STRUCTURE, SEDIMENTOLOGY, COAL QUALITY, AND HYDROLOGY OF THE BLACK WARRIOR BASIN IN ALABAMA: CONTROLS ON THE OCCURRENCE AND PRODUCIBILITY OF COALBED METHANE

TOPICAL REPORT
(August 1987 - December 1990)

Prepared by

J.C. Pashin

with contributions by

W. E. Ward, II, R. B. Winston, R. V. Chandler,
D. E. Bolin, K. E. Richter, W. E. Osborne, J. C. Sarnecki

Geological Survey of Alabama
P.O. Box 0
Tuscaloosa, Alabama 35486-9780

in association with
Bureau of Economic Geology
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16. Abstract (Limit: 200 words)

Geologic evaluation of critical production parameters in the Black Warrior basin employed an interdisciplinary approach that utilized structural, sedimentologic, coal-quality, hydrologic, completion, and production data. Results indicate that geologic structure affected sedimentation, coalification, hydrogeology, and the ultimate occurrence and producibility of coalbed methane. Geologic trend analysis was used to characterize regional coalbed-methane potential, and results indicate that many parts of the basin have untapped resources.

Some highly productive trends coincide with northeast-trending structures that apparently are zones of enhanced fracture permeability. Water-production data indicate that many high-permeability trends exist that are not associated with exceptional coalbed-methane production and that the coal beds are structurally compartmentalized reservoirs. Water-level data indicate that all highly productive coalbed-methane wells occur where reservoir pressure has been lowered significantly. Therefore, highly productive areas apparently represent structural compartments where formation pressure has been lowered enough to facilitate desorption of a large quantity of methane. Results of this research suggest that completion technology and field design can be tailored to specific geologic settings to produce from reservoir compartments that are readily depressurized, thereby optimizing reservoir drainage.

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RESEARCH SUMMARY

Title Structure, sedimentology, coal quality, and hydrology of the Black Warrior basin in Alabama: controls on the occurrence and producibility of coalbed methane.

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Principal Investigator W. B. Ayers, Jr.; Project Manager, Geological Survey of Alabama, R. M. Mink.

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Objective To develop a data base and understanding of structure, coal quality, sedimentology, hydrology, and well productivity in order to characterize coalbed-methane reservoirs and to identify critical production parameters for coalbed methane in Alabama.

Technical Perspective Coalbed methane is a major potential source of domestic gas reserves. Detailed evaluation of the geologic, hydrologic, and production parameters affecting coalbed-methane occurrence and production in the Black Warrior basin of Alabama will lead to economic development of this resource.

Results Geologic evaluation of critical production parameters in the Black Warrior basin indicates that geologic structure affected sedimentation, coalification, hydrogeology, and the ultimate occurrence and producibility of coalbed-methane. Geologic trend analysis was used to characterize regional coalbed methane potential, and results indicate that many parts of the basin have untapped resources. Some highly productive trends coincide with northeast-trending structures that apparently are zones of enhanced fracture permeability. Water-production data indicate that many high-permeability trends exist that are not associated with exceptional coalbed-methane production and that the coal beds are structurally compartmentalized reservoirs. Water-level data indicate that all highly productive coalbed-methane wells occur where reservoir pressure has been lowered significantly. Therefore, highly productive areas apparently represent structural compartments where formation pressure has been lowered enough to facilitate desorption of a large quantity of methane. Results of this research suggest that completion technology and field design can be tailored to specific geologic settings to produce from reservoir compartments that are readily depressurized, thereby optimizing reservoir drainage.

Technical Approach This study employed an interdisciplinary approach that utilized structural, coal-quality, gas-composition, sedimentologic, hydrologic, completion, and production data to evaluate geologic controls on the occurrence and producibility of coalbed methane in the Black Warrior basin of Alabama. Structural analysis utilized data from well logs, joints, cleats and lineaments to provide a regional structural and tectonic framework and to relate structural geology to localized productivity trends. Sedimentologic analysis was based on data from geophysical well logs and outcrops and was performed to develop models of coal occurrence at various geologic scales. Coal-quality and gas-composition data were evaluated to determine the controls on the origin and occurrence of coalbed methane. Hydrologic analysis was based on water-level, reservoir-pressure, and chemical data from wells and surface water and was used to determine the hydrodynamics of the coalbed-methane reservoir. Analysis of engineering and well productivity was based on completion and stimulation data and included statistical analysis and mapping of geologic and production parameters.

Project Implications

This report describes the structural and depositional frameworks, hydrologic regime, coal occurrence and developed coal rank along with coalbed-methane production for the upper Pottsville Formation in the Black Warrior basin. This comprehensive report integrates these factors into a regional map of the basin. The report significantly advances our understanding of regional variations in the occurrence and producibility of coalbed methane in the Black Warrior basin. Moreover, this report provides technical insights and approaches that may be transferable to the central and northern Appalachian coal basins.

GRI Project Manager
Richard C. Klem
Methane from Coal deposits

CONTENTS

CONTENTS—CONTINUED

ILLUSTRATIONS

ILLUSTRATIONS–CONTINUED

ILLUSTRATIONS–CONTINUED

ILLUSTRATIONS–CONTINUED

TABLES

INTRODUCTION

OBJECTIVES

Understanding geologic controls on the occurrence and producibility of coalbed methane is essential for constructing field- and well-design strategies that will help ensure a long-term, low-cost supply of domestic natural gas; characterizing those controls is the objective of this study. Early coalbed-methane research in the Black Warrior basin of Alabama focused on determining the economic feasibility of producing the gas and quantifying the gas resource, which is estimated to be between 10 and 19.8 Tcf (Hewitt, 1984; McFall and others, 1986), whereas recent studies have focused on identifying geologic controls on coalbed-methane occurrence and production (Epsman and others, 1988; Pashin and others, 1990). Important results of these investigations have been refinement of geologic models for the Black Warrior basin and the development of a preliminary exploration and production philosophy.

This report summarizes previous annual reports written under this contract (Epsman and others, 1988; Pashin and others, 1990) and integrates findings from those studies with new data from Oak Grove field that provide additional perspective regarding geologic controls on coalbed-methane occurrence and production. Our objective is to show how structure, sedimentology, coal quality, and hydrology are critical production parameters for coalbed-methane resources. Structural activity influenced sedimentation, coalification, hydrology, and the ultimate occurrence and producibility of coalbed methane in the Black Warrior basin. Therefore, this study uses the structural framework of the basin as a starting point and discusses sedimentation, coalification, hydrology and producibility in light of that framework.

BACKGROUND

BLACK WARRIOR BASIN

Development of Alabama's coalbed-methane industry began with the drilling of Oak Grove field (fig. 1) in 1977 and 1978 and issuance of the first drilling permits by the State Oil and Gas Board of

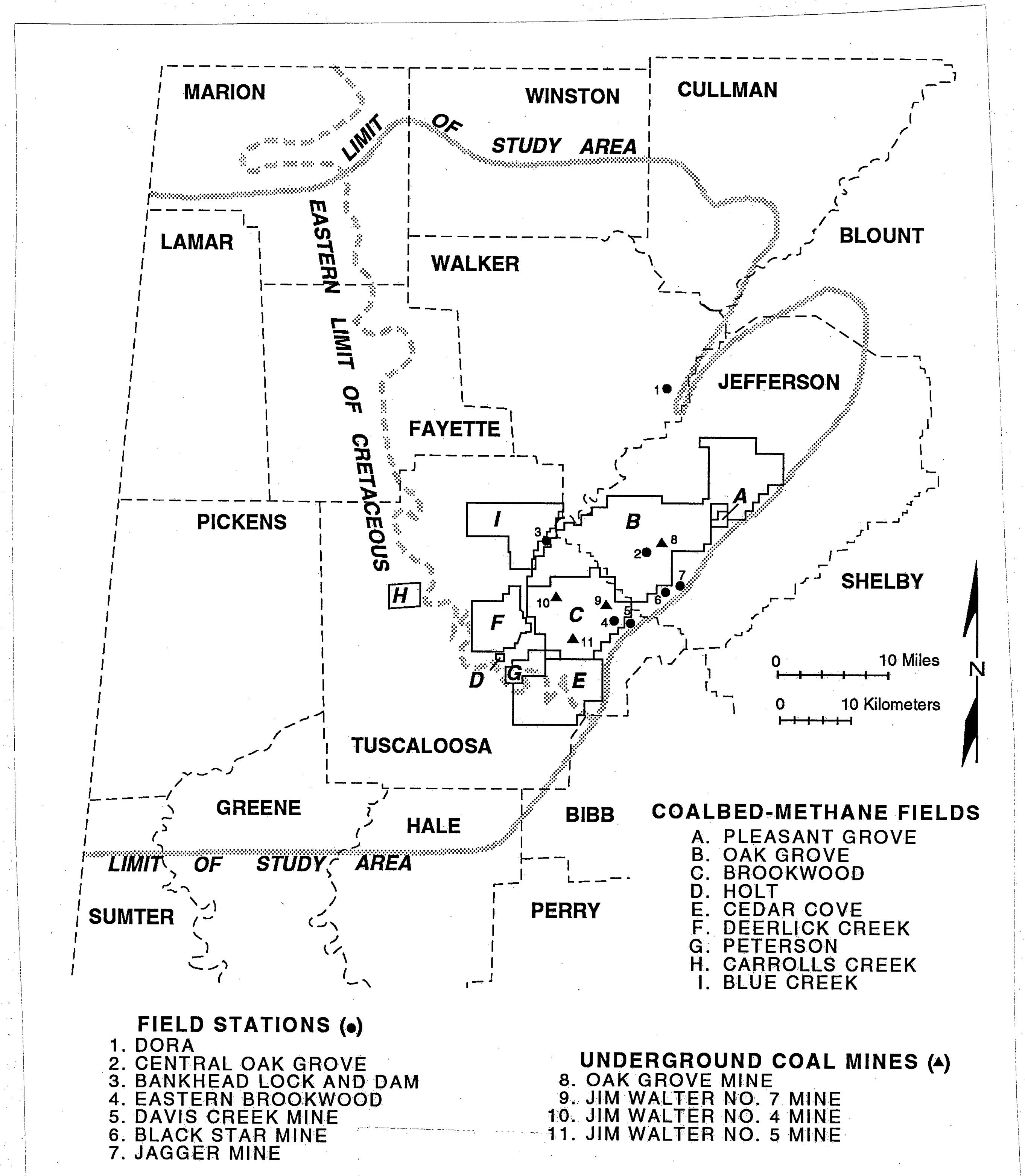


Figure 1. Index map of study area showing location of coalbed-methane fields, underground coal mines, and field stations.

Alabama in 1980. Since that time, coalbed methane has developed into an economically viable energy resource, and the Black Warrior basin leads the nation in coalbed-methane well completion.

As of November 30, 1990, 1,517 coalbed-methane wells were producing in the Black Warrior basin. As of December 31, 1990, 2,265 additional wells were in various stages of drilling and testing, thus making a total of 3,782 coalbed-methane wells in the basin. The established coalbed-methane fields in the Black Warrior basin are in Jefferson and Tuscaloosa Counties (fig. 1). Through November 1990, 83 percent of the coalbed-methane production in the Black Warrior basin has been in Brookwood and Oak Grove fields (fig. 1) where a mutually beneficial relationship exists between underground mining and coal degasification (Elder and Deul, 1974; Epsman and others, 1988; Pashin and others, 1989); drilling in areas unaffected by underground mining is in an early phase.

Cumulative production of coalbed methane in the Black Warrior basin of Alabama has exceeded 125 billion cubic feet (Bcf) in only 10 years. In 1981, coalbed methane represented only 0.04 percent of the gas produced in Alabama, whereas in 1989, coalbed-methane production accounted for more than 34 percent (23 Bcf) of the natural gas produced in the Black Warrior basin of Alabama and approximately 13 percent of the state's total gas production.

The study area chosen for this investigation is the part of the Black Warrior basin of Alabama underlain by the Pennsylvanian upper Pottsville Formation, which contains the principal coalbed-methane target interval (McFall and others, 1986). The Black Warrior basin is the most actively developing coalbed-methane region in the eastern United States and is the only eastern coal basin that contains numerous coalbed-methane wells. Hence, results of this study may serve as important guidelines during initial development of the Appalachian basin of Virginia, West Virginia, Pennsylvania, Kentucky, and Ohio, which has significant coalbed-methane potential (Kelafant and others, 1988).

OAK GROVE FIELD

In addition to the regional study, Oak Grove field (figs. 1, 2) was chosen for a detailed study because (1) data are abundant, (2) the field is representative of geological conditions in most parts of the Black Warrior basin, and (3) it has the longest production history of any coalbed-methane field in the basin. Most of the western part of the field has been drilled with the exception of the Big Indian Creek site which is naturally depleted of methane (Briscoe and others, 1986) (fig. 2). Drilling is just beginning in the northeastern part of the field, which is not included in many of the maps in this text.

The Oak Grove mine, which was established in 1974 and is operated by U.S. Steel Mining Company, is in the east-central part of the field (fig. 2). In the mine, the Blue Creek bed of the Mary Lee coal group is mined at a depth of approximately 1,150 feet. Deep underground coal mines in the Blue Creek bed in Brookwood and Oak Grove fields impact the hydrogeologic system and coalbed-methane production (Briscoe and others, 1988; Epsman and others, 1988; Oyler, 1989; Pashin and others, 1989, 1990).

In 1977 and 1978, a pattern of 23 coalbed-methane wells was drilled immediately east of the mine as part of a U. S. Bureau of Mines pilot program to reduce methane-related mine hazards and to enhance mine productivity. The program demonstrated the feasibility of coalbed methane as an economic resource, and in 1980, Oak Grove field was formally established in the area around the mine by the State Oil and Gas Board. Fewer than 50 wells were on line from 1981 to 1985, and less than 1 Bcf of methane was produced annually. Shortly thereafter, permitting activity increased dramatically, and the field was expanded to its present size in 1988. As of November, 1990, 519 wells had produced 31 Bcf of coalbed methane, and a total of 803 wells had been permitted, the most of any economically producing coalbed-methane field in the United States.

Oak Grove field contains the Rock Creek test site (fig. 2), which is operated jointly by the Gas Research Institute and Taurus Exploration, Incorporated, the principal developer of the field. The Rock Creek site is approximately 2 miles north of the Oak Grove mine and is the principal engineering research center in the eastern United States for the development of multiple coal-seam completion

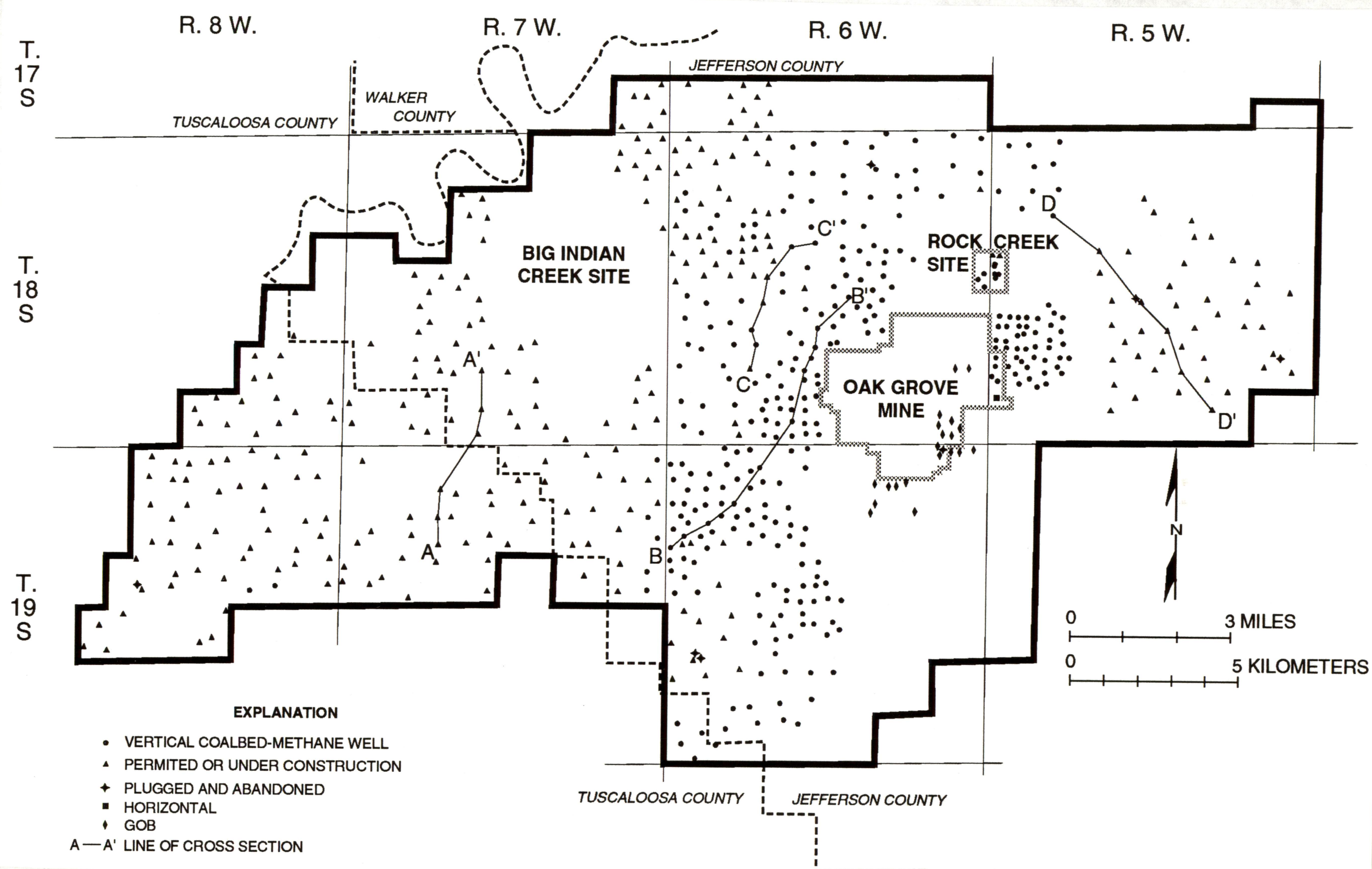


Figure 2. Index map of Oak Grove field showing location of coalbed-methane wells, the Oak Grove mine, the Rock Creek test site, and lines of cross section.

technology. This study includes characterizing the structural geology at the test site to aid engineering investigations.

REGIONAL GEOLOGIC SETTING

The Black Warrior basin (fig. 3) encompasses a triangular area in Alabama and Mississippi that is bounded on the southeast by the Appalachian orogen, on the southwest by the Ouachita orogen, and on the north by the Nashville dome (Mellen, 1947; Thomas, 1988a, b). The Black Warrior basin is contiguous with the Appalachian basin in the northeast and is separated from the Arkoma basin in the west by the Mississippi Valley graben (Thomas, 1988b). Tectonically, the Black Warrior basin is a Late Paleozoic foreland basin that formed flexurally in response to converging Alleghanian thrust and sediment loads in the Appalachian and Ouachita orogens (Beaumont and others, 1988; Hines, 1988).

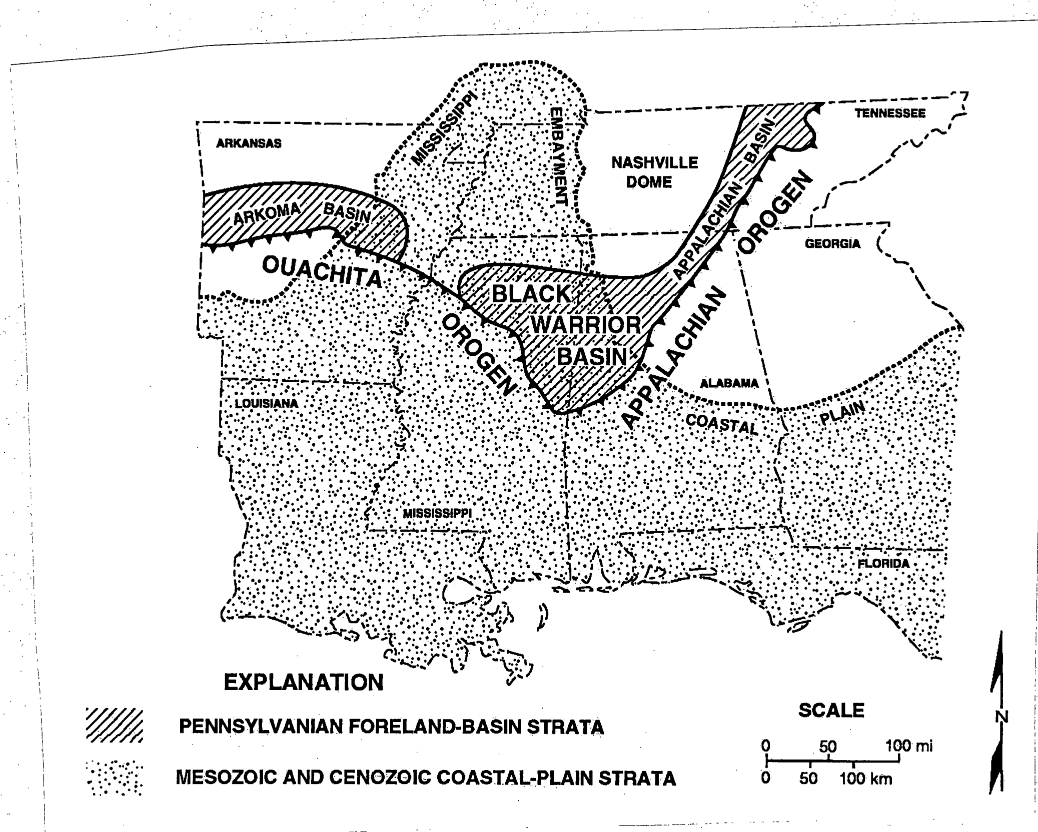


Figure 3. Regional geologic setting of the Black Warrior basin.

The northern margin of the basin is generally considered the outcrop limit of the of the Lower Pennsylvanian Pottsville Formation, which contains all of the coal beds that have been identified as economic coalbed-methane reservoirs. The Pottsville crops out only in the eastern part of the Black Warrior basin in Alabama, and approximately two thirds of the basin is buried beneath Cretaceous and younger overburden of the Mississippi Embayment and the Gulf Coastal Plain (fig. 3). Cretaceous strata of the Tuscaloosa Group overlie the Pottsville Formation disconformably, and adjacent to the deeply buried Ouachita orogen in Mississippi, Mesozoic and Cenozoic overburden is thicker than 6,000 feet. The Tuscaloosa Group consists of unconsolidated sand, gravel, and clay and contains a major aquifer (Coker Formation) that intercepts groundwater recharge west of the Pottsville outcrop area (Pashin and others, 1990).

The Pottsville Formation has been divided into two parts in Alabama (McCalley, 1900). The lower Pottsville is dominated by quartzose sandstone and contains thin, discontinuous coal beds that have not been examined fully for their coalbed-methane potential. The upper Pottsville contains numerous economic coal beds and the majority of Alabama's coal resources (fig. 4). The major coal beds in the upper Pottsville occur in stratigraphic bundles called coal groups (McCalley, 1900); coal groups have formed the basis of most stratigraphic subdivisions of the upper Pottsville (McCalley, 1900; Butts, 1910, 1926; Culbertson, 1964; Metzger, 1965).

Coal groups generally cap regressive, coarsening-upward sequences, or cycles (fig. 4). The cycles have as much as 350 feet of marine mudstone at the base and typically coarsen upward into sandstone. At the top of each cycle is the interbedded mudstone, sandstone, underclay and coal that make up a coal group. Subsurface investigations indicate that most cycles can be traced throughout the Black Warrior basin (Cleaves, 1981; Sestak, 1984; Hines, 1988).

The Black Creek-Cobb interval of the upper Pottsville (figs. 4, 5) is the major coalbed-methane target zone in Alabama (McFall and others, 1986). The Black Creek-Cobb interval contains 5 regionally extensive cycles named (1) Black Creek, (2) Mary Lee, (3) Gillespy/Curry, (4) Pratt, and (5) Cobb after the associated coal groups. Subdivision of some cycles is possible. For example, the Black Creek cycle was subdivided into lower and upper subcycles, which can be identified only in the eastern part of the

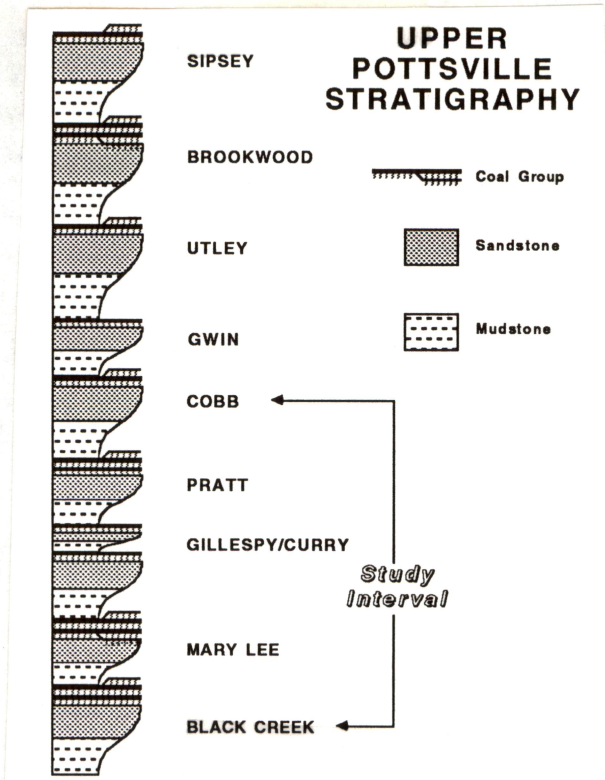


Figure 4. Stratigraphy of the upper Pottsville Formation showing major depositional cycles.

study area, to aid subsurface mapping in Oak Grove field. The Gillespy and Curry coal beds (Gillespy/Curry cycle) were separated from the Pratt coal group (Pratt cycle) because they cap separate genetic sequences that are regionally extensive (Pashin and others, 1990). Bed names are most readily applied in the Mary Lee and Gillespy/Curry cycles and are listed in figure 5. As a rule, however, coal-body geometry is too complicated to apply bed names in most cycles except in local studies.

STRUCTURAL GEOLOGY: FRACTURE ARCHITECTURE

INTRODUCTION

The objectives of this chapter are to synthesize the available structural data to define the attitude, fracture architecture, and structural history of coal-bearing strata in the Black Warrior basin. Regional structure controls burial depth which, along with geothermal history, determines how much methane may have been generated during coalification. Structure also affects the depth at which coal occurs and consequently how much methane may be retained in the coal following erosional

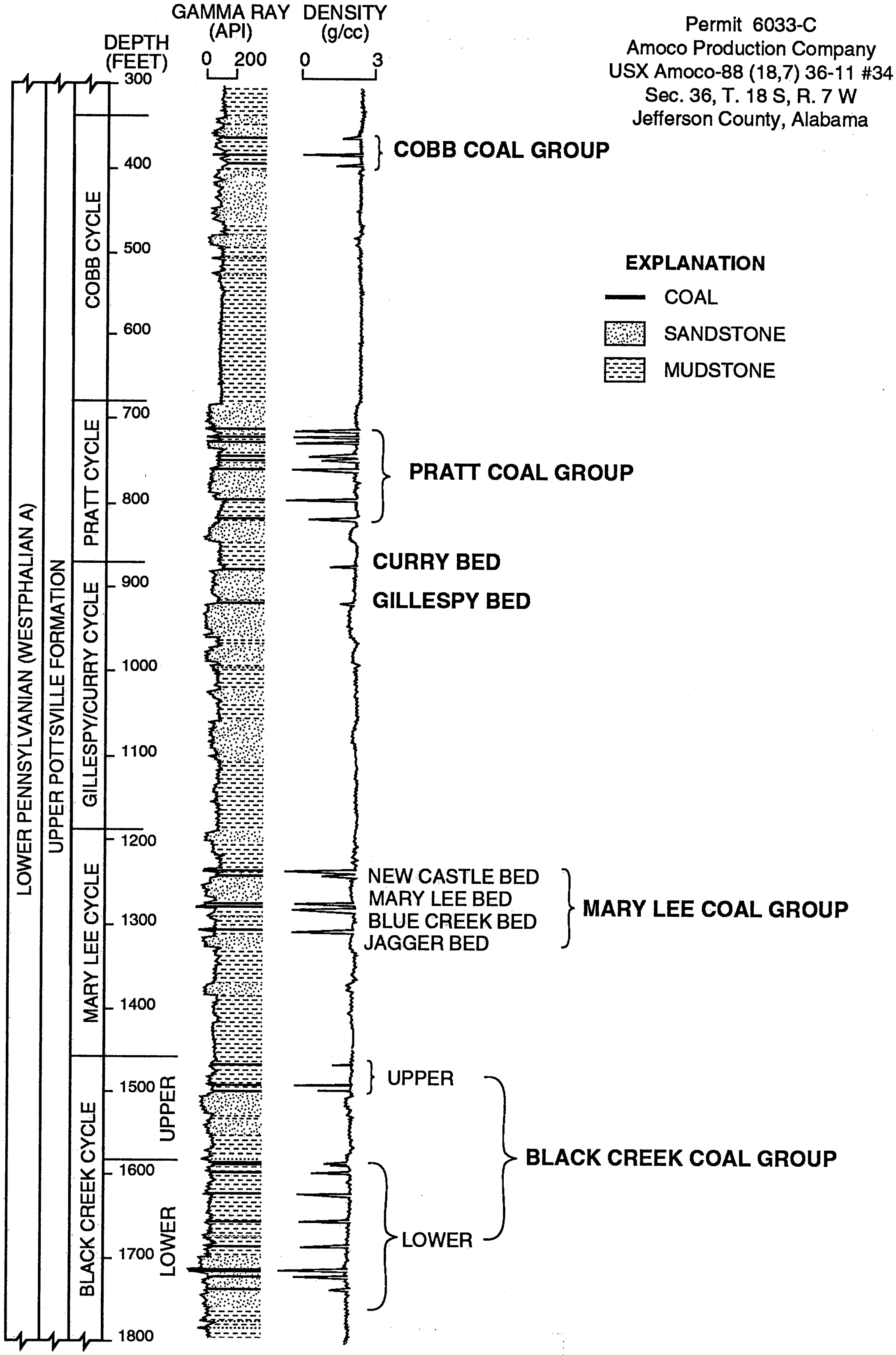


Figure 5. Sample coalbed-methane well log of Black Creek-Cobb interval showing depositional cycles and named coal beds used in sedimentologic analysis.

unroofing of the sedimentary basin (Jüntgen and Karweil, 1966). The distribution and openness of fractures also play a major role in determining the pathways along which water and gas may migrate.

Geologic structure is a unifying concept in this study because it affected sedimentation, coalification, hydrogeology, and the ultimate occurrence and producibility of coalbed methane in the Black Warrior basin. Structural methods are critical for coalbed-methane exploration and production planning because they are necessary to define the attitude, depth, and fracture architecture of target coal-bearing strata. Fracture analysis is critical for identifying avenues of permeability and for showing how permeability varies with respect to folds, thrust faults, normal faults, joints, cleats, and associated fractures. Structural analysis confirms that the Black Warrior basin had a polyphase tectonic history that included Alleghanian orogenesis, Mesozoic rifting, and ongoing epeirogenesis. This polyphase history resulted in diverse structural patterns that today affect fluid flow, and hence, the occurrence and producibility of coalbed methane.

METHODS

To define the attitude of Pottsville strata, a structural contour map of the top of the Mary Lee cycle was drawn using data from density logs (fig. 6). Numerous faults and folds in the Black Warrior basin are too small to be shown at the scale of a basin-wide structural contour map. Therefore, an additional map showing the location of folds and faults was made; the map is based on (1) reports and dockets on file at the State Oil and Gas Board (2) maps that are on file at the Geological Survey of Alabama, and (3) published reports (Kidd, 1982; Ward and others 1984, 1989; Epsman,1987; Raymond and others, 1988). A structural contour map of the top of the Mary Lee coal bed in Oak Grove field also was made to clarify structural relationships in the eastern part of the Black Warrior basin.

Folds, faults, joints, cleat, and associated fractures were described in Oak Grove and Brookwood fields and adjacent areas where structural features are well exposed. Joint, cleat, and lineament orientation were mapped regionally and locally or were compiled from the files of the Geological Survey of Alabama. Joint and cleat data are available only from Pottsville outcrops and underground

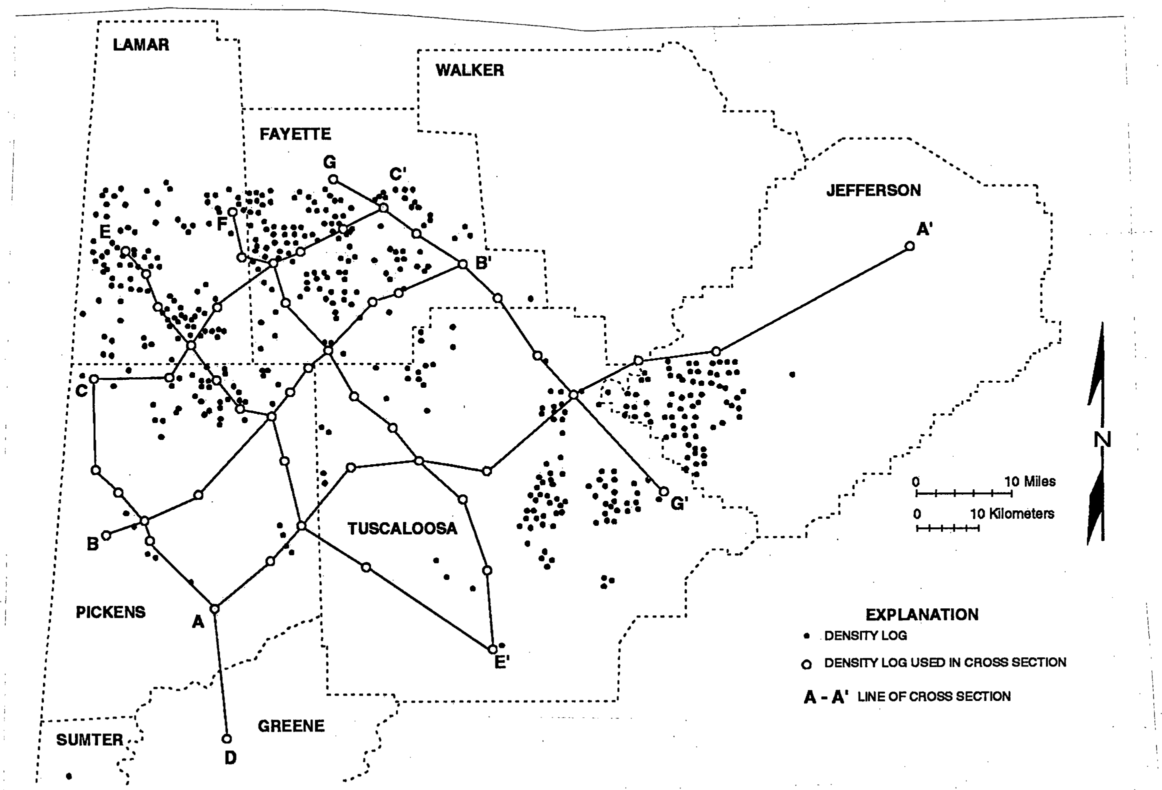


Figure 6. Location of wells and cross sections used in regional structural and sedimentologic analysis.

coal mines, because fractures are generally not exposed in unconsolidated Cretaceous and Tertiary strata owing to deep weathering.

A regional lineament map was made using Landsat band 6 and 7 images (scale 1:250,000). Lineaments on the map are straight stream segments, topographic offsets, and tonal anomalies. To test the relationship of lineaments to geological features in central Oak Grove field, lineaments from Landsat, Sidelooking Airborne Radar (SLAR) (scale 1:250,000; east-west look direction), and orthophotoquads (scale 1:24,000) were compared with structural data from the field.

FOLDS AND THRUST FAULTS

Appalachian folds and thrust faults strike approximately N 40° E and occur along the southeastern margin of the Black Warrior basin (figs. 7, 8). The basin is bounded on the southeast by the Birmingham anticlinorium of the Valley and Ridge province. Thrust faults occur in the core of the anticlinorium, and Cambrian-Ordovician carbonate rocks are exposed along the axial trace of the

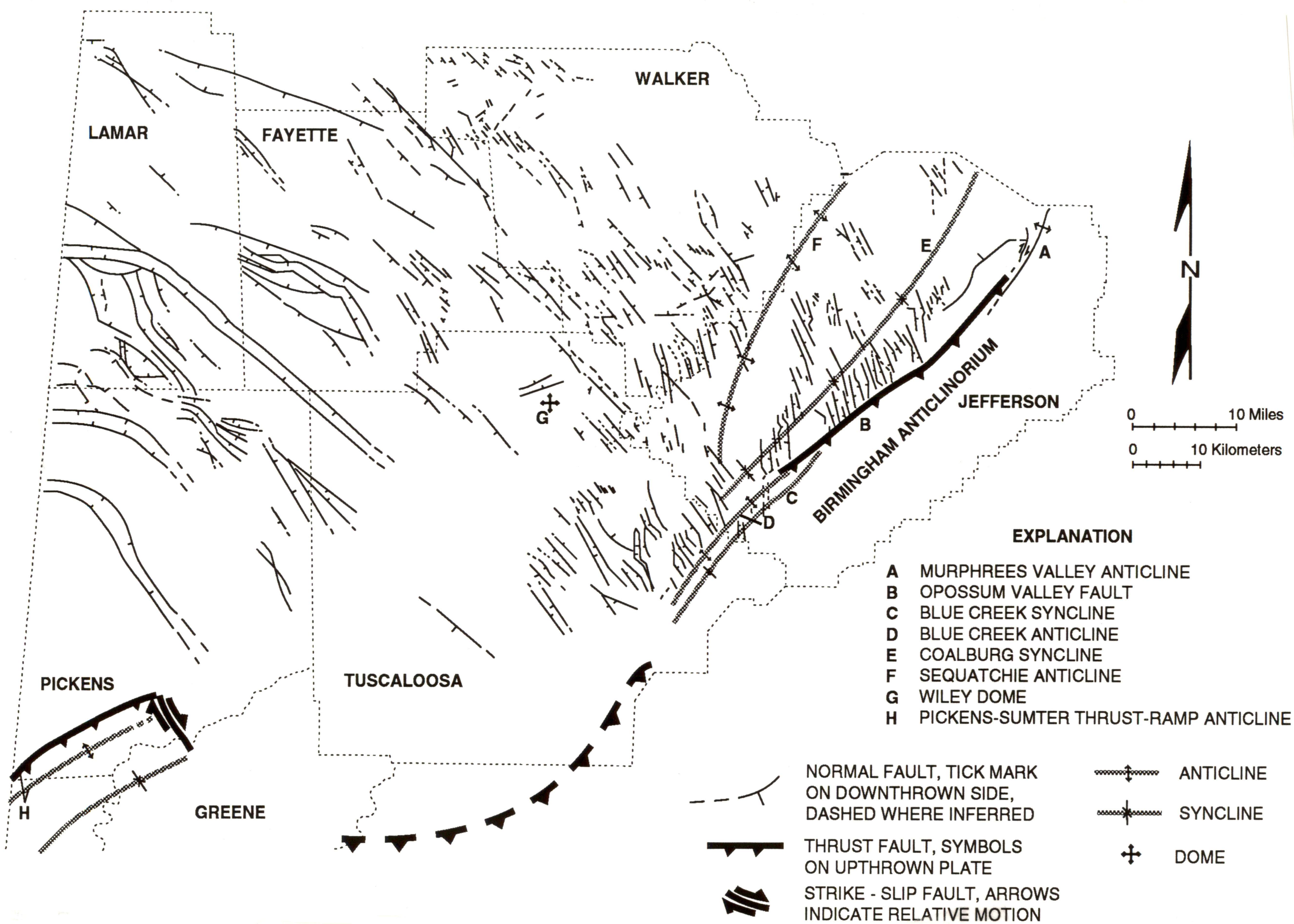


Figure 7. Folds and faults, Black Warrior basin, Alabama.

Figure 11. Reverse fault in mudstone with convoluted shaly gouge.

Figure 12. Reverse fault in mudstone and sandstone with convoluted shaly gouge and fractured sandstone gouge. Note that gouge tapers downward in mudstone.

in the Mary Lee group. Displacement is generally less than 10 feet, and the faults are oblique to primary bedding by less than 8° and scarcely penetrate adjacent strata.

NORMAL FAULTS

Normal faults are abundant throughout the Black Warrior basin and define a series of linear to arcuate horst-and-graben systems (figs. 7, 8). The faults are generally oriented northwest and turn westward in Mississippi. In the easternmost part of the basin, fault length generally is less than 2 miles, and fault throw generally is less than 200 feet; regional dip is approximately 70 feet per mile ($<1°$). In eastern Pickens County, however, several contours turn sharply northward and mark a hinge zone to the east of several arcuate faults. The faults define a series of narrow grabens in Lamar and Pickens Counties that extend for tens of miles and have throw in excess of 1,000 feet.

A structural contour map of the unconformable surface at the top of the Pottsville Formation (Kidd, 1976) (fig. 13) indicates that the surface strikes northwest and that dip increases gently toward the southwest. Structure contours parallel those on the Mary Lee map in the southwesternmost part of the map area, but contours are oblique elsewhere. The map indicates that normal faults do not penetrate Cretaceous strata, and cross sections from Mississippi (Thomas, 1988a) indicate that normal faults in the Pottsville terminate at the unconformable surface.

The structural contour map of Oak Grove field shows a strong relationship between normal faults, the Coalburg syncline, and the Sequatchie anticline (fig. 10). Right-stepping horst-and-graben systems are abundant in the Coalburg syncline, and a major system traverses the south-central part of Oak Grove field; that system marks the southwest limit of the Sequatchie anticline and the Coalburg syncline. Strike of the faults is N 20-40° W; throw is locally 80 feet and generally decreases toward the north-central part of the field. In addition, trace length generally decreases from 4 miles in the south to 1 mile in the north, and fault orientation becomes less consistent toward the north.

Three normal faults are well exposed in the Oak Grove area. At Bankhead Lock and Dam (NE$\frac{1}{4}$ sec. 27, T. 18 S., R. 8 W.; fig. 1), a normal fault strikes N 25° W and dips 80° NE. Throw of the fault is approximately 200 feet (Rheams and Benson, 1982), and marine mudstone of the Brookwood cycle is

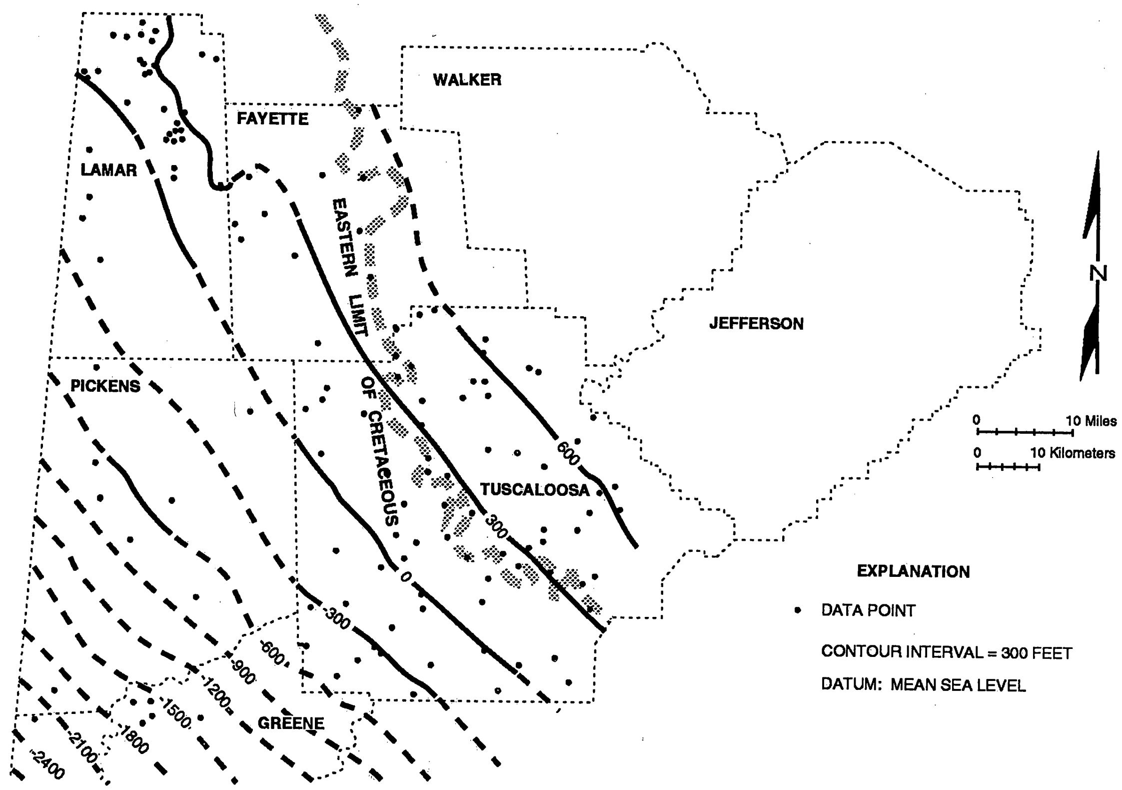


Figure 13. Structural contour map of the unconformable surface at the top of the Pottsville Formation, Black Warrior basin, Alabama (after Kidd, 1976).

in contact with marginal-marine sandstone of the Utley cycle (fig. 14). The fault contains approximately 1 foot of shaly gouge and intensely fractured sandstone and includes a sandstone horse block that has been transported down the fault plane.

A fault plane in central Oak Grove field (SE$\frac{1}{4}$ sec. 32, T. 18 S., R. 6 W.; fig. 1) was exposed by road construction. The fault strikes N. 35° W and dips 80° SW; it has a throw of approximately 100 feet and juxtaposes marine mudstone of the Utley cycle with terrestrial sandstone and mudstone of the Gwin cycle. Numerous drag structures occur along the fault trace. Drag folds occur in a zone approximately 3 feet wide in the mudstone, whereas fibrous slickensides and closely spaced (approximately 2 inches) shear fractures are abundant in the sandstone.

Another fault is exposed in easternmost Brookwood field (NE$\frac{1}{4}$ sec. 13, T. 20 S., R. 7 W.; fig. 1). The fault strikes N 25° W and dips 50° NE, which is low for normal faults in the Black Warrior basin. Stratigraphic relationships indicate that net slip is normal and approximately 30 feet. In the footwall,

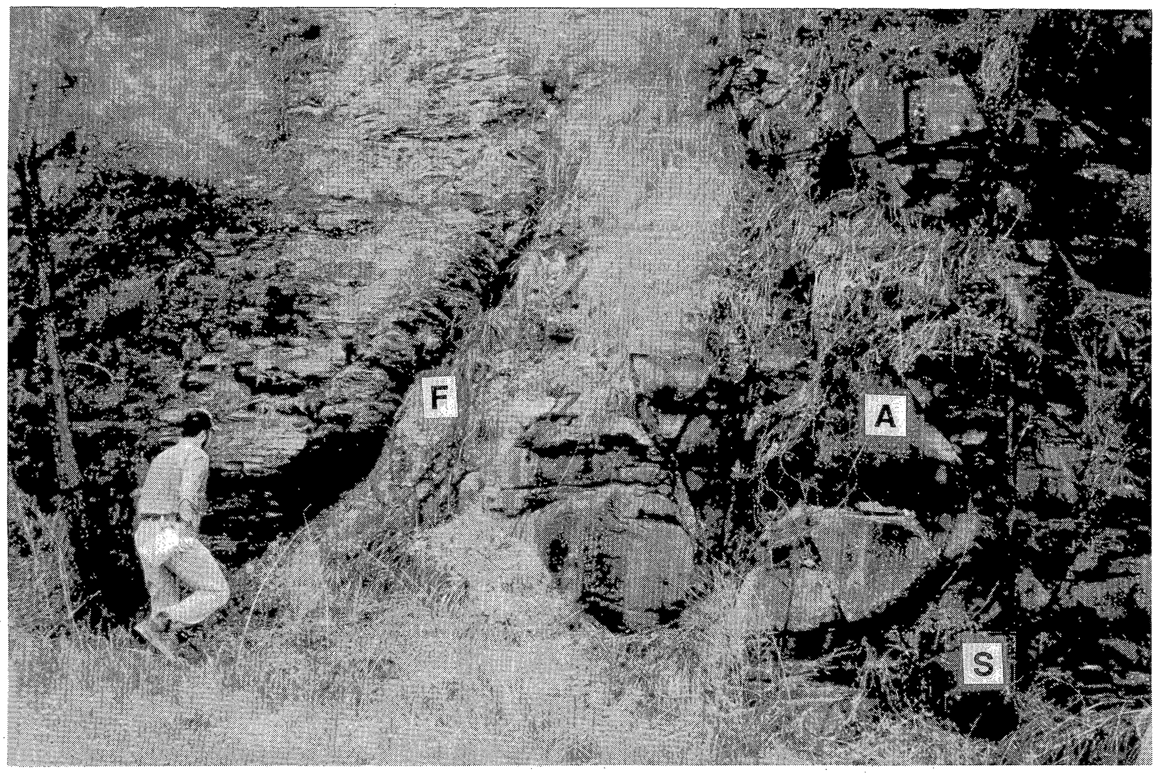


Figure 14. Normal fault at Bankhead Lock and Dam showing fault gouge and fault-related shear fractures (F = fault gouge, S = synthetic joint, A = antithetic joint).

however, drag folds and reverse faults with less than 1 foot displacement indicate that the last episode of fault movement was reverse.

Faults with other characteristics are exposed in the Oak Grove mine (fig. 15). One normal fault is associated with a small rollover structure (McDaniel, 1986), and several normal faults contain horizontal slickensides that demonstrate a strike-slip component (Epsman and others, 1988). One strike-slip fault contains several feet of mudstone and sandstone gouge that posed a significant mining hazard (McDaniel, 1986). Thus far, the largest normal fault observed in the mine has net throw of only 7 feet.

STRUCTURAL GEOLOGY OF THE ROCK CREEK SITE

Structural contour maps of the top of the Mary Lee and Pratt coal beds at the Rock Creek site (fig. 16) were made to clarify local geology and to aid in application of well-siting and well-completion techniques. The Mary Lee map shows anticlines and synclines with axial traces that trend northeast,

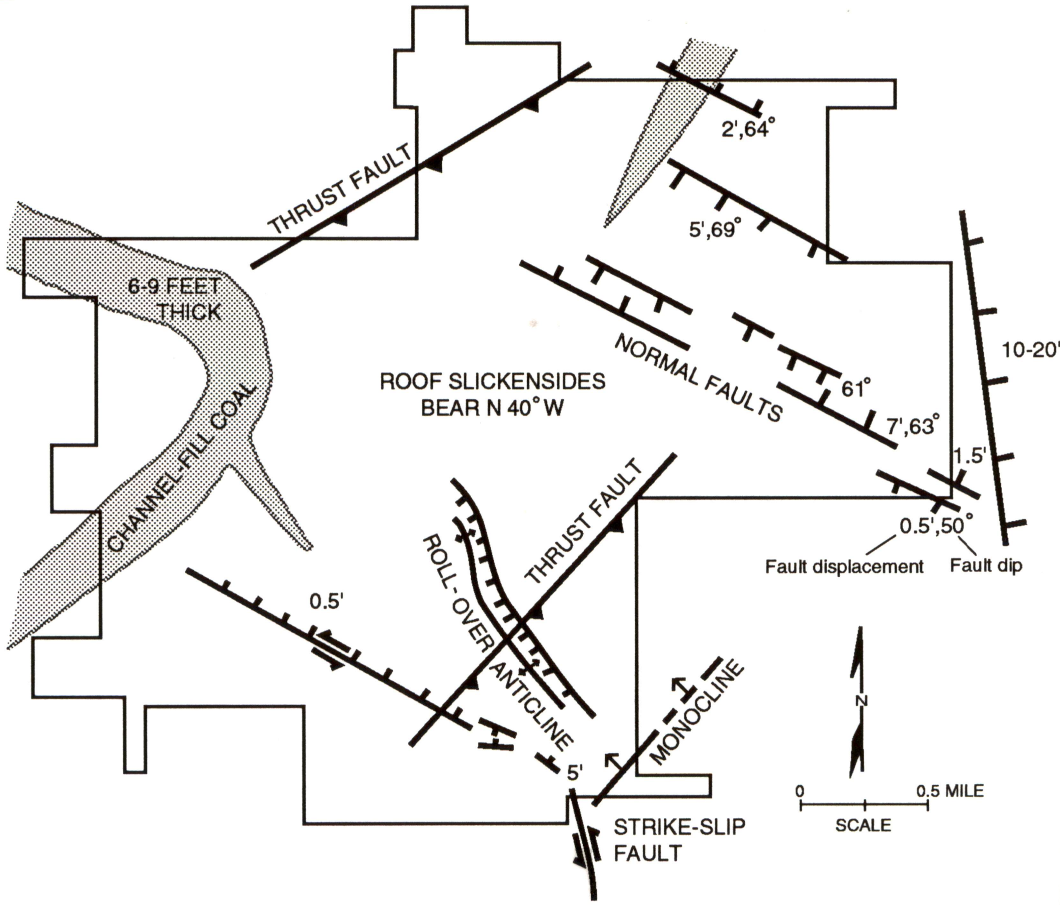


Figure 15. Geologic structures in the Oak Grove mine (after McDaniel, 1986).
See figure 2 for mine location.

whereas the Pratt structure map depicts a southeast-dipping surface that curves northeast and has approximately 40 feet of structural relief.

Pashin and others (1990) suggested that the structure in the Mary Lee is compactional. The Blue Creek bed fills channels in the nearby Oak Grove mine (McDaniel, 1986) (fig. 15), so the structural contours may also reflect accumulation of peat on an erosional surface. As is the case with the Mary Lee map, much of the structure in the Pratt can be accounted for by differential compaction following sedimentation. The isopach map of the siliciclastic interval between the upper two coal beds of the Pratt cycle shows that the interval thins by 20 feet from west to east (fig. 16). Therefore, only 10 feet of structural relief along the southern part of the structure may not be accounted for by

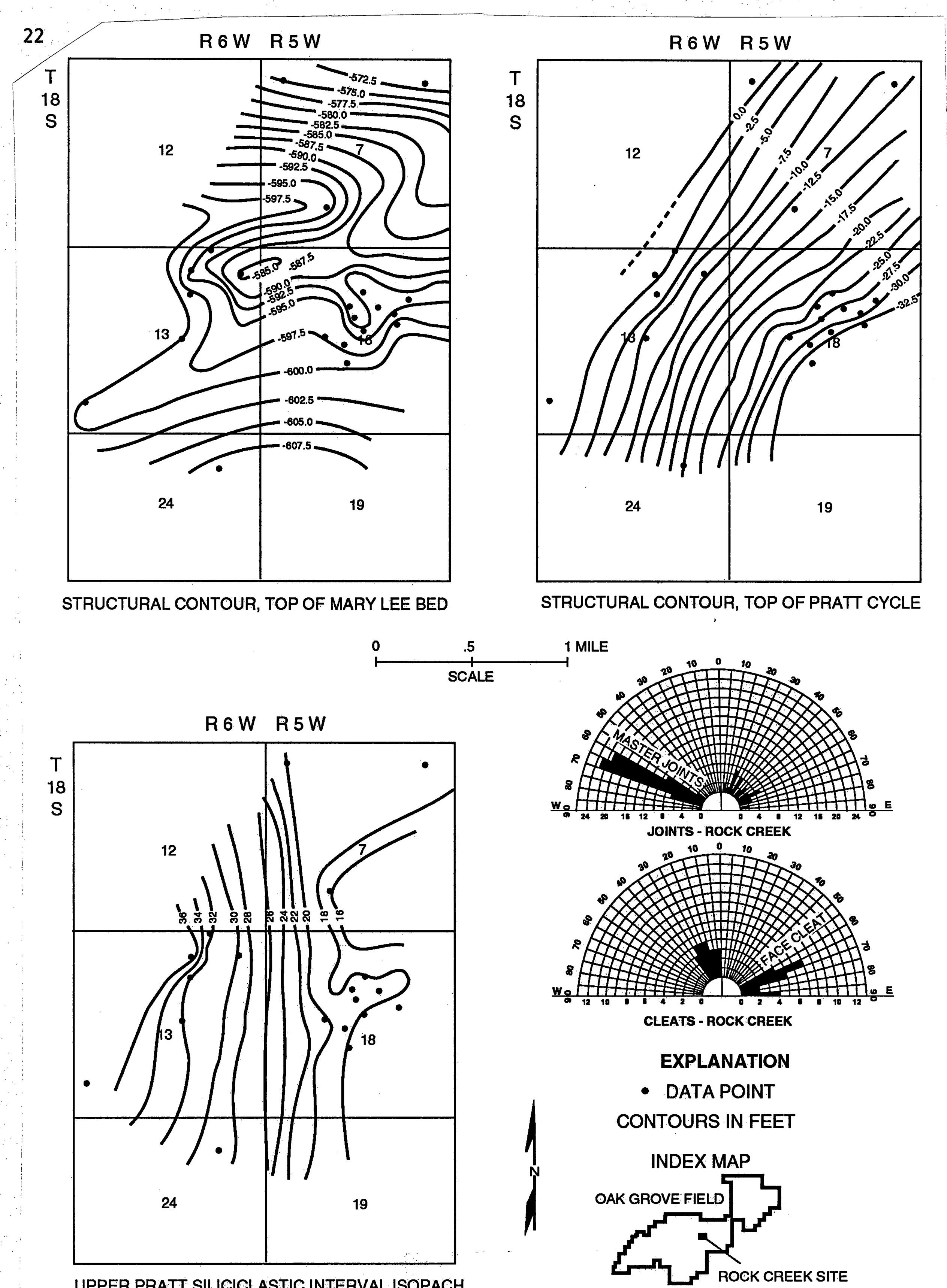


Figure 16. Structural geology of the Rock Creek test site.

differential compaction. However, thickness of the siliciclastic interval is fairly uniform in the north where the contours may more accurately reflect structure.

Results of mapping indicate that structural contour maps based on different coal beds in the same area may bear little resemblance to each other. Therefore, local structure maps should be interpreted with caution. Even so, such maps are useful in coalbed-methane exploration and production, because they define the attitude of target coal beds and thus provide a basis for predicting coal occurrence.

JOINTS

Two regional joint systems, systems A and B, occur in the Black Warrior basin (Ward, 1977; Ward and others, 1984; Pashin and others, 1990) (fig. 17). Each system is composed of a well-developed master joint set (set I) and a poorly developed orthogonal complement (set II). Set I joints are generally planar and vertically persistent (fig. 18), whereas set II joints commonly curve in plan view and cross section. Many joints are simple fractures, whereas others, especially set II joints, are broad fracture zones. The fracture-zone style of jointing has been observed only at the surface and may simply be a weathering phenomenon. Cross-cutting relationships among the joint sets are in places inconsistent, but set II joints commonly abut set I joints.

System A joints are distributed throughout the Pottsville outcrop area (fig. 17), and on the basis of 463 readings, the master set has a vector-mean azimuth of N 47° E. In contrast, system B joints occur only in the vicinity of the Appalachian folds (Sequatchie anticline and Coalburg syncline), and on the basis of 356 readings, the master set has a vector-mean azimuth of N 64° W. Where system A and B joints occur together, system B joints are most abundant. Master joints are strongly aligned and have consistency ratios (Potter and Pettijohn, 1977), or degrees of alignment, of 93 (system A) and 94 (system B). System B joints have a lower consistency ratio than system A joints because they are generally perpendicular to the curving axial trace of the Sequatchie anticline.

Data from underground mines demonstrate that subsurface joint populations differ from those at the surface. For example, set II joints are scarce in the Jim Walter #4 mine in Brookwood field (fig. 1) at a depth of more than 2,000 feet and in the Oak Grove mine at an approximate depth of 1,150

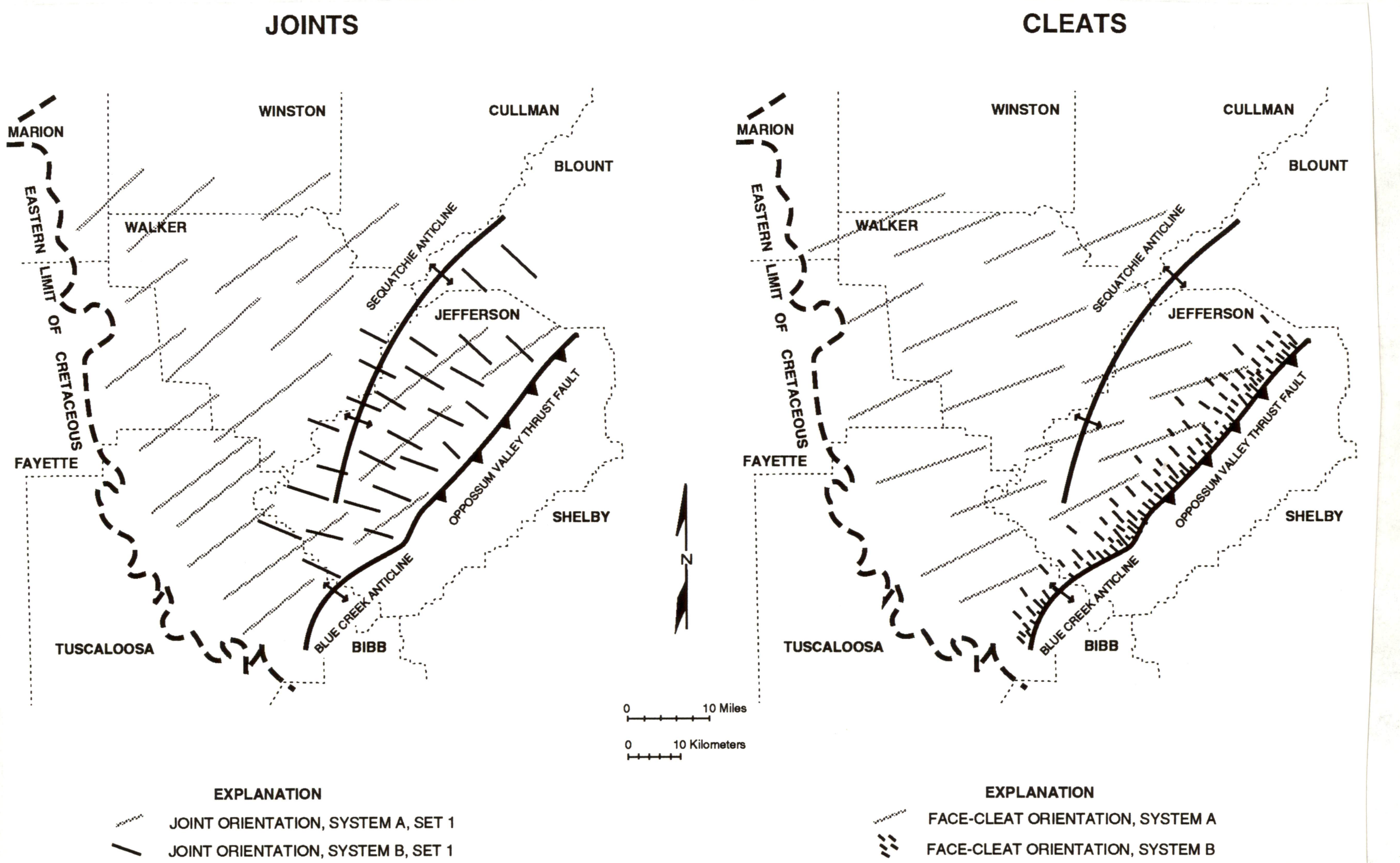


Figure 17. Joint and cleat systems of the Black Warrior basin.

