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**INVESTIGATION OF THE COAL PROPERTIES AND  
THE POTENTIAL FOR COAL-BED METHANE  
IN THE FOREST CITY BASIN**

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

## ABSTRACT

The Forest City basin in Missouri, Kansas, Iowa, and Nebraska, contains substantial coal resources in numerous beds too deep and thin to be mined by conventional methods. However, these coal beds have the potential to produce commercial quantities of coalbed methane. The four State geological surveys of Missouri, Kansas, Iowa, and Nebraska, and the U.S. Geological Survey conducted a preliminary assessment of existing geologic data to determine the thickness and areal extent of deep coals in parts of the Forest City basin. In addition, coal quality, thermal maturity (rank), and coalbed methane composition analyses were performed on some of the coal beds where good-quality coal samples could be obtained.

Methane desorption and composition analyses performed on 11 coal beds from Kansas and Missouri confirm that coalbed methane is indeed present in coal beds of the Forest City basin. Although the volume of that coalbed methane is still unknown, the amount of methane in those areas tested during the current study is sufficient to warrant additional investigations. Reports of excessive methane occurrence in abandoned underground coal mines in Missouri may suggest that greater quantities of coalbed methane may be present at other localities in the basin.

A coalbed methane industry within the Forest City basin would be an energy resource of great economic value to the four States. Cost-benefit analyses for Missouri alone indicate that, in a best-case scenario, an industry the size of that currently operating in the Black Warrior basin of Alabama (an industry that has produced 23.4 billion cubic feet of gas from 910 wells and 590 new jobs) would generate \$74 million annually in economic benefits to the State of Missouri from business and industry, increased personal income, and local and State government revenue. Even the most conservative scenario would generate over \$4 million annually to Missouri's economy and \$2.5 million in benefits to business and industry. The revenue generated in each of the four States would be primarily in underdeveloped rural regions. The results of the current investigation would provide citizens and local governments in these areas with the information necessary to make sensible determinations relative to the benefits of exploring and developing coalbed gas.

## INTRODUCTION

During the past four years, the State geological surveys of Missouri, Kansas, Iowa, and Nebraska have received numerous inquiries from out-of-state coalbed methane producers requesting geological and analytical data on the deep coal beds in the Forest City basin and the potential for commercial production of coalbed methane. During that period, insufficient geological data and little coal quality or rank data were available on the deep coal beds to accurately assess the potential for coalbed methane in the four-State region of the basin. Most of the coal-related research in the basin had been conducted on near-surface-minable coal reserves close to the perimeter of the basin, and the deeper parts of the basin had not been explored.

These requests from industry stimulated concurrent inquiries from interested parties such as landowners, electric utility companies, local and State officials, and environmental regulatory agencies on potential issues such as new clean energy sources, mineral lease rights, economic benefits to local and State economies, and possible adverse effects on the environment from commercial-scale production of coalbed methane. To respond to these requests and concerns, the four State geological surveys and the U.S. Geological Survey conducted a preliminary assessment of existing geological data to determine the thickness and areal extent of deep coals in parts of the basin. In addition, coal quality, thermal maturity (rank), and coalbed methane composition analyses were performed on some of the coal beds where good-quality coal samples could be obtained.

The Forest City basin is a geologic subsurface structure that underlies northwestern Missouri, northeastern Kansas, southwestern Iowa, and southeastern Nebraska (fig. 1), approximately 46,400 sq mi, and has potential for commercial quantities of coalbed methane. Coalbed methane is a clean-burning fuel often found in economic quantities in coal beds of many ranks (thermal maturities). The methane produced within coal beds is a byproduct of the coalification process in which plant material is converted to coal; much of the coalbed gas generated during this process is retained within the coal matrix. Although minor differences in geologic conditions alter production methods, coalbed methane can be produced, used, and transported in a manner similar to that in which natural gas is produced, used, and transported from conventional gas and petroleum fields. Large quantities of coalbed methane

are currently being produced from coal beds in the San Juan basin of Colorado and New Mexico and in the Black Warrior basin of Alabama (fig. 1).

The Forest City basin contains a substantial amount of coal resources in numerous beds too deep and thin to be mined by conventional methods. Coalbed methane producers operating in other parts of the United States have overlooked the Forest City basin in their previous exploration efforts because of the lack of geological data on the extent, thickness, quality, and rank of the coal beds in the basin. If coalbed methane is found to be present in commercial quantities in the basin, these deep coal beds would represent a vast, untapped energy source.

This report contains the results of a preliminary assessment of the coal resource and coalbed methane potential in the Forest City basin. Coal beds were evaluated at 10 localities in the basin for thickness, areal distribution, and depth of burial. Samples of a number of the deep coal beds were collected and analyzed for geochemical composition, quality, thermal maturity (rank), gas content, and gas composition. This project is a cooperative effort between the Missouri Department of Natural Resources, Division of Geology and Land Survey; the Kansas Geological Survey; the Iowa Department of Natural Resources, Geological Survey Bureau; the Nebraska Geological Survey; and the U.S. Geological Survey.

## GEOLOGIC SETTING OF COAL-BEARING ROCK SEQUENCES

The Forest City basin is a cratonic basin of Pennsylvanian age underlying adjoining portions of southwestern Iowa, southeastern Nebraska, and northwestern Missouri (figs. 1, 2). The deepest part of the basin is in northeastern Kansas, where the depth of the basement is ???. In this study, the basin's areal limits in each State have been modified from previous work to include important geologic information on the coal-bearing rock sequences at the perimeter of the basin (fig. 2). In Iowa, the edge of the basin is defined as the outcrop/subcrop edge of the Pennsylvanian System strata. In Missouri, the edge of the basin coincides with the 300-ft-thickness isopach line of Pennsylvanian strata. The southern boundary of the basin in Kansas and Missouri is the Bourbon Arch. The western edge of the basin in Kansas and Nebraska is the Humboldt fault zone, which forms the eastern boundary of the Nemaha Uplift.

Coal beds in the Forest City basin are present in two major stratigraphic units, the Atokan and Desmoinesian Series. In ascending order, the coal-bearing units are the Riverton Formation (terminology restricted to Missouri) and the Cherokee, Marmaton, and Pleasanton Groups. In Iowa, the Pleasanton is accorded formation status and is assigned to the Bronson Group. In this study, the top of the coal-bearing geologic rocks is defined as the base of the Hertha Limestone of the Kansas City Group. Coal-bearing sequences consist predominantly of shale and sandstone and subordinate amounts of limestone and coal. The base of the sequence is carbonate rock of Mississippian age. The combined thickness of the coal-bearing units in the basin ranges from the eroded edge of the lower Pennsylvanian rocks on the northern and eastern edges of the basin to a maximum thickness of approximately 900-1,000 ft in southwestern Iowa. Along the axis of the basin in northeastern Kansas and northwestern Missouri, the combined thickness exceeds 1,000 ft (Anderson and Wells, 1968, p. 274).

#### GEOLOGIC CHARACTERISTICS OF COAL BEDS IN THE FOREST CITY BASIN

A large number of coal beds are recognized in the surface and subsurface in all four States. Over 25 different coal beds have been recognized in Kansas and Iowa, 17 coal beds have been found in Nebraska, and nearly 40 coal beds in Missouri. In all four States, most of the coal beds are present within the Cherokee Group, and near the perimeter of the basin in Iowa, Kansas, and Missouri several of the coal beds have been mined by conventional methods.

Two of the most important characteristics of the coal beds in the four-State area are their widespread distribution and their persistent thickness which indicate that broad regions in the basin are underlain by coal. In ascending order, coal beds correlated across State boundaries are: the Riverton, Weir-Pittsburg, Mineral, Scammon, Fleming, Tebo, Croweburg (Whitebreast in Iowa), Bevier (Wheeler in Missouri), Summit, Mulky, Mystic (Lexington in Missouri), and Mulberry.

This study evaluated the geologic characteristics of deep coal beds at 10 localities in the basin (figs. 2 - 12). At least 16 individual coal beds were identified from drill core, well cuttings, and geophysical logs. The cumulative thickness of coal beds in individual drill holes ranged

from 8.3 ft in Clay County, Missouri to 22 ft in Iowa. Individual coal beds have thicknesses of up to 6 ft in Iowa, 5 ft at several localities in Kansas, and as much as 10 ft in one locality in Missouri. On the basis of core holes described in this study, however, most of the coal beds are less than 2 ft thick. At single localities, multiple coal beds having thicknesses of 1 to 2 ft may provide good targets for development of coalbed methane.

A core test drilled by the Kansas Geological Survey (KGS Edmonds #1A) (fig. 2) in Leavenworth County penetrated 13 coal beds in the Cherokee Group (figs. 3, 4). Total thickness of the coals is 10.9 ft; 5 of the 13 coal beds exceed 1 ft in thickness (fig. 4). The thickest coal bed is the Riverton (Kansas term), which is 2.1 ft thick (fig. 4). In the Anadarko Petroleum Co. Chapple "A" #1 well in Doniphan County, Kansas, (fig. 5), 5 coal beds ranging from 1.7 to 4.5 ft in thickness occur within a 150-ft thick interval at depths of 1,500 to 1,650 ft. The Alco Rubick #1 well in Franklin County, Kansas (fig. 6), on the southern side of the basin, penetrated 6 coal beds with cumulative thickness of 10 ft; between the depths of 1,120 and 1,220 ft, 8 ft of coal is present in five different coal beds.

The Iowa Geological Survey core test (IGS CP78) (figs. 2, 7) penetrated 15 coal beds, providing a complete representation of all the identified coal beds in the lower Marmaton and Cherokee Groups in that area. Coal bed thicknesses in that well range from less than 1.0 to 1.9 ft; cumulative thickness is 11.7 ft. Several of the coal beds are known to be thicker a few miles from the core-hole locality. Detailed studies of the geophysical logs from the Miller #1 oil test in Montgomery County, Iowa, showed 16 coal beds ranging in thickness from less than 1 to 5 ft and a cumulative thickness of approximately 22 ft (fig. 7). In the deepest part of the basin in southwestern Iowa, where strata of the Cherokee Group are thickest, insufficient data are available to determine the areal extent of the coal beds; however, the character of the coal beds and associated strata at the edge of the basin suggests a good potential for coal resources in the deeper portion of the basin.

Nine coal beds were identified in the gamma-ray log of the Big "J" Oil Co., No. 5 Sibbernson well in Richardson County, Nebraska (fig. 8). A preliminary examination of geophysical well logs from 38 other drill holes indicate that coal beds may be present at similar horizons in the Nebraska part of the basin and are most likely continuous across that part of the basin.

However, no subsurface data are available to determine the thickness of the coal beds or to correlate individual beds with those in adjacent States.

