# GEOLOGIC EVALUATION OF CRITICAL PRODUCTION PARAMETERS FOR COALBED METHANE RESOURCES

## PART II, BLACK WARRIOR BASIN

ANNUAL REPORT
(August 1988 - July 1989)

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Geologic evaluation of critical production parameters for coalbed-methane resources in the Black Warrior basin of Alabama employed an interdisciplinary approach that utilized structural, coal-quality, sedimentologic, hydrologic, and engineering data. Results indicate that geologic factors are a major control on the producibility of coalbed methane and that completion techniques may be used to increase recovery if tailored to specific geologic settings. Sedimentologic and coal-quality parameters may be used to locate regions for coalbed-methane development by characterizing the occurrence, rank, and grade of coal resources. However, high-productivity trends within those regions are localized, and geologic data suggest that productivity trends may be predictable. Several highly productive trends occur along northeast-oriented lineaments. These lineaments are the inferred surface expression of zones of enhanced permeability which are related to fractures. Productive trends also are associated with areas of low reservoir pressure, and salinity maps indicate that fresh water has migrated toward areas with low reservoir pressure. The available data indicate that structure and hydrology are critical production parameters that may be used to identify favorable well sites within regions containing significant coalbed-methane resources.

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| Title | Geologic Evaluation of Critical Production Parameters for Coalbed Methane Resources; Part II, Black Warrior basin. |
| Contractor | Bureau of Economic Geology, The University of Texas at Austin. GRI Contract No. 5087-214-1544. |
| Principal Investigator | W. B. Ayers, Jr.; Project Manager, Geological Survey of Alabama, R. M. Mink. |
| Report Period | August 1, 1988 - July 31, 1989 |
| Objective | To develop a data base and understanding of structure, coal quality, sedimentology, hydrology, and well productivity in order to determine the critical controls on the occurrence and producibility of coalbed methane in Alabama and to characterize the coalbed-methane reservoir. |
| 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 production in the Black Warrior basin of Alabama will lead to a better understanding of factors critical to methane production. |
| Results | Characterization of coalbed-methane occurrence and producibility in the Black Warrior basin of Alabama indicates that geologic factors are a major control on the occurrence and producibility of coalbed methane. Results indicate that completion techniques may be used to increase recovery if tailored to specific geologic settings. Sedimentologic and coal-quality parameters may be used to locate regions for coalbed-methane development by characterizing the occurrence, rank, and grade of coal resources. However, high-productivity trends within those regions are localized, and geologic data suggest that productivity trends may be predictable on the basis of structural and hydrologic parameters. Several highly productive trends occur along northeast-oriented lineaments. These lineaments are the inferred surface expression of zones of enhanced permeability which are related to fractures. Productive trends also are associated with areas of low reservoir pressure, and salinity maps indicate that fresh water has migrated toward these areas from the southeast margin of the basin. The available data indicate that structure and hydrology are critical production parameters that may be used to identify favorable well sites within regions containing significant coalbed-methane resources. |
| Technical Approach | The study employed an interdisciplinary approach that utilized structural, coal-quality, gas-composition, sedimentologic, hydrologic, engineering, and production data to evaluate the 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. Coal-quality and gas-composition data were evaluated to determine the controls on the origin and occurrence of coalbed methane. Sedimentologic analysis was based on data from geophysical well logs and was used to define a regional stratigraphic and depositional framework for the study interval. 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 a statistical analysis of 11 key parameters to identify |

geologic controls on the productivity of coalbed-methane wells in the Black Warrior basin.

**Project Implications**

This report describes the geologic framework and hydrologic regime of coalbed-methane in the Black Warrior Basin, and it reports the relationships of these factors to coalbed-methane production. This effort has significantly improved understanding of geologic and hydrologic controls on gas occurrence and production. The preliminary models developed in this study will be further investigated and confirmed by research that focuses on Oak Grove coalbed methane field, including Rock Creek experimental field site in the Black Warrior Basin. In addition, these models will be used to test the transferability of coalbed-methane technology to the Northern and Central Appalachian coal basins.

## CONTENTS

## CONTENTS—CONTINUED



## ILLUSTRATIONS

## ILLUSTRATIONS—CONTINUED

# ILLUSTRATIONS—CONTINUED



## TABLES

# INTRODUCTION

## OBJECTIVES

An interplay of geological factors, including structure, coal quality, sedimentology, and hydrology, determines the occurrence and producibility of coalbed methane. A regional resource assessment of coalbed methane in the Black Warrior basin in Alabama is available (McFall and others, 1986), but the impact of basin geology on resource recoverability has not been addressed in detail. The objective of this study is to develop a detailed geologic framework for the Black Warrior basin of Alabama and to relate that framework to well design and methane production. This approach was undertaken to characterize the coalbed-methane reservoir and to identify the geological controls on the occurrence and producibility of coalbed methane.

This study employed an interdisciplinary approach to characterize the coalbed-methane reservoir. Structural features were analyzed to determine permeability trends and possible migration pathways. Coal quality and methane composition were evaluated to determine the pattern of methane generation, migration, and retention. Sedimentologic analysis provided a stratigraphic and depositional framework for the identification of areas having abundant coal resources. Hydrologic analysis elucidated the hydrodynamics of the reservoir system and delineated the relationship among water chemistry, reservoir pressure, and methane production. Analysis of production and well-completion data was performed to define a short-term measure of the overall productivity of a well and to determine how well design affects the producibility of coalbed methane.

## GENERAL BACKGROUND

Development of Alabama's coalbed-methane industry began with the issuance of the first drilling permits by the State Oil and Gas Board of Alabama in 1980. Since that time, coalbed methane has developed into a viable energy resource, and the Black Warrior basin now leads the nation in coalbed-methane well completion. The Black Warrior basin is the only sedimentary basin in the eastern United States that contains abundant coalbed-methane wells. Hence, this study is applicable in developing the Appalachian basin of Virginia, West Virginia, Pennsylvania, Kentucky, and Ohio, which is presently of interest (Kelafant and others, 1987).

The established coalbed-methane fields in Alabama are located in the eastern part of the Black Warrior basin in Jefferson and Tuscaloosa Counties (fig. 1). Drilling is presently localized, but considerable expansion may take place in coming years. Therefore, the 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).

Cumulative production of coalbed methane in the Black Warrior basin of Alabama has exceeded 70 billion cubic feet (Bcf) in only 8 years. In 1981, coalbed methane represented only 0.1 percent of the methane produced in Alabama and approximately 0.04 percent of the state's total gas production. In 1988, production from coalbed-methane operations totaled 20 Bcf or more than 28 percent of the methane produced in the Black Warrior basin of Alabama and approximately 11 percent of the state's total gas production.

As of April 31, 1989, 593 coalbed-methane wells were producing in Alabama. As of June 1, 1989, 629 additional wells were in various stages of drilling and testing, making a total of 1,222 coalbed-methane wells in the Black Warrior basin. Ninety percent of the production in the Black Warrior basin is in Brookwood and Oak Grove fields (fig. 1) where there has been a mutually beneficial relationship between underground-mining and coalbed-degasification efforts (Epsman and others, 1988; Pashin and others, 1989); exploration in areas unaffected by underground mining is in the early phases of development.

## REGIONAL GEOLOGIC SETTING

The Black Warrior foreland basin of northwestern Alabama and northern Mississippi (fig. 2) is the southernmost coal-bearing basin of the Appalachian Plateaus. Coal resources are largely restricted to the lower Pennsylvanian Pottsville Formation which is the youngest Paleozoic unit in the basin. The Pottsville of the Black Warrior basin crops out only in Alabama and is traceable westward into

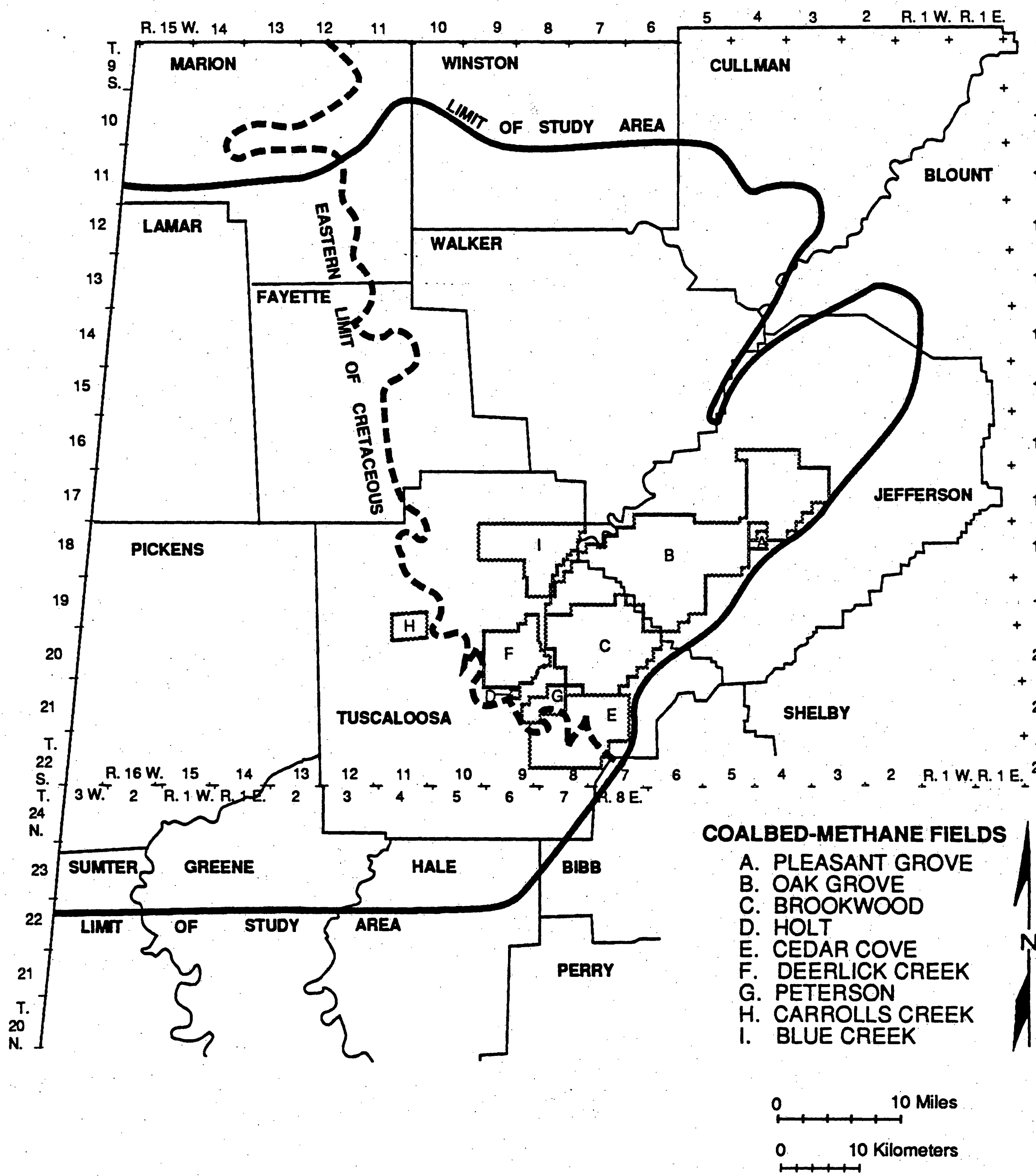



Figure 1. Index map of study area showing location of coalbed-methane fields.

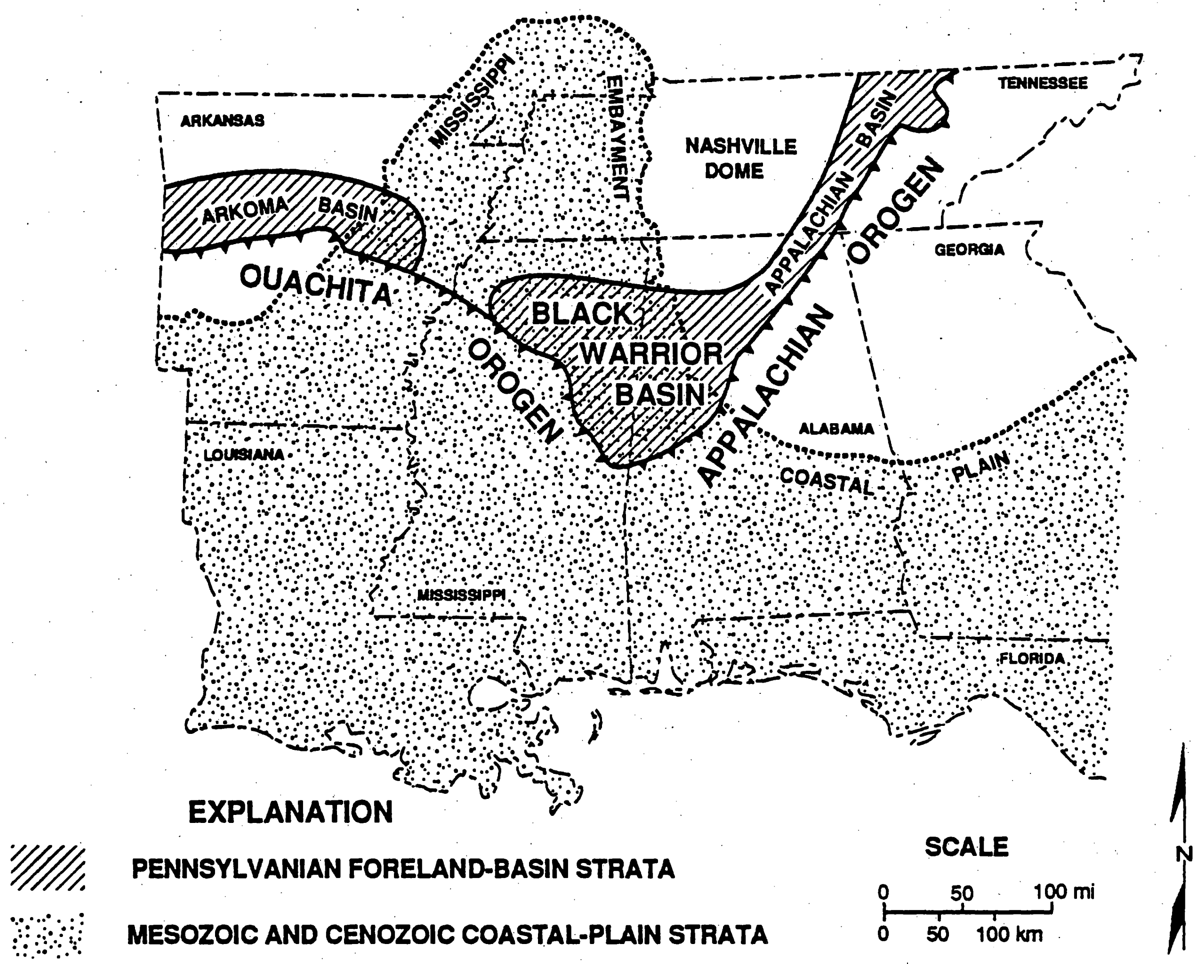



Figure 2. Regional geologic setting of the Black Warrior basin.

Mississippi where the formation is overlain as much as 6,000 feet of Cretaceous and Tertiary strata of the Mississippi Embayment.

## TECTONIC FRAMEWORK

The Black Warrior basin is bounded on the southeast by the Valley and Ridge province of the Appalachian orogen (fig. 2). In Mississippi, the Ouachita orogen defines the southwest margin of the basin; however, the Ouachitas are known only from the subsurface in this area (Thomas, 1985, 1988a, b). The Nashville dome is north of the Black Warrior basin, and the outcrop limit of Pennsylvanian strata is commonly considered the northern limit of the basin.

The Black Warrior basin has been interpreted to have formed flexurally in response to converging Alleghanian thrust loads in the Appalachian and Ouachita orogens (Beaumont and others, 1988;

Hines, 1988). Therefore, applying flexural models of foreland-basin formation (Jordan, 1981; Quinlan and Beaumont, 1984), the Black Warrior basin represents a flexural moat that subsided in response to the episodic emplacement of thrust loads. In contrast, the Nashville dome represents a peripheral bulge, or interbasinal uplift, that narrowed during the emplacement of thrust loads and widened toward the orogen during episodes of tectonic relaxation caused by a general cessation of thrusting and by the erosion of those loads.

A major Mesozoic rifting event followed the Alleghanian orogeny and concomitant foreland-basin formation; Pennsylvanian strata of the Black Warrior basin are overlain unconformably by Cretaceous strata. Rifting resulted in southwest tilting of the Black Warrior basin related to rapid subsidence of the Mississippi Embayment and the Gulf Coastal Plain. Extensional subsidence caused deep burial of the western part of the basin and the Ouachita orogen below the coastal plain, thereby giving the basin its present configuration (Klitgord and others, 1983; Thomas, 1985, 1988b).

## STRATIGRAPHIC AND SEDIMENTOLOGIC FRAMEWORK

The Pottsville Formation has been divided into two parts in Alabama (McCalley, 1900). The lower part, or lower Pottsville, is dominated by quartzose sandstone and contains thin, discontinuous coal beds that are mined locally and have not been examined fully for their coalbed-methane potential. The upper part, or upper Pottsville, contains numerous economic coal beds and the majority of Alabama's coal resources (fig. 3). The major coal beds in the upper Pottsville are contained in stratigraphic bundles called coal groups (McCalley, 1900); the coal-group concept has 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. 3). The cycles have as much as 350 feet of marine mudstone at the base; typically, the mudstone coarsens upward into sandstone. At the top of each cycle is the interbedded mudstone, sandstone, underclay and coal that makes up a coal group. The cycles are easily traced in Alabama (McCalley, 1900; Butts, 1910,

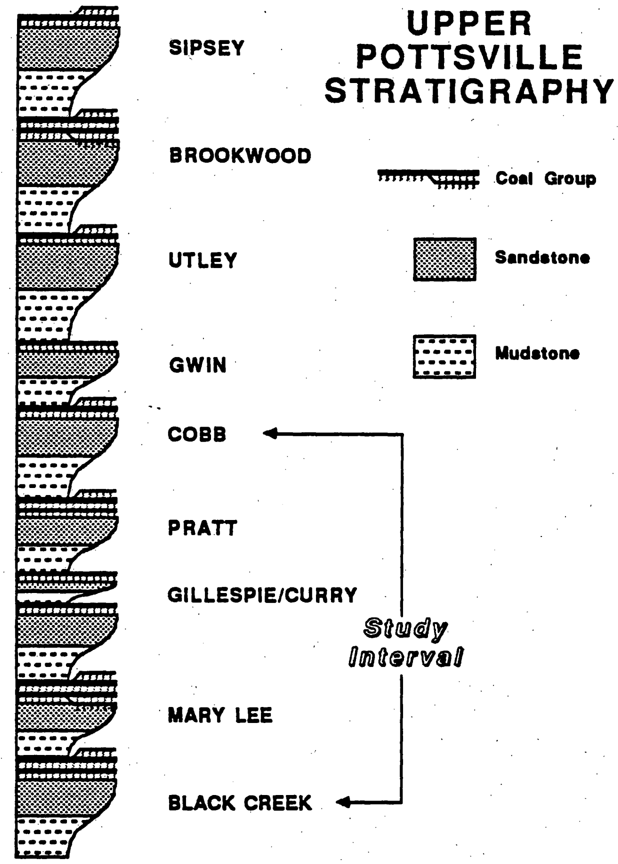



Figure 3. Stratigraphy of the upper Pottsville Formation showing major depositional cycles and study interval.

1926), and recent 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 is the principal coalbed-methane target in Alabama (McFall and others, 1986) and is the focus of this study (fig. 3). In this study, the Black Creek-Cobb interval was divided into five cycles which are, for the most part, named after the capping coal groups. In ascending order, the cycles are named (1) the Black Creek, (2) the Mary Lee, (3) the Gillespie/Curry, (4) the Pratt, and (5) the Cobb. The Gillespie/Curry cycle includes the lower part of the Pratt coal group (Gillespie and Curry beds of McCalley,1900). The Pratt coal group was subdivided to reflect the genetic significance of the cycles; subdivision of other cycles is possible. The Gillespie/Curry cycle itself may be treated as two cycles, because the coal beds are traceable throughout the study area and are separated by a thin interval of marine strata (McCalley, 1900). However, because the Curry cycle is thin (generally less than 70 feet thick) and is of limited significance in coalbed-methane exploration, the two cycles were combined for this study.

Several workers have distinguished between light-colored, quartzose sandstone and darker, lithic sandstone in the Pottsville (Ferm and others, 1967; Hobday, 1974; Horne and others, 1976; Cleaves and Broussard, 1980; Horsey, 1981). Quartzose sandstone is dominant in the lower Pottsville but is also present in some upper Pottsville cycles. Because of high porosity and permeability, quartzose sandstone forms potential conventional petroleum reservoirs. In the literature, quartzose sandstone commonly is referred to as quartzarenite, but the sandstone is better characterized petrographically as sublitharenite (Mack and others, 1983; Raymond and others, 1988). Nearly all workers in Alabama have interpreted the quartzose sandstone to have formed in beach-barrier environments.

Lithic sandstone is dominant in the upper Pottsville and is an integral part of the coal-bearing intervals. The sandstone has a high proportion of argillaceous rock fragments and detrital matrix and has been characterized petrographically as litharenite (Graham and others, 1976; Mack and others, 1983). Because of the argillaceous component, lithic sandstone has low porosity and permeability (Rightmire and others, 1984) and apparently does not form conventional petroleum reservoirs. Investigators have traditionally interpreted the lithic sandstone to be deltaic in origin, but Epsman and others (1988) indicated that alluvial deposits also are present.

Coal-bed geometry in the upper Pottsville is complex. Whereas many beds may be traced for more than 50 miles in outcrop (McCalley, 1900), other beds are discontinuous and split profusely (Horsey, 1981). Recently, Weisenfluh and Ferm (1984), Epsman and others (1988), and Pashin and others (1989) showed that splitting of coal beds may be related to synsedimentary fault movement. Additionally, Epsman and others (1988) demonstrated the importance of autogenic sedimentary processes, such as the development of crevasse-splay lobes, in determining the location of some bed splits in Alabama. Like the lithic sandstone, most coal in the Black Warrior basin has been attributed to deltaic environments. However, recent sedimentologic evidence indicates that many economic coal beds in the Pottsville may have formed on an alluvial plain (Epsman and others, 1988).

The source of Pottsville sediment has been argued for many years. Most workers have relied upon petrographic data (Graham and others, 1976; Mack and others, 1983) and paleocurrent data (Metzger, 1965) and have opted for an Ouachita source in the southwest or an Appalachian source in the northeast. However, the Appalachians probably contributed some sediment from the southeast during Pratt deposition (Sestak, 1984; Thomas, 1988a).

# STRUCTURAL GEOLOGY

## INTRODUCTION

Compressional, extensional, and epeirogenic events have shaped the habitat of petroleum in the Black Warrior basin. The basin has a diverse suite of tectonic structures that includes folds, normal faults, thrust faults, joints, and cleats. These structures may have a strong influence on the occurrence and producibility of coalbed methane.

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 coal following erosional unroofing of a sedimentary basin (Jüntgen and Karweil, 1966). Additionally, the distribution and openness of fractures may play a major role in determining the pathways along which coalbed methane may migrate. Therefore, the major objectives of this section are to synthesize the available structural data to determine the structural controls on the occurrence and producibility of coalbed methane.

## METHODS

Data from density logs (fig. 4) were used to make a structure-contour map of the top of the Mary Lee cycle in order to define the attitude of the Pennsylvanian coal-bearing strata in Alabama. Numerous faults and folds are known in the Black Warrior basin that are too subtle to be shown at the scale of a basin-wide structure-contour map. Therefore, an additional map showing the location of folds and faults in the basin was made; the map is based on (1) reports and dockets on file at the

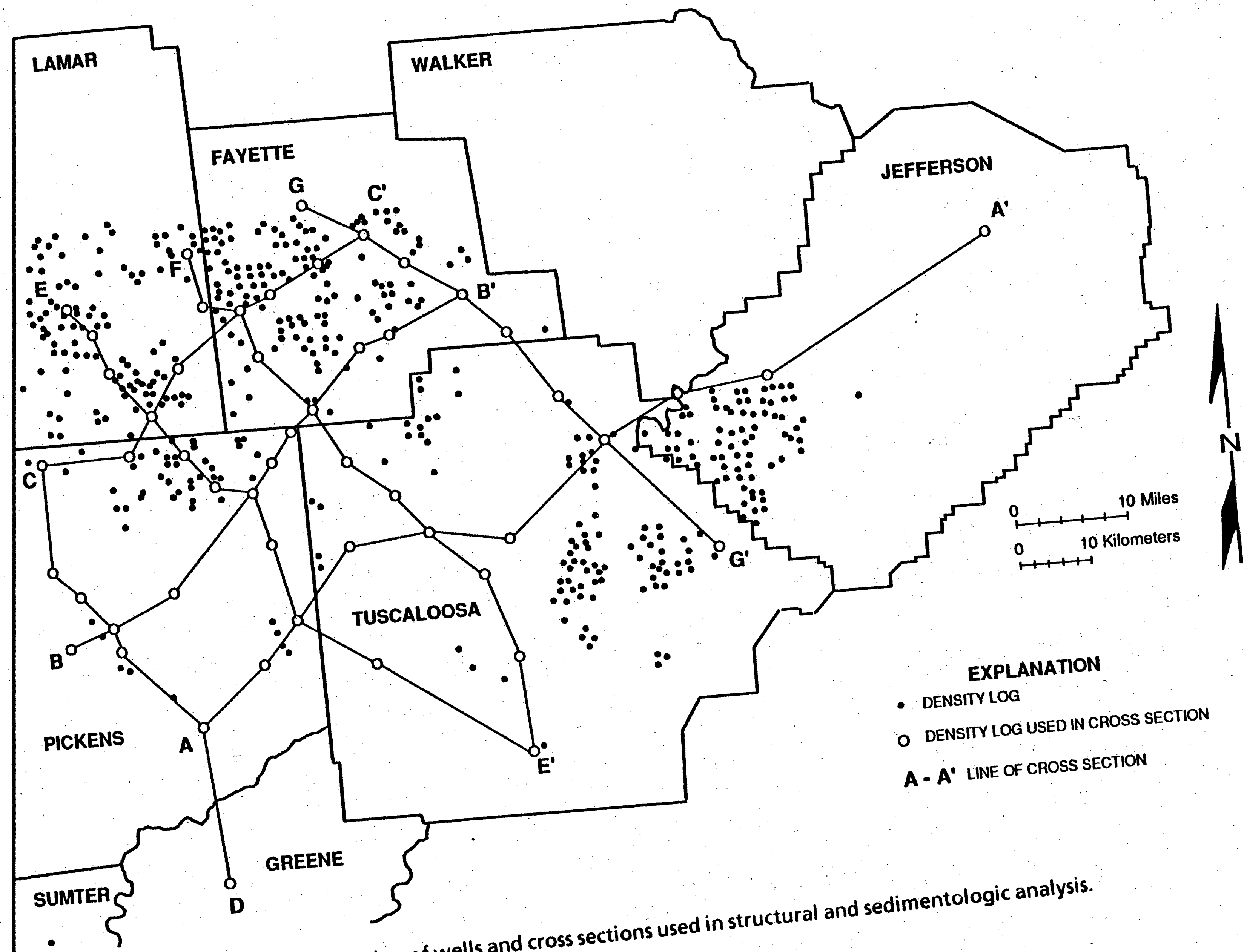



Figure 4. Location of wells and cross sections used in structural and sedimentologic analysis.

State Oil and Gas Board (2) maps that are on file at the Geological Survey of Alabama, and (3) published reports (Ward and others 1984, 1989; Kidd, 1982; Epsman,1987; Raymond and others, 1988).

Joint, cleat, and lineament orientation were mapped to analyze the fracture architecture of the study area. Most of the joint and cleat data were compiled from the files of the Geological Survey of Alabama. Joint and cleat data are available only from Pottsville outcrops and underground coal mines, because fractures generally are not exposed in unconsolidated Cretaceous and Tertiary strata in the western part of the study area. To characterize the spatial variation of fracture systems, the Pottsville outcrop area was divided into four quadrants. Statistical analysis of joint and cleat data utilized the methods for directional data given in Potter and Pettijohn (1977).

A regional lineament map was made using Landsat images (scale 1:250,000). Lineaments on the map include straight stream segments, topographic offsets, and tonal anomalies. To test the relationship of lineaments to geological features and productivity trends in Oak Grove field, lineaments from Landsat, Sidelooking Airborne Radar (SLAR), orthophotoquads and aerial photographs were determined. The lineaments were then plotted on structural contour maps that also depict fracture patterns and the locations of highly productive wells.

## REGIONAL STRUCTURE

### Folds and Thrust Faults

The structure-contour map (fig. 5) indicates that Pennsylvanian strata in the Black Warrior basin of Alabama dip toward the southwest at approximately 70 feet per mile. Only a few major structures are defined in the map because of the large contour interval of 300 feet. In the southeast part of the basin, the southwest dip is obscured by the presence of some major northeast-trending Appalachian folds and thrust faults.

Definition of the southeast margin of the Black Warrior basin is based on folds and thrust faults of the Valley and Ridge province of the Appalachians. The basin is bounded on the southeast by the steeply dipping northwest limb of the Blue Creek anticline (D) and by the thrust-faulted northwest

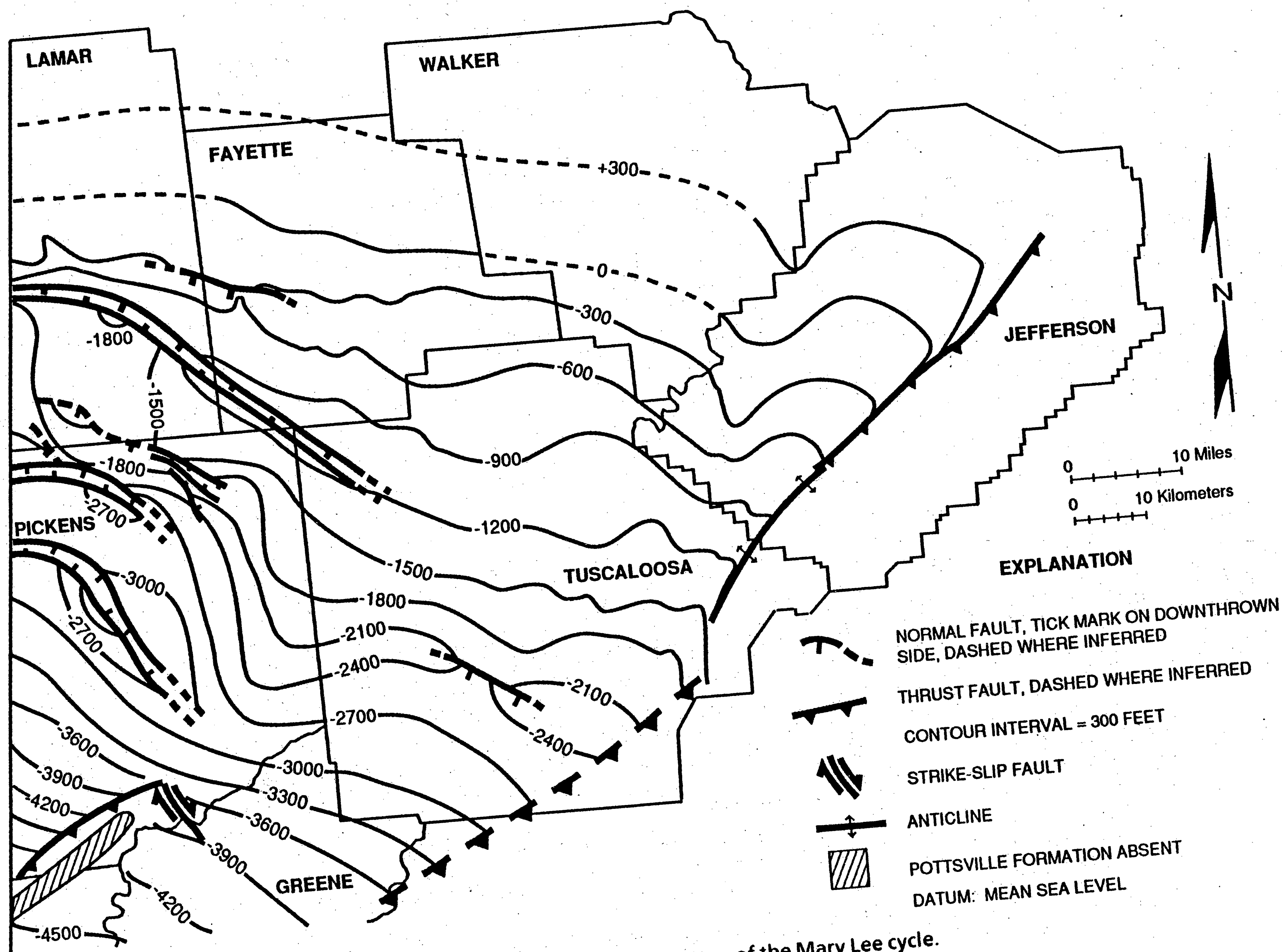



Figure 5. Regional structure map of the top of the Mary Lee cycle.

limb of the Birmingham anticlinorium (figs. 5, 6). The Opossum Valley fault (B), a major northeast-trending thrust fault, cuts the northwest limb of the Birmingham anticlinorium and forms the northern part of the southeast border of the Black Warrior basin (Butts, 1910) (fig. 6). Farther south, the thrust fault passes into the Blue Creek anticline, the axis of which has an approximate azimuth of 40° in southeastern Jefferson and eastern Tuscaloosa Counties. Structural relief of the anticline locally exceeds 2,000 feet (fig. 7). The Blue Creek syncline (C) is southeast of the Blue Creek anticline, and because the syncline contains upper Pottsville coal beds, the structure commonly is included as the southeasternmost part of the Black Warrior basin.