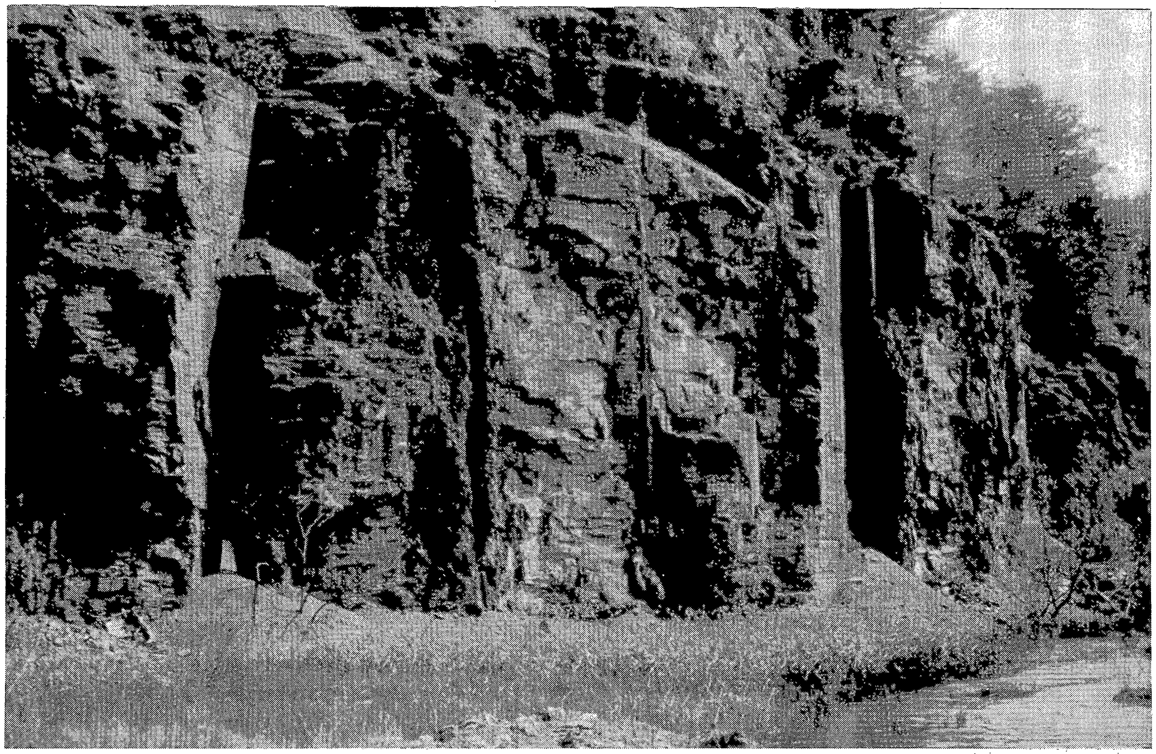


Figure 18. Planar set I joints in abandoned mine highwall, Oak Grove field.

feet. Additionally, system A and system B joints are abundant in the Jim Walter # 4 mine, whereas only system A joints are common above the mine at the surface.

Dipping synthetic and antithetic joints are associated with normal faults. These fractures dip steeper than 45°; synthetic joints parallel the associated fault plane, whereas antithetic joints are the dihedral complement, or mirror image, of the fault plane. Such joints are most common in the footwall of faults and are generally simple, planar structures. However, some of the fractures have more than 1 inch of reverse throw. Most synthetic and antithetic joints strike parallel to the associated fault and can be used to determine the presence and orientation of a fault in the field.

Fault-related joints are well exposed at the Bankhead Lock and Dam (figs. 1, 14). The joints are abundant in the sandstone of the footwall and occur only within 100 feet of the fault. However, joints in the mudstone of the hanging wall are poorly and sporadically developed and only occur within 30 feet of the fault. The fractures strike N 20° W, parallel to the fault; synthetic joints dip 50-

70° NE, whereas antithetic joints dip 50-70° SW. Antithetic joints are much more common than synthetic joints, and spacing increases systematically away from the fault plane. Synthetic joints, in contrast, are irregularly spaced and only sporadically developed.

CLEAT AND OTHER FRACTURES IN COAL

Cleat is a miner's term for joints in coal; cleat is much more closely spaced than joints in adjacent rocks. Face cleat is the master joint set that is perpendicular to bedding, planar, laterally persistent, strongly aligned, and generally is evenly spaced. Butt cleat is typically orthogonal to the face cleat and commonly has an irregular surface. Butt cleat commonly terminates where it intersects the face cleat, indicating that the butt cleat is younger. Face-cleat spacing varies regionally in the Black Warrior basin and increases from approximately 0.2 inch along the Blue Creek anticline to 0.75 inch in the northwesternmost part of the Pottsville outcrop area (McFall and others, 1986).

Calcite is the most common cleat-filling mineral in the Black Warrior basin, although pyrite and clay occur at some localities. In surface exposures, reddish ferruginous stain and yellowish to whitish sulfate stain are common on face-cleat planes. Stained butt-cleat surfaces are scarce. Cleat fillings vary in abundance in the Pottsville outcrop area. Where present, cleat fillings are generally patchy, occupy only a small proportion of the fracture system, and are developed mainly on the face cleat. At most outcrops, the fill ranges from a thin film to as much as 0.2 inch wide; only the widest cleat fills extend for more than 2 feet.

As with joints, two cleat systems, systems A and B, occur in the Black Warrior basin (fig. 17). System A occurs throughout the Pottsville outcrop area, and cleat orientation is uniform; cleat orientation in underground mines corresponds closely with that at the surface (McCulloch and others, 1976; Ward and others, 1984). The vector-mean azimuth of the face cleat of system A is N 62° E, and the consistency ratio is 91. However, a local cleat system, system B, occurs along the southeast basin margin near the Blue Creek anticline and the Opossum Valley thrust fault (figs. 7, 17). These fractures locally obscure and cut across the regional cleat system. System B face cleat is perpendicular to the axial trace of the Blue Creek anticline and has a vector-mean azimuth of N 36° W; butt cleat is generally not apparent and may coincide with the face cleat of system A. Along the Blue Creek anticline and Opossum Valley thrust fault, spacing of the local cleat system is approximately 0.2 inch, and only 3 miles northwest, cleat spacing is approximately 3 inches. Cross-cutting relationships between the joint and cleat systems are inconclusive.

In the Oak Grove mine, the Blue Creek coal bed is internally deformed and has unusual fracture systems. Similar systems were observed in the Mary Lee coal group at surface mines along the Blue Creek anticline and syncline. In many areas, these fracture systems occur adjacent to normal and thrust faults. Inclined fractures are extremely abundant and are in places spaced closer than 0.125 inch; close fracture spacing obscures coal banding in outcrop. The fractures generally dip 40 to 60° SE and are curved in plan. Most of the fractures curve approximately 120°, are 1 to 3 feet long, and define a fanlike pattern. Some fractures are strongly curved and contain shear cones (cone-in-cone structures) between 1 and 3 inches wide and tall; similar structures have been described from coal in West Virginia, Great Britain, and New Zealand (Price and Shaub, 1963).

Polished slabs establish that coal banding is preserved and largely undisturbed—even where fractures are closely spaced (fig. 19). Inclined fractures are best developed in dull bands (clarain), whereas bright bands (vitrain) also contain vertical fractures resembling normal cleat; fusain lenses are generally not fractured. Some bands are dislocated along normal faults and thrust faults with displacement less than 1 inch, and horizontal and inclined slickensides were observed in some beds. In the Oak Grove mine, slickensides on the mine roof bear approximately N 40° W (fig. 15), and the faults and slickensides give a sense of northwest-directed, bedding-parallel shear.

TOPOGRAPHIC LINEAMENTS

Topographic lineaments may represent the surface expression of fracture zones; some of those zones could have enhanced permeability. Lineaments pose an interpretive difficulty in petroleum exploration, however, because they are surface features. Therefore, the origin of a given lineament is difficult to interpret unless it can be related to a specific geologic structure. The following discussion is a general account of lineament populations in the Black Warrior basin of Alabama. Results indicate

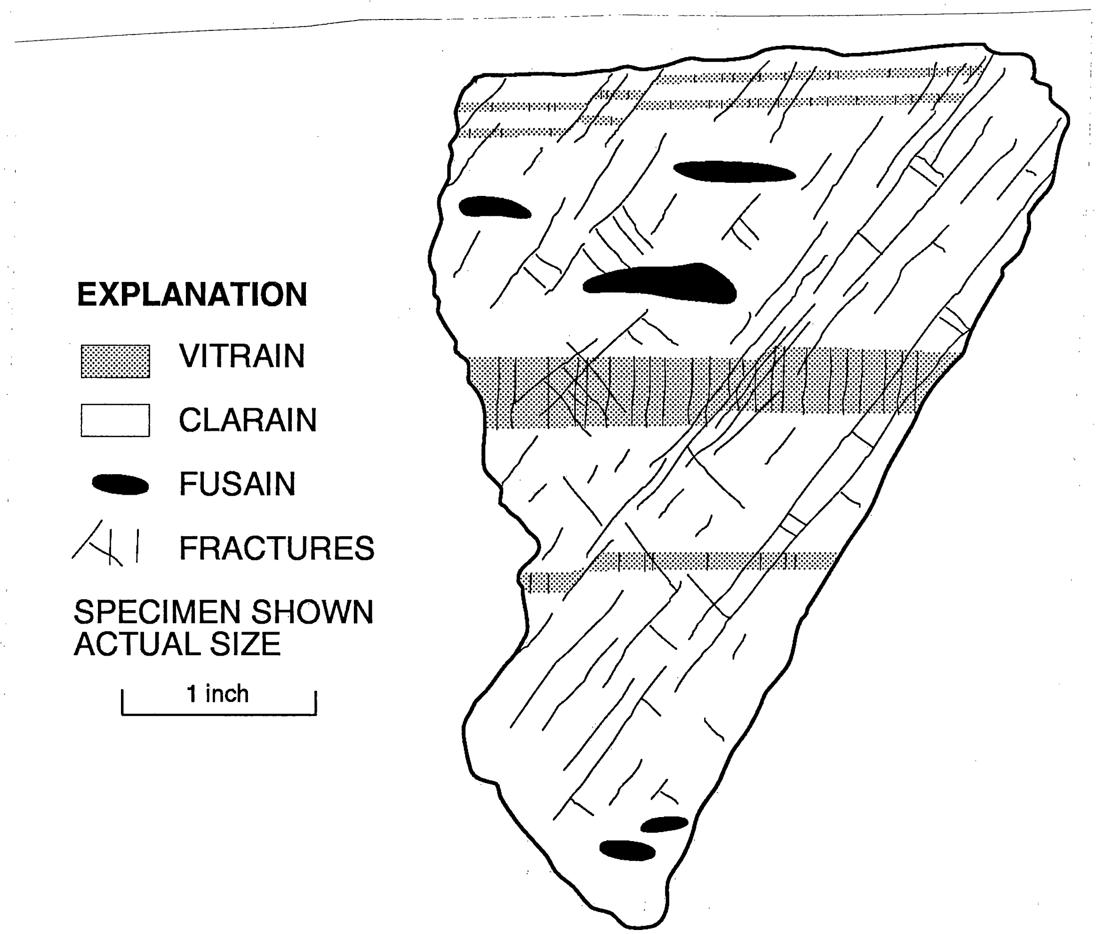


Figure 19. Sketch of polished coal slab from the Jagger mine showing relationship of fractures to bright and dull coal bands.

that determining the origin of lineaments is difficult and that caution should be applied in using lineament analysis for developing coalbed-methane exploration and production strategies. However, advanced image-analysis techniques, which were not employed in this study, may provide insight into the utility of remotely sensed data in strategic well siting.

The Landsat lineament map of the Black Warrior basin (fig. 20) contains more than 90 percent northeast (N 20° E to N 70° E) and northwest (N 20° W to N 70° W) lineaments. As a rule, therefore, these lineaments span only 56 percent of the compass. Although a regional lineament map may demonstrate the general topographic grain of a sedimentary basin, such maps are of limited use for petroleum exploration, because most lineaments are too short to be shown. Moreover, lineaments

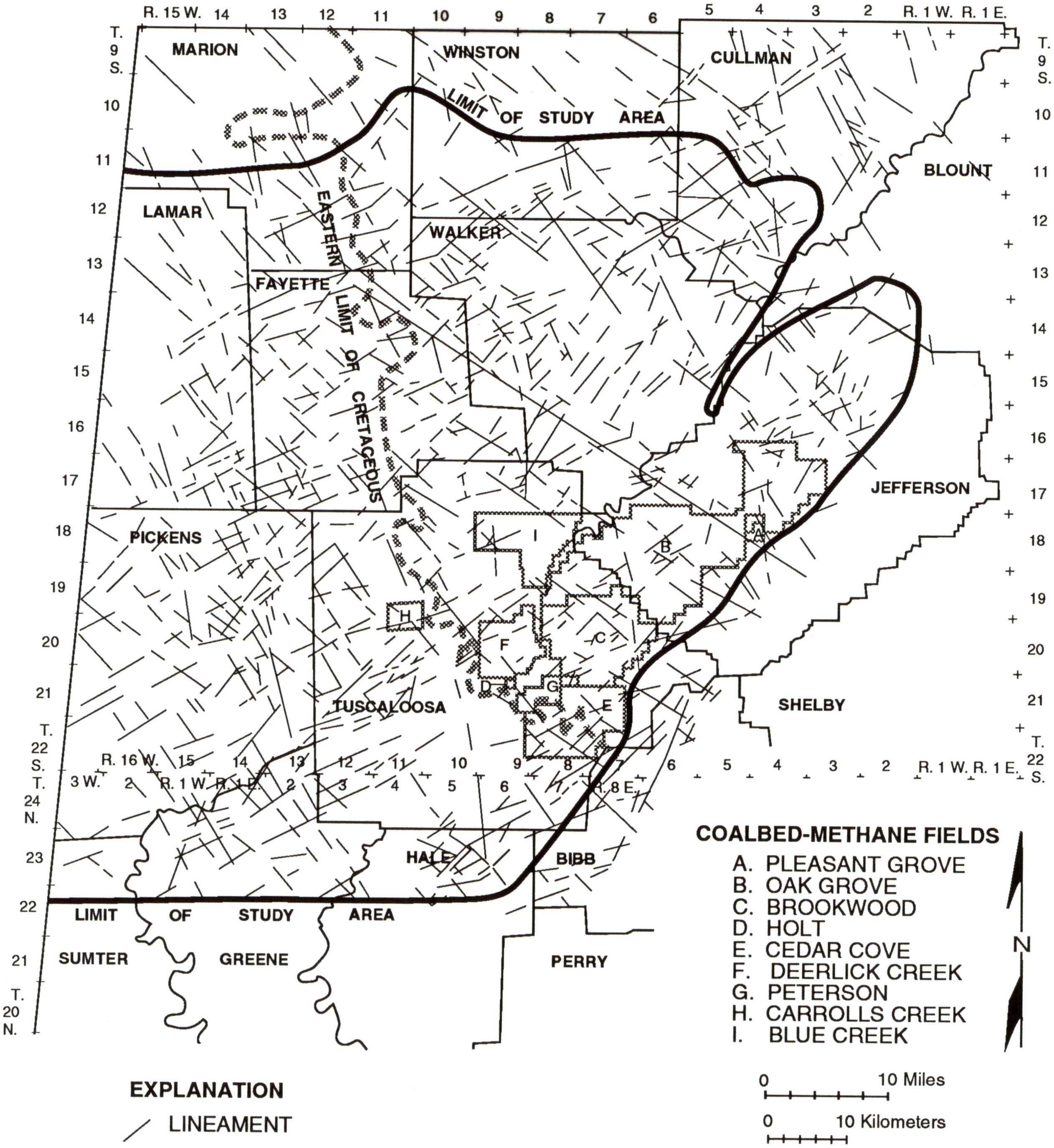


Figure 20. Lineaments from Landsat bands 6 and 7 scenes, Black Warrior basin, Alabama.

are plotted differently at various map scales, and as a rule, more lineaments with shorter length are identified at a map scale of 1:24,000 than at a map scale of 1:250,000.

Like the basin, Oak Grove field contains dominantly northeast and northwest lineaments (figs. 21-23). Landsat and SLAR lineaments (scale 1:250,000) are generally longer than 1 mile, whereas orthophotoquad lineaments (scale 1:24,000) are generally shorter than 0.5 mile; the difference in lineament length reflects a difference in imagery scale (figs. 21, 22). Comparison of rose diagrams establishes that each type of imagery yields different lineament populations (fig. 23). Northeast lineaments comprise more than 80 percent of the Landsat population, whereas northeast and northwest lineaments are evenly distributed on the orthophotoquads; SLAR imagery shows three peaks at N 55° W, N 25° W, and N. 55° E.

Relating lineament trends to structural trends is difficult. Orthophotoquad lineaments correspond with the vector-mean joint, cleat, and fault orientations, but lineament populations representing each type of structure are not separable from each other (fig. 23). Landsat and SLAR data have peaks that match the vector-mean azimuth of set I joints of system B, and the SLAR peak at N 25° W corresponds approximately with vector-mean fault orientation. However, normal-fault orientation ranges from N 8° W to N 43° W, so the origin of the SLAR peak is enigmatic.

More lineaments in central Oak Grove correspond with the face cleat of system A than any other type of structure (fig. 23). Cleat is restricted to coal, however, and thus probably does not have a significant effect on surface topography. Rather, lineaments oriented between N 50° E and N 70° E have been interpreted as part of a lineament set that extends from Mississippi to Georgia that also occurs in Cretaceous and younger deposits; these lineaments coincide locally with open fracture systems and enhanced water yield from wells drilled in various stratigraphic intervals (Richter, 1990).

INTERPRETATION OF STRUCTURAL HISTORY

ALLEGHANIAN FOLDING

Appalachian folds and thrust faults (figs. 7, 8) evidently formed in Pennsylvanian and Permian time in response to compressional forces of the Alleghanian orogeny (Thomas, 1985a, 1988b). The

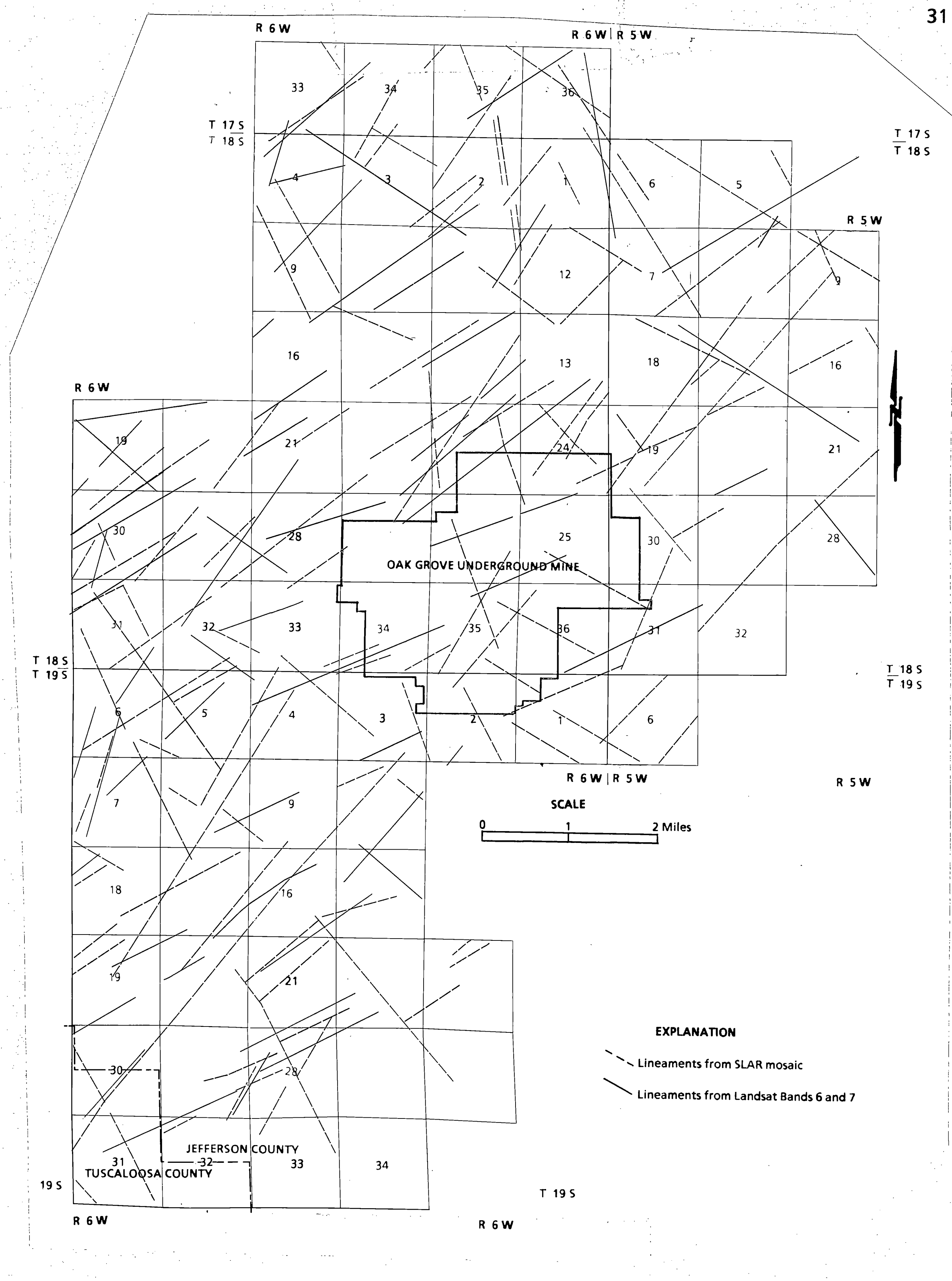


Figure 21.--Lineaments from Landsat and SLAR, central Oak Grove field.

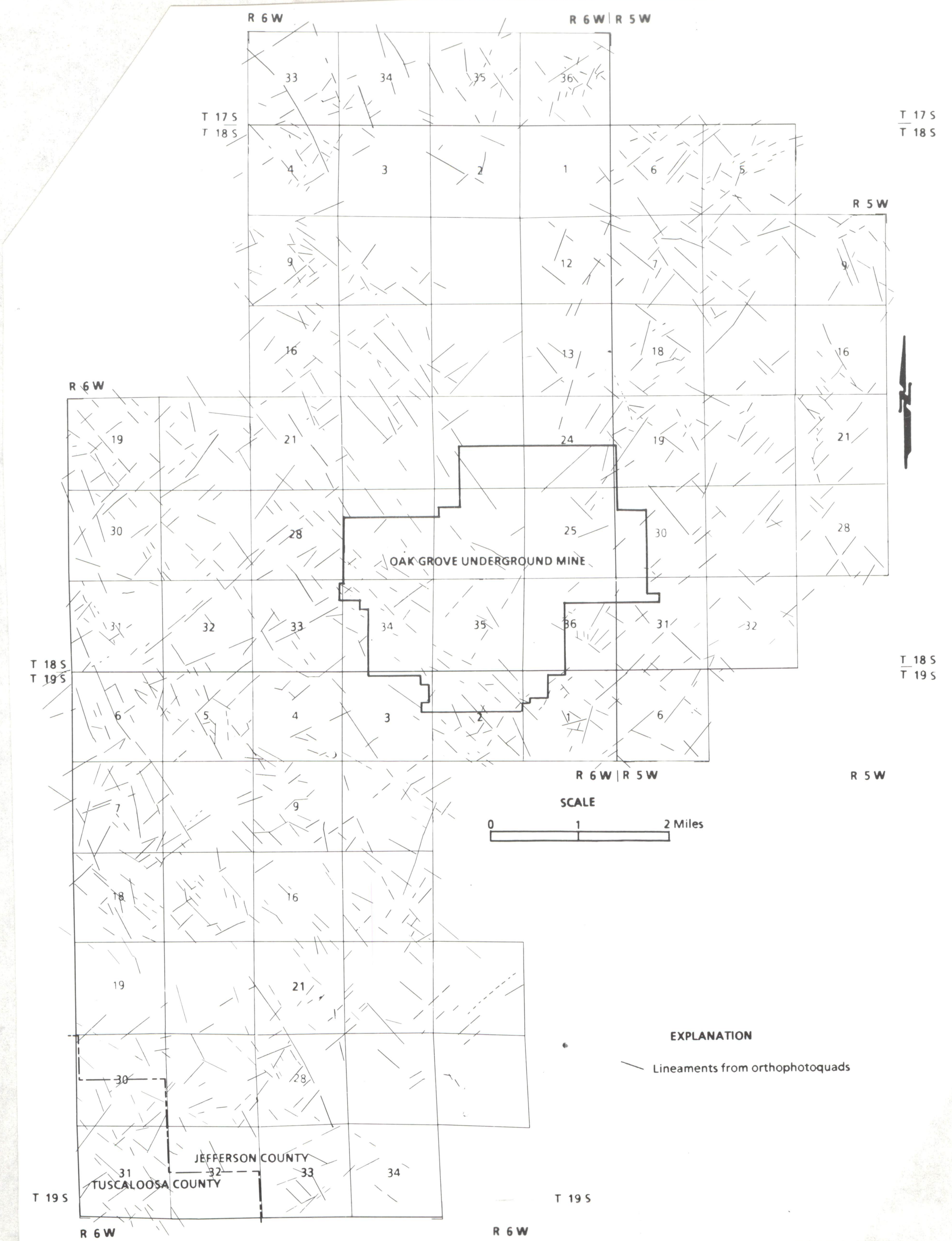


Figure 22. Lineaments from orthophotoquads, central Oak Grove field.

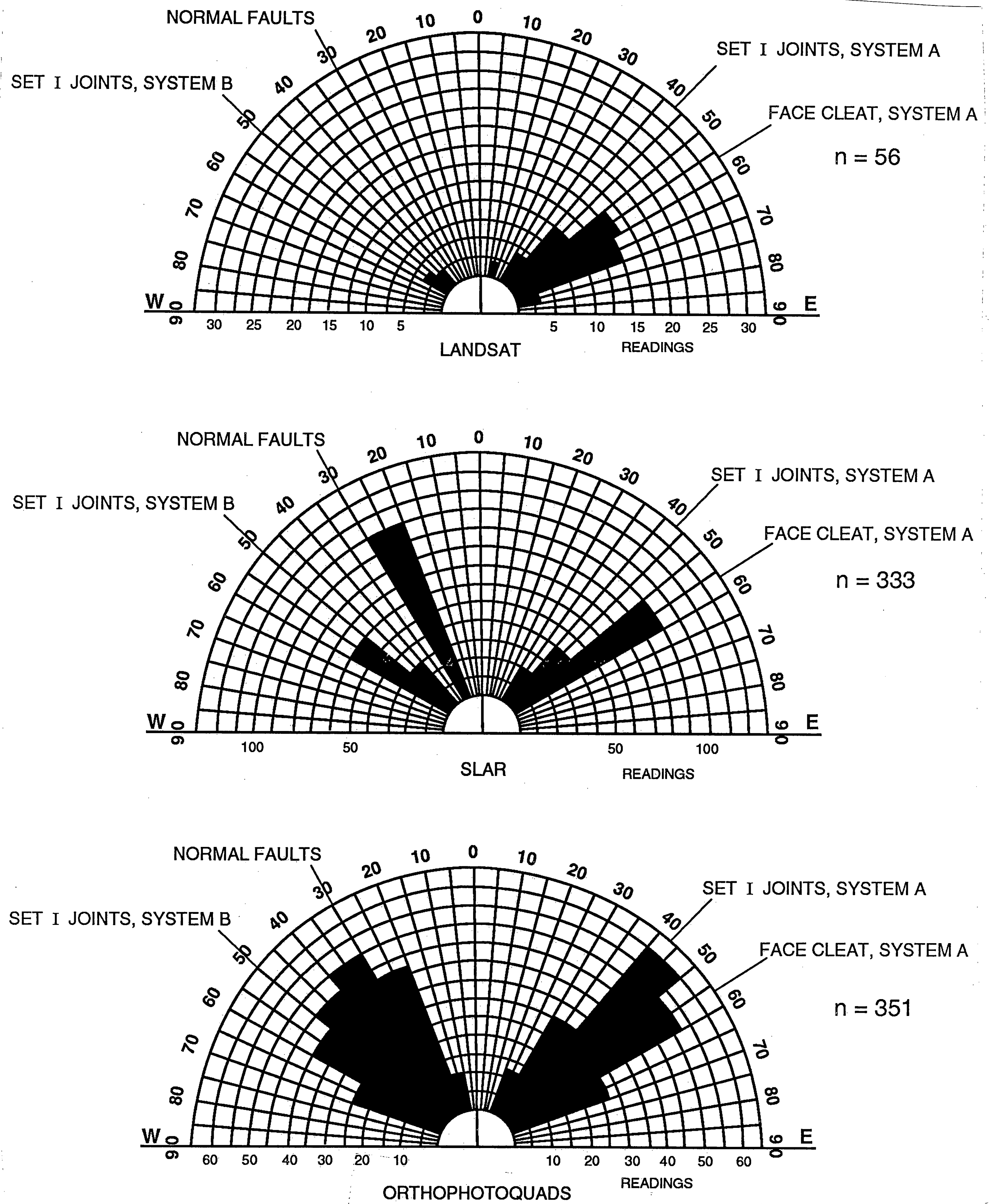


Figure 23. Rose diagrams showing relationship of lineaments to vector-mean azimuths of major geologic structures, central Oak Grove field.

major folds in the eastern part of the basin apparently are detached structures (Rodgers, 1950; Thomas, 1985a, b). The Blue Creek anticline and syncline are thought to overlie the frontal ramp of an upper-level decollement in Mississippian or Pennsylvanian strata that may be a splay of the major thrust faults of the Birmingham anticlinorium. In contrast, the Sequatchie anticline has been interpreted to have developed at a frontal thrust ramp of a basal decollement in Cambrian shale below the Coalburg syncline. Lack of surface detachment in Oak Grove field indicates that the thrust associated with the Sequatchie anticline is blind near the terminus of the anticline.

Inclined fractures in coal of the Blue Creek anticline and syncline (fig. 19) evidently formed by bedding-plane slip during Alleghanian folding. Occurrence of inclined fractures in the Blue Creek coal bed in the Coalburg syncline suggests a similar mode of formation and also suggests that the thick coal acted as a minor decollement zone during thrusting. Back-thrust structures in the Blue Creek and Sequatchie anticlines also appear to represent small-scale adjustments to regional folding.

NORMAL FAULTING

Predominance of horst-and-graben structure in the Black Warrior basin of Alabama (fig. 7) indicates a genesis related to extensional tectonics. In Mississippi, the faults closely parallel the Ouachita orogenic belt, and fault displacement increases toward the orogenic front. Therefore, the extensional faults appear to have formed during rapid subsidence caused by Ouachita thrust and sediment loading (Hines, 1988). Synsedimentary movement of normal faults in Alabama during the Pennsylvanian has been suggested (Weisenfluh, 1979; Weisenfluh and Ferm, 1984; Epsman and others, 1988; Pashin and others, 1989), and new evidence based on sandstone and coal occurrence is presented later in this report. However, it is unclear whether faulting was initiated during Ouachita orogenesis or whether some of the faults have pre-Alleghanian precursors.

Termination of Appalachian folds at normal faults in Oak Grove field (fig. 10) indicates that some faults define transcurrent pull-apart structures that mark the limit of the master decollement below the Coalburg syncline. This hypothesis is supported by evidence for strike-slip motion along faults in the Oak Grove mine (fig. 15). Reverse reactivation of some faults, like the one in eastern Brookwood field, may also be related to pull-apart tectonics.

Absence of Triassic and Jurassic strata in the Black Warrior basin makes post-Alleghanian structural history uncertain. Extensional faulting may have recurred during the Mesozoic but must have ceased before the Late Cretaceous, because normal faults have not displaced Upper Cretaceous strata (figs. 7, 8, 13). Extensional tectonics related to the opening of the Gulf of Mexico and subsidence of the Mississippi Embayment are generally thought to be the principal cause of tilting and burial of the western part of the Black Warrior basin (Klitgord and others, 1983; Thomas, 1988b). The structural contour map of the post-Pottsville unconformity surface (fig. 13) indicates that only southwest basin tilting has occurred since the Late Cretaceous.

JOINT AND CLEAT FORMATION

Orthogonal fracture systems, including joint and cleat systems, have been interpreted to be extension-release systems with the dominant set resulting from extension perpendicular to the maximum horizontal compressive stress and the subordinate set developing as stress-release fractures (Griggs and Handin, 1960; Nickelsen and Hough, 1967; Engelder, 1985). The fracture pattern of the Black Warrior basin indicates that joint and cleat systems are genetically related (fig. 17). The difference in orientation of the regional joint and cleat systems (systems A) suggests that the regional stress field rotated approximately 15° during fracturing. However, the direction of rotation and the relative timing of joint and cleat development are unclear, because crosscutting relationships between joint and cleat systems are inconclusive.

Restriction of joint and cleat systems B to the area of the Appalachian folds and thrust faults (fig. 17) suggests that fracturing was related to orogenesis (Murrie and others, 1976; Ward and others, 1984). This hypothesis is supported by the orthogonal relationship between set I joints of system B and the curving axial trace of the Sequatchie anticline. Moreover, occurrence of system B joints farther west in the subsurface than at the surface suggests that the joint system plunges with the anticline. Cleat system B may have a genesis similar to that of joint system B, but the cleat did not propagate very far northwest and may have been controlled mainly by stress release associated with the Blue Creek anticline and other thrust-related structures along the southeast basin margin.

Although crosscutting relationships between joint and cleat systems B are inconclusive, crosscutting relationships between the two cleat systems suggest that cleat system B is younger than system A. Therefore, cleat system A preceded Appalachian thrusting and apparently is the product of a regional, northeast-oriented compressive stress field; that stress field may been related to Ouachita tectonism (Ward, 1977; Ward and others, 1984). Similarly, formation of the regional joint system (system A) may also have preceded Appalachian thrusting.

The orientation of unloading joints is controlled either by a residual strain in the rocks from an earlier tectonic event or by the orientation of the maximum horizontal compressive stress axis in the contemporary stress field (Engelder, 1985). Crosscutting relationships indicate that set I joints are commonly older than set II joints, and abundance of set II joints at the surface relative to the subsurface suggests that set II joints are unloading structures. The orientation of set I joints of system A deviates by as much as 30° from the orientation (approximately N 75° E) of the modern compressive stress field (Engelder, 1982; Park and others, 1984). Hence, the orthogonal relationship between the two joint sets suggests that the orientation of unloading joints is controlled by older set I joints rather than by the modern stress field.

SEDIMENTOLOGY: MODELS OF COAL OCCURRENCE

INTRODUCTION

Pennsylvanian sedimentation in Alabama reflects the evolving structural framework of the Black Warrior basin, and the following discussion focuses on formulating sedimentologic models of coal occurrence that can be applied in coalbed-methane exploration and production. Modeling coal occurrence is vital to successful recovery of Alabama's coalbed-methane resources, because it provides a predictive framework that is advantageous in exploration and production planning. The objective of this section is to develop models of coal occurrence for the Black Warrior basin in Alabama at three separate scales and to demonstrate the utility of different approaches to sedimentologic basin analysis in coalbed-methane exploration and production. The first section is a regional sedimentologic basin analysis of the Black Creek-Cobb interval in Alabama. The second section is a detailed outcrop study of the Mary Lee coal group along the Blue Creek anticline and syncline. The final section is a detailed subsurface investigation of Oak Grove field.

Regional sedimentologic analysis can be used to identify major facies relationships, to evaluate coal occurrence, and thus, to identify prospective areas for coalbed-methane development. This approach is applicable to most basins, such as the Appalachian basin, which contain numerous conventional petroleum wells that provide an adequate database for regional basin analysis of coal-bearing strata. Outcrop study may be used to identify specific depositional systems and to develop predictive depositional models, especially with regard to coal thickness, continuity, and geometry, that may be applied to the subsurface during early stages of coalbed-methane development. From a driller's perspective, study of coal occurrence in coalbed-methane fields may be the most important aspect of sedimentologic analysis, because it provides detailed information to characterize and predict coal-body thickness and geometry, and hence reservoir distribution. Field-scale study of coal occurrence is useful for resource assessment, strategic well siting, and identifying completion targets.

REGIONAL COAL OCCURRENCE

INTRODUCTION

Regional sedimentologic analysis includes constructing a general, cycle-based stratigraphic framework for correlation and mapping, determining major facies relationships, and evaluating basin-scale patterns of coal occurrence. This approach may be used to identify the nature and location of coal resources and is thus key to implementing a successful exploration and production program for coalbed methane. The following discussion is a regional sedimentologic analysis of the Black Warrior basin in Alabama and is based primarily on data from geophysical well logs. A similar approach may be employed in most other eastern coal basins, including the Appalachian and Illinois basins, which contain numerous conventional petroleum wells.

Few geophysical data had been available to characterize facies relationships and basin evolution in southeastern Tuscaloosa and western Jefferson Counties, but in the past five years, coalbed-methane exploration in this area has provided a voluminous data base. Earlier studies, which did not have the benefit of data from coalbed-methane wells, provided evidence that Ouachita tectonism caused subsidence of the Black Warrior basin and also supplied most basin-filling sediment (Ferm and others, 1967; Cleaves, 1981; Thomas and Womack, 1983; Sestak, 1984; Hines, 1988; Thomas, 1974; 1988a). However, new data from coalbed-methane wells have augmented existing knowledge of the sedimentologic and tectonic evolution of the Black Warrior basin by providing evidence for subsidence and sediment sources related to Appalachian tectonism.

Results of regional sedimentologic analysis in the Black Warrior basin of Alabama establish that coal beds in the cyclic Black Creek-Cobb interval are most abundant in southern Tuscaloosa and western Jefferson Counties. Occurrence of a major coal resource base in this area is interpreted to be related to a proximal sediment source that helped maintain fluvial-deltaic platforms which were protected from marine influence. West of those platforms, peat (coal) could accumulate only late in deposition of each cycle when most or all of the study area was emergent.

METHODS

Density logs are available for wells throughout the Black Warrior basin in Alabama and provide the principal data base for regional investigation of the Black Creek-Cobb interval (fig. 6). Four rock types were distinguished using density logs that were calibrated with cores, cuttings, and drillers logs on the basis of variation in the gamma-ray, bulk-density, density-porosity, and neutron-porosity signatures (figs. 5, 24). The rock types are (1) coal, (2) mudstone, (3) lithic (nonporous) sandstone, and (4) quartzose (porous) sandstone.

Coal is distinctive on well logs because of low bulk density and gamma count and because of high density and neutron porosity (figs. 5, 24). Mudstone contains the highest proportion of clay and mica of any rock type in the Pottsville and thus has a moderate to high gamma count. Lithic sandstone is characterized by low gamma count, and the density-porosity and neutron-porosity curves do not

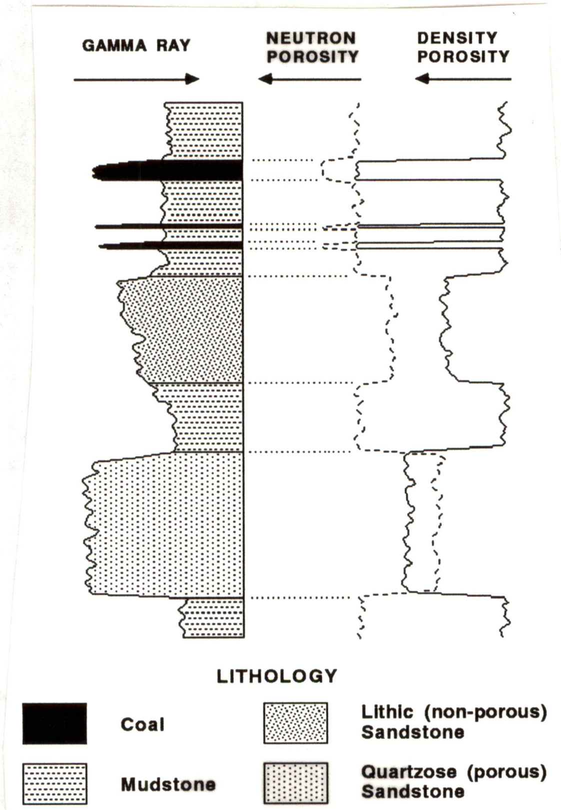


Figure 24. Sample gamma-ray-density log showing relationship between log signature and lithology.

cross owing to very low porosity and gas content. Quartzose sandstone has an extremely low gamma count, apparently because of a lack of clay minerals, and the density-porosity and neutron-porosity curves cross because it is porous and commonly contains gas; crossing of the curves is a reliable distinguishing feature. Whereas quartzose sandstone typically has a blocky log signature, lithic sandstone has a variable signature.

Quartzose sandstone varies compositionally from quartzarenite to sublitharenite (Mack and others, 1983; Raymond and others, 1988; Raymond, 1990). Lithic sandstone is dominant in the upper Pottsville, contains a high proportion of argillaceous and low-grade metamorphic rock fragments, and is compositionally litharenite (Graham and others, 1976; Mack and others, 1983). Several workers in Alabama have interpreted quartzose sandstone to have formed in marine and marginal-marine environments, whereas lithic sandstone, which is closely associated with economic coal beds, has been interpreted to have formed in fluvial and deltaic environments (Ferm and others, 1967; Hobday, 1974; Horne and others, 1976, Cleaves and Broussard, 1980; Horsey, 1981).

To determine stratigraphic relationships in the Black Creek-Cobb interval, cross sections (fig. 6) were made using the top of the Pratt coal group as a datum. Next, cycles were defined on the basis of a thick mudstone unit at the base of each cycle and the presence of a coal or sandstone bed at the top of each cycle. The top of the Fayette sandstone of the lower Pottsville (Epsman, 1987) was used to mark the base of the study interval. Finally, the following subsurface maps were made for each cycle: (1) cycle-isopach, (2) lithic-sandstone isolith, (3) quartzose-sandstone isolith, and (4) coal abundance. Isopach and coal-abundance maps also were made for the combined Black Creek-Cobb interval. Only selected maps are presented in this paper, and a complete map set is available in Pashin and others (1990).

Regional coal-isolith maps were not constructed because density-log signature is inconsistent with respect to coal thickness. Although high-resolution geophysical logs in the degasification fields may be used for localized isopach maps, conventional logs can be deceptive because of fast logging speed and large source-receiver spacing. Therefore, regional coal-abundance maps, or maps showing the number of coal beds, provide an estimate of coal resources.

STRATIGRAPHIC ARCHITECTURE

Cross sections show the five cycles of the Black Creek-Cobb interval in Alabama (figs. 6, 25-31). In eastern Tuscaloosa and western Jefferson Counties, simple coarsening-upward cycles culminate in coal groups. However, defining the base of the Mary Lee cycle is difficult in parts of Fayette and Lamar Counties, because the basal mudstone is thin and Mary Lee quartzose sandstone occurs in close proximity to Black Creek quartzose sandstone. Locally, the top of the Mary Lee cycle is also difficult to identify in well logs because a sandstone or coal marker is absent. Although these relationships suggest intertonguing between the Mary Lee and Gillespy/Curry cycles, outcrop evidence demonstrates that the two cycles are separated by a marine-flooding surface that locally truncates Mary Lee strata (Liu, 1990a, b; Demko, 1990a).

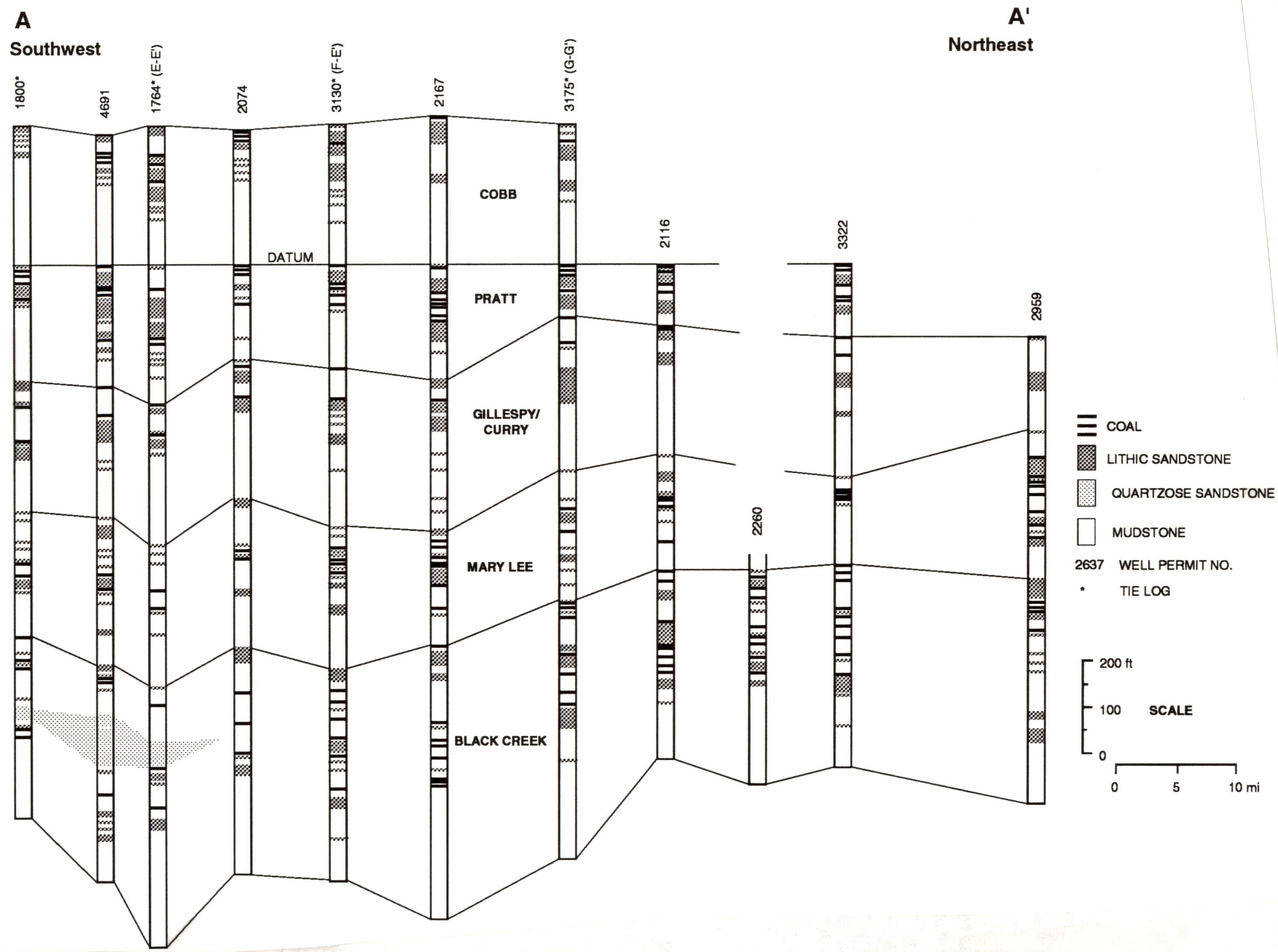


Figure 25. Stratigraphic cross section A-A'. See figure 6 for location.

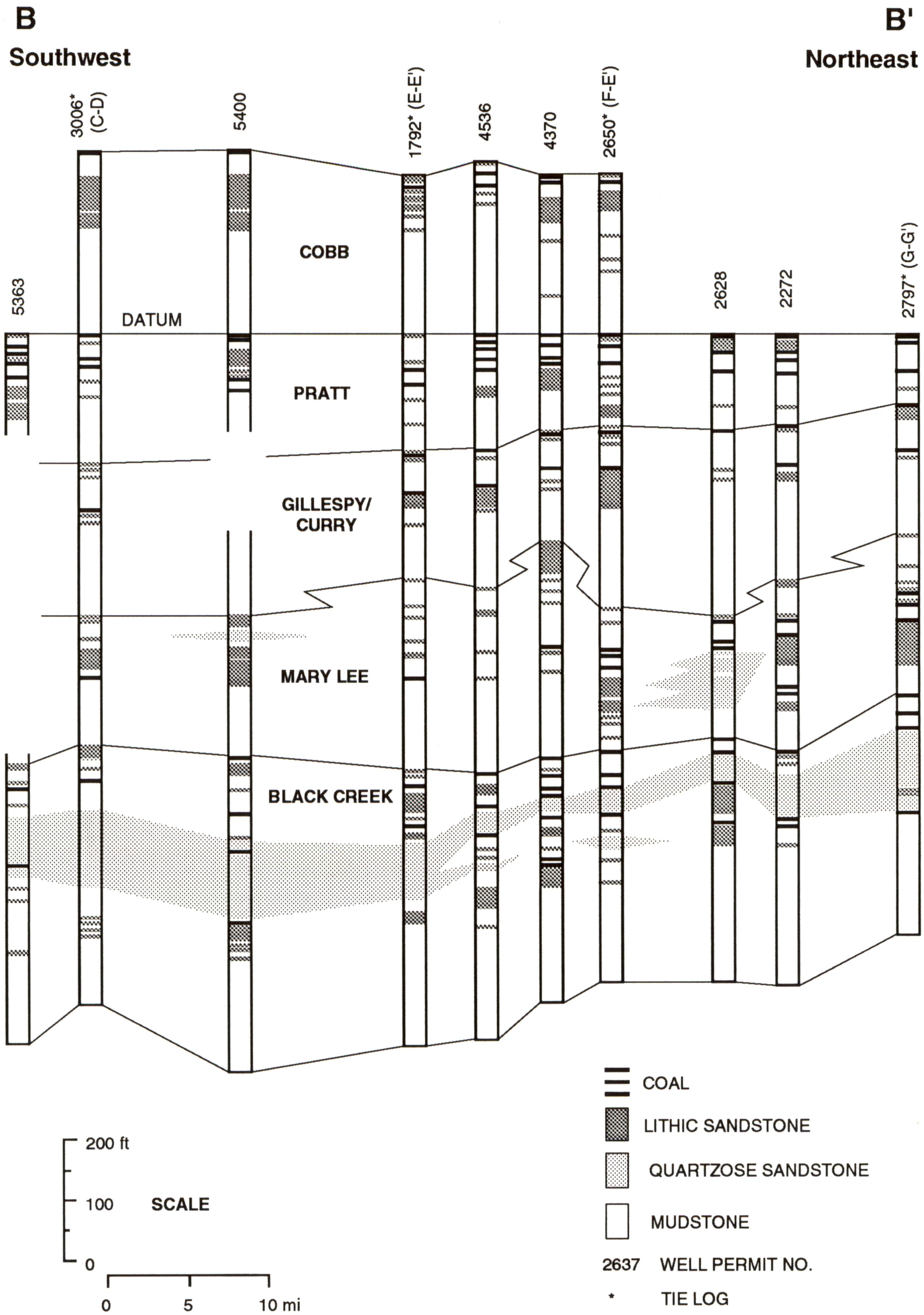


Figure 26. Stratigraphic cross section B-B'. See figure 6 for location.

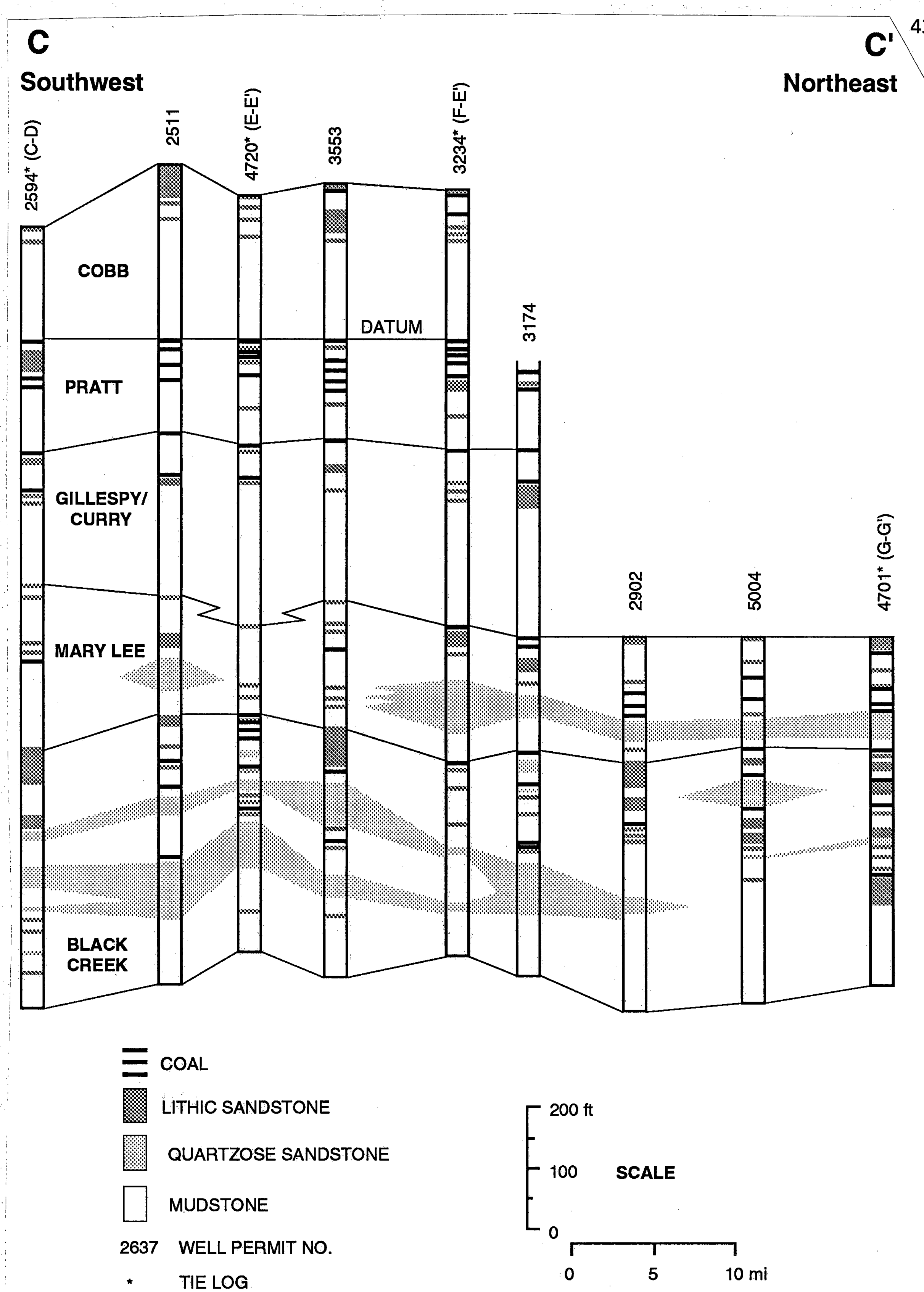


Figure 27. Stratigraphic cross section C-C'. See figure 6 for location.

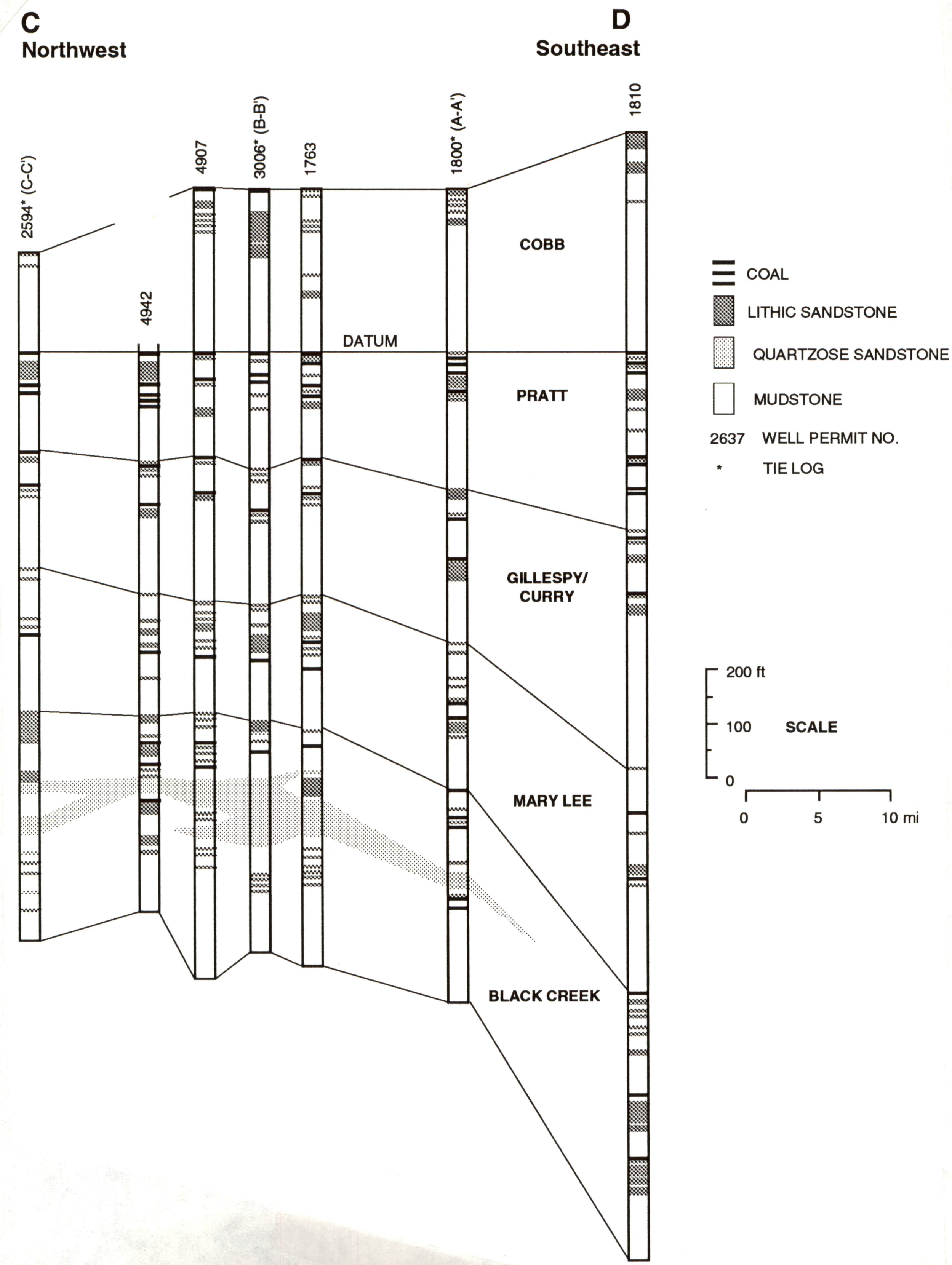


Figure 28. Stratigraphic cross section C-D. See figure 6 for location.