Drill core acquired by the Missouri Department of Natural Resources' Division of Geology and Land Survey in the deeper part of the basin in Atchison County, Missouri (WM-4, figs. 2, 9), contain 16 coal beds having a cumulative thickness of 14.2 ft at depths of 1,050 to 1,800 ft. Six of the coals are more than 1 ft thick. The Mineral coal bed, at 2.4 ft, is the thickest coal present. Most of these coal beds are also present in the WM-5 core in Nodaway County, Missouri (fig. 10). In WM-5, 15 coal beds have a cumulative thickness of 12.9 ft. The thickest coal beds are the Weir-Pittsburg (2.0 ft) and the Mulberry (1.8 ft).

In Missouri, in the south-central part of the basin, seven coal beds were penetrated in the MGS No. 22018 core hole in Clay County (figs. 2, 11). At this location, the Lexington coal bed (Mystic coal of Iowa) is the thickest at 2.9 ft. The cumulative thickness of the coal beds is 8.3 ft. This core hole did not penetrate the base of the Pennsylvanian strata, which lies at approximately 750 ft below the surface, therefore, no data are available on the lower Cherokee and Riverton coal beds.

In Cass County, Missouri, eight coal beds were penetrated in the Landmark Production; Smith No. 1 well (figs. 2, 12). The cumulative thickness of the coal beds in this well is 12.1 ft, six of the coals attain individual thicknesses of 1 to 3 ft. The Mulberry coal bed is 3 ft thick at this locality.

## POTENTIAL FOR COALBED METHANE

### *Current Investigations*

The Leavenworth County core hole (KGS Edmonds #1A) (figs. 2, 4) was drilled through Pennsylvanian rocks into the top of Mississippian carbonates (base of the coal-bearing sequence) to determine the thickness of the coal beds and to determine the amounts of methane that might be present in the coal beds. Thirteen coal beds in the Cherokee Group were penetrated in the core hole. The total thickness of the coal beds was 10.9 ft; five coal beds exceeded 1 ft in thickness. The thickest coal is the Riverton coal bed (Kansas

terminology) which has a total thickness of 2.1 ft. The thickness of the coals and the intervals sampled are shown in figure 4. The Leavenworth core hole, however, was not in an optimal locality in the basin for potential maximum methane yield. Limitations of the drill equipment and the convenience of the site dictated the selection of that drill location. Thicker coal beds are known at several other localities [five coal beds ranging from 1.7 to 4.5 ft thick in a 150-ft interval (1,500 - 1,650 ft) in the Anadarko Petroleum Co., Chapple "A" #1 well (fig. 5) in Doniphan County, Kansas], and future cores should include thicker coal intervals.

Measurements of gas desorbed from the coal core samples of the Leavenworth County core hole show gas content values of 21 to 94 ft<sup>3</sup> per ton of coal (table 1). These values were calculated on an ash-free basis following the U.S. Bureau of Mines methodology. However, the methane content would be greater if the values were calculated on a moisture- and ash-free basis. In general, the coals having the higher gas contents are located at greater depths in this core hole (table 1). The Riverton coal bed appears to have the best potential for development at this locality.

After the gas was desorbed, the crushed coal samples and desorbed gas were sent to U.S. Geological Survey laboratories for chemical analyses and gas compositional analyses. Analysis of the gas content of the Riverton coal samples showed a methane content of 96 to 97 percent (table 2). Other coals tested showed methane contents ranging from 72 to 93 percent (table 2). One sample (1 Edmonds 4) contained large amounts of ethane (11 percent) (table 2). Drill-core samples of two coal beds were obtained from active drilling in southwestern Cass County, Missouri in March 1992 and submitted for gas analysis as well. The composition of gases from these coal beds showed high percentages of methane (table 2).

Two main processes produce coalbed gas: 1) biogenic and 2) thermogenic. Biogenic gas is generated in the early stages of coalification by the degradation of organic matter through a complex series of bacterial processes (Rice and others, in press). The isotope values ( $\delta^{13}\text{C}$ ) of biogenic methane are generally in the range of -55 to -90‰ (Rice and others, in press). Although biogenic gas is most often associated with low-rank coals, (lignite to hvCb), it can, in some cases, be generated from high-rank coals. Thermogenic gas, on the other hand, is



produced in association with the increased temperatures and pressures. Thermogenic gas begins forming at approximately high volatile C bituminous rank ( $R_o$  0.6 percent) and is isotopically heavier than biogenic methane (Rice and others, in press). Thermogenic gases contain methane but also contain heavier hydrocarbons in the form of ethane, propane, and butane. The isotope ( $\delta^{13}C$ ) values of thermogenic methane are heavier than -55‰ and the isotope values of ethane are heavier than -33‰ (Rice and others, in press). The isotopic compositions of the methane from samples in this study are found in table 2. Unfortunately, isotope values for the heavier hydrocarbons (ethane and pentane) present in these coal beds (table 2) were unobtainable.

In addition to the isotopic analyses (table 2), samples of coal beds from Missouri, Kansas, and Iowa were submitted for a variety of rank-determining analyses. Ultimate and proximate analyses were performed on 10 coal samples from Iowa, 10 coal samples from Kansas, and 5 coal samples from Missouri. The gross calorific value (on a moist, mineral-matter-free basis) was calculated according to American Society for Testing and Materials (1992) standards. In addition, vitrinite reflectance (mean maximum reflectance) analyses were performed on the 5 Missouri and 10 Kansas samples. The results of all these analyses are found in table 3.

Study of the proximate analyses of the coal samples obtained from coal beds in this study indicate apparent coal ranks ranging from high volatile C to high volatile A bituminous (with two exceptions in Iowa). In Kansas, ranks range only from high volatile B bituminous for the stratigraphically higher coal beds to high volatile A bituminous for coal beds below a depth of approximately 950 ft. The values determined in the proximate analyses of the core samples from Kansas compare favorably with the proximate values of Bevier coal mined at the Kansas Penitentiary Mine at Lansing, Kansas. This mine was located approximately 5 miles northeast of the KGS Edmonds #1 core. Coal beds farther to the west in the Kansas and Nebraska portion of the basin might have higher ranks because of greater burial depths and the influence of large-scale geologic structures that might have resulted in higher heat flow and higher coal ranks.

Another determination that measures rank is vitrinite reflectance ( $R_o$ ) (table 3). The vitrinite

reflectance values also indicate a range in rank from high volatile C to high volatile A. However, the reflectance values are not as high as calculated calorific values suggest they should be, possibly because of vitrinite reflectance suppression. There are several possible causes of reflectance suppression, but the most likely is the unusually high sulfur content of the coal (table 3), especially if the sulfur is in the form of pyrite.

The rank of the coal determined in this study is in agreement with previous studies conducted on coal beds in Iowa by Hatch and others (1984). These authors reported apparent ranks of high volatile C bituminous with a mean calorific value of 12,040 BTU/lb (recalculated to moist, mineral-matter-free basis) for 90 coal samples from drill cores and coal mines located in southeastern and south-central Iowa. The depths of the coal beds sampled ranged from a few feet to a maximum of 483 ft. Coal beds in the deeper parts of the basin in southwestern Iowa were not analyzed. In Missouri, 113 coal samples from 13 coal beds in 5 districts were collected from active surface mines (Wedge and Hatch, 1980). In general, apparent rank increases in Missouri from high-volatile C in the north-central part of the State to high-volatile A bituminous in southwestern Missouri. Calorific values (moist, mineral-matter-free basis) ranged from 11,250 BTU/lb in north-central Missouri to 15,250 BTU/lb in the southwestern part of the State. Depth of the coal beds sampled ranged from 40 to 90 ft.

In general, coalbed gas content increases with rank (Rice and others, in press). The large increase in the amount of coalbed gas between the ranks of subbituminous A and high volatile C is due mainly to the fact that thermal processes produce much more methane than the microbial processes operative at the lower ranks (REF). The ability to retain and store methane generated within a coal is also a function of rank (REF). Higher pressure within coal beds increases storage capacity whereas higher temperature decreases storage capacity. At the rank of medium volatile bituminous, for example, some coal beds may have generated more methane than they can store, and the methane may be expelled. Therefore, the rank of the coal beds studied here seems to be at an optimal level for coalbed methane production and storage.

In addition, it should be noted that, although rank is a promising indicator, a stronger

relationship exists between the quantity and composition of coalbed gas to depth (REF). Therefore, data must be obtained from the deeper parts of the Forest City basin to evaluate the potential for coalbed gas at depth.

Another aspect of coal quality is its relationship to conventional mining. The coal beds analyzed within this study, aside from being very thin and deep, are of poor quality. Coal that is mined conventionally is generally less than 15 percent ash and less than 4 percent sulfur. The ash values for these coal beds range from 6 to more than 35 percent, many being greater than 15 percent. The sulfur content is also quite variable, ranging from 3 to 14 percent. These coal beds, then, would be considered high-sulfur coal. The quality of these coal beds would hinder their use conventionally, mainly because of their ash yield and sulfur contents.

### *Historical Data*

No direct data are available from historical sources on the quality or quantity of coalbed methane from deep coal beds in the Forest City basin. However, historical reports by the Missouri State mine inspector of excessive methane and methane explosions in shallow underground coal mines may be an indication of coalbed methane in these areas. Several of these mine explosions occurred when the mine shafts were initially constructed; others occurred when the shafts penetrated coal beds lower than the principal beds mined.

Excessive methane and (or) mine explosions were reported in 13 coal mines in 5 counties in Missouri during the period from 1881 to 1905 (fig. 13, table 4). The deepest of these 13 coal beds (tentatively correlated as the Bevier) lies at a depth of 420 ft in southwestern Clay County. Excessive methane was reported in the Mineral coal bed, which was mined near Rich Hill in southwestern Bates County. These mines lie on the southwestern flank of the Schell City-Rich Hill anticline, where the coal beds have been distorted by structural movement (Gentile, 1976). Migration of methane along structural features such as this one may have contributed to the excessive methane reported in the mines.

In Iowa, a few mines were reported to have had problems with carbon dioxide, but only one

mine was reported to have had problems with methane (Lemish and Palmquist, 1980). Iowa coal mines are relatively shallow, nearly all occurring less than 300 ft below the land surface (Iowa Department of Natural Resources Geographic Information System coal mine database). It is likely that methane generated in the coalification process was lost from these shallow coal beds. As a result, most of the coal mines that operated in Iowa were free of methane gas.

## STRUCTURAL GEOLOGY: POTENTIAL IMPACT ON COAL RANK

Numerous structural features that are present in the Forest City basin may have caused an increase in coal rank on a local and regional scale and may have implications for increased coalbed methane potential. Temperature plays an important role in the thermal maturity of coal. Coal rank, a measure of thermal maturity, increases with increasing temperature. One potential source of heat in the basin is structural movement that displaced coal-bearing geologic units to greater depths in the basin. Coal-quality data within this report are insufficient to determine whether these structural features had an impact on the thermal maturity of the coals. Additional study of coal quality in the vicinity of these structural features may indicate elevated coal rank in some parts of the basin.

