S		FEATHERSTON NW		
WELL NAME	SMALLEY NO. 1-12		LANE NO. I-28		KOBERTS NO. 1		
LOCATION	SEC. 12, T.3N.. R.11E.		SEC. 28, T.4N., R.12E.		SEC. 3, T.7N., R.17E.		
OWNER	CONTINENTAL OIL CO.		CONTINENTAL OIL CO.		POTTS STEPHENSON EXPL. CO.		
COMPLETED	NOT GIVERN		09/02/76		05/26/76		
SAMPLED	09/30/76		12/11/76		10/12/76		
FORMATION	PENN-HARTSHORNE		PENN-HARTSHOKNE		PENN-HARTSHORNE		
GEOLOGIC PROVINCE CODE	345		345		345		
DEPTH, FEET	3320		3401		2502		
WELLHEAD PRESSURE, PSIG	500		495		585		
OPEN FLOW, MCFD	5300		4200		6900		
COMPONENT, MOLE PCT							
METHANE	85.4		91.2		94.6		
ETHANE..	3.1		3.6		3.8		
PROPANE	%		1.7		0.7		
N-BUTANE	0.4		0.4		0.1		
ISOBUTANE	0.2		0.3		TRACE		
N-PENTANE	0.1		TRACE		0.0		
ISOPENTANE	0.1		0.1		0.1		
CYCLOPENTANE	TRACE		TRACE		TRACE		
HEXANES PLUS	0.1		TRACE		TRACE		
OXYGEN	0.3		TRACE		TRACE		
ARGON	0.1		TRACE		TRACE		
HYDROGEN	0.0		0.0		0.0		
HYDROGEN SULFIDE”	0.0		0.0		0.0		
CARBON DIOXIDE	0.3		0.4		TRACE		
HELIUM	0.12		0.13		0.04		
HEATING VALUE*.	993		1060		1052		

*Calculated Gross Btu Cu Ft, Dry, at 60 Degrees Fahrenheit and 30 Inches of Mercury.

**Due to the Absorption of H_2S During Sampling, the Reported Results May Not Be Reliable

Table 5-9 Composition of Natural Gas From the Hartshorne Sandstone in Haskell and Le Flore Counties, Oklahoma (Iannacchione and Puglio, 1980).

Location	Well No.	δC^{13} Methane Per Mil	Percent						Rank of Coal Associated With Gasfield
			Methane	Ethane	Propane	Butane	CO^2	O^2+N	
Camaron Gasfield	C-1	-35	95.85	0.41	0.02	1400 ppm	0.08	2.90	Low-Volatile Bituminous to Semianthracite
	C-2	-34	98.20	0.61	0.04	2000 ppm	1.00	0.11	
	C-3	-35	89.15	0.61	0.05	1800 ppm	0.77	9.40	
Poteau-Gilmore Gasfield	PG-1	-36	98.00	0.75	0.03	5000 ppm	0.87	0.27	Semianthracite Coal
	PG-2	-36	94.50	1.10	0.06	1000 ppm	0.44	3.83	
	PG-3	-36	98.15	1.10	0.07	8000 ppm	0.45	0.13	
Quinton	Q-1	-43	92.85	5.15	0.52	0.16	1.00	0.23	High-Volatile A to Medium-Volatile Bituminous Coal
	Q-2	-43	93.35	4.85	0.83	0.22	0.44	0.24	
	Q-3	-42	94.85	3.50	0.61	0.14	0.53	0.31	

1/ = Ppm, Parts Per Million.

Table 5-10 Chemical Composition of Hartshorne Coalbed Gas (Iannacchione and Puglio, 1980).

Location	Well No.	δC^{13} Content Per Mil	Percent				Rank of Coal
			Methane	Heavier Hydrocarbon&/	CO^2	O^2+N	
Horizontal Degasification System, Choctaw Mine, Haskell County	HC-1	-44	97.65	0.05	1.5	0.36	Medium-Volatile Bituminous Coal
	HC-2	-44	97.75	.49	1.6	.18	
	HC-3	2/ND	97.80	.50	1.5	.19	
	HC-4	-43	97.40	.81	1.6	.18	
	HC-5	-44	97.35	.86	1.6	.19	
	HC-6	-43	97.85	.50	1.2	.44	
	HC-7	-43	97.35	.85	1.6	.20	
	HC-8	-45	94.20	4.21	1.3	.28	
Coal Core, LeFlore County	HC-9	ND	98.50	0.07	0.08	1.35	Low-Volatile Bituminous coal
	HC-10	ND	99.25	.02	.10	0.63	

1/ Predominately Ethane With Small Amounts of Propane and Butane.
2/ Not Determined.