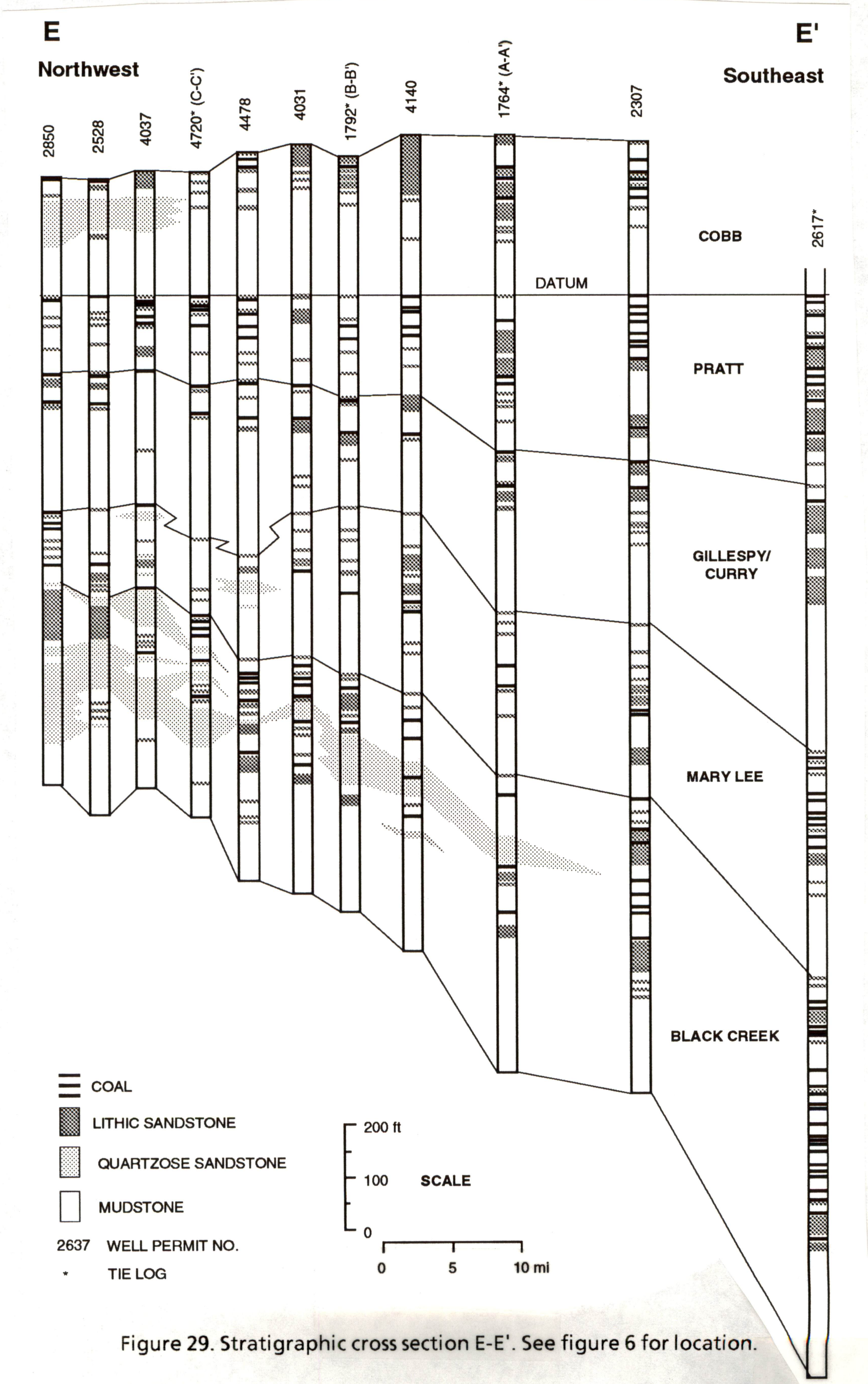


Figure 29. Stratigraphic cross section E-E'. See figure 6 for location.

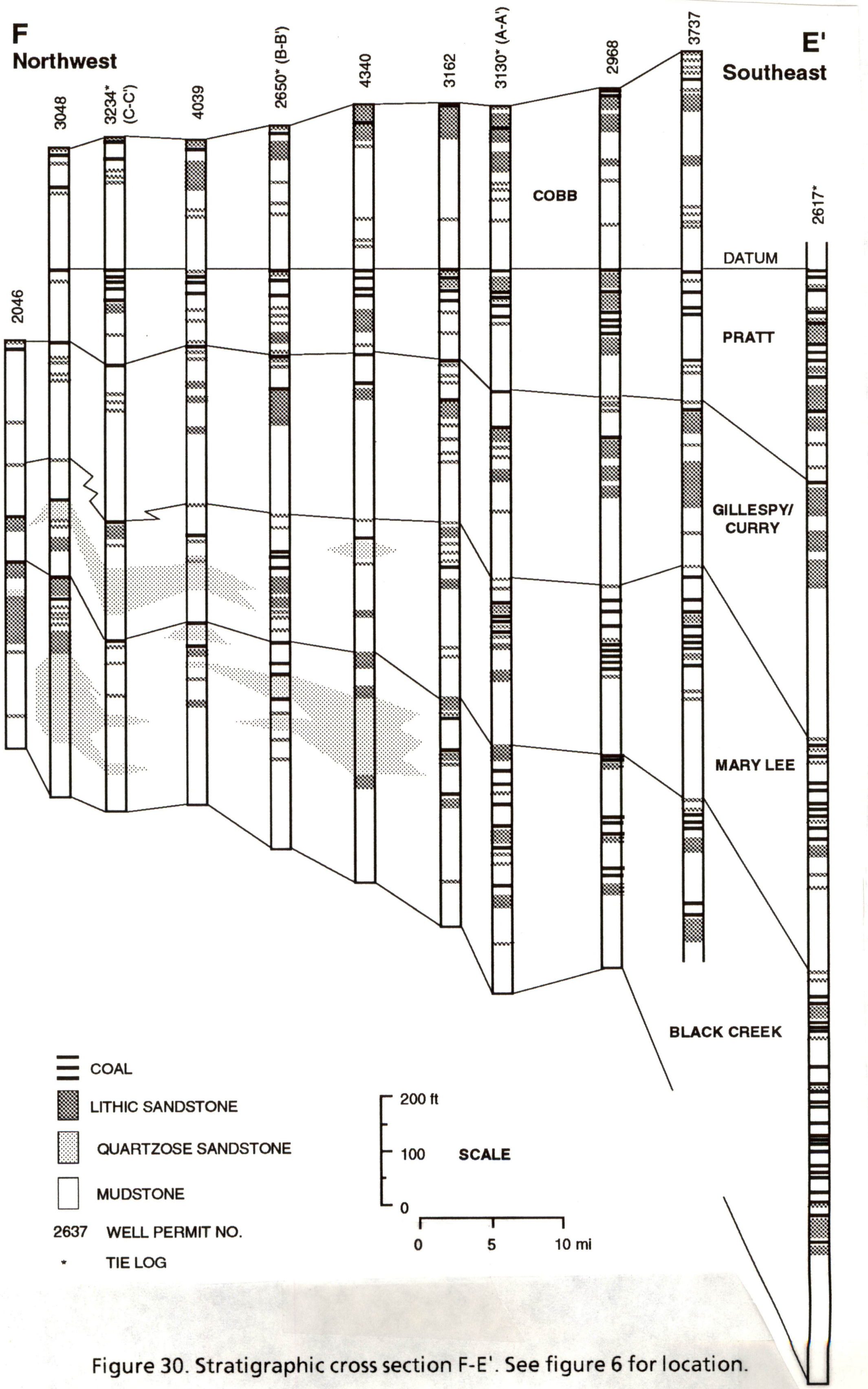


Figure 30. Stratigraphic cross section F-E'. See figure 6 for location.

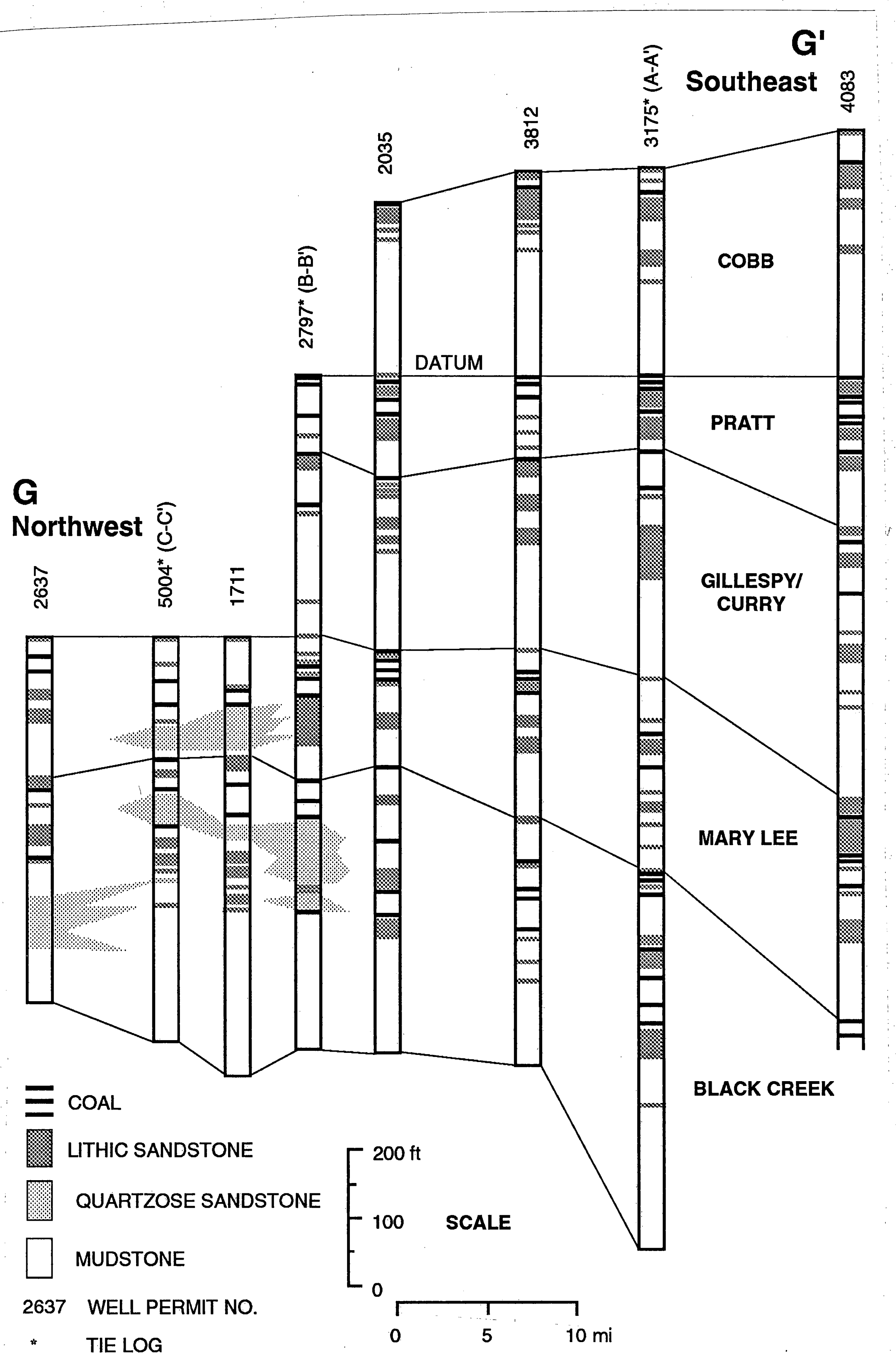


Figure 31. Stratigraphic cross section G-G'. See figure 6 for location.

Cycle thickness is fairly uniform along the southwest-northeast cross sections (figs. 25-27), whereas the cycles thicken markedly toward the southeast in the northwest-southeast cross sections (figs. 28-31). Lithic sandstone is dispersed throughout the upper part of most cycles but is thickest between the mudstone- and coal-bearing intervals of the Gillespy/Curry and Cobb cycles. Quartzose sandstone occurs in the Black Creek, Mary Lee, and Cobb cycles. In the Black Creek cycle, quartzose sandstone is below the coal-bearing strata in the northwest part of the study area, but in the south and east, the sandstone extends into the middle of the coal group (fig. 29). In contrast, quartzose sandstone generally underlies the coal-bearing part of the Mary Lee cycle in the northwest part of the study area, although localized lenses are dispersed throughout the section (figs. 28-31). In Lamar County, the Cobb cycle contains a localized quartzose sandstone body (fig. 29).

Coal is restricted to the upper part of the cycles, and the number (0-20) and continuity of the beds vary (figs. 25-31). Some beds, such as those in the Gillespy/Curry cycle, are traceable throughout most of the basin in Alabama and are useful stratigraphic markers. Other beds, such as many in the Black Creek cycle, only occur locally. The northwest-southeast cross sections (figs. 28-31) demonstrate that coal beds are most abundant where cycles are thickest along the southeast margin of the basin.

CYCLE THICKNESS

The Black Creek-Cobb isopach map illustrates the overall geometry of the study interval (fig. 32). The interval thickens from Lamar and Fayette Counties toward the south and southeast. Thickening is greatest south of the 1,500-foot contour which defines an arcuate trend of thick sediment that extends from Tuscaloosa County into Mississippi. In the southwesternmost part of the study area, the Black Creek-Cobb interval is thicker than 2,400 feet.

Although the Black Creek-Cobb isopach map depicts a simple, arcuate thickness trend, individual cycle-isopach maps establish that cycle thickness varied systematically with time. For example, the Black Creek cycle contains more than 700 feet of sediment in a depocenter that was located in southeastern Tuscaloosa County (fig. 33). The Gillespy/Curry cycle, however, is characterized by a sublinear depoaxis (area southeast of the 400-foot contour, fig. 34) that extended across the

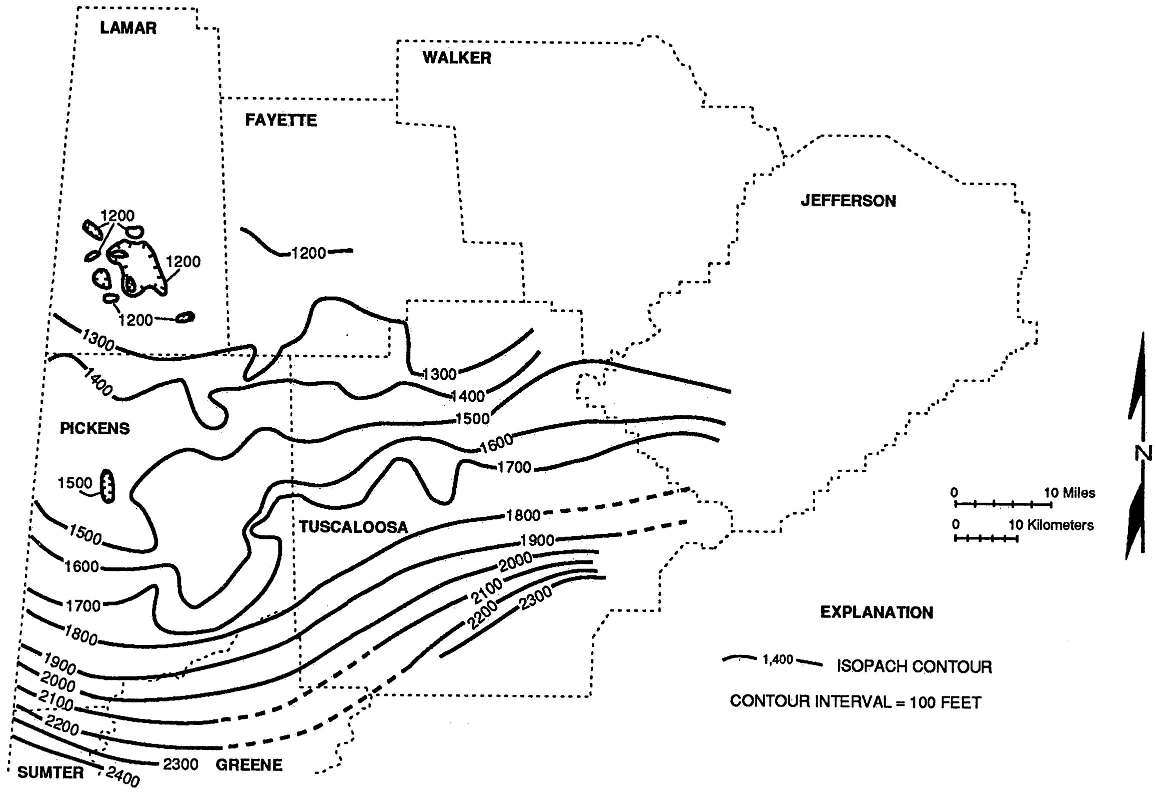


Figure 32. Isopach map of the Black Creek-Cobb interval, Black Warrior basin, Alabama.

southeastern part of the study area. The depoaxis of the Cobb cycle (area south of the 350-foot contour), was arcuate and similar in geometry to that of the composite Black Creek-Cobb interval (figs. 32, 35).

Sequential variation of cycle thickness with time (figs. 33-35) provides a record of subsidence history and foreland-basin evolution. Contours on the Black Creek-Cobb isopach map are strongly oblique and in places perpendicular to those on the structural contour map, indicating that the present basin differs structurally from that which existed during Pottsville deposition. The Black Creek depocenter indicates that subsidence in the study area was for a time dominated by Appalachian tectonism. Expansion of the depocenter into an arcuate depoaxis, however, suggests increasing influence of Ouachita orogenesis in Alabama during Black Creek-Cobb deposition. Cycle-isopach maps demonstrate systematic merging of the Black Creek depocenter with the trough of subsidence that persisted throughout most of the Carboniferous adjacent to the Ouachita orogen in Mississippi.

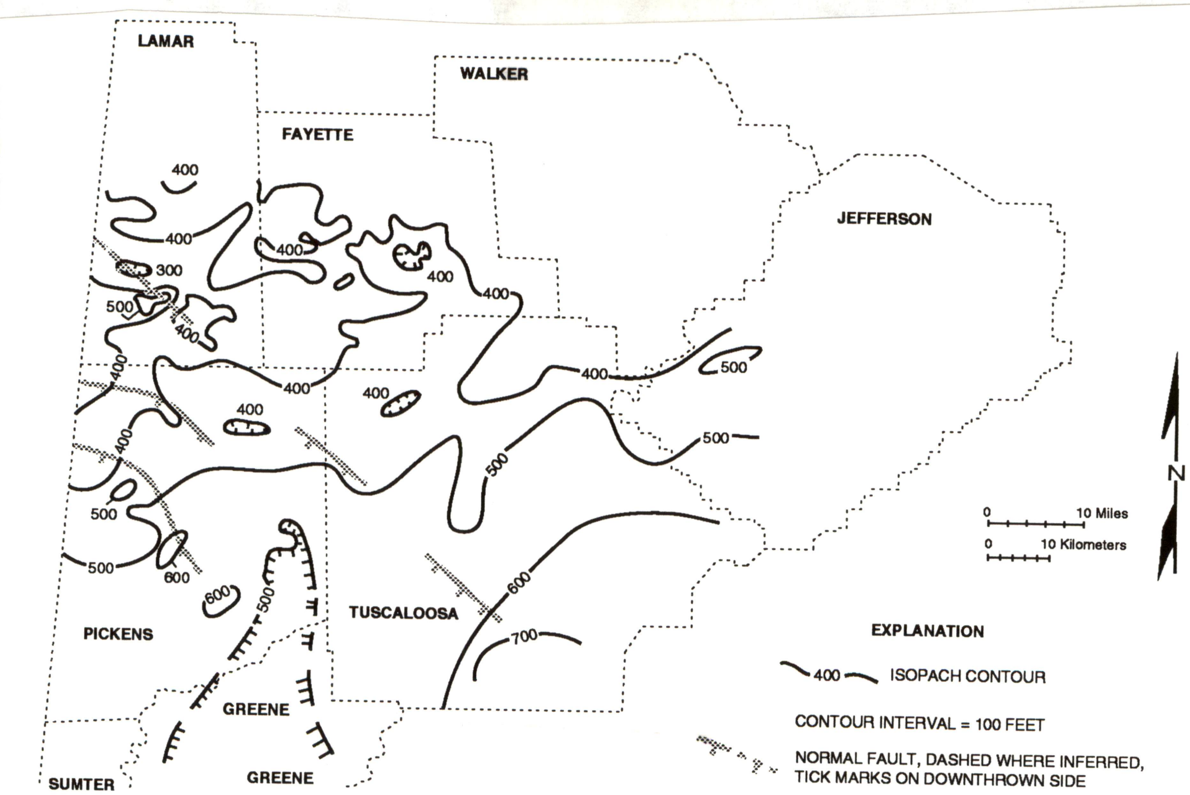


Figure 33. Isopach map of the Black Creek cycle, Black Warrior basin, Alabama.

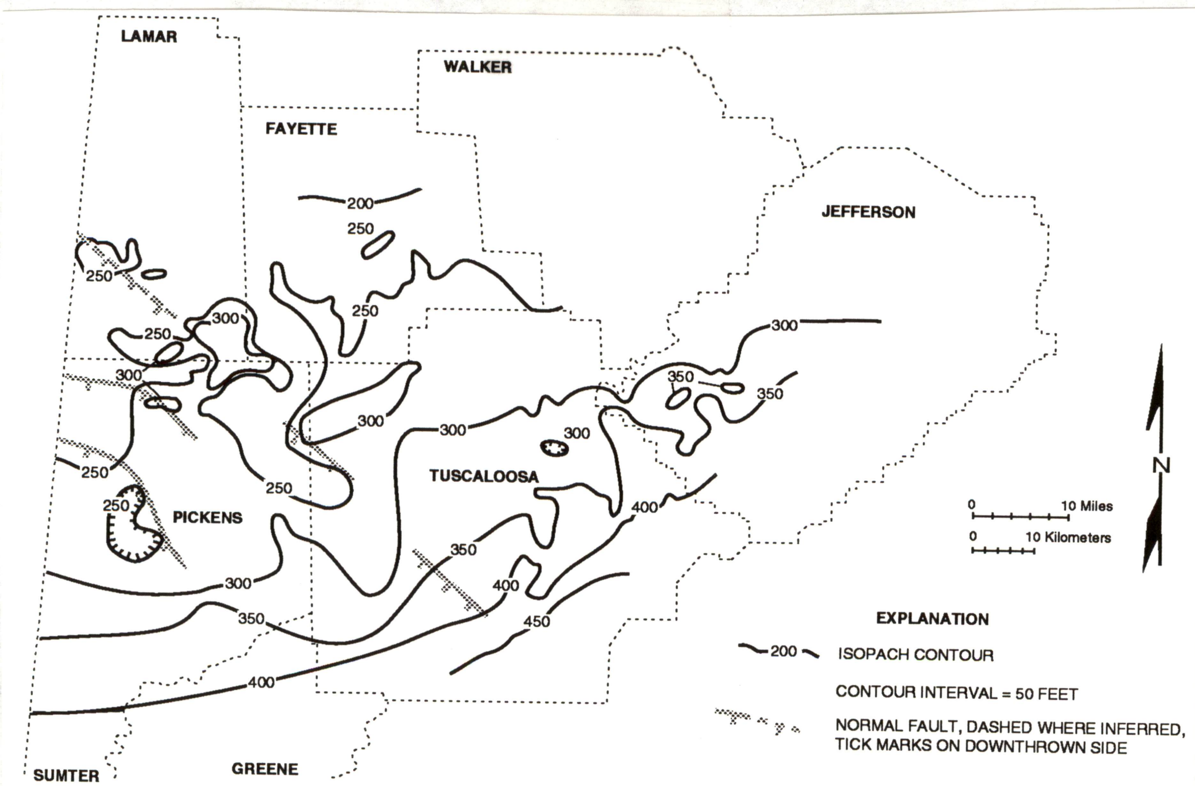


Figure 34. Isopach map of the Gillespy/Curry cycle, Black Warrior basin, Alabama.

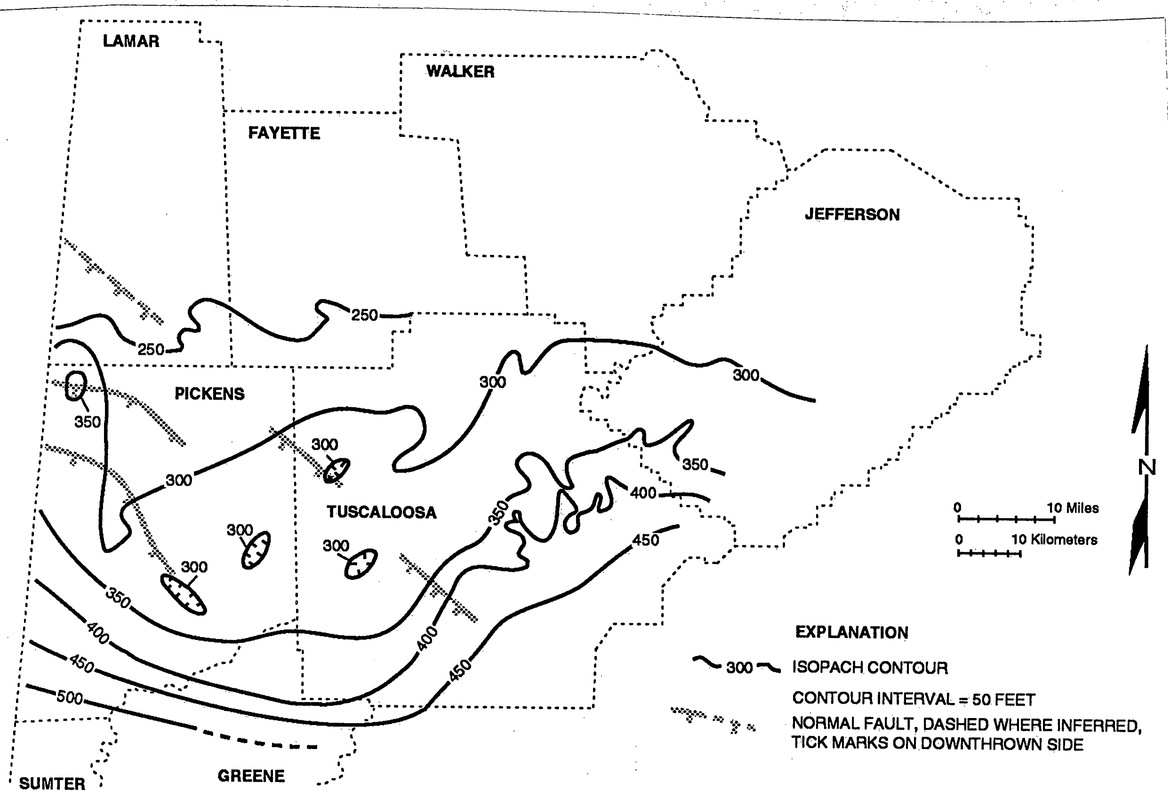


Figure 35. Isopach map of the Cobb cycle, Black Warrior basin, Alabama.

LITHIC-SANDSTONE DISTRIBUTION

Although cycle thickness varied in time and space, regional lithic-sandstone distribution varied little among the cycles. Comparison of the Mary Lee, Gillespy/Curry, and Pratt maps (figs. 36-38) establishes that lithic sandstone is consistently thickest in southeastern Tuscaloosa County. Each map shows two major lobate to elongate sandstone axes; one is in eastern Tuscaloosa County, and the other is in southwestern Tuscaloosa County.

Faulting apparently controlled lithic sandstone distribution. In each cycle, the southwestern depositional axis occurs southwest of a series of major faults (figs. 36-38). In the Gillespy/Curry cycle, parts of the elongate, bifurcated trend outlined by the 50-foot contour in western Tuscaloosa and northern Pickens Counties follow faults, and the southwestern part of the bifurcated trend terminates at a fault. Similar structural control of sandstone occurrence is apparent in the Pratt cycle and to a lesser extent in the Mary Lee cycle.

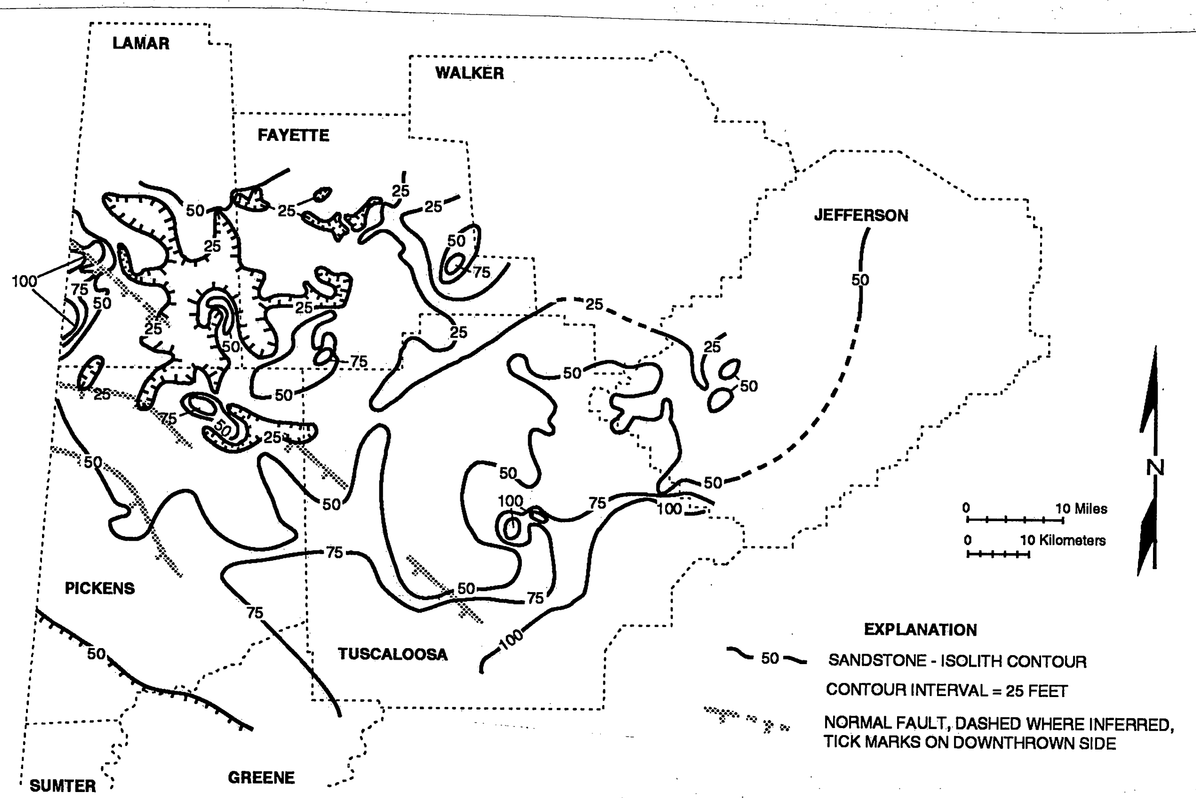


Figure 36. Lithic-sandstone isolith map of the Mary Lee cycle, Black Warrior basin, Alabama.

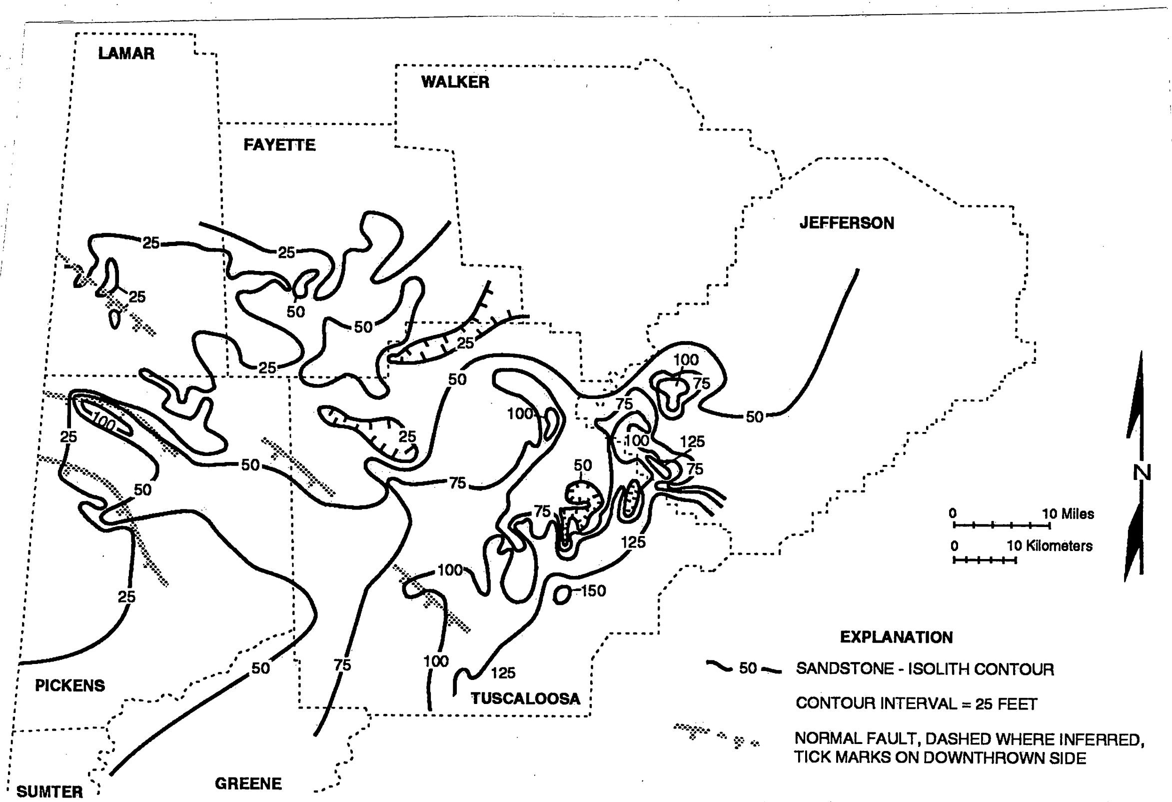


Figure 37. Lithic-sandstone isolith map of the Gillespy/Curry cycle, Black Warrior basin, Alabama.

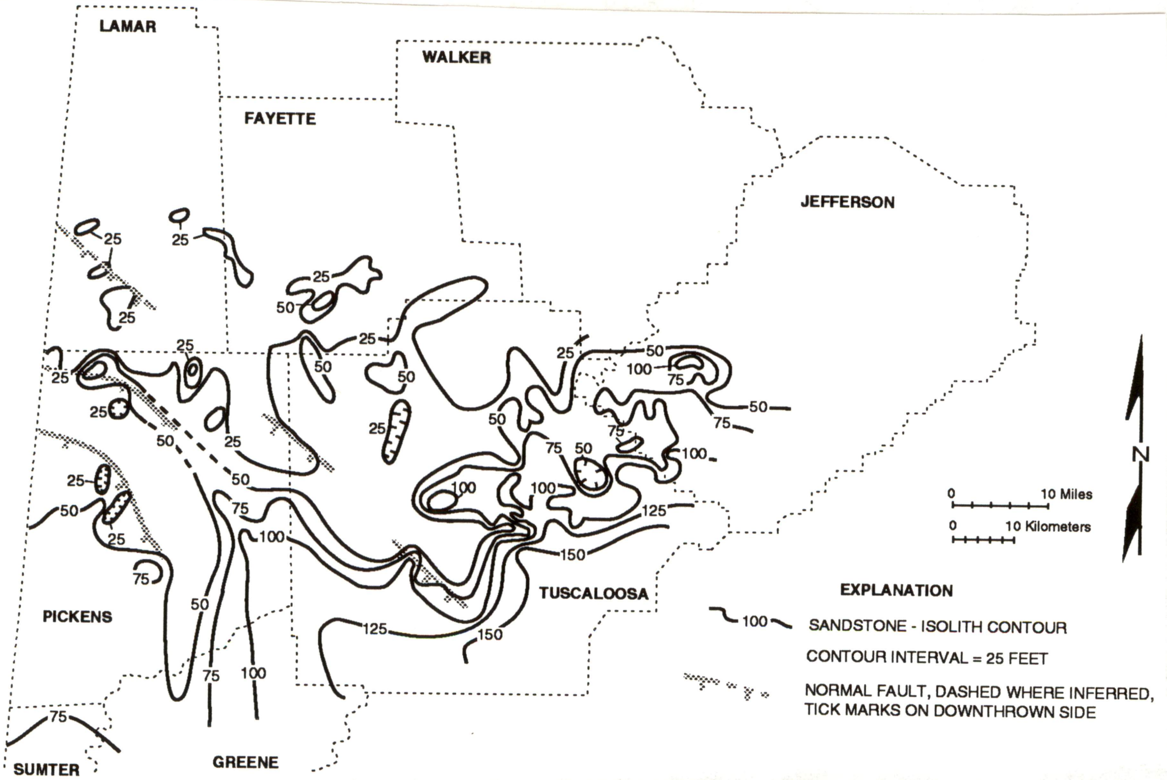


Figure 38. Lithic-sandstone isolith map of the Pratt cycle, Black Warrior basin, Alabama.

Some lobate and elongate sandstone bodies may represent major fluvial-deltaic systems (fig. 39) that prograded northwest. In the Gillespy/Curry cycle, for example, the elongate, bifurcated trend (fig. 37) may be interpreted as a deltaic lobe analogous to the modern bird-foot lobe of the Mississippi Delta (Gould, 1970). A similar elongate trend in the Pratt cycle (fig. 38) suggests that the trunk channel of the deltaic system was reactivated.

In the Mary Lee and Pratt cycles (figs. 25-31), several coal beds are interspersed with lithic sandstone and extend well beyond the lobate trends, suggesting that some trends represent differentially subsiding fluvial axes rather than deltaic distributary systems. Additionally, mapping of individual sandstone bodies in the Mary Lee cycle of Oak Grove field (see section on fluvial and structural control of coal-body geometry) indicates that tributary channels in the easternmost part of the northeastern sandstone lobe were directed west, suggesting a more westwardly paleoslope than is readily apparent in the sandstone isolith maps. Moreover, muddy depositional systems that are

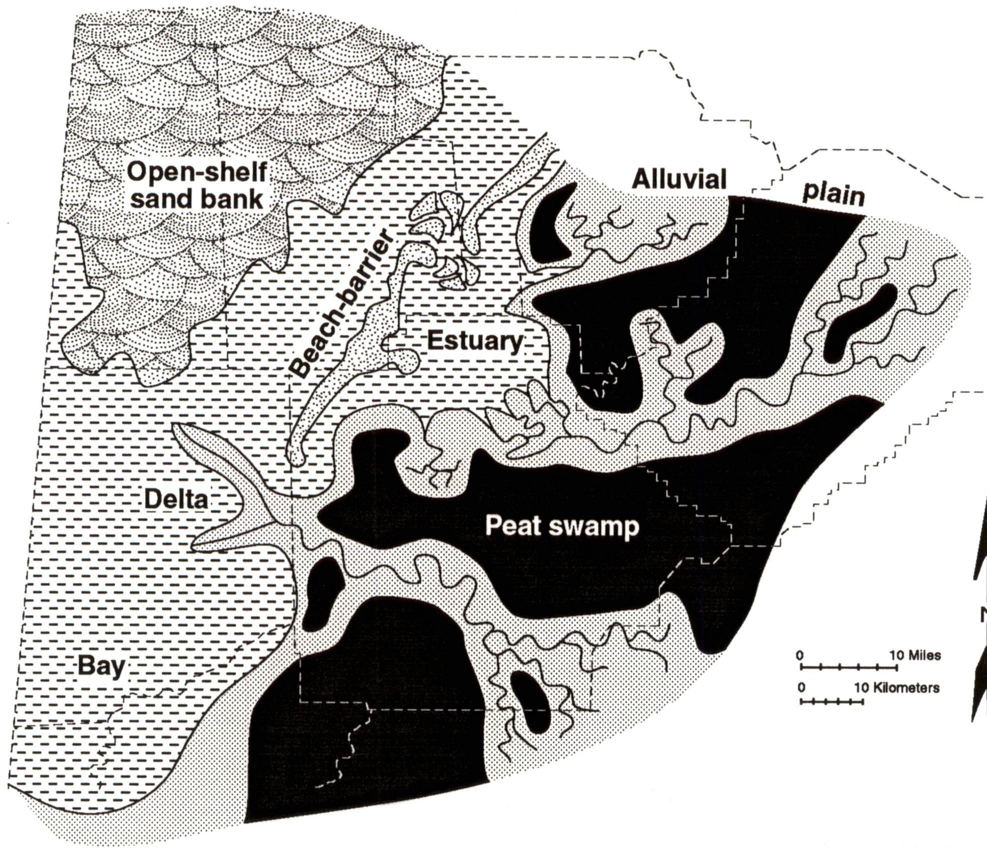


Figure 39. Depositional model for the Black Creek-Cobb interval, Black Warrior basin, Alabama.

difficult to recognize in the subsurface, such as estuaries and tidal flats (fig. 39), have been recognized in outcrop (Demko, 1990a, b; Liu, 1990a, b).

Isolith maps indicate that lithic-sandstone distribution represents a composite of fluvial and marginal-marine depositional systems. Constancy of lithic-sandstone distribution despite changing cycle-isolith patterns suggests that regional sand supply and dispersal in Alabama were largely independent of the changing subsidence pattern. Persistence of thick, lobate sandstone bodies in southeastern Tuscaloosa County provides evidence that a major proximal sand source lay in the Appalachian orogen (fig. 39). Thick lithic sandstone in the Mary Lee cycle of southwest Lamar County apparently was derived from a deltaic complex in Mississippi that had an Ouachita source (Sestak, 1984).

QUARTZOSE-SANDSTONE DISTRIBUTION

In the Black Creek cycle, a major quartzose-sandstone belt defined by the 50-foot contour extends northeast from Sumter County to eastern Fayette County (fig. 40). Locally, sandstone in this belt is thicker than 100 feet. Quartzose sandstone commonly is absent immediately northwest of the belt, but an irregular quartzose-sandstone body that is locally thicker than 200 feet occurs in Lamar County. This irregular body terminates abruptly along a fault zone in western Lamar County; southwest of this zone, all or most of the lower Pottsville quartzose-sandstone units are absent (Engman, 1985), and Mary Lee lithic sandstone is thicker than 100 feet (fig. 36).

Quartzose sandstone in the Mary Lee cycle occurs in a series of distinct, geographically restricted bodies (fig. 41). Thick Mary Lee quartzose sandstone coincides with thick Black Creek quartzose sandstone in central Pickens County and in eastern Fayette County. In contrast, thick Mary Lee quartzose sandstone in southwest Fayette County occurs in a distinctive southwest trend and is thicker than 50 feet where Black Creek quartzose sandstone is thin or absent.

Black Creek quartzose sandstone has been interpreted to represent fluvial-deltaic systems in the subsurface (Sestak, 1984; Thomas, 1988a) and beach-barrier systems in outcrop (Shadroui, 1986). The quartzose-sandstone belt parallels depositional strike as determined from cycle-isopach and lithic-

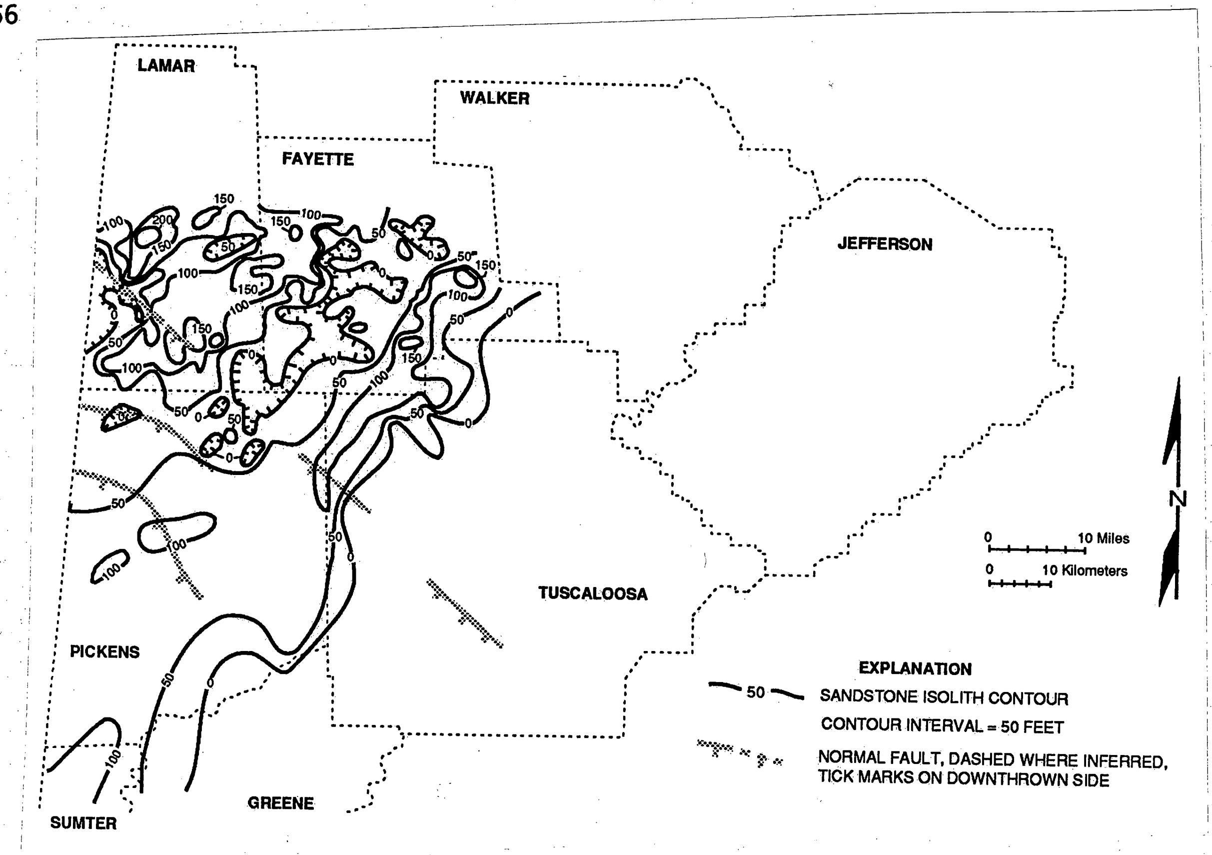


Figure 40. Quartzose-sandstone isolith map of the Black Creek cycle, Black Warrior basin, Alabama.

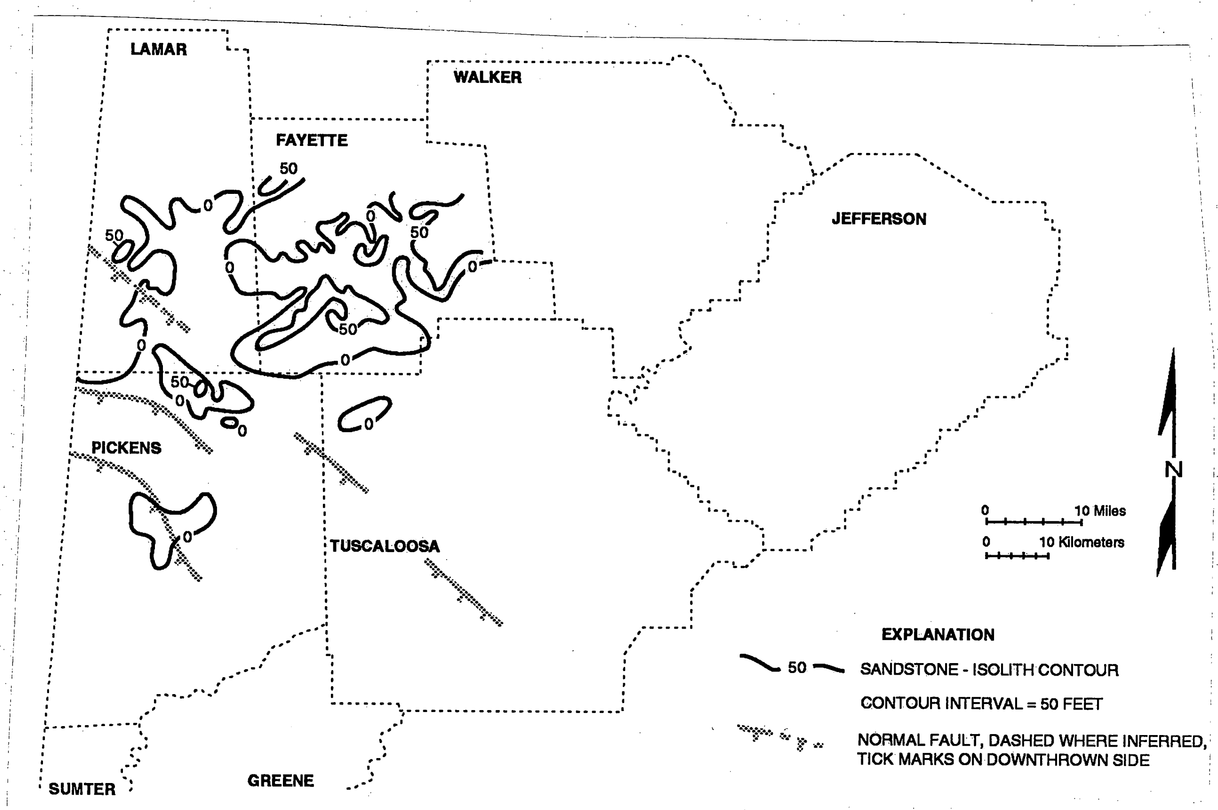


Figure 41. Quartzose-sandstone isolith map of the Mary Lee cycle, Black Warrior basin, Alabama.

sandstone isolith maps (figs. 36-38) and is thus interpreted as a marginal-marine deposit in the subsurface (fig. 39). The narrow northeast part of the belt has the plan-view geometry of a barrier-island complex, whereas the broad southwest part of the belt resembles shoreface deposits derived from the barrier system by longshore drift.

Although earlier investigators have interpreted quartzose sandstone as a beach-barrier deposit, new subsurface and outcrop evidence indicate that some quartzose sandstone was deposited in open-marine environments (Pashin and others, 1990, 1991; Demko, 1990a, b). The location, thickness and irregular geometry of the Black Creek quartzose sandstone body in Lamar County (fig. 40) is suggestive of a structurally influenced open-marine sand bank (fig. 39). The thickness and stratigraphic position of the sandstone in Lamar County suggests that the area was a persistent site of shoaling, and southeastward extension into the middle of the Black Creek coal group suggests that the shoal area expanded in response to marine transgression.

Sedimentary structures in outcrops of Mary Lee quartzose sandstone are characteristic of open-shelf sand banks, including sand waves and sand ridges, that migrated southwest and have been modified into barrier islands (Demko, 1990a, b; Pashin and others, 1991). Offset of Mary Lee and Black Creek quartzose sandstone bodies (figs. 40, 41) demonstrates the importance of relict topography and differential compaction on the distribution of open-shelf bedforms. Coincidence of thick Mary Lee and Black Creek quartzose-sandstone bodies in central Pickens County and eastern Fayette County are interpreted to be the result of shoaling on inherited topographic highs, whereas offset sandstone bodies, like those in southern Fayette County, are interpreted to be the result of currents that were restricted to topographic lows.

Much quartzose sandstone may have the same source as lithic sandstone, because quartzose sandstone can be a product of the destruction of labile grains by marine reworking (Mack and others, 1983). However, southwest crossbed orientations have consistently been recorded from quartzose sandstone in outcrop throughout the Appalachian region (Horne, 1978). Moreover, Mary Lee lithic sandstone contains abundant chert grains, whereas Mary Lee quartzose sandstone generally lacks chert (Raymond, 1990). Therefore, some sand may have been transported southwestward into the basin from distal orogenic sources by tides and longshore drift.

COAL DISTRIBUTION

Coal in the Black Creek-Cobb interval is most abundant in southeast Tuscaloosa County where more than 40 coal beds occur (fig. 42). However, fewer than 10 coal beds occur in much of the northern and western parts of the study area, and fewer than 5 coal beds occur locally in northwest Pickens and southwest Lamar Counties. Coal-abundance maps of the Black Creek, Mary Lee, and Pratt cycles (figs. 43-45) reflect the regional trend (fig. 42) and show little change through time. The Gillespy/Curry and Cobb cycles generally contain only two coal beds, and coal-abundance maps for those cycles are available in Pashin and others (1990). The Black Creek and Mary Lee cycles lack coal in parts of Lamar and Pickens Counties, whereas the Pratt cycle contains two or more coal beds throughout most of the study area.

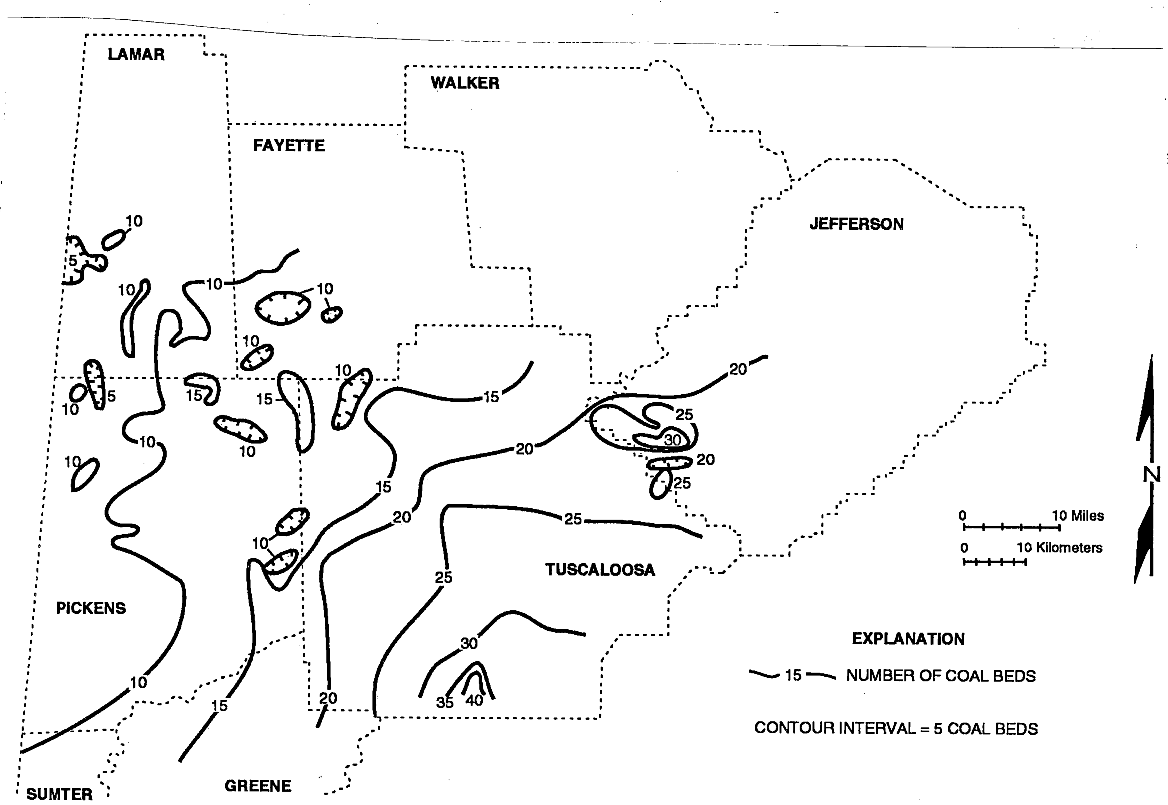


Figure 42. Coal-abundance map of the Black Creek-Cobb interval, Black Warrior basin, Alabama.

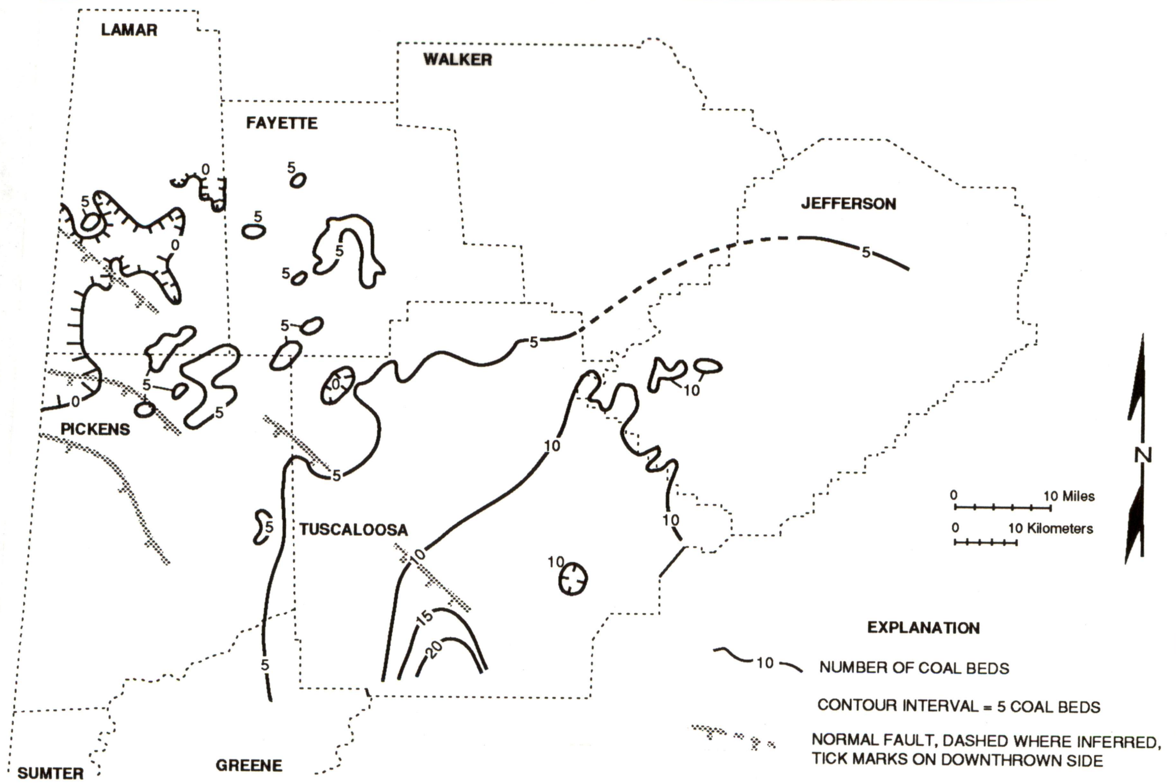


Figure 43. Coal-abundance map of the Black Creek cycle, Black Warrior basin, Alabama.

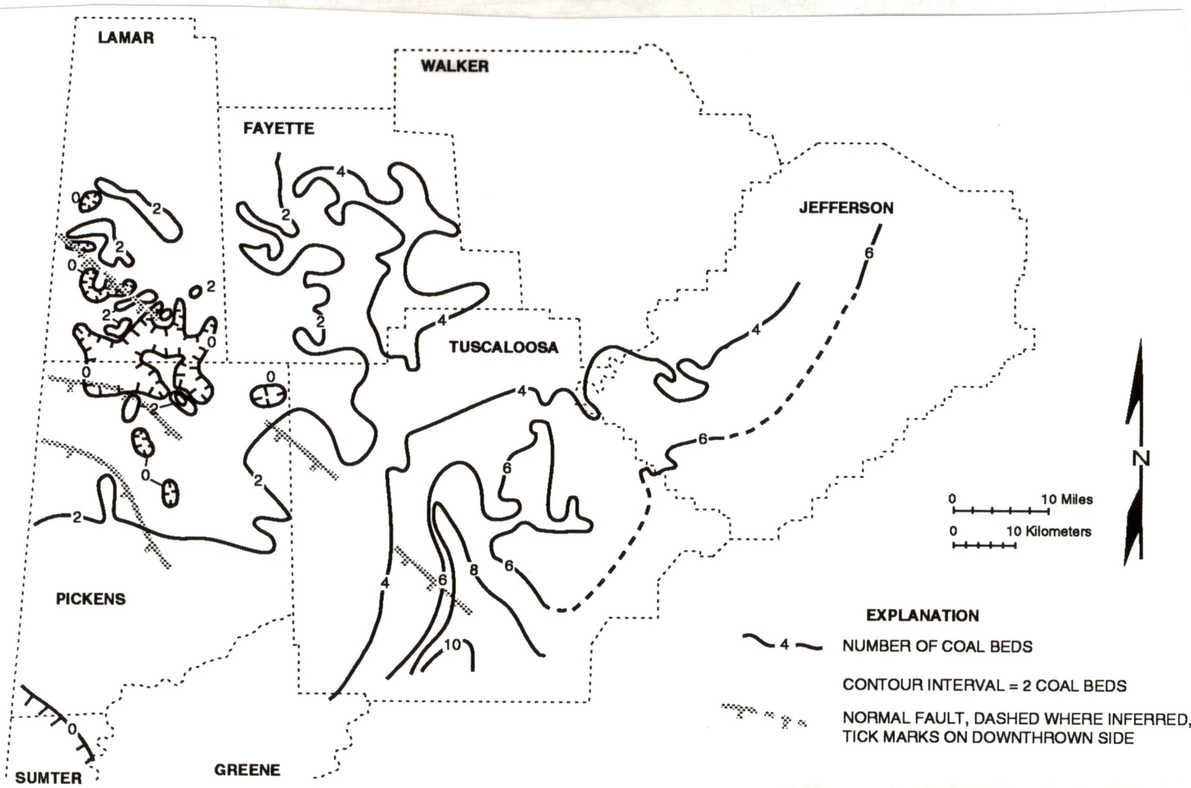


Figure 44. Coal-abundance map of the Mary Lee cycle, Black Warrior basin, Alabama.

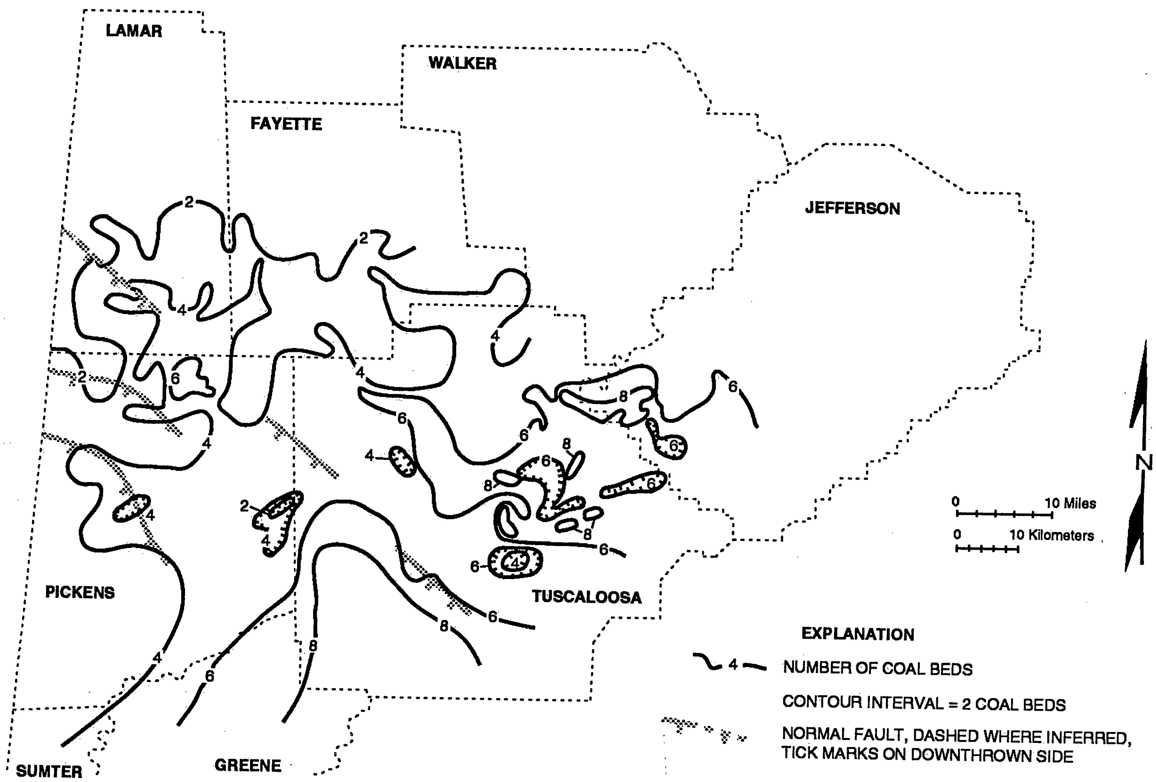


Figure 45. Coal-abundance map of the Pratt cycle, Black Warrior basin, Alabama.