Two major tectonic features in the basin are the Nemaha Uplift and the Thurman-Redfield structural zone. The Nemaha uplift involved rock units from Precambrian through Permian age. The main movement was post-Mississippian, but there have been earlier movements (Lee, 1943; Berendsen and Blair, 1986). The Nemaha uplift, with its eastern Humboldt fault zone, forms the western boundary of the Forest City basin in Kansas and Nebraska. Faulting was active before and after deposition of strata in the Cherokee group (Chelikowsky, 1972; Berendsen and Blair, 1986). The Thurman-Redfield structural zone, which underlies the deepest part of the basin in southwestern Iowa, is a horst and graben structure in the Precambrian basement rock. Evidence of movement is present well into the middle Pennsylvanian along the southeastern flank of the structural zone. Structural movement or increased heat flow along these two features may have generated sufficient heat over the geologic past to increase coal rank in parts of the Forest City basin.

In Missouri, a series of parallel anticlines, synclines, and faults lie in a northwest-southeast direction in the basin (McCracken, 1971). These features, which often displace coal-bearing geologic sequences in the subsurface, may have had the potential to increase coal rank on a local or regional scale. This trend appears to continue into Iowa, although it is less clearly defined because of a thick cover of glacial till and the paucity of useful data.

The Forest City basin, however, is relatively undeformed structurally. This fact is important because, by analogy, most of the coalbed methane in the United States is produced from basins that are relatively undeformed. In large part this is because complex folding and major deformation destroys the cleating system (natural fracture system) within the coal beds, thereby destroying the reservoir properties and reducing the production potential of coalbed methane. A coal-bearing basin must have been subjected to enough structural deformation to develop the cleat system within the coal, but not deformed enough to destroy this vital criterion to coalbed methane development.

#### DATA AVAILABLE FOR FUTURE INVESTIGATIONS

The large number of oil and gas tests that have been drilled in the Forest City basin are an important source of information for future investigations on the distribution and amount of coal resources in the basin. The most useful types of data for identifying, correlating, and estimating thickness of the coal beds are the gamma-ray-neutron logs and gamma-ray-density logs.

More than 1,000 gamma-ray-density logs have been logged to a minimum of 900 ft in Kansas. In addition, nearly 4,000 more oil and gas tests have had geophysical logs run to depths less than 900 ft or have had a log type other than the preferred logs mentioned above. There appears to be a good distribution of these deep gamma-ray-density and (or) gamma-ray-neutron logs in the Forest City basin. Approximately 5,000 wells of all types have been drilled in the basin in Missouri and about 600 wells have been drilled in the Nebraska portion of the basin, including geophysical logs run on 38 deep holes. In the Iowa portion of the Forest City basin, several hundred logs of all types have been run. Analysis of these logs should establish a better correlation of the coal beds in the basin and indicate areas of thicker

coal beds or combinations of thick coal beds. Such areas could provide potentially high methane volumes from either a single thick coal bed or from multiple-coal bed well completions.

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## CONCLUSIONS

1. Significant coal resources in the Forest City basin have the potential for commercial quantities of coalbed methane, although the volume is not yet known.
2. Methane content ranges from 72 to 97 percent by volume for gas in 11 coal beds sampled during this investigation (table 2). Nine of these coal samples were from the KGS Edmonds #1A core hole. The other two samples were from the Mulberry coal bed in Cass County, Missouri.
3. The amount of methane present in the nine Kansas coal beds sampled ranged from 21 to 94 ft<sup>3</sup> per ton of coal (table 1). The Riverton coal bed (Kansas terminology) contained the greatest amount of methane in the KGS Edmonds #1A core hole, Leavenworth County, Kansas where it was 2.1 ft thick. The Riverton is known to be thicker at other localities in the Kansas part of the basin.
4. In general, coalbed methane content increased with depth at the KGS Edmonds #1A core hole.

5. Several individual coal beds are widespread in distribution within the four States in the basin. Individual coal beds, in general, are less than 2 ft thick; however, coals as thick as 6 and 10 ft have been identified within the basin.
6. Multiple coal beds (typically 10 or more), 1 to 2 ft thick, are present in several of the drill cores studied during this investigation. Such localities would be suitable for simultaneous production of coalbed methane throughout the basin.
7. Geochemical analysis and vitrinite reflectance studies of 30 coal samples analyzed during this investigation show that coal rank ranges from high volatile C to high volatile A bituminous. The rank of the coal beds, in combination with the compositional gas analyses and isotopic values, is a promising indicator for coalbed methane production and storage and, hence, exploration.
8. Reports of excessive methane in 13 abandoned underground coal mines in the Missouri part of the basin may further indicate the presence of commercial quantities of methane.
9. Although the amount of geological data (geochemical, vitrinite reflectance, and so on) available at this time is insufficient for a thorough assessment of the coalbed methane potential in most parts of the basin, the data collected in the past year indicate that methane is present in the basin and further indicate that there is reason for additional study. Additional core holes need to be drilled in all four States in the basin to acquire this information.
10. Abundant data are available for future investigations in the Forest city basin. Kansas has more than 1,000 gamma-ray-density logs and almost 4,000 oil and gas tests having geophysical logs; Missouri has approximately 5,000 wells of many types; Nebraska has approximately 600 wells and 38 deep geophysical logs; Iowa has several hundred logs of all types.

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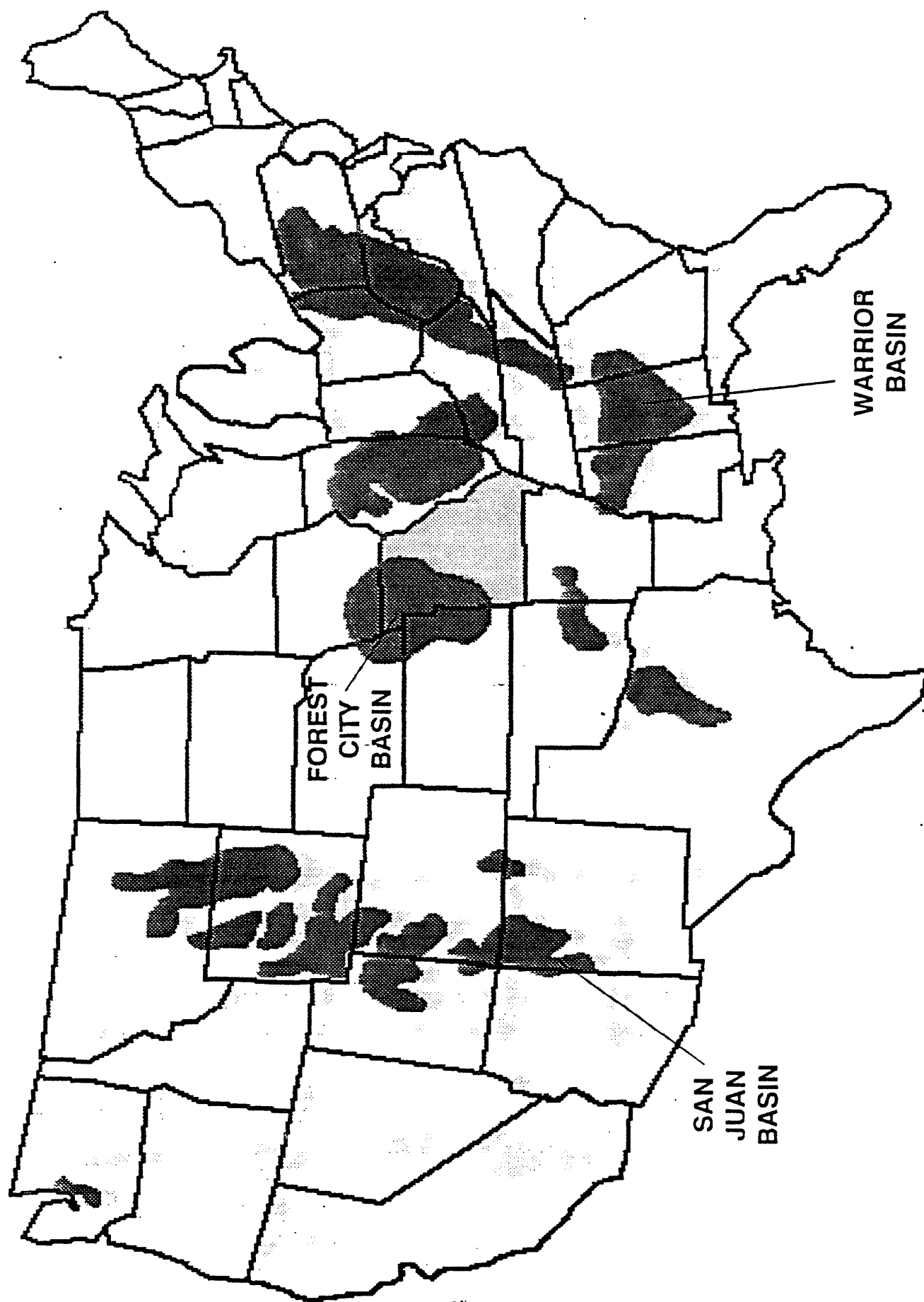


Figure 1.  
Map of major coal basins of the United States. Coalbed methane is currently produced in the San Juan and Warrior Basins.