Along the southeast margin of the Black Warrior basin, the Pottsville locally dips as much as 70° to the northwest. Coal groups that are drilled for coalbed methane at a depth exceeding 1,000 feet only a few miles to the northwest are exposed on the Blue Creek anticline. The Sequatchie anticline (F) is located northwest of the basin margin, and the Blue Creek anticline and Birmingham anticlinorium are separated from the Sequatchie anticline by a broad, flat-bottomed structure called the Coalburg syncline (E) (figs. 5, 6). The Coalburg syncline contains numerous normal faults and mesoscale structures. For example, small-scale, northeast-striking thrust faults with a displacement of approximately 1 foot occur in underground mines within the syncline, and deformed coal banding is common (Epsman and others, 1988).

The axis of the Sequatchie anticline (fig. 6) strikes approximately parallel to the Birmingham anticlinorium (35°-45°), plunges southwest, and verges toward the northwest. Northeast of the study area, a major thrust fault forms the core of the anticline (Butts, 1926; Szabo and others, 1988). Displacement diminishes toward the southwest, and in the study area, the anticline is a fairly simple, open fold; the dip of both limbs typically is less than 10°.

The Pickens-Sumter anticline (H) occurs in the subsurface of southern Pickens County and northern Sumter County (Thomas, 1973) (figs. 5, 6). The Pottsville is absent along the crest of the anticline which has a maximum structural relief of 6,000 feet. Seismic data indicate that the anticline is a thrust-ramp structure and that lateral displacement along the thrust fault is less than 1 mile (William A. Thomas, personal communication, 1989).

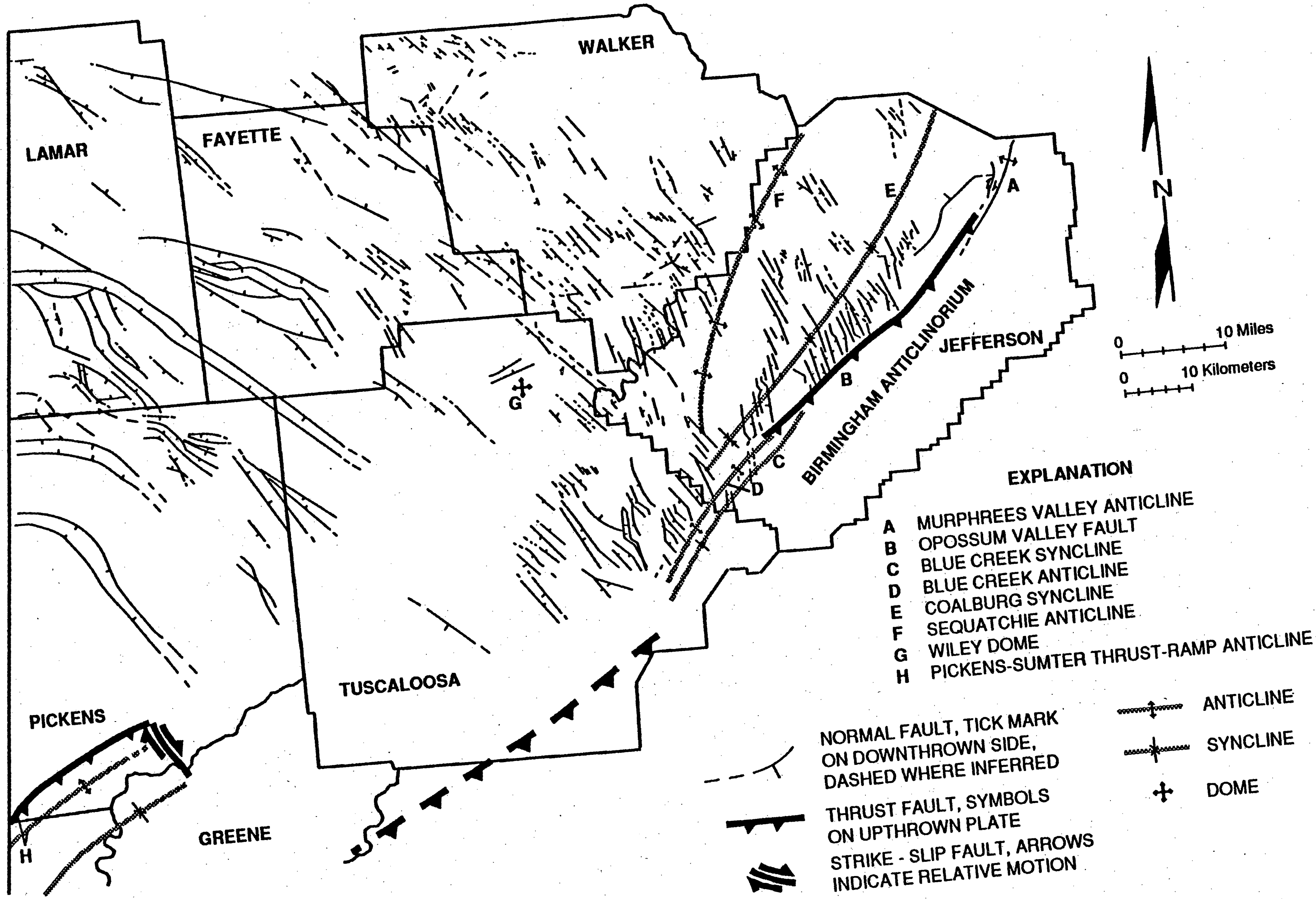



Figure 6. Faults and folds in the Black Warrior basin of Alabama.

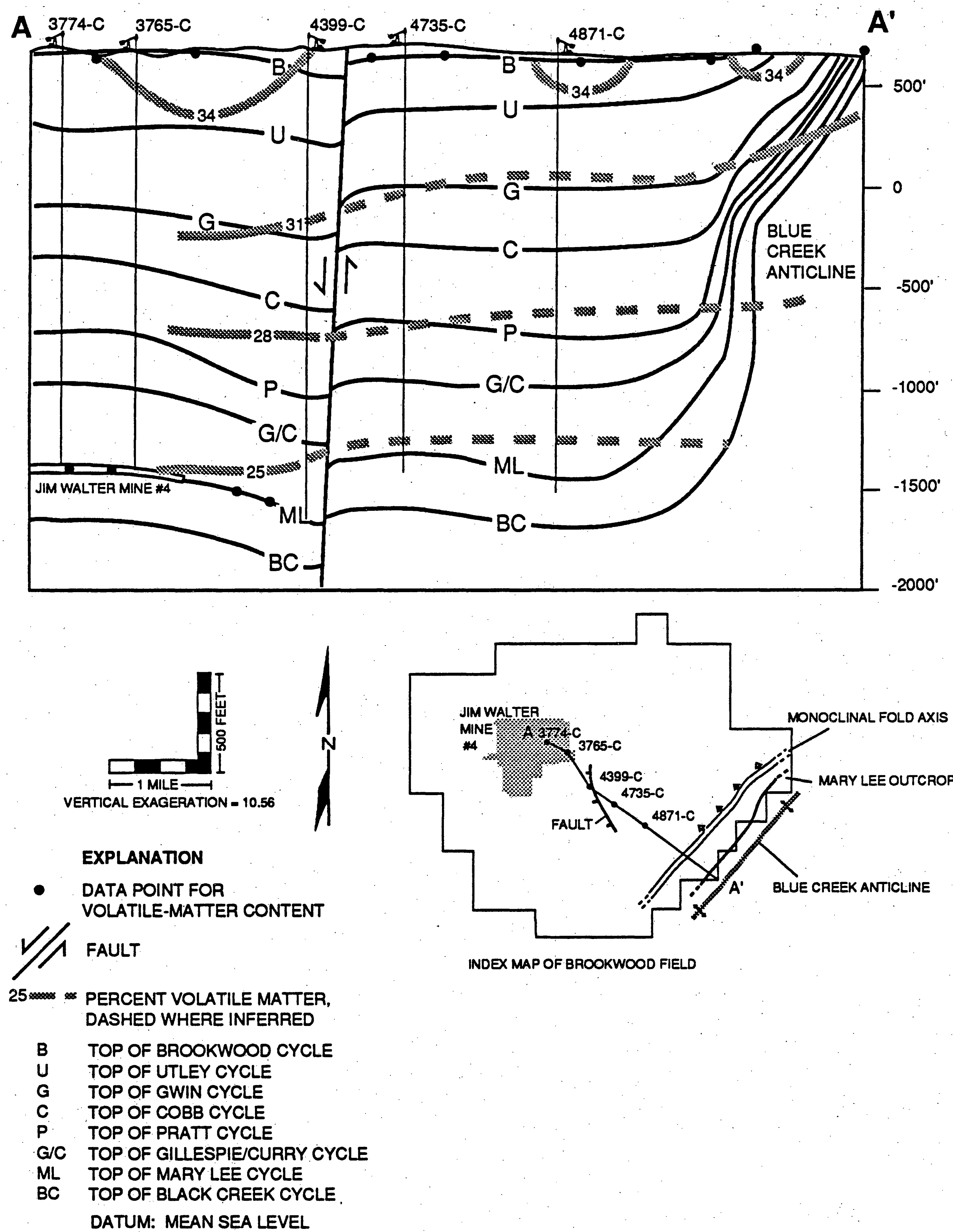



Figure 7. Structural cross section of upper Pottsville strata in Brookwood field showing approximately horizontal isovols. Monoclinal fold axis from Epsman and others (1988). See figure 1 for location of Brookwood field.

## Normal Faults

The Black Warrior basin is dominated by northwest trending, high-angle normal faults that define a horst-and-graben system (fig. 6). Displacement across normal faults scarcely exceeds 200 feet in the eastern part of the basin. Northwest of the Appalachian folds and thrust faults, structural contours define a fairly uniform southwest dip (fig. 5). In east Pickens County, however, several contours turn sharply northward, marking a hinge zone to the east of several major normal faults. The faults define a series of narrow grabens in Lamar and Pickens Counties, and in some faults, throw exceeds 1,000 ft.

Most normal faults in the eastern part of the basin have a sublinear trace. Some faults, however, have an arcuate or sinuous trace, particularly the major faults in Lamar and Pickens Counties (figs. 5, 6). Typically, displacement is greatest near the central part of a given fault trace and decreases toward the termini. Fault length and fault displacement increase toward the southwest, and fault traces tend to turn west near Mississippi. Many faults in the Coalburg syncline have a more northerly strike than faults in other areas, and most of the faults form a series of right-stepping horsts and grabens.

The structure map of the unconformable surface at the top of the Pottsville Formation (Kidd, 1976) (fig. 8) indicates that the surface generally strikes uniformly northwest and that dip increases toward the southwest. Structure contours parallel those on the Mary Lee structure map in the southwesternmost part of the study area, but the contours are generally oblique throughout the remainder of the region (figs. 5, 8). The map shows that upper Cretaceous strata in the western part of the study area are not displaced by normal faults. Cross sections from Mississippi (Thomas, 1988a) also demonstrate that normal faults in the Pottsville terminate at the unconformable surface.

## Joints

Two dominant joint systems, systems A and B, are discernible where the Pottsville crops out (fig. 9); each system consists of two dominant joint sets, sets I and II. Set I joints make up the master set of each joint system; the joints generally are planar, vertically persistent, and have a high constancy ratio (table 1). Set II joints are typically curved, less vertically persistent than set I joints, and commonly

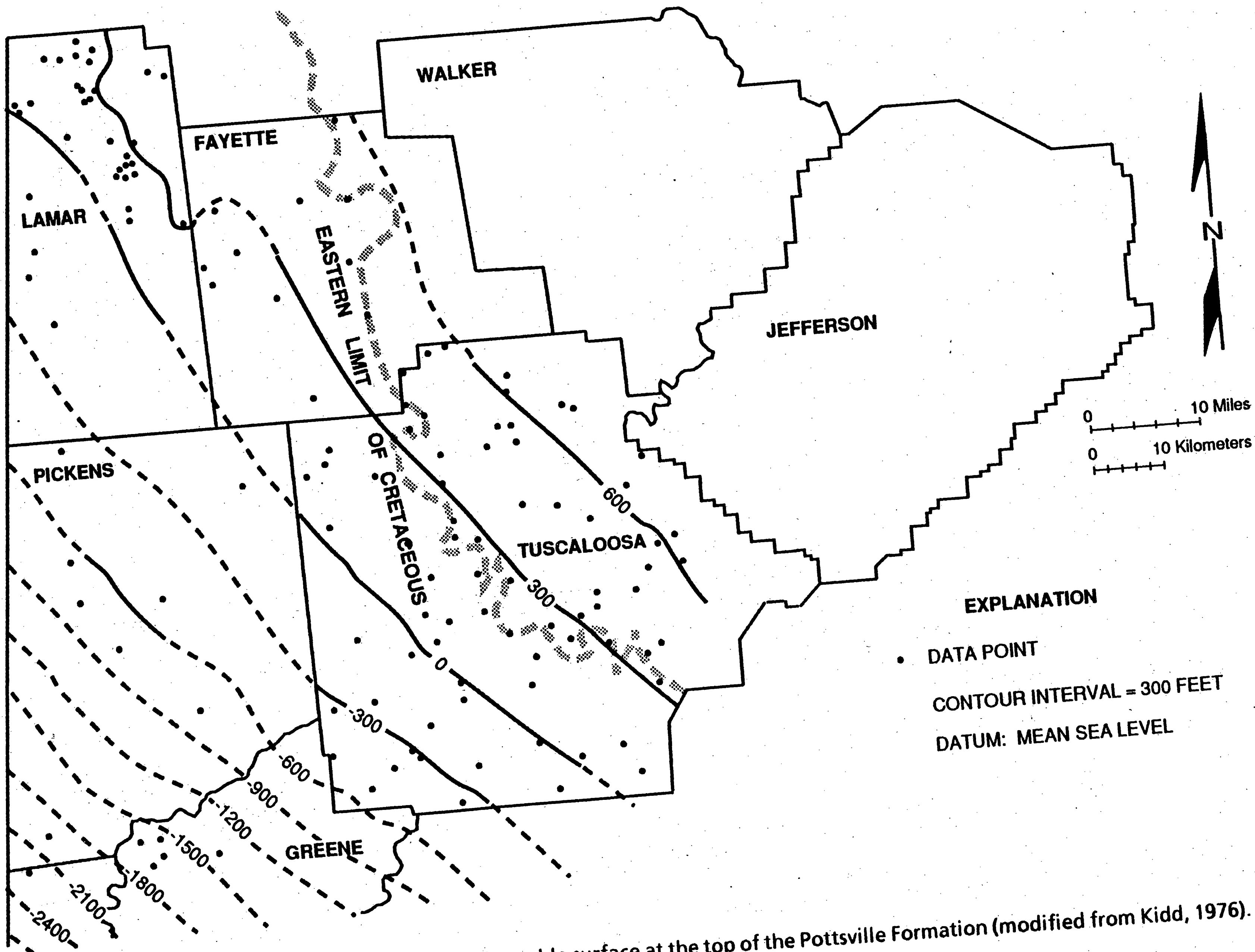



Figure 8. Structural contour map of the unconformable surface at the top of the Pottsville Formation (modified from Kidd, 1976).

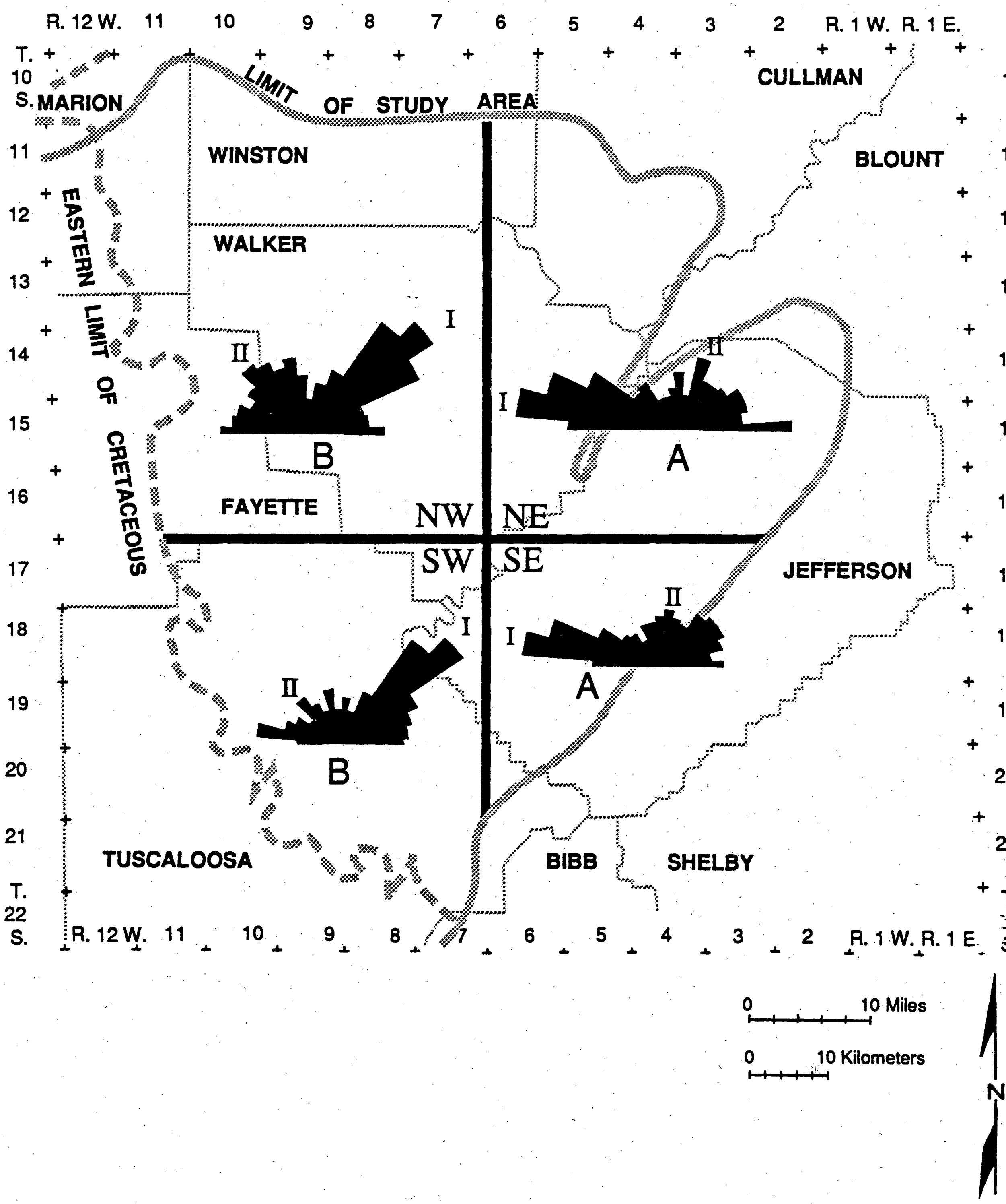



Figure 9. Joint orientation in the study area (modified from Ward, 1977).

Table 1. Results of statistical analysis of joint and cleat orientation in the Pottsville outcrop area

| | | Number of readings | Vector-mean azimuth | Vector magnitude | Constancy ratio (%) |
|---|---|---|---|---|---|
| **JOINTS** | | | | | |
| **System A** | | | | | |
| NE quadrant | set I | 203 | 296 | 189 | 93 |
| SE quadrant | set I | 153 | 296 | 142 | 93 |
| **System B** | | | | | |
| NW quadrant | set I | 249 | 48 | 234 | 94 |
| SW quadrant | set I | 214 | 47 | 202 | 94 |
| **CLEATS** | | | | | |
| NE quadrant | face cleat | 124 | 57 | 117 | 94 |
| | butt cleat | 107 | 327 | 99 | 93 |
| SE quadrant | face cleat | 103 | 54 | 101 | 99 |
| | butt cleat | 67 | 311 | 64 | 95 |
| SW quadrant | face cleat | 68 | 46 | 63 | 93 |
| | butt cleat | 88 | 321 | 87 | 98 |
| NW quadrant | face cleat | 120 | 55 | 117 | 98 |
| | butt cleat | 95 | 320 | 91 | 96 |

[1]The minimum constancy ratio for data restricted to a 90° range is 89.

terminate at intersections with set I joints. Joint sets of each system generally are orthogonal (Ward, 1977; Ward and others, 1984). Poor alignment of set II joints is caused by curving joint planes, which in places, are visible in outcrop. The peaks for set II joints are poorly defined (fig. 9) and are in places obscured by localized joint sets. Therefore, calculated vector means for set II joints did not reflect the orthogonal relationship observed in the field and are not included in table 1.

Joint system A is largely restricted to the area southeast of the Sequatchie anticline (fig. 9) and is densest in the vicinity of the axial trace. The dominant joint set (set I) of system A has a vector-mean azimuth of 296° and a constancy ratio of 93 in each quadrant (table 1). These joints are subperpendicular to the axial trace of the anticline and, as the trace curves toward the south in west Jefferson County, joints trend west (Ward and others, 1984). Joint system B occurs west of the Sequatchie anticline. The dominant joint set (set I) of system B has a vector-mean azimuth of 48° in the northwest quadrant and 47° in the southwest quadrant.

In Oak Grove field, joints of both sets in system A are present in equal abundance at a depth of 1,100 ft below the surface in the Oak Grove Mine. At the surface, however, northeast-oriented set II joints are more abundant than in the mine (Epsman and others, 1988). In Brookwood field, northeast-oriented joints constitute the dominant set at the surface but are scarce at a depth of 2,000 ft in the Jim Walter Resources No. 4 Mine. At surface exposures containing both northwest and northeast joints, cross-cutting relationships are inconsistent. Some set II joints in surface mines near the southeast margin of the study area are perpendicular to bedding in rocks that dip as much as 20° toward the northwest.

In addition to the dominant joint systems in the Black Warrior basin, localized joint sets occur along normal faults. The diagnostic characteristic of normal-fault-related joints is that the joint planes dip approximately 60°. Whereas most joints in systems A and B are oblique to normal faults, fault-related joints generally parallel fault traces, and less commonly, are perpendicular to fault traces.

## Cleats

Coal in the Black Warrior basin has a well-developed cleat system. The face cleat is perpendicular to bedding, planar, laterally persistent, strongly aligned, and generally is evenly spaced. The butt cleat is perpendicular to bedding and is more or less perpendicular to the face cleat. The butt-cleat surface typically is irregular and commonly terminates at intersections with the face cleat.

Cleat fillings are uncommon in the Pottsville outcrop area. Where present, cleat fillings are patchy and occupy only a small proportion of the fracture system; they generally are developed on the face cleat. Calcite is the most common type of cleat fill, although pyrite occurs at some localities. In surface exposures, reddish ferruginous stain and yellowish to whitish sulfate stain are common on the face-cleat plane. Stained butt-cleat faces are scarce.

Face-cleat spacing varies regionally (McFall and others, 1986). Spacing is generally 0.2 inches in Jefferson County and 0.4 inches in Tuscaloosa County and southeastern Walker County. The largest regional face-cleat spacing is 0.6 to 0.75 inches in Fayette, Marion, and northwest Walker Counties.

Although two regional joint systems were distinguished, cleat orientation is fairly uniform throughout the entire Pottsville outcrop area, and the constancy ratio varies from 93 to 99 (fig. 10;

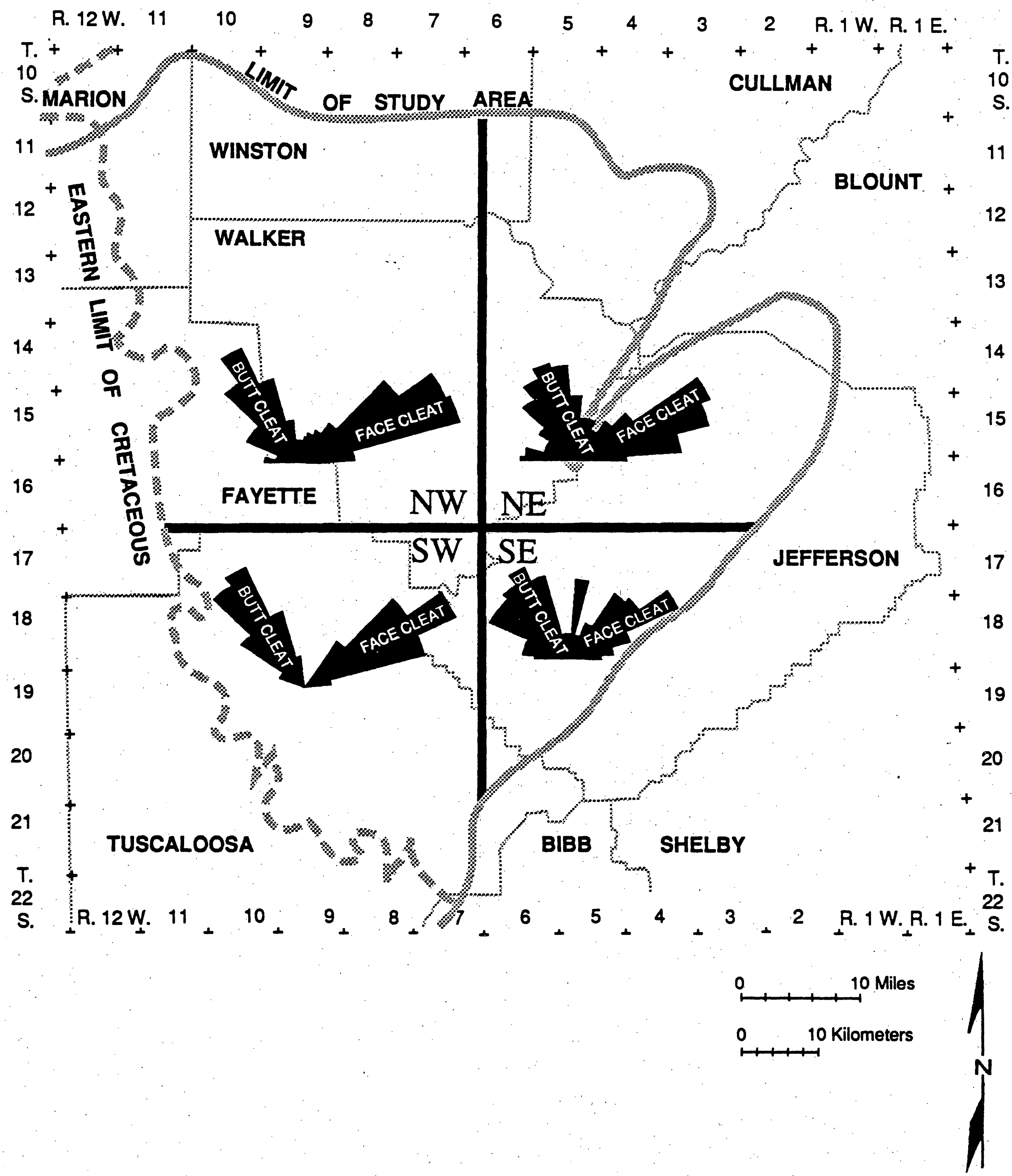



Figure 10. Cleat orientation in the study area (modified from Ward, 1977).

table 1). The vector-mean azimuth of the face cleat varies from 46° to 57° among the quadrants and is subparallel to the strike of the Valley and Ridge. The butt cleat is orthogonal to the face cleat and has a vector-mean azimuth ranging from 311° to 327°.

A local fracture system is restricted to coal beds that crop out along the southeast margin of the basin near the Blue Creek anticline. These fractures cut across and in places obscure the regional cleat system. Most of the fractures are perpendicular to the axial trace of the anticline, and a subordinate set is parallel to the axial trace. The fractures attenuate rapidly to the northwest with increasing distance from the Blue Creek anticline.

## Lineaments

Lineaments pose an interpretive difficulty because they only represent features that are visible on the surface of the earth. Therefore, the significance of a given lineament is unknown unless it can be related to the local geology. The Landsat lineament map (fig. 11) shows a variety of northeast and northwest elements. Abundant northeast-trending lineaments occur along a trend from Greene County to Oak Grove field in westernmost Jefferson County. Many of the most productive coalbed-methane wells are located along this trend. Therefore, geological data were compiled for parts of Oak Grove field where productivity trends coincide with known lineaments.

In western Oak Grove field, faults, structure contours of the top of the Mary Lee coal bed, lineaments, and wells producing initially more than 300 Mcfd of methane were plotted (fig. 12). Joint and cleat data for Oak Grove field as a whole are also shown. The highly productive wells are located directly on some major lineaments which can be related to structural features in the area.