A salient characteristic of the upper Pottsville is that a regionally extensive marine unit forms the base of each cycle and a regionally extensive coal bed or coal group occurs near the top of each cycle. Therefore, the cycles represent regional marine-alluvial transitions, and coal in the Black Warrior basin probably formed in a range of depositional settings (fig. 39). For example, localized marginal-marine peat domes, which may be analogs for localized coal bodies near the base of some coal groups, are forming on the Klang-Langat delta-estuary system of Malesia (Coleman, 1970). Geographically widespread peat bodies, which may be analogs for the thickest and most continuous Pottsville coal beds, are forming on alluvial plains in Indonesia (Anderson, 1964, 1983; Anderson and Müller, 1975). Low-lying, planar peat accumulations are also forming as much as 70 miles inland between exposed Pleistocene beach ridges in Georgia (Cohen, 1974) and may thus be analogs for coal bodies associated with quartzose sandstone.

CONTROLS ON REGIONAL COAL OCCURRENCE

Interpretations proposed in this study differ markedly from those of earlier studies (Ferm and others, 1967; Cleaves, 1981; Thomas and Womack, 1983; Sestak, 1984; Thomas, 1988a) which favored an Ouachita source for most Pottsville sediment in the Black Warrior basin. However, earlier investigators had few data from southeastern Tuscaloosa and western Jefferson Counties and were thus unable to identify with confidence subsidence centers related to and sandstone bodies derived from the Appalachian orogen. Identifying the effect of Appalachian and Ouachita tectonism on sediment distribution in the Black Warrior basin offers explanations for regional patterns of coal occurrence.

Why are coal beds most abundant in southern Tuscaloosa and western Jefferson Counties? In short, coal abundance can be related to proximity to a sediment source and tectonic subsidence. Three facts stand out with regard to coal abundance: (1) coal abundance increases as net lithic-sandstone thickness increases, (2) in Tuscaloosa and Jefferson Counties, coal abundance and net lithic-sandstone thickness increase as cycle thickness increases, and (3) in Greene and Sumter Counties, coal abundance and net lithic-sandstone thickness do not increase as cycle thickness increases.

Restriction of the thickest fluvial-deltaic lithic sandstone to the southeast part of the study area reflects proximity to a sediment source and dominance of fluvial sedimentation. Therefore, high sediment input and a northwestwardly to westwardly paleoslope in southern Tuscaloosa and western Jefferson Counties helped maintain fluvial-deltaic platforms where peat accumulated. The remaining parts of the study area were dominated by mudstone and quartzose-sandstone deposition and were thus far from a sediment source and were subject to marine influence. Consequently, peat deposition only occurred in these distal areas late in each cycle when most or all of the region was emergent and an extensive alluvial plain was established.

OUTCROP INVESTIGATION OF THE MARY LEE COAL GROUP ALONG THE BLUE CREEK ANTICLINE AND SYNCLINE

INTRODUCTION

The Blue Creek anticline and syncline (fig. 7) are in one of the oldest coal-mining areas of Alabama and lie along the southeast margin of Oak Grove and Brookwood fields. The Mary Lee coal group is exposed in mine highwalls along the anticline and syncline less than two miles from where it is mined and degassed at a depth of more than 1,000 feet. Each highwall transects of a series of depositional systems and provides a basis for detailed depositional models of coal occurrence. Therefore, outcrop analysis of the Mary Lee coal group in proximity to the coalbed-methane fields provides an excellent opportunity to determine the depositional environment of coalbed-methane target strata and to identify small-scale controls on coal occurrence that are difficult to discern in the subsurface but may affect coalbed-methane production.

Results of outcrop analysis indicate that the Mary Lee coal group of the Blue Creek anticline and syncline accumulated in fluvial and swamp environments. Fluvial environments included sinuous trunk channels with point bars, muddy flood plains with lakes, and crevasse splays. Peat (coal) accumulated in interfluvial swamps, and interaction between fluvial and swamp environments is interpreted to be the dominant control on coal occurrence. Crevasse splays formed along the flanks of fluvial axes and therefore controlled coal thickness and geometry locally; splay-related bed splits may be difficult to predict in the subsurface and thus have limited significance in coalbed-methane exploration and production. In contrast, channel avulsion involved abandonment and establishment of complete fluvial axes and therefore controlled coal thickness and geometry regionally; avulsion-related bed splits are predictable using subsurface data and may thus be important for developing coalbed-methane exploration and production strategies.

METHODS

Strata of the Mary Lee coal group in the Blue Creek anticline and syncline were described and measured using standard field techniques. Diagrams of mine highwalls were made that show the distribution of the various rock types and sedimentary structures. Modern and ancient analogs for the Mary Lee coal group were identified and were used to develop depositional models that may be applied in subsurface analysis. Photographs of the strata described below are included in Epsman and others (1988) and in a field-trip guidebook (Pashin and Sarnecki, 1990).

LITHOLOGY

SANDSTONE

Sandstone of the Mary Lee coal group typically is very fine to medium grained and light to medium gray (N7-N5). The sandstone is well indurated and contains a variety of lithic fragments that can be distinguished with a hand lens. In places, argillaceous lithic fragments are abundant enough that weathered sandstone resembles mudstone. Pebbles and granules of shale and siderite are common, and platy, unbanded coal spars were observed in a few layers; pebbles and cobbles are common near the base of some sandstone beds. Sideritic root casts were noted in many layers, and well-preserved fern fronds are exposed on some bedding planes. On the basis of bedding style, two major types of sandstone, channel sandstone and sheet sandstone, were recognized.

Channel Sandstone

Channel sandstone is variable in terms of bedding and sedimentary structures. Channel sandstone is very fine to medium grained and contains some conglomeratic beds. Although the style of channel fill varies, two end members were distinguished: (1) epsilon-crossbedded sandstone and (2) scour-and-fill sandstone.

Epsilon-crossbedded sandstone (Allen, 1963) in the Mary Lee coal group occurs in solitary sets and has a sharp, typically conglomeratic base and commonly has a heterolithic upper part that contains both sandy and shaly strata. Major bounding surfaces that define the crossbeds are generally traceable from the top of the sandstone to the base; the crossbeds characteristically contain smaller, grouped cross strata. These features are well exposed in a 23-foot thick sandstone unit at the Jagger mine (SW¼ sec. 28, T. 19 S., R. 5 W.) (figs. 1, 46). Rooted, heterolithic strata at the top of the set are exposed at the southwest end of the highwall. Epsilon-crossbedded sandstone with a low crossbed dip angle (less than 2°) occurs in interval C in the northeastern part of the Black Star mine (SE¼ sec. 19, T. 19 S., R. 5 W.) (figs. 1, 47). Here, one epsilon-crossbedded unit truncates the adjacent sheet sandstone, and another epsilon-crossbedded unit truncates the previous epsilon crossbed.

Scour-and-fill structures are ideally U-shaped, sandstone-filled depressions that truncate subjacent strata. Such structures are widespread in the Mary Lee coal group and exhibit a variety of bedding styles and sedimentary structures. Scour-and-fill sandstone is well exposed in the Davis Creek mine (NW¼ sec. 19, T. 20 S., R. 6 W.) (figs. 1, 48) and Black Star mines (fig. 47).

In the northeast part of the Davis Creek mine (fig. 48), a channel-sandstone body that is locally thicker than 30 feet is a composite of multiple scour-and-fill structures that are individually less than 15 feet deep. The scour surfaces are lined with shale and siltstone pebbles, and the dominant sedimentary structures in the scour fills are tangential crossbeds and current-ripple-drift cross laminae. Lateral accretion surfaces are locally present near the southwest margin of the sandstone body.

Different styles of scour-and-fill are exposed at the Black Star mine where the structures range from symmetrical U-shapes with concentric fills to asymmetrical scalloped forms resembling epsilon crossbedding (fig. 47); most of the structures are less than 9 feet deep and 25 feet wide. A few scour fills at the Black Star mine truncate subjacent strata and contain crossbedded sandstone. However, most of the structures contain alternating sandstone and mudstone that resembles sheet sandstone, which is discussed below, and some beds in the scalloped structures pass laterally into sheet sandstone and are associated with lensoid sandstone beds. The principal difference between scour-and-fill sandstone and sheet sandstone at the Black Star mine is bed geometry.

At the Jagger mine, two scour-and-fill structures less than 3 feet deep truncate the uppermost parts of the epsilon-crossbedded sandstone (fig. 46). One of the structures has an intensely rooted,

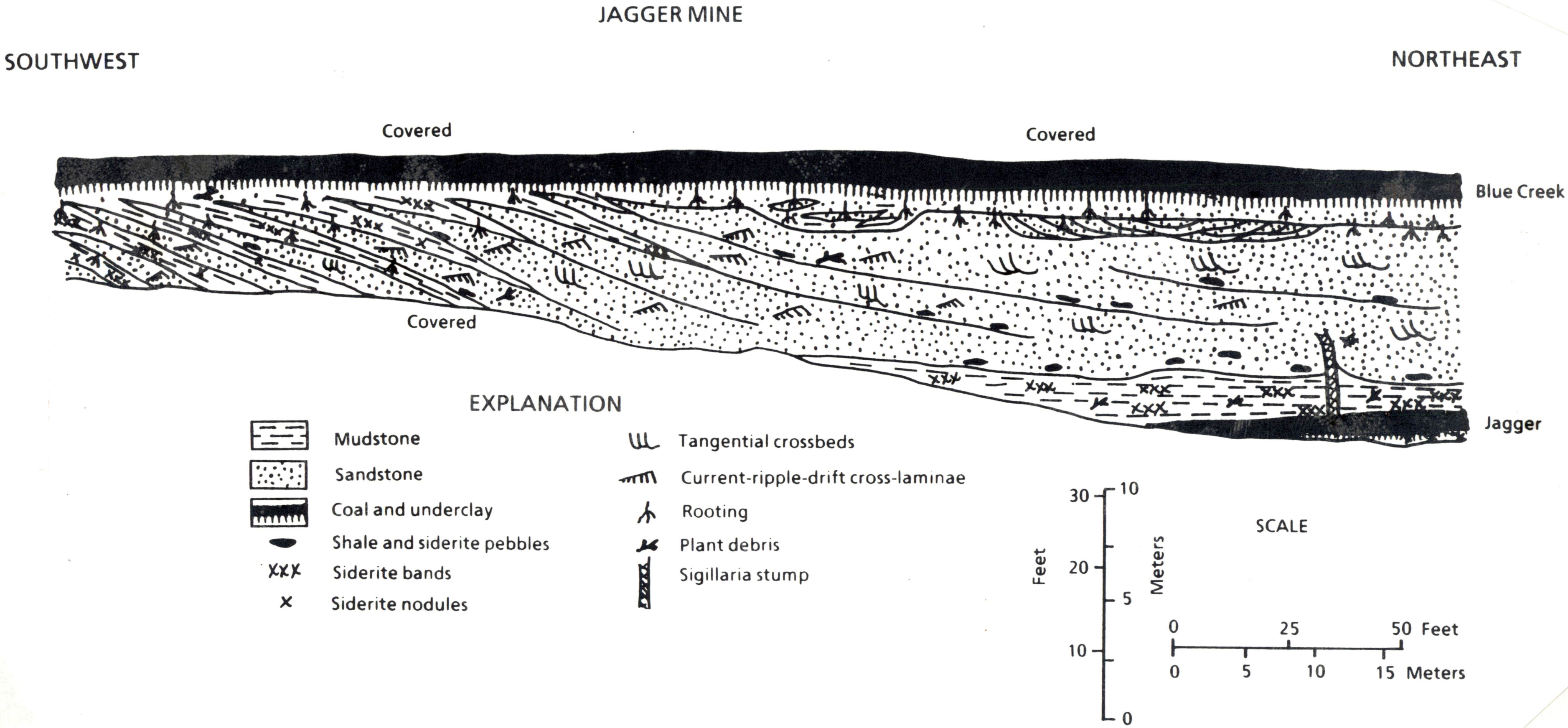


Figure 46. Diagram of the Jagger mine highwall.

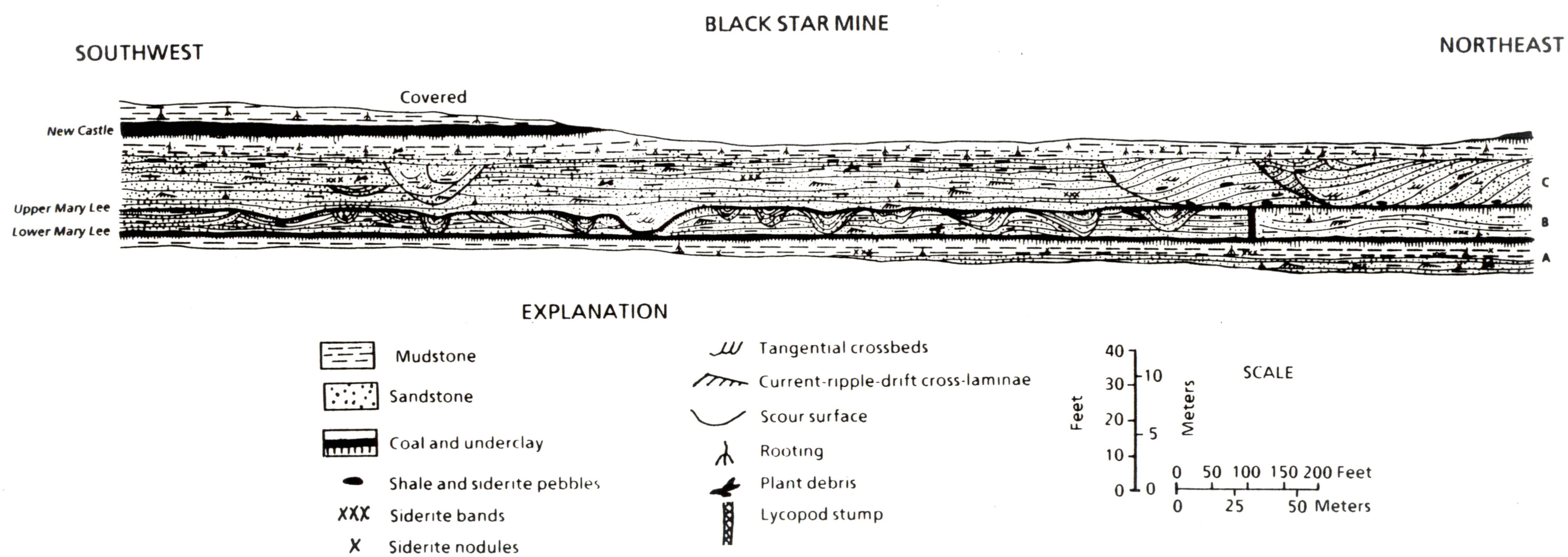


Figure 47. Diagram of the Black Star mine highwall.

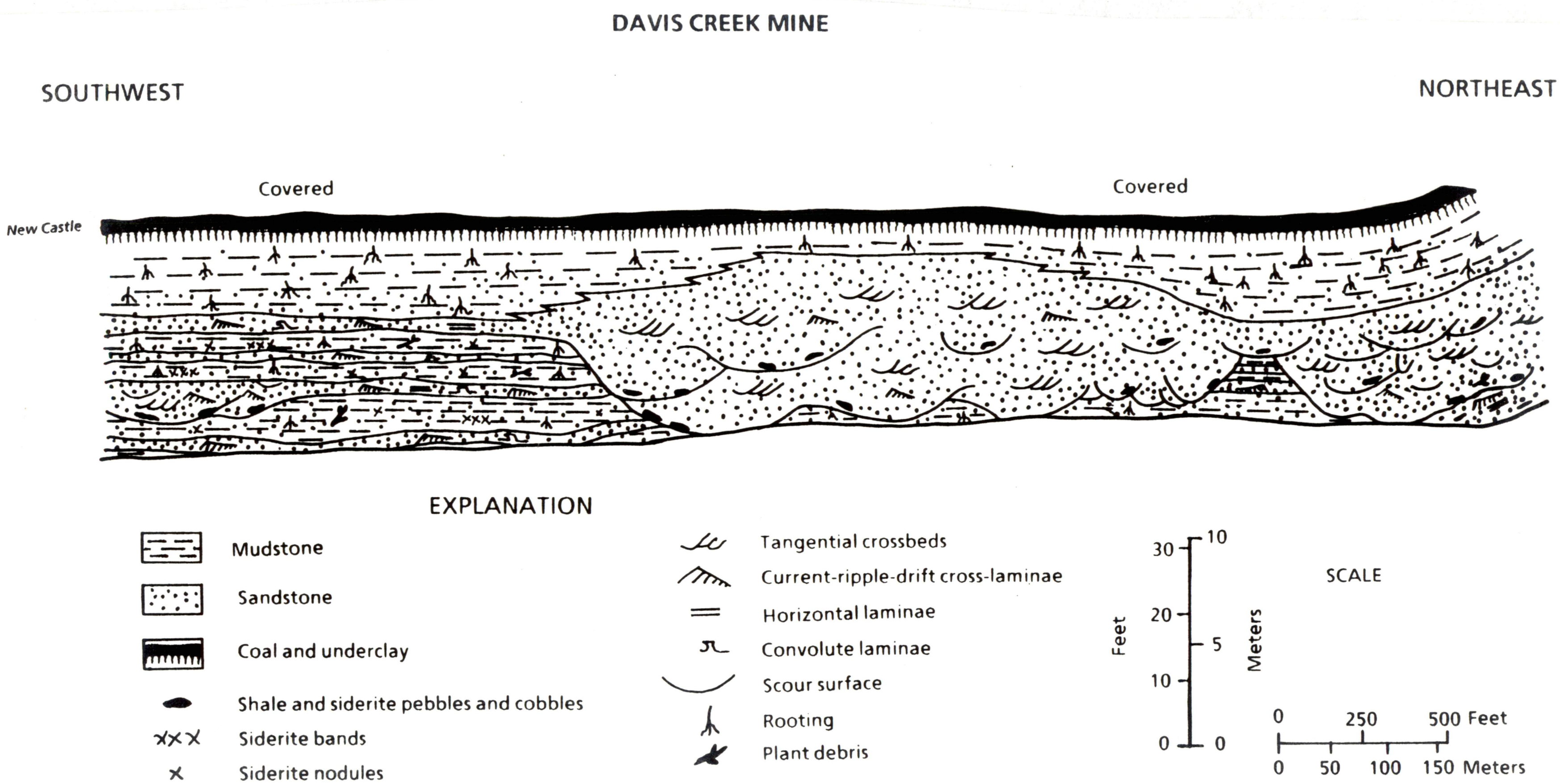


Figure 48. Diagram of the Davis Creek mine highwall.

mudstone-rich fill containing irregular, lensoid sandstone beds. The other is filled with crossbedded sandstone and is a composite of several smaller scour-and-fill structures.

Sheet Sandstone

Sheet sandstone is very fine to fine grained and occurs in laminae to thick beds that are separated by mudstone; sheet sandstone is well exposed at the Black Star and Davis Creek mines (figs. 47, 48). The sheet-sandstone beds can be traced laterally for tens, or more commonly, hundreds of feet and are locally thicker than 4 feet at the Davis Creek mine. Sheet-sandstone beds at the Davis Creek mine are wavy and undulatory, in part due to folding, and several wavy lensoid beds are exposed at the Black Star mine.

The sheet-sandstone beds commonly have sharp basal contacts along which scattered shale pebbles, siderite pebbles, and plant debris occur. In several beds, the basal contact is overlain by horizontal laminae, which are in turn overlain by current-ripple-drift cross laminae and convolute laminae. The succession is typically completed with a gradational, rooted upper contact with the overlying mudstone. In the thinner beds, ripple-drift cross laminae predominate, whereas some of the thickest sheet-sandstone beds have gradational basal contacts and a variable internal stratification sequence.

The highwall in the Davis Creek mine shows clearly some of the relationships between the sheet sandstone and the scour-and-fill sandstone units (fig. 48). At the southwestern end of the highwall, some sheet-sandstone beds extend laterally for more than 1,000 feet. To the northeast, sheet-sandstone beds are truncated by a major scour-and-fill structure, which defines the western margin of a channel-sandstone body that is as thick as 30 feet. The channel sandstone passes southwestward into the uppermost thickly bedded sheet sandstone, and the uppermost part of the channel sandstone intertongues with rooted sandstone and mudstone near the top of the highwall.

MUDSTONE

Fine-grained rocks in the highwalls generally range from silty and sandy shale to shaly siltstone and are grouped together as mudstone for convenience. Mudstone is medium gray to medium dark gray (N5-N4), brittle, and generally has a poorly developed platy parting or is nonfissile; the dominant lithologic constituents are silt- to sand-size quartz grains, mica flakes, and finely macerated plant debris. Examination with a hand lens reveals that the grains are set in an argillaceous matrix that accounts for a significant volume of the rock.

Mudstone occurs in laminae to thick beds, and bed geometry varies from even to wavy or lensoid. Siderite bands and well-preserved fern fossils are common in thick, laminated beds, such as those at the Jagger mine (fig. 46). Rooted mudstone is abundant, particularly below each coal bed and in the thinner mudstone beds, and most of the root traces are assignable to the lycopod taxon, *Stigmaria*. Sideritic root casts, which commonly have a nodular appearance, are characteristic of the thinner, intensely rooted strata. Intensely rooted mudstone generally occurs below coal beds and in interbeds between sandstone. Carbonized plant fossils are most abundant where root traces are scarce. In layers dominated by mudstone, particularly in proximity to thick sandstone beds, sandstone occurs in even, wavy, or lenticular laminae and thin beds.

Thick coal beds overlie sandy underclay containing abundant *Stigmaria* rootlets. The underclay is very gritty and is lithologically similar to mudstone. Root traces are pervasive, and poorly oriented slickensides are developed. The underclay ranges in thickness from 0.3 foot to more than 5 feet and is traceable with the coal beds. Although underclay is sharply overlain by coal, it commonly grades downward into mudstone or sandstone (figs. 46-48). Below the New Castle coal in the Davis Creek and Black Star mines and below the Jagger coal at the Jagger mine, sandstone and mudstone are rooted and locally have a nodular appearance, and discontinuous laminae and thin beds of coal are locally present in the mudstone.

In-situ, sand-filled lycopod trunks occur in a few layers at the Jagger and Black Star mines (figs. 46, 47), and leaf litter is concentrated less than 2 feet above those layers. At the Jagger mine, an erect *Sigillaria* trunk is rooted near the upper contact of the Jagger coal, extends upward through approximately 9 feet of laminated mudstone with siderite bands, and continues upward through the basal 3 feet of a thick sandstone bed (fig. 46). Another layer of in-situ lycopod trunks occurs approximately 1.5 feet from the base of the mudstone, and another layer occurs approximately 1.5

feet from the top of the unit; the middle of the mudstone is fissile and lacks root traces and lycopod trunks. In interval B at the Black Star mine, a lycopod trunk extends upward through 12 feet of interbedded mudstone and sandstone (fig. 47).

COAL

Coal in the field area is bright banded and typically forms even, thin to thick beds with well-defined contacts. Thick coal beds, like the Blue Creek bed, contain numerous partings of clay and bone coal which may impede vertical fluid flow, but most beds thinner than 1 foot lack abundant partings. Most coal beds contain alternating thin to thick vitrain and clarain bands with some fusain layers. At the Jagger mine, vitrain bands in the lower part of the Jagger coal are as much as 1 inch thick. The upper 1 to 4 inches of most coal beds are fairly dull, and the upper contact is commonly less distinct than the lower contact.

The coal beds generally have uniform thickness and can be traced for the length of a given highwall (figs. 46-48). However, at the Black Star mine, two fairly thin beds occur at the level of the Mary Lee coal (fig. 47). The lower coal bed is subhorizontal and is approximately 1.3 feet thick along the length of the exposure (2,000 feet). The upper coal bed is undulatory, sagging slightly above several scour-and-fill structures. The upper bed is generally 0.3 foot thick but is 0.6 foot thick in a scour-and-fill structure where it sags and nearly joins the lower bed. In a recently reclaimed highwall approximately 0.5 mile west of the Black Star mine, the lower Mary Lee coal joins the Blue Creek coal to form a bed that is as thick as 12 feet and is the thickest coal in the region (Epsman and others, 1988).

DEPOSITIONAL MODEL

EPSILON-CROSSBEDDED SANDSTONE: SINUOUS FLUVIAL CHANNELS

Epsilon crossbedding (figs. 46, 47) is formed by the process of lateral accretion in a variety of depositional settings, such as intertidal, deltaic, and alluvial environments, but is almost everywhere the product of sinuous channels with point bars (Allen, 1963, 1965) (figs. 49, 50). Abundant root

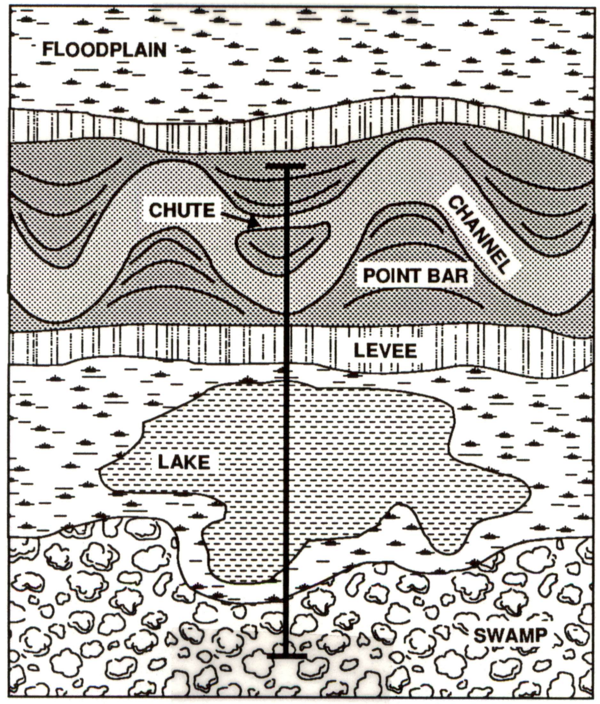


Figure 49. Paleoenvironmental model for Jagger mine. Bar indicates facies sequence in highwall.

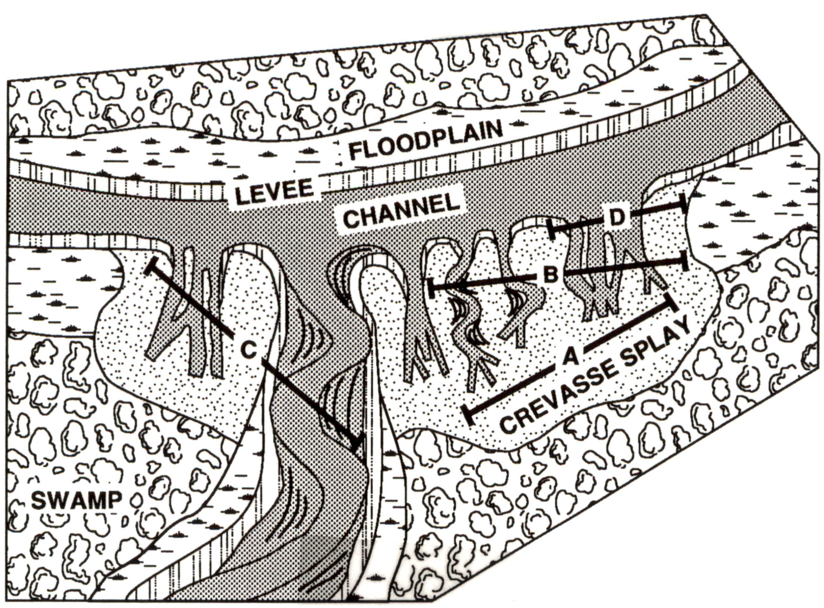


Figure 50. Paleoenvironmental model for Black Star and Davis Creek mines. Bars indicate stratigraphic intervals labeled in figure 47; bar D is transect at Davis Creek mine (fig. 48).

traces and plant fossils in the Jagger and Black Star mines indicate a fluvial origin for the epsilon crossbeds.

The thickness of an epsilon-crossbed set provides a reliable estimate of bankfull channel depth (Allen, 1965; Gardner, 1983). Applying this principle to sets in the Jagger and Black Star mines (figs. 46, 47), channel depth exceeded 20 feet. Because epsilon crossbeds at the Jagger and Black Star mines are thicker than any of the scour fills in the area, the point bars are interpreted to represent major fluvial channels that provided the primary skeletal framework for the Mary Lee coal group in the field area.

Lateral truncation of adjacent strata by an epsilon-crossbed set, as in the northeastern end of the Black Star mine (fig. 47), indicates preservation of cutbanks (Allen, 1965; Nami and Leeder, 1978). Near the truncation surfaces and upward in section, the epsilon sets become subhorizontal, suggesting gradual aggradation, infilling, and abandonment of the channels. Scour-and-fill structures that truncate the upper part of epsilon-crossbed sets are commonly interpreted to be chute fills (Allen, 1965) (figs. 46, 49). At the Jagger mine, the muddy, rooted scour fill indicates that the chute was active only during high-water stage and that low-water stage was long enough to allow plant colonization. In contrast, the sandy set of scour fills at the Jagger mine may represent a more active chute system that was filled rapidly.

MUDSTONE: LEVEES AND FLOOD PLAINS

Along channel margins in modern flood plains, fine-grained sediment is deposited by overbank flooding. As flood water crosses the bank, sediment is deposited, and a ridge, or levee, is built and vegetated (Allen, 1965; Hughes and Lewin, 1982) (figs. 49, 50). Abundant plant fossils and root traces suggest that mudstone in the Davis Creek, Jagger, and Black Star mines formed in a terrestrial setting, and where in proximity to epsilon-crossbed sandstone, may be interpreted as levee and flood-plain sediment deposited adjacent to rivers.

Layers containing in-situ lycopod trunks, like those at the Jagger and Black Star mines (figs. 46, 47), have been interpreted to represent fossil swamp forests that have been preserved by major floods, and the leaf litter that is concentrated above the trunk layers has been interpreted to represent dead forest canopy that fell to the substrate after those floods (Gastaldo, 1986, 1990). The *Sigillaria* trunk at the Jagger mine (fig. 46), which extends upward through 9 feet of mudstone, indicates high sedimentation rate. However, the unfossiliferous interval in the middle of the mudstone is interpreted to represent a flood-plain lake. Flood-plain lakes may form by ponding of water on flood plains as a new fluvial system, like that represented by the epsilon crossbeds, is established and siliciclastic sediment subsides into rapidly compacting peat, like that represented by the Jagger coal (fig. 49).

SCOUR-AND-FILL AND SHEET SANDSTONE: CREVASSE-SPLAY SYSTEMS

A crevasse splay is a coarse sediment lobe or apron that develops where a channel levee is breached and water spills into a flood basin or bay (fig. 50). Although crevasse splays in the upper reaches of deltas may closely resemble alluvial splays, most deltaic splays, such as those on the Mississippi Delta (Arndorfer, 1973), represent the infilling of marine bays and thus typically contain indicators of marine processes (Elliott, 1974). Crevasse-splay deposits in the field area are interpreted to be alluvial in origin because they are associated with coal rather than with marine deposits.

In the proximal crevasse-splay system, channels erode the breached levee and the nearby flood plain; scouring and channel filling are the dominant processes (fig. 50). Distal reaches of crevasse-splay complexes are characterized by building of splay lobes and filling of flood basins; sheet flow is typically the most important process. Therefore, fining-upward, channel-fill dominated sequences are characteristic of proximal-splay deposits, whereas coarsening-upward, sheet-sandstone dominated deposits are characteristic of distal splays. Natural examples most commonly deviate from this general scheme due to shifting of channel position as well as abandonment and rejuvenation of splay lobes (Guion, 1984; Bridge, 1984).

Scour-and-fill structures and associated features in the Davis Creek and Black Star mines can be characterized by crevasse-splay models. Straight channels generally do not shift and migrate and thus tend to form U-shaped scour-and-fill structures like those at the highwalls (Schumm, 1977). The array of scour-and-fill structures in the Davis Creek mine (fig. 48) is typical of proximal splay deposits (fig. 50, bar B). Although the sandstone is thicker than 30 feet locally, individual scour fills are scarcely thicker than 15 feet, so the internal architecture of the sandstone body is probably a product of coalescing splay channels in a subsiding flood basin near a major break in a levee. Traceability of a scour fill into one of the thickest sheet-sandstone beds (fig. 48) represents an abrupt lateral transition to sheet flow, perhaps in a protected area adjacent to a major splay-channel system and behind an unbroken levee segment (fig. 50). Some of the splay channels apparently had levees, because the upper part of the main channel sandstone intertongues with rooted sandy mudstone.

Abundant scour-and-fill structures and sheet-sandstone beds in the middle of the Black Star mine (fig. 47) are interpreted to represent the middle part of a crevasse-splay complex where channelized flow gave way to sheet flow (fig. 50). This interpretation is supported by the lithologic similarity of the scour fills to the associated sheet sandstone and by the poorly defined boundaries of some of the scour-and-fill structures. The scalloped scour-and-fill structures at the Black Star mine resemble epsilon crossbedding, which indicates that some of the channels were sinuous and had point bars (Nami and Leeder, 1978). On the basis of the width of the scalloped fills, the point bars were less than 25 feet wide. Point bars typically develop where channels are at or near grade (Allen, 1965), indicating that local relief was low and that the channels formed a considerable distance into the flood basin.

The sharp bases, rooted tops, and lateral continuity of many of the thinner sheet-sandstone beds (figs. 47, 48) are characteristic of classical sheet-flood deposits which are deposited by ephemeral, temporarily erosive, waning flows (Stanley, 1968). Sheet sandstone similar to that in the field area is widespread in the distal parts of crevasse-splay sequences in coal-bearing strata (Horne and others, 1978; Guion, 1984). Variable stratification sequences in the thickest sheet-sandstone beds at the Davis Creek and Black Star mines indicate that flow was in places irregular, and the gradational bases of some sheet-sandstone beds, particularly at the Black Star mine, indicate that flow was locally semipermanent. Therefore, the thinner sheet-sandstone beds apparently were deposited during brief floods, whereas the thicker beds evidently were deposited during long-term floods in which flow was more variable.

COAL: PEAT SWAMPS

Thick peat accumulates in swamp areas protected from siliciclastic sedimentation (McCabe, 1984, 1987). Outcrop evidence from the Mary Lee coal group indicates that peat accumulated in interfluvial swamps in the area of the present-day Blue Creek anticline and syncline and that fluvial processes were the dominant control on coal distribution and geometry in the field area. Interaction between fluvial and swamp environments is characterized in the following discussion and is then synthesized into a working model of fluvially controlled coal occurrence that can be applied and tested using subsurface interpretation.

Evidence from highwalls indicates that levees were a barrier to sedimentation that permitted swamps to develop close to river banks and that breaching of levees made parts of the swamp vulnerable to siliciclastic influx (fig. 50). Hence, the swamps probably were low lying, or at least were not domed above the level of the river banks, because splay deposits were developed directly on the swamp surface at the Black Star mine (figs. 47, 50). However, after each major splay event, swamps were reestablished on the abandoned crevasse-splay surface. Thus, development, abandonment, and rejuvenation of crevasse-splay systems was a control on coal-bed geometry; similar control has been recognized in other Appalachian coal-bearing sequences (Ferm and Cavaroc, 1968; Howell and Ferm, 1980; Ferm and Staub, 1984).

Near joining of upper and lower Mary Lee coal beds in a scour-and-fill structure at the Black Star mine (fig. 47) demonstrates how abandonment and rejuvenation of splay systems may affect coal-bed geometry. Thickening of the bed in the scour-and-fill structure is typical of coal formed in channels. All of the other scours at the mine have sandy fill, which is associated with gradual channel abandonment (Hopkins, 1985), whereas the coal-filled channel indicates rapid abandonment. Because the bed that fills the channel is traceable throughout the highwall, channel abandonment was evidently synchronous with abandonment of the splay system. Northwest of the Black Star mine, joining of the lower Mary Lee coal with the Blue Creek coal by simple pinchout of the intervening clastics is a classic outcrop-scale example of crevasse-splay control of coal-bed splitting.

The uppermost crevasse-splay sequence between the upper Mary Lee and New Castle coal beds at the Black Star mine is truncated by epsilon-crossbed sets (fig. 47), indicating development of a major, sinuous fluvial channel in the splay area. A splay channel commonly provides an avulsion site for the fluvial channel that fed it (Allen, 1978; Smith and others, 1989), so the epsilon crossbeds are interpreted to have formed by avulsion, or diversion, into the flood basin of the main fluvial channel that fed the splay systems (fig. 50). Development of the thick epsilon-crossbed set between the Jagger and Blue Creek beds at the Jagger mine (fig. 46) may be interpreted as another example of a fluvial channel that was diverted into a swamp area.

IMPLICATIONS FOR SUBSURFACE STUDIES

Applying fluvial sedimentation models to Pottsville coal groups is useful in coalbed-methane exploration and production because it provides a conceptual framework for predicting coal distribution and thickness. In the Mary Lee coal group of the Blue Creek anticline and syncline, crevasse splays formed along the flanks of fluvial axes and thus controlled coal thickness and geometry locally. For example, splay-related bed splits are observable in outcrop. However, small-scale bed splits may not be identified easily or correlated for a significant distance using data from coalbed-methane wells, which generally have an effective spacing between 40 and 160 acres. Also, channel-fill coal is commonly thicker than adjacent coal and may therefore have enhanced coalbed-methane potential. Most channel-fill coal bodies, particularly those related to crevasse splays, are small and difficult to target in the subsurface. Even so, large-scale valley channels, which are discussed in the following section, contain some of the thickest and most gas-productive coal beds in the Black Warrior basin.

Channel avulsion involves shifting of major fluvial channels and flood basins and is therefore, in contrast to crevasse-splay control, a regional control on coal-bed geometry. Hence, avulsion-related bed splits may be identified readily using subsurface data and may be thus be critical in formulating successful coalbed-methane exploration strategies. According to the avulsion model (Ferm and Cavaroc, 1968), thick coal beds should occur between contemporaneous fluvial axes which may be identified by mapping sandstone trends. However, compaction of thick peat between fluvial axes provides considerable accommodation space for successive fluvial deposits to accumulate. Therefore, axial fluvial deposits are commonly deposited above thick peat (coal) beds following channel avulsion, resulting in juxtaposition of thick coal and sandstone bodies.

A CASE STUDY OF FLUVIAL AND STRUCTURAL CONTROL OF COAL-BODY GEOMETRY: OAK GROVE FIELD

INTRODUCTION

In addition to fluvial control of coal-body geometry, structural control of coal-body geometry by synsedimentary movement of normal faults has been recognized in outcrops of the Appalachian region (Horne and others, 1978). Hence, interplay of structural and fluvial processes may be a crucial concern in exploration and production planning. In the Black Warrior basin of Alabama, which contains abundant horst-and-graben systems, core data from underground mines have been used to identify structural control of coal-body geometry (Weisenfluh and Ferm, 1984). According to this structural model, the thickest coal beds occur in upthrown fault blocks; the coal splits and thins in the adjacent downthrown blocks (Weisenfluh and Ferm, 1984; Epsman and others, 1988; Ferm and Weisenfluh, 1989, Pashin and others, 1989).

Although most sedimentologic studies of coal distribution in the eastern United States have stressed outcrop and core data (Horne and others, 1978; Ferm and Staub, 1984), many eastern coal basins contain abundant oil-and-gas data, particularly geophysical well logs (fig. 5). These logs can be used to test existing models and to formulate new models of fluvial and structural control of coal occurrence. One advantage of using geophysical well logs is that depositional models can be formulated by evaluating several depositional cycles in a given area. The advent of coalbed-methane as a viable energy resource, moreover, has made formulating such models timely and practical because they can be used for resource assessment, strategic well siting, and selecting completion targets. Results of subsurface analysis in Oak Grove field demonstrate that styles of coal occurrence differ in each depositional cycle and are the result of interwoven sedimentologic, tectonic, and biologic processes.

METHODS

High-resolution (20-inch) density logs are abundant in Oak Grove field and provide a database for identifying geologic controls on coal occurrence. These logs record bed thickness with a minimum resolution of 0.3 to 0.4 foot. A series of cross sections (fig. 2) was made to determine sandstone- and coal-body relationships. In the Black Creek and Pratt cycles, which contain numerous beds with complex geometry, maximum coal thickness maps were made; these maps depict the thickest coal bed in a given interval regardless of stratigraphic position within that interval. Because individual beds in the Mary Lee cycle extend throughout Oak Grove field, isopach maps of each coal bed were made. Additionally, isopach and net-sandstone isolith maps of selected siliciclastic intervals separating regionally extensive coal beds were made to demonstrate the depositional architecture of the coal groups. Only lithic sandstone is present in the Black Creek-Cobb interval of Oak Grove field.

FLUVIAL CONTROL

LOWER BLACK CREEK SUBCYCLE

Density logs demonstrate that the lower Black Creek subcycle contains a thinning-upward sequence containing five to eight coal beds (fig. 5). Nearly all beds thicker than 1 foot are in the lower half of the coal-bearing part of the subcycle, and the thickest bed occurs at or near the bottom of the coal group. Net-coal thickness in the lower Black Creek typically varies from 4 to 10 feet (fig. 51), and maximum bed thickness varies from 1 to 5 feet (fig. 52). As a rule, net coal thickness increases with maximum bed thickness, although the highest values on each map are slightly offset in most areas, reflecting joining of coal beds at different stratigraphic levels.

The lower Black Creek contains two major sets of coal beds (fig. 53). Bed geometry in the lower set is variable, whereas beds in the upper set are more continuous and contain splits with less relief.

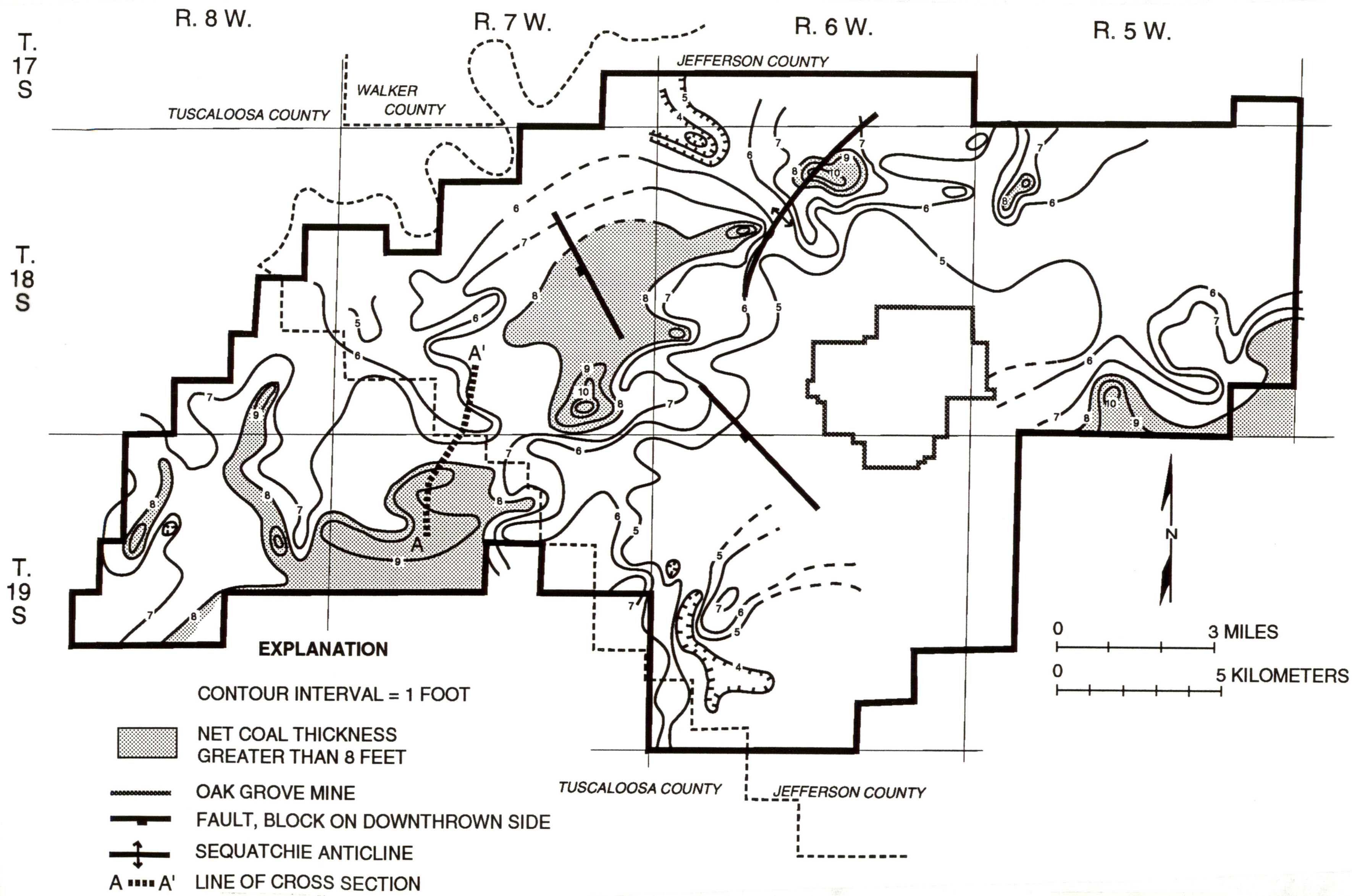


Figure 51. Net-coal isolith map of the lower Black Creek subcycle, Oak Grove field.

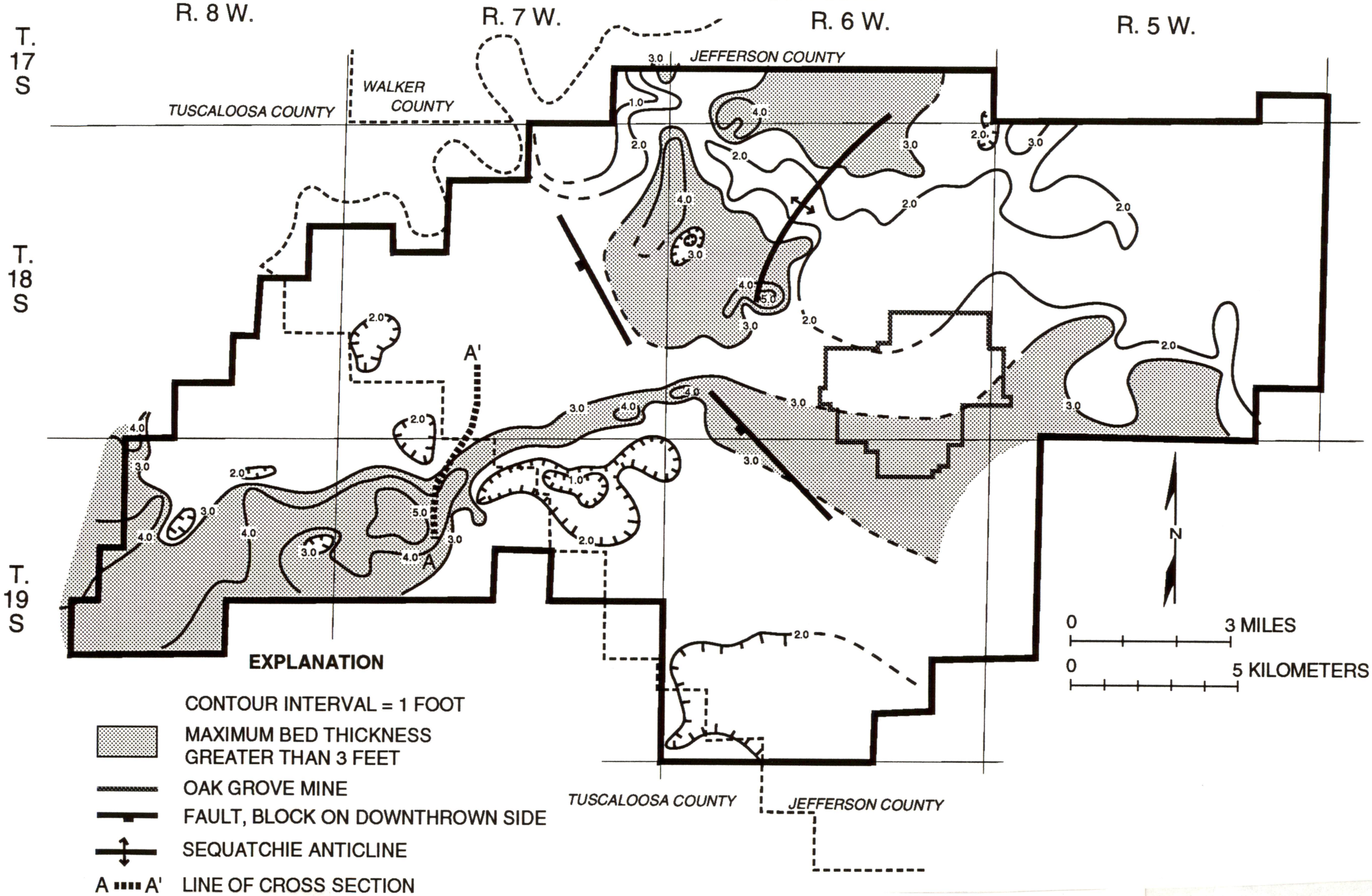


Figure 52. Maximum coal thickness map of the lower Black Creek subcycle, Oak Grove field.

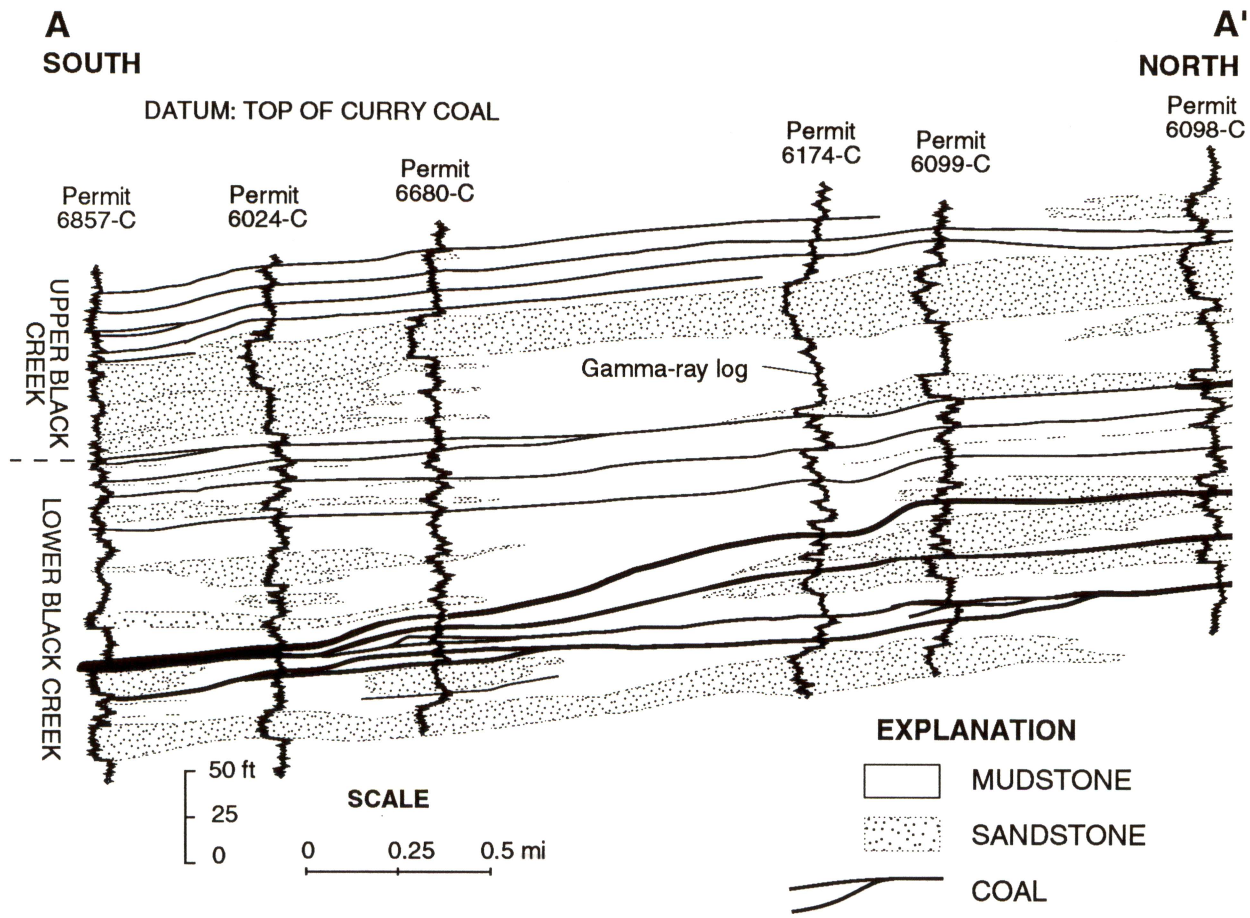


Figure 53. Stratigraphic cross section A-A', Oak Grove field. See figure 51 for location.

Although the lower Black Creek typically contains these two sets of coal beds, they do not form regionally significant marker units. Rather, stratigraphic variability of the lower Black Creek simply decreases upward, and if traced far enough, beds in the upper set pass into the lower set.

Most beds in the lower set merge into one of the thickest beds in Oak Grove field (fig. 53). Stacked sandstone bodies separate coal beds at the north end of the cross section, and the associated siliciclastic intervals fine and thin southward as the coal beds merge. In the southern part of the cross section, however, another series of stacked sandstone bodies occurs above the thickest coal.

Features in the lower Black Creek subcycle fit well into the classic compactional model of Ferm and Cavaroc (1968) in which differential compaction of peat and siliciclastic sediment provides avulsion sites for channel axes, thereby juxtaposing thick sandstone and coal bodies. Where the coal beds merge (fig. 53), a large volume of compactible peat had accumulated. Compaction of that peat apparently promoted establishment of a new fluvial trend that is represented by the three stacked sandstone bodies in the southern part of the cross section.

Stacking of sandstone bodies between coal beds in the northern part of the cross section suggests that the peat was domed above river-bank level, thus causing avulsion and establishment of fluvial axes beyond the line of cross section. Only after fluvial deposits built above the level of the peat accumulation could the river avulse toward the south, thereby forming stacked sandstone bodies above the thickest coal. Upward decrease in stratigraphic variability within the lower Black Creek subcycle suggests that topography had become subdued and that development of avulsion sites by peat compaction was not a dominant process near the close of lower Black Creek deposition.

UPPER BLACK CREEK SUBCYCLE

The upper Black Creek subcycle contains one to six (generally two or three) thin coal beds that cap a coarsening-upward sequence that is approximately 100 feet thick (figs. 5, 53). Core data (Boyer and others, 1986) indicate that marine mudstone is present below the upper Black Creek coal beds, suggesting a deltaic origin for the lower part of the subcycle, but are absent within the coal-bearing interval, suggesting an alluvial origin for the upper part of the subcycle. Individual beds in the upper Black Creek are thinner than 1 foot throughout most of Oak Grove field and may thus have limited significance as completion targets. However, maximum coal thickness exceeds 1.5 feet in south-central Oak Grove field and 3 feet in the easternmost part of the field (fig. 54). Net coal thickness varies from less than 0.5 foot in the west-central part of the field to more than 4 feet in the easternmost part (fig. 55).

The sandstone-isolith map of the upper Black Creek depicts a major east-west-trending sandstone body (fig. 56). The 30-foot contour on the sandstone isolith map outlines an east-west trending, sinuous sandstone body that is locally 2 miles wide and more than 50 feet thick; the main sandstone body narrows and joins another sinuous body in the westernmost part of the field. Localized lobate

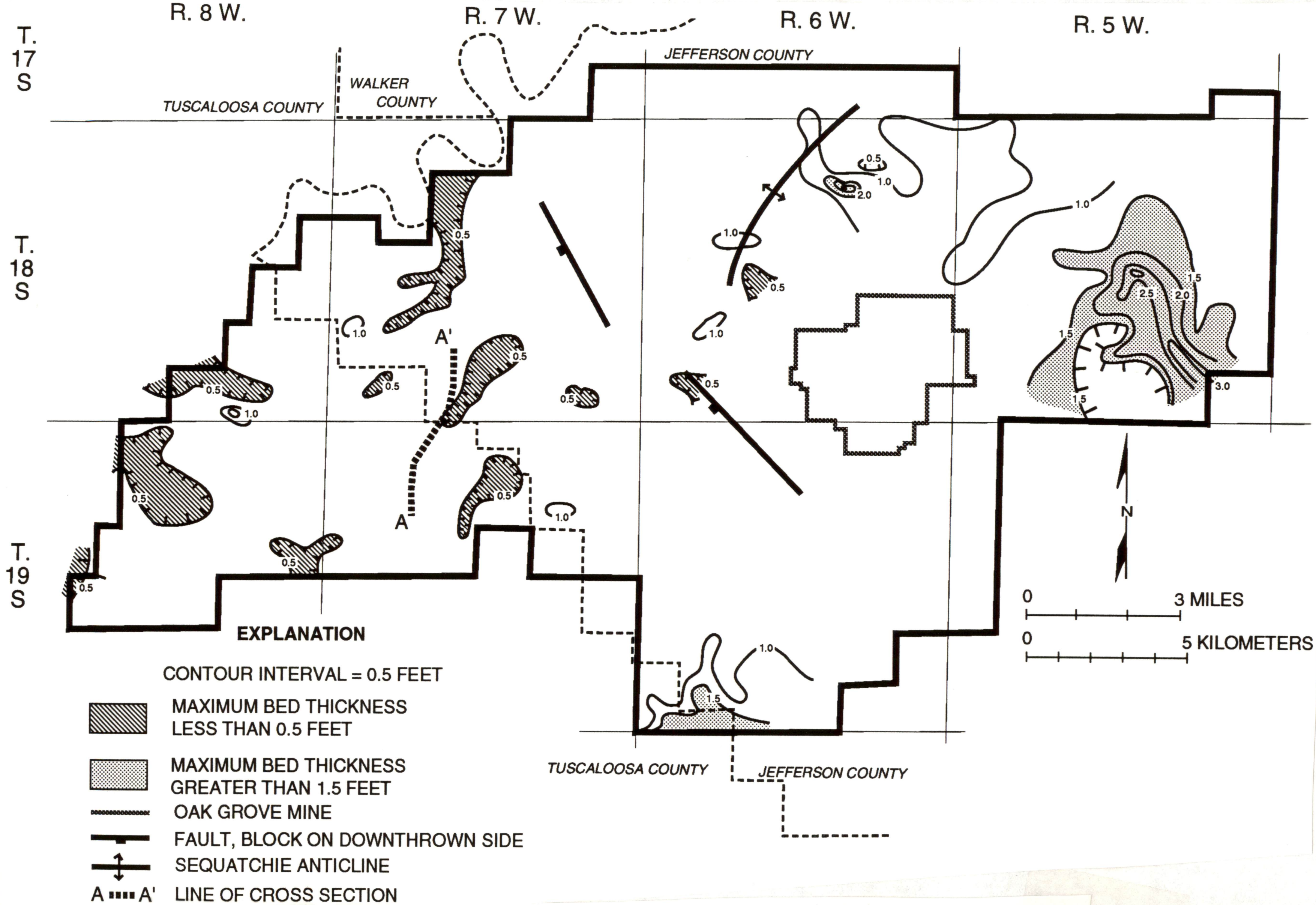


Figure 54. Maximum coal thickness map of the upper Black Creek subcycle, Oak Grove field.

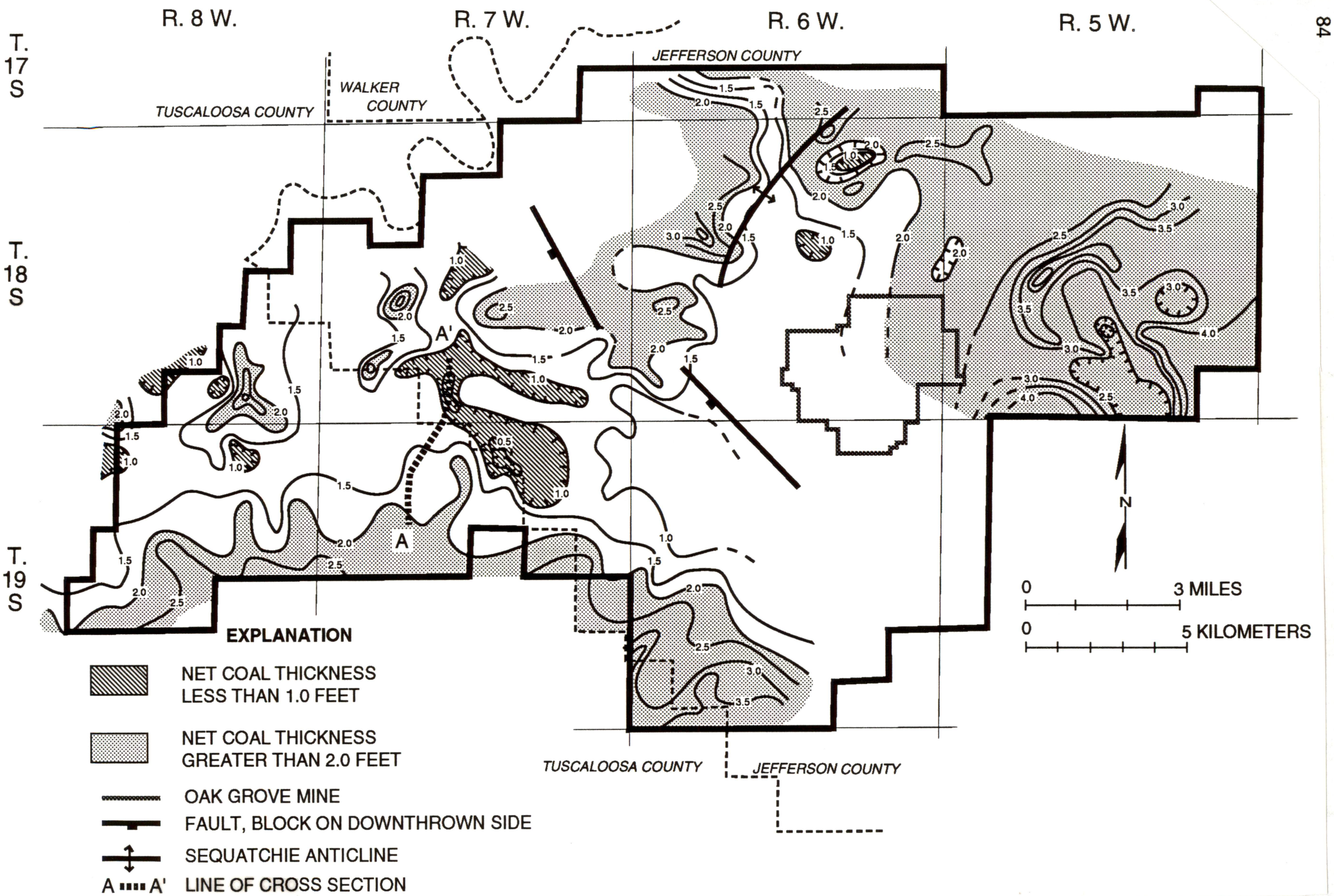


Figure 55. Net-coal isolith map of the upper Black Creek subcycle, Oak Grove field.