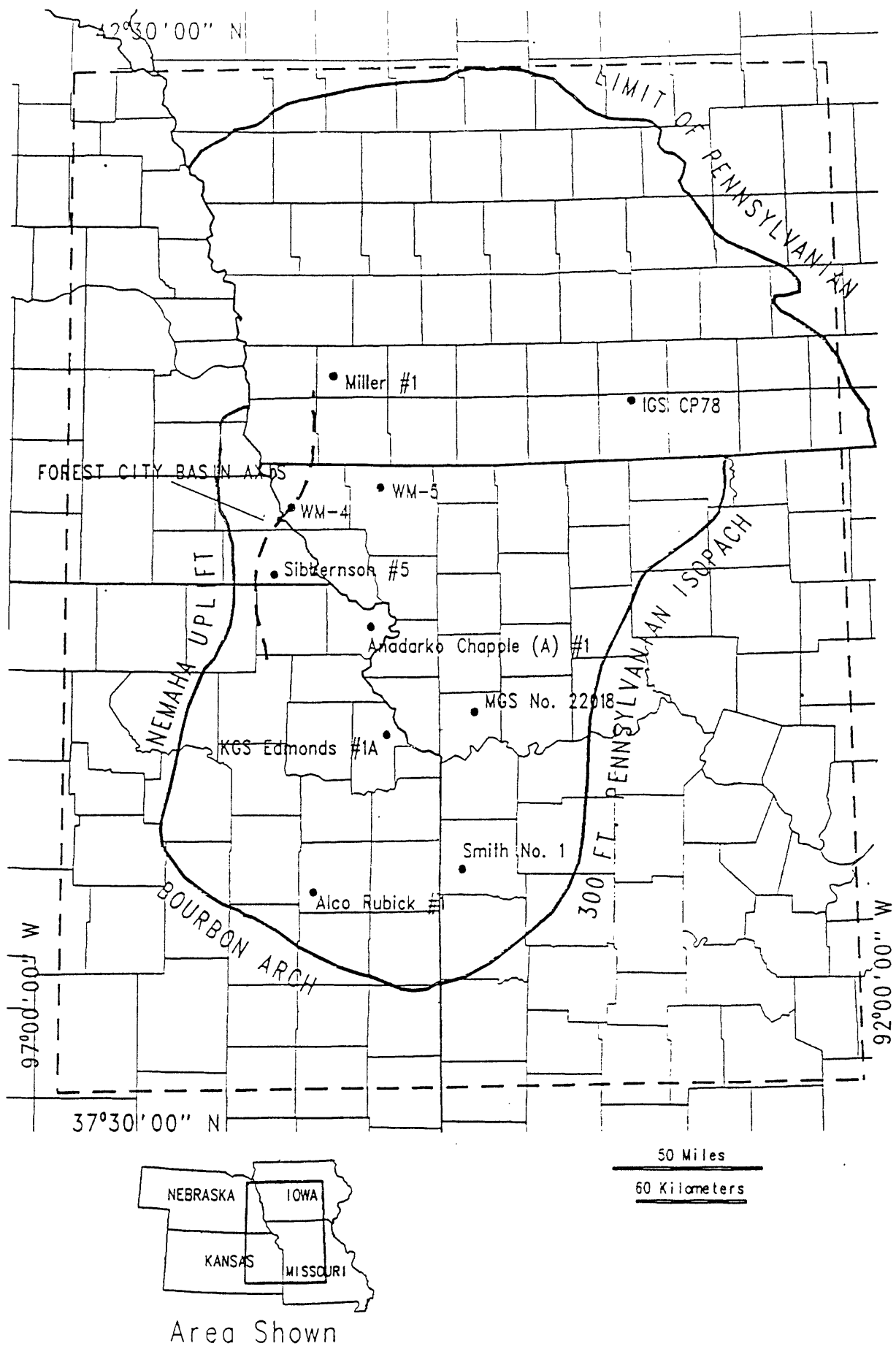


Figure 2. Forest City basin study area showing location of drill holes discussed in this study.

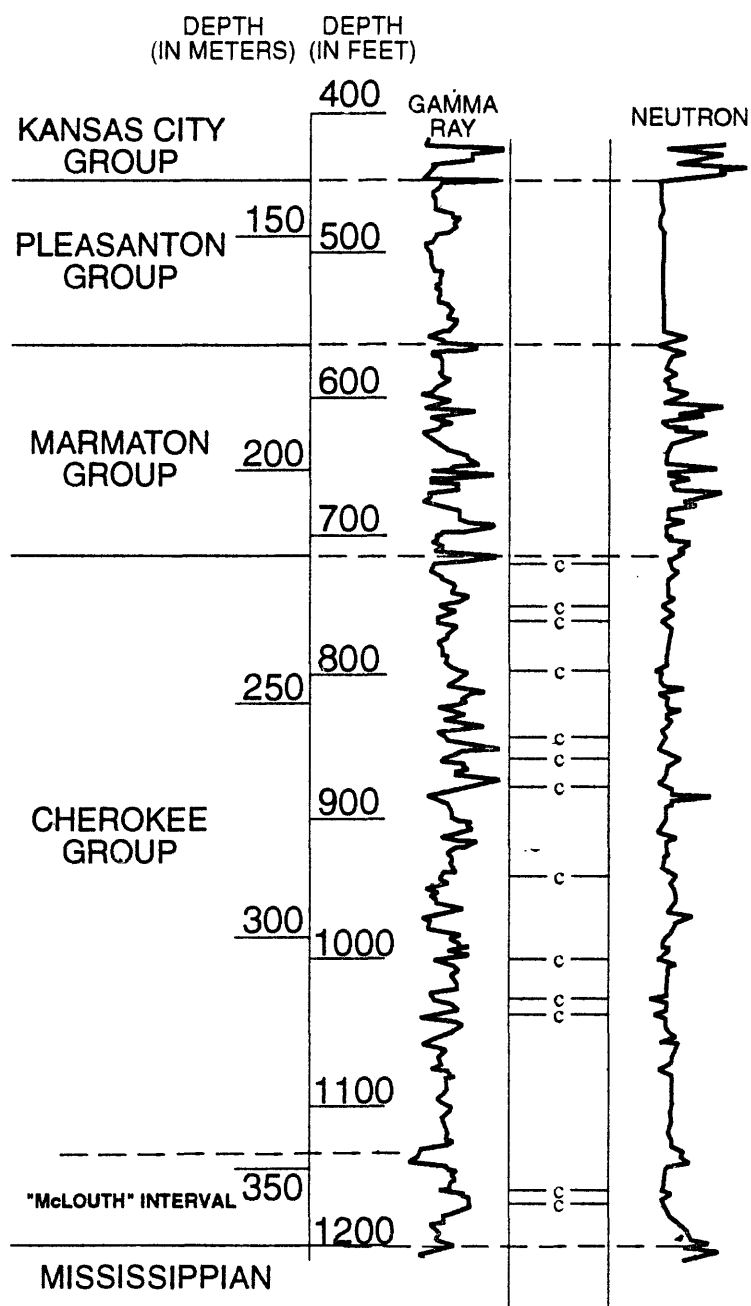


Figure 3. Geophysical log, Kansas Geological Survey  
Edmonds #1A, NW, SW, sec. 35, T. 9 S., R. 22 E.,  
Leavenworth County, Kansas.  
Location shown in figure 2.

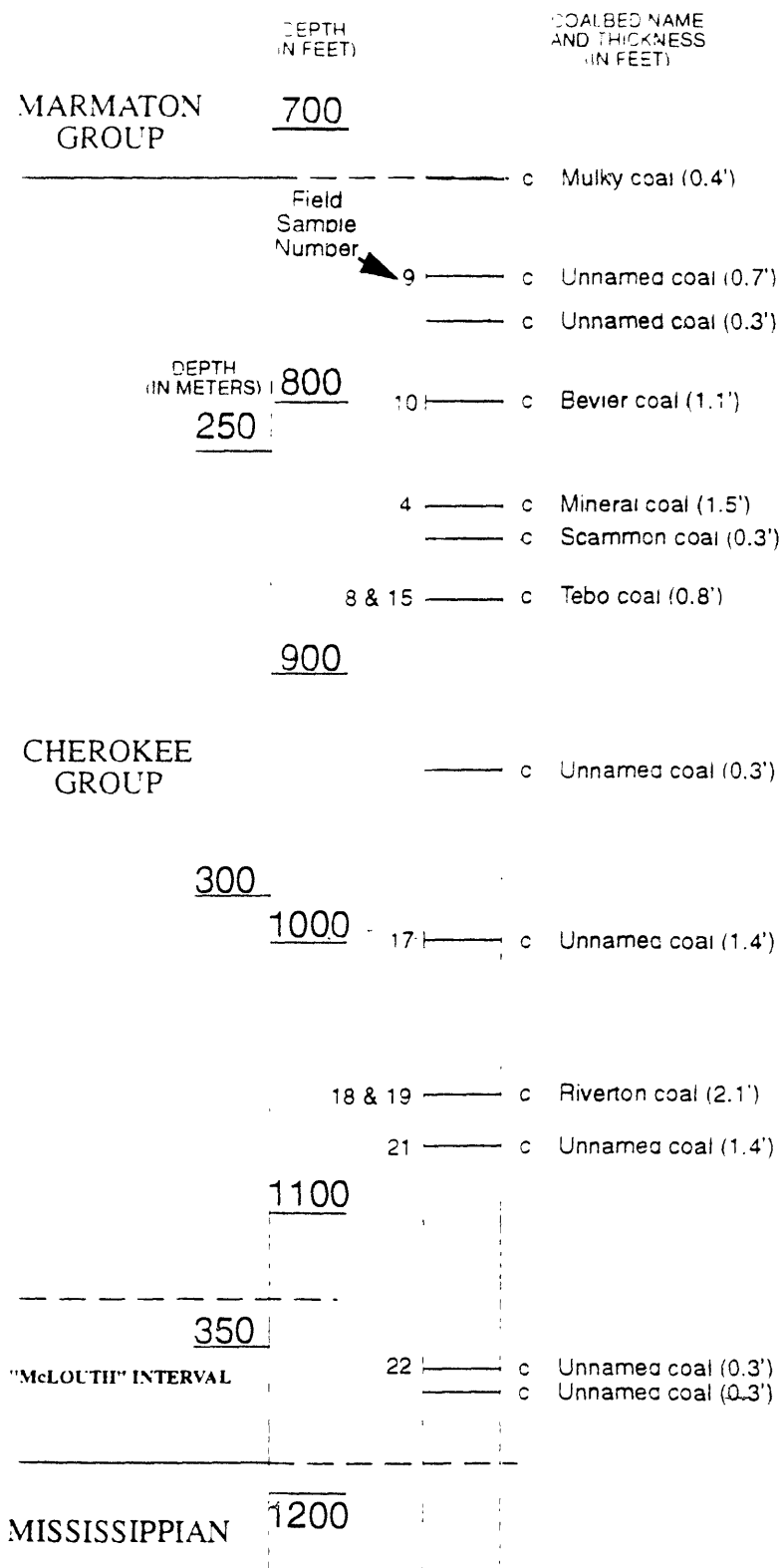


Figure 4. Geologic column, Kansas Geological Survey Edmonds #1A, NW, SW, sec. 35, T. 9 S., R. 22 E., Leavenworth County, Kansas. Location shown in figure 2.