The closely spaced contours at the top of figure 12 depict the southern terminus of the Sequatchie anticline. A narrow northeast-oriented syncline or graben is located in the northeast part of the map area, and the northwest margin of the structure coincides with some lineaments. Field check of the surface expression of the lineament traces was hampered by scarce exposure; however, dipping strata were observed at or near the lineament traces at three locations. Changes in coal-bed geometry and sandstone distribution in the Mary Lee cycle across the lineament suggest that the

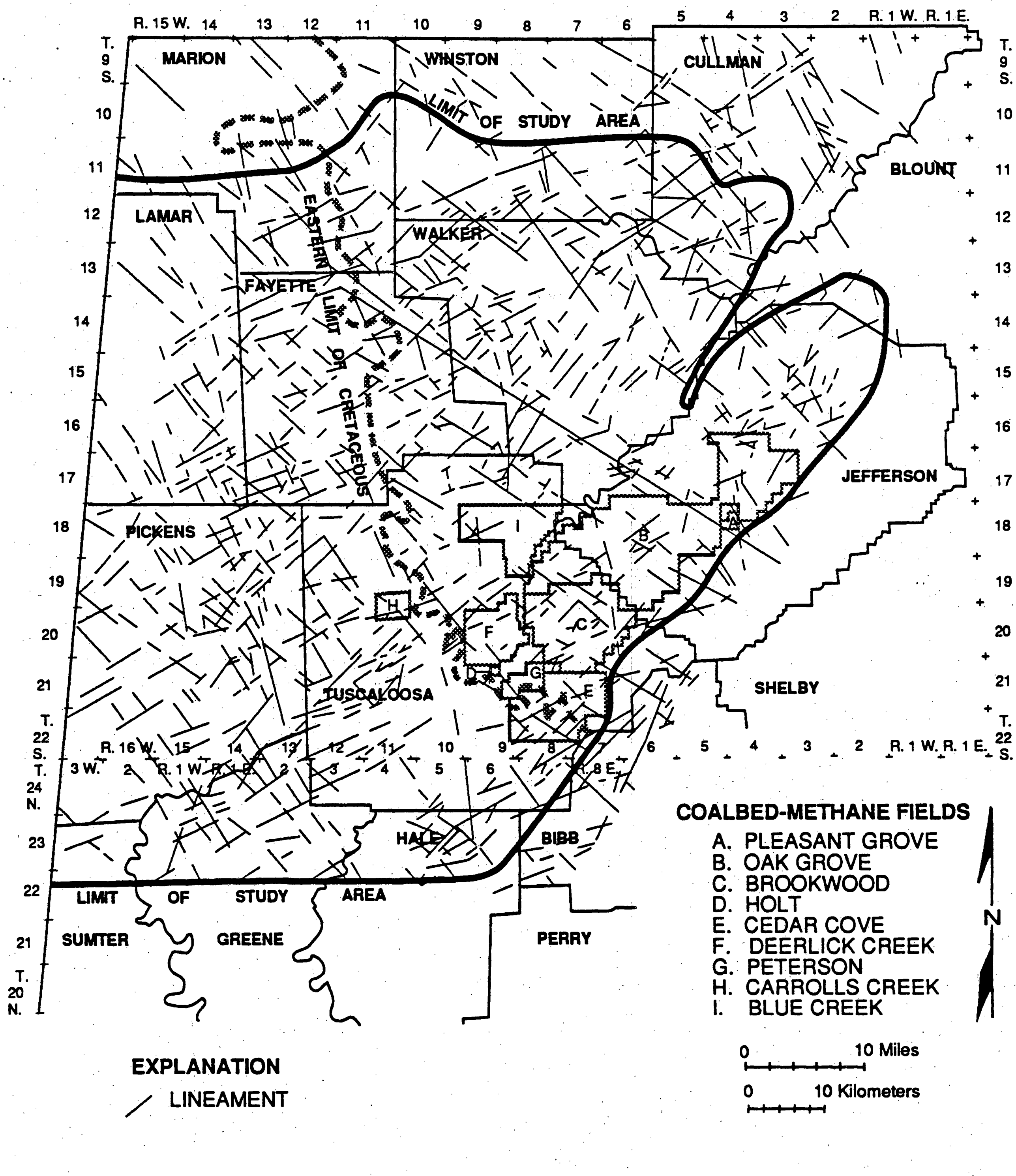



Figure 11. Selected lineaments from Landsat 2, band 6 and 7 scenes.

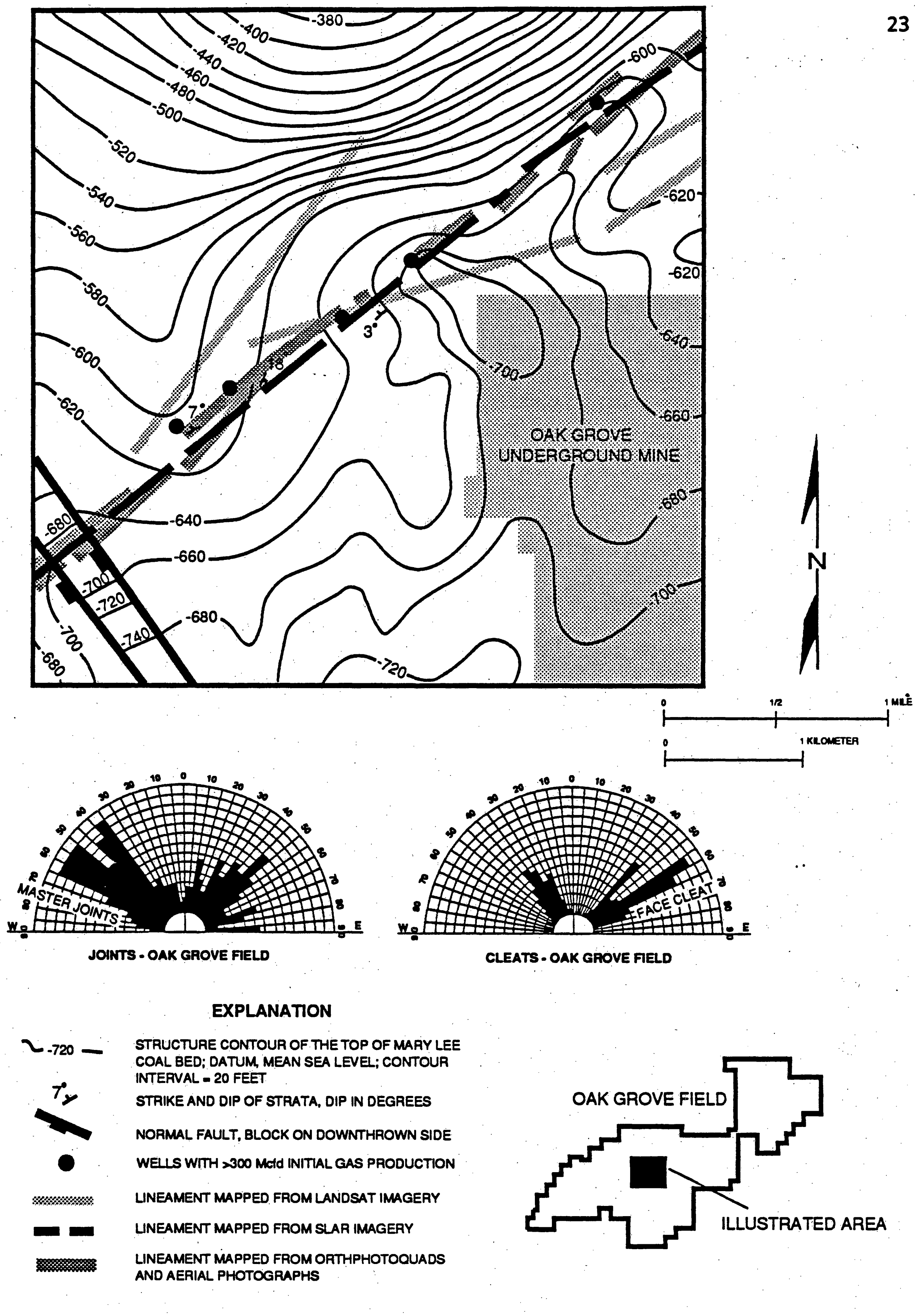



Figure 12. Structural configuration of the top of the Mary Lee coal bed and surface-fracture orientation in a selected part of Oak Grove field, Jefferson County, Alabama (structure contours from Epsman and others, 1988). See figure 11 for location of Oak Grove field.

lineament coincides with a Paleozoic fault that is not apparent on the structure map (Epsman and others, 1988). Hence, the lineaments appear to be the surface expression of tectonic structures.

Reconnaissance of fracture systems and subsurface mapping at the Gas Research Institute's Rock Creek site in Oak Grove field (Boyer and others, 1986) (fig. 13) was performed to investigate the local structure and to determine whether fracture orientation and density vary near the P-2 well, which reached peak gas production at 460 Mcfd. Several northeast-trending joints occur along the general trace of the lineament near the P-2 well. Determination of fracture patterns and fracture density was hampered because of scarce surface exposure, so it is difficult to determine the significance of the northeast joints.

Structure contours show that the Pratt coal bed dips uniformly southeast on the east limb of the Sequatchie anticline; however, a southwest-plunging anticline occurs at the level of the Mary Lee coal bed (fig. 13). The axial trace of the anticline is aligned with the SLAR lineament which is located immediately southeast of the P-2 well. Because the structure has little relief and is discernible only in the Mary Lee coal bed, the anticline may be compactional rather than layer-parallel compressional in origin.

Two geologic hypotheses may explain exceptional production from the P-2 well. One hypothesis is that abundant northeast joints along the lineament have increased permeability, thus facilitating methane production from the Mary Lee and Pratt coal groups. The other hypothesis is that production may be related to preferential migration of methane toward the crest of the anticline, thus facilitating methane production from only the Mary Lee coal group. Several wells are located on the anticline, but only the P-2 well, which is closest to a lineament, has exceptional production. Therefore, production of the P-2 well is probably due to increased permeability along the lineament.

## STRUCTURAL HISTORY

### Alleghanian Orogeny

The principal Alleghanian structures in the eastern part of the basin include the Sequatchie anticline (F), the Blue Creek anticline (D), and the Opossum Valley thrust (B) (fig. 6). Because the

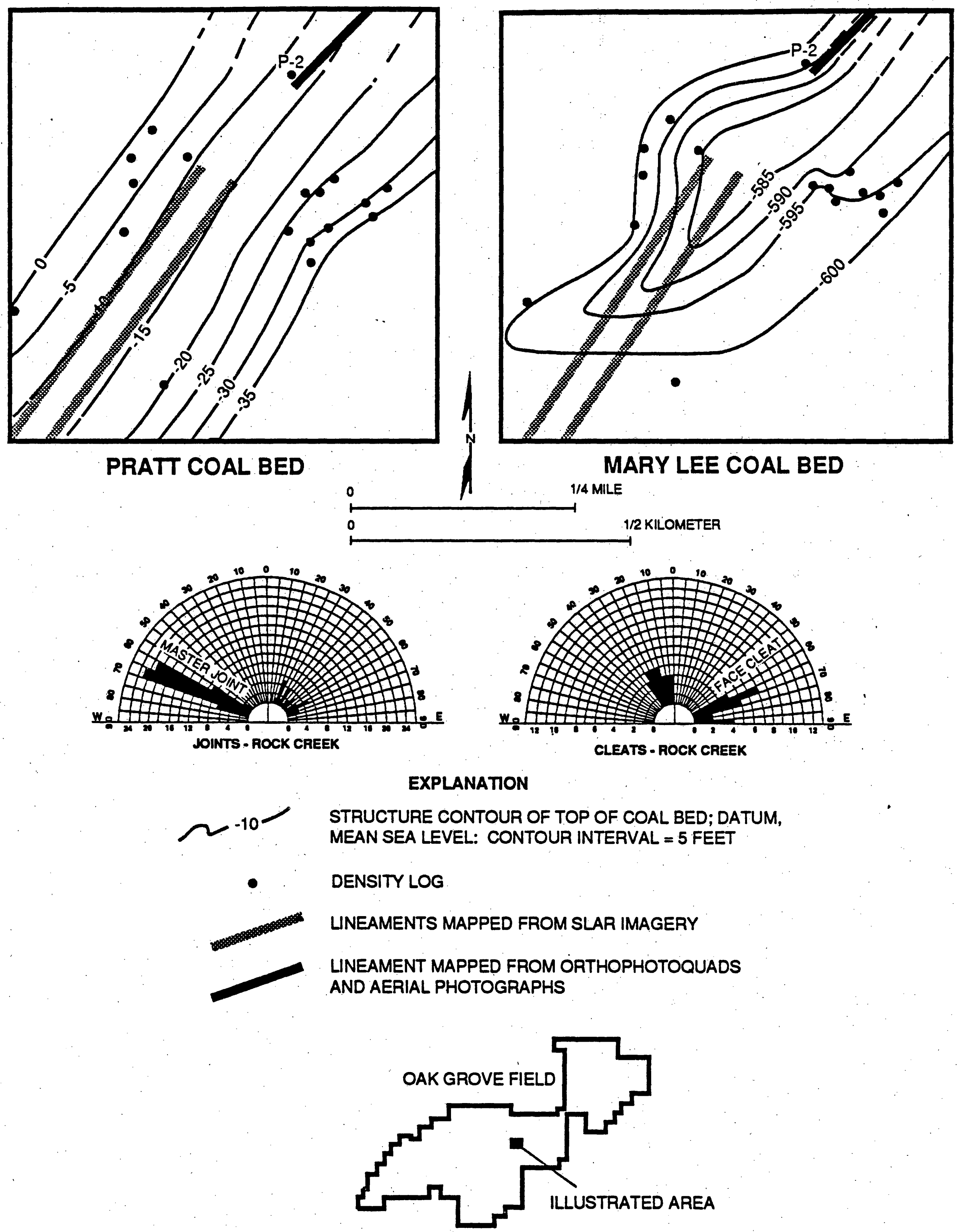



Figure 13. Structural configuration of the top of the Pratt and Mary Lee coal beds and surface-fracture orientation in a selected part of the Rock Creek site, Oak Grove field, Jefferson County, Alabama. See figure 1 for location of Oak Grove field.

Sequatchie anticline can be traced into a thrust fault, a decollement that ramped upward to form the Sequatchie structure must be present beneath the flat-bottomed Coalburg syncline. Therefore, the small-scale thrust faults and deformed coal beds within the syncline may be minor decollements and ramps related to the Appalachian orogen.

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 distribution and cycle thickness is presented later in this report. The structural cross section (fig. 7) shows thickening of cycles on the downthrown side of a normal fault, thus providing further documentation of synsedimentary fault movement. The predominance of horst-and-graben structure in the Black Warrior basin of Alabama (fig. 6) indicates a genesis related to extensional tectonics. In Mississippi, the faults closely parallel the Ouachita orogen and increase in displacement toward the orogenic front. Therefore, the extensional faulting has been interpreted as a response to thrust loading in the Ouachita orogen (Hines, 1988). However, it is unclear whether initial development of normal faults was during Ouachita orogenesis, or whether the faults have pre-Alleghanian precursors that were reactivated.

Structural relationships indicate that joint and cleat systems in the Black Warrior basin have a polyphase origin. Although cross-cutting relationships are inconsistent in many places, in the Jim Walter No. 4. Mine, cross-cutting relationships indicate that, in that area, the coal cleat formed first, followed by the northwest-oriented set I joints, and then by the northeast-oriented set II joints (Epsman and others, 1988). The coincidence of joint system A with the Coalburg syncline plus the orthogonal relationship between joint orientation and the axial trace of the Sequatchie anticline suggest that the joints formed during the Alleghanian orogeny or during post-Alleghanian relaxation. Dipping joints that are perpendicular to bedding on some Alleghanian folds suggests that development of some northeast joints preceded folding.

Cross-cutting relationships and the uniformity of cleat direction throughout the study area suggest that cleats began to form before Alleghanian thrusting. The regional face-cleat orientation in Alabama is unusual because the face cleat in the Appalachian basin is generally perpendicular to

Alleghanian fold axes (Nickelsen and Hough,1967; McCulloch and others, 1974). One interpretation is that the regional cleat system formed early in response to northeast-southwest layer-parallel compression related to Ouachita orogenesis. The localized set of cross fractures on the Blue Creek anticline apparently postdates the regional cleat system and probably is genetically related to the Appalachian orogen (Murrie and others, 1976; Ward and others, 1984).

## Mesozoic Rifting

Mesozoic rifting related to the opening of the Gulf of Mexico and subsidence of the Mississippi Embayment is 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, 1985). Absence of Triassic and Jurassic strata in the Black Warrior basin makes structural history during this time uncertain. Extensional faulting may have continued during the Mesozoic, but normal faults have not displaced Upper Cretaceous strata (figs. 5, 8). Thus, fault activity in the Black Warrior basin apparently ceased before the Late Cretaceous.

## Cenozoic Epeirogenesis

The Cenozoic history of the Black Warrior basin evidently has been dominated by regional erosion and the development of unloading joints. 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).

Development of a northeast-oriented compressional stress field related to Ouachita orogenesis may have caused formation of the western joint set. However, scarcity of northeast-oriented joints in underground mines (Epsman and others, 1988) suggests that many of the joints are unloading structures related to the modern compressional stress field for North America recognized by Engelder (1982).

At the Jim Walter Resources No. 4 Mine in Brookwood field, the compressional stress field is oriented east-northeast (Park and others, 1984). Induced fractures generally align with the local maximum horizontal compressive stress and are therefore indicators of stress conditions at the point of fracture. Induced fractures in Brookwood field are oriented east-northeast to east-west (Epsman and others, 1988) in agreement with Park and others' (1984) work. Although data are scarce in Oak Grove field, induced fracture azimuth is approximately 70° (Lambert and others, 1988).

Perhaps an Ouachita stress field caused initial formation of the northeast joint set, and the similarly oriented modern stress field influenced the development of unloading joints. Deviation of the dominant joint orientation at the surface in Brookwood field from the contemporary east-northeast stress by as much as 30° may be explained by residual strain controlling fracture orientation or by local variation of the stress vector.

## COAL QUALITY AND GAS COMPOSITION

### INTRODUCTION

Few regional studies of rank and grade trends in the Black Warrior basin have been made (Semmes,1920, 1929; Culbertson, 1964; Murrie and others, 1976; McFall and others, 1986), and a general synthesis of all the available data is lacking. Gas-composition data obtained from conventional and coalbed-methane reservoirs in the Black Warrior basin were used to determine the origin of the gas. The principal objectives of this section are to present a regional framework of rank, grade, and gas-composition parameters in the Black Warrior basin of Alabama and to relate these parameters to the occurrence and producibility of coalbed methane.

Understanding coal-quality parameters is important in the exploration for coalbed methane, because rank and grade determine how much methane may have been generated and retained by coal. A significant amount of catagenetic (thermal) methane is not generated until coal reaches bituminous rank (Jüntgen and Klein, 1975), and high ash content may adversely affect methane retention in coal (Wyman, 1984). The effect of sulfur on the occurrence and producibility of coalbed methane is presently unknown, but high sulfur content may adversely affect the quality of methane and production water. Analysis of gas composition may verify that the methane was indeed derived from coal (Rightmire, 1984).

# METHODS

Maps of volatile matter (dry, ash-free), Btu content (moist, mineral-matter free), ash (dry), and sulfur (dry, ash-free), were prepared for coal groups of the Black Creek-Cobb interval. A map of vitrinite reflectance in the Mary Lee coal group was also prepared. Sample localities for chemical analyses are from throughout the Pottsville outcrop area (figs. 14-18), and data for the Mary Lee and Pratt coal groups are particularly abundant. Volatile-matter, Btu, ash, and sulfur values are available for nearly all data points. Where analyses from more than one coal bed in a coal group were available, the average value was plotted for each rank parameter. New vitrinite-reflectance samples are mostly from mines in the Pottsville outcrop area.

For grade parameters, more specifically ash and sulfur content, only data from selected coal beds in the Black Creek, Mary Lee, Pratt, and Cobb coal groups were used. In the Black Creek group, data from the Black Creek, Jefferson, and Murphy coal beds of McCalley (1900) were used, and in the Mary Lee coal group, data from the Mary Lee and Blue Creek coal beds were used, although a separate map of sulfur content in the New Castle coal bed was also prepared. In the Pratt coal group, data were mapped for the Pratt, American, and Nickel Plate coal beds.

Coal analyses used in this report were provided by mining companies to the Geological Survey of Alabama or were obtained from the National Coal Resource Data System (NCRDS) operated by the U.S. Geological Survey. The published analyses of Fieldner and others (1925), Shotts (1956, 1960), and Fanning and Moore (1989) were used for areas where other data are scarce. Locality information for many of those analyses is poor, but most of the analyses can be assigned to a specific mine.

The method by which coal is treated before analysis greatly influences analytical results. Some investigators use heavy-liquid separation to divide coal into fractions of differing density before analysis; density of the cleaned coal typically ranged from $<1.50$ to $<1.65$ g/cc. Many of the NCRDS analyses were made using uncleaned coal.

Mean-maximum vitrinite reflectance was measured using standard procedures (Stach and others, 1982; ASTM standard D2798-85). Vitrinite-reflectance measurements were made using channel and

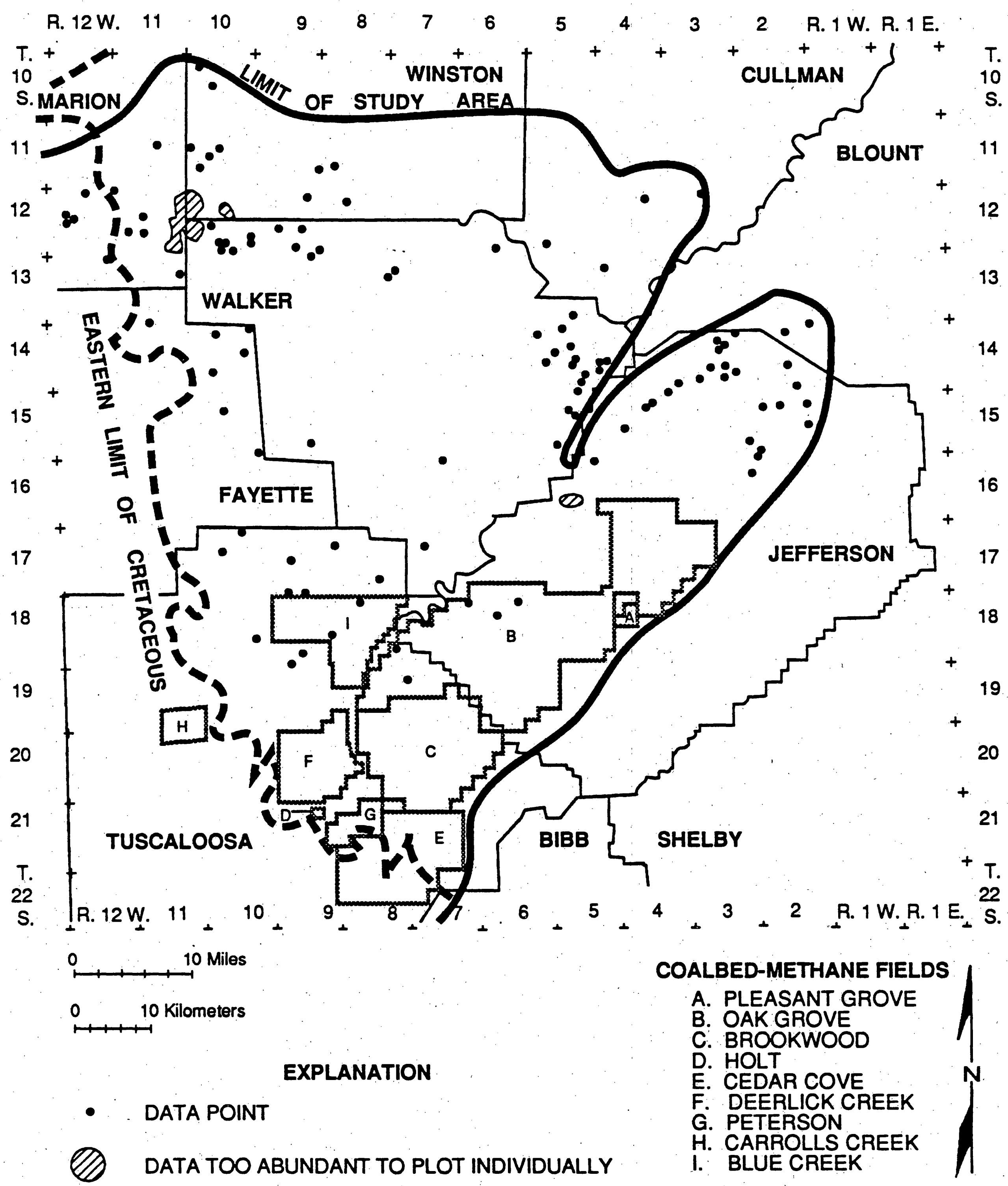



Figure 14. Sample location, Black Creek coal group.

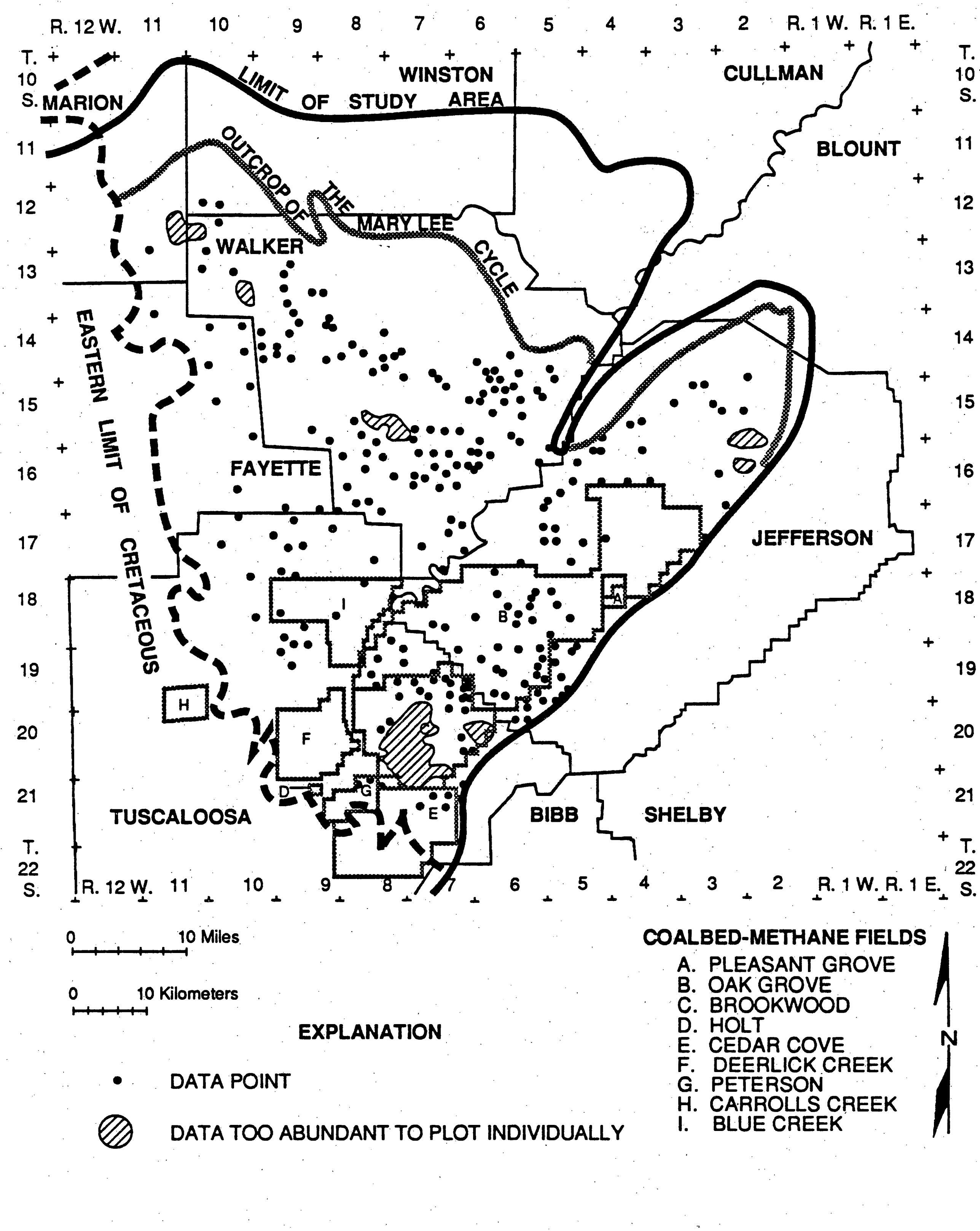



Figure 15. Sample location, Mary Lee coal group.

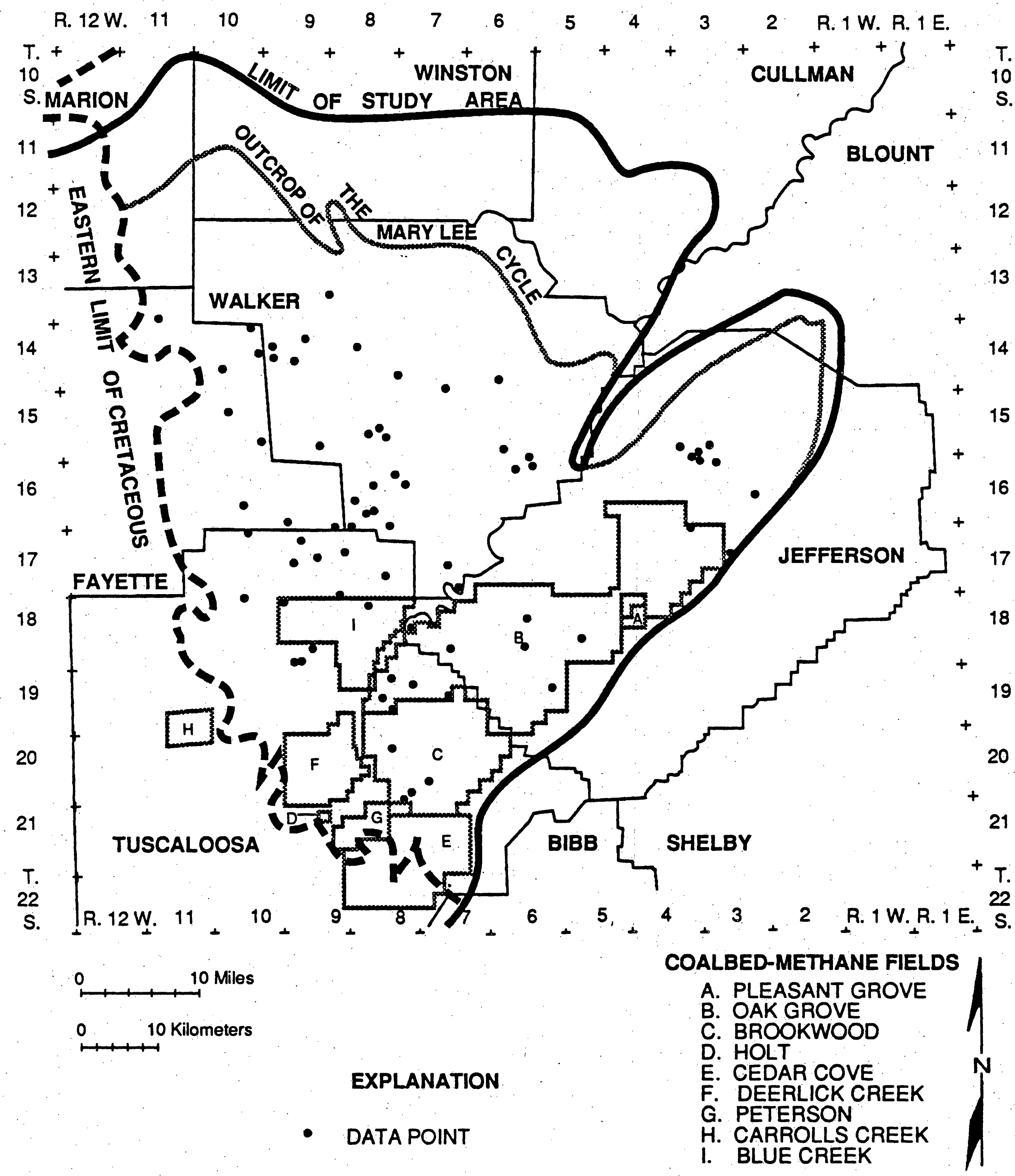



Figure 16. Sample location, New Castle coal bed, Mary Lee coal group.