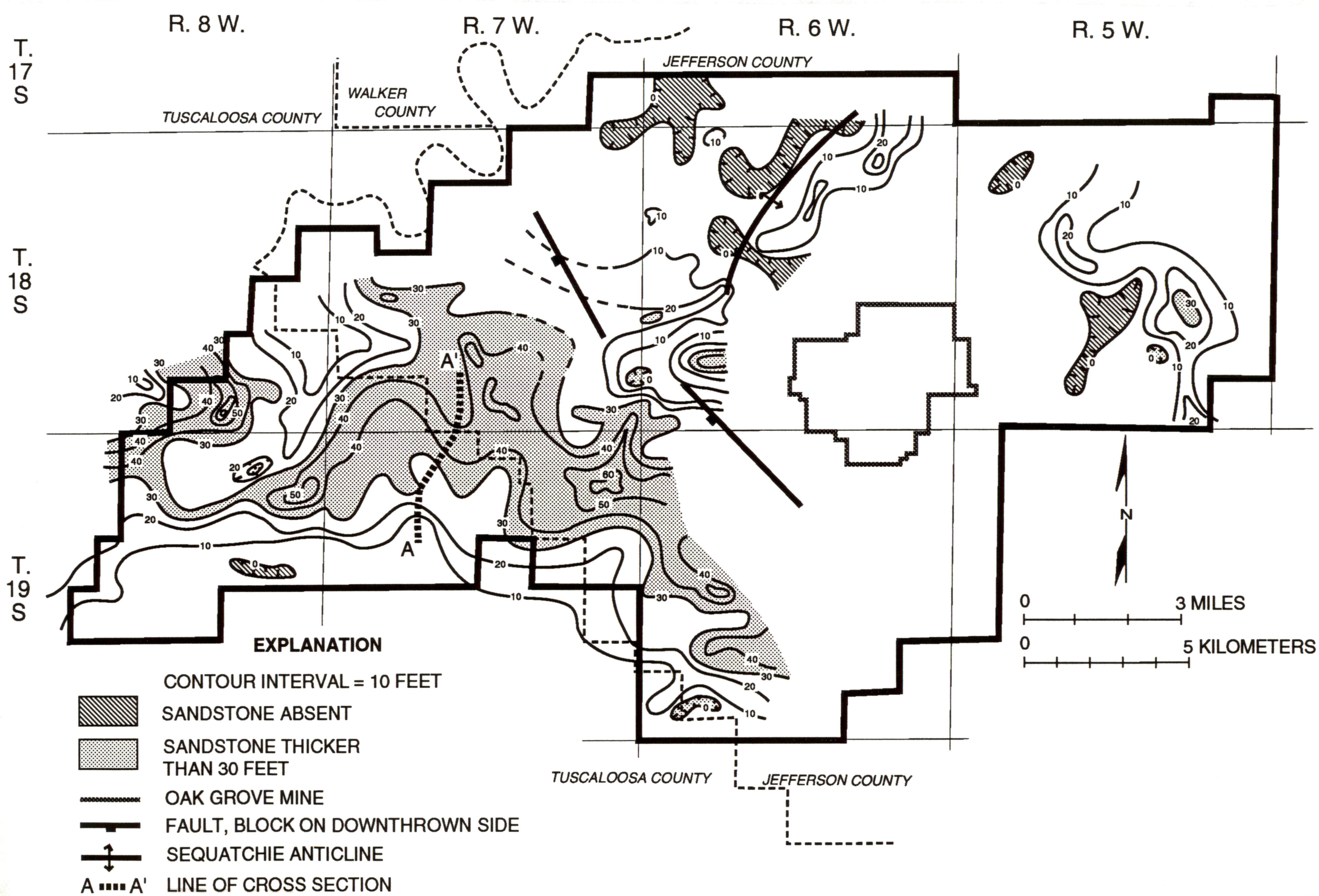


Figure 56. Sandstone isolith map of the upper Black Creek subcycle, Oak Grove field.

and apron-like bodies, like the one defined by the 40-foot contour in west-central Oak Grove, are present along the flanks of the main axial trend. Sandstone and coal thickness have a strong inverse relationship in the upper Black Creek of western Oak Grove field (figs. 53, 55, 56). As many as six beds occur in the south, whereas only two beds in the north where correlative sandstone is thickest.

The axial sandstone trend (fig. 56) is interpreted to be a sinuous fluvial channel, and the flanking lobate and apron-like bodies are interpreted to be crevasse-splay complexes. Joining of the two sinuous sandstone bodies in westernmost Oak Grove may define part of a tributary system. The upper Black Creek fluvial system is similar in scale to that of the Tombigbee and Alabama Rivers of southwest Alabama which have meander belts that are approximately 2 miles wide north of where they join to form the Mobile River.

The inverse relationship between sandstone thickness and coal thickness and abundance (figs. 53, 55, 56) indicates strong fluvial control on coal occurrence. Increase in coal thickness away from the fluvial axis suggests that the fluvial system controlled where peat could accumulate. The uniform increase in coal abundance away from the fluvial axis plus the lateral continuity of the siliciclastic intervals separating the coal beds suggests that the flood basins were extensive and that peat (coal) accumulated only in flood basins isolated from clastic influx.

STRUCTURAL CONTROL

MARY LEE CYCLE

The Jagger coal bed ranges from 0 to 3 feet thick and is generally 1.5 to 2 feet thick in Oak Grove field (fig. 57). The bed terminates sharply at the master fault of a horst-and-graben system in central Oak Grove; that fault evidently exerted strong control on coal distribution from Mary Lee to Cobb deposition (fig. 58). The Jagger is absent on much of upthrown fault block, which includes the Oak Grove mine, and in most of western Oak Grove field. However, the bed does occur east of the mine and along the axial trace of the Sequatchie anticline north of the mine.

The Jagger-Blue Creek siliciclastic interval, where present, is typically between 20 and 30 feet thick and has fairly uniform thickness (fig. 59); however, the interval pinches out sharply. The interval

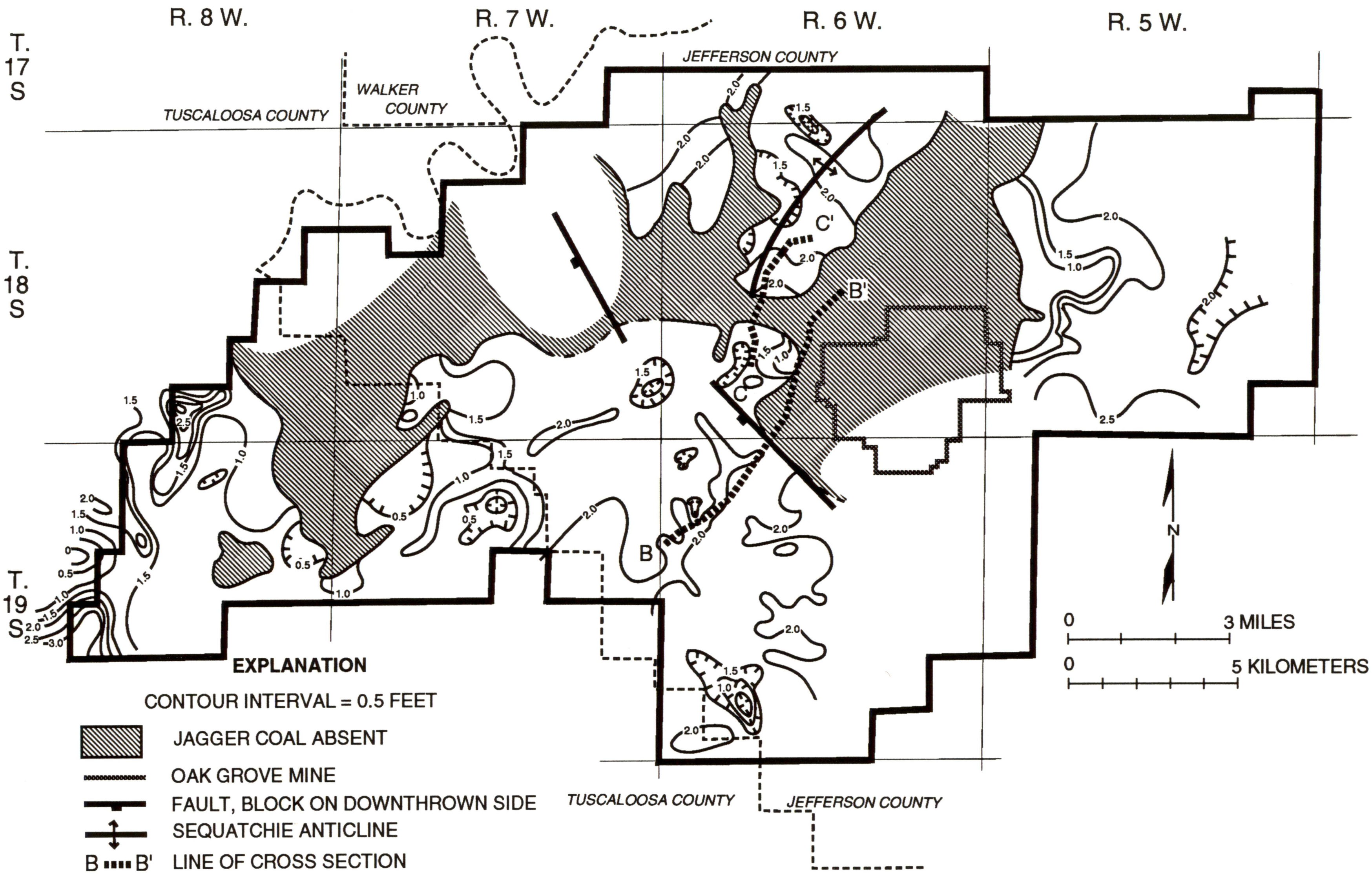


Figure 57. Isopach map of the Jagger coal bed, Mary Lee coal group, Oak Grove field.

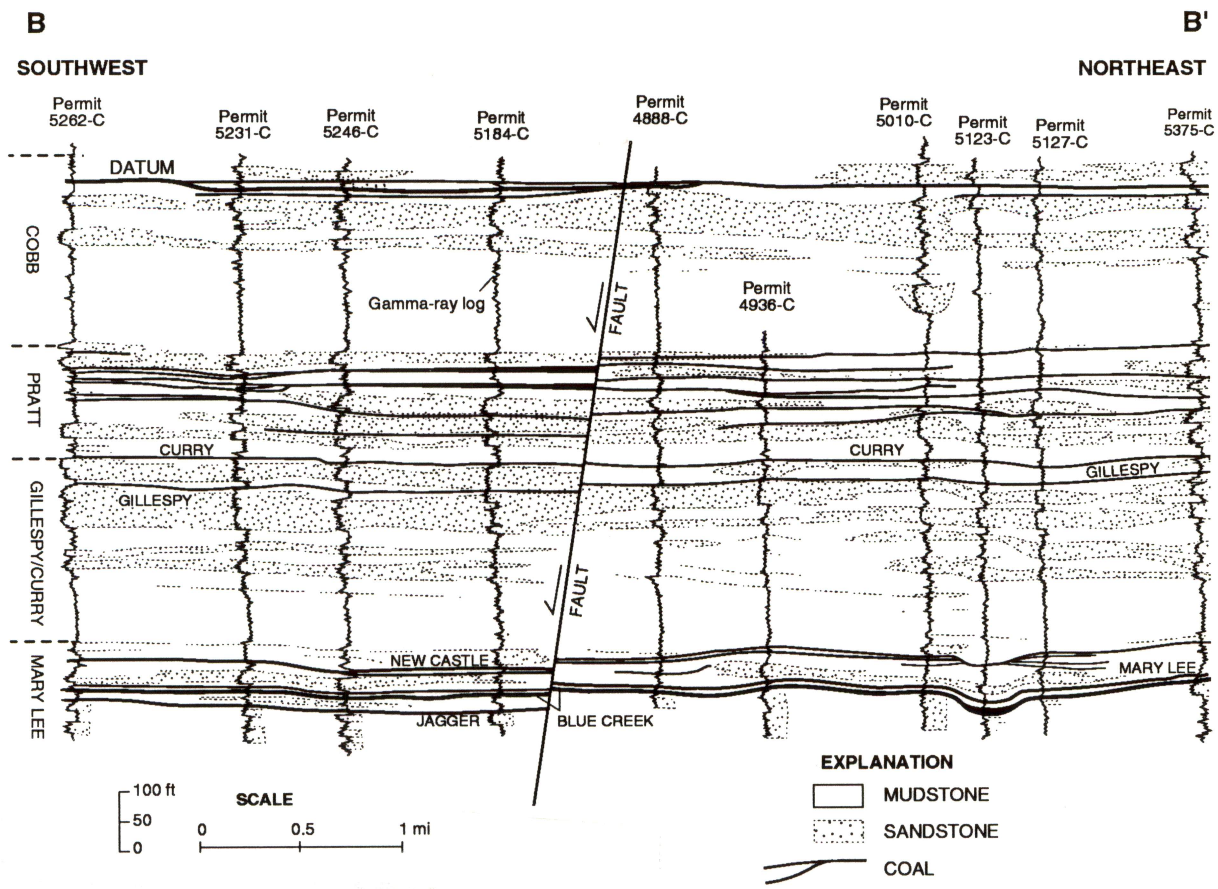


Figure 58. Stratigraphic cross section B-B', Oak Grove field. See figure 57 for location.

is absent in the upthrown fault block in eastern Oak Grove field but thickens gradually in the easternmost part of the map area. The interval is approximately 20 feet thick along the axial trace of the Sequatchie anticline in north-central Oak Grove. Sandstone in the Jagger-Blue Creek interval occurs in a series of linear to sinuous trends and is locally thicker than 20 feet; one of those trends parallels the master fault (fig. 60).

Unlike the Jagger bed, the Blue Creek bed occurs throughout Oak Grove field (fig. 61) and is the principal completion target. The Blue Creek bed is generally 3 to 5 feet thick and is thicker than 6 feet in the south-central part of the field; the bed is only 3 feet thick along the axial trace of the Sequatchie anticline. In central Oak Grove field, coal thicker than 6 feet has a dendritic plan geometry

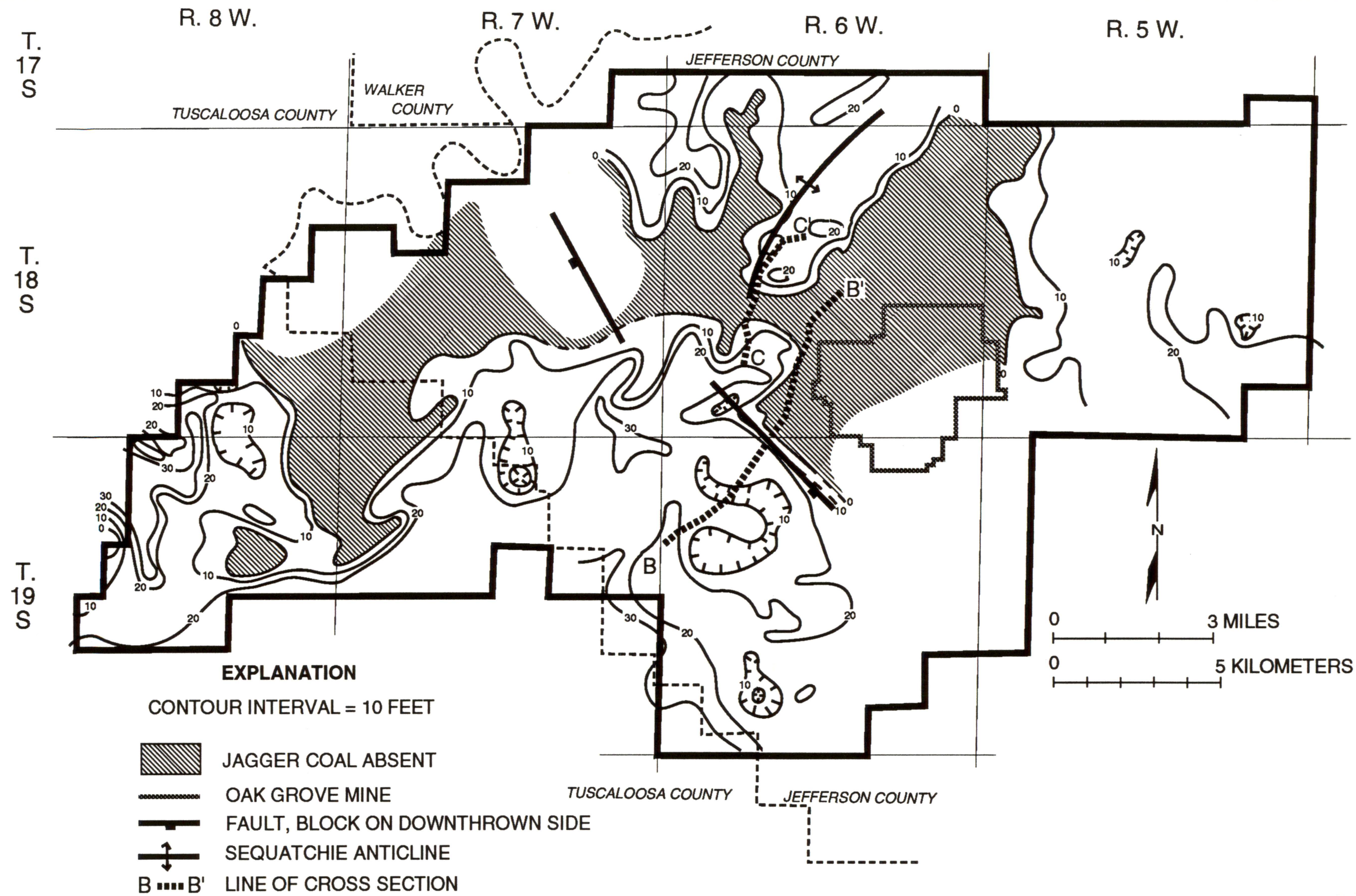


Figure 59. Isopach map of Jagger-Blue Creek siliciclastic interval, Mary Lee coal group, Oak Grove field.

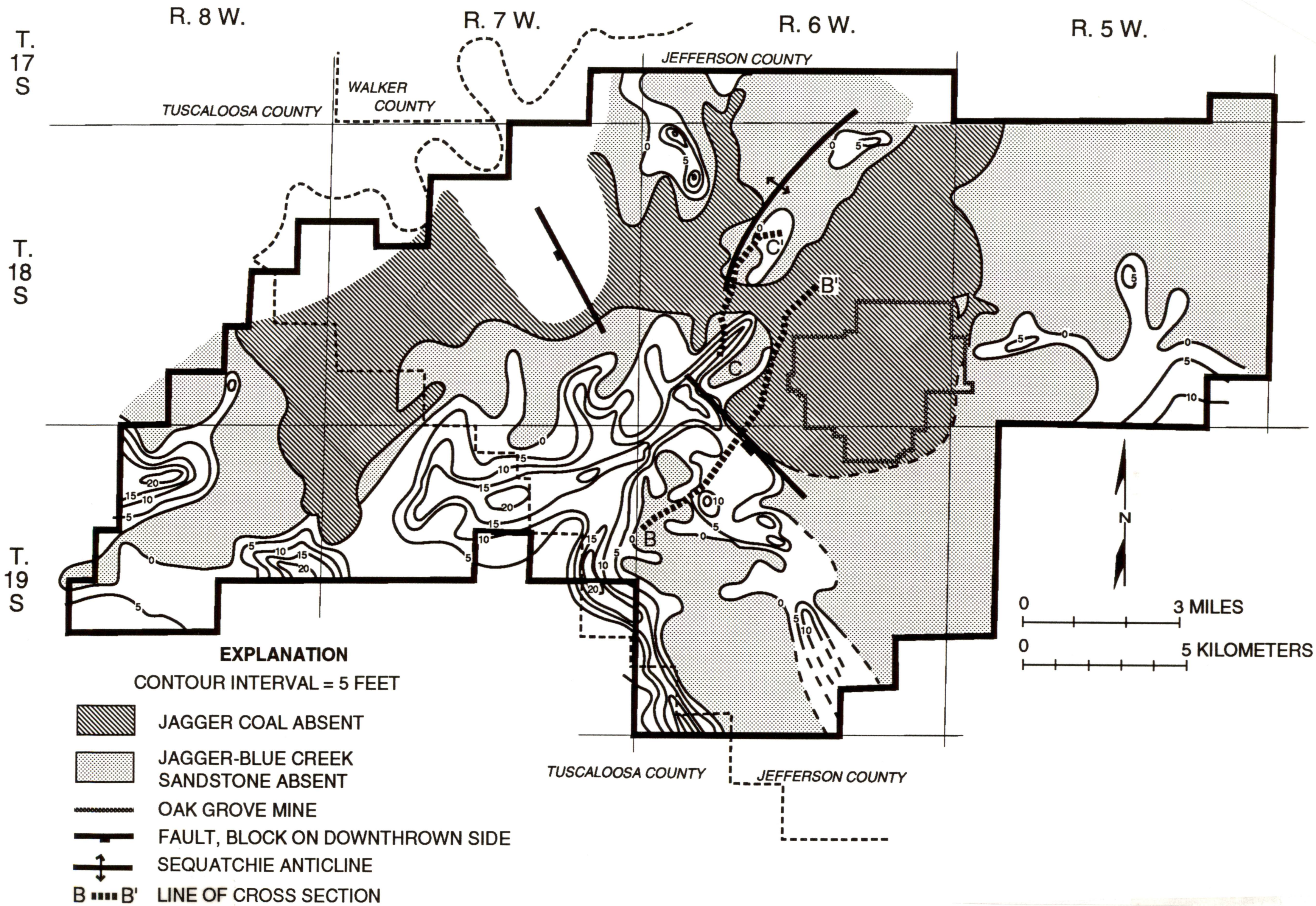


Figure 60. Sandstone isolith map of Jagger-Blue Creek siliciclastic interval, Mary Lee coal group, Oak Grove field.

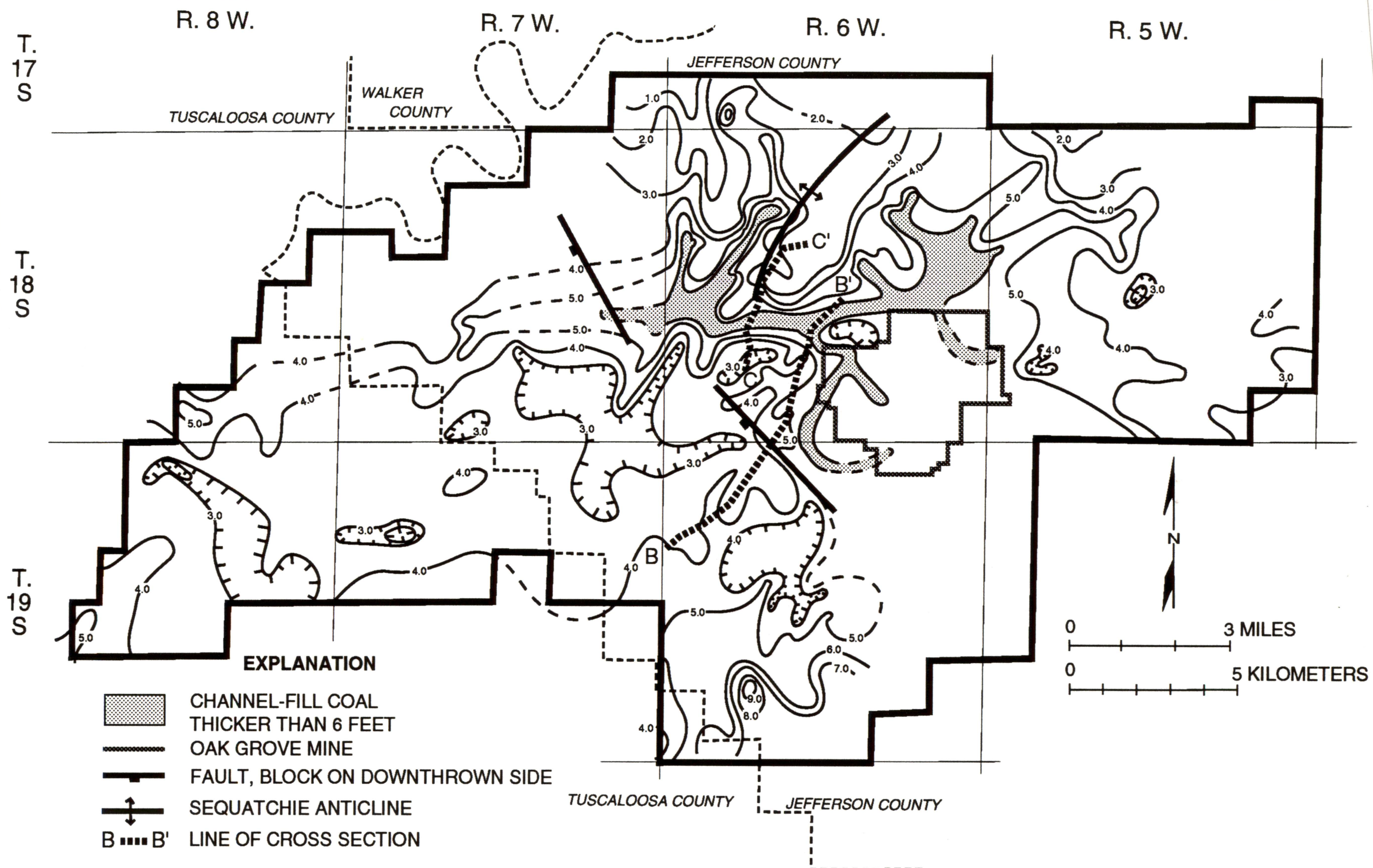


Figure 61. Isopach map of Blue Creek coal bed, Mary Lee coal group, Oak Grove field.

in the upthrown fault block, and in the Oak Grove mine, coal thicker than 6 feet occurs in channels (fig. 15). The trunk channel is locally deeper than 60 feet and truncates the Jagger bed at the southern channel margin and is at the level of the Jagger in the northern part (fig. 62).

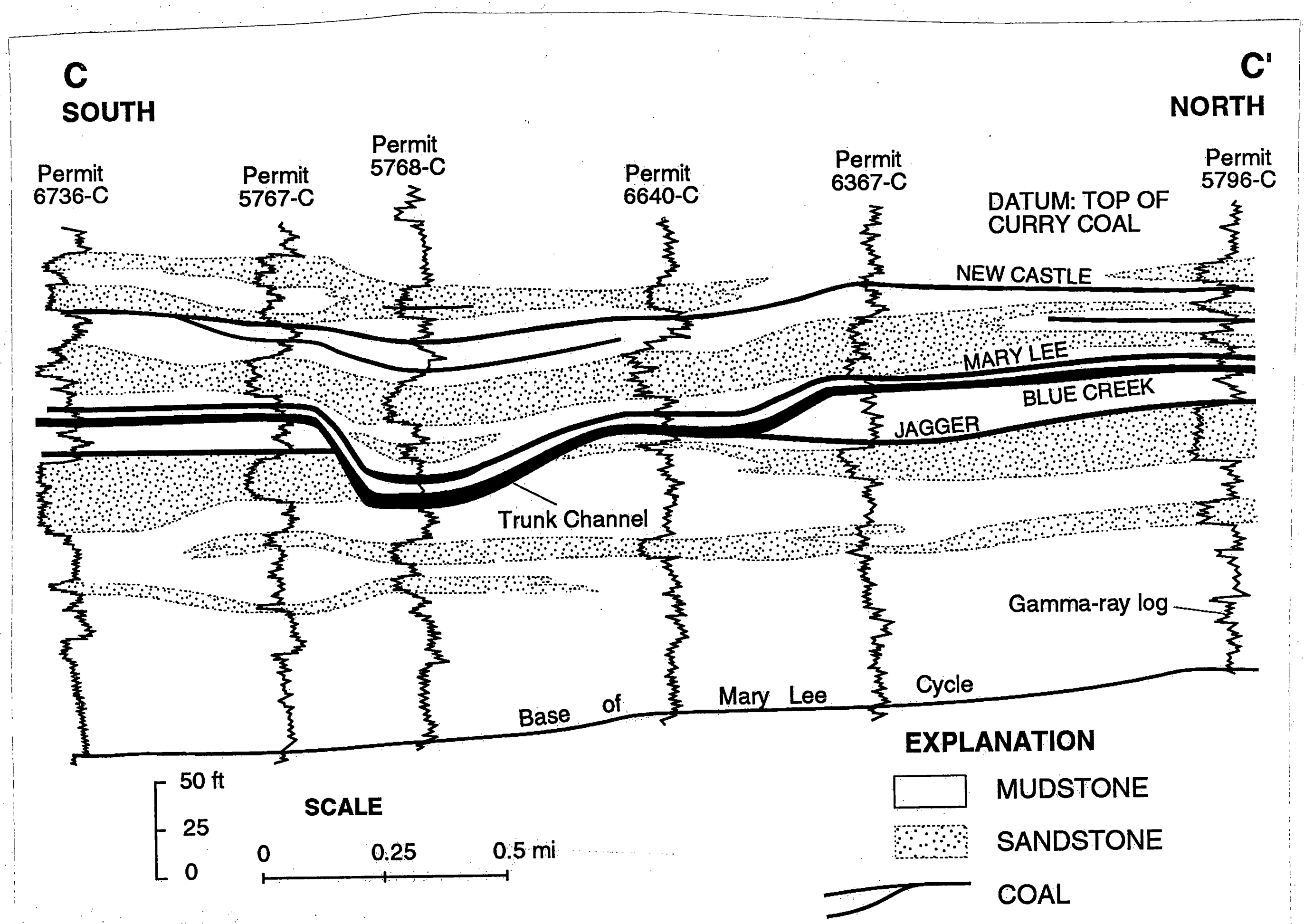


Figure 62. Stratigraphic cross section C-C', Oak Grove field. See figure 61 for location.

The Mary Lee coal bed occurs between 4 and 8 feet above the Blue Creek bed throughout Oak Grove field (fig. 58, 62). The Mary Lee bed is typically 1.5 to 2.5 feet thick in eastern Oak Grove field and is only 1 foot thick in the western part of the field (fig. 63). Thickness trends in the bed do not parallel the fault, but coal thicker than 3 feet in central Oak Grove coincides with thick Blue Creek channel-fill coal (figs. 61, 63). Within the trunk channel, thickness of the Mary Lee bed is variable and has a maximum value of 4.5 feet.

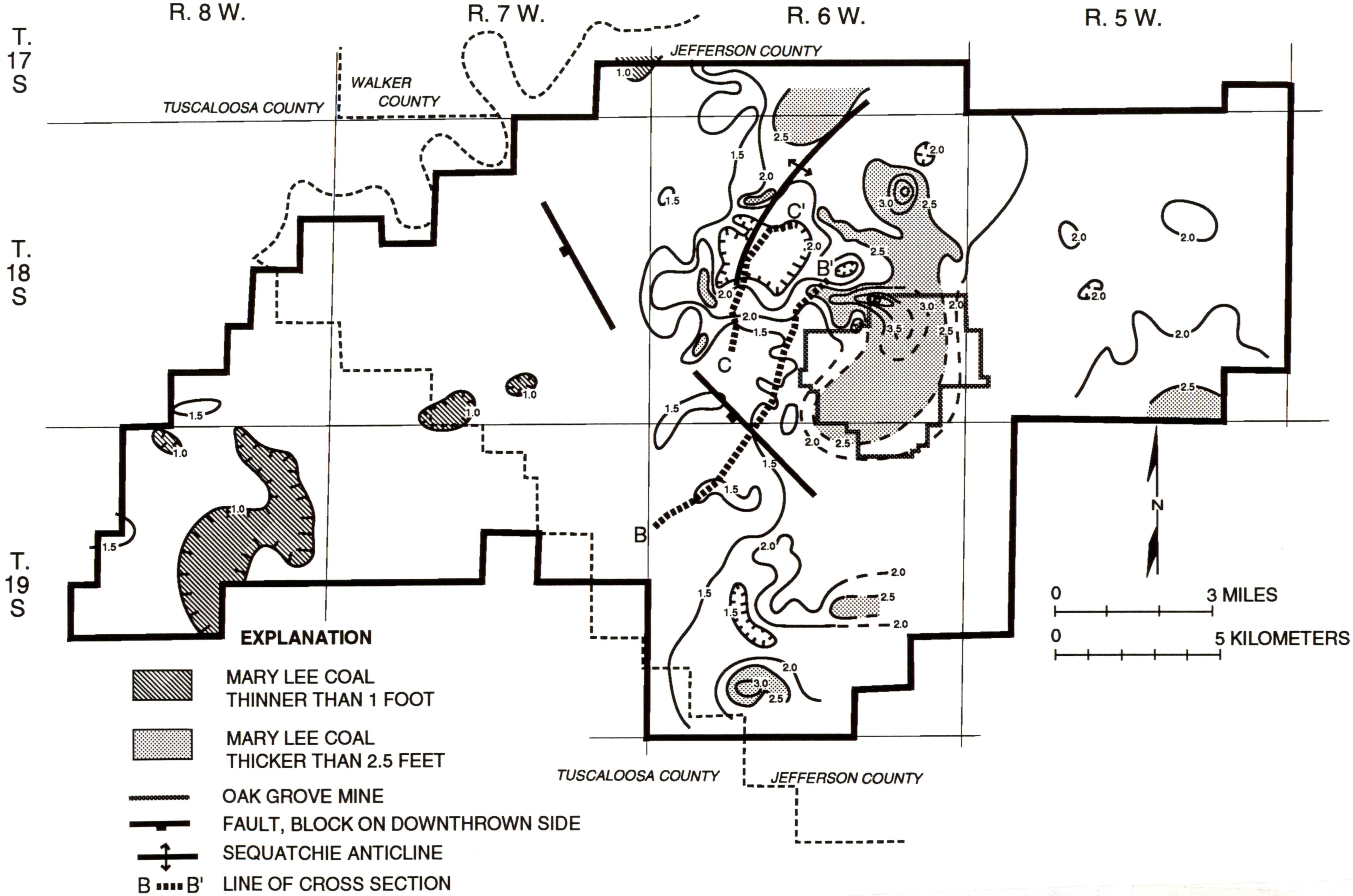


Figure 63. Isopach map of Mary Lee coal bed, Mary Lee coal group, Oak Grove field.

The Mary Lee-New Castle siliciclastic interval is generally 30 to 60 feet thick (fig. 64). Only the 50-foot thickness contour parallels the fault trend, and like the Mary Lee bed, the interval is thickest in the area of Blue Creek channel-fill coal (figs. 61, 64). The Mary Lee-New Castle interval is thin along the axial trace of the Sequatchie anticline and is thinner than 10 feet in northernmost Oak Grove field. Net-sandstone thickness in the Mary Lee-New Castle interval locally exceeds 30 feet (fig. 65). Several linear sandstone bodies in the eastern and central parts of the field merge to form a sinuous sandstone belt that extends into the westernmost part of the field. The sinuous sandstone belt is approximately 2 miles wide in westernmost Oak Grove and is characterized by lobate trends on the outside parts of the curves.

The New Castle coal is the uppermost bed of the Mary Lee cycle; the coal splits profusely, but a major bed is traceable throughout most of the field (figs. 58, 66). The New Castle is thin or absent in the area containing most of the channel-fill coal bodies (figs. 61, 63, 66), and in core, the seat earth of the New Castle is not rooted near where it pinches out (Epsman and others, 1988). The bed is continuous in western Oak Grove field and is locally thicker than 4 feet; it is a more significant coalbed-methane target than the Blue Creek in much of this area.

Sedimentologic evidence indicates interplay among structural, fluvial, and compactional processes during Mary Lee cycle deposition. Occurrence of the channel network delineated by thick Blue Creek coal on the upthrown fault block (fig. 61) suggests that the network was a tributary system. Sharp pinchout of the Jagger-Blue Creek interval (fig. 59) indicates that the tributaries occupied a steep-walled valley. Some of the tributary channels skirt the axial trace of the Sequatchie anticline, suggesting that an ancestral structure was present; synsedimentary activity of ancestral structures associated with Appalachian folds has been reported by Thomas (1974) and Thomas and Neathery (1982).

Peat is resistant to erosion, so occurrence of the Blue Creek bed at the level of the Jagger near the northern margin of the main channel suggests that terraces formed on peat beds exhumed during valley incision. Joining of the Jagger and Blue Creek beds throughout much of Oak Grove field signifies that the Jagger provided channel floors in a large area. Termination of the Jagger coal and

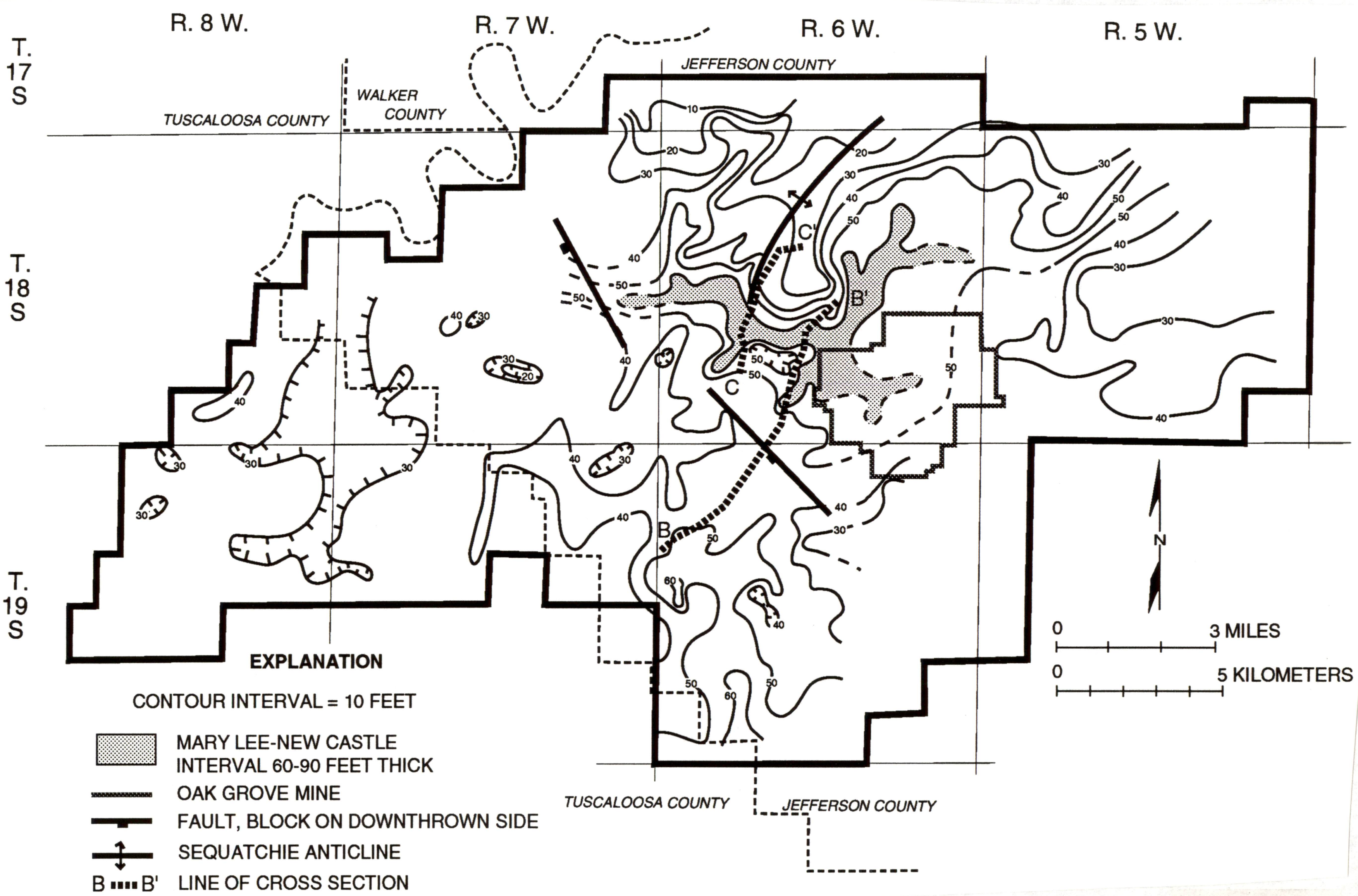


Figure 64. Isopach map of Mary Lee-New Castle siliciclastic interval, Mary Lee coal group, Oak Grove field.

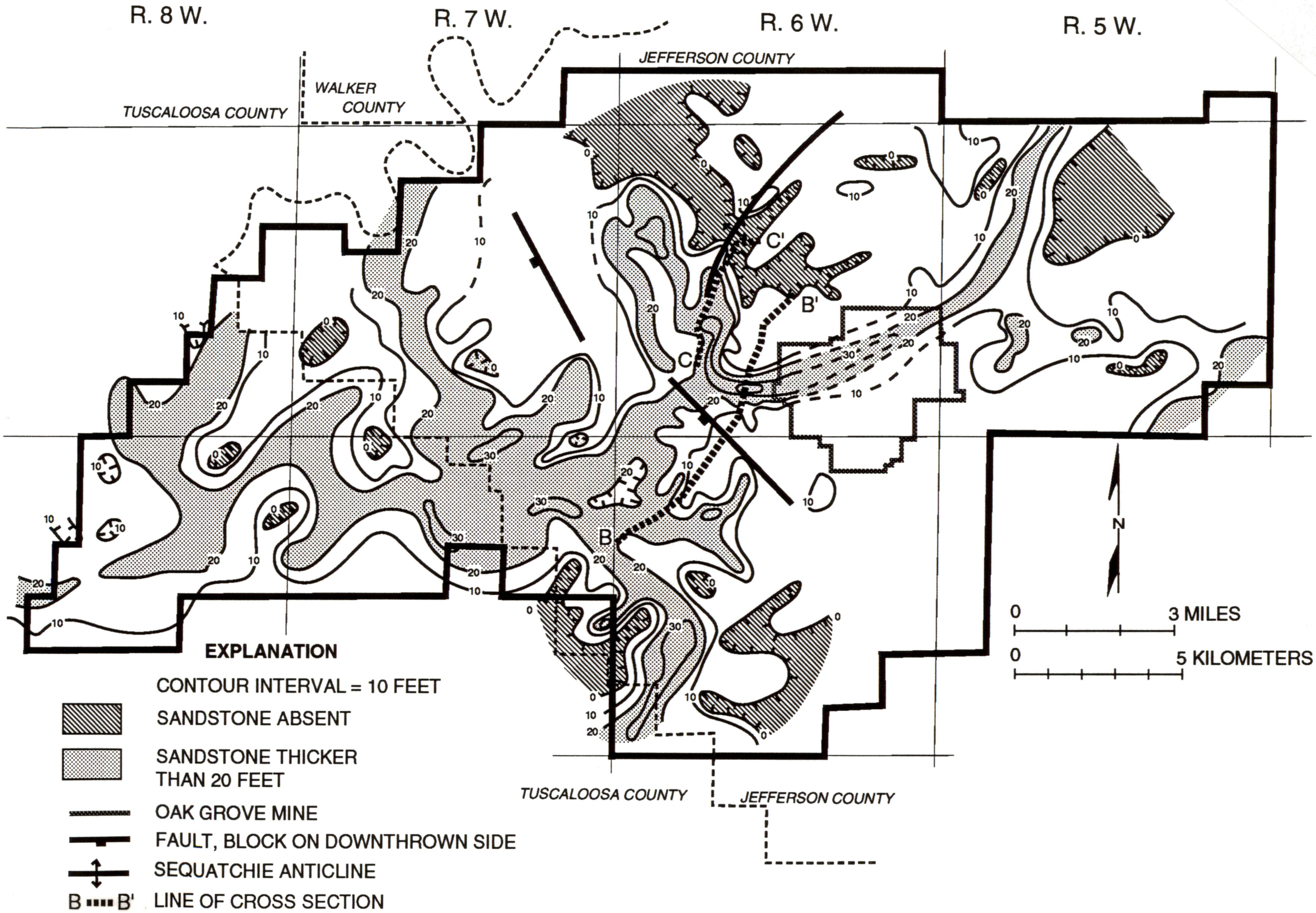


Figure 65. Sandstone isolith map of Mary Lee-New Castle siliciclastic interval, Mary Lee coal group, Oak Grove field.

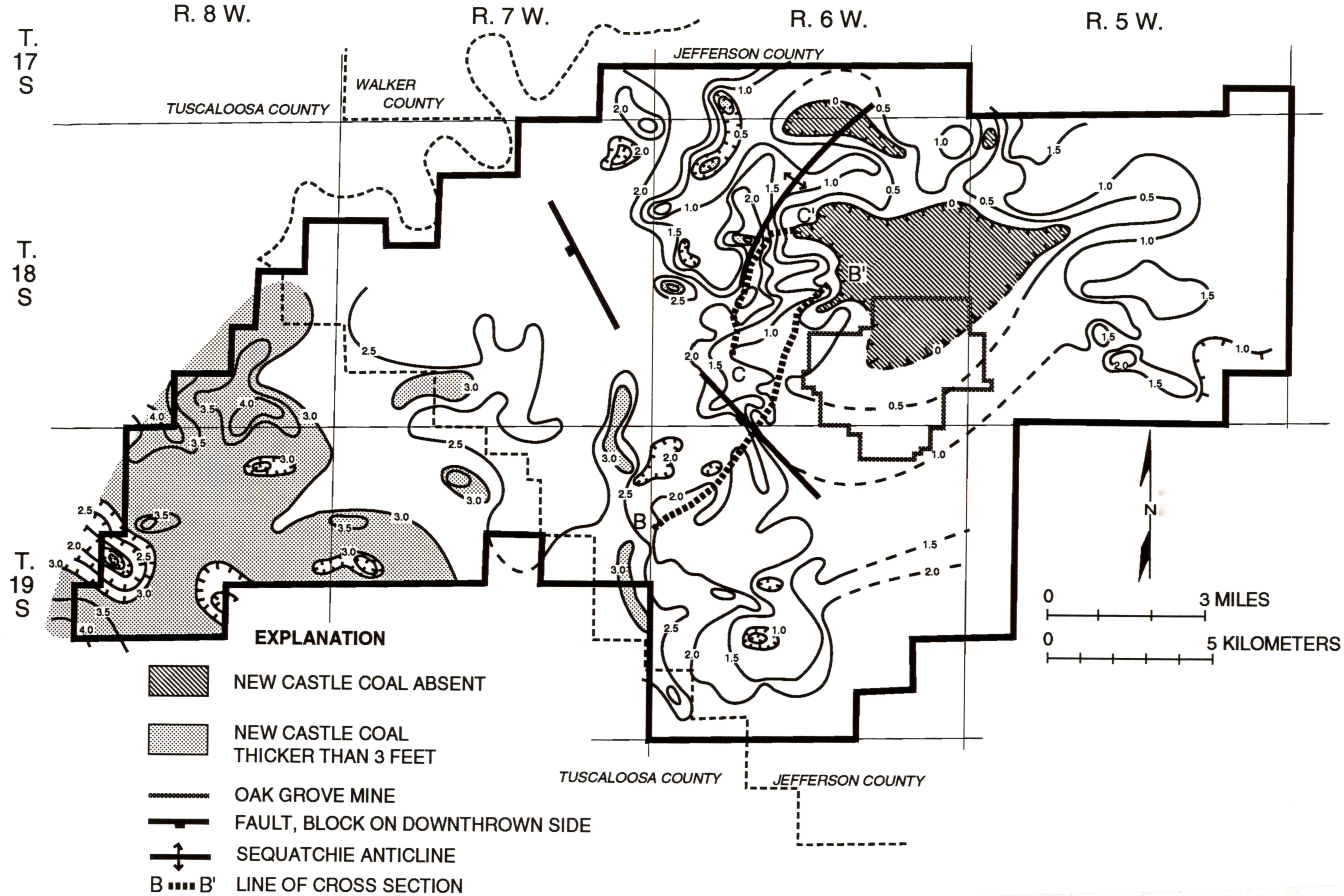


Figure 66. Isopach map of New Castle coal bed, Mary Lee coal group, Oak Grove field.

the Jagger-Blue Creek siliciclastic interval at a fault (figs. 57-59) indicates that the coal and associated siliciclastic rocks were eroded or never deposited on the upthrown block and were preserved on the downthrown block by differential subsidence and compaction; presence of the Jagger coal and the Jagger-Blue Creek siliciclastic interval east of the mine (figs. 58, 59) suggests that the area subsided more rapidly than the area immediately northeast of the major faults, thus defining an uplift in the mine area. This uplift evidently caused Mary Lee valley incision and may have been associated with the Sequatchie anticline.

Comparing the pattern of sandstone bodies of the Jagger-Blue Creek interval (fig. 60), which may represent fluvial axes, with the Blue Creek tributary system (fig. 61) demonstrates the variety of erosional and depositional processes that can be controlled by faulting. Following erosion of the upthrown block, the tributary system apparently was abandoned, swamp environments were established, and the tributaries filled with Blue Creek and Mary Lee peat, resulting in formation of some of the thickest and highest quality coal in the Black Warrior basin.

Thick channel-fill coal can be used to estimate peat-to-coal compaction ratio in ancient sequences (Cobb and others, 1981). Assuming the channel was completely filled with peat, the difference in coal thickness in the channel from that outside the channel may represent the amount of peat that filled the channel. Therefore, the ratio of channel depth to the difference in coal thickness yields the peat-to-coal compaction ratio. In cross section C-C', the Blue Creek coal in the channel is as thick as 9 feet, whereas adjacent to the channel it is approximately 3 feet thick (fig. 62). From dividing the channel depth (60 feet) by the difference in coal thickness (6 feet), the compaction ratio is 10:1, which is the same value derived by Cobb and others (1981) for Pennsylvanian channel-fill coal in Kentucky.

Valley-fill peat accumulation apparently had a strong impact on the remainder of Mary Lee cycle sedimentation. The Mary Lee bed represents a fairly uniform peat blanket throughout the map area, but thickening of the Mary Lee bed and the overlying Mary Lee-New Castle siliciclastic interval in the area of the tributary system (figs. 61, 63, 64) indicates compactional control of sedimentation. Extreme thickness variation of the Mary Lee bed within the tributary trend (fig. 63), however, indicates that compaction did not proceed uniformly and that parts of the paleovalley may have been underfull or even overfull with Blue Creek peat. The compaction ratio derived above uses the thickest coal in the channel system and is thus a maximum value.

Contours on the Mary Lee and Mary Lee-New Castle isopach maps (figs. 63, 64) do not parallel the fault trend as clearly as those on the previous maps, suggesting that fault-related topography had been subdued, probably because sedimentation rate exceeded subsidence rate. However, sandstone-isolith patterns in the Mary Lee-New Castle interval (fig. 65) suggest that the regional gradient remained essentially unchanged. Merging linear sandstone bodies in eastern Oak Grove may represent a fluvial tributary system. Those tributaries join the sinuous axial sandstone body in western Oak Grove which may represent a low-gradient, meandering fluvial system similar in scale to that in the upper Black Creek subcycle. The lobate forms protruding from the sinuous sandstone bodies suggest crevasse-splay systems in meandering fluvial systems, because they are outside of each curve (Allen, 1965; Schumm, 1977).

Splitting and local thickening of the New Castle coal in the westernmost tributaries (figs. 62, 66) indicates continued compactional control of sedimentation, but pinchout of the coal in the eastern part of the tributary trend (fig. 66) and thickening in western Oak Grove field indicates that controls on coal occurrence had changed. Sedimentologic relationships suggest that the New Castle pinches out because the compactional subsidence rate in the tributary system exceeded the sedimentation rate, resulting in a lake instead of swamps. Unrooted coal near the pinchout of the New Castle may represent log or peat flotants at the lake margin.

GILLESPY/CURRY CYCLE

The Gillespy and Curry beds (fig. 5) are the two most reliable stratigraphic markers in the upper Pottsville because they are widespread, closely spaced, and scarcely split (figs. 25-30, 58). Even where coal is absent, the stratigraphic position of the beds is easily recognized by the presence of coarsening-upward sequences below the stratigraphic position of the coal. However, additional beds occur in the cycle below the level of the Gillespy bed, particularly in the westernmost and easternmost parts of the map area, and eastern Oak Grove field is the only area of the Black Warrior basin where the Gillespy and Curry beds split abundantly (fig. 67).

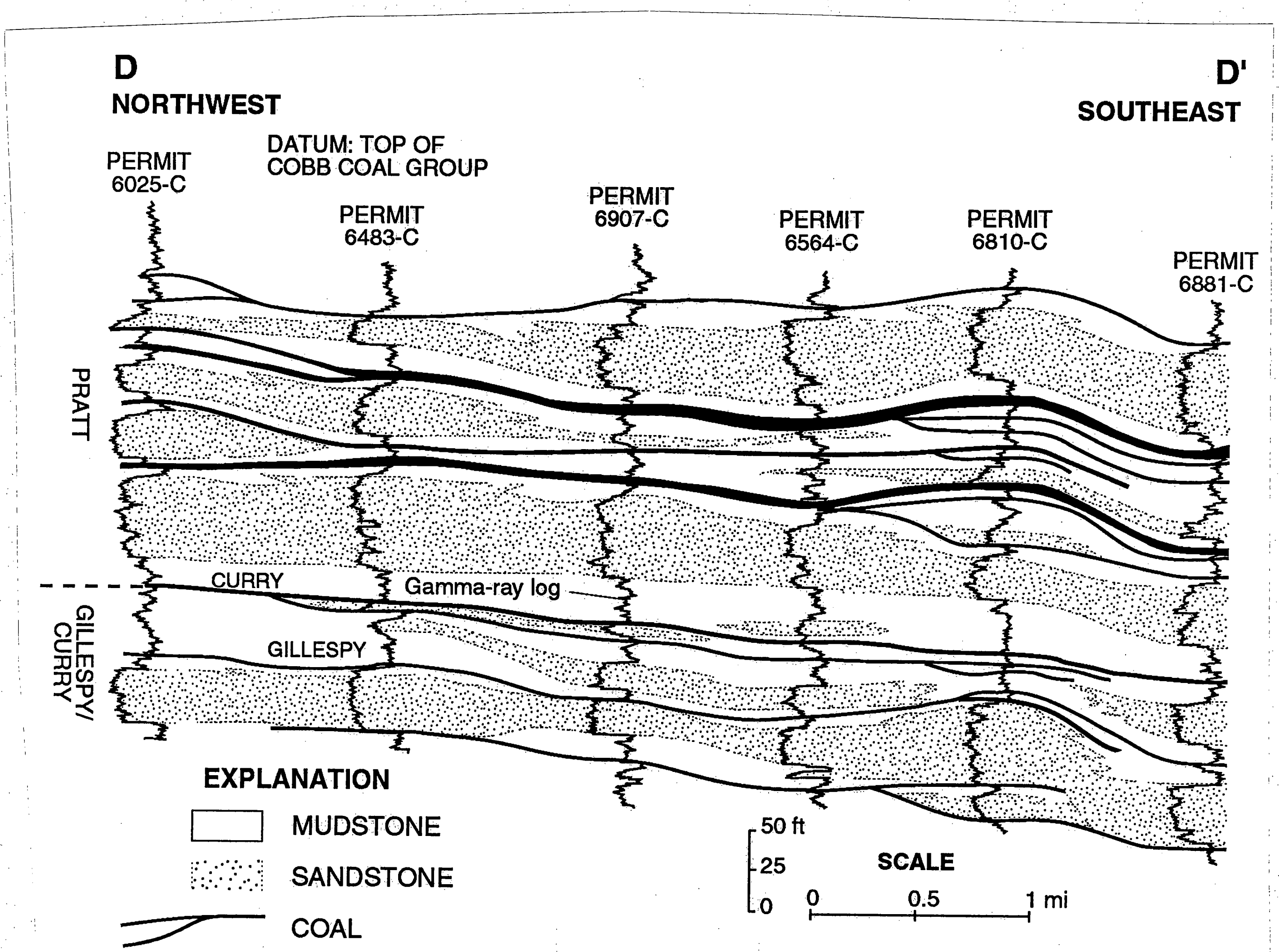


Figure 67. Stratigraphic cross section D-D', Oak Grove field. See figure 68 for location.

Throughout much of Oak Grove field, the Gillespy and Curry beds are very thin and are at the lowest limit of log resolution. Therefore, net coal thickness is equal to the number of beds times 0.4 foot. The Gillespy and Curry beds have a combined thickness of 1 foot or less in much of western Oak Grove field (fig. 68) and may thus have limited coalbed-methane production potential. In the eastern part of the field, however, numerous beds occur in the cycle (fig. 67) and net coal thickness locally exceeds 4 feet.

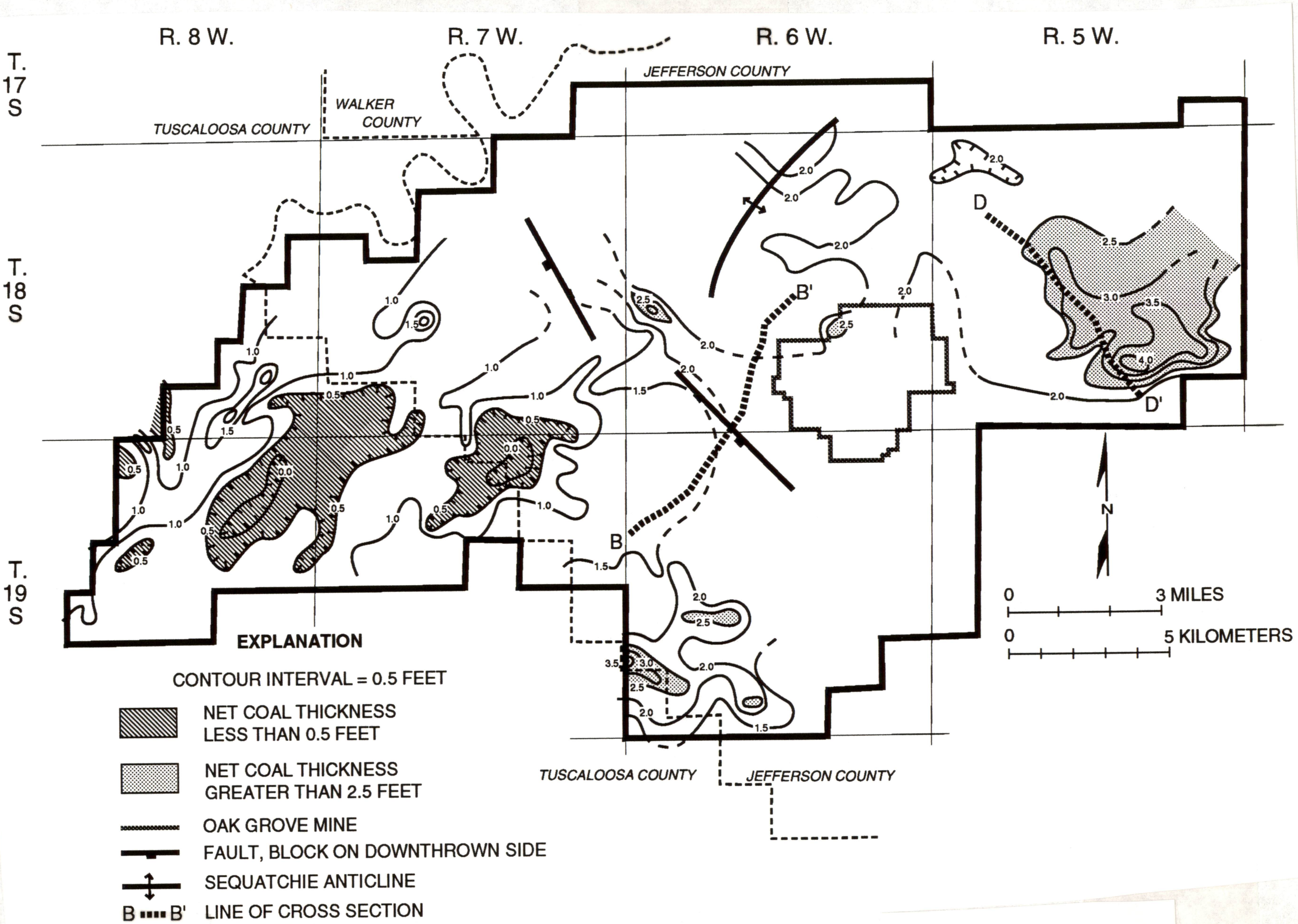


Figure 68, Net-coal isolith map of Gillespy/Curry cycle, Oak Grove field.