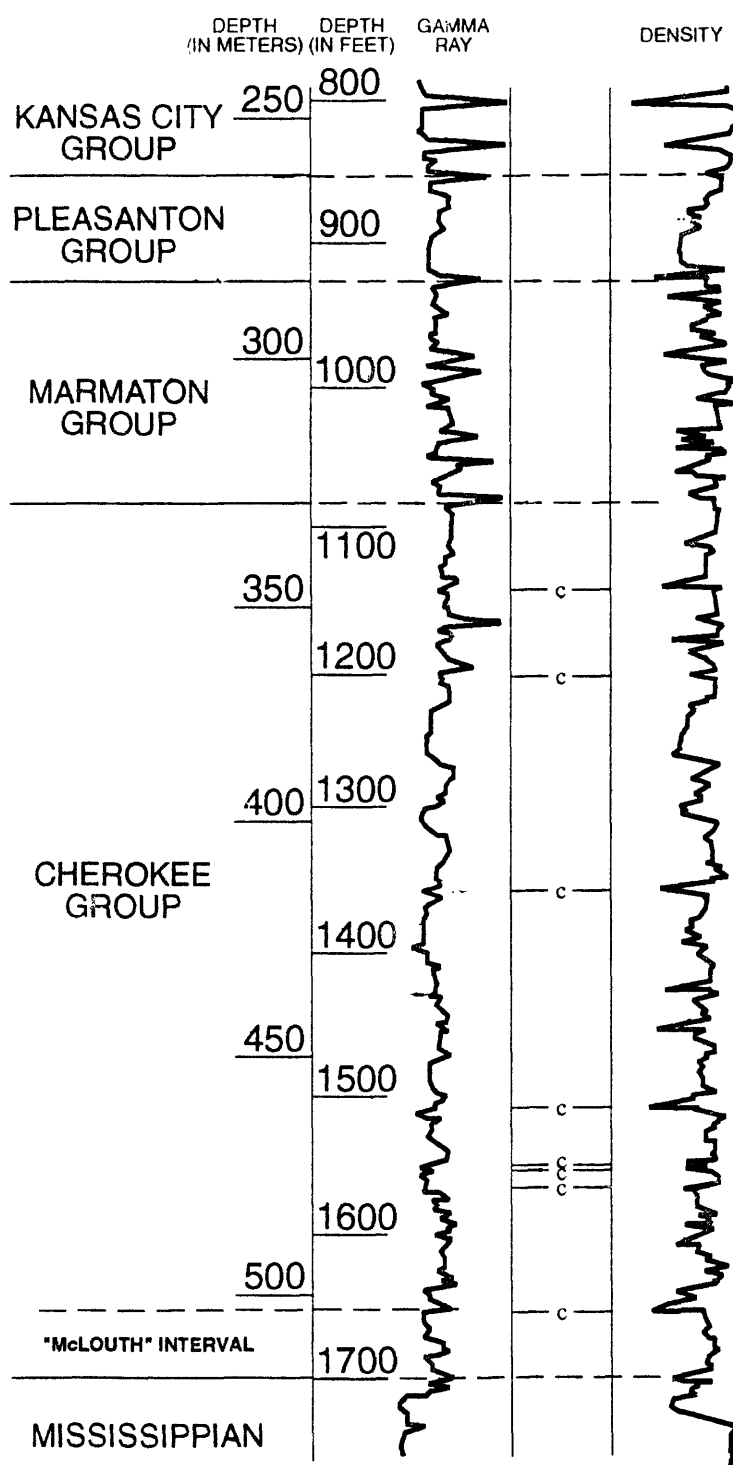


Figure 5. Geophysical log, Anadarko Chapple "A" #1, NW, sec. 13, T. 20 E., R. 3 S., Doniphan County, Kansas. Location of well shown in figure 2.

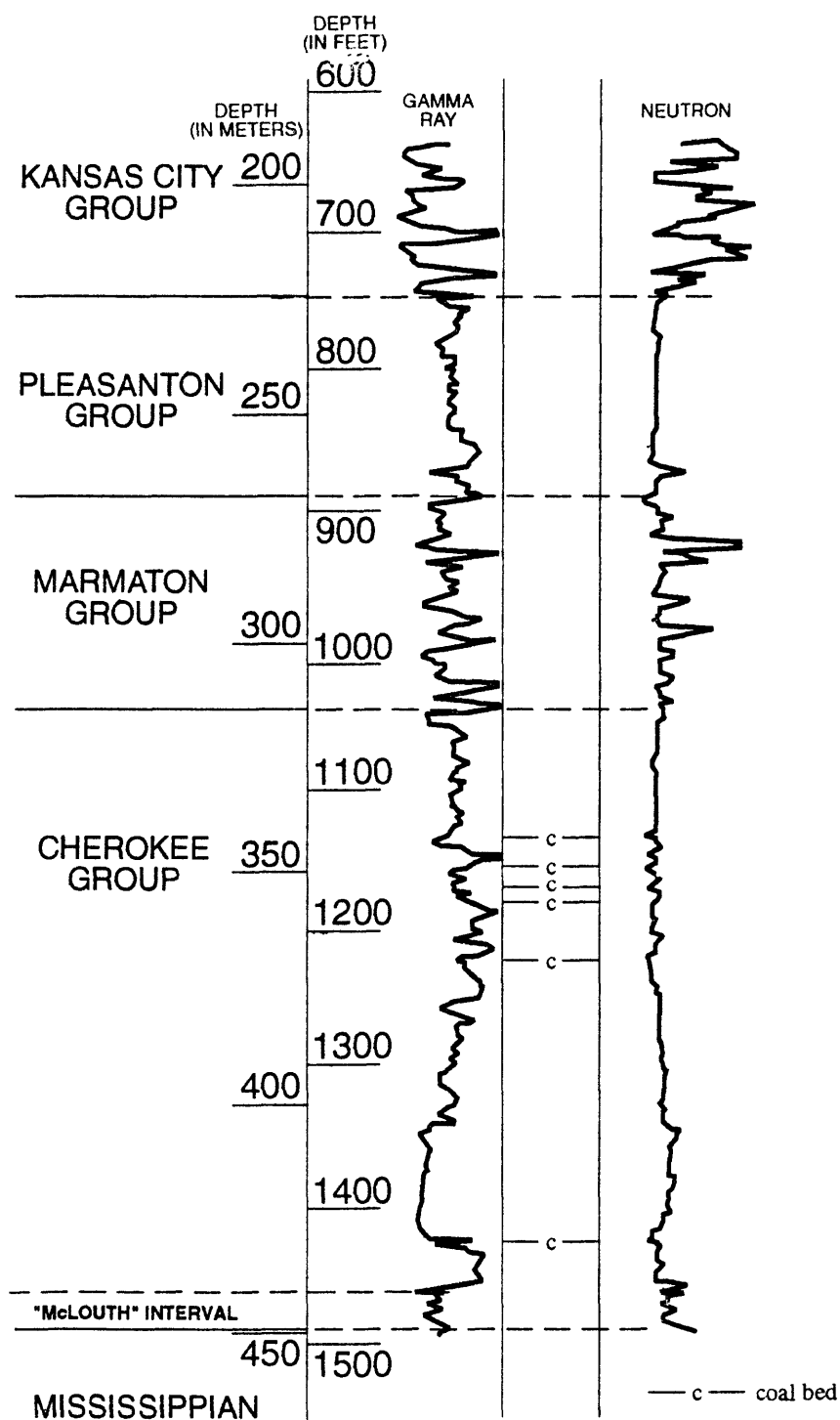


Figure 6. Geophysical log, Alco Rubick #1, SW, SE, sec. 16, T. 18 S., R. 18 E., Franklin County, Kansas. Location shown in figure 2.

DEPTH  
feet  
meters

MILLER #1

DEPTH  
feet  
meters

IGS CP78

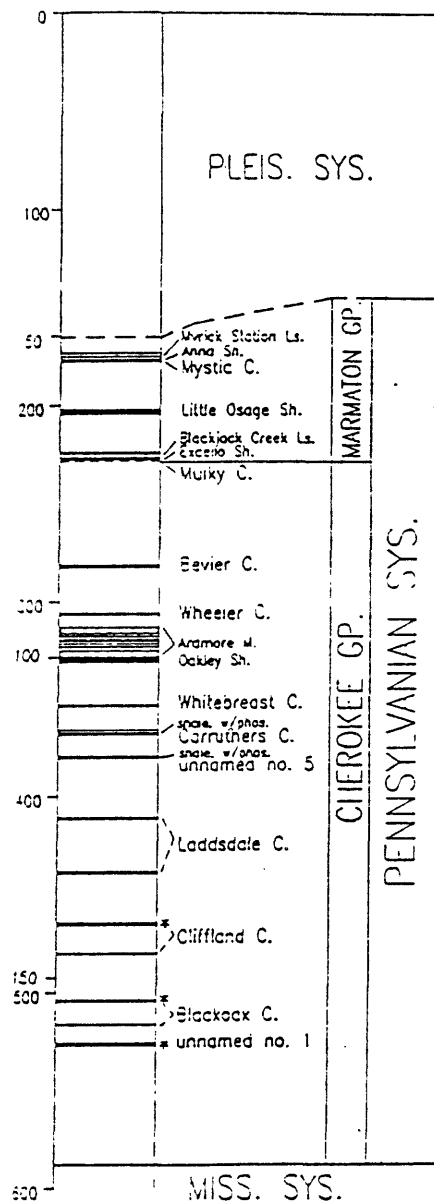
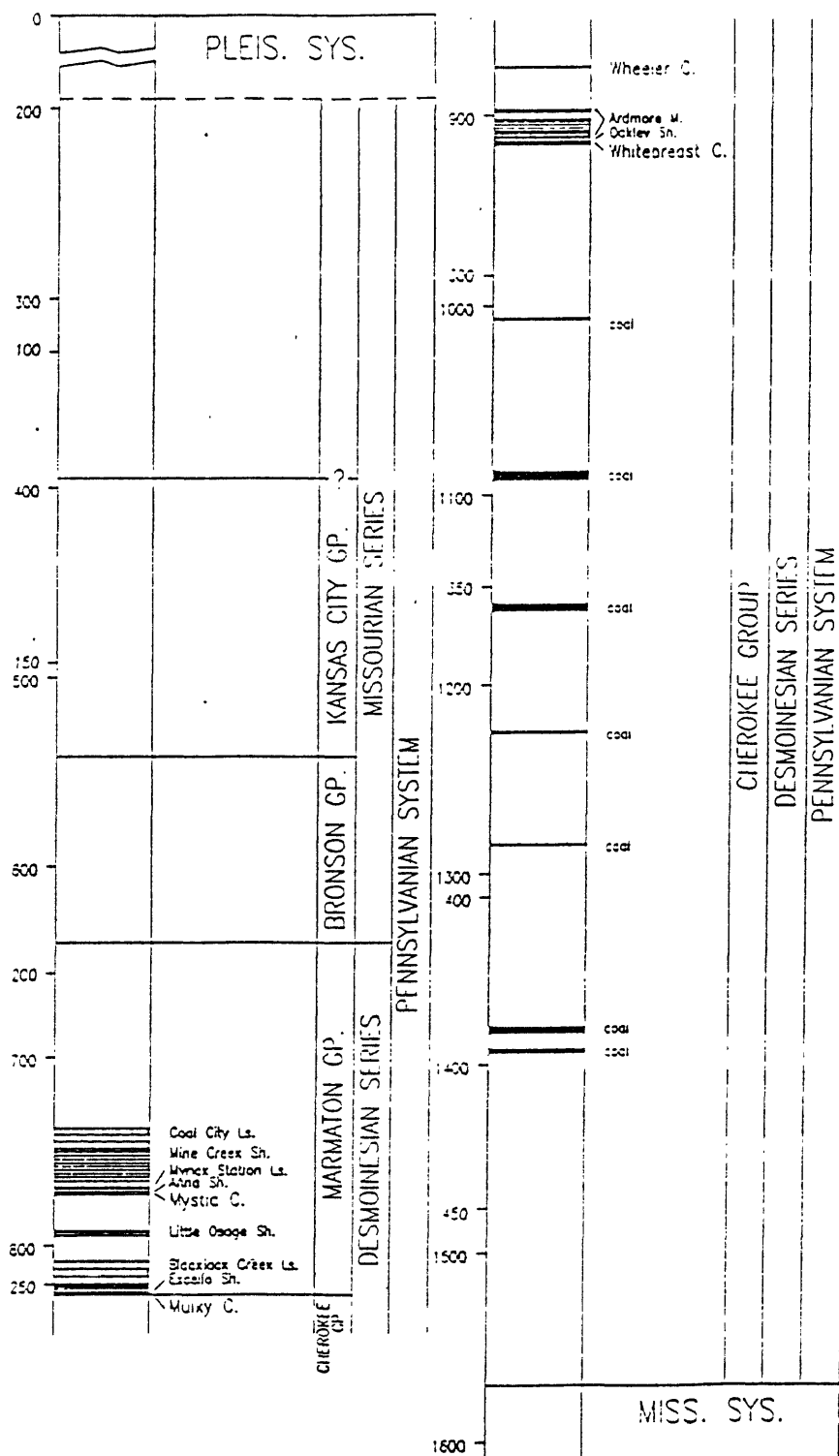