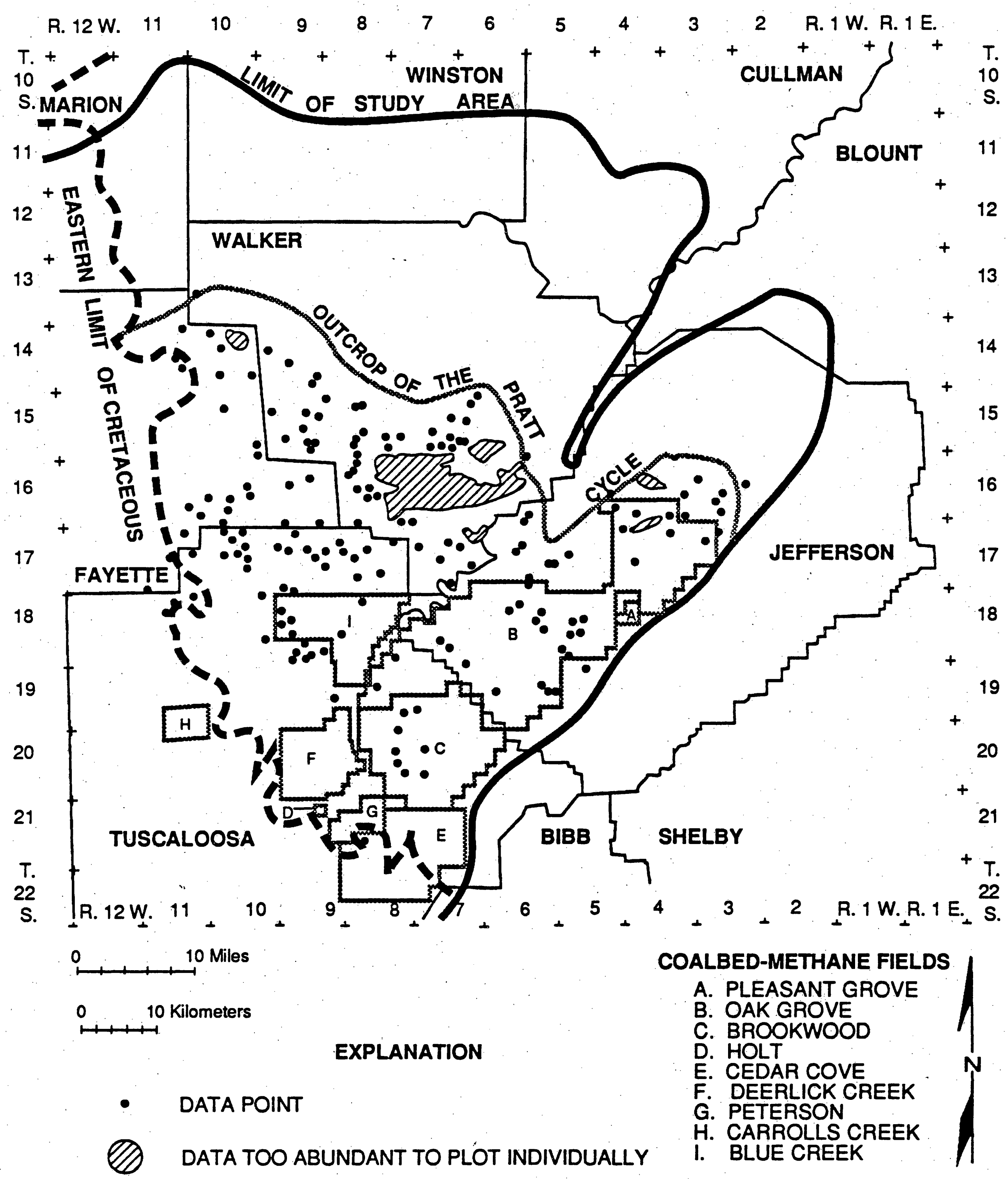



Figure 17. Sample location, Pratt coal group.

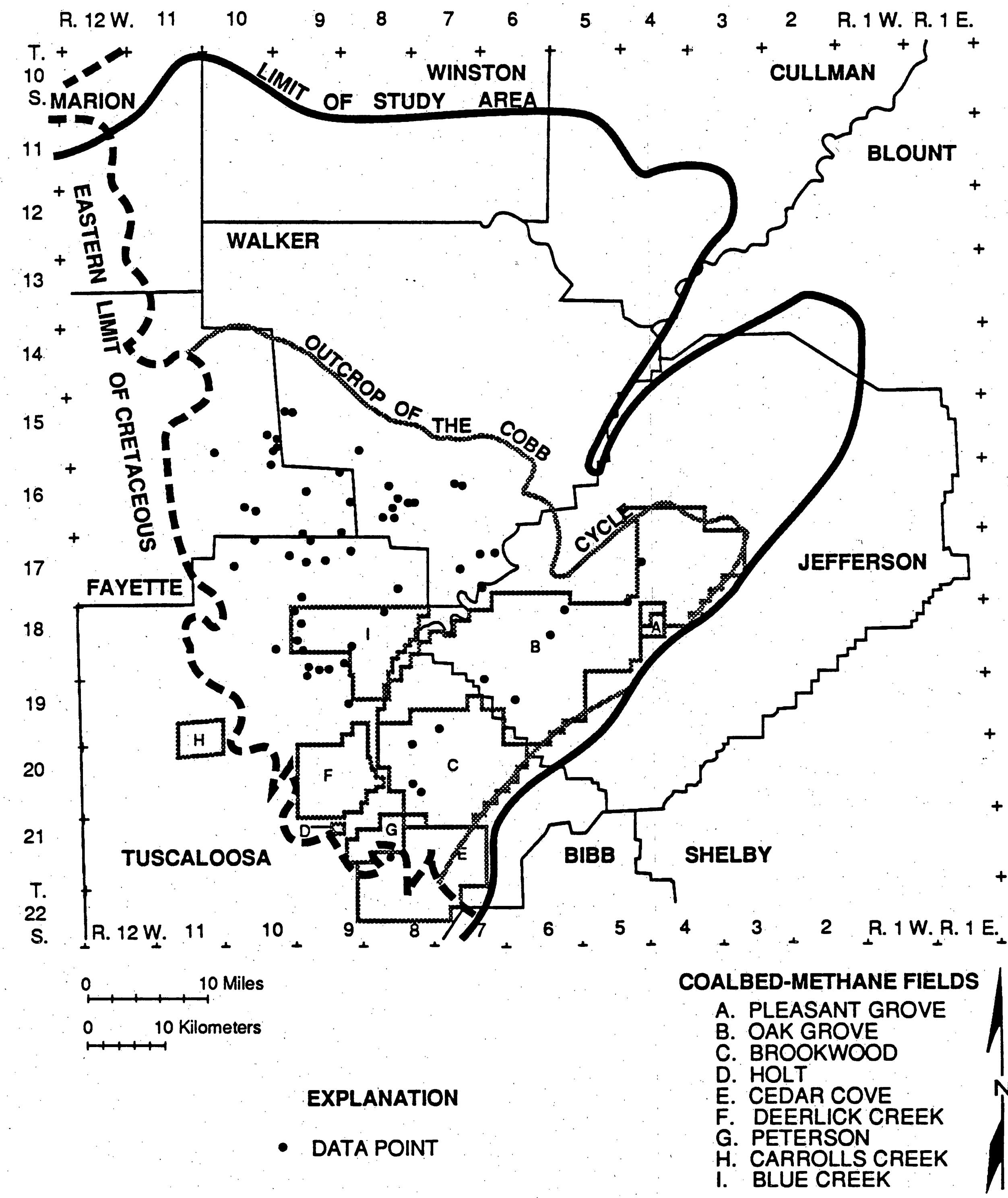



Figure 18. Sample location, Cobb coal group.

column samples of coal from outcrops and mines and coal cuttings from oil and gas wells; some measurements were compiled from published and unpublished sources. Several measurements come from coal groups other than the Mary Lee; vitrinite reflectance at the level of the Mary Lee was estimated from these data. In many places, the coal-group identification given by the original authors was incorrect. Using geophysical well logs, the correct stratigraphic position was determined. Additional vitrinite-reflectance data have been published by Hildick (1982), Robertson Research (U.S.) Inc. (1985), Hines (1988), and Geochem Laboratories (1986).

A vitrinite-reflectance profile was made in the area of high-rank coal using data from a core drilled by Jim Walter Resources, Inc. Other vitrinite-reflectance profiles have been made by Robertson Research (U. S.), Inc. (1985), Geochem Laboratories (1986), and Hines (1988). Telle and others (1987) published estimates of paleogeothermal gradient based on vitrinite-reflectance profiles. However, the profiles themselves have not been published.

# RESULTS

## Rank

Coal rank in the Black Creek-Cobb interval ranges from low-volatile bituminous to high-volatile C bituminous, and all coal groups have a similar rank pattern (figs. 19-27). Table 2 is an abbreviated classification of coal rank in terms of heating value, volatile-matter content, and vitrinite reflectance. The highest rank coal (lowest volatile-matter content) in the Black Warrior basin occurs along the Tuscaloosa County-Jefferson County border in the Coalburg syncline immediately northwest of the Blue Creek anticline. In the Black Creek, Mary Lee, and Pratt coal groups, the coal is of low-volatile bituminous rank (figs. 19-21). However, in the Cobb coal group, the coal is only medium-volatile bituminous in rank (fig. 22).

Volatile-matter content increases sharply by approximately 6 percent to the southeast across the the northwest limb of the Blue Creek anticline (figs. 6, 19-22). This trend is particularly conspicuous in the Mary Lee coal group because data are particularly abundant (fig. 20). The trend also is visible in the Pratt coal group but is less well defined owing to a paucity of data (fig. 21). The structural cross

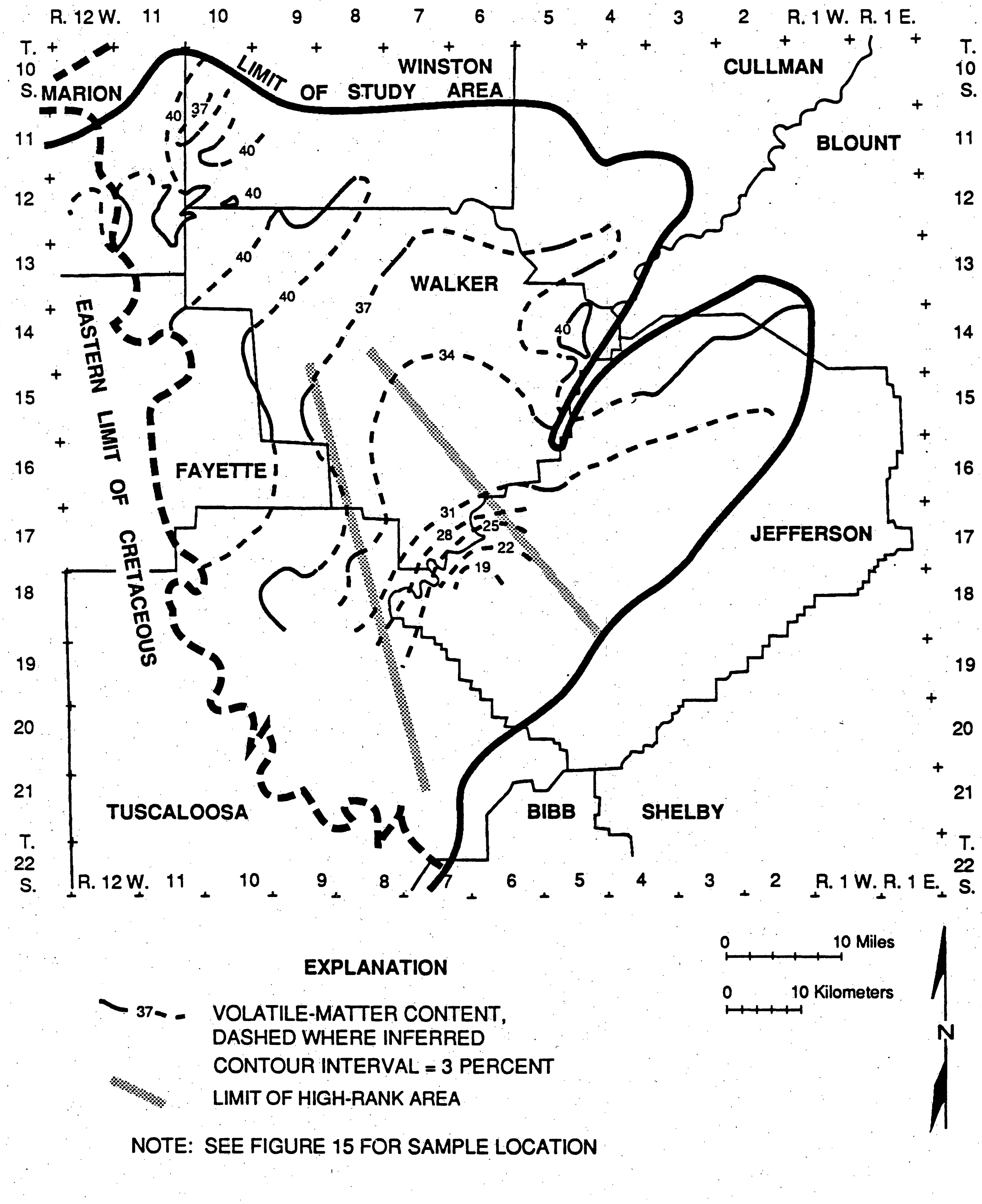



Figure 19. Map of volatile-matter content (dry, ash-free) in the Black Creek coal group.

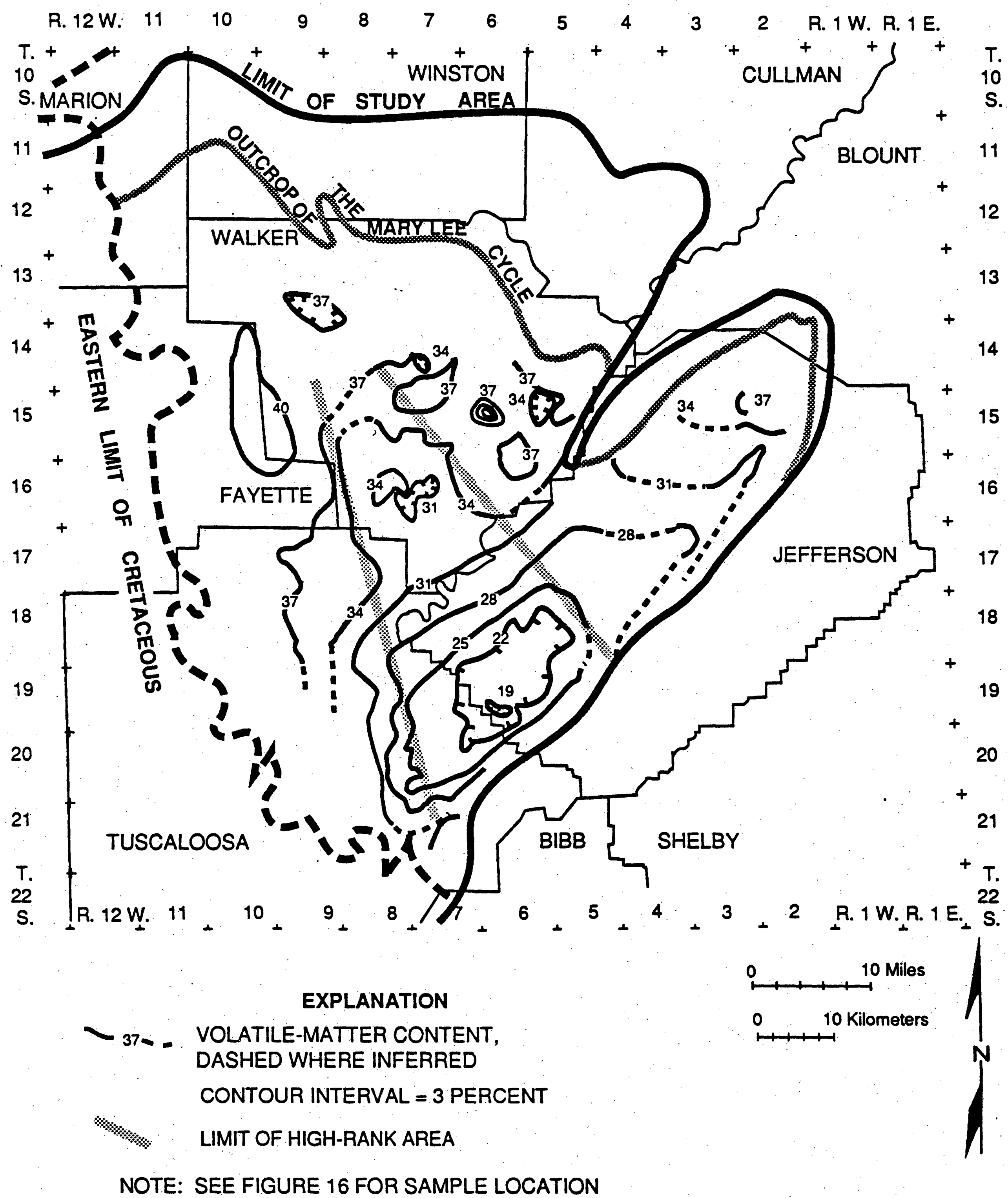



Figure 20. Map of volatile-matter content (dry, ash-free) in the Mary Lee coal group.

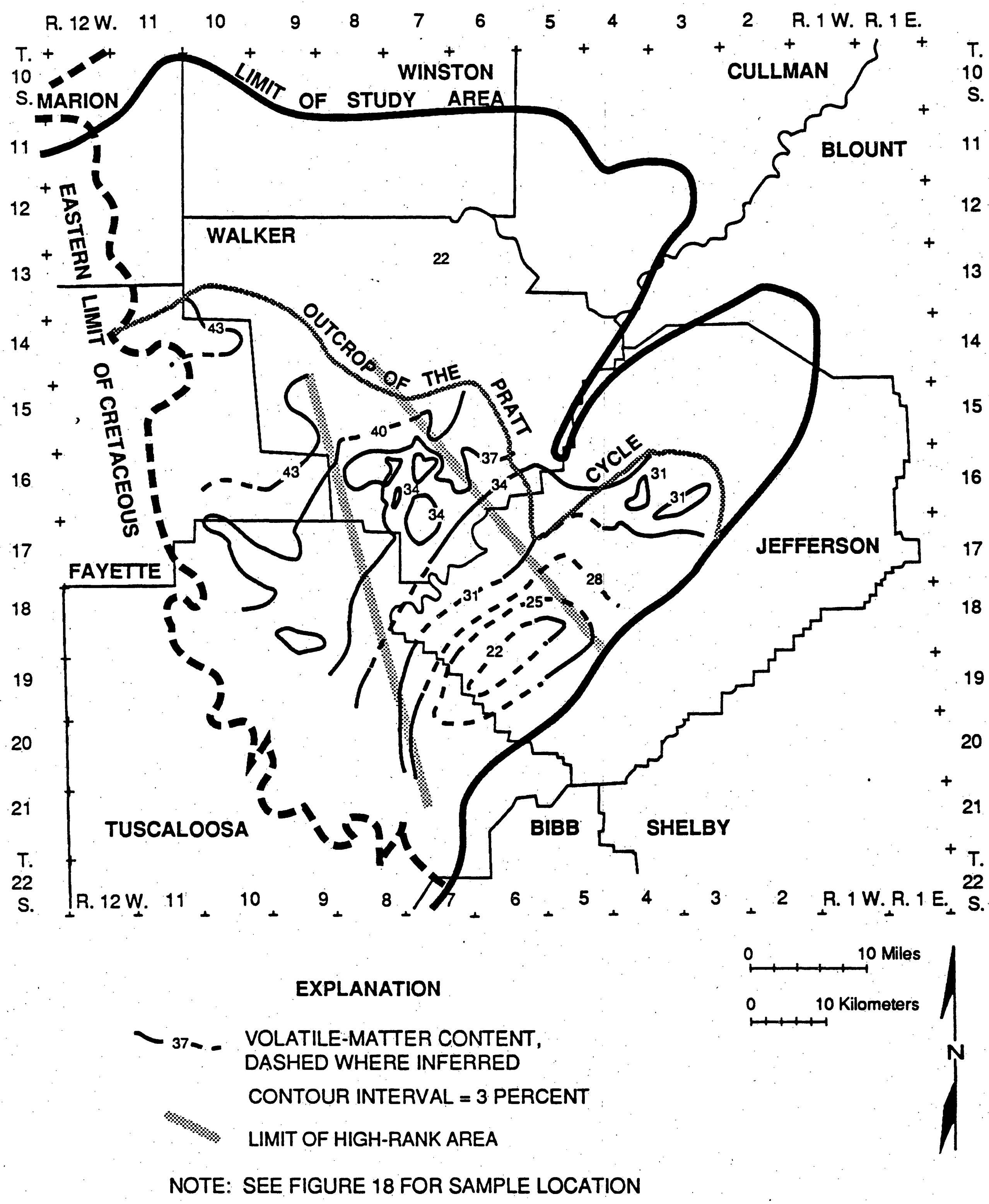



Figure 21. Map of volatile-matter content (dry, ash-free) in the Pratt coal group.

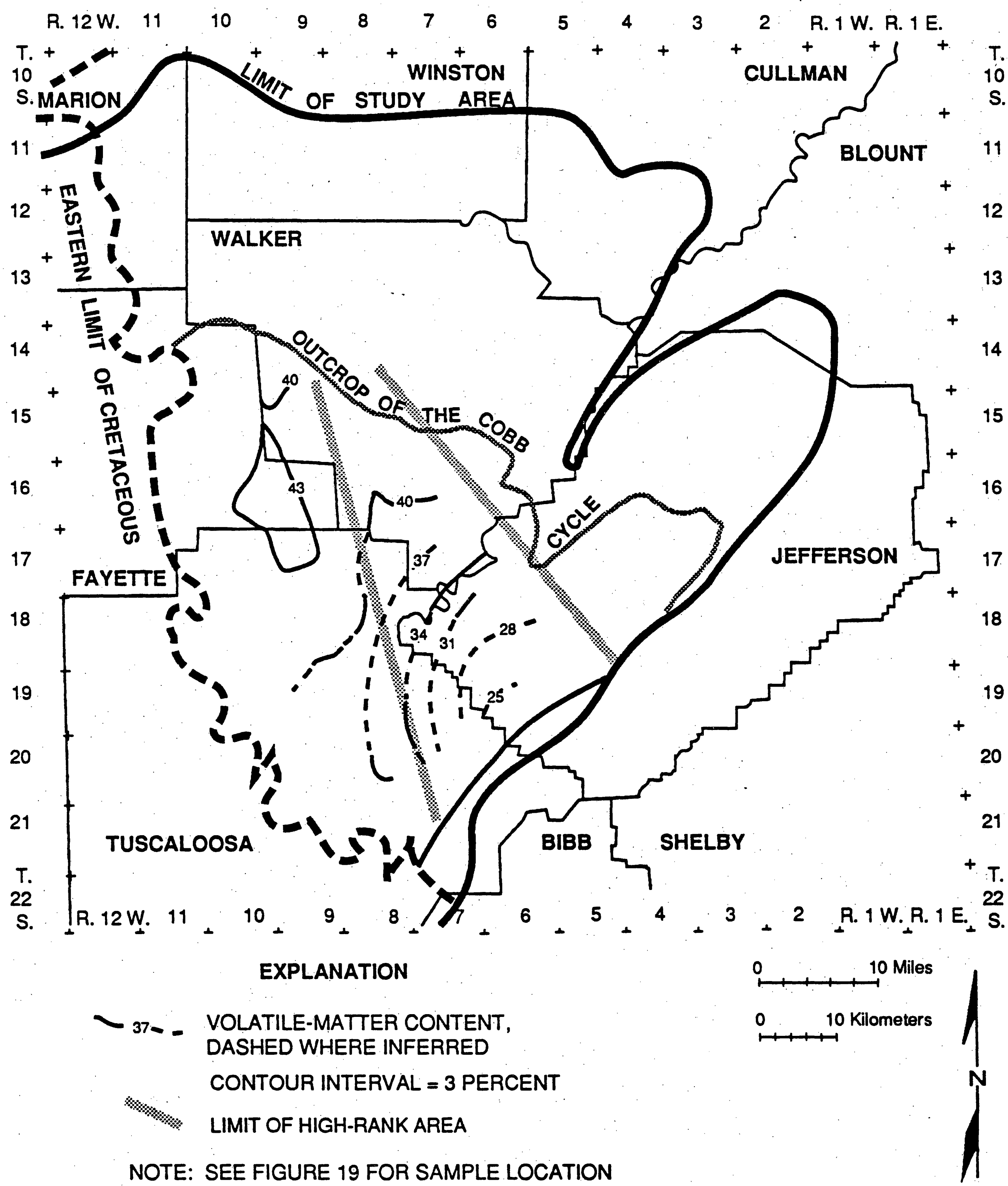



Figure 22. Map of volatile-matter content (dry, ash-free) in the Cobb coal group.

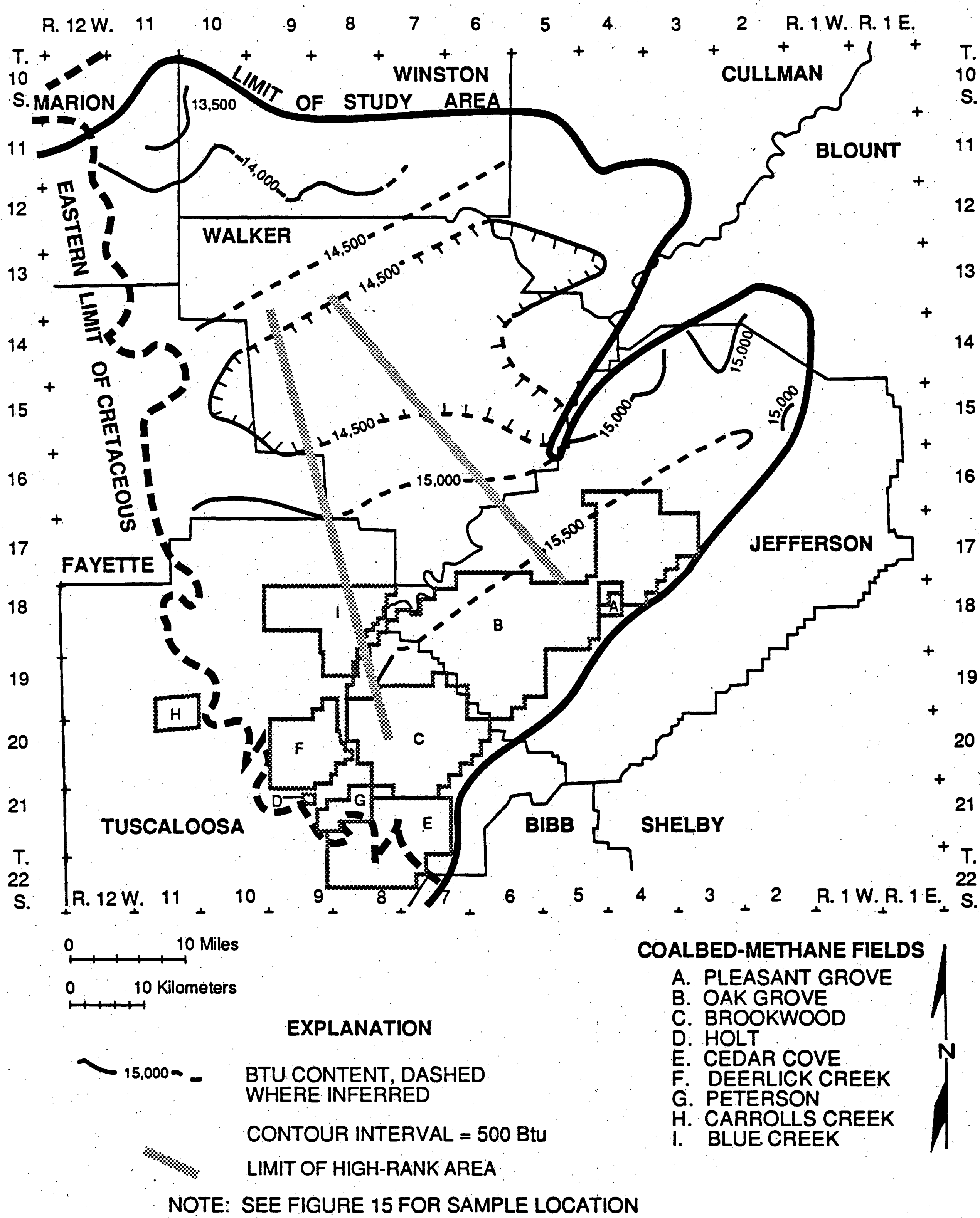



Figure 23. Map of Btu content (moist, mineral-matter free) in the Black Creek coal group.

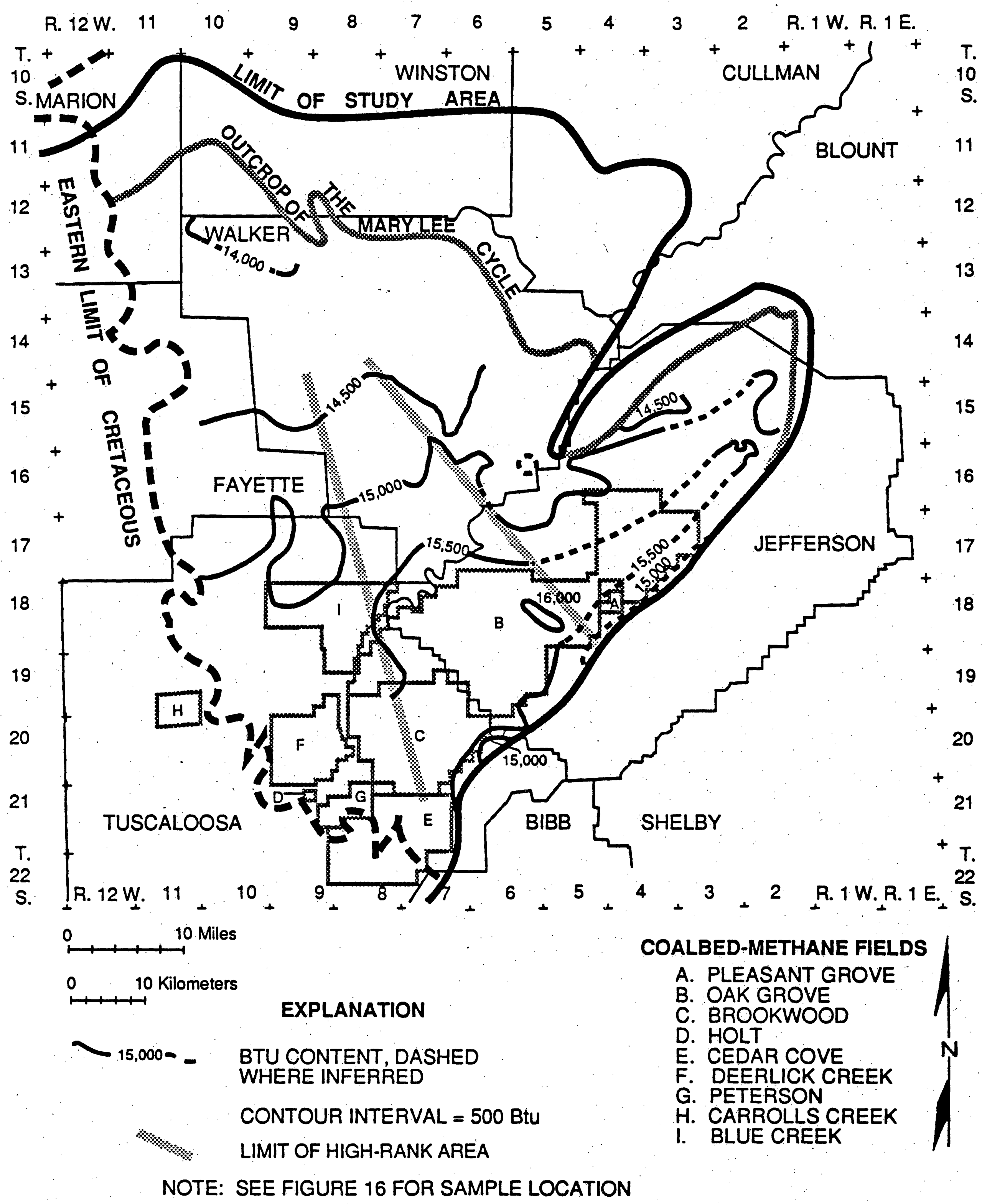



Figure 24. Map of Btu content (moist, mineral-matter free) in the Mary Lee coal group.