The Gillespy-Curry siliciclastic interval thickens from less than 30 feet in northern Oak Grove field to more than 70 feet in the southwestern part of the field (fig. 69). In central Oak Grove field, the interval thickens from less than 40 feet to more than 50 feet across the fault trace. Net-sandstone thickness in the Gillespy-Curry interval is greater than 30 feet in an east-west belt that is approximately 3 miles wide; sandstone is absent in much of northern Oak Grove field (fig. 70). In the western part of the field, lobate and elongate sandstone bodies outlined by the 10-foot contour extend north from the sandstone belt. In central Oak Grove, sandstone occurs mainly in the downthrown fault block.

Thickening of the Gillespy-Curry siliciclastic interval in a bifurcated trend in western Oak Grove (fig. 69) may represent filling of an abandoned channel system below the Gillespy coal. However, the channel was not filled with peat as was the case in the Blue Creek bed, because the Gillespy coal does not thicken significantly. Controls on coal-body geometry in the Gillespy/Curry cycle in eastern Oak Grove field will be discussed in the following section on the Pratt and Cobb cycles.

The major sandstone belt (fig. 70) may represent a fluvial complex, and the flanking lobate and elongate sandstone bodies may represent crevasse-splay systems. The fluvial system may have been the largest in the map area during Black Creek-Cobb deposition, because the sandstone belt is approximately 3 miles wide. Although the fault did not greatly affect thickness of the Gillespy-Curry siliciclastic interval (figs. 69, 58), restriction of thick sandstone to the downthrown fault block (fig. 70) indicates that the fault scarp had enough relief to control the position of the fluvial system.

PRATT AND COBB CYCLES

The Pratt cycle contains four to eight coal beds throughout most of Oak Grove field; only the Black Creek cycle contains more coal beds than the Pratt. Pratt cycle coal beds split profusely and are discontinuous, and coal-body geometry changes abruptly at the synsedimentary fault (figs. 58, 67). Contrary to earlier reports (Weisenfluh and Ferm, 1984; Epsman and others, 1988; Pashin and others, 1990), coal beds are thickest and least abundant in the downthrown block.

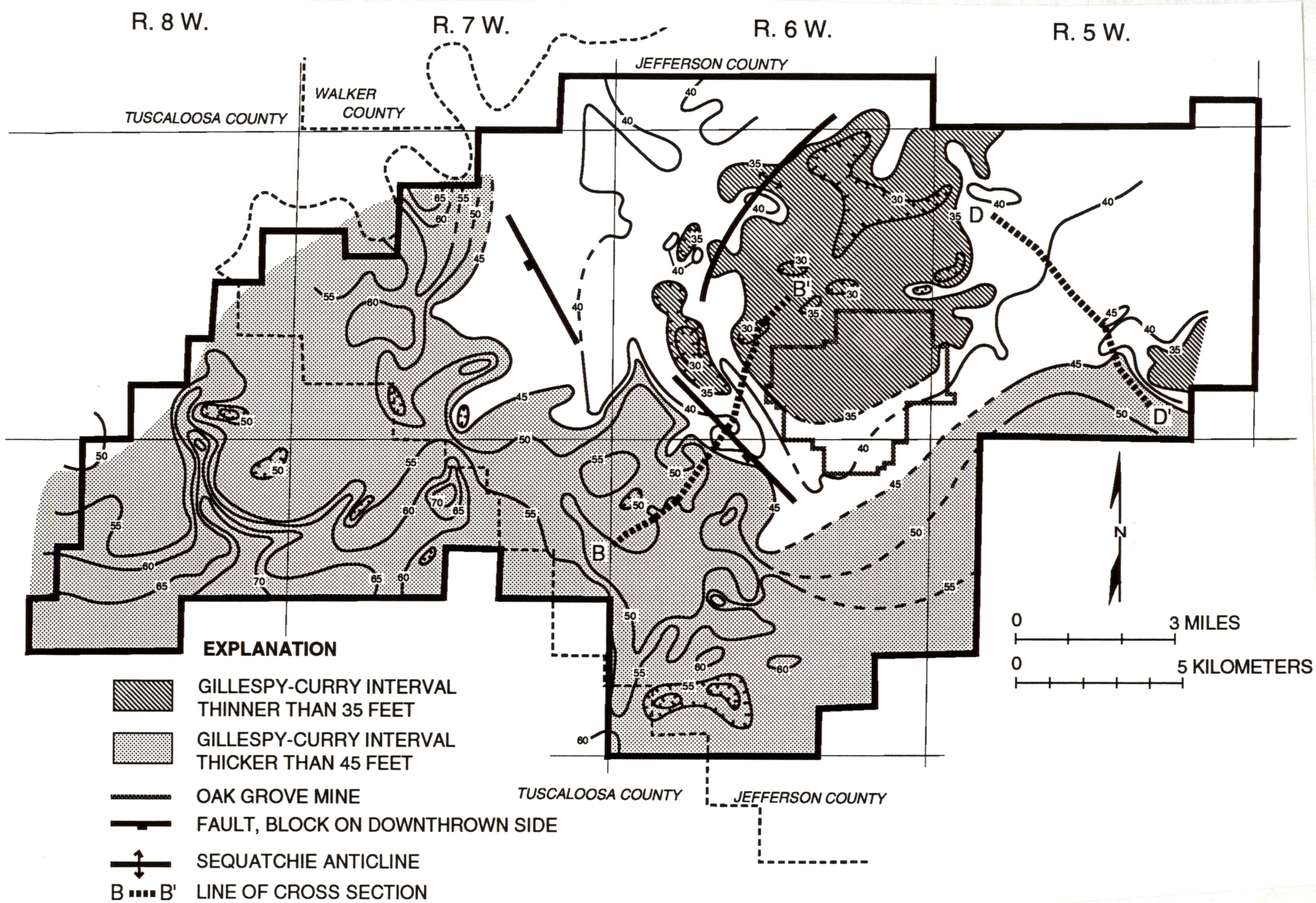


Figure 69. Isopach map of the Gillespy-Curry siliciclastic interval, Oak Grove field.

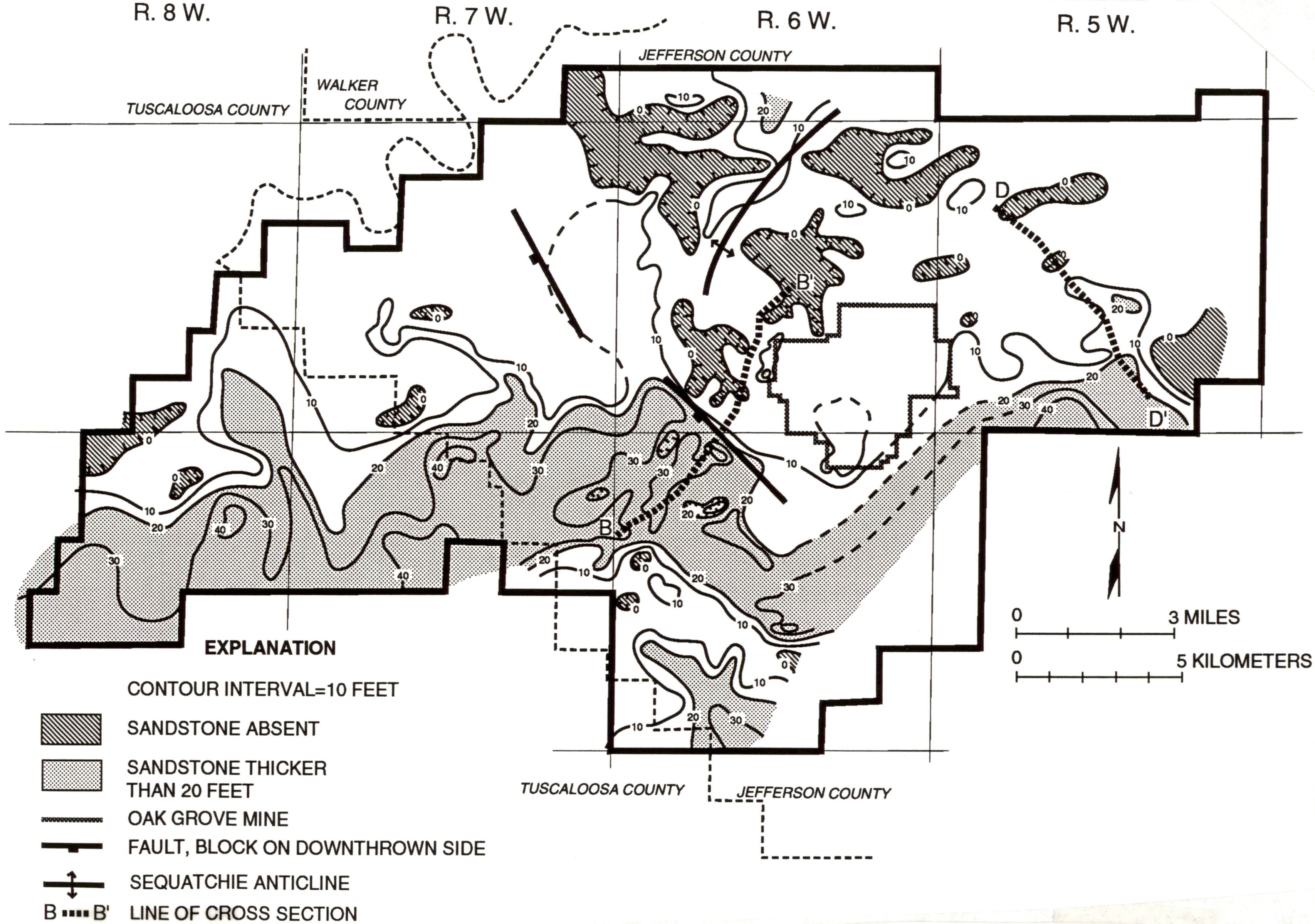


Figure 70. Sandstone isolith map of the Gillespy-Curry siliciclastic interval, Oak Grove field.

Net coal thickness in the Pratt cycle of Oak Grove field varies from 3 feet in the northern part of the field to 22 feet in the eastern part (fig. 71). Similarly, maximum coal thickness varies from less than 1.5 feet in the northern part of the field to approximately 9 feet in the eastern part (fig. 72). Net coal thickness increases from 7 to 9 feet across the master fault, and maximum bed thickness increases sharply from 2 to 5 feet in the downthrown block (figs. 58, 71, 72). A belt of coal with net thickness greater than 9 feet parallels the fault trend and extends into northwest Oak Grove field; local patches of thick coal occur southwest of this belt. In contrast, maximum coal thickness exceeds 4 feet in a rectangular area southwest of the fault, reflecting joined beds.

The Cobb cycle generally contains three or fewer coal beds in Oak Grove field (fig. 58), and only one of these beds is typically thicker than 0.4 foot. Net coal thickness ranges from less than 1.5 feet to more than 5 feet (fig. 73). More coal beds occur in the downthrown block than in the upthrown block, but splitting is not coincident with the fault (fig. 58). Even so, net coal thickness doubles from less than 1.5 feet in the upthrown block to more than 3 feet in the downthrown block (fig. 73).

Inability to trace coal beds in the Pratt cycle for a large distance suggests that the fluvial systems that formed the siliciclastic intervals avulsed more frequently and were perhaps narrower than those in other cycles. For example, fluvial systems in the Mary Lee cycle formed siliciclastic intervals that are mappable throughout Oak Grove field (figs. 59, 60, 64, 65), whereas no regionally mappable siliciclastic intervals were identified in the Pratt (fig. 58). However, data from the Rock Creek site demonstrate that Pratt siliciclastic intervals are mappable locally and may be used to solve structural problems (fig. 16).

In the Pratt and Cobb cycles, increase in coal thickness in the downthrown fault block (figs. 58, 71-73) suggests that differential subsidence favored peat accumulation and subsequent formation of desirable coalbed-methane completion targets, but the fluvial response to subsidence differed greatly in each cycle. In the Cobb cycle, splitting of beds in the downthrown block indicates that differential subsidence favored clastic influx; fault-related topography may have been subdued thereby facilitating distal flood-basin sedimentation on the upthrown block, because bed splitting

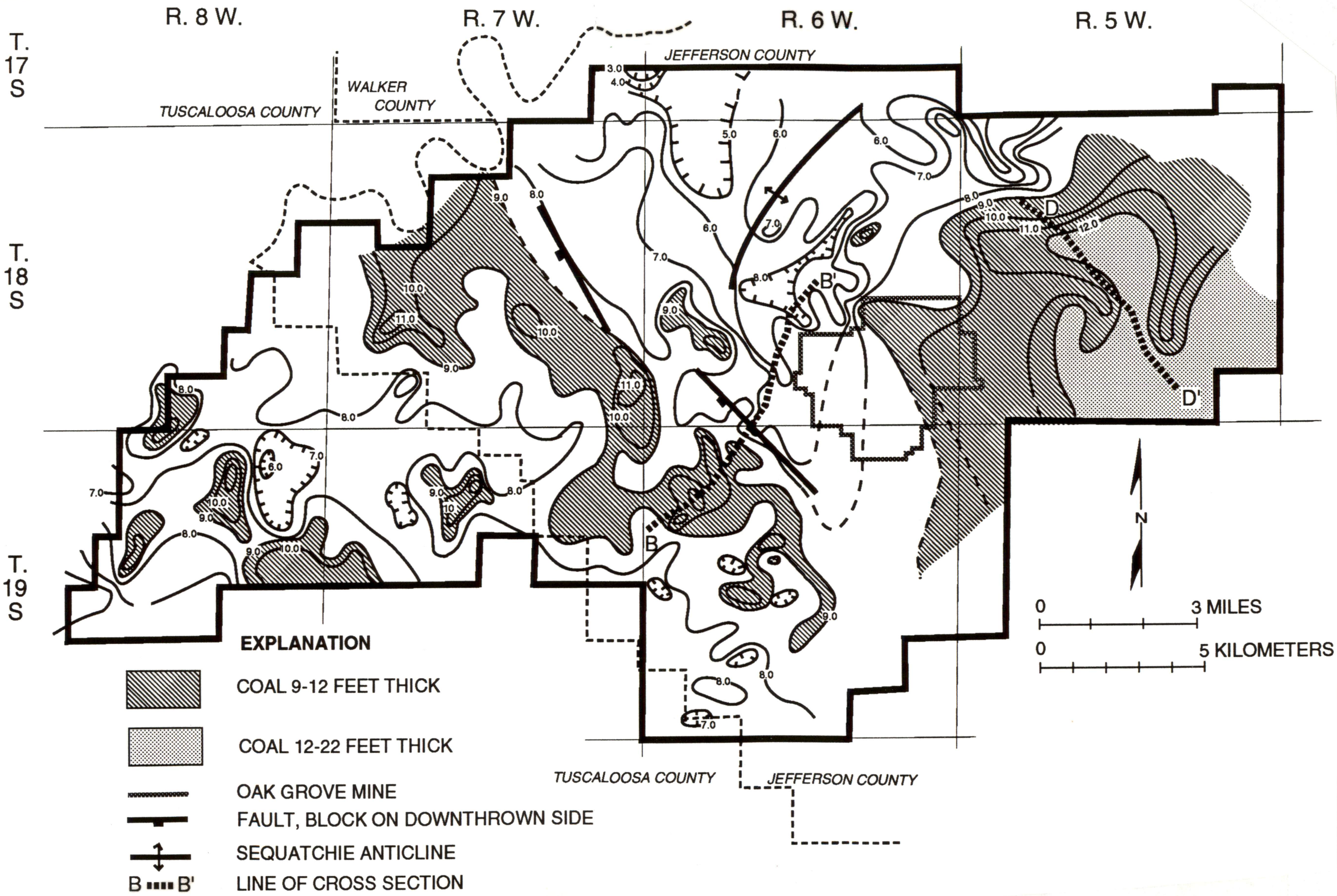


Figure 71. Net-coal isolith map of the Pratt cycle, Oak Grove field.

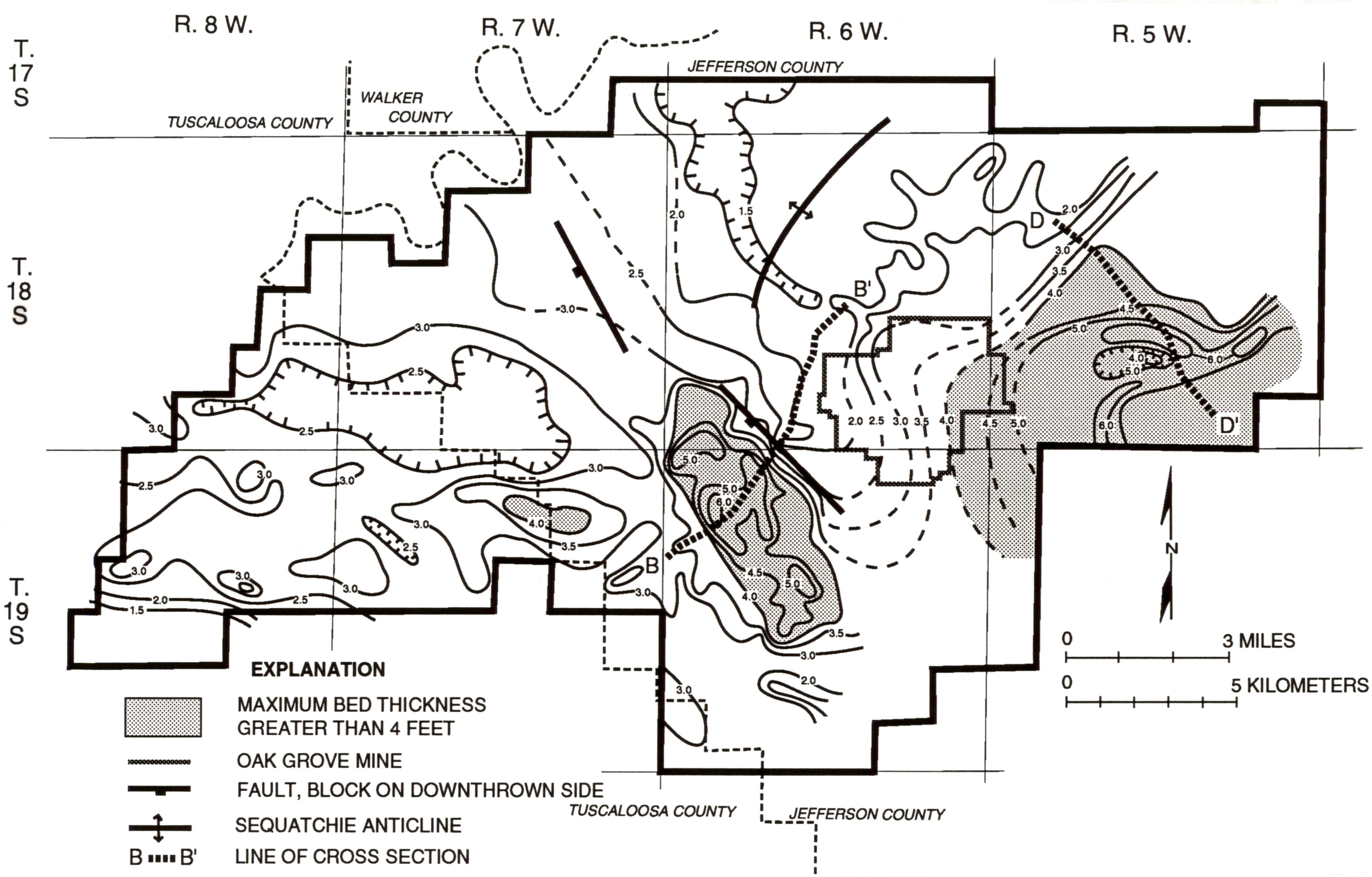


Figure 72. Maximum coal thickness map of the Pratt cycle, Oak Grove field.

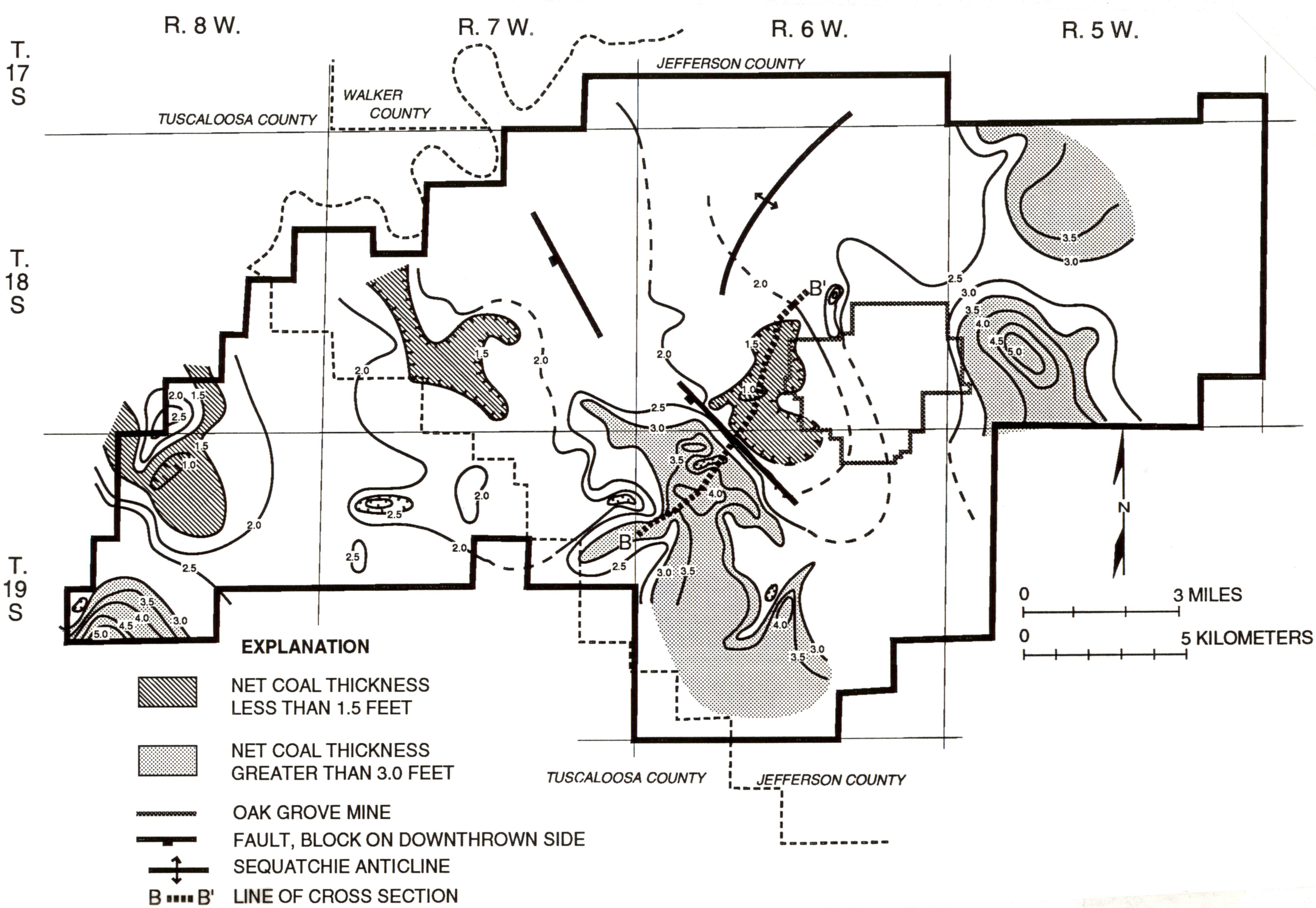


Figure 73. Net-coal isolith map of the Cobb cycle, Oak Grove field.

does not coincide precisely with the fault trace. In the Pratt cycle, however, merging of coal beds suggests that the fault sheltered the downthrown block from clastic influx.

Splitting of beds in the Gillespy/Curry and Pratt cycles in easternmost Oak Grove field (fig. 67) indicates that increased subsidence rate acted in concert with alternating episodes of clastic influx and peat accumulation (figs. 68, 71). The western margins of the thick coal bodies in this area do not coincide with known faults, so subsidence may have been expressed by gentle downwarping. In addition to splitting and thickening of coal in the Gillespy/Curry, Pratt, and Cobb cycles, occurrence of thick coal in the Black Creek cycle (figs. 51, 52, 54, 55) and southeastward thickening of the Jagger-Blue Creek siliciclastic interval of the Mary Lee cycle (fig. 59) indicate that downwarping was operative in this area throughout Black Creek-Cobb deposition.

STYLES OF COAL OCCURRENCE IN OAK GROVE FIELD

Subsurface analysis of coal occurrence in Oak Grove field demonstrates that interaction of fluvial and structural processes resulted in varied styles of coal occurrence that must be understood to formulate effective exploration and production strategies (fig. 74). Fluvial processes apparently were the major controls on coal occurrence in the Black Creek cycle. In the lower part of the cycle, stacking of thick sandstone sequences above the thickest coal beds suggests that differential compaction provided sites for channel avulsion. In the upper part of the cycle, an inverse relationship between sandstone and coal thickness also indicates fluvial control of coal occurrence.

Above the Black Creek, structural and fluvial processes apparently acted in concert to determine patterns of coal occurrence (fig. 74). In the Mary Lee and Cobb cycles, more coal beds occur in the downthrown fault block than in the upthrown block; in the Gillespy/Curry cycle, sandstone is generally restricted to the downthrown block. Contrary to earlier models, however, the thickest coal in the Pratt and Cobb cycles occurs in the downthrown block. The Pratt cycle also contains the fewest coal beds in the downthrown block. Only in the Mary Lee cycle, where thick coal occurs in an abandoned tributary system, is coal thickest on the upthrown block. In the eastern part of the field,

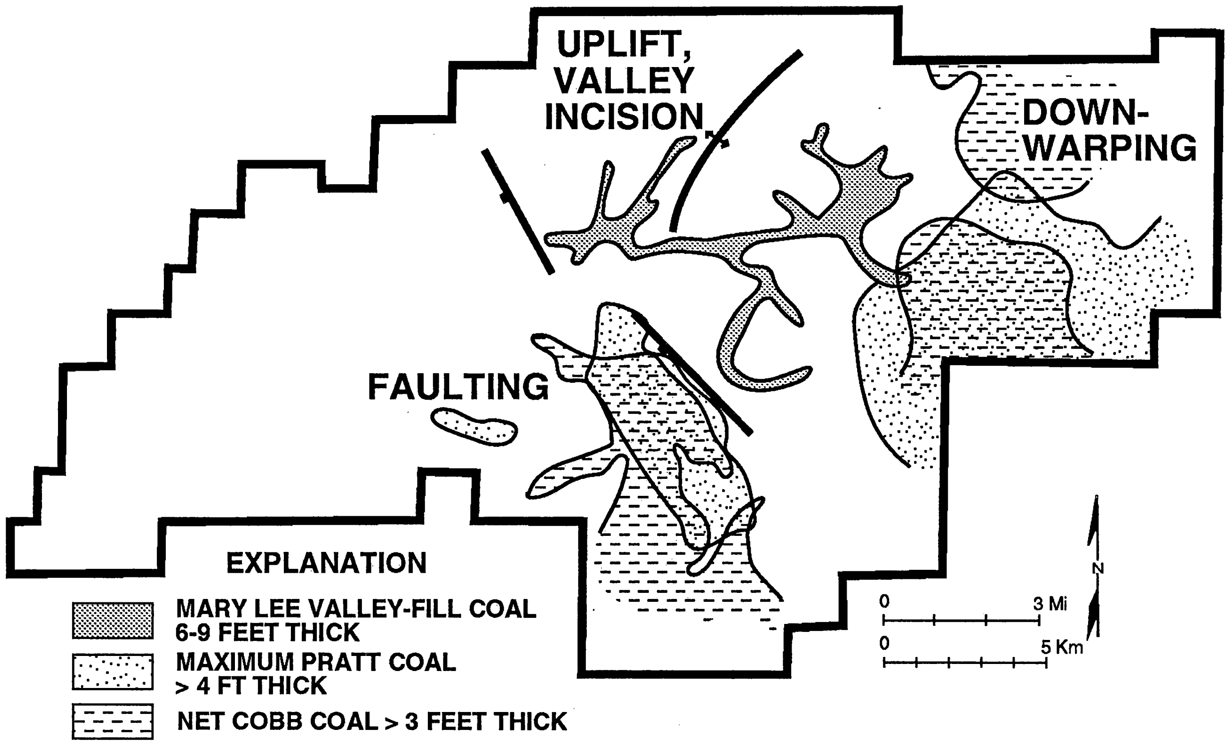


Figure 74. Relationship of coal occurrence to structure, Oak Grove field.

gentle downwarping evidently promoted splitting and preservation of some of the thickest coal beds in the Black Creek-Cobb interval.

Most coal beds in Oak Grove field apparently are thickest in the downthrown fault block and in the area of downwarping because differential subsidence promoted peat accumulation. In most cycles, clastic influx evidently favored bed splits in the downthrown block, but joining of beds in the Pratt cycle may reflect sheltering by the fault. In contrast, channel incision prior to formation of the Blue Creek coal provided relief sufficient for thick peat to accumulate in lows on the upthrown block, and compaction of thick peat within the channel system had a marked effect on sedimentation for the remainder of Mary Lee cycle deposition.

Structural control of coal occurrence in Oak Grove field (fig. 74) may provide a record of detachment below the Coalburg syncline. The synsedimentary fault is interpreted to be an early transcurrent pull-apart structure, whereas control of channel pattern and coal-body geometry in the

Mary Lee cycle of north-central Oak Grove field is interpreted to have been caused by uplift of an ancestral structure related to the Sequatchie anticline. This ancestral structure apparently evolved during Black Creek-Cobb deposition, because the area of thin or eroded coal in the Mary Lee, Pratt, and Cobb cycles northeast of the synsedimentary fault is variable in shape. Evidence for downwarping in the eastern part of the field, moreover, is suggestive of an early folding episode associated with the modern-day Coalburg syncline. Although styles of coal occurrence in Oak Grove field are varied and apparently reflect a complex sedimentologic and tectonic history, models of coal occurrence in this area have resulted in a predictive framework that may aid in resource assessment, strategic well siting, and selecting completion targets.

COAL QUALITY AND GAS ANALYSIS: ORIGIN OF COALBED METHANE

INTRODUCTION

Following sedimentation, peat is buried, heated, and coalified, and gas is generated. The objectives of this section are to characterize coal rank, coal grade, and gas composition in order to evaluate the thermal history and origin of coalbed gas in the Black Warrior basin of Alabama. Coal-quality parameters are important in coalbed methane exploration and production, because little methane is generated thermally before coal reaches bituminous rank (Jüntgen and Klein, 1975). Ideally, ash content and gas content in coal are inversely related (Wyman, 1984), and high-ash coal commonly has a poorly developed cleat system (Macrae and Lawson, 1954). Compositional data are useful for determining the source of gas, because different kerogen types generate different types of hydrocarbons (Rightmire, 1984). For example, sapropelic kerogen, which is abundant in oil shale, can generate heavy hydrocarbons, whereas humic kerogen, which is abundant in coal, generates mainly methane.

Results of coal-quality analysis demonstrate that coal in the Black Warrior basin ranges in rank from high-volatile C bituminous to low-volatile bituminous. Comparison of rank and structural data suggests that regional burial coalification was overprinted by hydrothermal coalification in Oak Grove and Brookwood fields, thereby forming the highest rank coal in the basin. Grade parameters indicate that ash and sulfur content tend to be lowest in the easternmost part of the Pottsville outcrop area, apparently owing to protection from marine water. Gas-analysis data suggest that coal is the principal source of coalbed methane in the Pottsville and that the gas may have locally undergone thermal cracking and bacterial alteration. Some coalbed-methane evidently contains comingled biogenic and thermogenic gas, and some gas may have migrated into coal from deep sources.

METHODS

Maps of volatile-matter content (dry, mineral-matter-free) and vitrinite reflectance (mean-maximum) were made for the Mary Lee coal group to evaluate coal rank. Where volatile-matter data were available for more than one bed in the coal group, the average value was plotted. Maps of volatile-matter and and Btu content for each coal group of the Black Creek-Cobb interval are in Pashin and others (1990). Mean-maximum vitrinite reflectance was measured using standard procedures (Stach and others, 1982; ASTM standard D2798-85). Vitrinite-reflectance measurements were made from channel and column samples from outcrops and mines and coal cuttings from oil and gas wells. Additional measurements were compiled from various sources (Hildick, 1982; Robertson Research, Inc., 1985; Geochem Laboratories, 1986; Hines, 1988; Levine and others, 1989).

To map grade parameters, specifically ash and sulfur content, data from selected coal beds in the Black Creek, Mary Lee, Pratt, and Cobb coal groups were used. On the basis of bed names employed by McCalley (1900), data were collected from the Black Creek, Jefferson, and Murphy beds of the Black Creek group; the Blue Creek and Mary Lee beds of the Mary Lee group; the Pratt, American, and Nickel Plate beds of the Pratt group; and the Cobb bed of the Cobb group. Ash content was mapped on a dry basis, whereas sulfur content was mapped on a dry, ash-free basis.

Coal analyses used to map rank and grade parameters were obtained from the files of the Geological Survey of Alabama and from the National Coal Resource Data System (NCRDS) of the U.S. Geological Survey. Published analyses (Fieldner and others, 1925; Shotts, 1956; Fanning and Moore, 1989) also were used where data are scarce. Maps showing the locations of analyses used in this study are included in Pashin and others (1990). The analyses span a long range of time and come from several sources, so the methodology used, especially the cleaning method, varied. Consequently, the results of analysis, particularly ash and sulfur determination, also varied. For this reason, the grade maps made for this report show only generalized regional relationships.

To identify sources of gas in the Black Warrior basin, samples for compositional gas analysis were collected from Mississippian sandstone reservoirs and Pottsville coalbed reservoirs. The samples were collected at the well head and were analyzed by Dudley D. Rice at the U.S. Geological Survey. Analytical results were tabulated, and a compositional plot was made to separate gas populations with sapropelic and humic sources.

RESULTS

COAL RANK

Coal rank of the study interval ranges from high-volatile C bituminous to low-volatile bituminous (figs. 75-79; table 1). Rank decreases upward in section such that coal groups below the Cobb have a maximum rank of low-volatile bituminous, whereas the Cobb and higher coal groups have a maximum rank of only medium-volatile bituminous. The highest rank coal in the Black Warrior basin occurs in a "bullseye" pattern along the Tuscaloosa County-Jefferson County border. The bullseye is in the Coalburg syncline immediately northwest of the Blue Creek anticline. In the heart of the bullseye, volatile-matter content is as low as 19 percent, and vitrinite reflectance is locally higher than 1.4 percent in the Mary Lee coal group (fig. 79). Volatile-matter content increases by approximately 6 percent toward the southeast across the northwest limb of the Blue Creek anticline (figs. 75-78), and the structural cross section of the southeast basin margin indicates that isorank lines are subhorizontal and oblique to bedding in the anticlinal limb (fig. 9).

The 34-percent volatile-matter contour on the Mary Lee map defines a northwest extension of the bullseye, and the northeast and southwest boundaries of the high-rank anomaly can be defined by two straight lines that extend from the southeast basin margin into Walker County (fig. 76). Between those lines, volatile-matter content is generally 3 to 8 percent lower than in adjacent areas.

Table 1. Abbreviated rank classification of bituminous coal

Rank	Btu/lb (mmmf)	Percent volatile matter (dmmf)[1]	Approximate percent vitrinite reflectance[2]
Low volatile		14 - 22	1.5 - 2.0
Medium volatile		22 - 31	1.0 - 1.7
High volatile A	<14,000	>31	0.6 - 1.2
High volatile B	13,000 - 14,000	>31	0.5 - 0.8
High volatile C	11,000 - 13,000	>31	0.4 - 0.7

[1] From ASTM Standard D388-88.
[2] From Damberger and others, 1984.

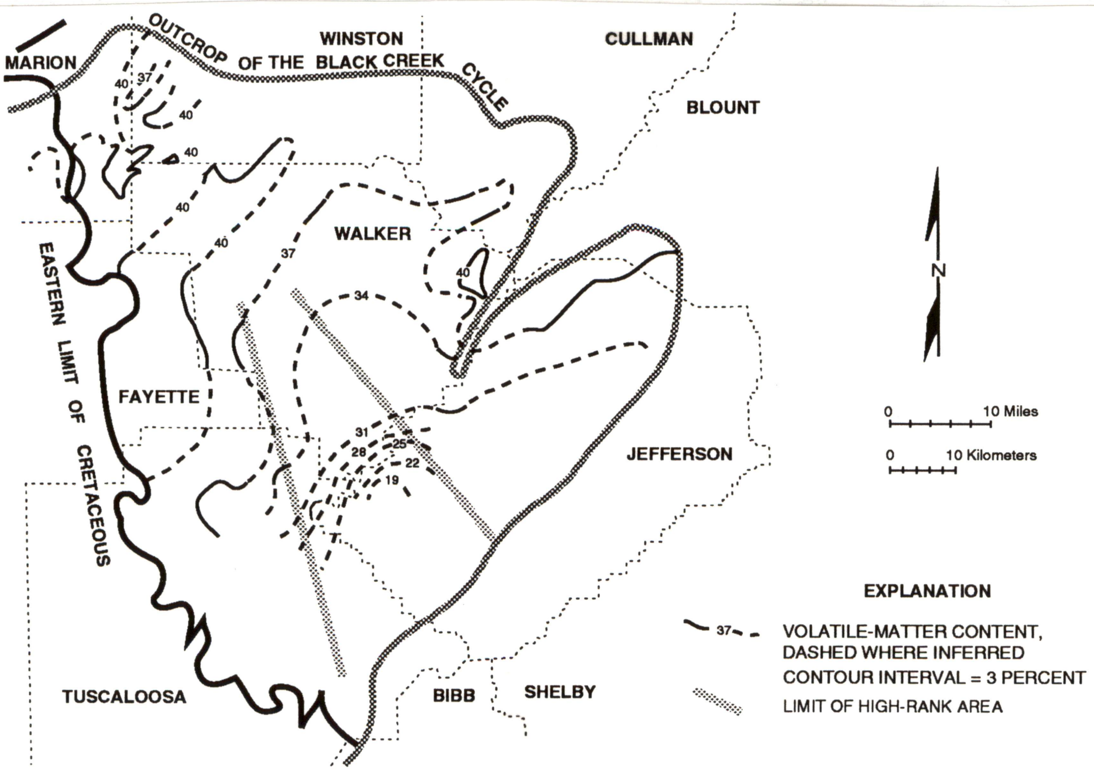


Figure 75. Volatile-matter content, Black Creek coal group, Black Warrior basin, Alabama.

The northeastern line extends from Jefferson County to Walker County and is aligned with the southwest margin of the Bessemer cross-strike structural discontinuity (CSD) of Thomas and Bearce (1986) and may define an extension of that discontinuity into the Black Warrior basin. However, the southwestern line, which stretches from Tuscaloosa County to Walker County, does not coincide with any known structural feature.

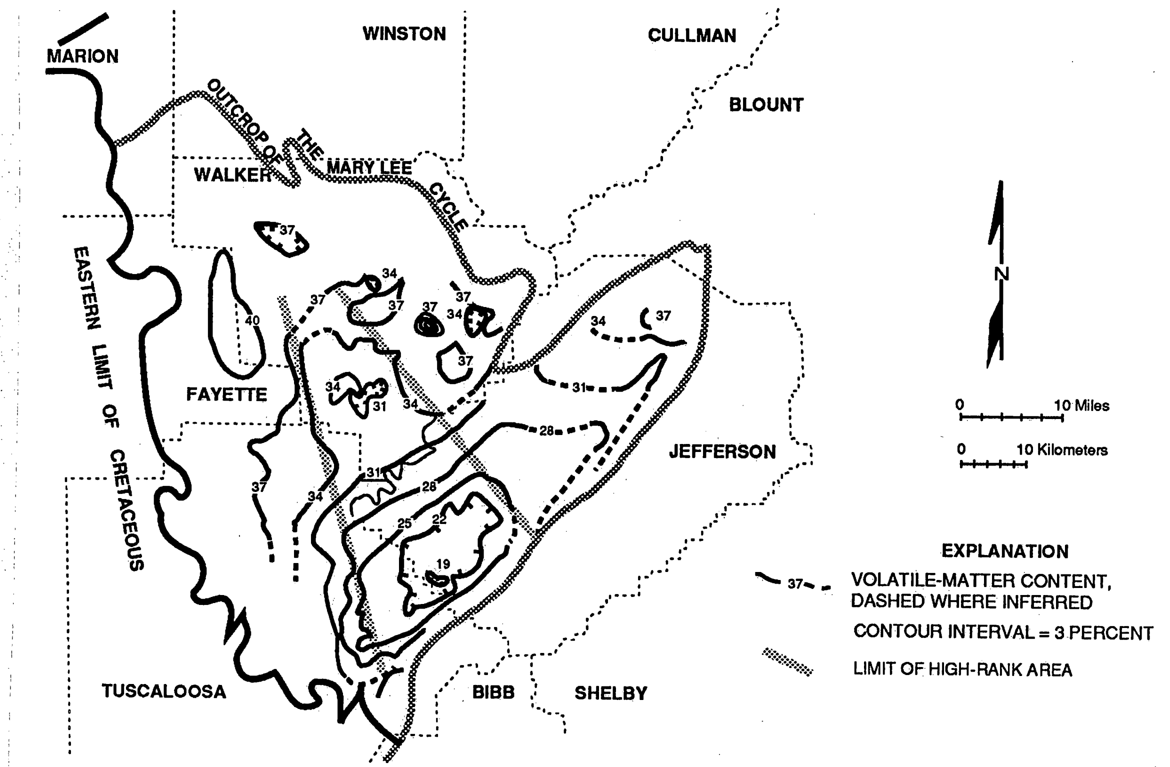


Figure 76. Volatile-matter content, Mary Lee coal group, Black Warrior basin, Alabama.

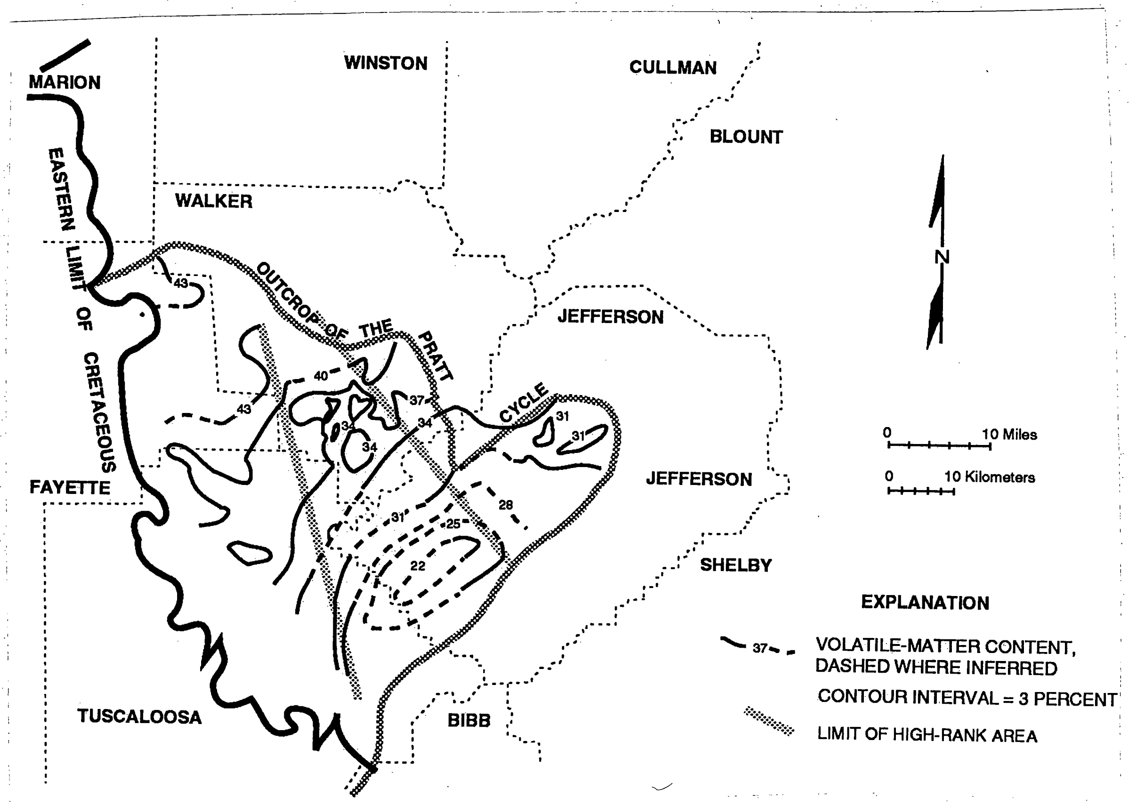


Figure 77. Volatile-matter content, Pratt coal group, Black Warrior basin, Alabama.

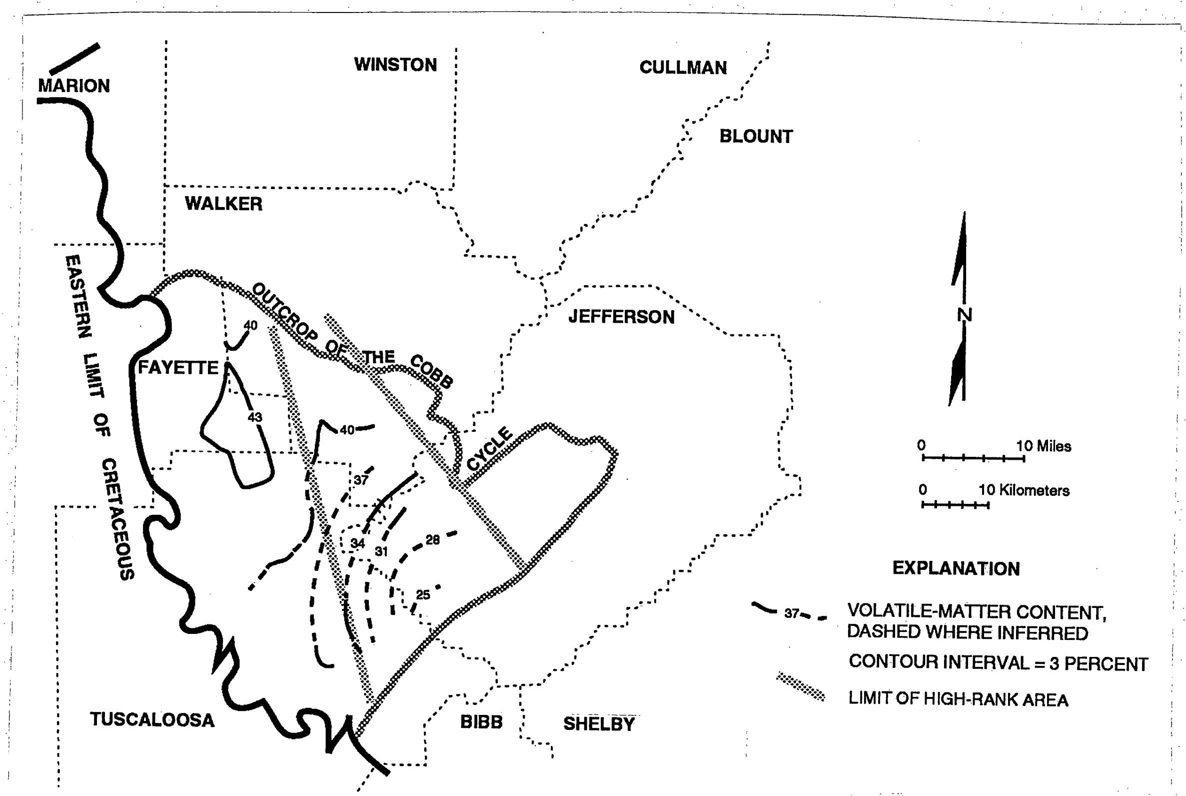


Figure 78. Volatile-matter content, Cobb coal group, Black Warrior basin, Alabama.

The only available rank information for Pottsville coal below thick Cretaceous overburden is vitrinite reflectance (fig. 79). Most coal in the Mary Lee coal group is of high-volatile A bituminous rank. However, coal rank is as low as high-volatile C bituminous in an area that extends from western Fayette County to northeast Pickens County and is defined by the 0.6-percent vitrinite-reflectance contour. A single vitrinite-reflectance value indicates that medium-volatile bituminous coal may occur in northern Sumter County.

COAL GRADE

Coal in the Black Creek group contains less than 6 percent ash throughout most of Jefferson and Tuscaloosa Counties and in much of the northern part of the study area (fig. 80). Coal with ash content higher than 6 percent occurs throughout most of Fayette and Walker Counties and locally in southeastern Marion and southwestern Winston Counties. Sulfur content in the Black Creek group is less than 2 percent throughout much of Tuscaloosa County and in the northern part of the study area

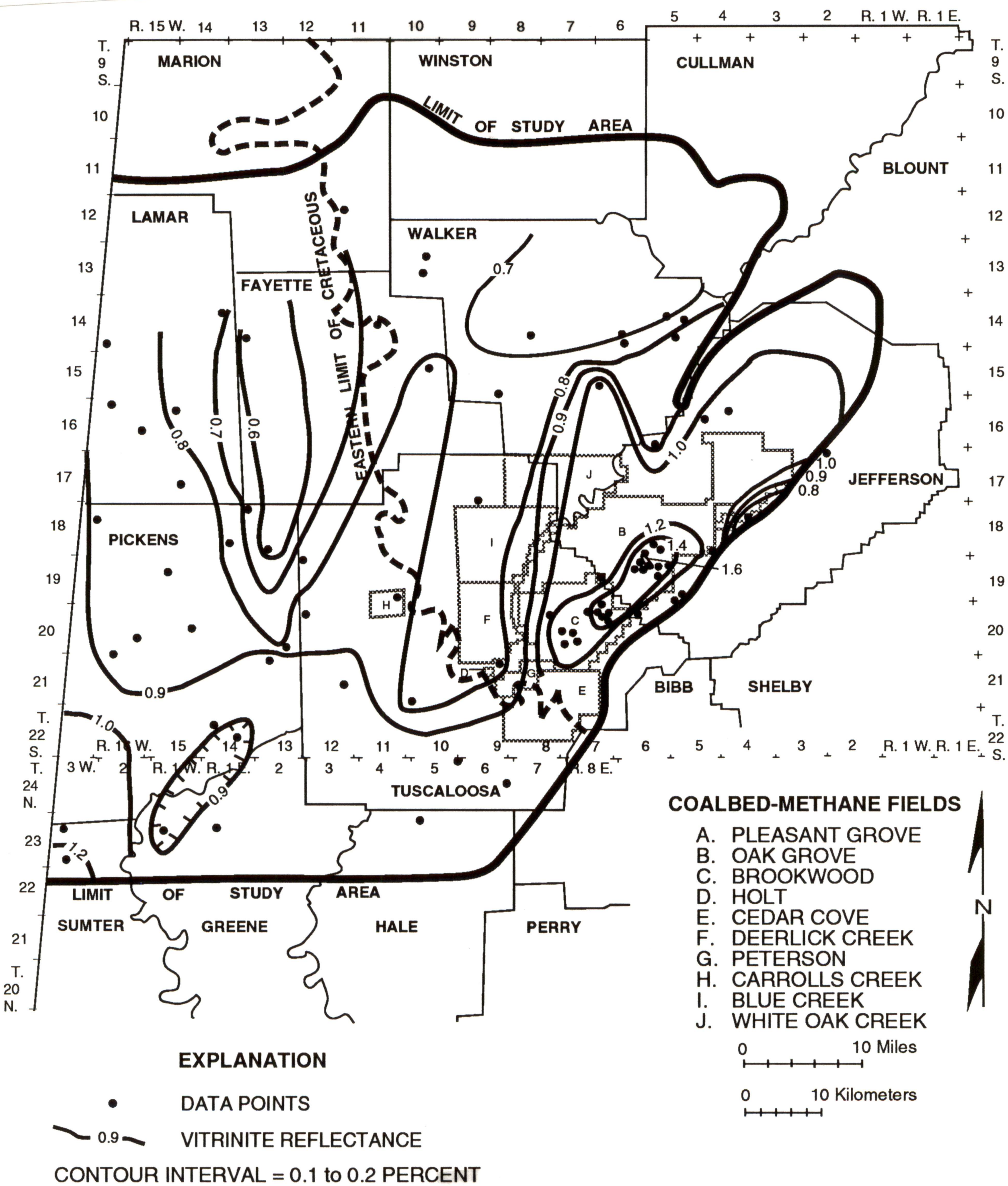


Figure 79. Vitrinite reflectance of the Mary Lee coal group, Black Warrior basin, Alabama.

(fig. 81). A wide belt of coal with more than 3 percent sulfur occurs throughout most of Walker County and coincides largely with coal containing more than 6 percent ash (fig. 80).

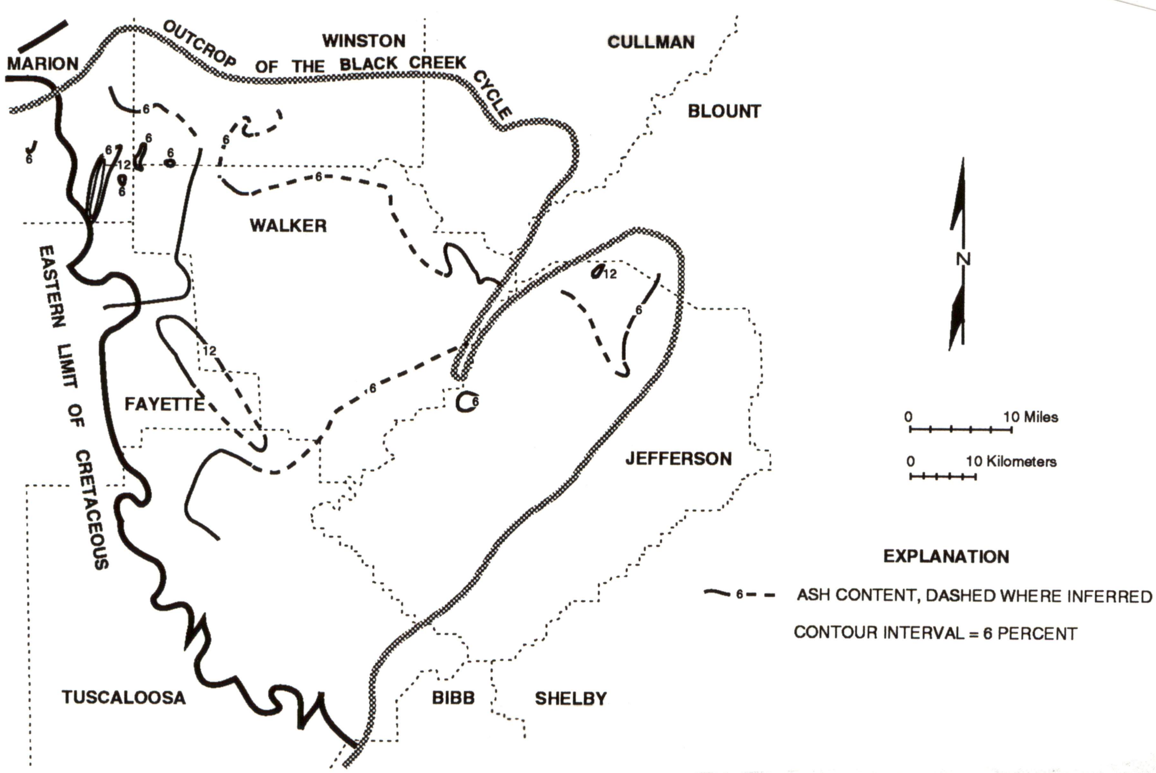


Figure 80. Ash content, Black Creek coal group, Black Warrior basin, Alabama.

Ash content is generally higher in the Mary Lee group than in the Black Creek group but is less than 12 percent throughout much of the southern part of the study area (figs. 80, 82). In the northern part, ash content is generally between 12 and 18 percent, and coal beds with more than 18 percent ash are most abundant in northern Tuscaloosa County. Sulfur content in the Mary Lee group is 1 percent or less throughout most of the study area (fig. 83). Sulfur content greater than 2 percent occurs in a series of isolated areas in a belt that extends from northern Tuscaloosa to north-central Jefferson County. Sulfur content in the Blue Creek and Mary Lee beds tends to be the lowest of any coal beds in the Black Warrior basin.

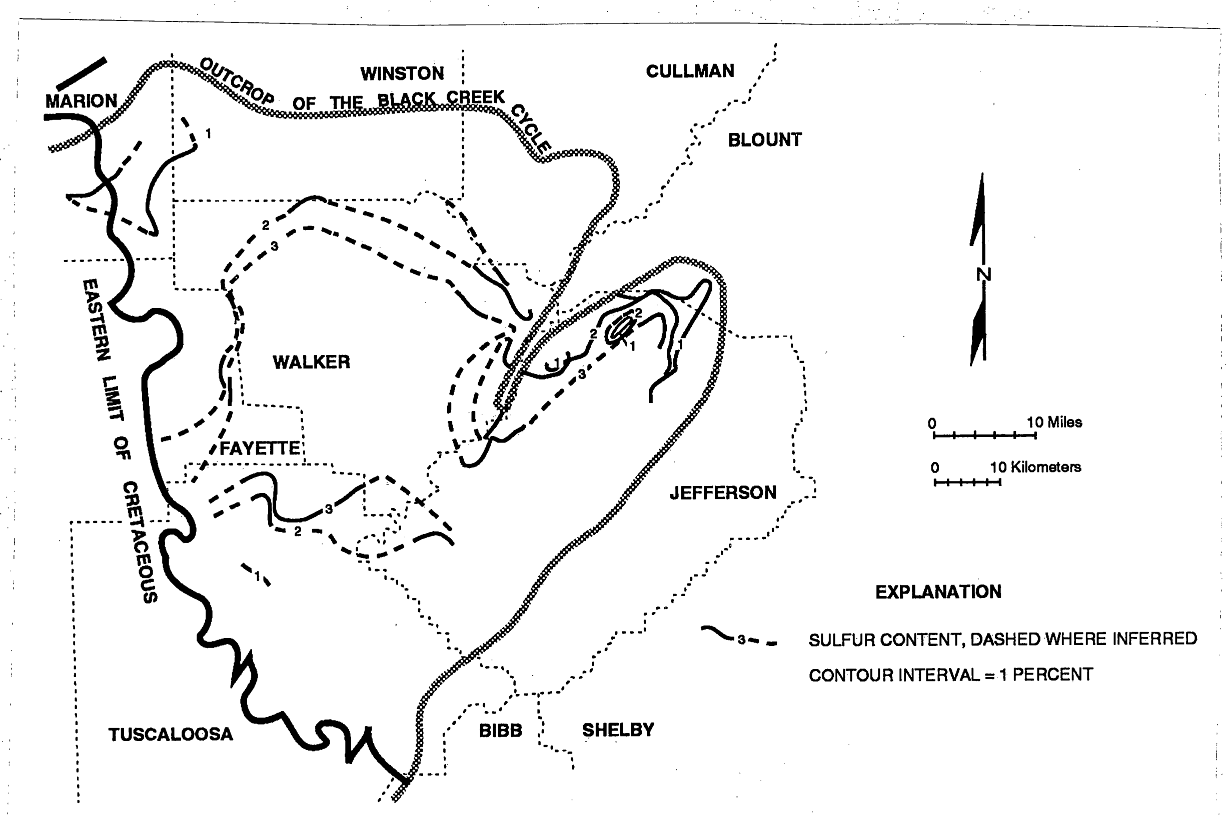


Figure 81. Sulfur content, Black Creek coal group, Black Warrior basin, Alabama.

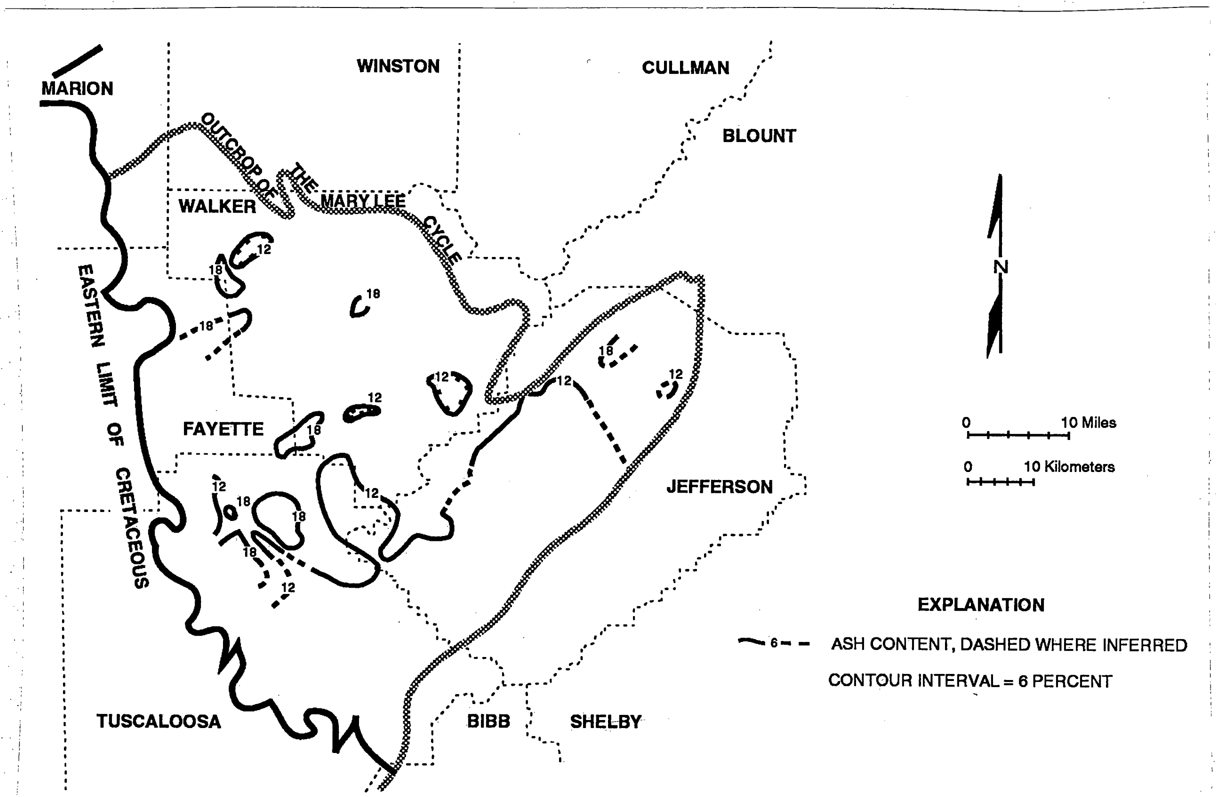


Figure 82. Ash content, Mary Lee coal group, Black Warrior basin, Alabama.