Figure 7. Two sections through Pennsylvanian rocks in Iowa illustrating coal beds in the Cherokee and Marmaton groups together with related strata which are significant stratigraphic markers. Note the thicker Cherokee section in Miller #1 compared with CP78. The coals below the Whitebreast in Miller #1 could not be correlated at this time. The section for Miller #1 was prepared from geophysical logs. The section for CP78 was prepared from the core description. The asterisks (\*) indicate coals which were sampled for ultimate, proximate, and calorific value analysis.



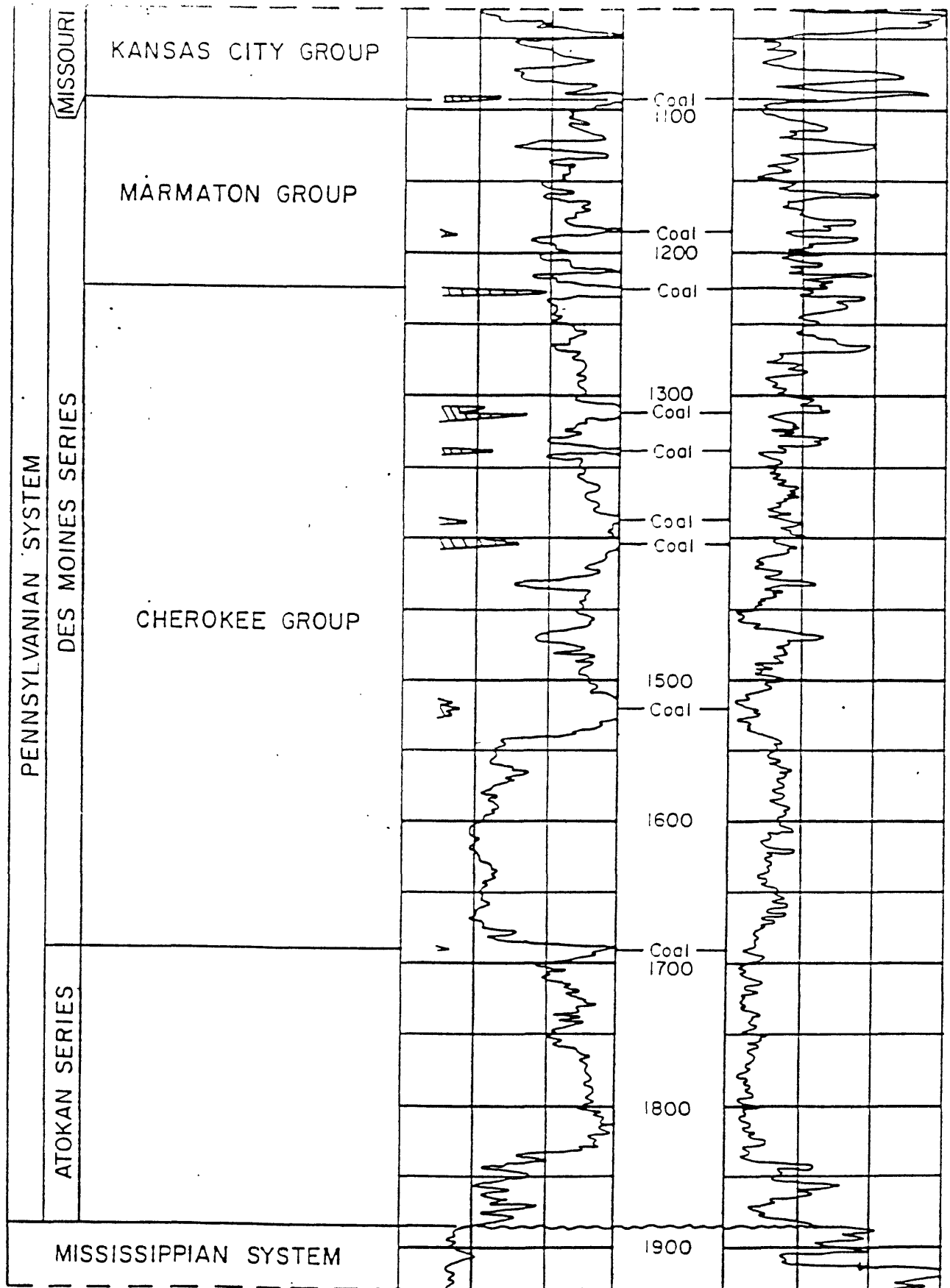
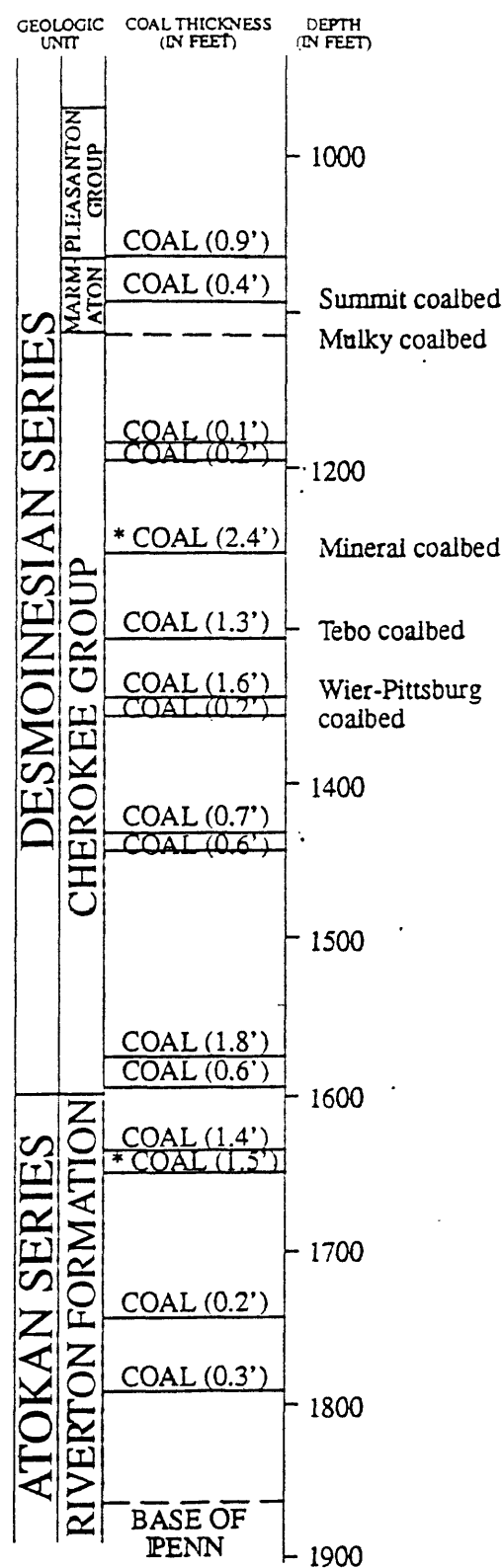


Figure 8. Radioactivity log of Big "J" Oil Co. No. 5 Sibbernson showing occurrences of potential deeply buried coal in Richardson, County.

Figure 9. Geologic column showing depth and thickness of coal beds in Well No. WM-4, Atchison County, Missouri. NW, NE, sec. 17, T. 64 N., R. 41 W. Location of well shown in figure 2. Asterisks denote coal beds sampled for geochemical and vitrinite reflectance analyses.



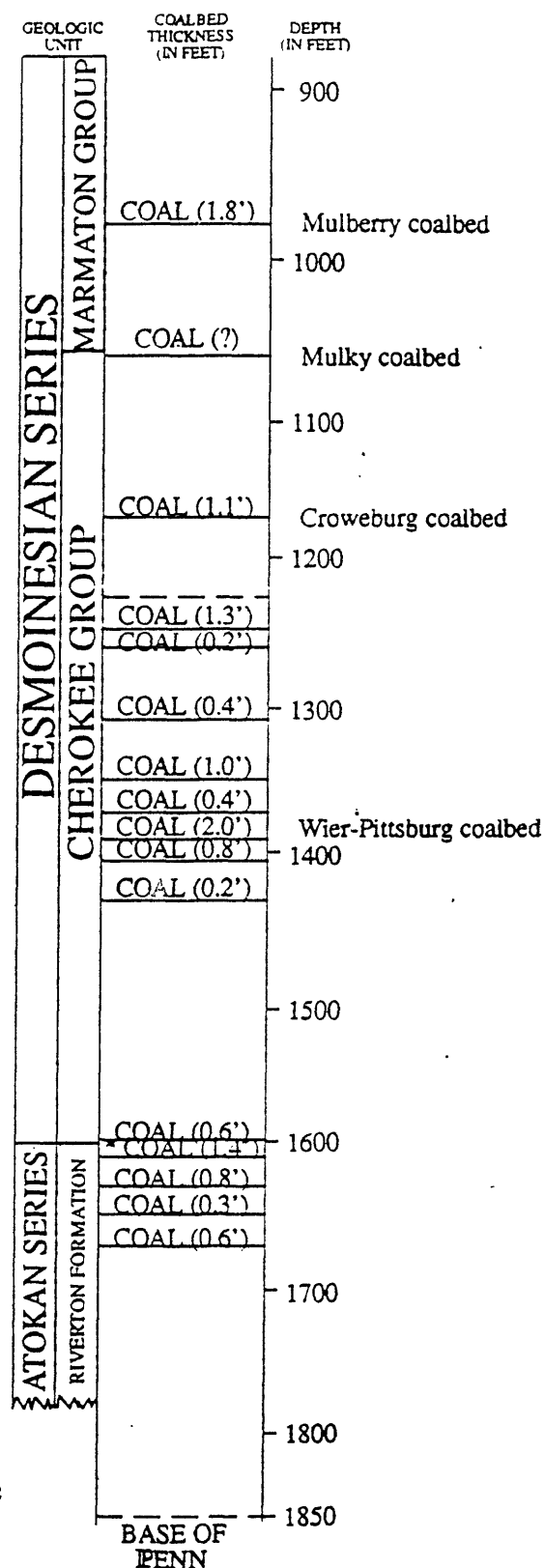


Figure 10. Geologic column showing depth and thickness of coal beds in Well No. WM-5, Nodaway County, Missouri. NW, SE, sec. 10, T. 65 N., R. 36 W. Location of well shown in figure 2. Asterisk denotes coal beds sampled for geochemical and vitrinite reflectance analyses.