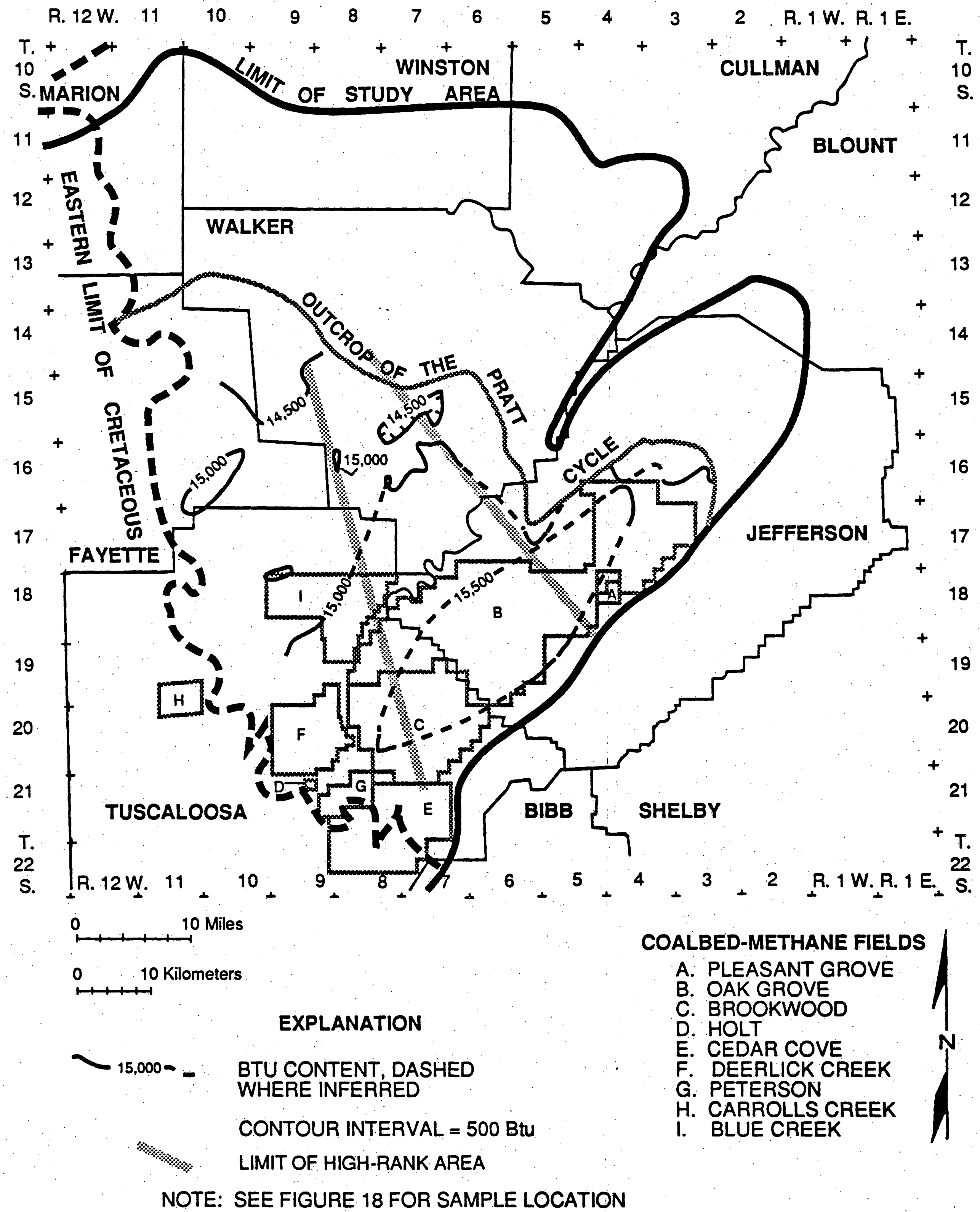



Figure 25. Map of Btu content (moist, mineral-matter free) in the Pratt coal group.

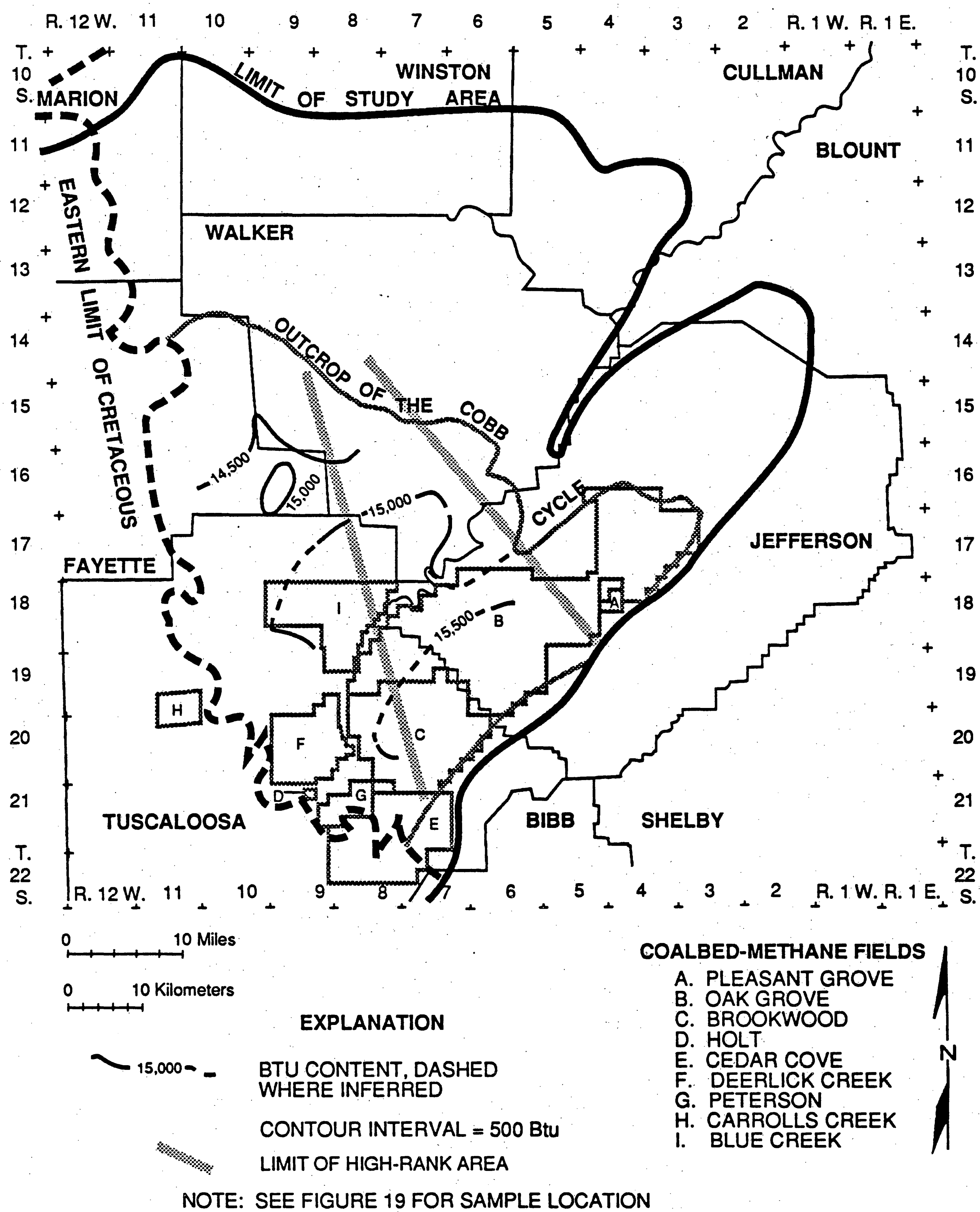



Figure 26. Map of Btu content (moist, mineral-matter free) in the Cobb coal group.

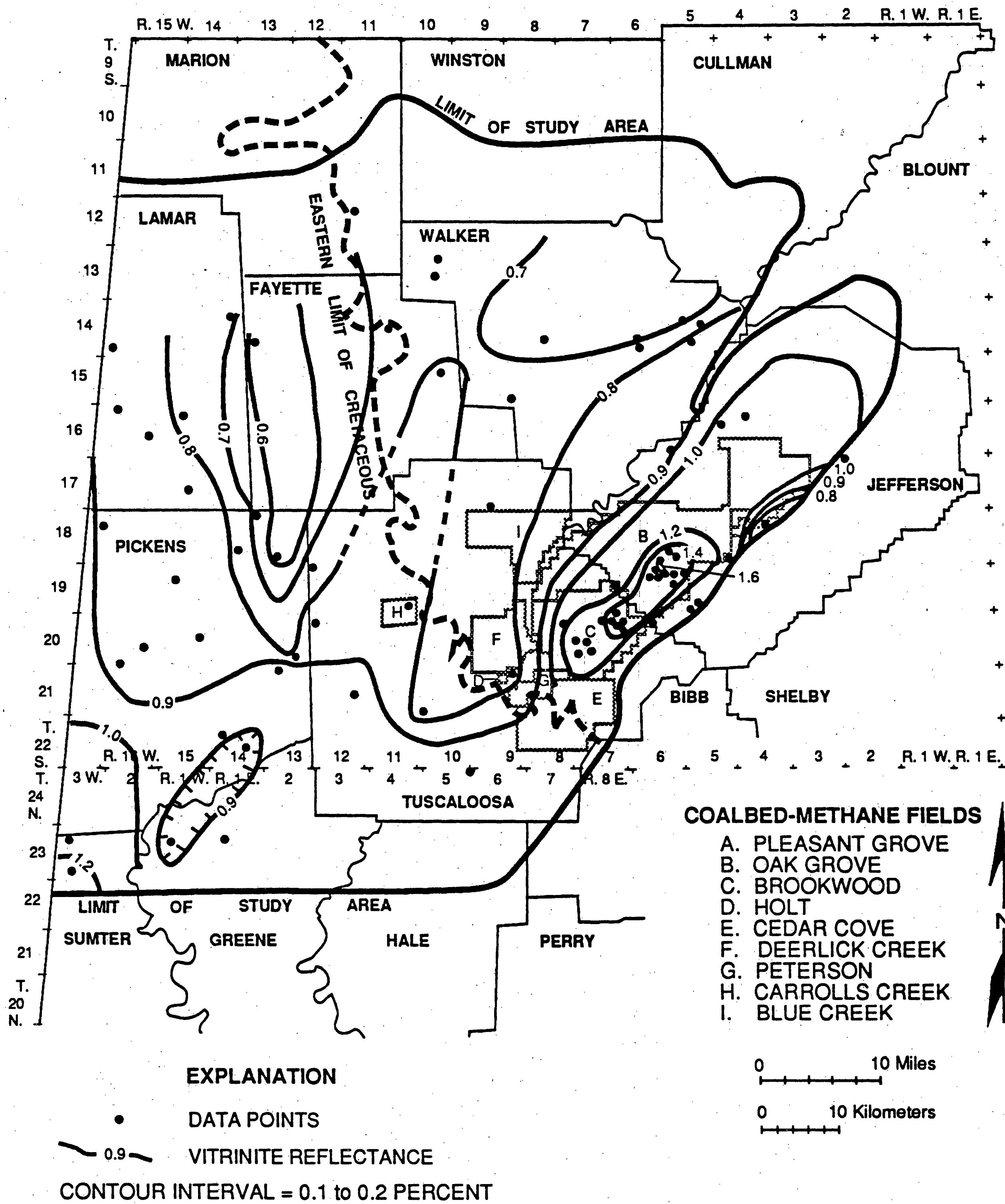



Figure 27. Map of vitrinite reflectance in the Mary Lee coal group.

Table 2. 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.

section shows that the isorank lines are subhorizontal and are oblique to bedding in the anticlinal limb (fig. 7).

The northeast and southwest boundaries of an area with anomalously high rank in Tuscaloosa and Jefferson Counties can be defined by two straight lines that extend into Walker County (fig. 20). Between the two lines, Volatile-matter content is generally 3 to 8 percent lower and heat content is approximately 400 Btu higher than in adjacent areas. The northeastern line extending from Jefferson County to Walker County 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. The southwestern line stretching from Tuscaloosa County to Walker County, however, does not coincide with any known structural feature. This rank pattern is discernible in all coal groups and is especially evident in the Mary Lee and Pratt groups (figs. 20, 21).

No chemical analyses are available for Pottsville coal below thick Cretaceous overburden; the only available rank information is vitrinite reflectance (fig. 27). Most coal in the Mary Lee coal group is of high-volatile A bituminous rank. However, the lowest rank coal in the Black Warrior basin of Alabama has an estimated high-volatile C bituminous rank and occurs in Fayette and northeast Pickens Counties. A single vitrinite-reflectance value indicates that medium-volatile bituminous coal is present in northern Sumter County.

## Grade

As with rank, most coal groups show similar geographic patterns of ash and sulfur content. The Black Creek group, however, has a unique grade pattern and contains a belt approximately 20 miles wide of low-ash coal (ash content less than 6 percent) (fig. 28). Ash content in the Mary Lee through Pratt coal groups tends to be least in a belt 10 to 15 miles wide along the southeast margin of the study area (figs. 29-31). In this belt, the ash content of most coal groups is commonly less than 12 percent.

In the Black Creek coal group, a high-ash belt containing coal with ash content higher than 6 percent occupies most of Walker County and extends southwest into eastern Fayette and northern Tuscaloosa Counties (fig. 28). In the Mary Lee through Cobb coal groups, a belt of high but variable ash content approximately 15 miles wide occurs immediately northwest of the low-ash belt (figs. 29-31). However, the high-ash belt is only approximately 5 miles wide in the Pratt coal group. Ash content is locally more than 18 percent in the Mary Lee coal group and is more than 12 percent in the Pratt and Cobb groups. The belt widens toward the west, but much of the data from the western part of the belt are from NCRDS files and may thus represent the differences in coal treatment mentioned earlier.

A third belt characterized by moderate ash content is located northwest of the high-ash belt (figs. 28-30). The Black Creek group generally has ash content less than 6 percent in outcrop, and some coal with more than 12 percent ash is present in eastern Fayette and northern Tuscaloosa Counties. Ash content in the Mary Lee coal group is generally 12 to 18 percent (fig. 29), and ash content in the Pratt coal group (fig. 30) is quite variable. The moderate-ash belt is not identifiable in the Cobb coal group (fig. 31).

The regional pattern of sulfur content can be divided into 3 belts (figs. 32-36) that generally coincide with the ash-content belts. Sulfur content is generally quite low in the low-ash belt, establishing the area as a high-quality coal belt. The pattern of sulfur content in the Black Creek coal group differs greatly from that of the Mary Lee through Cobb coal groups; Black Creek sulfur content

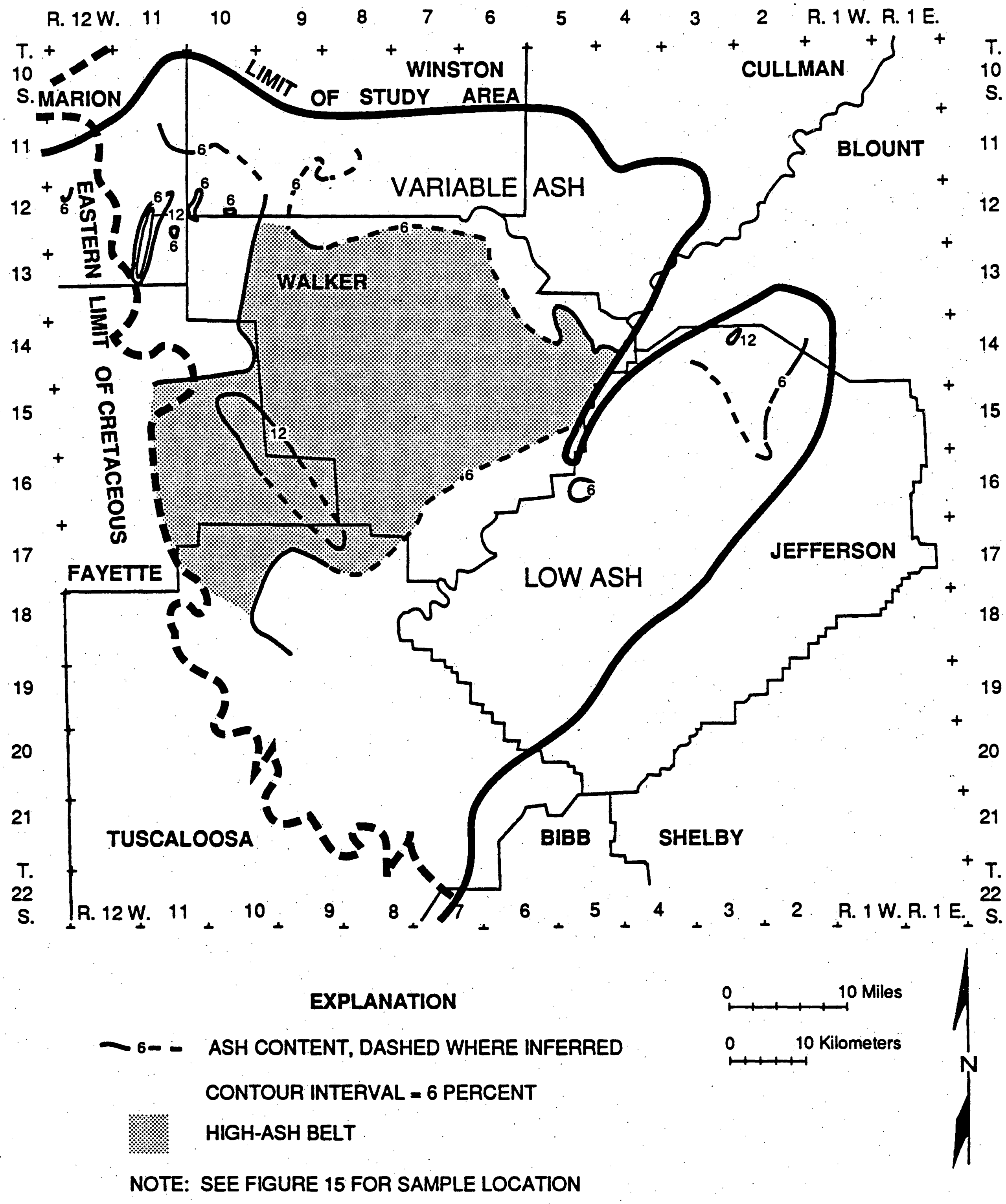



Figure 28. Map of ash content (dry) in the Black Creek, Murphy and Jefferson coal beds, Black creek coal group.

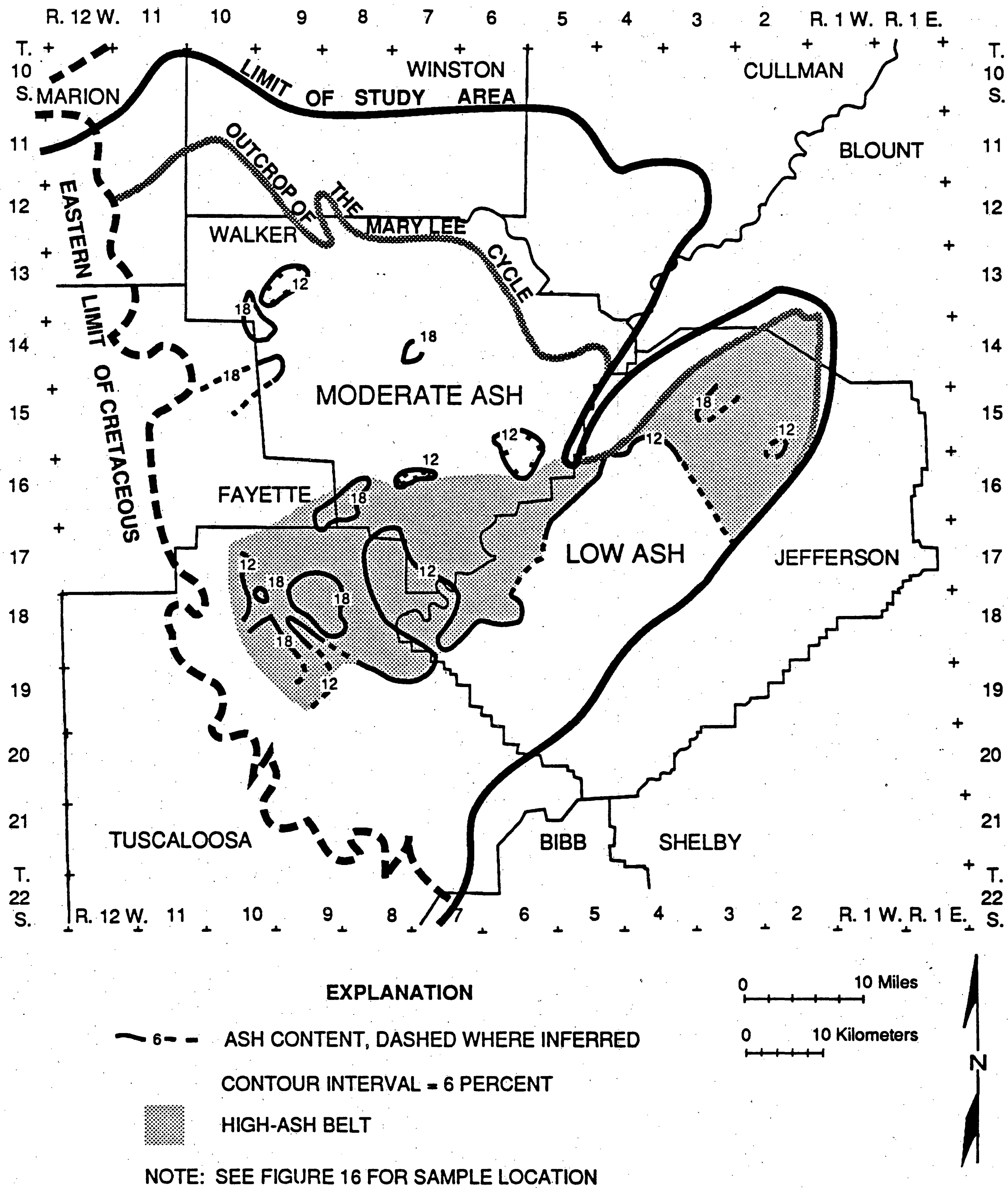



Figure 29. Map of ash content (dry) in the Mary Lee and Blue Creek coal beds, Mary Lee coal group.

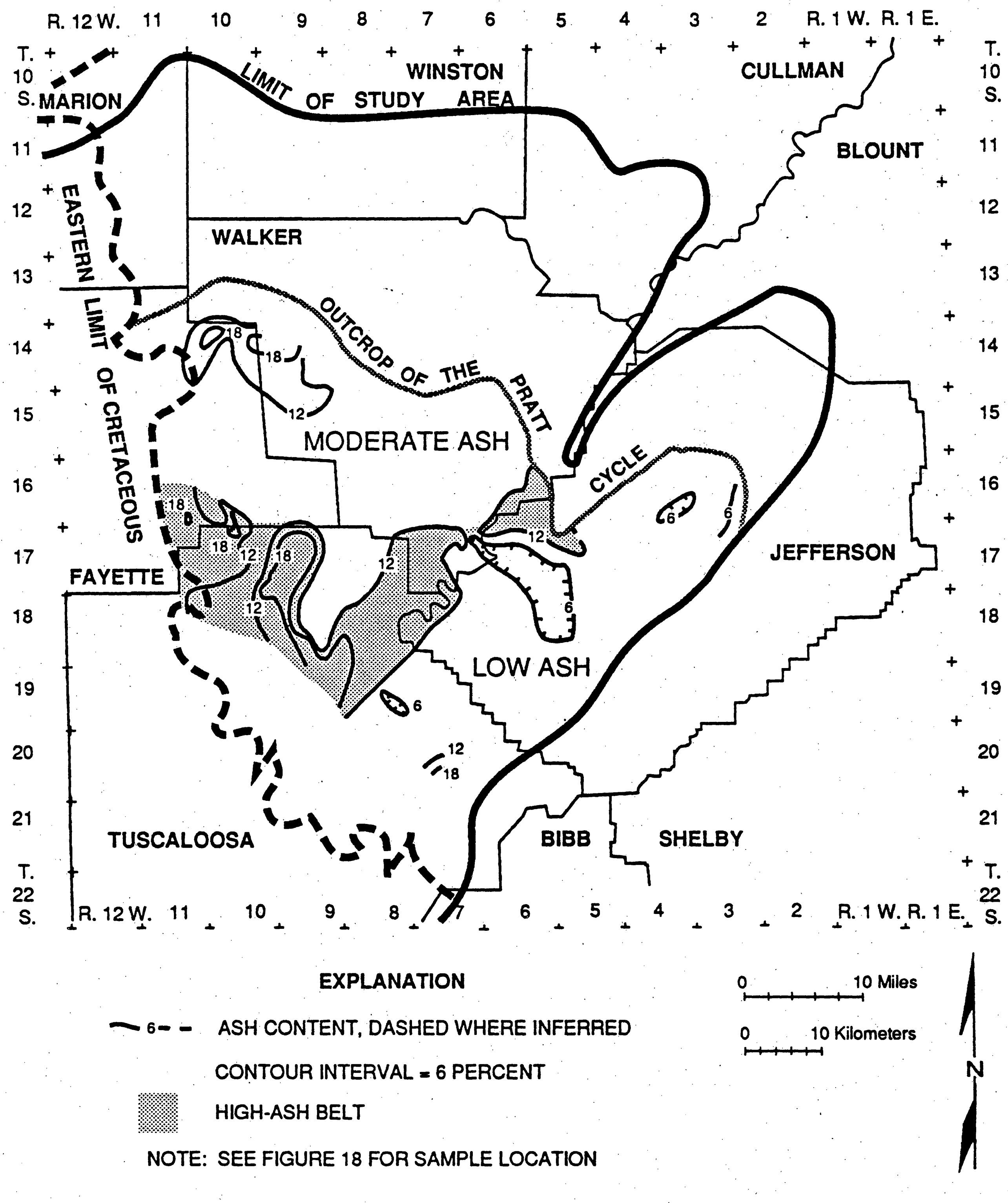



Figure 30. Map of ash content (dry) in the Pratt, American and Nickel Plate coal beds, Pratt coal group.

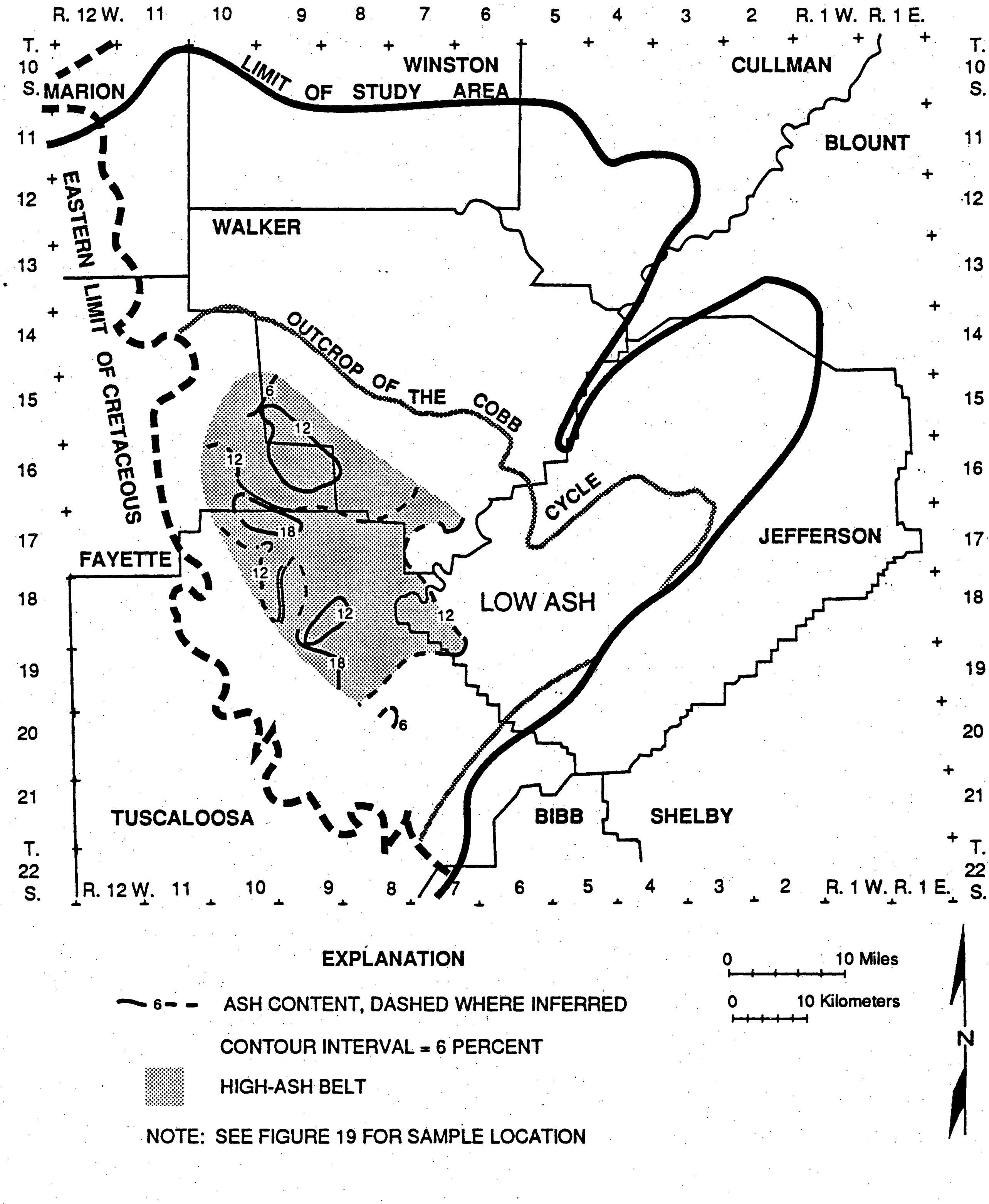



Figure 31. Map of ash content (dry) in the Cobb coal group.