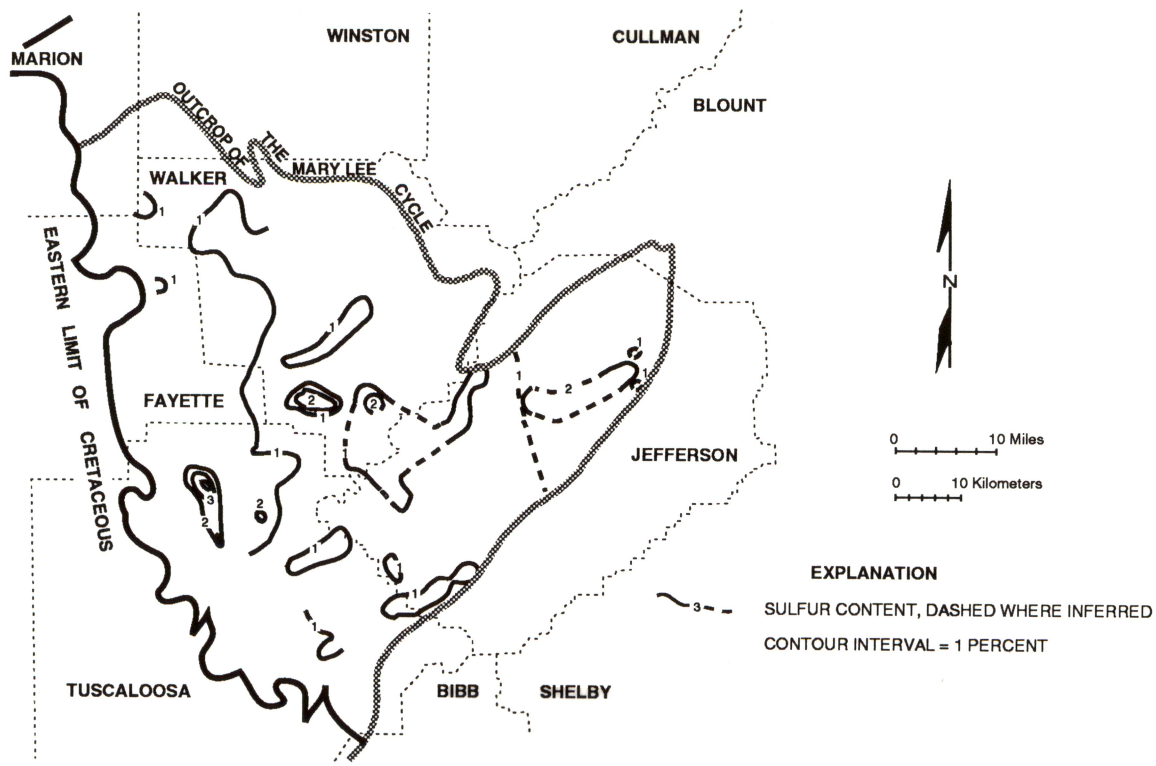


Figure 83. Sulfur content, Mary Lee coal group, Black Warrior basin, Alabama.

In the Pratt group, ash content is similar to that in the Mary Lee group, but some areas containing coal with less than 6 percent ash occur in Jefferson and Tuscaloosa Counties (fig. 84). Coal with ash content ranging from 12 percent to more than 18 percent occurs in a belt extending from northern Tuscaloosa to western Jefferson Counties, and locally near the northern outcrop in Fayette and Walker Counties. Sulfur content is quite variable in the Pratt group but is generally less than 2 percent in the east-central part of the study area (fig. 85). In the central and northwestern parts of the study area, however, sulfur content is locally greater than 4 percent.

The Cobb group contains less than 12 percent ash throughout much of the eastern part the map area (fig. 86). In the west, however, ash content is quite variable and locally exceeds 18 percent. Sulfur content in the Cobb group is less than 2 percent in the east where ash content is low (fig. 87). In contrast, sulfur content locally exceeds 6 percent, which is higher than in the other coal groups, in the northwest where ash content is high.

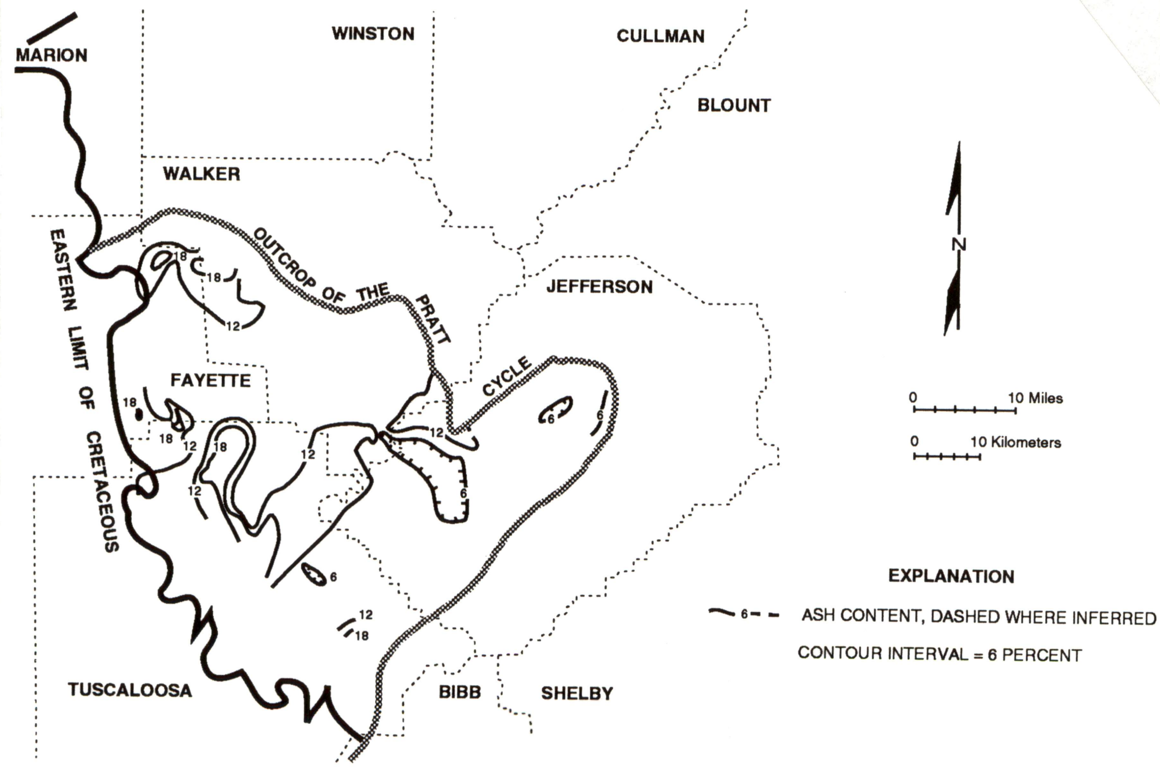


Figure 84. Ash content, Pratt coal group, Black Warrior basin, Alabama.

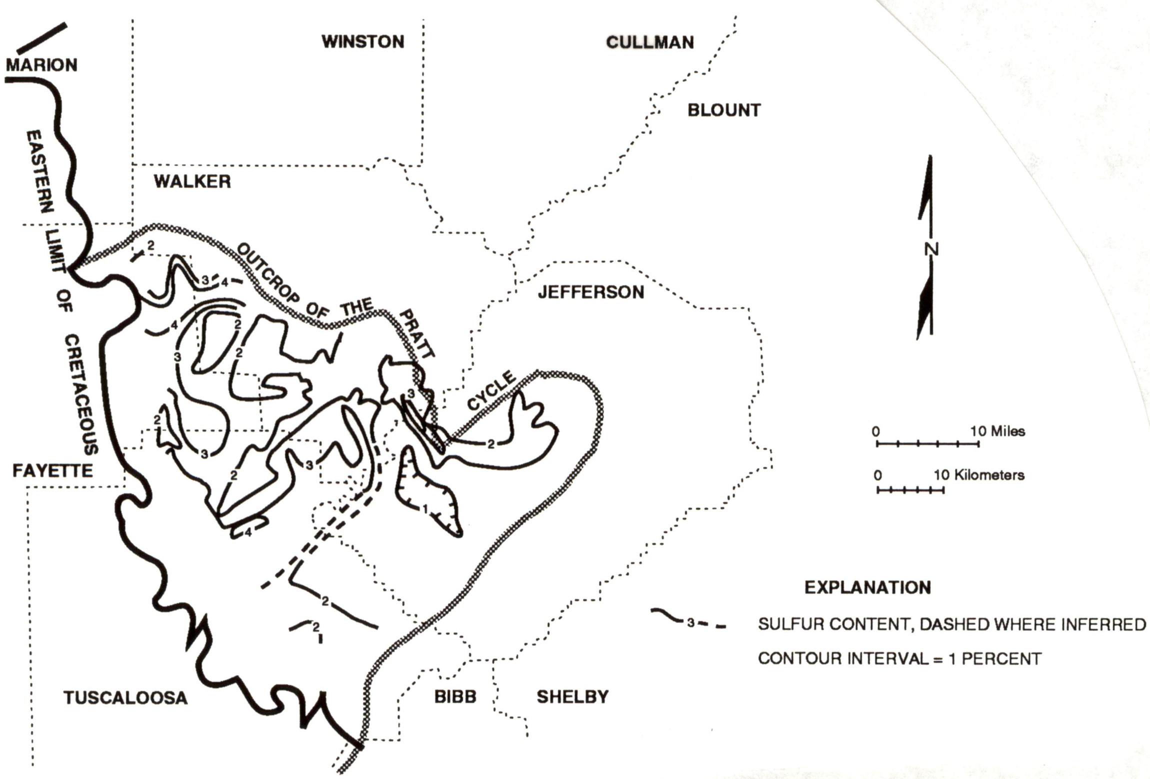


Figure 85. Sulfur content, Pratt coal group, Black Warrior basin, Alabama.

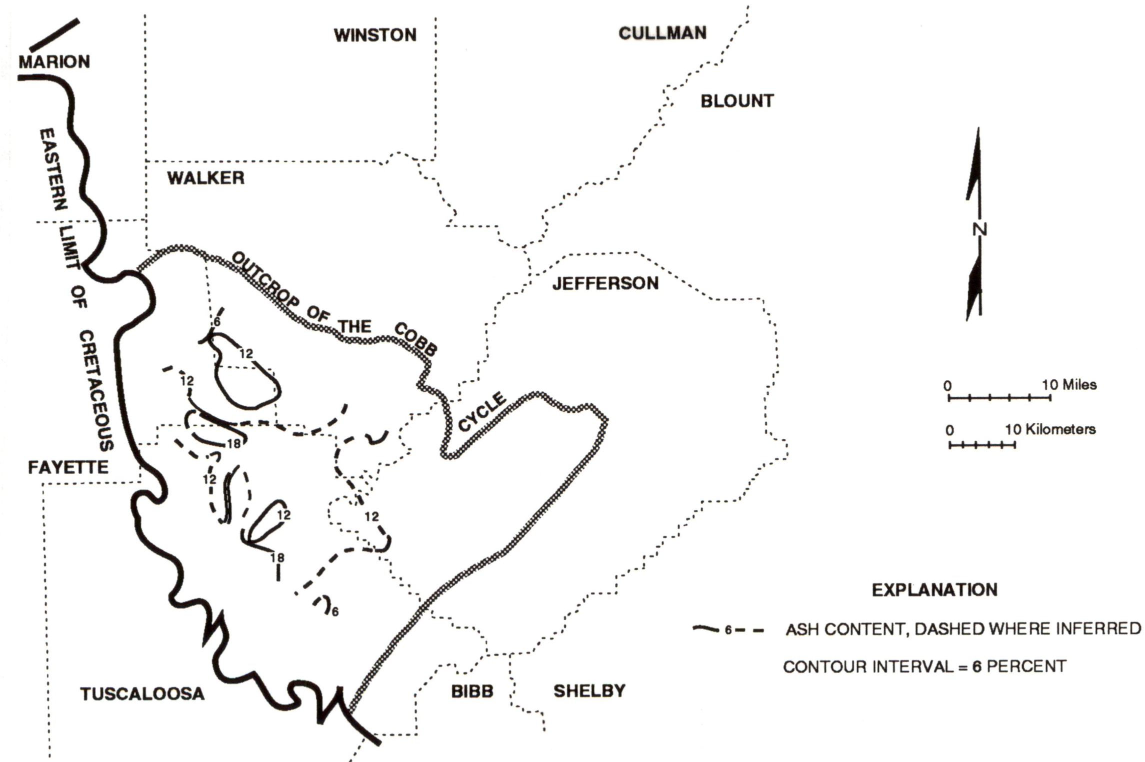


Figure 86. Ash content, Cobb coal group, Black Warrior basin, Alabama.

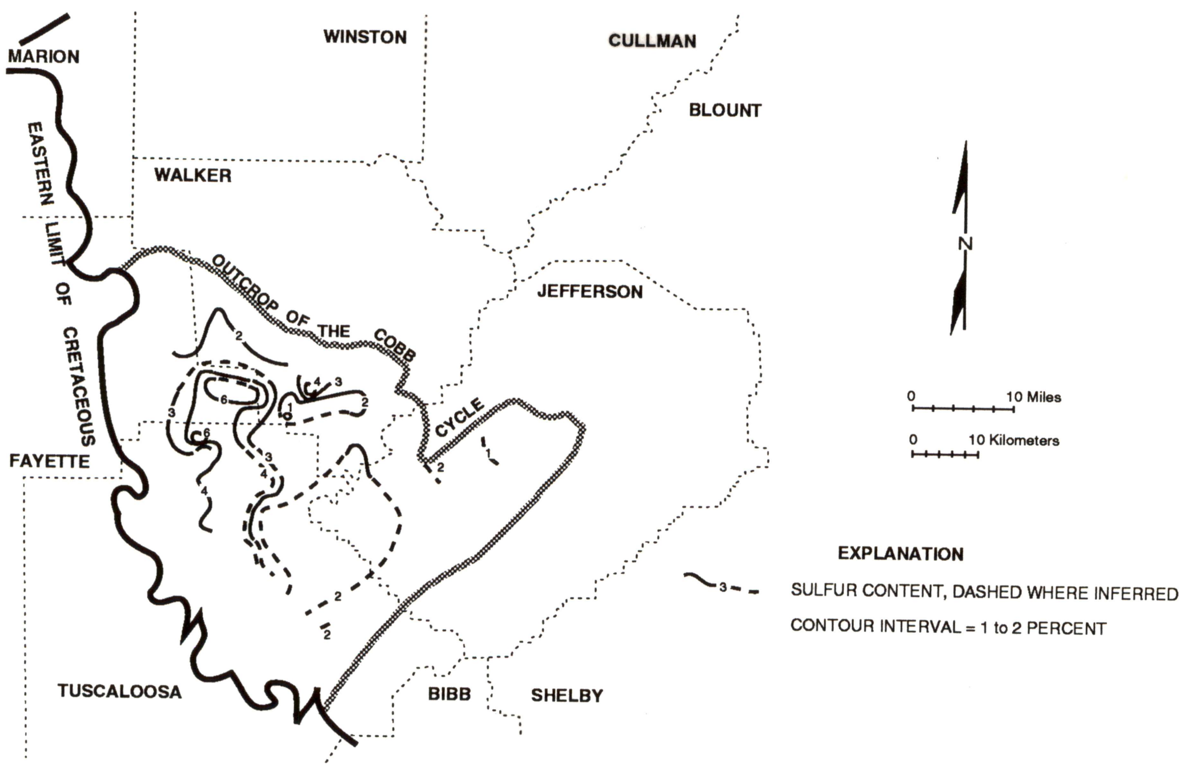


Figure 87. Sulfur content, Cobb coal group, Black Warrior basin, Alabama.

In general, low-ash coal corresponds with low-sulfur coal. In all coal groups, ash and sulfur content tend to be lowest and least variable in the eastern and southern parts of the Pottsville outcrop area where coal is thickest and most abundant and tend to be highest in a belt extending from southern Fayette County and northern Tuscaloosa County to eastern Jefferson County. In the northern part of the outcrop area, however, ash and sulfur content are variable and unpredictable. The reason for the correlation between ash and sulfur content is unclear, but occurrence of high-grade coal in the eastern and southern parts of the outcrop area may owe partly to development of broad interfluvial swamps and isolation from marine water.

GAS COMPOSITION

Methane in the Black Warrior basin of Alabama may be divided into two groups on the basis of isotopic variation ($\delta^{13}C_1$) and ethane (C_2) content (fig. 88; table 2). Gas from Mississippian conventional reservoirs, which are located in the deep subsurface in the northwestern part of the study area, is characterized by a narrow range of isotopic variation and has a considerable ethane component. The Mississippian gas samples have $\delta^{13}C_1$ values between -47 and -50 parts per thousand (ppt), and ethane content ranges from 0.5 to 3.5 percent.

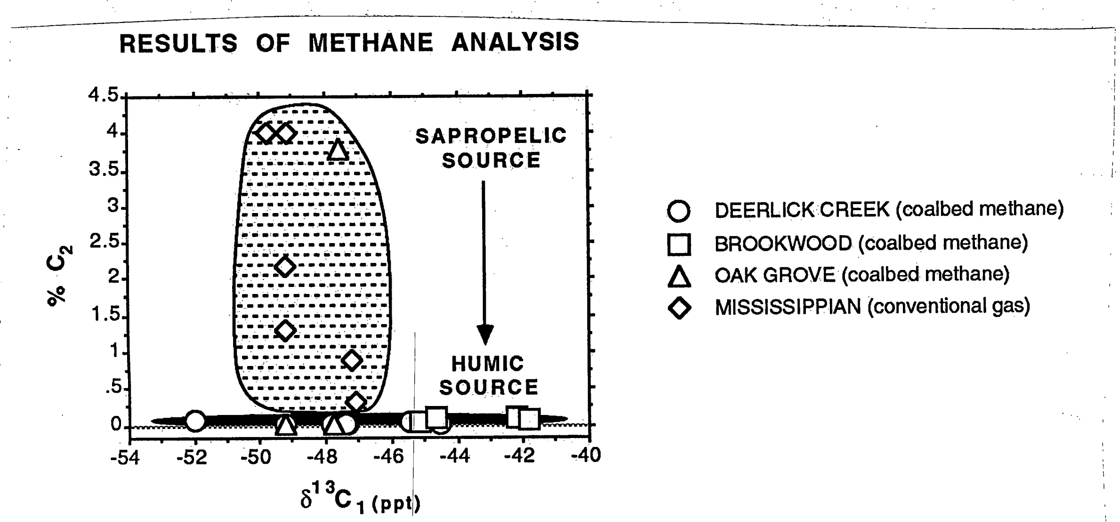


Figure 88. Scattergram showing variation of gas composition, Black Warrior basin, Alabama.

Table 2. Gas-analysis data[1]

Sample number	Location	$\delta^{13}C_1$ (ppt)	C_1 (%)	C_2 (%)	C_3 (%)	iC_4 (%)	nC_4 (%)
10470	Deerlick Creek	-45.45	95.86	0.06	0.02	0.08	--
10472		-44.55	99.91	.02	--	--	--
10473		-47.33	99.95	.01	--	--	--
10474		-49.21	95.62	.01	--	--	--
10477		-47.82	99.89	.01	.10	.13	--
10478		-47.42	99.30	.33	.22	--	--
10479	Mississippian	-47.10	98.51	.93	.31	.02	0.01
10480		-47.19	96.64	3.03	.25	.02	--
10481		-49.77	97.34	2.28	.29	.02	.01
10482		-49.25	98.40	1.37	.16	.01	.01
10486		-49.21	94.61	4.21	.78	.08	.08
10487		-49.17	90.14	4.01	.74	.07	.08
10488	Brookwood	-45.15	99.75	.02	--	--	--
10489		-44.67	99.72	.10	--	--	--
10490		-42.20	99.83	.08	.09	--	--
10491		-41.86	99.92	.08	--	--	--
10492		-49.77	99.94	--	--	--	--
10493		-51.02	95.03	--	--	--	--
10494	Oak Grove	-47.60	95.99	3.78	--	--	--
10495		-47.79	99.94	.01	--	--	--
10496		-49.26	99.93	.01	--	--	--
10497		-46.60	99.93	--	--	--	--
10498		-49.22	95.05	--	--	--	--

[1] Data courtesy of Dudley D. Rice, U.S. Geological Survey.

In contrast, coalbed methane is characterized by a wide range of $\delta^{13}C_1$ values, and C_2 values are less than 0.3 percent (fig. 88; table 2). Whereas gas from Brookwood field has $\delta^{13}C_1$ values ranging between -41 and -46 ppt, gas from Oak Grove and Deerlick Creek fields has $\delta^{13}C_1$ values ranging from -44 to -54 ppt. One gas sample from Oak Grove field has an anomalously high C_2 content and has a $\delta^{13}C_1$ value similar to the Mississippian gas, and some samples from the other fields contain minor amounts of C_3 and C_4 hydrocarbons.

NATURE AND TIMING OF CATAGENESIS

Gas-analysis data indicate that Mississippian gas and coalbed methane in the Black Warrior basin of Alabama are derived from different sources (fig. 88). The high C_2 content of the Mississippian gas indicates a large contribution of gas from sapropelic kerogen, and some Mississippian gas is associated with oil; this conventional gas was evidently derived from Mississippian shale units (Rice and others, 1989). However, the low C_2 content of some samples may indicate a major contribution from humic kerogen, although thermal cracking and bacterial alteration may also contribute to dryness in gas reservoirs (James and Burns, 1984).

Pottsville coal is the probable source of coalbed methane in Alabama. The low C_2 content of coalbed methane (fig. 88; table 2) suggests a humic source, although again, thermal cracking and bacterial alteration may have affected gas composition. Rank data indicate that nearly all coalbed-methane production up to December, 1988 is from coal mature enough to have generated methane thermally. However, biogenic methane has $\delta^{13}C_1$ values between -90 and -40 ppt (Jenden, 1985), so some of the isotopically lightest gas in the Black Warrior basin may represent comingled biogenic and thermogenic methane. The high C_2 content of one sample from Oak Grove field plus minor amounts of longer-chain hydrocarbons in the other fields suggests that hydrogen-rich components in coal, such as sporinite, generated wet gas. Locally high C_2 content also raises the possibility that hydrocarbons have migrated into some coalbed reservoirs from deeper sources.

On a basin-wide scale, coal rank is poorly related to regional structural trends. However, decrease in rank from the high-rank anomaly to the northwest limb of the Blue Creek anticline can be related directly to structure. Coalification of the highest rank coal in western Jefferson and eastern Tuscaloosa Counties (fig. 79) postdated or occurred during the late stages of folding because isorank lines are subhorizontal and crosscut bedding on the anticline (fig. 9).

Structural relief equivalent to the northwest limb of the Blue Creek anticline would be required to explain the decrease in coal rank to the northeast and southwest of the high-rank anomaly in terms of burial depth. Because no such structure exists (fig. 8), this anomaly may have been formed by a local increase in the paleogeothermal gradient. The origin of the high-rank coal remains enigmatic, but one explanation for elevated thermal maturity is hydrothermal activity adjacent to the Blue Creek anticline in fractured strata between two northwest-trending structural discontinuities.

Although a southwestward increase in burial depth may explain high rank in Sumter County (fig. 79), thrust faulting (fig. 7) and scarcity of wells make interpretation difficult. Development of the high-rank anomaly of Jefferson, Tuscaloosa, and Walker Counties apparently occurred during or after Alleghanian thrusting, because the Blue Creek anticline was already present. Lignitic plant debris have been reported from the Late Cretaceous Tuscaloosa Group which rests unconformably on the bituminous-coal-bearing Pottsville Formation (Stephenson, 1926). This rank discontinuity indicates that the Pottsville was coalified before Tuscaloosa deposition.

STRUCTURAL CONTROL AND MODERN DISTURBANCE OF THE HYDROLOGIC SYSTEM

INTRODUCTION

Tectonic, sedimentologic, and thermal processes all acted together to form the present-day configuration of the Black Warrior basin, and hence, provided the hydrogeologic framework of the Pottsville Formation. Water must be removed from coalbed-methane reservoirs to reduce fluid pressure, thereby facilitating desorption of methane from coal. Thus, hydrology is important in coalbed methane exploration and production because of water disposal and related economic and environmental concerns (O'Neil and others, 1989). The principal objective of hydrologic analysis was to identify hydrologic controls on the occurrence and producibility of coalbed methane. Water-level, water-production, reservoir-pressure, and water-chemistry data were analyzed with respect to the structural and sedimentologic framework of the Black Warrior basin in order to develop a predictive hydrologic model for the Pottsville Formation.

Results of hydrologic analysis indicate that structural geology is a primary control on the hydrologic system and that mining and coalbed-methane production have also impacted regional hydrology. Black Creek-Cobb strata have minimal primary permeability, so coal beds are the principal aquifers owing to closely spaced cleat. Most other groundwater flow also is through secondary conduits, such as joints and faults. Water-level data indicate that reservoir pressure has been lowered significantly by underground mining and coalbed-methane production. Hydrochemical data demonstrate that a series of structurally controlled fresh-water plumes minimizes water-disposal concerns along the southeast basin margin, whereas recharge transmitted by Cretaceous aquifers may increase water-disposal concerns in the western part of the basin. Water production from the Black Creek-Cobb interval is extremely variable, and water-production data suggest that many coalbed-methane reservoirs are structurally compartmentalized.

METHODS

Water-level data from more than 1,000 water, petroleum, and coalbed-methane wells were used to map the potentiometric surface in the upper Pottsville Formation. Water level was measured to the nearest 0.1 foot in coalbed-methane wells in Jefferson and Tuscaloosa Counties in 1987 and 1988 using a battery-powered Powers Well Sounder. Reservoir pressure was determined using available water-level and construction information for coalbed-methane wells by multiplying the length of the water column by 0.433 psi/ft. Pressure-depth plots for Brookwood and Oak Grove fields were made to determine the pressure regime of the coalbed-methane fields. The pressure-depth quotient for each well was plotted on a map to determine the relationship between reservoir pressure, geologic structures and underground mines in the coalbed-methane fields.

Water samples were collected from 59 coalbed-methane wells and 13 water wells in Jefferson and Tuscaloosa Counties in 1988, and standard chemical analyses of the samples were made in the Geochemical Laboratory of the Geological Survey of Alabama using the procedures described in Brown and others (1970), Skougstad and others (1979), and the U.S. Environmental Protection Agency (1979). Results of chemical analysis were used to make scattergrams and Stiff diagrams (Stiff, 1951) to identify relationships among water type, degree of mineralization, and depth. Maps of TDS content also were made to determine the distribution of saline water and to characterize basin hydrodynamics.

To determine geologic controls on water production, a map of peak water production was made for Oak Grove field. Water-production data through November 1989 were collected from the files of the State Oil and Gas Board (Form OGB-7) and were plotted on a map showing major folds and faults.

Water-production maps for all coalbed-methane fields in Alabama are available in Pashin and others (1990).

AQUIFER CHARACTERISTICS

Quartzose sandstone has sufficient primary permeability to form conventional aquifers and petroleum reservoirs in the Pottsville Formation of Alabama (Epsman, 1987), but primary permeability in lithic sandstone is generally on the order of only 0.1 millidarcy (md) (Tucker and Kidd, 1973). Therefore, secondary conduits, such as faults, joints, and cleats, are the dominant source of permeability in the coalbed-methane fields.

Permeability in the Pottsville Formation decreases markedly with depth. Hydrologic test data from Cedar Cove, Brookwood, and Oak Grove fields indicates that permeability is approximately 100 md at a depth of 100 feet and is less than 10 md at a depth of more than 1,000 feet (McKee and others, 1986). Downward decrease of permeability may reflect scarcity of set II joints (see section on structural geology) plus closure of fractures at depth in response to high confining pressure.

Because cleat is closely spaced relative to other fractures, coal is the most permeable rock type in the Pottsville and thus has a strong effect on aquifer behavior. For example, results from the Rock Creek site (Boyer and others, 1986) demonstrate that the cone of depression generated by wells completed in the Pratt cycle, where the cleat system is well developed, is elongate in the face-cleat direction. In contrast, the cone of depression in the Blue Creek coal of the Mary Lee cycle, which contains inclined and curving fracture systems, has no preferred orientation. Fractures adjacent to coal beds, such as joints, also affect gas flow and permeability anisotropy.

The Pottsville may be modeled as an unconfined aquifer, although low permeability at depth may cause local confinement. For unconfined aquifers, the terms potentiometric surface and water table are synonymous. The potentiometric surface is locally higher than 1,000 feet above msl in the upland areas of Cullman County and descends southwestward to less than 200 feet above msl in central Tuscaloosa County near the Cretaceous overlap (fig. 89). In the Pottsville outcrop area, near-surface groundwater flow is generally perpendicular to potentiometric contours and toward major surface

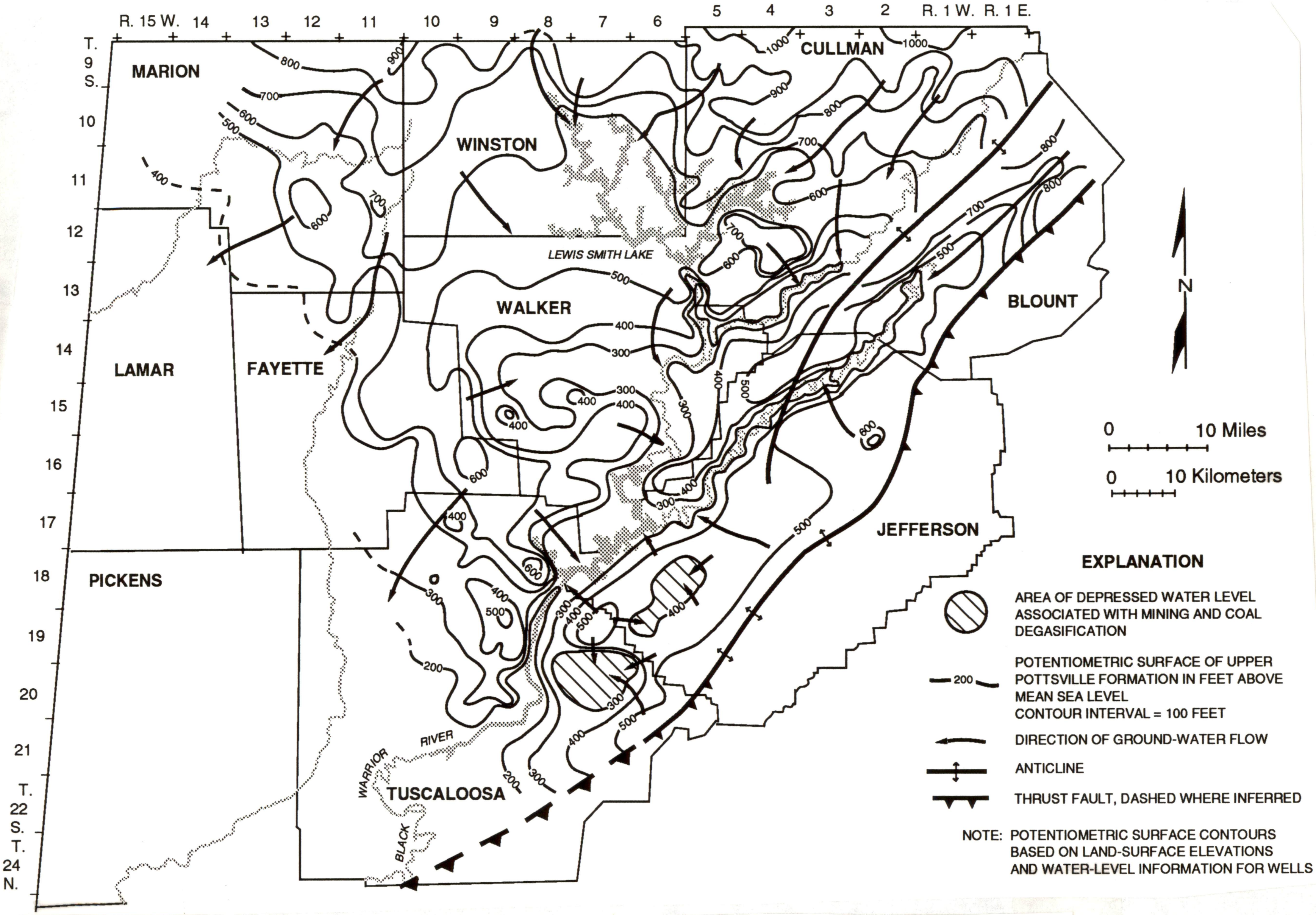


Figure 89. Generalized potentiometric-surface map of the upper Pottsville Formation in Alabama.

drainage features like the Black Warrior River. West of the Pottsville outcrop area, the unconsolidated Cretaceous sand that overlies the Pottsville is a major aquifer that intercepts and transmits meteoric recharge.

Modern disturbance of the hydrologic system is apparent in western Jefferson and eastern Tuscaloosa Counties (Oak Grove and Brookwood fields) where the water table has been lowered by as much as 200 feet by underground mine dewatering (fig. 89). In this area, deep underground mines have been operating less than 25 years. Hence, lowering of the water table may reflect rapid dewatering of fracture systems with high permeability and limited volume.

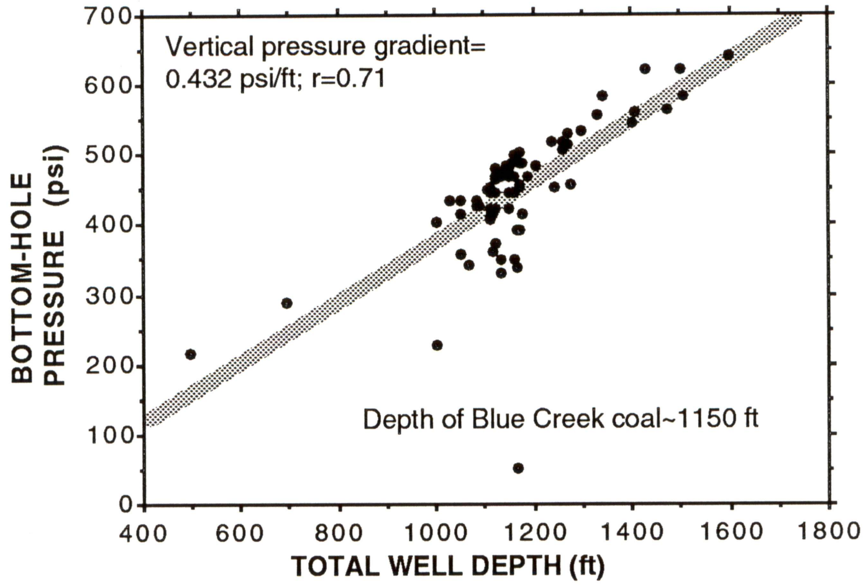
RESERVOIR PRESSURE

Reservoir-pressure data yielded important results regarding the effects of coalbed-methane wells and underground mines on basin hydrodynamics. In Oak Grove field, most data plot along a line with a slope of 0.432 psi/ft, which essentially is hydrostatic pressure (fig. 90). However, the regression coefficient of the line is only 0.71, and many data wells completed in the Blue Creek coal (approximately 1,175 feet) have pressure far below hydrostatic. In all other coalbed-methane fields, such as Brookwood field, pressure does not correlate significantly with depth, and pressure-depth quotients are well below hydrostatic (0.433 psi/ft).

Water-level data used to calculate reservoir pressure in Oak Grove field west of the Oak Grove mine were collected shortly after the wells began producing, whereas water-level data for all other studied wells were collected more than 3 months after wells began producing and thus indicate pressure conditions after significant dewatering. The Oak Grove results suggest that near-hydrostatic conditions prevail in parts of the Black Warrior basin where the natural hydrologic system has not been significantly altered. However, low reservoir pressure at the level of the Blue Creek coal (fig. 90) is interpreted to be a long-term effect of pumping in the original Oak Grove degasification pattern where wells have been completed in the Blue Creek bed. Mining operations in the Blue Creek bed may also contribute to low reservoir pressure.

PRESSURE-DEPTH PLOTS

OAK GROVE FIELD



BROOKWOOD FIELD

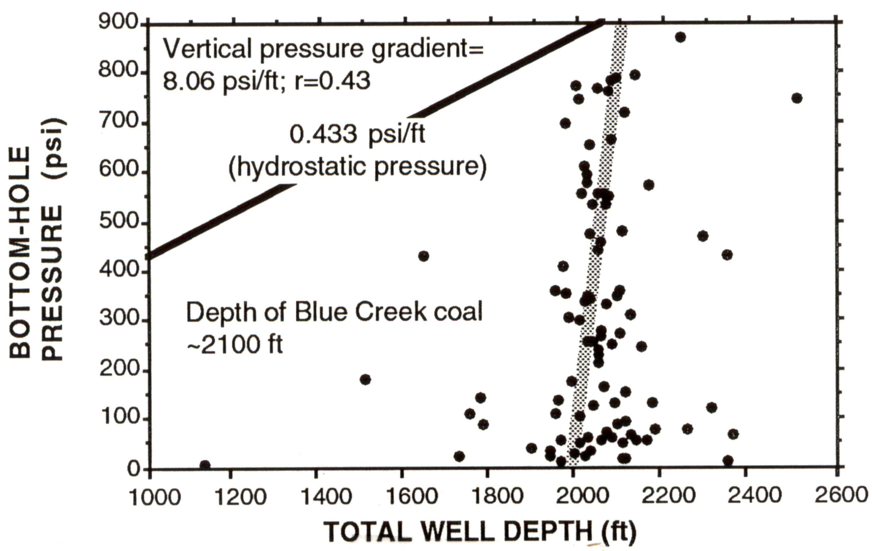


Figure 90. Pressure-depth plots, Oak Grove and Brookwood fields.

Areas where reservoir pressure is low (<0.32 psi/ft) occur around the underground coal mines in Oak Grove and Brookwood fields and also occur in coalbed-methane fields that lack underground coal mines (fig. 91). In most fields, low reservoir pressure coincides with the distribution of producing wells. In Deerlick Creek field, however, low reservoir pressure is restricted to the southeastern part of the field. Apparently, coalbed-methane wells have reduced water level, and hence reservoir pressure, throughout much of the producing area. However, prolonged pumping tests need to be performed to determine how effective depressurization has been, because water-level data are more sensitive to wellbore conditions than to ambient reservoir conditions.

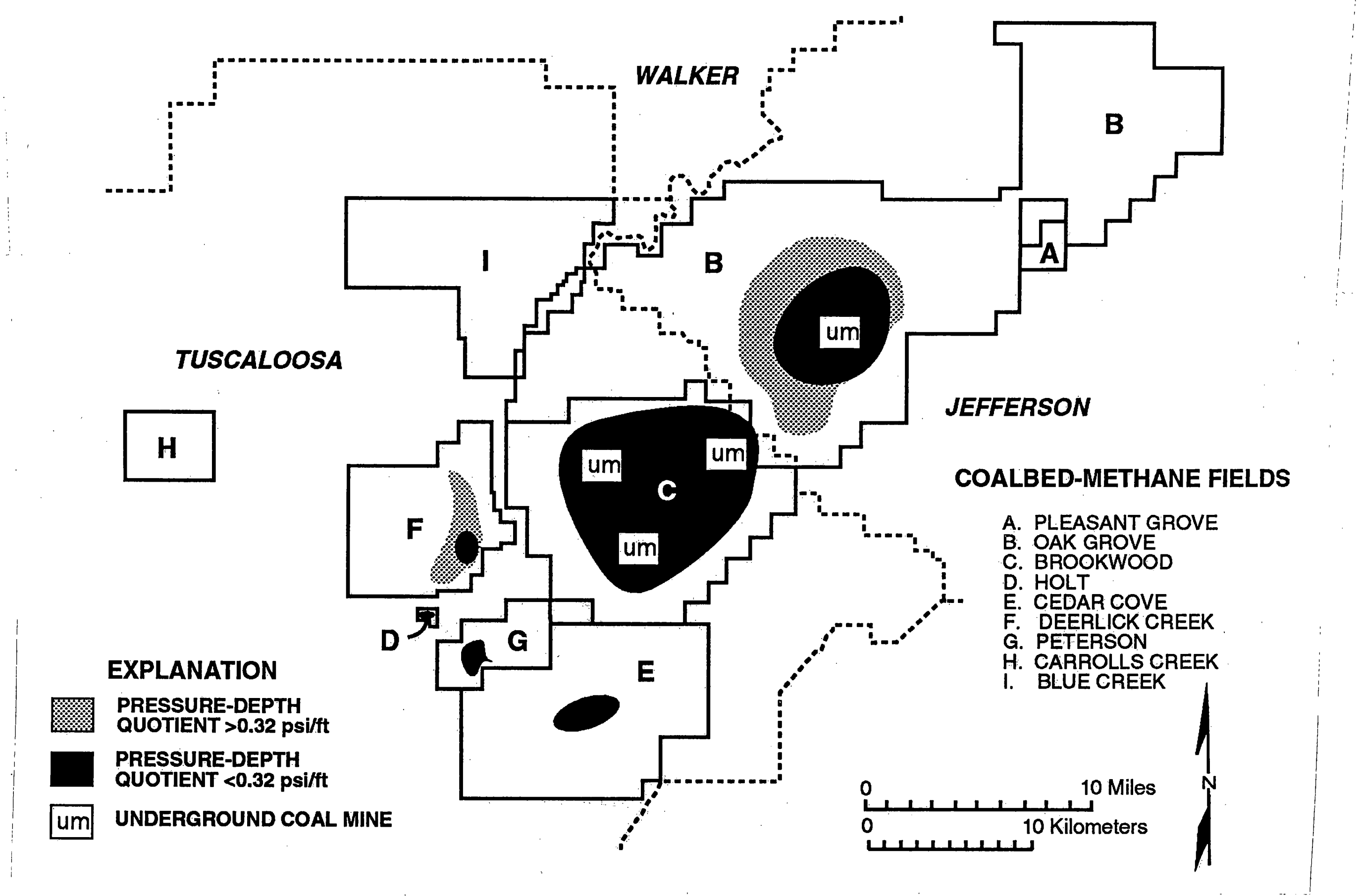


Figure 91. Areas in the coalbed-methane fields where pressure-depth quotient is less than 0.32 psi/ft.

WATER CHEMISTRY

The hydrochemical system of the Black Warrior basin is influenced by oxidation, carbonation, hydration, and ion exchange associated with weathering of rock and soil. Graphing total-dissolved-solids (TDS) content versus depth establishes that salinity increases greatly with depth and locally exceeds 30,000 milligrams per liter (mg/L) (fig. 92). However, the degree and type of mineralization vary greatly.

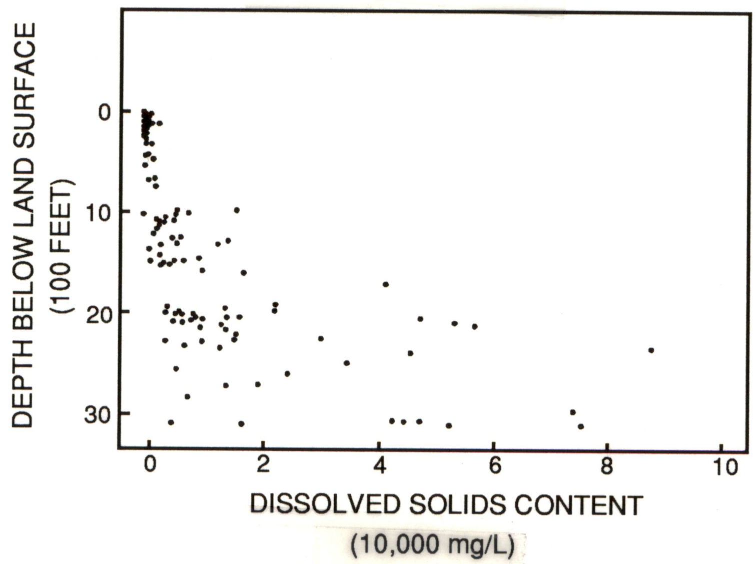


Figure 92. Scattergram showing increase in TDS content with depth.

Stiff diagrams for the coalbed-methane fields show vertical trends in the degree and type of mineralization (fig. 93). Surface water from unmined areas generally is not mineralized, whereas that from mined areas is enriched in magnesium and sulfate. In the shallow subsurface, water generally contains a low concentration of sodium bicarbonate, but between 1,000 and 1,500 feet in Oak Grove and Pleasant Grove fields, both sodium-bicarbonate and sodium-chloride water types occur. In these fields, sodium-bicarbonate concentration is less than 20 equivalents per million (epm), and sodium-chloride concentration is approximately 80 epm. Beyond 1,500 feet, sodium-chloride concentration increases sharply and exceeds 200 epm in Cedar Cove field.

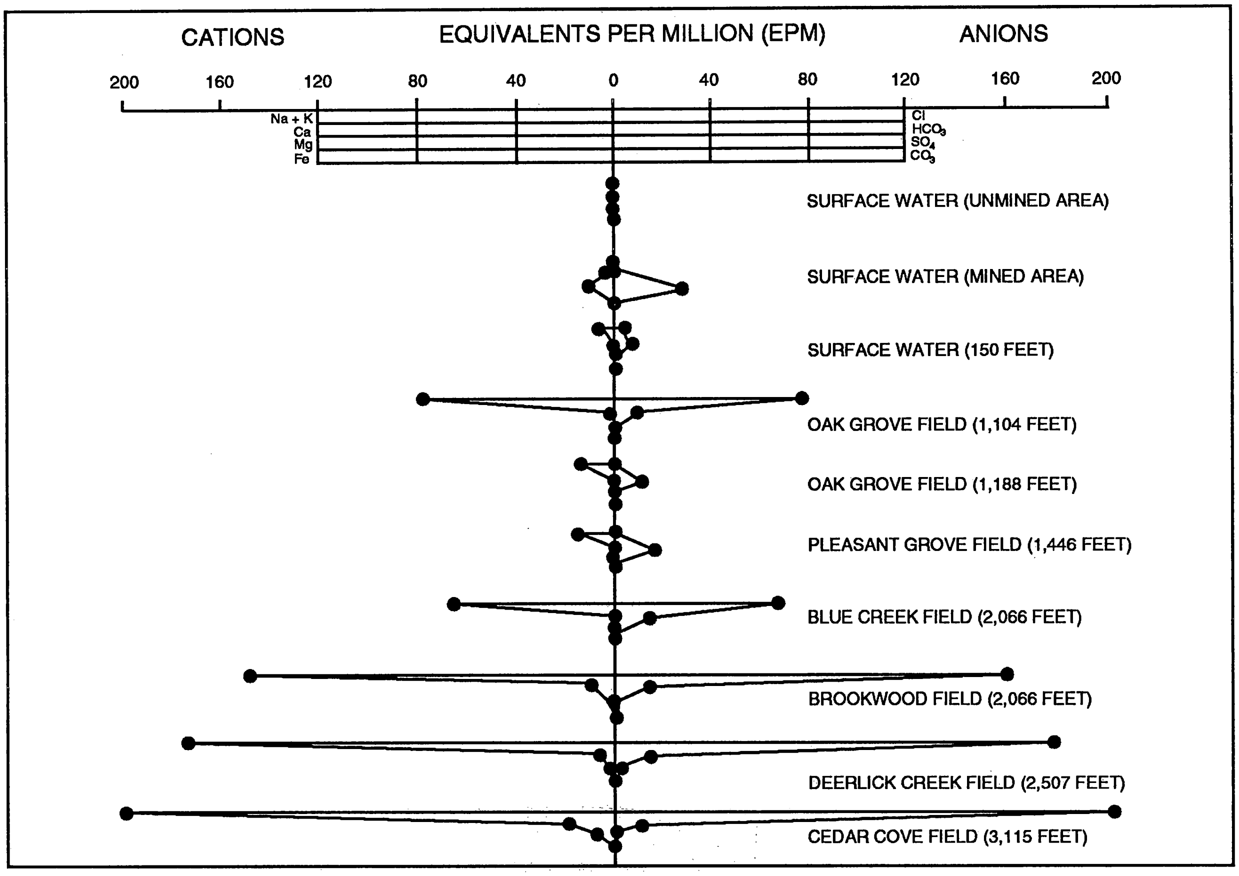


Figure 93. Stiff diagrams showing general trends in water chemistry with depth.

A map depicting the elevation of very saline water (>10,000 mg/L TDS) is based on geophysical log response and water-quality data (fig. 94). Very saline water is higher than 500 feet below msl in part of Fayette and northern Tuscaloosa Counties and is lower than 2,000 feet below msl in an arcuate belt extending from western Jefferson County to northwestern Tuscaloosa County. Along the northwest flank of the fractured Blue Creek anticline in western Jefferson and eastern Tuscaloosa Counties, very saline water is lower than 2,500 feet below msl.

Mapping TDS content in the Mary Lee coal group demonstrates that fresh water (<3,000 mg/L TDS) extends farther northwest in the area of the Blue Creek anticline than in adjacent areas (fig. 95). The 3,000 mg/L contour defines a series of northwest-trending fresh-water plumes, and in Oak Grove field, TDS content is lower than 1,000 mg/L in the largest of the plumes. Several fresh-water plumes extend northwest between faults, and although data are scarce in the southwest, the plumes appear

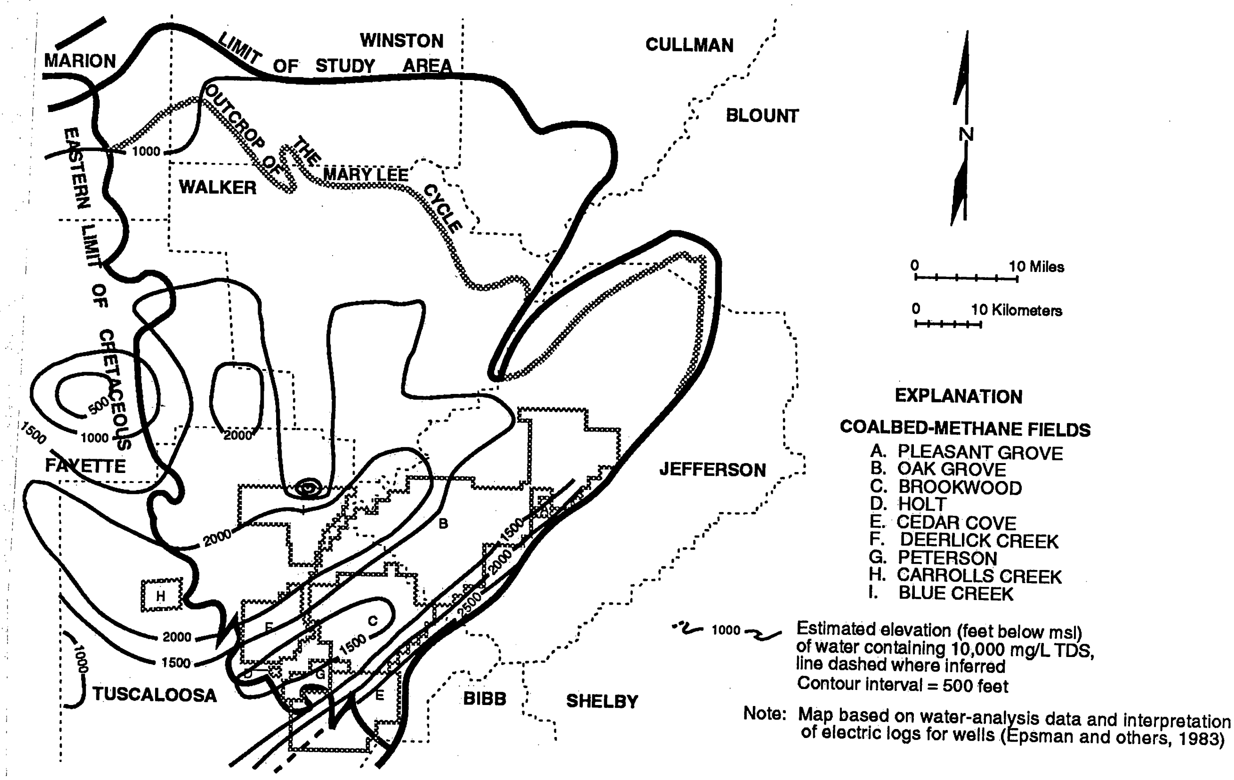


Figure 94. Elevation of very saline water (>10,000 mg/L TDS), Black Warrior basin, Alabama.

to terminate abruptly at the eastern limit of the Cretaceous cover. Northwest of the plumes, water with TDS content greater than 10,000 mg/L occurs in some faulted areas. Detailed TDS mapping of central Oak Grove field (fig. 96) shows that a spur of water with less than 1,000 mg/L TDS occurs immediately northwest of the Oak Grove mine and extends southwest from a major plume. That fresh-water spur coincides with a synclinal structure and terminates at a fault.

Fresh-water plumes coincide with only a few underground mines (fig. 95), so they apparently reflect the natural flow system rather than the effects of mine dewatering. However, mining may have had an impact in Oak Grove field, because the synclinal fresh-water spur may have formed by downward percolation of fresh water along a zone of enhanced permeability in response to lowering of the water table. Northwest extension of the plumes from the Blue Creek anticline suggests that structure has played a major role in recharge and development of head along the southeast margin of the basin. This hypothesis is supported by the abundance of fractures on the anticline, which

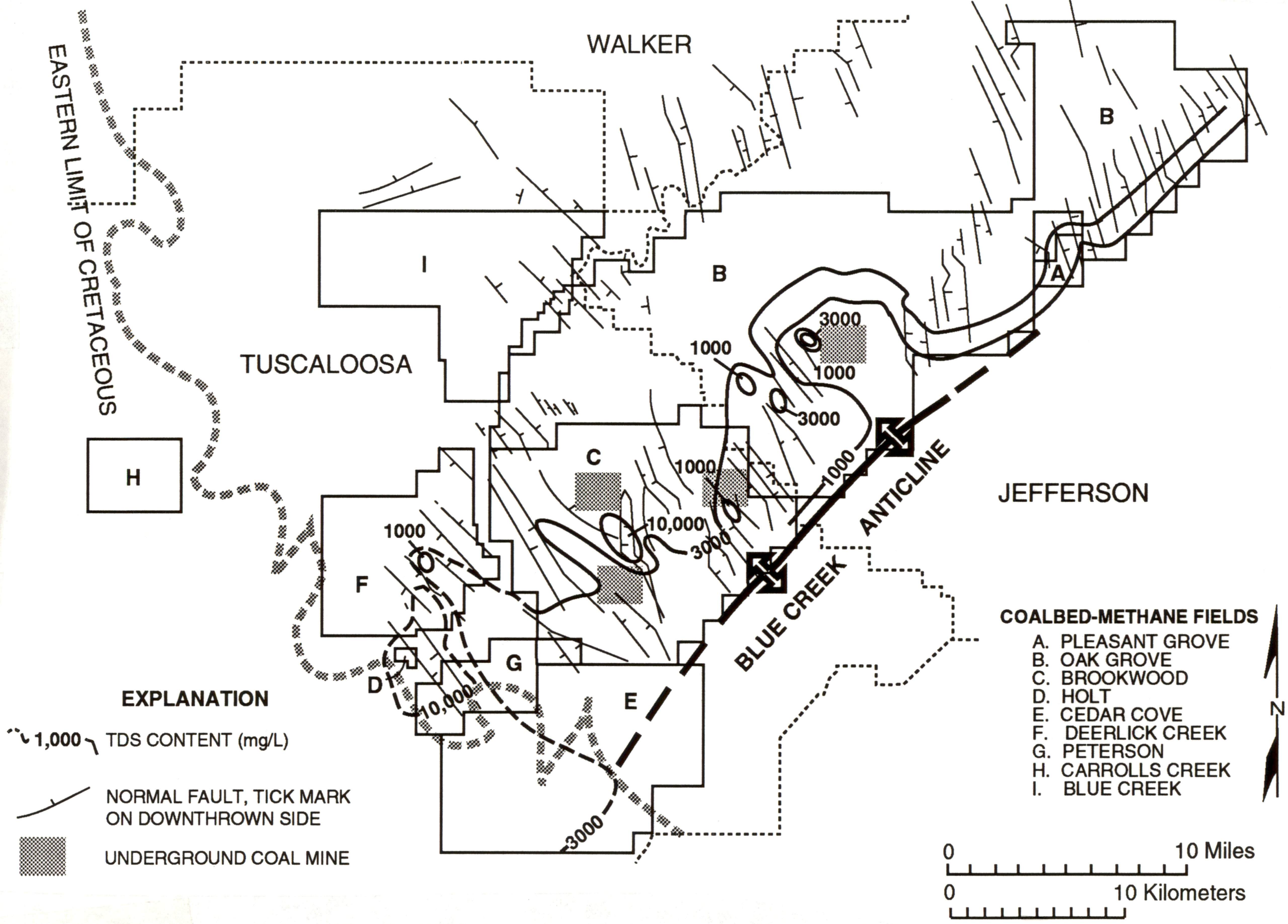


Figure 95. Relationship among water salinity, structural features, and underground mines.

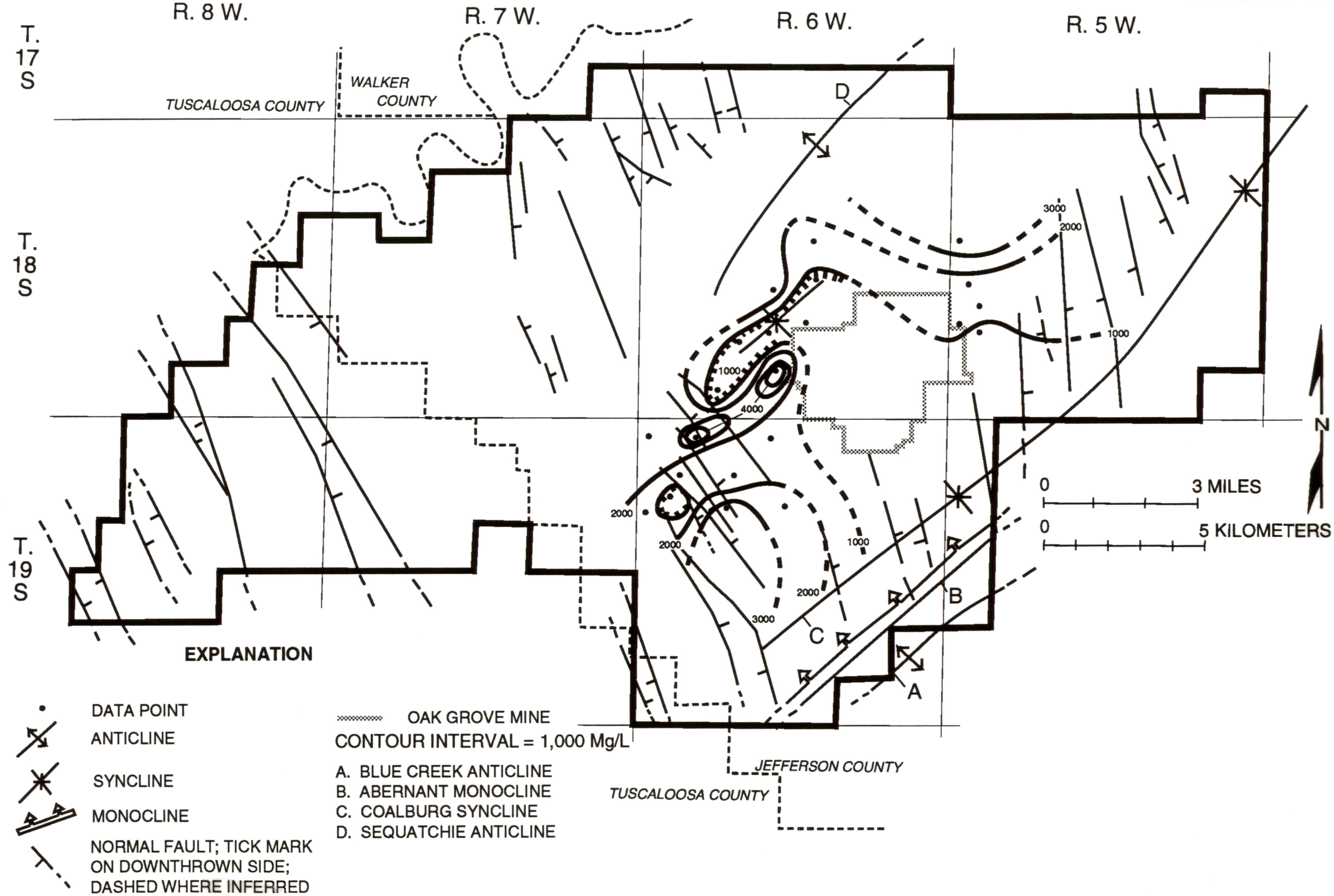


Figure 96. Relationship of water salinity to geologic structures, Oak Grove field.

include fracture cleavage in siliciclastic rocks and inclined fractures in coal, and by the deep occurrence of fresh-water adjacent to the anticline. In the interior of the basin, faults apparently act as barriers to lateral flow and help define fresh-water plumes. In effect, faults serve to compartmentalize the Pottsville hydrologic system.

Termination of the plumes at the limit of thick Cretaceous overburden (fig. 95) may reflect the increased depth of Pottsville target strata and the ability of high-permeability Cretaceous strata to intercept and transmit most of the available recharge. Data from below Cretaceous cover are few, and local hydraulic communication between Cretaceous aquifers and the Pottsville formation may reduce water salinity. However, potential for high TDS water exists in the Pottsville where Pottsville and Cretaceous aquifers are not interconnected.