6. CONCLUSIONS AND RECOMMENDATIONS

Although the methane data are derived from a relatively small data base, it appears that the methane content of the coalbeds in the Arkoma Basin is low to moderate (73-211 cubic feet per ton) in the northwest subshelf area, moderate to high (200-700 cubic feet per ton) in the central trough, and unknown in Arkansas. There appears to be a general increase in the gas content within the trough portion of the basin towards the east.

6.1 EXPLORATION CRITERIA

Data worldwide tend to indicate that petroleum and natural gas generation and entrapment are enhanced in basins of high heat flow. Iannacchione and Puglio (1980) worked on the premise that the methane gas was generated with increased thermal maturation (coalification). Kim (1978) pointed out that the gas content of a coalbed depends primarily upon rank, temperature and pressure. However, it must be noted that coals of the same rank may exhibit a 10,000-fold difference in gas content (Kim, 1978). This is an indication that present gas content of a coalbed is related not only to gas formation during coalification but also to the post-deposition geologic history of the coalbed. The degree of fracturing, distance to outcrop, depositional environment, depth of burial, bed thickness, rate of burial, and the permeability of adjacent strata could be important. Keeping this information in mind, the following criteria were developed for use in redefining areas with the greatest potential methane resource. Reference is made to Isocarb Results (Section 4.2.2.1).

- Thick coalbeds have higher methane contents.
- Higher the coal rank, greater the amount of thermally generated methane present in the coalbed.
- Lower the fixed carbon values for bituminous coal, higher the remaining methane content in the Arkoma Basin coalbeds.
- Fixed carbon values in the Arkoma Basin coals are related to structural deformation.
- Coals in anticlines have a higher percentage of fixed carbon than those in adjacent synclines.
- Anticlines in the basin are narrower than the synclines, indicating more deformation.

- More deformation - more fractures - more gas loss to surrounding sediments.
- Anticlines occupy approximately 35 percent of the total basin area.
- Synclines occupy 65 percent of the total basin area.
- Methane content in the Hartshorne coalbeds increases with depth of burial.
- Thick Hartshorne sand development -- thin lower Hartshorne coalbed.
- Optimum conditions - Look for:
  - Broad synclines
  - Thick coalbeds
  - Deeply buried coalbeds
  - Rank greater than Hvab; less than anthracite.

6.2 REDEFINED TARGETS

The target areas which best meet these criteria are given in Figure 6-l.

Recommendations for completing the delineation of the Arkoma coalbed methane resource base area are:

- Type I tests:
  - Cavanal syncline (Le Flore County, Oklahoma)
  - Cavanal syncline (Sebastian County, Arkansas)
  - Lehigh syncline (Coal County, Oklahoma)
- Type III tests:
  - Kiowa syncline (Pittsburg County, Oklahoma; Barringer No. 1-11 well)
  - Sanbois syncline (Haskell County, Oklahoma; Day No. 1-14 well)
  - Cavanal or Lehigh syncline are needed

The Cavanal syncline is the largest single structural feature in the Arkoma Basin (Disney, 1960). This syncline runs from Latimer County, Oklahoma into the eastern part of Sebastian County, dying out at the Sebastian-Logan boundary. The Hartshorne coals lie deeper than 6,000 feet at the center of the syncline in Le Flore County. Other coalbeds also would be available for testing, such as the Secor, Lower Witteville, Cavanal, and McAlester coalbeds. The exact nature of these coals in the

syncline is unknown. Both areas in Le Flore County, Oklahoma and Sebastian County, Oklahoma should receive high priority. Methane desorption data from the USBM indicates high methane contents, up to 700 cubic feet/ton, for the Hartshorne coals in Le Flore County.

Thick (>28 inches) Lower Hartshorne coal in Sebastian County coupled with no methane desorption data makes this area one of interest. The beds are buried at depths greater than 1,000 feet.