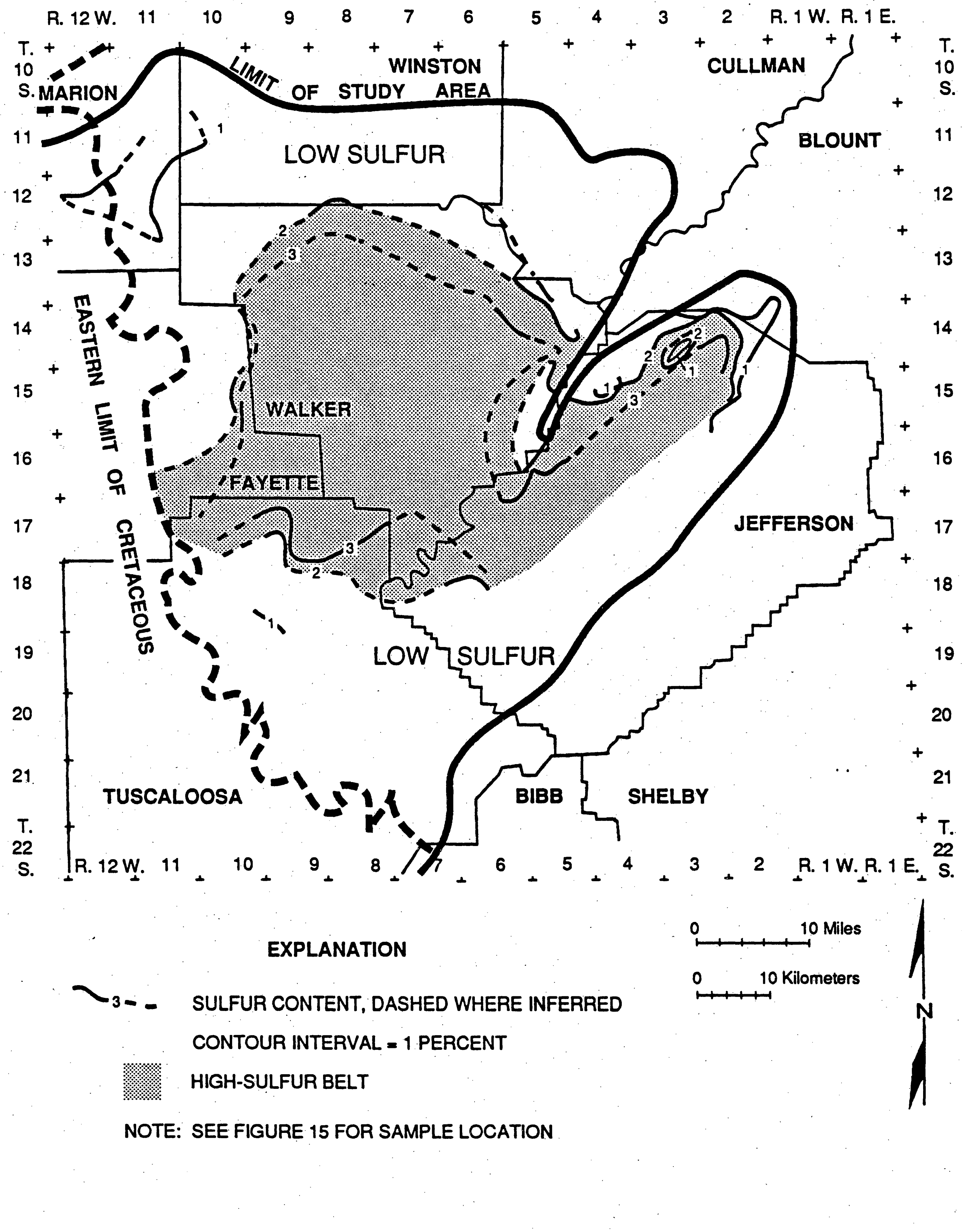



Figure 32. Map of sulfur content (dry, mineral-matter-free) in the Black Creek, Murphy and Jefferson coal beds, Black creek coal group.

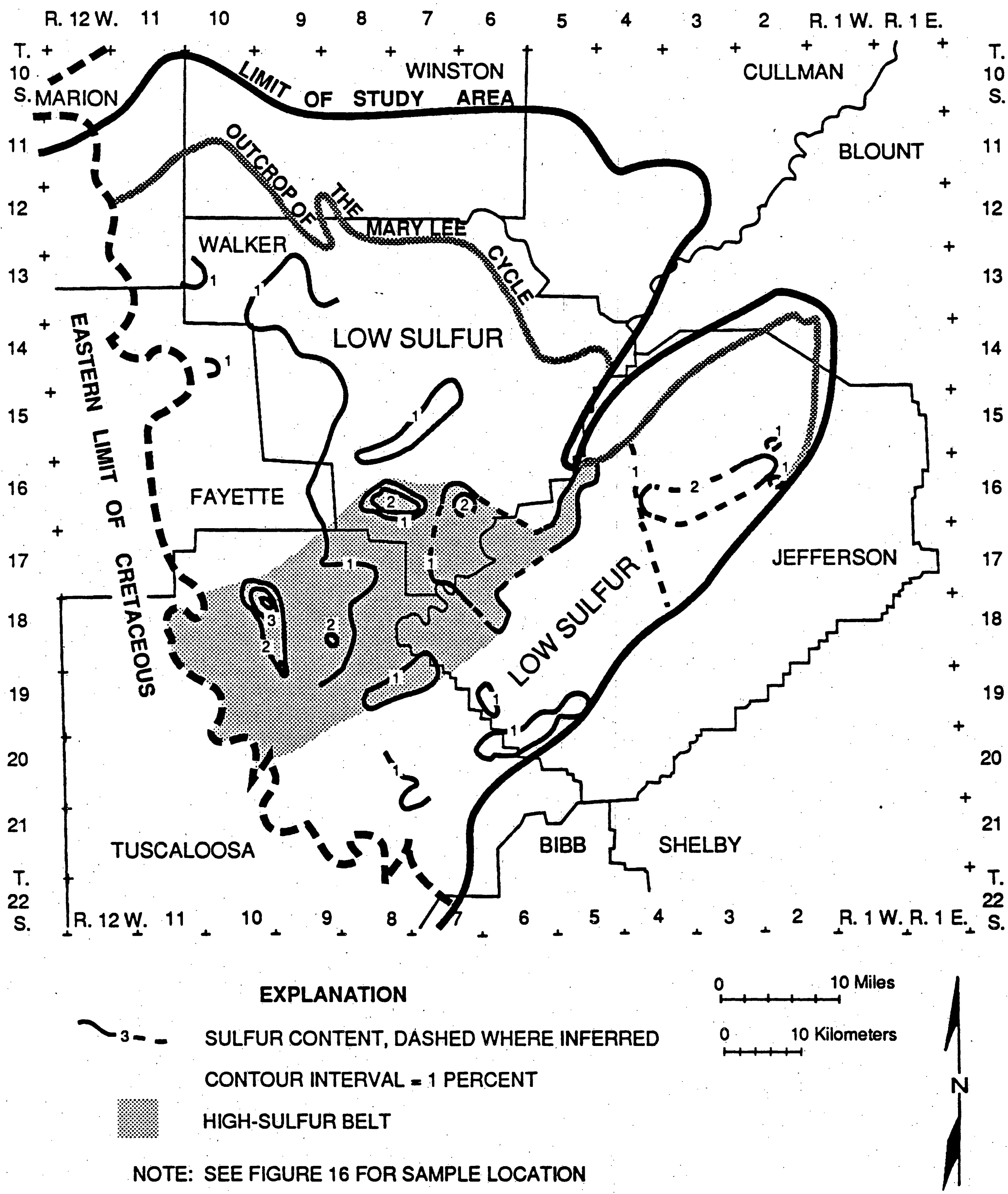



Figure 33. Map of sulfur content (dry, mineral-matter-free) in the Mary Lee and Blue Creek coal beds, Mary Lee coal group.

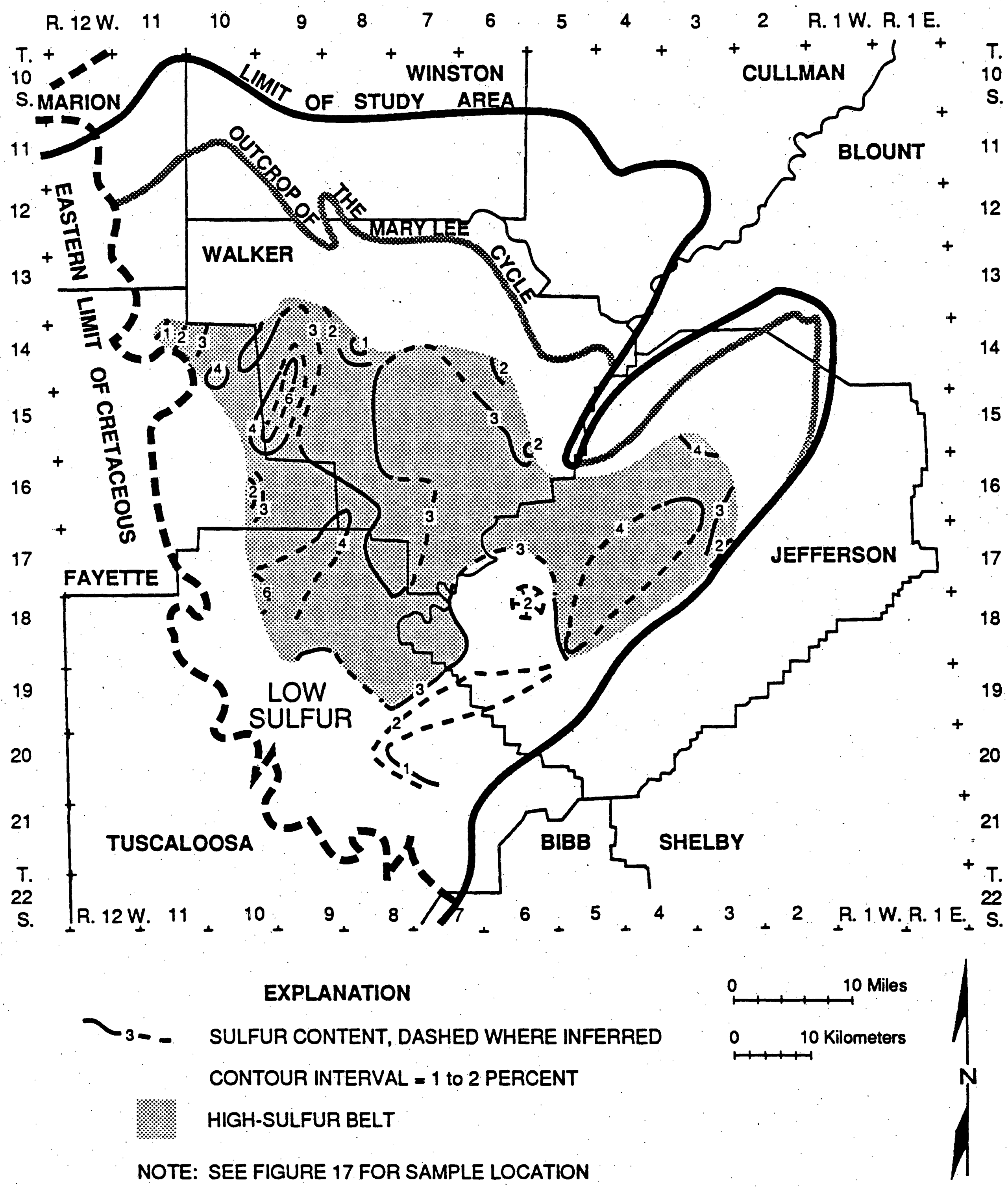



Figure 34. Map of sulfur content (dry, mineral-matter-free) in the New Castle coal bed, Mary Lee coal group.

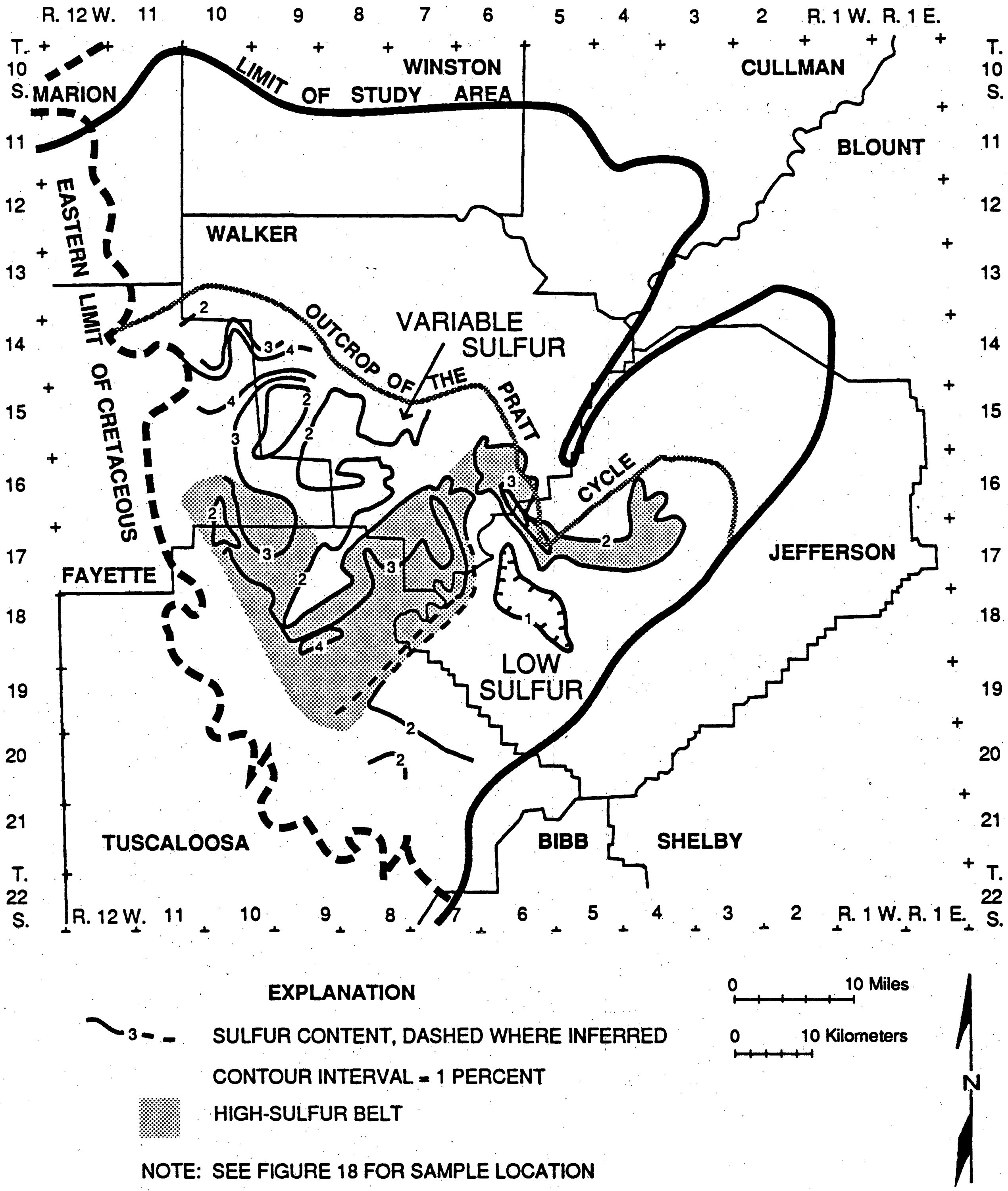



Figure 35. Map of sulfur content (dry, mineral-matter-free) in the Pratt, American and Nickel Plate coal beds, Pratt coal group.

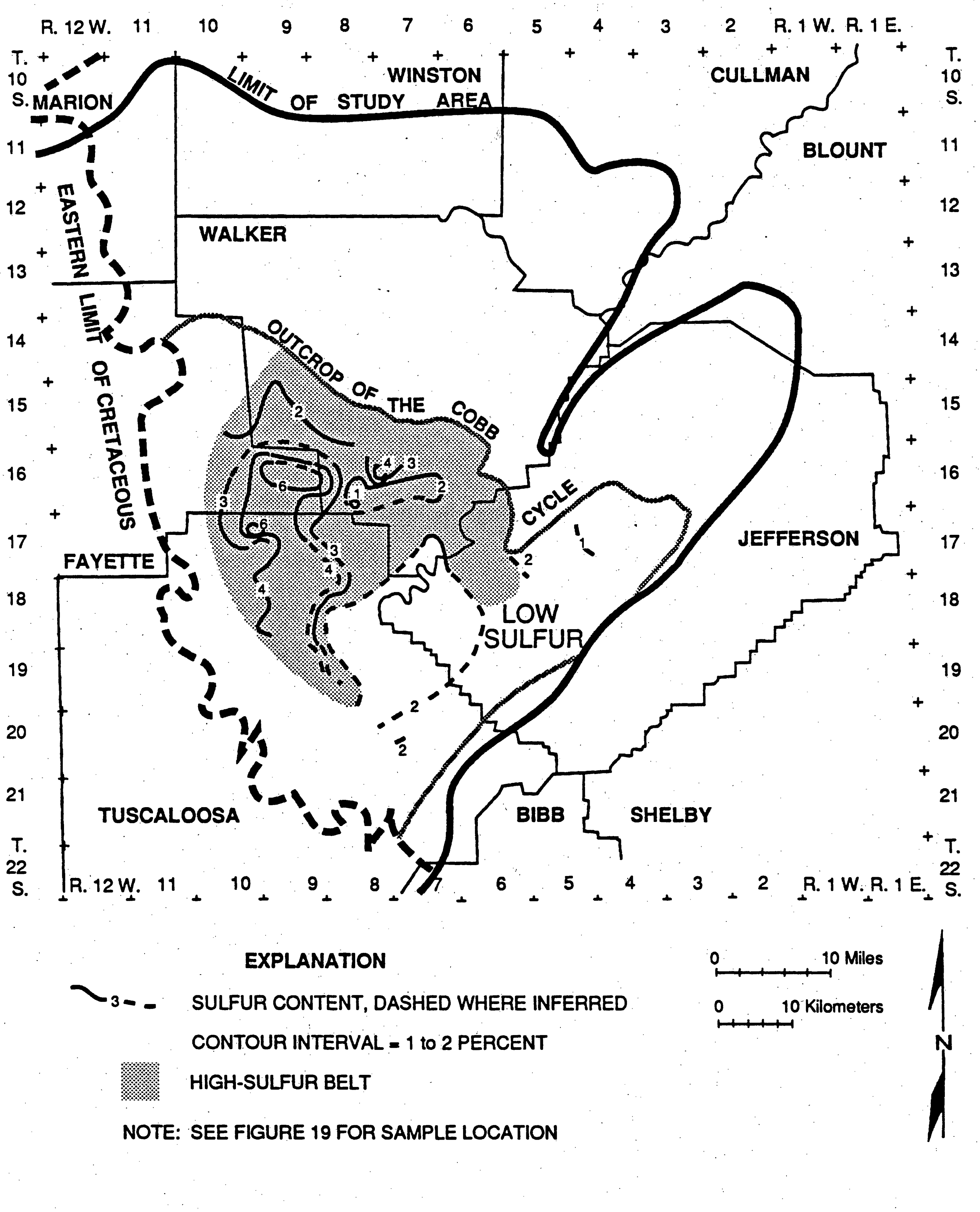



Figure 36. Map of sulfur content (dry, mineral-matter-free) in the Cobb coal group.

is lowest near its outcrop area in the northern and eastern parts of the study area (fig. 32). In the Mary Lee group, sulfur content is typically less than 1 percent (fig. 33), and in the Pratt, and Cobb groups, sulfur content is typically less than 2 percent (figs. 35, 36) in the high-quality belt.

The high-ash belt also contains coal with high sulfur content, establishing a low-quality coal belt. Sulfur content is consistently more than 2 percent in the Pratt coal group (fig. 35) but is variable in the Mary Lee and Cobb coal groups (figs. 33, 36). However, data from the Black Creek group are scarce (figs. 14, 32).

The moderate-ash belt contains coal with variable sulfur content, establishing an intermediate-quality coal belt. Sulfur content is generally less than 2 percent in the Mary Lee coal group (fig. 33) and is generally between 2 and 3 percent in the Pratt coal group (fig. 35). In the Cobb coal group, the intermediate-quality belt cannot be distinguished from the low-quality belt (fig. 36).

Because the New Castle coal of the Mary Lee group is the only coal bed proximally overlain by marine strata for which abundant data were available, sulfur content was mapped separately to test the relationship of sulfur content to marine overburden (fig. 34). Although sulfur content is commonly greater than in the other beds of the Mary Lee group, sulfur content is locally less than 3 percent in the high-quality belt. However, the low- and intermediate-quality belts are indistinguishable, so the regional sulfur pattern for the New Castle is similar to that of the Cobb coal group.

## Gas Composition

Methane in the Black Warrior basin of Alabama may be divided into three groups on the basis of isotopic variation ($\delta^{13}C_1$) and ethane ($C_2$) content (fig. 37; table 3). Gas from Mississippian conventional reservoirs, which are located in the deep subsurface of the western part of the study area, is characterized by a narrow range of isotopic variation and has a considerable ethane component. All of the Mississippian samples have $\delta^{13}C_1$ values between -47 and -50 parts per thousand (ppt). Two samples have a $C_2$ content of more than 3.5 percent and define one group,

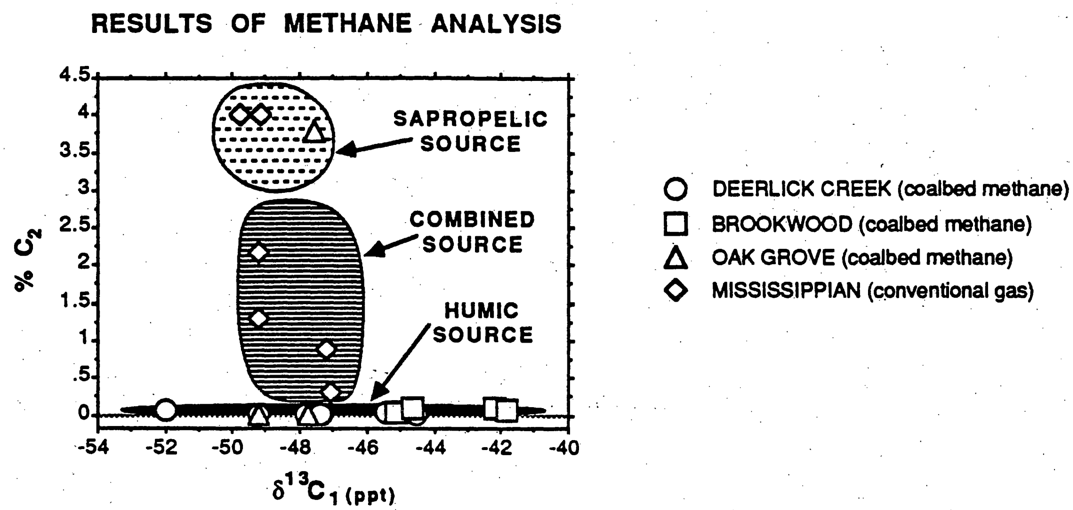



Figure 37. Scattergram showing ethane content and isotopic variation of gas in the Black Warrior basin of Alabama (unpublished data, courtesy of Dudley D. Rice, U.S. Geological Survey).

Table 3. 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.

whereas the remaining four samples have $C_2$ values ranging from 0.3 percent to 2.5 percent and define the other group. Distinction between the two groups of Mississippian gas does not represent a compositional discontinuity and is intended only to reflect difference in origin.

Coalbed methane has a different signature from the conventional gas (fig. 37; table 3). Coalbed methane is characterized by a wide range of $\delta^{13}C_1$ values, and $C_2$ values are less than 0.3 percent. Whereas the gas from Brookwood field has $\delta^{13}C_1$ values ranging between -41 and -46 ppt, the gas from Oak Grove and Deerlick Creek fields have a wide range of $\delta 13C_1$ values ranging from -44 to -54 ppt. One data point from Oak Grove field has an anomalously high $C_2$ content and has a $\delta^{13}C_1$ value similar to the Mississippian gas.

# DISCUSSION

## Nature and Timing of Catagenesis

Gas-analysis data indicate that Mississippian gas and coalbed methane in the Black Warrior basin of Alabama were derived from different sources (fig. 37). The high $C_2$ content of the Mississippian gas indicates a large contribution of gas from oil-prone, sapropelic kerogen, and some Mississippian gas is associated with oil (Rice and others, 1989). However, the low $C_2$ content of some samples indicates a major contribution from gas-prone, humic kerogen in some Mississippian reservoirs. Rice and others (1989) suggested that the conventional gas was derived from Mississippian shale units which contain a significant amount of sapropelic material.

The low $C_2$ content of the coalbed methane (fig. 37; table 3) is indicative of a humic source. Therefore, coal in the Pottsville is the probable source of coalbed methane in Alabama; this hypothesis is supported by the rank data. However, the anomalous $C_2$ content of one sample from Oak Grove field suggests local migration of gas from a Mississippian source. If this is indeed the case, then some coalbed-methane reservoirs in the upper Pottsville may contain a combination of in situ and migrated gas.

On a basin-wide scale, coal rank is difficult to relate to regional structural trends. However, the decrease in rank to the southeast across the northwest limb of the Blue Creek anticline in the high-rank area can be related directly to structure. Because the isorank lines are subhorizontal and do not parallel bedding on the anticline (fig. 7), coalification evidently postdated or occurred during the late stages of folding in the high-rank area.

Vitrinite-reflectance data indicate that rank increases southwest to medium-volatile bituminous in Sumter County (fig. 27). These data are from the deepest part of the Black Warrior basin in Alabama and are from a thrust sheet (fig. 6). Although a southwest increase in burial depth may explain the high rank, structural complications in Sumter County require that caution be used in interpreting the data solely in terms of burial depth.

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 area of Jefferson and Tuscaloosa Counties in terms of burial depth. Because no such structure exists (fig. 5), this trend may have been caused by a local increase in the paleogeothermal gradient. Perhaps high paleogeothermal gradient was related to high fracture density in the high-rank area (fig. 20). High fracture density may have enabled upward movement of hot fluid thereby enhancing the catagenetic process. However, the driving mechanism for the fluid is unclear. Gravity and magnetic data show no evidence for an igneous intrusion that may explain the rank anomaly.

The age of the principal catagenetic events in the Black Warrior basin of Alabama can be estimated. Because the Blue Creek anticline apparently was present before the main thermal episode associated with the high-rank area of Tuscaloosa and Jefferson Counties, maximum rank in this area was attained after Alleghanian thrusting. However, definition of the regional cleat orientation apparently preceded thrusting. Because cleat does not begin to form until the lignite stage, coalification was probably well under way throughout the study area by the Alleghanian orogeny.

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 coalification of the Pottsville had ceased before Tuscaloosa deposition. Hence, catagenesis in the Black Warrior basin evidently occurred in response to the Alleghanian orogeny and perhaps Early Mesozoic extensional tectonics.

### Controls on Coal Grade

Development of distinct belts of coal grade in the Pottsville suggests that a persistent geological feature controlled ash and sulfur content on a regional scale. However, the origin of this relationship is unclear. The high sulfur content of the New Castle coal bed can be related to marine sedimentation. An association of high-sulfur coal with marine overburden has long been known (Williams and Keith, 1963), so infiltration of marine water into peat following marine transgression may be the principal source of sulfur in the New Castle.

# SEDIMENTOLOGIC ANALYSIS

## INTRODUCTION

Several detailed subsurface syntheses of upper Pottsville sedimentation in the Black Warrior basin have been made using well logs from conventional petroleum wells (Cleaves, 1981; Thomas and Womack, 1983; Sestak, 1984; Hines, 1988; Thomas, 1988a). However, the advent of widespread drilling for coalbed methane in Tuscaloosa and Jefferson Counties has provided a wealth of subsurface data for the southeastern part of the basin where little data was previously available. Although the distinction between quartzose and lithic sandstone has been stressed in outcrop studies (Ferm and others, 1967; Horne and others, 1976), investigators have not mapped the two sandstone types in the subsurface. Furthermore, cyclicity has long been known to be one of the salient characteristics of Carboniferous coal measures (Udden, 1912; Weller, 1930; Heckel, 1984; Klein and Willard, 1989), but studies of the upper Pottsville in Alabama have not stressed recognition of regional genetic cycles.

This study takes new data into account and distinguishes quartzose and lithic sandstone in the subsurface. The primary objective of this investigation is to develop a cycle-based stratigraphic and sedimentologic framework to aid in the exploration for coalbed methane in the Black Warrior basin of Alabama. Because of new data from coalbed-methane wells, the depositional model presented here contrasts markedly with those of earlier investigators.

# METHODS

Density logs provide the principal data base for regional investigation of the Black Creek-Cobb interval (fig. 4). Four rock types were distinguished using density logs on the basis of variation in the gamma-ray, density, and neutron-porosity signatures (fig. 38). The rock types are (1) coal, (2) mudstone, (3) lithic (nonporous) sandstone, and (4) quartzose (porous) sandstone.

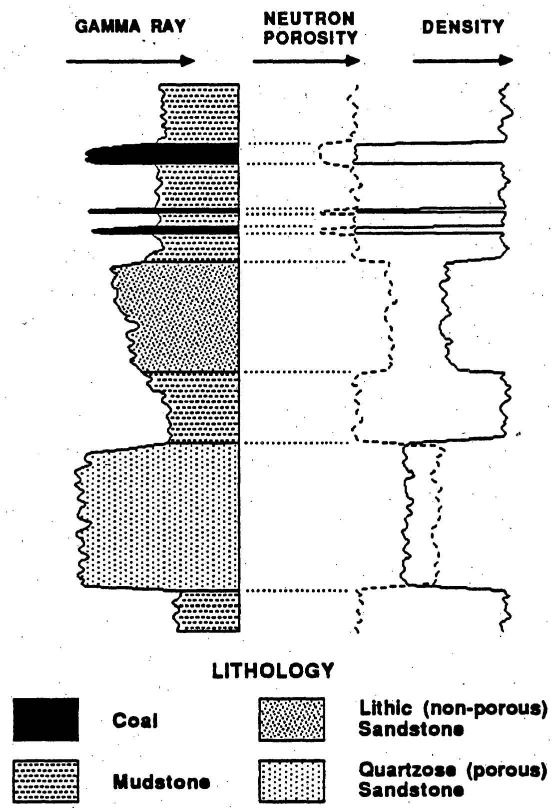



Figure 38. Sample geophysical log depicting the relationship between log signature and lithology.

Coal is distinctive on well logs because of low density and low gamma count (fig. 38). Because mudstone contains the highest proportion of clay and mica of any rock type in the Pottsville, it has a moderate to high gamma-ray count. Lithic sandstone is characterized by a low gamma count, and the density and neutron curves do not cross owing to a lack of porosity. Quartzose sandstone has an extremely low gamma-ray count, apparently because of a lack of clay minerals, and the density and neutron curves cross because the sandstone is porous and contains almost exclusively quartz; crossing of the curves is the distinguishing feature. Whereas quartzose sandstone typically has a blocky log signature, lithic sandstone has a variable signature.

Although the distinction between lithic and quartzose sandstone is based entirely on density-log characteristics and therefore reflects porosity rather than composition, the terms lithic and quartzose are used as facies terms that indicate dominance of quartz and rock fragments, respectively. Because of time constraints, samples and cores were not examined to verify the petrographic implications of this distinction, although examination of drillers logs seems to verify the hypothesis. Stratigraphic evidence argues strongly for recognition of lithic and quartzose sandstone on the basis of log characteristics because, as a rule, quartzose (porous) sandstone occurs only in the stratigraphic intervals where it has been described in outcrop by previous workers (Shadroui, 1986; Raymond and others, 1988). Furthermore, most sandstone in the lower Pottsville, which is known to be dominated by quartzose sandstone in Alabama, has the same log signature as what is interpreted as quartzose sandstone in this study.