WATER PRODUCTION

Water production is extremely variable in the Pottsville Formation of Alabama. Water wells are typically completed in the weathered, near-surface part of the Pottsville at an average depth of 150 feet; production ranges from 17 to 7,650 barrels per day (bpd) on the basis of a 72-well data set (Epsman and others, 1988). In contrast, coalbed-methane wells are completed in unweathered rock at a depth exceeding 1,000 feet; coalbed-methane wells produce 17 to 1,175 bpd on the basis of a 420-well data set (Pashin and others, 1990).

According to data submitted to the State Oil and Gas Board, initial and peak water production coincide mainly because of a decline in water production throughout the life of a coalbed-methane well (fig. 97). Throughout the Black Warrior basin, peak water production averages only 103 bpd in coalbed-methane wells (Pashin and others, 1990). Peak water production generally ranges from 50 to 1,000 bpd in Oak Grove field, and a map of peak water production shows a distinct relationship between production and geologic structures (fig. 98).

In the horst-and-graben system of south-central Oak Grove field, peak water-production contours trend northwest and parallel normal faults (fig. 98). Where faults are closely spaced, water production is only about 50 bpd. Where faults are approximately 1 mile apart, in contrast, water

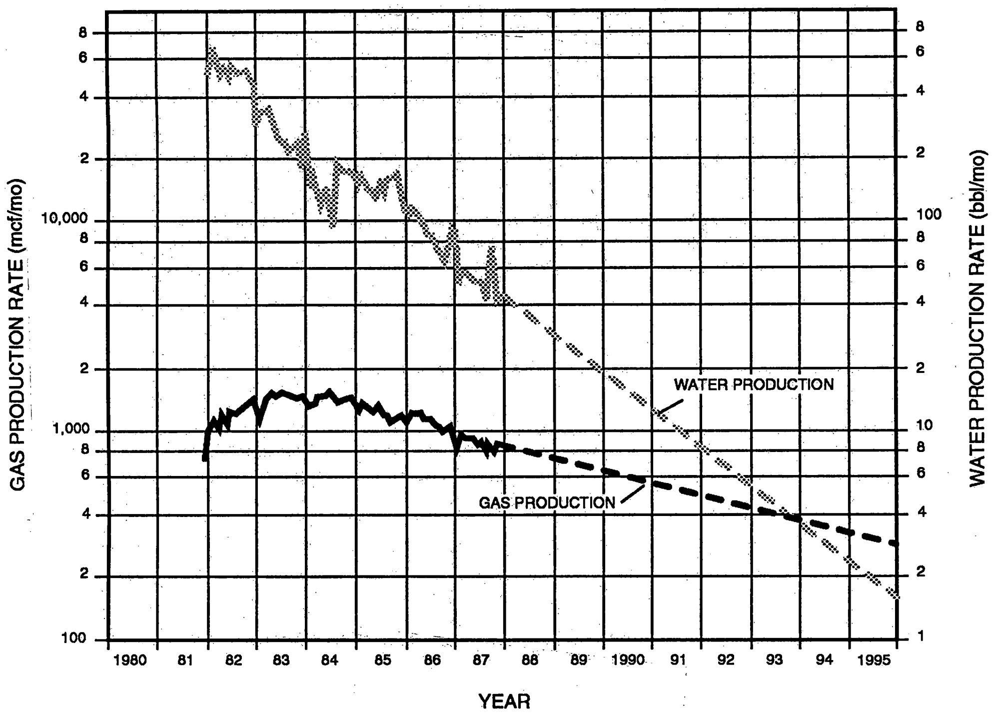


Figure 97. Production-decline curves, permit 3370, Oak Grove field.

production is as high as 1,000 bpd. Similarly, peak water production is higher than 300 bpd at many locations just outside the horst-and-graben system. North of the horst-and-graben system, water production increases toward the northwest. Near the Oak Grove mine, contours are generally aligned northeast approximately parallel to the axial trace of the Sequatchie anticline and to set II joints of joint system A (figs. 17, 98). Farther northwest, however, water-production trends are poorly defined and are difficult to relate to specific geologic structures.

The water-production map indicates that the Pottsville Formation in south-central Oak Grove field is compartmentalized by faults. In this area, close fault spacing appears to impede groundwater flow (fig. 98), suggesting that permeability is low and groundwater flow is limited in the horst-and-graben system. Perhaps limited groundwater flow owes to presence of clay-rich gouge along the fault planes. North of the horst-and-graben system, water-production values increase northwest from the Oak Grove mine, thus indicating depletion of groundwater by underground mine dewatering.

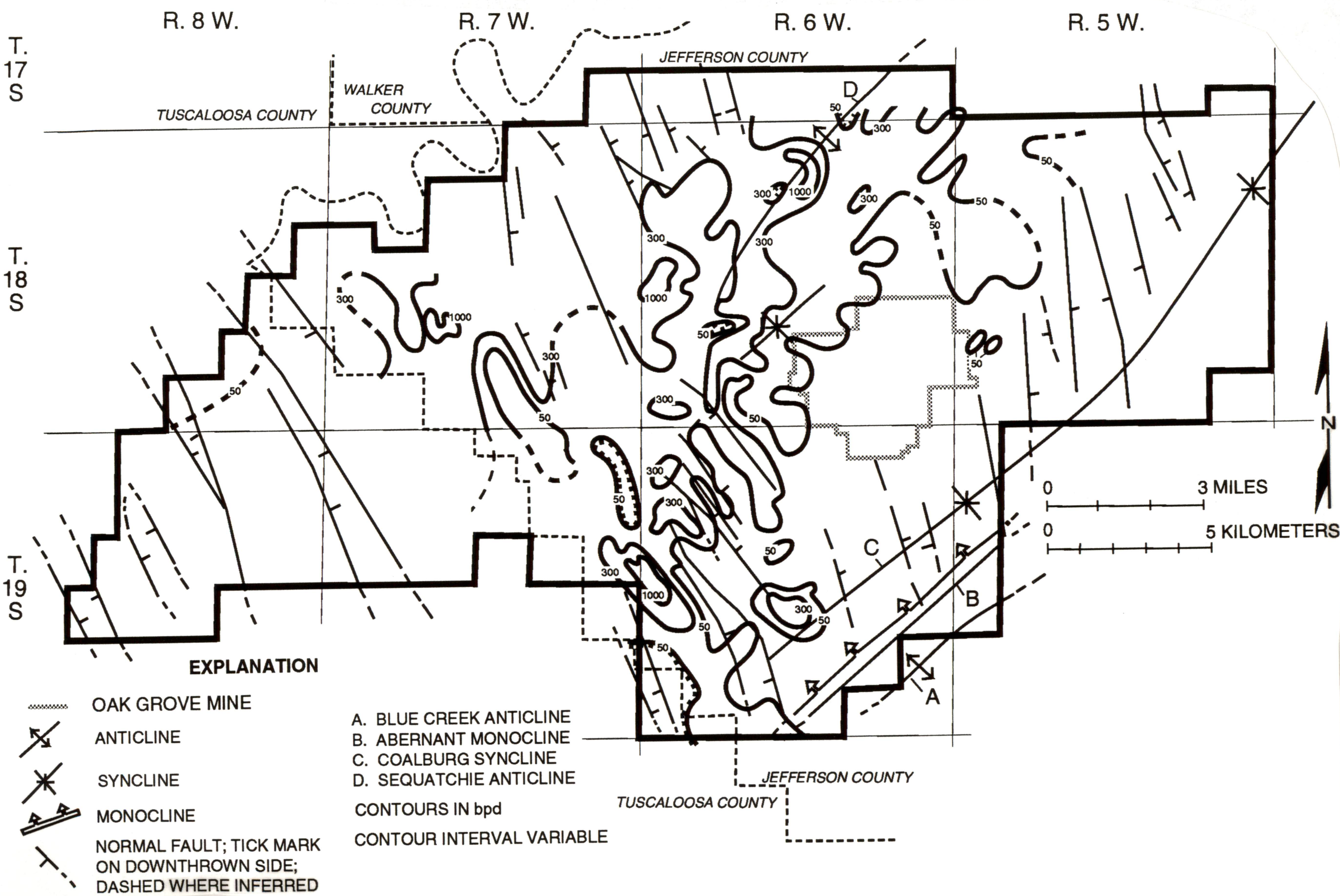


Figure 98. Peak water production and geologic structures, Oak Grove field.

HYDROLOGIC MODEL

Several factors evidently affect groundwater flow in the Black Warrior basin (fig. 99). Recharge to the hydrologic system is mainly by rainfall, but streams may also contribute (Harkins and others, 1980). In the weathered strata above the water table, flow is evidently dominated by downward percolation of meteoric water through fractures, and vadose infiltration is an increasingly important process where the water table has been lowered significantly by mine dewatering and coal degasification. Hydrochemical data indicate that intensely fractured areas, such as the northwest flank of the Blue Creek anticline, favor direct recharge into the Pottsville Formation. However, permeable Cretaceous cover strata probably intercept recharge in the western part of the study area.

Below the water table, high cleat density may accommodate bedding-parallel flow in coal and the development of fault-bounded fresh-water protrusions (fig. 95). However, regional disturbance of the hydrologic system by dewatering lowers water level and reservoir pressure, thereby providing considerable potential for downward movement of groundwater along zones of enhanced permeability like that along the syncline in Oak Grove field (figs. 96, 98). Therefore, dewatering of Pottsville strata is rapidly changing the hydrologic regime of the Black Warrior basin. Marked increase in sodium and chlorine content and occurrence of both sodium bicarbonate and sodium chloride water in Oak Grove and Pleasant Grove fields (fig. 93) suggest that a zone of mixing between surface-derived water and deep formation water exists between depths of 1,000 and 1,500 feet; this may be where water chemistry is most variable.

Permeability is probably greatest along fault segments containing fractured sandstone and may be minimal in fault segments with clay-rich gouge and poorly developed synthetic and antithetic joints. Therefore, hydrologic conditions may vary considerably along a single fault plane. Water-production and TDS data indicate that faults and other fractures compartmentalize the hydrologic system (figs. 98, 99). Areas with closely spaced faults may most commonly be a barrier to lateral flow; water production is low and faults bound fresh-water protrusions. Hence, high-TDS water may occur along some faults because they have not been flushed by meteoric water. However, drill-stem-test

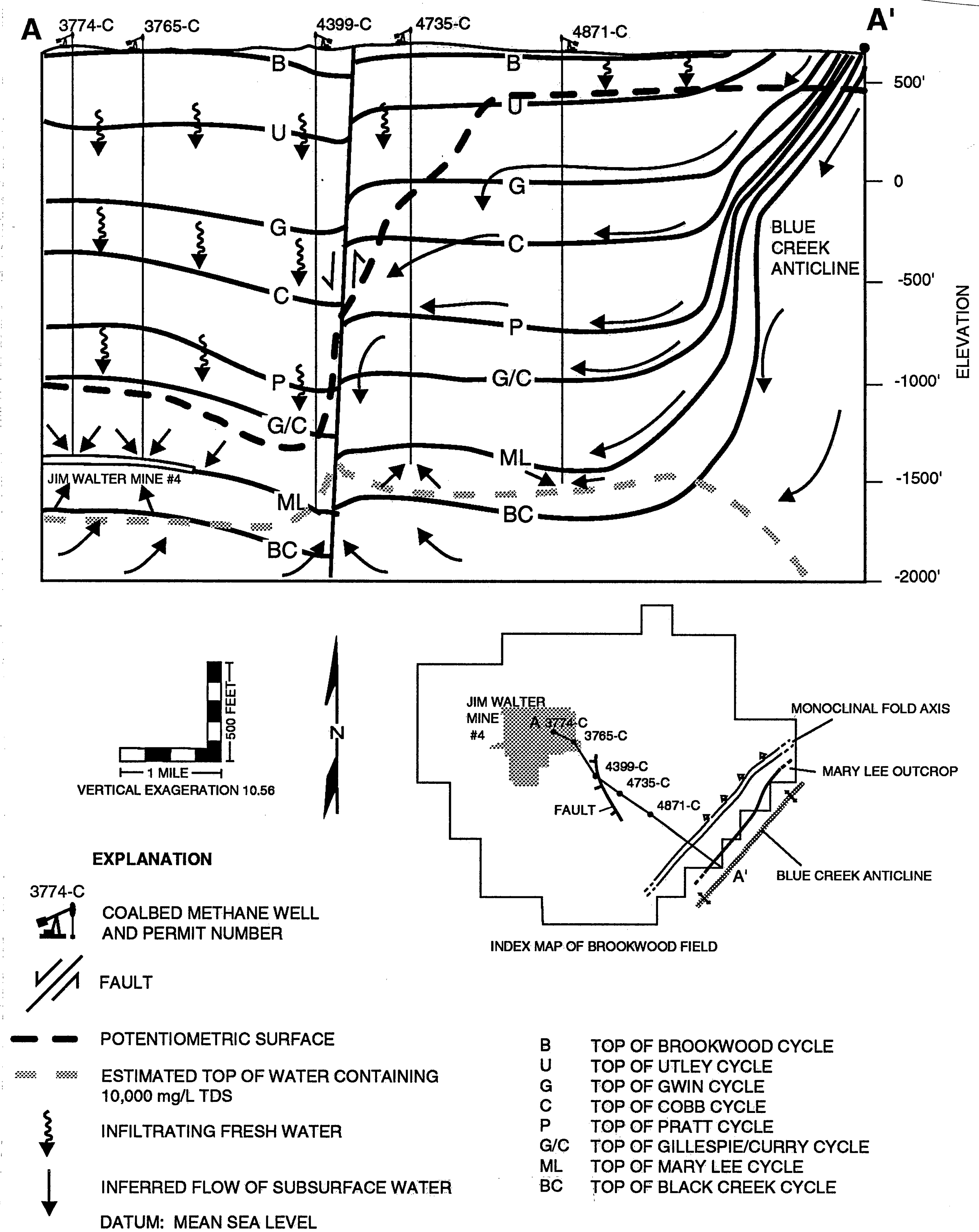


Figure 99. Idealized hydrogeologic cross section, Brookwood field.

data from Jefferson County indicate strong potential for upward flow from sub-Pottsville strata (Pashin and others, 1990), so faults may provide conduits for upward migration of deep basinal water (fig. 99). Faults also extend deeper into the subsurface and apparently have greater vertical continuity than joints and thus make the best conduits for vertical movement of such water.

WELL PRODUCTIVITY: EFFECTS OF WELL DESIGN AND GEOLOGY

INTRODUCTION

Having established a geologic framework for coalbed-methane target strata, controls on gas production can be evaluated. The objectives of this chapter are to identify the best short-term measure of long-term productivity and to determine how well design and geology affect coalbed-methane production. The chapter begins by deriving a short-term measure of productivity. Next, that measure is tested statistically against various engineering and geologic factors. The chapter concludes by comparing production with known geologic features to identify geologic controls on coalbed-methane production.

Statistical analysis indicates that peak gas production is the best available short-term measure of well productivity but yielded limited success in identifying the impact of well design and geology on coalbed-methane production. Results suggest that well-design factors, such as completion, stimulation, and well spacing are not global controls on coalbed-methane production despite changing engineering practice. Geologic factors, such as net completed coal thickness and well depth, also do not correlate well with peak has production. However, water production correlates weakly but significantly with peak gas production, reflecting the necessity of removing water from coalbed reservoirs to reduce reservoir pressure and desorb gas.

Production maps establish that wells with exceptional coalbed-methane production, or peak gas production higher than 200 Mcfd, are localized and locally occur in northeast trends. Detailed production and structure mapping indicates that exceptional gas production occurs in fractured reservoir compartments that can be dewatered effectively, thereby lowering reservoir pressure. Occurrence of minimal gas production in many wells that produce a considerable quantity of water suggests that high-permeability compartments are abundant in the Black Warrior basin, but only those compartments with limited recharge can be dewatered and depressurized effectively.

METHODS

Production and completion data through December 1988 were compiled from the files of the State Oil and Gas Board of Alabama; only vertical boreholes were evaluated in this study, and the performance of gob and horizontal boreholes was analyzed by Pashin and others (1990). Production evaluation utilized initial-production data for gas and water from Form OGB-9, First Production or Retest Report. Initial gas-production rate is generally based on a 24-hour test performed early in the life of a well. Peak gas-production rate was determined from the Board's monthly production records for each well, and the highest monthly volume of gas was divided by the number of days in that month to derive a daily rate. Average gas production was computed by dividing cumulative gas production by total production time in months; that number was divided by 30 days to derive a daily rate. Initial and peak water-production rates were derived by using the same methodology as used for gas. Completion type, such as open-hole, perforated casing, or slotted casing, was determined from Form OGB-7, Well Record and Completion or Recompletion Report. Stimulation type, such as water-sand and foam-sand-water, was determined from Form OGB-6, Report of Well Treatment.

PRODUCTIVITY

Three simple measures of coalbed-methane production are available in the State Oil and Gas Board's records: (1) initial production rate, (2) peak production rate, and (3) average production rate. Average production rate is a long-term measure of a well's ability to produce, whereas initial and peak rate occur within the first year of production of wells drilled with an 80-acre or smaller spacing. Linear regression indicates that initial and peak rate correlate positively and significantly with average rate, but the peak rate correlates much more highly (fig. 100). Most coalbed-methane wells have been on line less than 2 years, so peak rate may correlate highly with average rate partly because it accounts for a large part of total production. However, peak rate is a more reliable value than initial rate because it represents production throughout a full month rather than results of a 24-

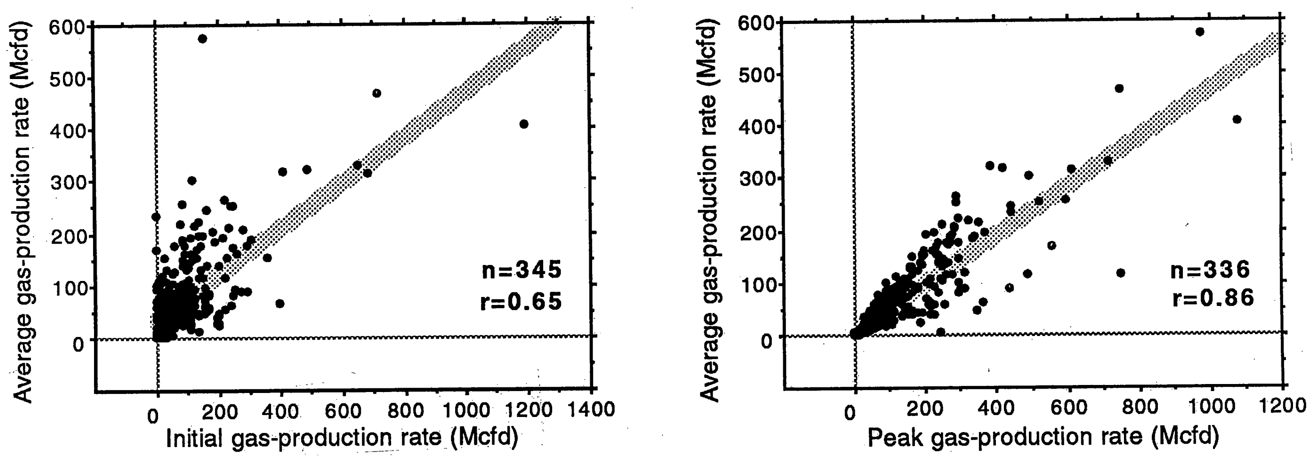


Figure 100. Relationship of initial and peak gas production to average gas production.

hour test which may be performed at different times. Thus, peak production is the best available short-term measure of long-term productivity.

Having defined a practical short-term measure of productivity, how much gas can a coalbed-methane well be expected to produce? Cumulative relative-frequency values for peak gas production indicate that 48 percent of the wells analyzed had peak production lower than 100 Mcfd (fig. 101). Only 22 percent of the wells produced more than 200 Mcfd, and only 5 percent produced more than 400 Mcfd. Observing the frequency graph, the 200 Mcfd peak rate is a logical dividing point between low- and high-productivity wells. Therefore, using the 200 Mcfd value as a guide, the effects of completion and geology were examined.

CONTROLS ON COALBED-METHANE PRODUCTION

STATISTICAL ANALYSIS

WELL DESIGN

Although improved design may increase production from individual wells, well design is not a dominant determinant of coalbed-methane production (Pashin and others, 1990). Peak production for wells on line through the end of 1988 does not correlate well with completion or stimulation

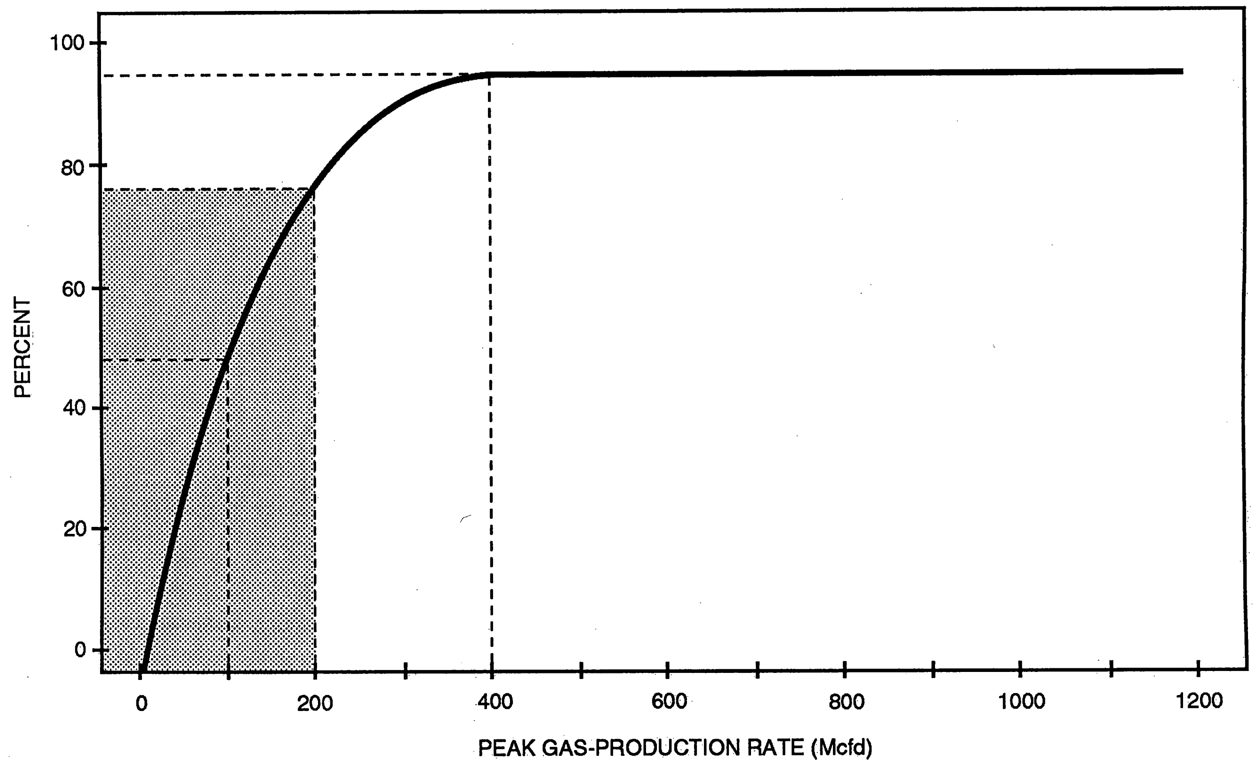


Figure 101. Cumulative relation-frequency diagram, peak gas production.

method (fig. 102), albeit only 5 percent of the wells producing more than 200 Mcfd were stimulated with foam, whereas 19 percent of the wells producing less than 200 Mcfd were stimulated by that method. Additionally, 9 percent of the wells producing more than 200 Mcfd were not stimulated, whereas only 3 percent producing less than 200 Mcfd were not stimulated. No significant correlation was found between peak production and well spacing, although spacing has increased through time from 25 to 80 acres.

Plotting peak production rate against permit numbers is one way to determine if production has changed over time. Results indicate that, despite production experience and changing completion practice, no correlation exists between permit number and peak gas production (fig. 103). Cross-linked gel and sand, however, is now employed more than any other stimulation method. Operators began using cross-linked gel in 1988, so few of those wells are included in our production analysis. Advantages of the cross-linked gel and sand method are long fracture length and full withdrawal of

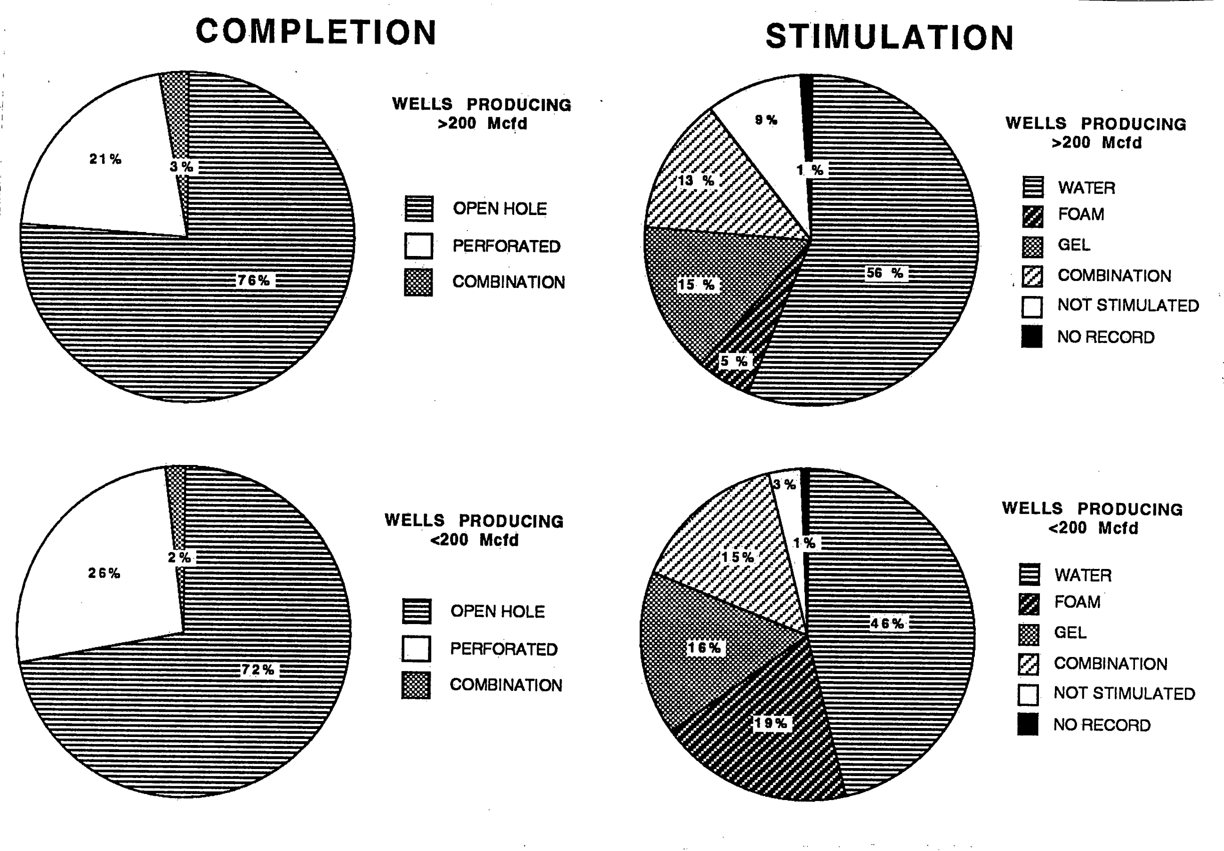


Figure 102. Comparison of completion and stimulation methods used in wells with peak production greater and less than 200 Mcfd.

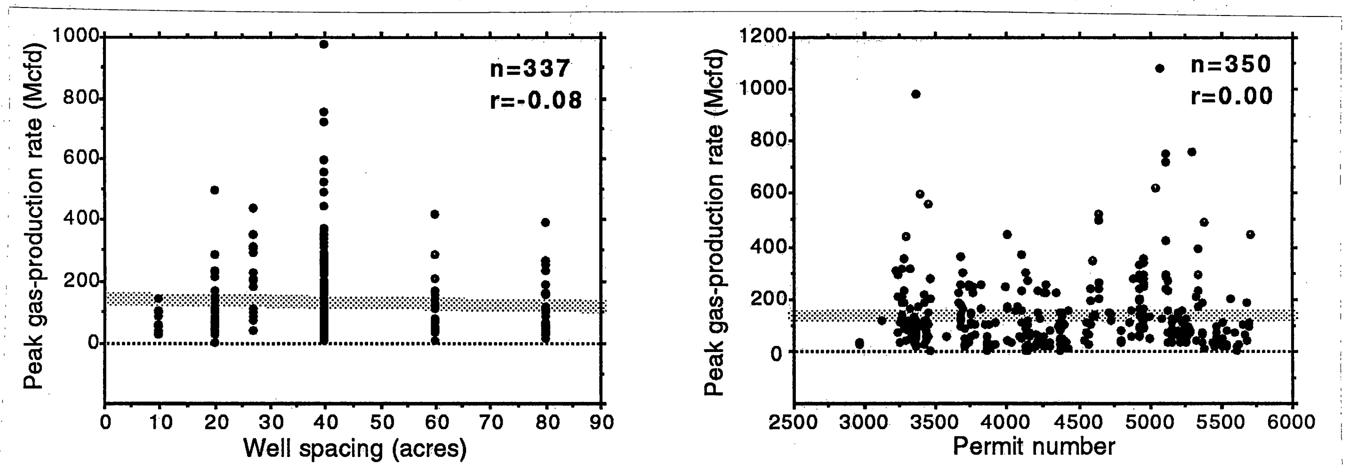


Figure 103. Relationship of well spacing and permit number to peak gas production.

stimulation fluid. Investigators at the Rock Creek site report increased methane production in wells stimulated with cross-linked gel (Steve Spafford, personal communication, 1990).

Several factors may account for the poor performance of wells completed with foam (fig. 102). Most foam wells are in the original Oak Grove pattern, so low production may be attributed partly to unrefined engineering strategies. However, wells in the Oak Grove pattern are the most closely spaced coalbed-methane wells in the Black Warrior basin (<25 acres), so poor performance may reflect competition among closely spaced wells for a limited methane resource.

The surprisingly high performance of unstimulated wells in Brookwood field (fig. 102) can be related to dewatering of a fracture system in response to mine advance. The most notable unstimulated well is the "glory hole", which is the only coalbed-methane well in Alabama that has peaked higher than 1,000 Mcfd. The "glory hole", like the other unstimulated wells, was drilled west of the advancing face of the Jim Walter Resources no. 4 Mine (fig. 1). Production increased rapidly for a time and then decreased as the mine face approached the well; a similar response to mine advance has been noted in Oak Grove field (Briscoe and others, 1988; Oyler, 1989). The mine face eventually passed beyond the well, and investigators observed that the well had penetrated open fractures that are oriented N 82° E and are as much as 0.5 inch wide.

GEOLOGY

As with well design, identifying correlations between geologic factors and coalbed-methane production is difficult. Surprisingly, statistical analysis indicates that net completed coal thickness does not correlate significantly with coalbed-methane production (fig. 104). Although coal thickness is not a dominant control on production, it is an important control on resource distribution and reservoir architecture. Therefore, coal occurrence is a critical production parameter from the standpoint of locating a gas resource that may be developed and for identifying specific completion targets.

One necessary shortcoming of this study is that geologic controls on gas content in coal have not been identified, particularly with respect to basin architecture and hydrology, because most gas-

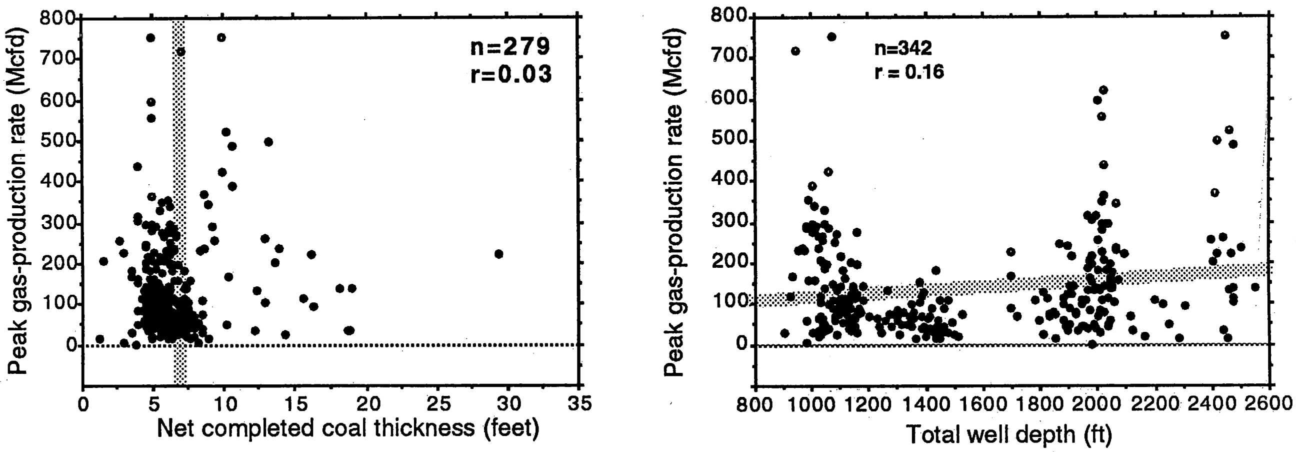


Figure 104. Relationship of net completed coal thickness and total well depth to peak gas production.

content data are proprietary. As data become available, regional and local mapping of gas content will be helpful in developing exploration and production strategies. Is gas content similar to coal thickness in that it is a prerequisite for rather than a control on coalbed-methane production?

An optimal depth for coalbed-methane production has been suggested to be 1,530 feet on the basis of permeability-depth functions (McKee and others, 1986). However, production data demonstrate that well depth and peak coalbed-methane production do not correlate significantly (fig. 104). This lack of correlation probably owes to a variety of geologic factors, particularly vertical variations of gas content, fracture architecture, and reservoir pressure.

Of the geologic parameters analyzed statistically, only initial and peak water production correlate significantly with peak gas production (fig. 105). However, the weakness of that correlation indicates that high water production, and hence permeability, does not guarantee reduction of reservoir pressure sufficiently for a large volume of methane to desorb. For this reason, water production is a poor predictor of well performance. Wells that produce a large volume of water but little gas have probably tapped hydrologic systems that are well interconnected and recharge rapidly. Comparing water-level and water-production data can determine whether reservoir pressure is being reduced sufficiently to promote methane desorption.

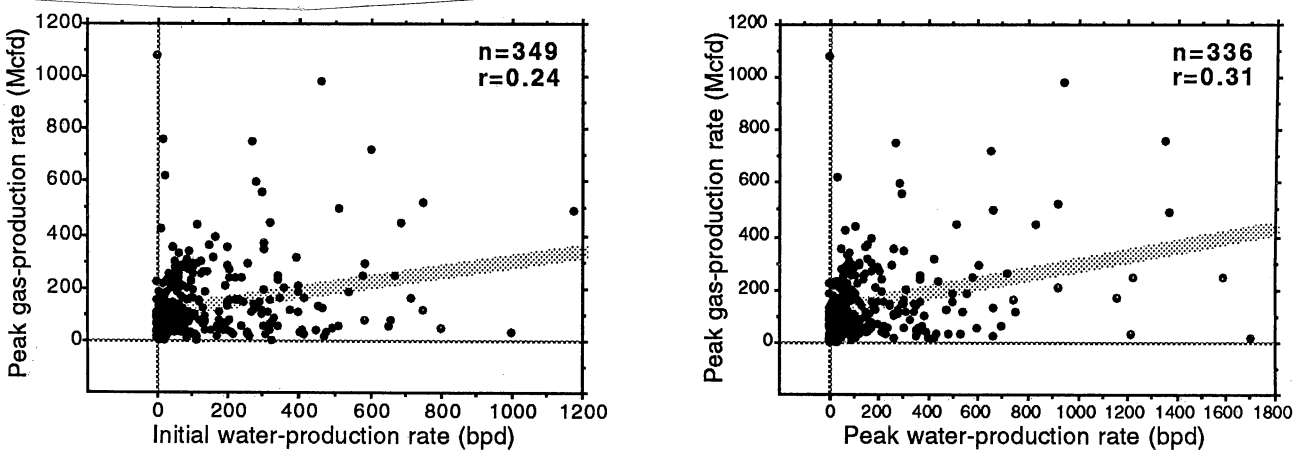


Figure 105. Relationship of initial and peak water production to peak gas production.

MAP ANALYSIS

Although statistical analysis yielded only limited success in identifying controls on coalbed-methane production, mapping production and comparing it with known geologic features produced conclusive results. A generalized map of coalbed-methane production in the coalbed-methane fields establishes that wells with exceptional coalbed-methane production, or peak gas production higher than 200 Mcfd, are localized (fig. 106). In several fields, such as Oak Grove, Brookwood, Deerlick Creek, and Cedar Cove, those wells are clustered together, and many of those wells occur along northeast trends.

Association between exceptional coalbed-methane production and northeast-trending topographic lineaments has been emphasized in previous studies (Epsman and others, 1988; Pashin and others, 1990). However, the coalbed-methane fields contain myriad northeast lineaments, and only a few of those lineaments are associated with highly productive wells. Therefore, lineament studies may be of limited use in strategic well siting, although advanced digital analysis of remotely sensed imagery may prove useful for identifying prospective lineament trends.

Northeast trends of exceptional coalbed-methane production are exemplified by the trend adjacent to the Oak Grove mine in Oak Grove field where wells drilled with a 40-acre spacing

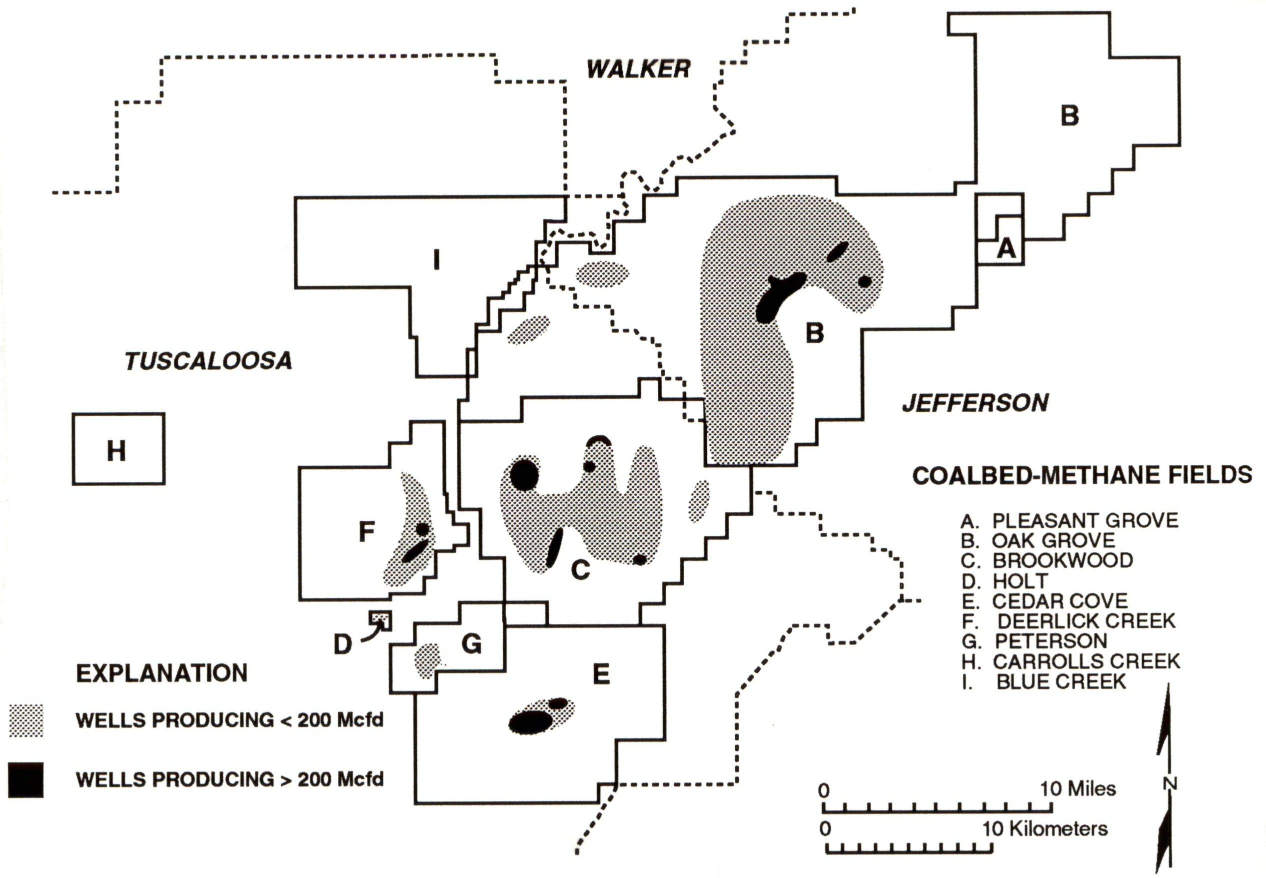


Figure 106. Coalbed-methane production trends, Black Warrior basin.

facilitate detailed mapping (fig. 107). In this area, peak production exceeds 300 Mcfd in a linear, northeast trend that coincides with a lineament that is visible on SLAR imagery. That lineament corresponds with a syncline and a fresh-water salinity anomaly (fig. 96) and is thus a zone of high permeability. Field check of that lineament revealed that beds dip as steeply as 18° near the synclinal axis.

A paramount concern in coalbed-methane production is reducing reservoir pressure sufficiently that an economic quantity of methane may be desorbed from coal. For example, all coalbed-methane wells in the Black Warrior basin with peak production higher than 200 Mcfd occur where pressure-depth quotient is less than 0.32 psi/ft (figs. 91, 106). Association of the Oak Grove productive trend (fig. 107) with a syncline and salinity anomaly indicates that the trend occurs in a fractured reservoir compartment that can be dewatered effectively, thereby lowering reservoir pressure.

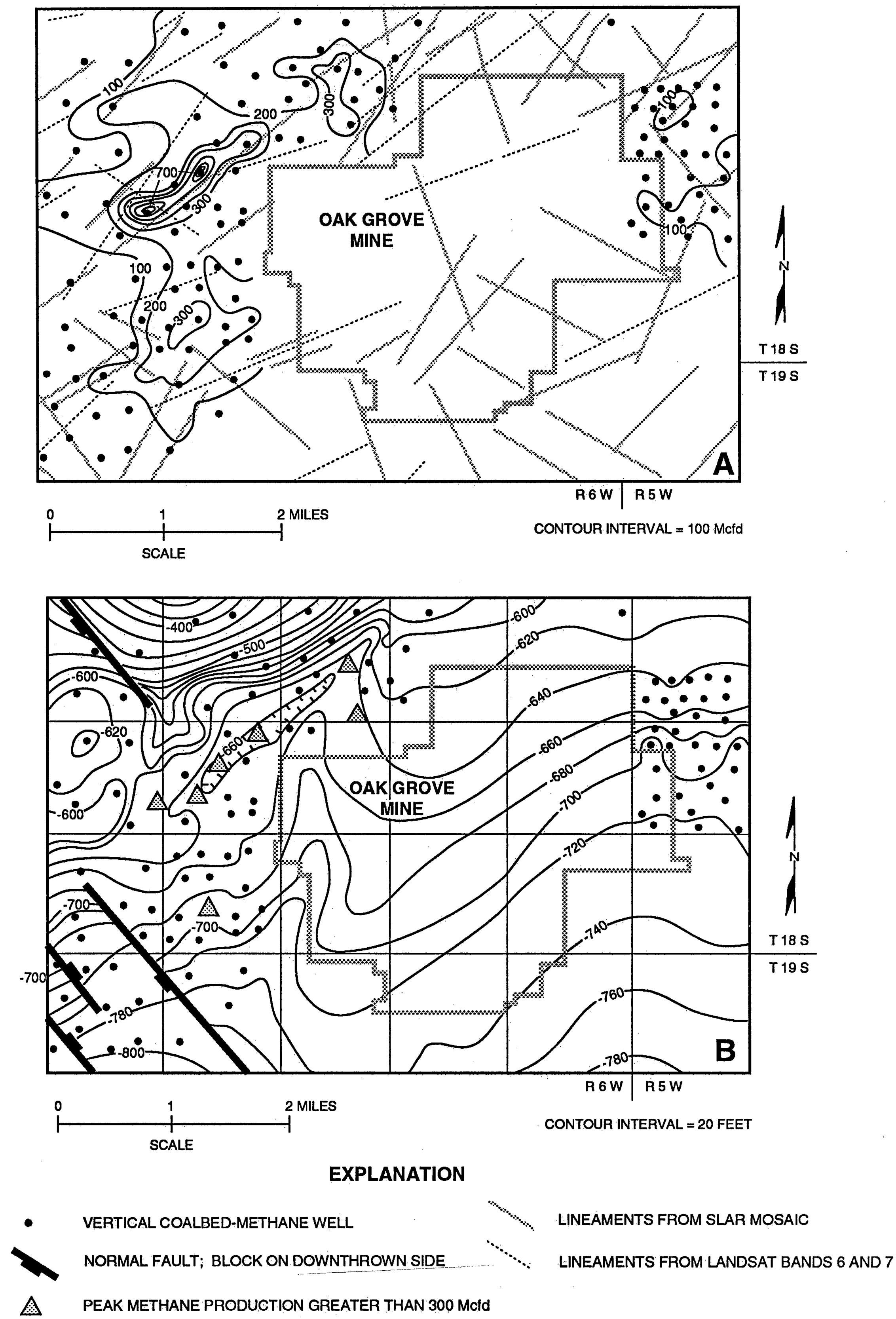


Figure 107. Peak gas production and geologic structures, central Oak Grove field. A = relationship of production to lineaments, B = occurrence of exceptionally productive wells along synclinal structure.

If exceptionally productive trends are associated with northeast-trending fracture compartments, why are the abundant northwest-trending fracture systems, such as fault systems in south-central Oak Grove field, less productive? Many faults contain clay-rich gouge that may reduce permeability, and faults may compartmentalize coal beds and thus limit the areal extent of coalbed-methane reservoirs. The modern east-northeast compressive stress field (Engelder, 1982; Park and others, 1984) may have also given rise to regional permeability anisotropy by closing fractures oriented perpendicular to the compressive-stress vector (north-northwest), like normal faults, and opening fractures oriented parallel to the stress vector (east-northeast), like the regional face cleat (cleat system A).

Peak water production of more than 1,000 bpd in several parts of Oak Grove field indicates that considerable permeability can exist where little gas is produced (figs. 98, 106). Hence, some strata with high permeability cannot effectively be depressurized owing to rapid recharge. Highly productive coalbed-methane wells in the Black Warrior basin, like those in Oak Grove field (fig. 107) apparently tap fractured reservoir compartments that have limited hydrologic communication with adjacent areas. Apparently, only in coalbed-methane reservoirs with limited recharge can efficient dewatering and lowering of reservoir pressure be achieved.

REGIONAL COALBED-METHANE POTENTIAL

Having identified geologic controls on the occurrence and producibility of coalbed methane, the regional coalbed-methane potential of the Black Warrior basin in Alabama can be characterized. A trend-analysis map was formulated using critical geologic production parameters that are mappable at basin scale (fig. 108). Criteria used to characterize coalbed-methane potential include depth of the Mary Lee coal group, coal abundance, coal rank, ash content, and salinity of formation water.

Depth to the Mary Lee cycle was approximated by using elevation contours from the regional structure map (figs. 8, 108). Depth, and thus formation pressure, increases toward the southwest, so gas-retention capacity may increase in that direction. In the northernmost part of the study area, the Mary Lee cycle is above sea level (shallower than 500 feet), and target coal groups crop out. However, the Black Creek group may have sufficient depth to retain an economic methane resource in part of

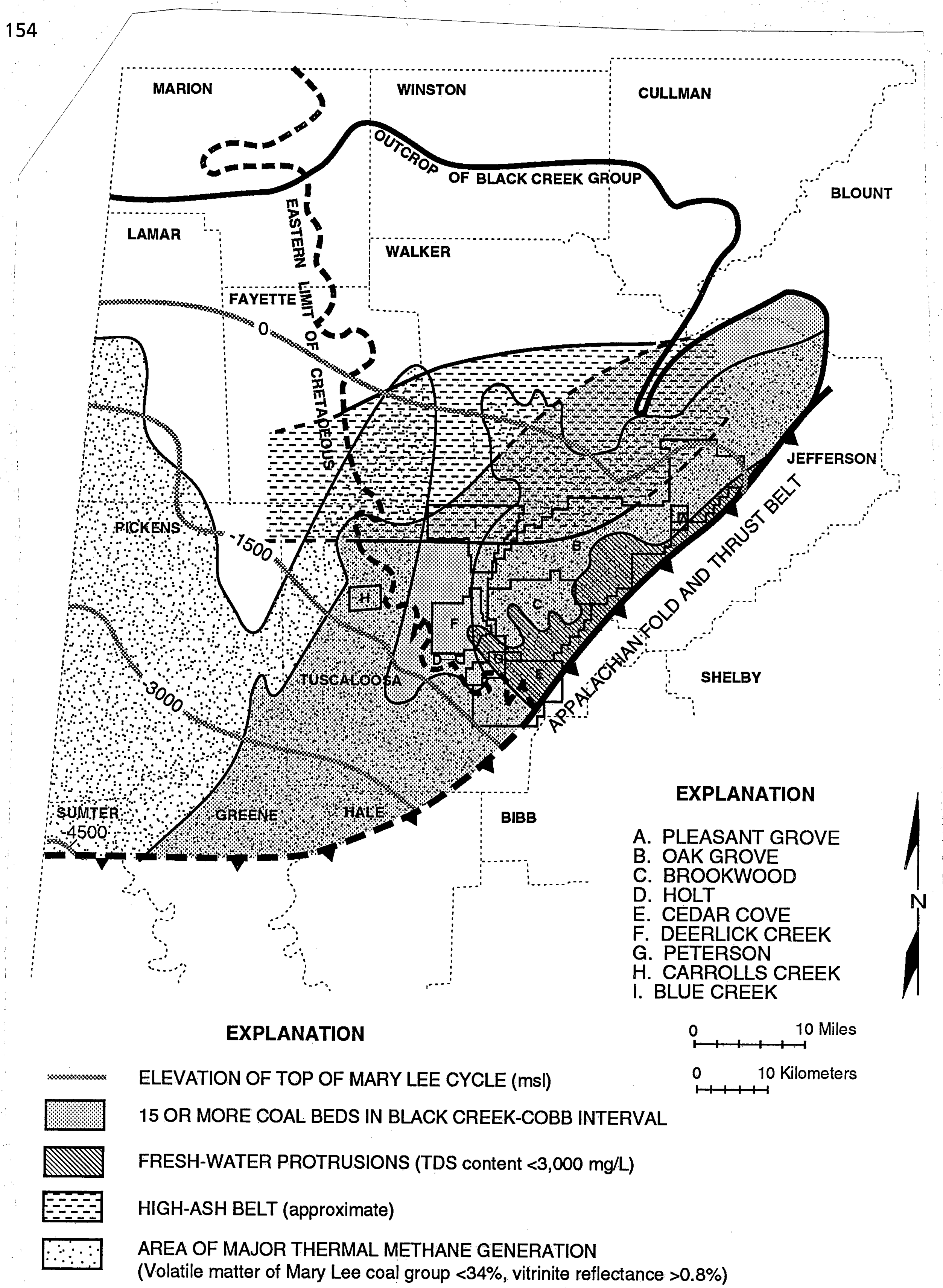


Figure 108. Geologic trend-analysis map of coalbed-methane potential, Black Warrior basin, Alabama.

this area, and lower Pottsville coal, which was not evaluated in this investigation, may also be a viable drilling target. To date, nearly all coalbed-methane production is between 500 and 3,500 feet below the surface. Southwest of the -3,000-foot contour, production potential is unknown, but permeability may be low because of high confining pressure (lithostatic and hydrostatic) and scarcity of unloading fractures (set II joints).

Coal beds are most abundant in the southeastern part of the Black Warrior basin, where fifteen or more coal beds occur in the Black Creek-Cobb interval, indicating a significant coalbed-methane resource (figs. 42, 108). Thus far, all coalbed-methane fields are in that area, and application of sedimentologic models of coal occurrence may improve exploitation of proven coalbed-methane resources. Production potential also exists where fewer than 15 coal beds are in the Black Creek-Cobb interval. The Pratt and Black Creek cycles contain more coal beds in a larger area than the other cycles and are thus the most attractive completion targets in the west; coal beds in the Pratt cycle are closely spaced and may thus warrant detailed investigation. However, thickness and gas-content data for coal in the western part of the study area are lacking.

The 34-percent volatile-matter contour in the Mary Lee coal group indicates areas where a significant methane resource has been generated thermally (figs. 76, 108). Where volatile matter data are not available, the 0.8-percent vitrinite-reflectance contour was plotted (figs. 79, 108). Methane has been generated thermally in the southern part of the study area, and areas with sufficient coal rank that lack coalbed-methane wells occur in southern Walker County and the western part of the study area. The coalbed-methane potential of the northern and central parts of the study area is questionable, because thermogenic methane resources may be limited, and in some places, only biogenic and migrated methane may be present. These areas include the western parts of Blue Creek and Deerlick Creek fields.

Thermal and burial history may be of concern in developing areas with thick Cretaceous cover (fig. 108), because Pottsville coal may be undersaturated with gas. The rank discontinuity between bituminous Pottsville strata and lignitic Mesozoic and Cenozoic strata indicates that coalification, and hence thermal gas generation, preceded formation of the Pennsylvanian-Cretaceous unconformity.

Therefore, Pottsville coal may have degassed to maintain equilibrium with decreasing lithostatic pressure during post-Pennsylvanian unroofing of the Black Warrior basin. Subsequent reburial of Pottsville strata below Mesozoic and younger sediment evidently raised lithostatic pressure without generating new gas, thereby increasing potential for undersaturated coal.

Another factor in the regional trend analysis is ash content of coal which may be inversely related to methane content. A generalized belt that extends from southeastern Fayette and northern Tuscaloosa Counties to western Jefferson County depicts areas with high ash content (fig. 108). Coal-quality data suggest that the high-ash belt extends westward at least a short distance below Cretaceous cover. Additionally, ash content and distribution vary considerably in each coal group, so ash maps (figs. 80-87) should be used to evaluate the production potential of individual coal groups and coal beds.

To identify permeability trends and characterize the quality of produced water, the area with low water salinity (<3,000 mg/L TDS) was included in the trend-analysis map (figs. 95, 108). Note that fresh-water protrusions in the Mary Lee group are restricted to a small part of the southeast basin margin. Water with less than 3,000 mg/L TDS also occurs in the Black Creek-Cobb interval along the northern margin of the Pottsville outcrop area (Pashin and others, 1990). Below Cretaceous cover in the western part of the study area, TDS content of production water is inferred to exceed 10,000 mg/L, so disposal of saline water probably will be a primary concern if major westward expansion takes place. Even so, low-salinity water may exist where the Pottsville Formation is in hydrologic communication with Cretaceous aquifers, but reservoirs in which such communication occurs may be difficult to dewater.

Results of regional trend analysis indicate that all parts of the study area have some coalbed-methane potential (fig. 108), but that potential is variable, and proven trends of exceptional productivity are localized (fig. 106). As has long been known, the Oak Grove-Brookwood area is favorable for coalbed-methane development, because coal occurs at considerable depth, is thick and abundant, has the highest rank in the basin, contains little ash, and contains fresh water. Potential decreases in all directions from the Oak Grove-Brookwood area and is perhaps lowest in the northern part of the study area where coal in the Black Creek-Cobb interval is shallow or crops out, is of limited abundance, has variable ash content and is thermally immature. However, rank and perhaps gas content increase with depth, so deep coal resources may have economic potential.

A large part of the study area has significant coalbed-methane potential but has yet to be drilled. This area includes southern Tuscaloosa, northern Hale, northeastern Greene, Pickens, southwestern Lamar, and northern Sumter Counties (fig. 108), where coal is of sufficient rank to have generated methane thermally. More than 15 coal beds occur in southern Tuscaloosa, northern Hale, and northeastern Greene Counties, but coal abundance is least in the western part of the study area. Perhaps the biggest problems in westward expansion of coalbed-methane development are potential for high-TDS water (>10,000 mg/L) and reduced permeability owing to the increased depth to coalbed-methane target strata. Even so, gas-content data from southern Tuscaloosa County (Levine and others, 1989) suggest that significant economic potential exists in undrilled areas.

SUMMARY AND CONCLUSIONS

Understanding geologic controls on the occurrence and producibility of coalbed methane is essential for developing exploration and production strategies that will help ensure a long-term, low-cost supply of domestic natural gas. Characterizing those controls was the objective of this study which focused on the Black Creek-Cobb interval of the upper Pottsville Formation in the Black Warrior basin of Alabama. This study was designed to establish ways in which structure, sedimentology, coal quality, and hydrology are critical production parameters for coalbed-methane resources in the Black Warrior basin.

Geologic structure was a unifying concept in this study because it affected sedimentation, coalification, hydrogeology, and the ultimate occurrence and producibility of coalbed methane. Understanding structure is crucial in exploration and production planning because it controls the attitude, depth, and fracture architecture of target coal-bearing strata. Strata in the Black Warrior basin generally dip southwest, are broken by numerous folds, thrust faults, normal faults, joints, and cleats that define avenues of permeability and reflect a complex tectonic history. Tectonism resulted in diverse structural patterns that affect fluid flow, and hence, the occurrence and producibility of coalbed methane.

Cyclic Black Creek-Cobb sedimentation reflected the evolving structural framework of the Black Warrior basin. Despite that evolving framework, regional sedimentologic basin analysis showed that coal beds in each depositional cycle are most abundant in southern Tuscaloosa and western Jefferson Counties because proximity to a sediment source and protection from marine water provided fluvial-deltaic platforms amenable to peat (coal) accumulation. Outcrop analysis of the Mary Lee coal group indicated that fluvial processes are major controls on coal-body thickness and geometry and was used to formulate detailed models of coal occurrence that can be applied in subsurface studies. Crevasse-splays formed along the flanks of fluvial axes and thus controlled coal occurrence locally. In contrast, channel avulsion involved abandonment and establishment of new fluvial axes and was thus a regional control on coal occurrence.

Subsurface investigation of coal occurrence in Oak Grove field identified varied and contrasting styles of coal occurrence and resulted in predictive models of coal occurrence that are advantageous for resource assessment, strategic well siting, and identifying completion targets. Fluvial processes were the major controls on coal occurrence in the Black Creek cycle, whereas fluvial and structural processes acted in concert to control coal occurrence in the other cycles. Thick coal beds in the Pratt and Cobb cycles occur on the downthrown side of a major fault, because differential subsidence promoted peat accumulation in the absence of detrital influx. In the Mary Lee cycle, however, channel incision provided sufficient topographic relief for thick peat to accumulate in a paleovalley system on the upthrown block. In the eastern part of the field, gentle downwarping promoted splitting of beds and preservation of some of the thickest coal bodies in the Black Creek-Cobb interval.

As sedimentation and tectonic subsidence continued, Pottsville peat was coalified, and gas was generated. Comparing rank and structural data suggests that regional burial coalification was overprinted hydrothermally in Oak Grove and Brookwood fields, thereby forming the highest rank coal in the basin. Ash and sulfur content tend to be lowest in the easternmost part of the Pottsville outcrop area on the major fluvial-deltaic platforms where thick peat accumulated. Coal is apparently the principal source of coalbed methane in the Pottsville, and the gas may have locally undergone thermal cracking and bacterial alteration. Coalbed methane evidently includes comingled biogenic and thermogenic gas, and some coalbed gas may have migrated into coal from deep sources.

Tectonism, sedimentation, and coalification all acted in concert to form the hydrogeologic framework that controls coalbed-methane production. Close cleat spacing makes coal beds the principal aquifers in the coalbed-methane fields, and most other groundwater flow is through secondary conduits, particularly joints. Underground mining and coalbed-methane production have lowered the water table and have reduced reservoir pressure significantly in many areas. Recharge along the southeast basin margin has formed structurally controlled fresh-water plumes that minimize water-disposal problems. However, Cretaceous aquifers intercept and transmit recharge in the western part of the basin and may thus increase water-disposal concerns in that area. Water production from the Black Creek-Cobb interval is variable, and water-production data suggest that many coalbed-methane reservoirs are structurally compartmentalized.

Statistical analysis yielded limited success in identifying the impact of well design and geology on coalbed-methane production. Despite changing engineering practice, well-design factors, such as completion, stimulation, and well spacing, do not correlate significantly coalbed-methane production. Geologic factors, such as net completed coal thickness and well depth, also do not correlate significantly with peak gas production. Water production correlates weakly with gas production, reflecting the necessity of removing water from coalbed reservoirs to reduce reservoir pressure and thus desorb methane from coal. Minimal gas production in many wells that produce water abundantly, however, suggests that permeable reservoirs are abundant in the Black Creek-Cobb interval, but only those reservoirs with limited recharge can be dewatered and thus depressurized effectively.

Production maps demonstrate that wells with exceptional coalbed-methane production, or peak gas production higher than 200 Mcfd, are localized, and water-level data indicate all of those wells occur where reservoir pressure has been lowered significantly. Exceptionally productive wells are commonly grouped in northeast trends, and detailed production and structure mapping in Oak Grove field showed that one of those trends occurs near an underground coal mine along a synclinal structure and an associated fresh-water salinity anomaly. These results suggest that exceptional gas production occurs in permeable, fractured reservoir compartments that can be dewatered effectively, thereby lowering reservoir pressure.

Perhaps the most important remaining avenue of research is to develop a strategic well-siting and well-design plan. For example, wells drilled in permeable fracture systems may not need to be stimulated, whereas wells between those systems may require advanced fracture treatments that can duplicate ideal geologic conditions. This study succeeded in identifying geologic controls on coalbed-methane production in trends of exceptional productivity, but much research remains to be performed regarding the controls on gas production between those trends. A well-spacing and well-design strategy needs to be developed for areas between exceptional production trends that will capitalize on regional permeability anisotropy and reservoir compartmentalization, thereby optimizing reservoir drainage.

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