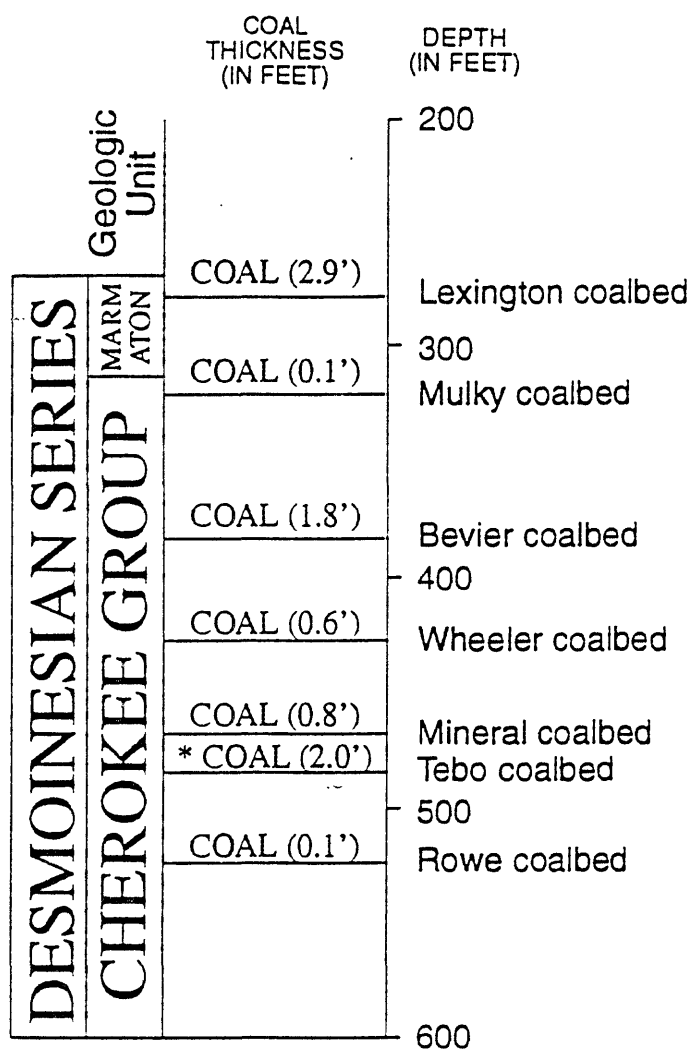
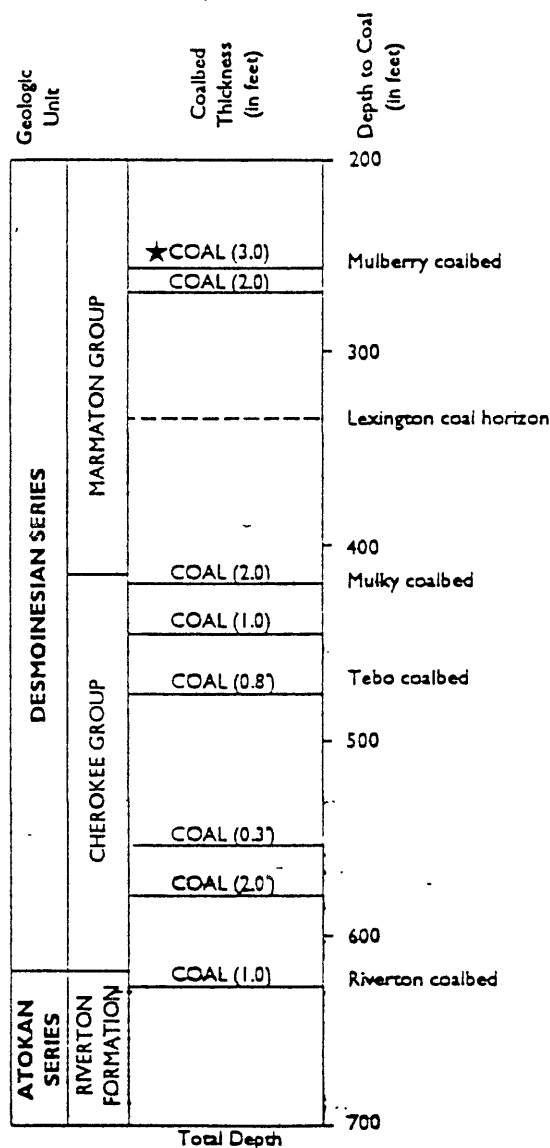


Figure 11. Geologic column showing depth and thickness of coal beds in Well No. 22018, Clay County, Missouri. NW, SE, sec. 22, T. 53 N., R. 31 W. Location of well shown in figure 2. Asterisk denotes coal bed sampled for geochemical and vitrinite reflectance analyses.

MISSOURI DEPARTMENT OF NATURAL RESOURCES  
DIVISION OF GEOLOGY AND LAND SURVEY

Landmark Production, Inc.  
Smith No. 1 Well  
NW Sec. 27, T.44N., R.33W.  
Cass County, Missouri



★ Denotes coalbed sampled for geochemical and vitrinite reflectance analyses.  
Methane desorption and methane quality tests were also conducted on this coalbed.

Figure 12 Geologic column showing depth and thickness of coalbeds in the Smith No. 1 Well.

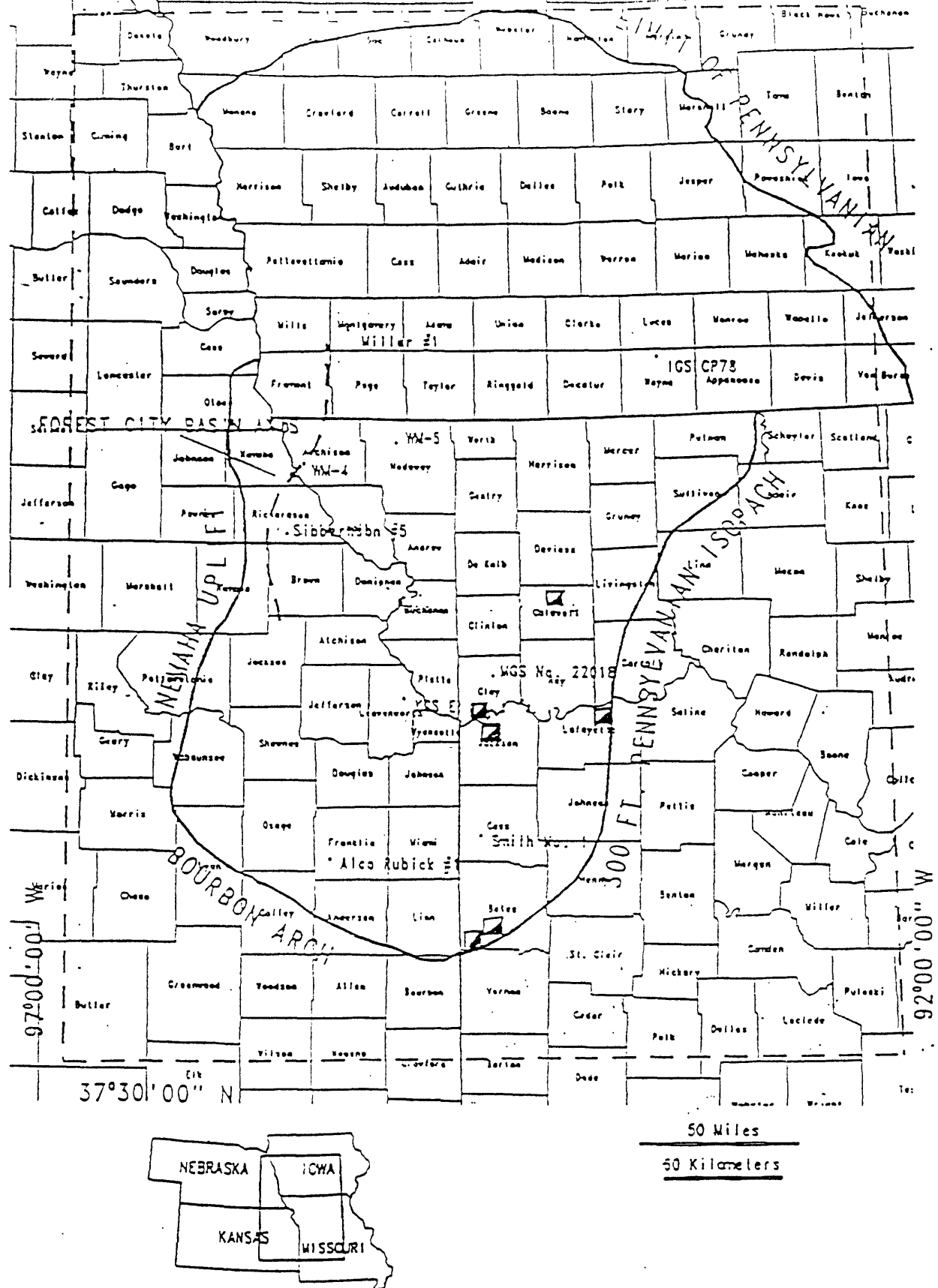


Figure 13. Location map of abandoned underground coal mines, indicated by rectangles, in the Missouri part of the Forest City basin in which excessive methane or explosions were reported by the state mine inspector.

Table 1. Analysis of coal-bed gas amounts obtained from coal samples from the Kansas Geological Survey Edmonds #1 and #1A core holes in Leavenworth County, Kansas. Methods used for collecting core, gas from coal, and quantity analysis are based on methods explained in McCulloch, and others (1975), Diamond and Levine (1981), and Close and Erwin (1989). Method of desorption of coalbed methane was the direct method determination developed by the U.S. Bureau of Mines.