The Lehigh syncline lies south and east of the Coalgate anticline and is bounded on the east by the northeastward-trending belt of steeply inclined Pennsylvanian strata that lies adjacent to the Choctaw fault in Coal and Atoka Counties, Oklahoma. The main axis of the syncline extends from a point near the southern boundary of Coal County northeastward into the McAlester District. From the main axis a minor synclinal axis branches northwestward and dies out near Coalgate, south of the Phillips fault, which cuts the Coalgate anticline near its south end; and around the southern and eastern margins of the syncline, the surface beds involved include all the formations from the Atoka Formation to the Boggy Shale. The McAlester coalbed (3 to 5 feet thick) lies at depths of about 2,200 feet, whereas the Hartshorne coals lie approximately 700 feet below the McAlester coal (up to 4 feet thick). This area should receive priority in testing because of its favorable geological setting, meeting the defined exploration criteria, and because there are no data existing on the methane gas content of the coals in this part of the Arkoma Basin. It is recommended that core samples be obtained from the McAlester and Hartshorne coalbeds.

The first Type III test is scheduled early 1980 for the Barringer No. 1-11 well in Pittsburg County, Oklahoma. If this test is successful then the Day well in Haskell County, Oklahoma should be the next candidate for a Type III test. Additional Type III testing should be planned for any of the proposed Type I test as described above, if these tests are successful.

The redefined target area covers about 3,600 square miles.

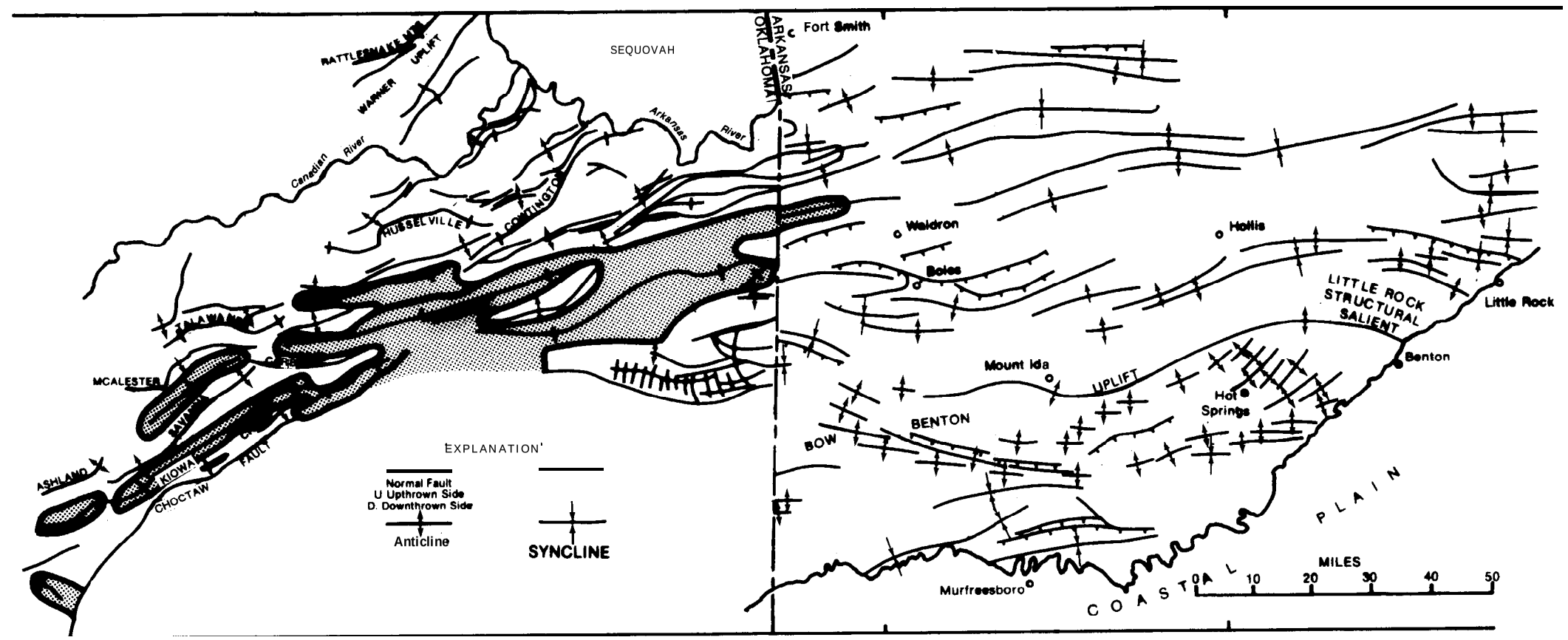


Figure 6-1. Redefined Target Areas in the Arkoma Basin.

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APPENDIX A

ENCLOSURES

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ENCLOSURES

C-l	Water-Resource Investigations in Arkansas, 1977
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