To determine stratigraphic relationships in the Black Creek-Cobb interval, seven cross sections were made using the top of the Pratt cycle as a datum (figs. 4, 39-45). 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 (1) cycle-isopach, (2) lithic-sandstone isolith, (3) quartzose-sandstone isolith, and (4) coal abundance. Additionally, an isopach map and a coal-abundance map were made for the combined Black Creek-Cobb interval.

Coal-isopach maps were not constructed in this study because of inconsistency of the density-log signature with respect to coal thickness. Although geophysical logs in the degasification fields afford some degree of precision and may be used for isopach mapping on a local scale, conventional logs can be deceptive because of fast logging speed. Comparison of core with density logs indicates that beds less than 1 foot thick may mimic the signature of beds thicker than 4 feet in conventional wells (Thomas and Womack, 1983). This problem also is apparent when correlating conventional wells with

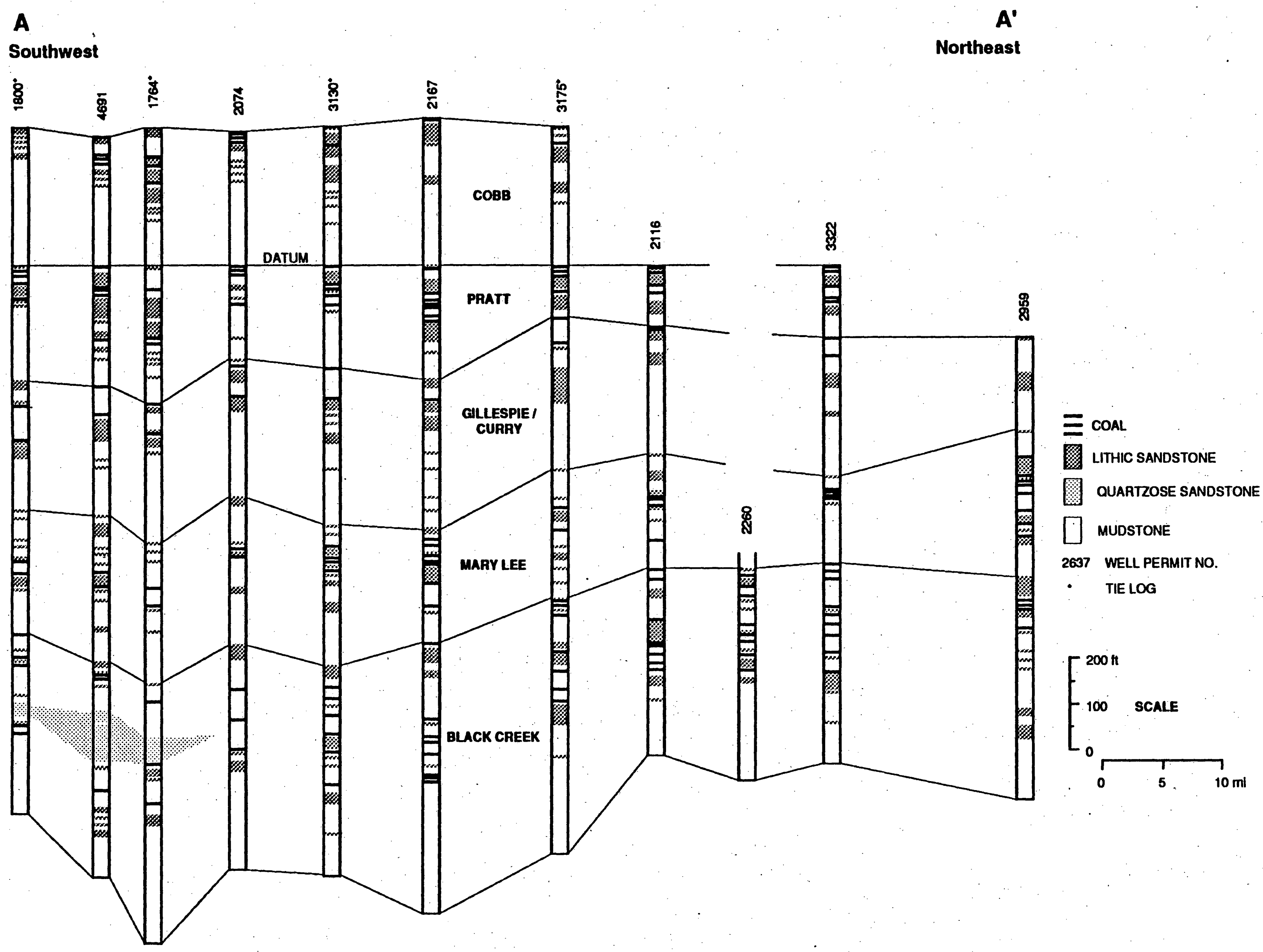



Figure 39. Stratigraphic cross section A-A'. See figure 4 for location of cross section.

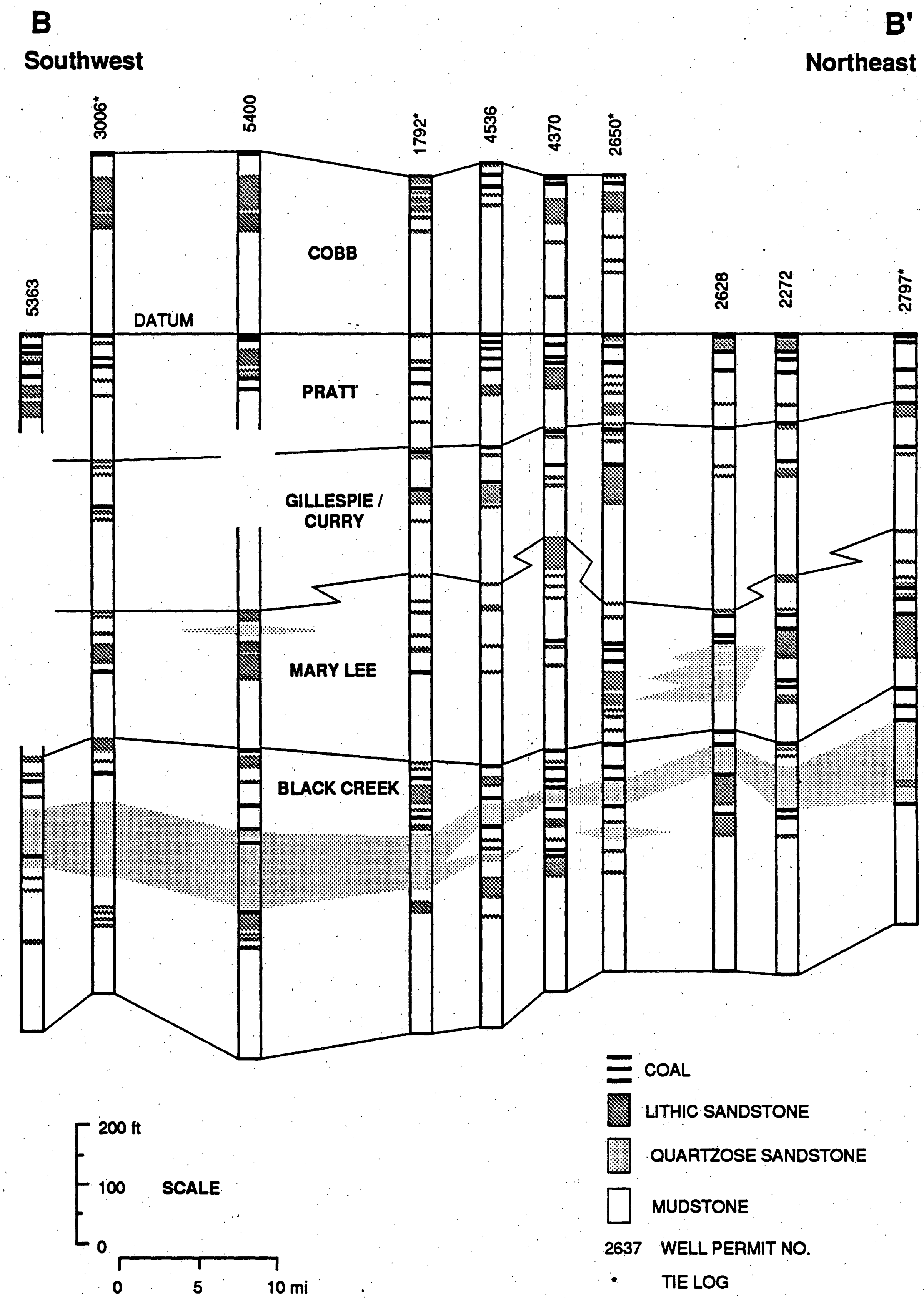



Figure 40. Stratigraphic cross section B-B'. See figure 4 for location of cross section.

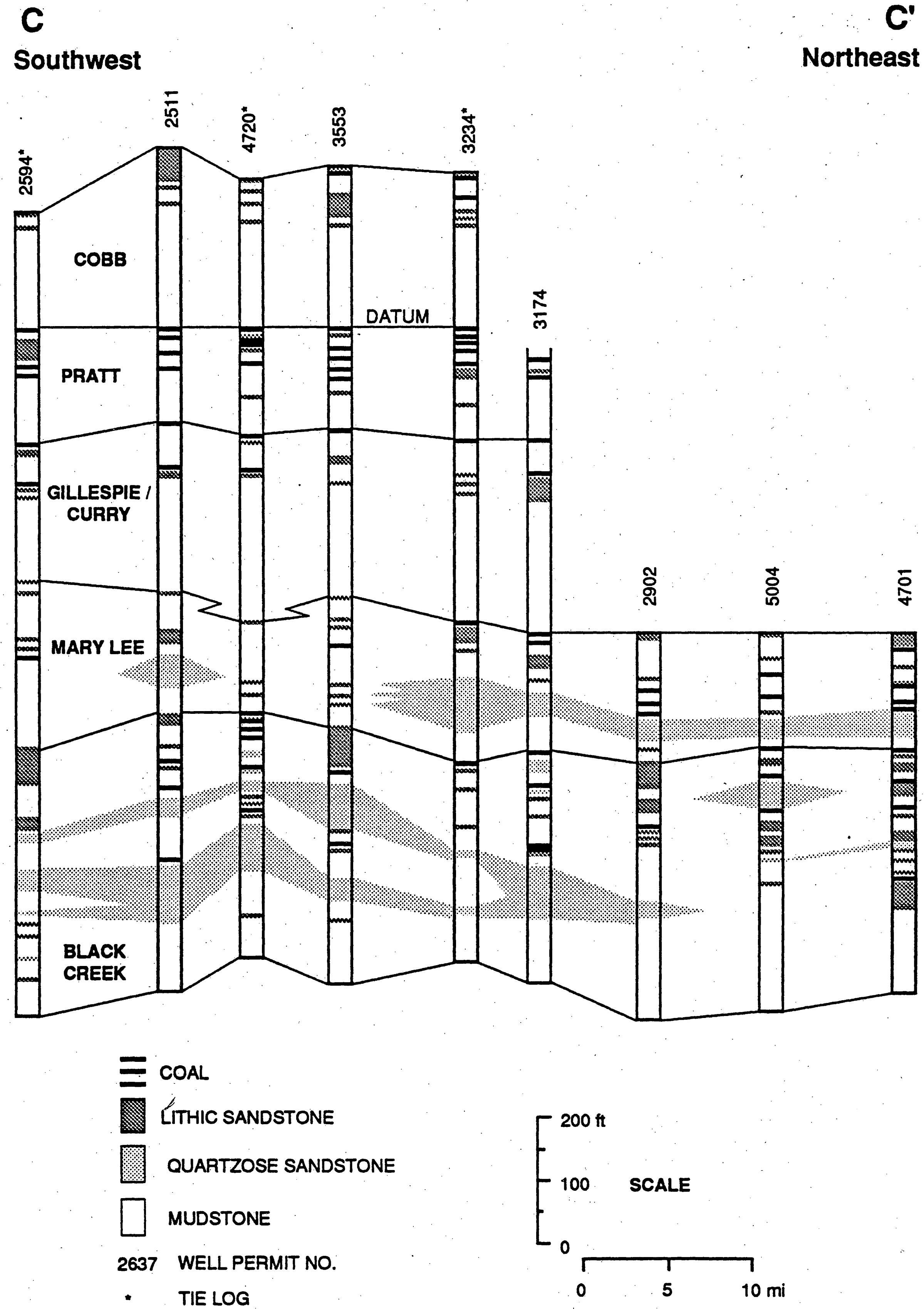



Figure 41. Stratigraphic cross section C-C'. See figure 4 for location of cross section.

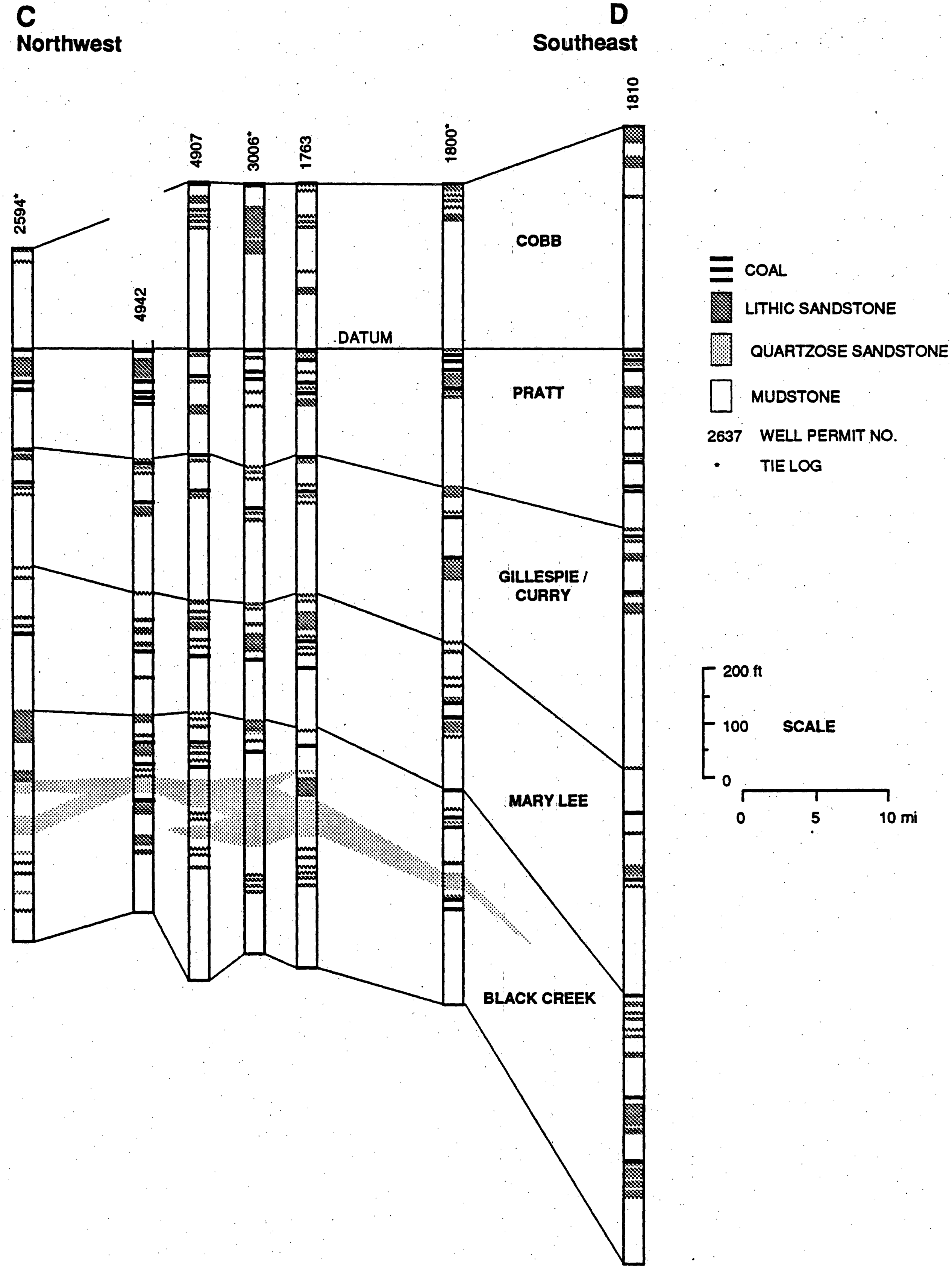



Figure 42. Stratigraphic cross section C-D. See figure 4 for location of cross section.

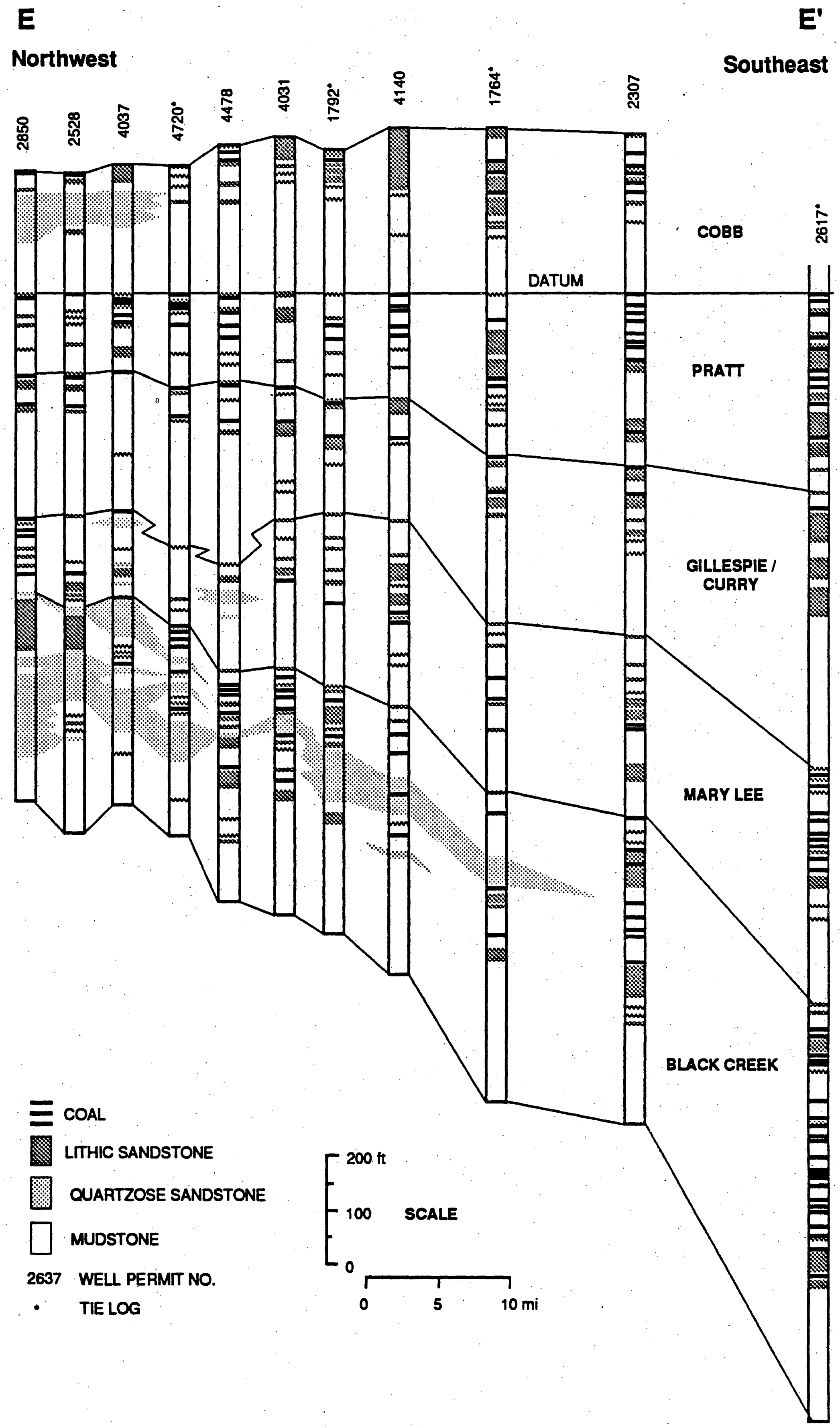



Figure 43. Stratigraphic cross section E-E'. See figure 4 for location of cross section.

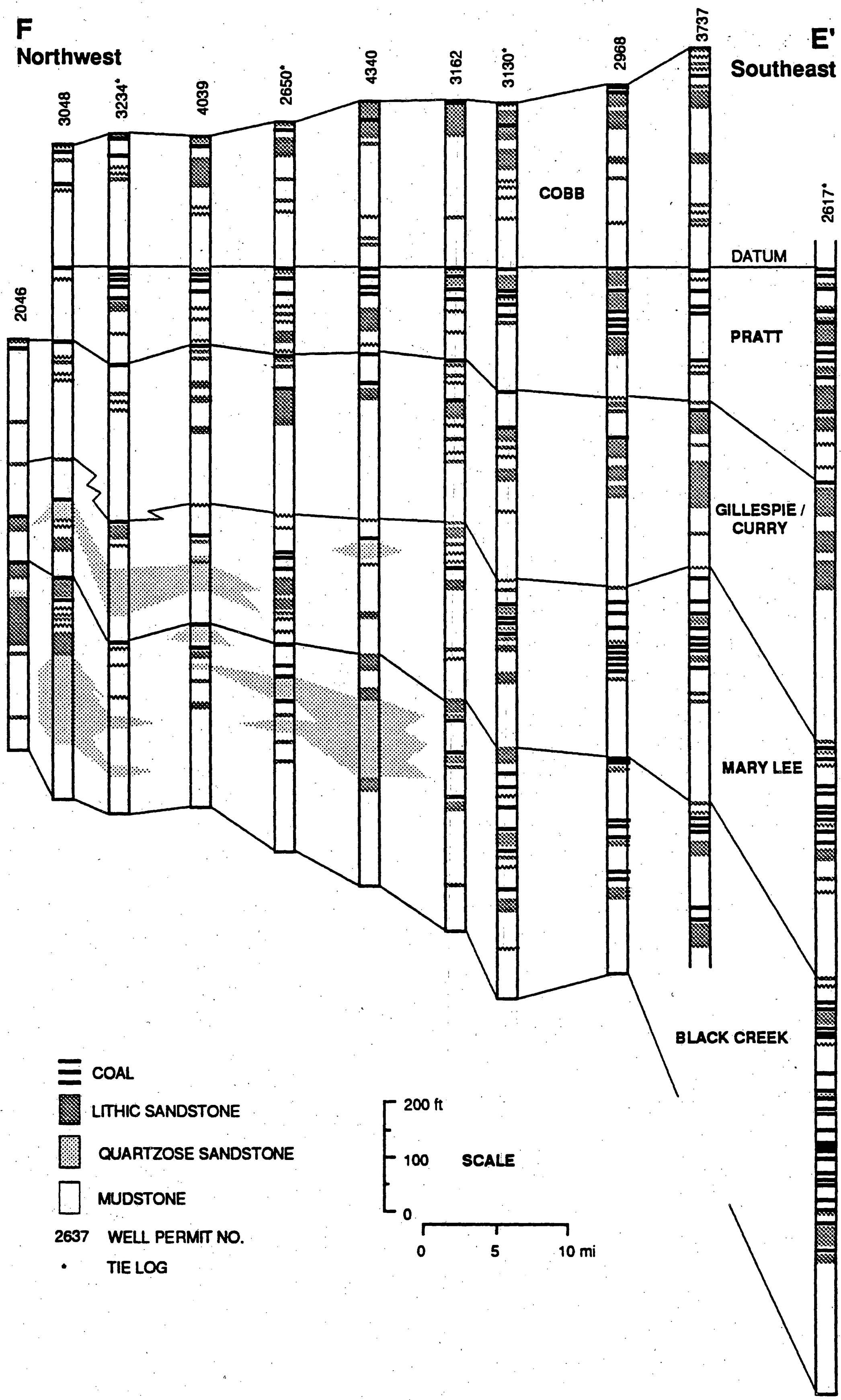



Figure 44. Stratigraphic cross section F-E'. See figure 4 for location of cross section.

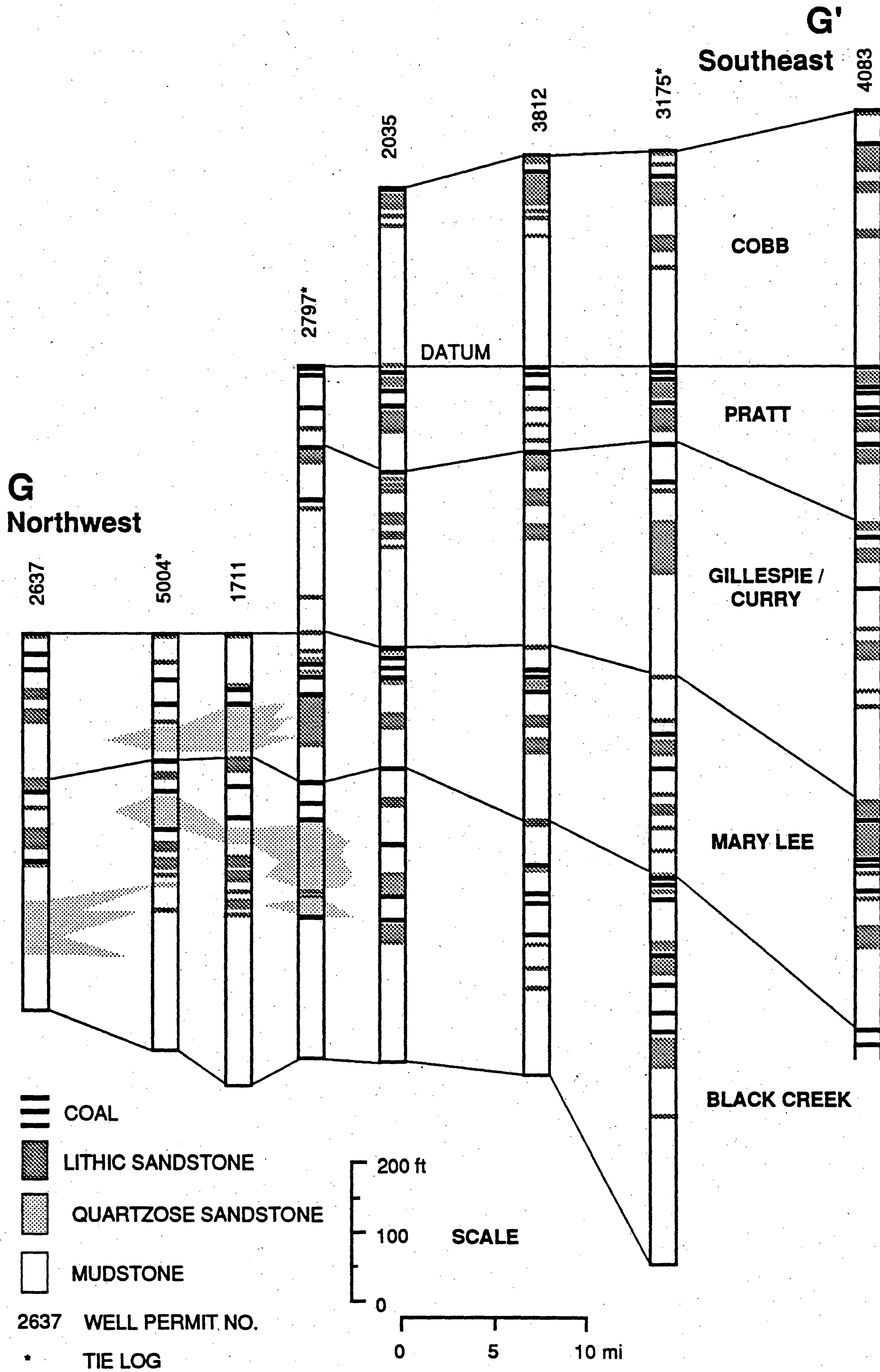



Figure 45. Stratigraphic cross section G-G'. See figure 4 for location of cross section.

nearby degasification wells. To avoid this problem, coal-abundance maps, or maps showing the number of coal beds, provide a sense of coal thickness (Thomas and Womack, 1983; Sestak, 1984).

## CROSS SECTIONS: STRATIGRAPHIC ARCHITECTURE

The cross sections demonstrate the correlation of the 5 cycles of the Black Creek-Cobb interval in Alabama (figs. 4, 39-45). In east Tuscaloosa and west Jefferson Counties, simple coarsening-upward cycles culminate in coal groups. However, there is minor difficulty in defining the base of the Mary Lee cycle in Fayette and Lamar Counties because quartzose sandstone is present near the base of the cycle. Another problem is presented by intertonguing of sandstone with mudstone near the top of the Mary Lee cycle (fig. 40). Even so, the Mary Lee is a definable cycle throughout the study area.

Cycle thickness is fairly uniform along the southwest-northeast cross sections (figs. 39-41), although thickening toward the southwest is apparent in cross section A-A' (fig. 39). In contrast, all of the cycles thicken to the southeast in the remaining cross sections (figs. 42-45). By definition, mudstone predominates in the lower part of each cycle (figs. 39-45). Lithic sandstone occurs in the upper part of most cycles, but is thickest below the coal-bearing intervals of the Gillespie/Curry and Cobb cycles. Quartzose sandstone occurs in the Black Creek, Mary Lee, and Cobb cycles. In the Black Creek cycle, quartzose sandstone is present below the coal-bearing strata in the northwest part of the study area (figs. 41, 43, 44), but in the south and east, it is traceable into the middle of the coal group (figs. 39, 40, 43). In contrast, quartzose sandstone generally underlies the coal-bearing part of the Mary Lee cycle, although localized lenses are dispersed throughout the entire section (figs. 39-45). In Lamar County, the Cobb cycle contains a local quartzose sandstone body (fig. 43) that was not mapped separately from lithic sandstone.

Coal is restricted to the upper part of the cycles, and continuity of the beds varies (figs. 39-45). Some beds, like those in the Gillespie/Curry cycle, are traceable throughout most of the basin in Alabama. Other beds, like many in the Black Creek cycle, are are difficult to trace across large areas. Each of the northwest-southeast cross sections demonstrates a general proliferation of coal beds where cycles thicken toward the southeast.

# SUBSURFACE MAPS: DEPOSITIONAL ARCHITECTURE

## Black Creek-Cobb Interval

### Characteristics

The Black Creek-Cobb isopach map illustrates the overall geometry of the study interval (fig. 46). The interval thickens from less than 1,200 feet in parts of Lamar and Fayette Counties toward the south and southeast. Thickening is less pronounced north of the 1,500-foot contour in Pickens and Lamar Counties than in Tuscaloosa County. The thickest Black Creek-Cobb interval occurs in an arcuate trend that is oriented southwest in Tuscaloosa County where the interval is locally more than 2,300 feet thick. The trend curves toward the west in Greene County and curves toward the northwest into Mississippi. In the southwesternmost part of the study area, the Black Creek-Cobb interval is thicker than 2,400 feet.

Coal abundance increases toward southeast Tuscaloosa County where more than 40 coal beds occur; more than 30 coal beds occur locally in western Jefferson County (fig. 47). 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. In the northwest part of the study area, however, coal abundance is quite variable.