Sample no. <sup>1</sup>	Coalbed	Depth to top of sample (ft)	Lost gas (cm <sup>3</sup> ) <sup>2</sup>	Desorbed gas (cm <sup>3</sup> ) <sup>3</sup>	Weight of sample (g) <sup>4</sup>	Gas content (cm <sup>3</sup> /g) <sup>5</sup>	Measured residual gas (cm <sup>3</sup> ) <sup>6</sup>	Time of m.ment of resid. gas (d) <sup>7</sup>	Lost desorbed gas (ft <sup>3</sup> /t) <sup>8</sup>	Ash (wt %) <sup>9</sup>	Moisture content (wt %) <sup>9</sup>	Normalized gas content (ft <sup>3</sup> /t) <sup>10</sup>
9	unnamed	757	29	305	610	0.548	57	210	18	18.48	5.6	21
4 <sup>11</sup>	Mineral	836	30	563	922	0.643	108	312	21	15.21	7.0	26
8 <sup>11</sup>	Tebo	874	20	701	795	0.907	225	285	29	14.79	5.6	34
15	Tebo	875	43	492	676	0.791	175	210	25	20.32	5.3	32
17	unnamed	999	75	1043	829	1.349	122	145	43	15.88	3.6	51
18	Riverton	1055	100	1364	641	2.284	177	145	73	8.44	3.4	80
19	Riverton	1056	95	1348	557	2.591	164	145	83	11.97	6.2	94
21	unnamed	1075	58	588	312	2.071	148	206	66	14.25	5.2	77
22	unnamed	1158	80	523	296	2.037	61	166	65	23.96	3.9	86

<sup>1</sup> Field sample number.

<sup>2</sup> Lost gas is a graphic method of determining the amount of gas lost from the core during retrieval from the bottom of the bore hole until the coal core is brought to the surface and sealed in a test canister.

<sup>3</sup> Desorbed gas is the gas measured from the canister that was desorbed from the coal. Following Diamond and Levine's (1981) methods, measurements of less than 10 cm<sup>3</sup> of gas per day for a period of 1 week terminates the amount of gas included in this category.

<sup>4</sup> Weight of the coal core.

<sup>5</sup> Amount of gas (lost and desorbed) per unit of coal core.

<sup>6,7</sup> Residual gas is the gas remaining in the coal core after determining the desorbed gas. Residual gas can be more accurately determined by fine crushing in a sealed ball mill and measuring the gas that is desorbed from the coal in the ball mill after a certain period of crushing (Diamond and Levine, 1981). In the cores of this study, residual gas was determined only by extended measuring of the gas from the coal sample (still sealed in the canister) for an extended period of time, measured in days (d).

<sup>8</sup> Calculation of gas content per ton of coal based on the amount of lost and desorbed gas content but not the residual gas amount. Coal weight is assumed to be 1,800 tons/acre-ft. No consideration is given in this column to ash content of the coal.

<sup>9</sup> Ash yield and moisture content are taken from the proximate analyses of the coal samples and are used in calculating the normalized gas content. The percentage of ash is a dry ash weight percent.

<sup>10</sup> Normalized gas content (Close and Erwin, 1989) calculated on a dry-ash basis. The content of dry ash is calculated from the coal weight. This value is important in order to make comparisons with the gas amount present in coals of other areas and ranks. Note that, if this analysis were calculated on a moisture-free basis, the values would be higher.

<sup>11</sup> Samples collected from KGS Edmonds #1. The rest of the samples are from KGS Edmonds #1A.

Table 2. Gas compositional data for samples from the Forest City basin. Analyses are reported on an air-free basis (because many samples collected during the desorption process had large amounts of air). Note that gas samples were taken at different times during the desorption process, and fractionation of both molecular and isotopic composition may have taken place.

Samples	(C <sub>1</sub> ) <sup>1</sup>	(CO <sub>2</sub> ) <sup>2</sup>	(C <sub>2</sub> ) <sup>3</sup>	(C <sub>3</sub> ) <sup>4</sup>	( <sup>13</sup> C <sub>1</sub> ) <sup>5,6</sup>	(C <sub>2+</sub> ) <sup>7</sup>
Missouri						
Gunnels 1						
Canister G-161	95.73	4.0	0.26	0.0	-59.73	0.9973
Gunnels 1	66.77	29.1	1.61	1.82	-58.52	0.9511
Kansas						
1 Edmonds 3	0.	0.	0.	0.	-46.13	-0.
1 Edmonds 4	76.82	12.8	10.9	0.	-	0.8756
1 Edmonds 15	0.	0.	0.	0.	-46.18	-0.
1 Edmonds 15	72.24	12.2	2.95	2.95	-46.18	0.9608
1 Edmonds 17	93.1	6.4	0.42	0.53	-	0.9899
1 Edmonds 18	97.08	2.13	0.69	0.	-59.39	0.9929
1 Edmonds 19	96.48	2.7	0.77	0.	-59.14	0.9921
1 Edmonds 21	82.65	16.6	0.68	0.	-46.17	0.9919
1 Edmonds 22	85.33	13.9	0.71	0.	-47.28	0.9918

<sup>1</sup> C<sub>1</sub> = percent methane

<sup>2</sup> CO<sub>2</sub> = percent carbon dioxide

<sup>3</sup> C<sub>2</sub> = percent ethane

<sup>4</sup> C<sub>3</sub> = percent propane

<sup>5</sup> <sup>13</sup>C<sub>1</sub> = isotopic value of methane

<sup>6</sup> isotopes of ethane (<sup>13</sup>C<sub>2</sub>) and propane (<sup>13</sup>C<sub>3</sub>) were not obtained.

<sup>7</sup> C<sub>2+</sub> = wetness = expression of the hydrocarbon composition of the gases (percentage of ethane and higher hydrocarbon gases).



Table 3. Quality data (ash and sulfur on an as-received basis), calculated moist, mineral-matter-free calorific value (ASTM, 1992), and mean maximum reflectance values (reported in  $R_o$ ) for coal samples from the Forest City basin (--, sample did not contain enough vitrinite for proper reflectance analyses).

Sample no.	Ash (%)	Sulfur (%)	Calorific value (BTU/lb)	$R_o$ max	Standard Deviation
Missouri					
MGSCQ1	5.54	3.00	12688	0.55	0.02
MGSCQ2	31.16	7.10	13443	0.55	0.02
MGSCQ3	15.42	3.32	12309	0.49	0.02
MGSCQ4	7.63	3.38	14031	0.54	0.03
Gunnels #1	19.38	3.04	15107	0.68	0.02
Iowa					
CP78-51-1	25.28	12.12	10089		
CP79-40-2	18.17	11.33	12432		
CP80-28-3	17.82	11.21	8489		
CP77-38-4	22.26	6.67	11284		
CP78-57-5	35.23	12.93	11113		
CP77-18-6	13.24	6.23	11532		
CP79-8-7	16.06	6.05	11289		
CP73-36-8	33.64	4.51	10323		
CP78-65-9	24.79	7.25	11650		
CP77-30-10	23.64	13.62	8240		
Kansas					
#4	14.13	3.20	13708	0.53	0.03
#8	13.96	3.44	13974	--	--
#9	17.45	5.63	14055	--	--
#10	14.19	4.00	13669	0.58	0.02
#15	19.25	5.92	13877	0.60	0.03
#17	15.32	10.65	14182	0.56	0.02
#18	8.16	5.18	14535	0.53	0.02
#19	11.22	4.39	14095	0.56	0.02
#21	13.51	3.25	14160	0.54	0.02
#22	23.00	14.20	14284	0.56	0.03

Table 4. Occurrences of excessive methane or explosions in abandoned underground coal mines in the Missouri part of the Forest City basin

County	Company/mine	Location (nearest town)	Year of Occurrence	Coal bed name	Depth of coal bed (ft)	Thickness (ft)
Bates	New Home Coal Co.	Foster	1904-05	Mineral	250	4.5
	Martin Gee	Unknown	1895	Unknown	Unknown	Unknown
	Rich Hill Coal Co.					
	Mine No. 14	Rich Hill	1891-92	Mineral	250	3-5
	Mine No. 15	Rich Hill		Mineral		
	Keith Perry Coal Co.					
Caldwell	Mine No. 6	Rich Hill	1890	Mineral	250	2.9
	Mine No. 7	Rich Hill	1890	Mineral	103	4.3
Caldwell	Caldwell Coal Co.	Hamilton	1887-93	Unnamed	365	2.1
	Hamilton Coal Co.	Hamilton	1887	Unnamed	300	2.1
Clay	Randolph Coal & Gas Co.	Randolph	1891	Bevier?	420	1.5
Jackson	Kansas City Clay & Coal Co.					
	Brushy Creek Coal Co.	Brush Creek	1893	Unnamed	400	2
		Brush Creek	1897	Unnamed	400	2
Lafayette	Francisco Coal Co.					
	Waverly Coal Co. (Waverly Brick & Coal Co.)	Waverly Station Waverly Station	1892	Mulky? Mulky?	110 100	3.5 3.5

## APPENDIX

### Economic Scenarios for Missouri

The following economic scenarios were prepared by the Missouri Department of Natural Resources, Division of Geology and Land Survey as their analysis of the potential economic benefits from a coal-bed methane industry specifically to the State of Missouri (table 5). Because the total methane resources in the Forest City basin are unknown at present, each scenario was prepared by using a different projected number of operating wells in order to compare the economic impacts of coal-bed methane industries of different sizes. The numbers of operating wells in scenarios I through IV are 910, 500, 200 and 50. The economic benefits to Missouri in each of the four scenarios were calculated by the Missouri Department of Economic Development by utilizing a computer economic modeling program developed by the School of Business of the University of Missouri-Columbia; this program determines the total economic benefits generated by the natural gas production sector of Missouri's economy. The annual payroll from new jobs and the annual value of coal-bed methane production were the initial figures put into the computer program. Raw data used to determine the value of coal-bed methane production in each economic scenario for Missouri were projected from economic data generated by Alabama's coal-bed methane industry.

**Scenario I:** Economic benefits to Missouri under scenario I represent a best-case scenario of a coal-bed methane industry--an industry the size of that currently operating in Alabama. In 1 year, an industry producing 23.4 billion ft<sup>3</sup> of gas from 910 wells and employing 590 people would generate \$74 million in economic benefits to the State of Missouri from business and industry, increased personal income, and local and State government revenue.

**Scenario II:** Scenario II represents an industry roughly half the size of that presented in scenario I and was prepared on the basis of the value of production from 500 wells and an annual payroll from 325 new jobs. Economic benefits to the State of Missouri from an industry this size would be \$40.9 million annually.

**Scenario III:** Should coal-bed methane be found in producible quantities sufficient to support an industry of only 200 methane wells, annual economic benefits to Missouri would be \$16.4 million. Annual payroll would be \$2.7 million from 130 new jobs.

**Scenario IV:** Scenario IV presents a very conservative estimate of the size of a coal-bed methane industry in Missouri. However, it was included in this assessment to show that even a small-scale industry would generate a considerable amount of general revenue. This scenario would represent a small production area in the

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