### Interpretation

The Black Creek-Cobb isopach map (fig. 46) establishes the tectonic configuration of the Black Warrior basin during upper Pottsville deposition. The arcuate trend of thick sediment south of the 1,800-foot contour represents the principal area of tectonic subsidence. The southwest-oriented part of the trend in Tuscaloosa County apparently is the result of flexural subsidence related to Appalachian thrusting, whereas the northwest-oriented part of the trend in Sumter and southern Pickens Counties apparently is a distal expression of Ouachita thrusting.

The Black Creek-Cobb isopach map (fig. 46) verifies that the structural configuration of the Black Warrior basin was quite different during deposition of the study interval than at present. The isopach

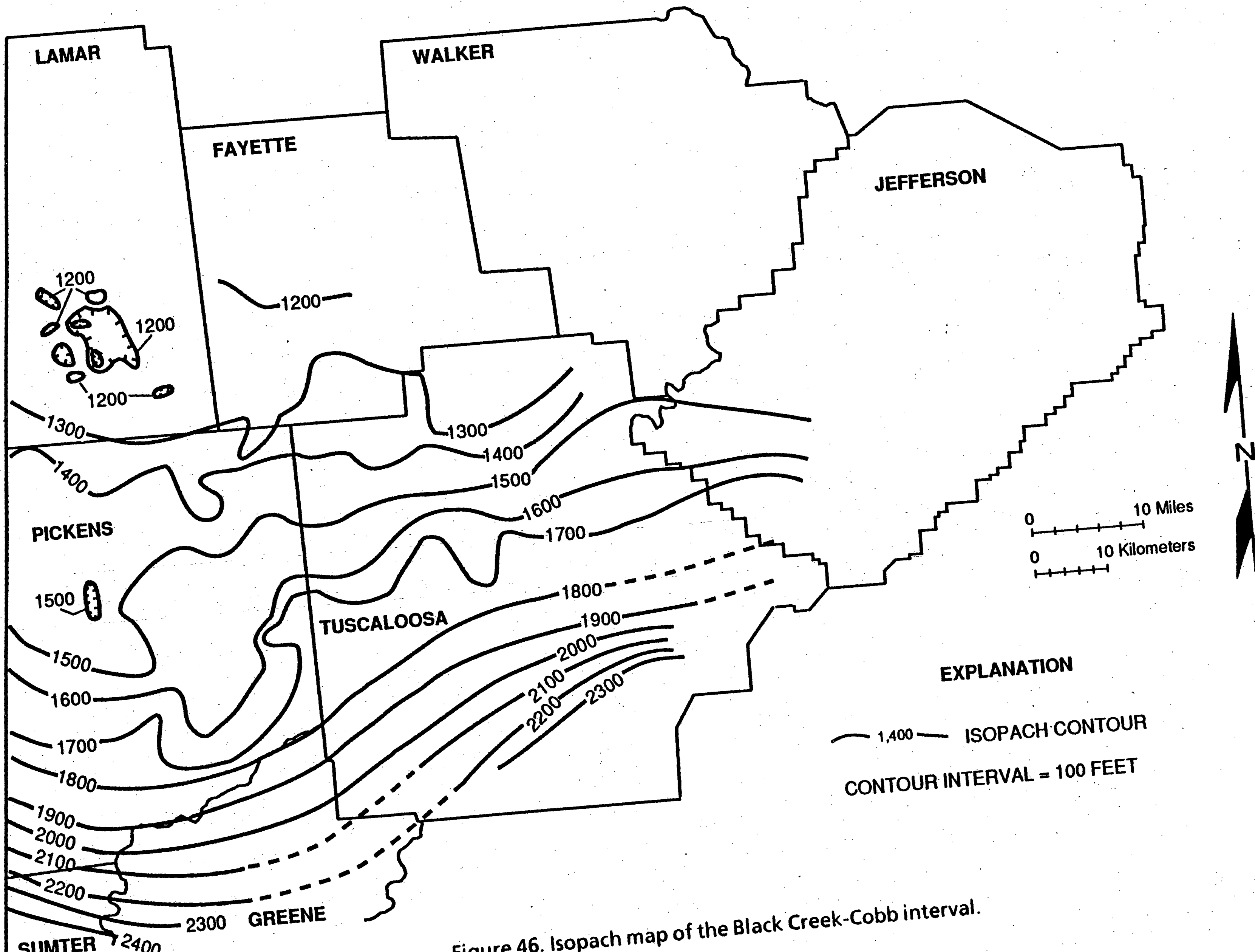



Figure 46. Isopach map of the Black Creek-Cobb interval.

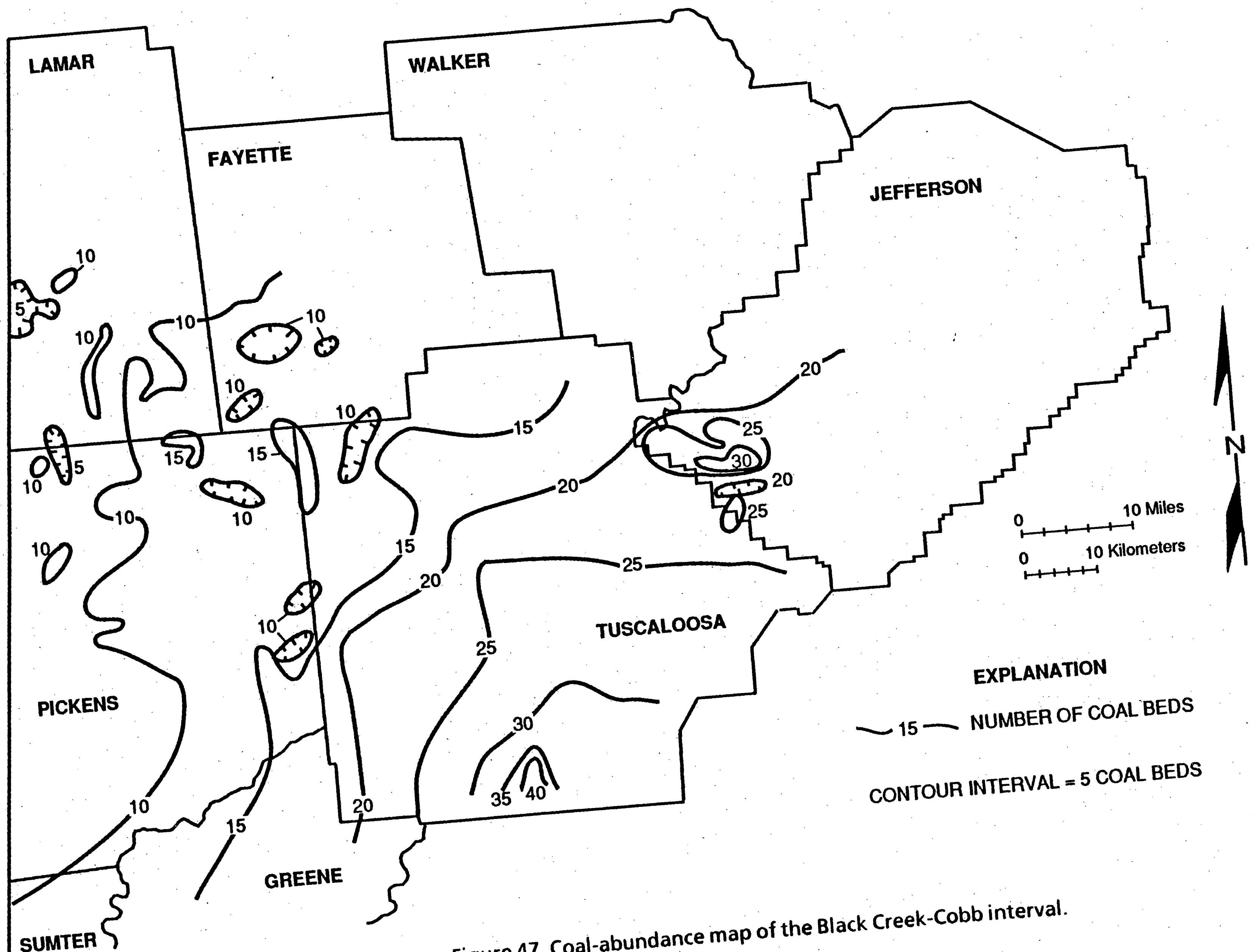



Figure 47. Coal-abundance map of the Black Creek-Cobb interval.

contours (fig. 46) are strongly oblique to the structure contours (fig. 5), and in many places the contours are nearly perpendicular. Therefore, comparison of the structure and isopach maps underscores the importance of post-Black Creek-Cobb tectonics in determining the present configuration of the Black Warrior basin.

The coal-abundance map indicates that southeastern Tuscaloosa and western Jefferson Counties provided ideal sites for peat accumulation (fig. 47). The trend toward abundant coal coincides with thickening of the Black Creek-Cobb interval in the eastern part of the study area, suggesting that rapid subsidence played a role in the preservation of coal. However, scarcity of coal in the southwest part of the study area indicates that subsidence was not the only factor that governed coal development.

## Black Creek Cycle

### Characteristics

The Black Creek cycle is at most places the thickest cycle in the study interval (fig. 48). The 700-foot contour defines a depocenter in southeast Tuscaloosa County. The cycle is less than 500 feet thick in Greene County and eastern Pickens Counties. In Lamar and Fayette Counties, the cycle is generally thinner than 500 feet, but cycle thickness is quite variable.

Lithic-sandstone distribution in the Black Creek-Cobb interval is perhaps the most complicated of any cycle in the study interval (fig. 49). Net-sandstone thickness is generally more than 100 feet in south and east Tuscaloosa County and Greene County. However, few coalbed-methane wells in Tuscaloosa County penetrate the base of the Black Creek cycle, so the thickness trend is based on scarce data. In Sumter County, lithic sandstone is less than 50 feet thick, and in southwest Lamar and northwest Pickens Counties, the sandstone is absent. Throughout most of Lamar and Fayette Counties, net lithic-sandstone thickness is highly variable.

Quartzose sandstone occurs only in the western part of the study area (fig. 50) which is not presently developed for coalbed methane. A major sandstone belt extending northeast from Sumter County to eastern Fayette County is defined by the 50-foot contour. The sandstone belt appears to be

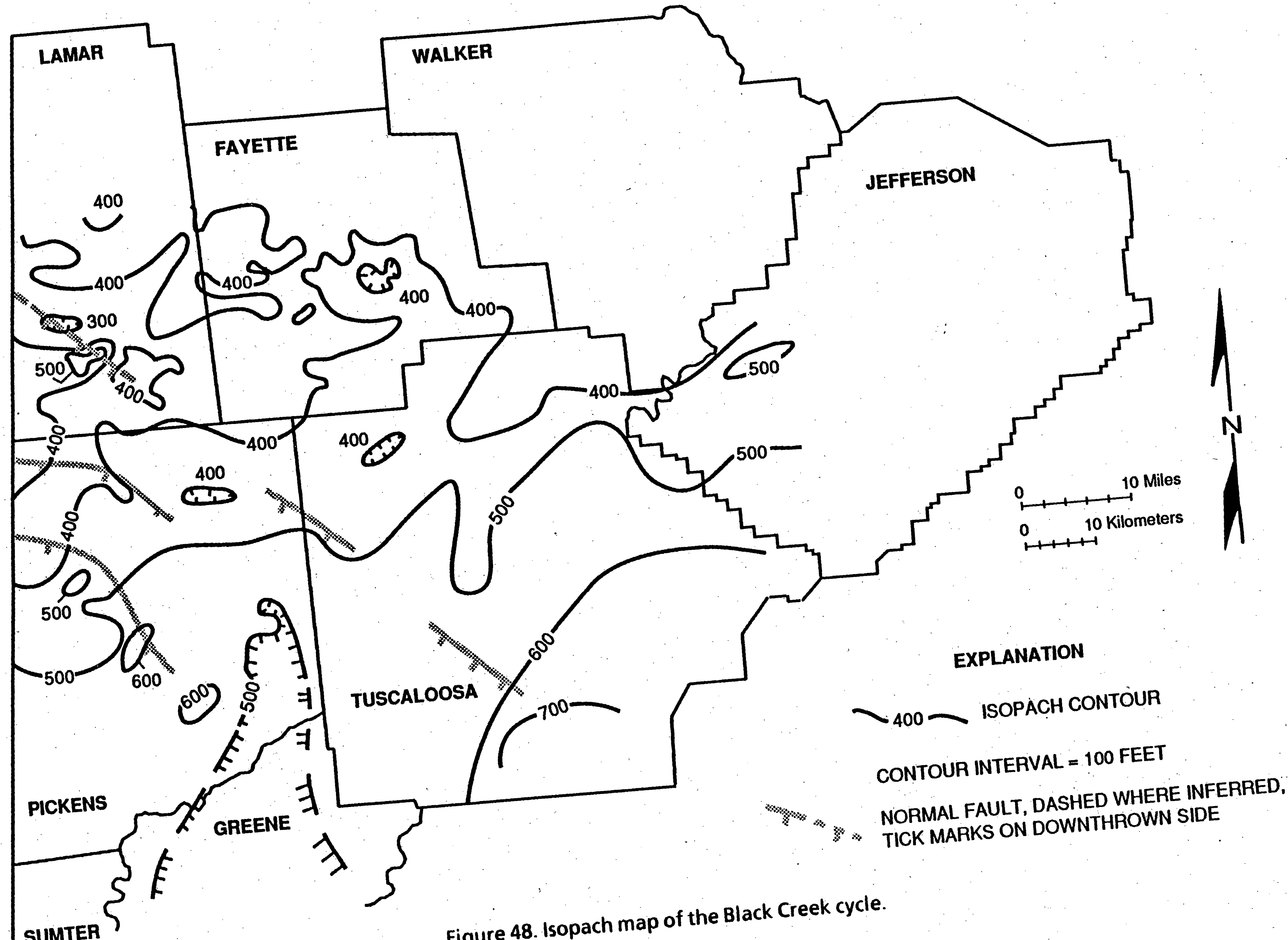



Figure 48. Isopach map of the Black Creek cycle.

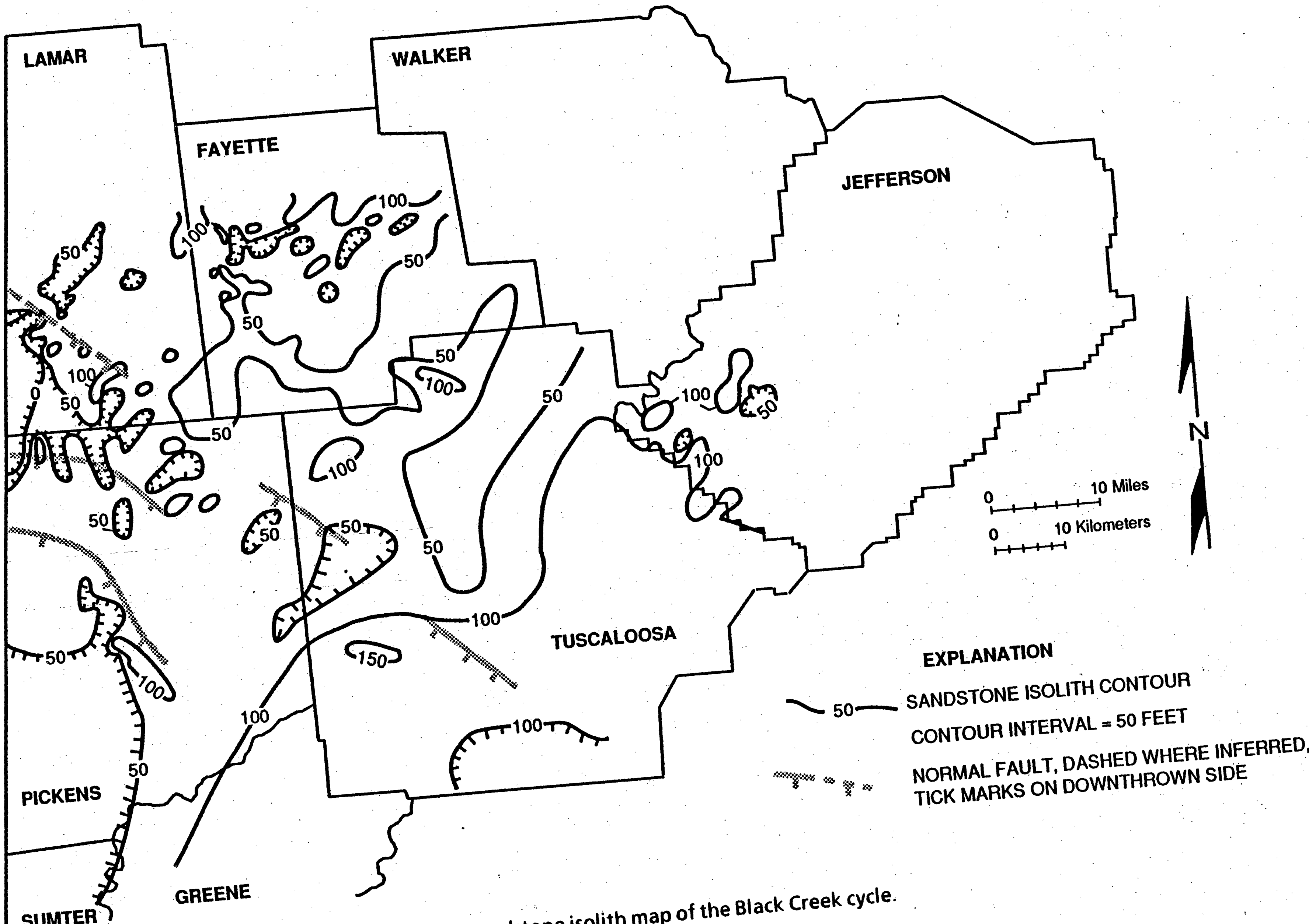



Figure 49. Lithic-sandstone isolith map of the Black Creek cycle.

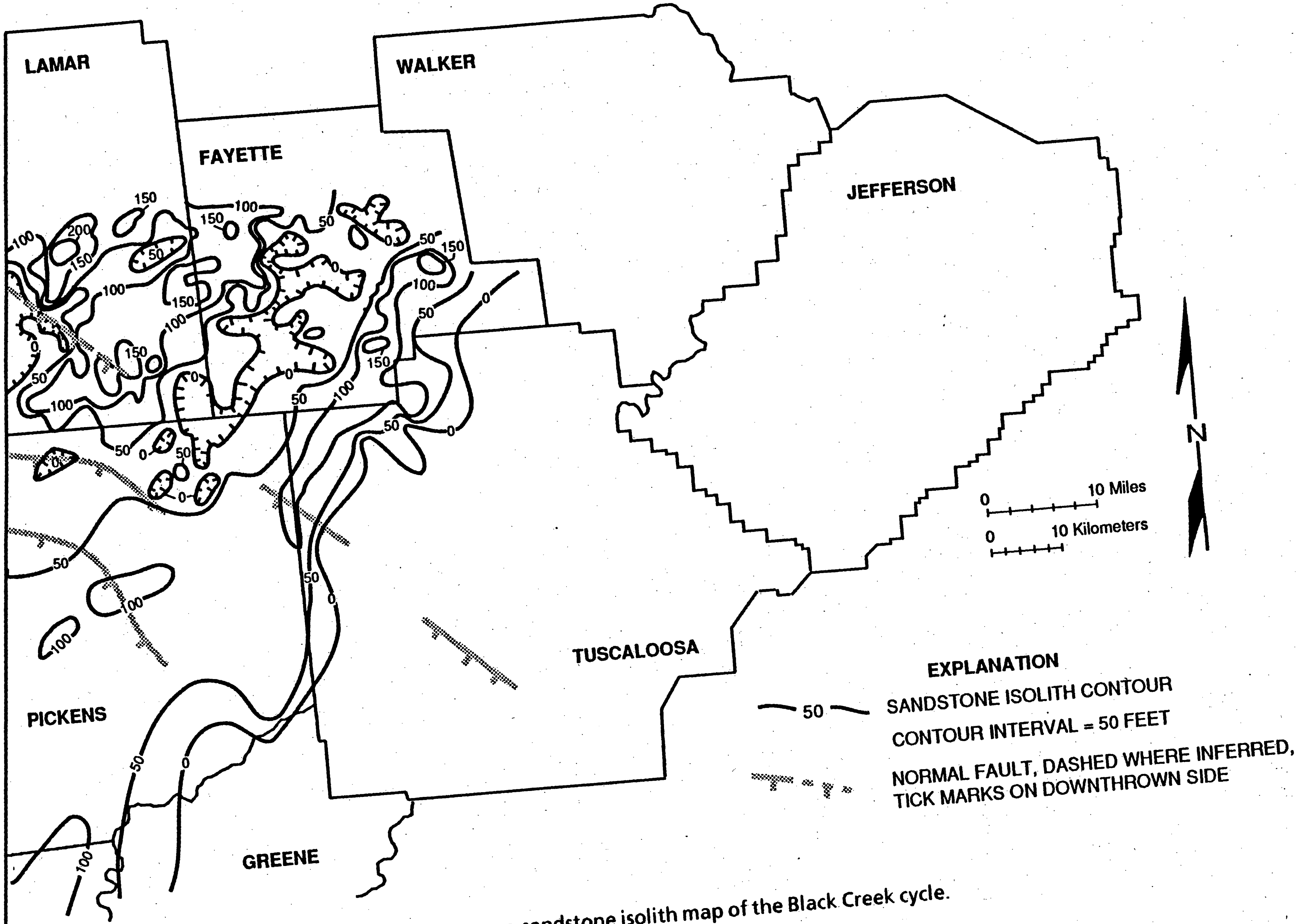



Figure 50. Quartzose-sandstone isolith map of the Black Creek cycle.

traceable into the Bremen Sandstone Member of Butts (1910) in outcrops in Walker County where the sandstone is in the middle of the coal group. At the northeast end of the sandstone belt, a distinctive trend is defined by the 100-foot contour in east Fayette and northwest Tuscaloosa Counties. The belt widens toward the southwest in Pickens County, and locally, quartzose sandstone is thicker than 100 feet.

West of the sandstone belt in southwest and central Fayette County, quartzose sandstone commonly is absent, and lithic sandstone is thick (figs. 49, 50). In Lamar County, net thickness of quartzose sandstone is locally more than 200 feet (fig. 50). The geometry of the bodies is highly irregular, and the sandstone terminates abruptly along a northwest-southeast line in western Lamar County where lithic sandstone also is absent. All or most of the lower Pottsville sandstone units also are absent southwest of this line (Engman, 1985), so definition of the Black Creek cycle is difficult. At those places where the Black Creek cycle can be defined south of the line, the cycle is more than 400 feet thick (fig. 48).

Coal-abundance trends in the Black Creek cycle are similar to those in the Black Creek-Cobb interval (figs. 47, 51). More than 20 coal beds are present in southern Tuscaloosa County, accounting for nearly half of the coal beds in the Black Creek-Cobb interval (fig. 51). More than 10 beds occur throughout southeast Tuscaloosa County and in parts of Jefferson County, particularly where the lithic sandstone is more than 100 feet thick. Fewer than 5 beds are generally present throughout the remainder of study area, although several localized areas between the quartzose sandstone bodies in Fayette and Pickens Counties contain more than 5 beds. In southern Lamar and northwestern Pickens Counties where sandstone is thin or absent, no coal beds are present in the Black Creek cycle.

## Interpretation

Thickening of the Black Creek cycle toward southeast Tuscaloosa County indicates that Appalachian tectonics were the principal cause of subsidence in Alabama and that the area of rapid subsidence was geographically restricted. Thinning in Greene and Pickens Counties (fig. 48) suggests a locally low subsidence rate. The northwest part of the study area had an irregular topography that is

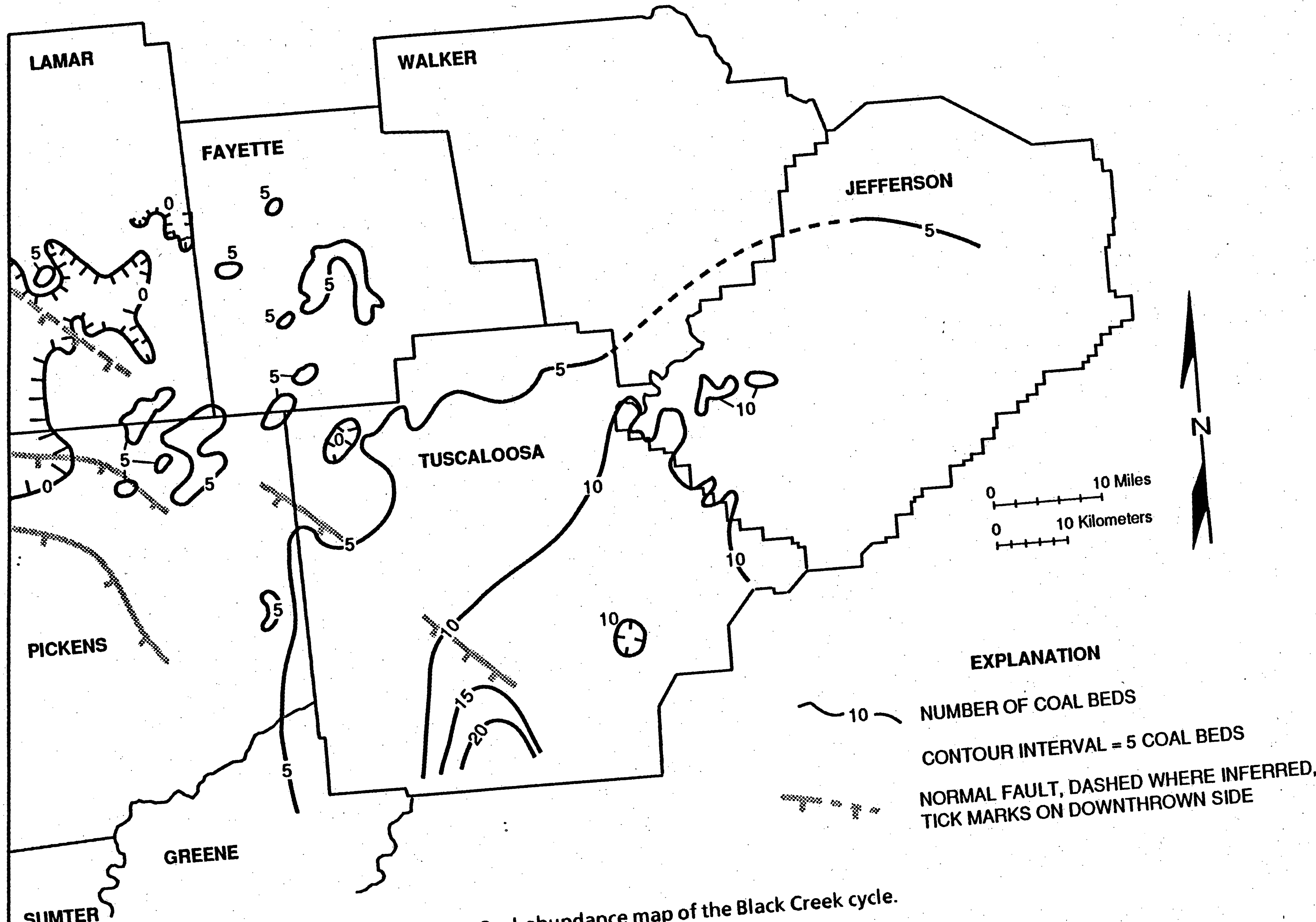



Figure 51. Coal-abundance map of the Black Creek cycle.

indicated by the complex configuration of the isopach contours. However, much of this irregularity can be related to sedimentary processes acting in this area.

Thick lithic sandstone and abundant coal in southern Tuscaloosa County indicates the development of a thick, terrestrial sediment package in the southeast part of the study area (figs. 49, 51). Correspondence of 10 or more coal beds with more than 100 feet of lithic sandstone along the border of Jefferson and Tuscaloosa Counties (figs. 49, 51) suggests that autogenic sedimentation, such as development of channel and crevasse-splay complexes, was a primary control on coal abundance. The decrease in coal abundance and net lithic-sandstone thickness toward the western and northern parts of the study area is suggestive of distal depositional environments.

The belt of quartzose sandstone extending from Fayette County to Sumter County (fig. 50) has been interpreted as the trunk of a fluvial-deltaic system that had a source in the Ouachita orogen (Thomas and Womack, 1983; Sestak, 1984). However, because the sandstone belt is more or less perpendicular to paleoslope in Alabama, an alternative interpretation is that the belt represents a shore-zone complex. The 100-foot contour in east Fayette and northwest Tuscaloosa Counties has a plan-view outline similar to that of a barrier-bar system. The curving of the extremities of the complex is suggestive of spits, and the small lobe in northwest Tuscaloosa County resembles a flood-tidal delta. Widening of the sandstone belt toward the southwest may represent shoreface and inner-shelf sand that was derived from the northeast by geostrophic flow. Absence of quartzose sandstone where the cycle is thin in Greene County suggests diversion of flow around a positive feature.

The barrier interpretation is supported by predominance of correlative coal beds southeast of the sandstone belt (figs. 44, 45). Because the sandstone belt is locally more than 150 feet thick (fig. 50), it probably represents a series of stacked barriers. The few correlative coal beds that are west of the sandstone belt may represent peat formed during sea-level lowstands when the entire barrier system was exposed. Thick, high-quality peat is presently accumulating between exposed Pleistocene barriers in Georgia (Cohen, 1974).

The location, thickness, and irregular geometry of the quartzose-sandstone bodies northwest of the main sandstone belt (fig. 50) are suggestive of an open-marine sand bank. Occurrence of quartzose sandstone below the coal-bearing part of the cycle in Lamar County (figs. 4, 43-45) indicates that this area was a persistent site of shoaling during Black Creek deposition. However, because quartzose sandstone is traceable into the middle of the coal-bearing part of the cycle in most other areas (figs. 39, 40, 43), widespread shoaling may have been related to transgression.

Abrupt pinchout of quartzose sandstone in the densely faulted area of southwest Lamar County may be structurally controlled, but the line of pinchout does not match well with any identified faults (figs. 5, 6, 50). However, sedimentary trends may be used to predict ancient faults that have been veiled by later tectonic events (Pashin and Ettensohn, 1987). Although evidence from the Black Creek cycle alone is inconclusive, facies changes are common in the lower Pottsville (Engman, 1985) and in other parts of the Black Creek-Cobb interval along the inferred fault trend. The trend also is aligned with other faults that may have influenced Black Creek-Cobb deposition (fig. 50).

## Mary Lee Cycle

### Characteristics

The Mary Lee cycle is more than 400 feet thick southeast of a northeast line extending from Sumter County to Tuscaloosa County (fig. 52). The 350-foot contour indicates thickening of the Mary Lee cycle in in west-central Tuscaloosa County; the contour parallels a fault in this area. The 250- and 300-foot contours demonstrate that the thickening extends northward into south-central Fayette County into the area where the Black Creek quartzose sandstone is thin or absent (figs. 50, 52) and show that the area of thick Mary Lee sediment narrows toward the southwest. Throughout most of Fayette, Lamar, and northern Pickens Counties, cycle thickness is approximately 200 feet.

Net lithic-sandstone thickness is more than 100 feet in southeast Tuscaloosa County and is less than 50 feet in the southwest part of the study area (fig. 53). In west Tuscaloosa County, the 50-foot contour defines thick sandstone trends that coincide partly with the thick Mary Lee section (figs. 52, 53). In east Tuscaloosa County, the 50-foot contour defines a general, lobate form with numerous sub-lobes. Net sandstone values are low and variable throughout most of Lamar and Fayette Counties. However, the sandstone thickens to more than 75 feet in eastern Fayette County and to

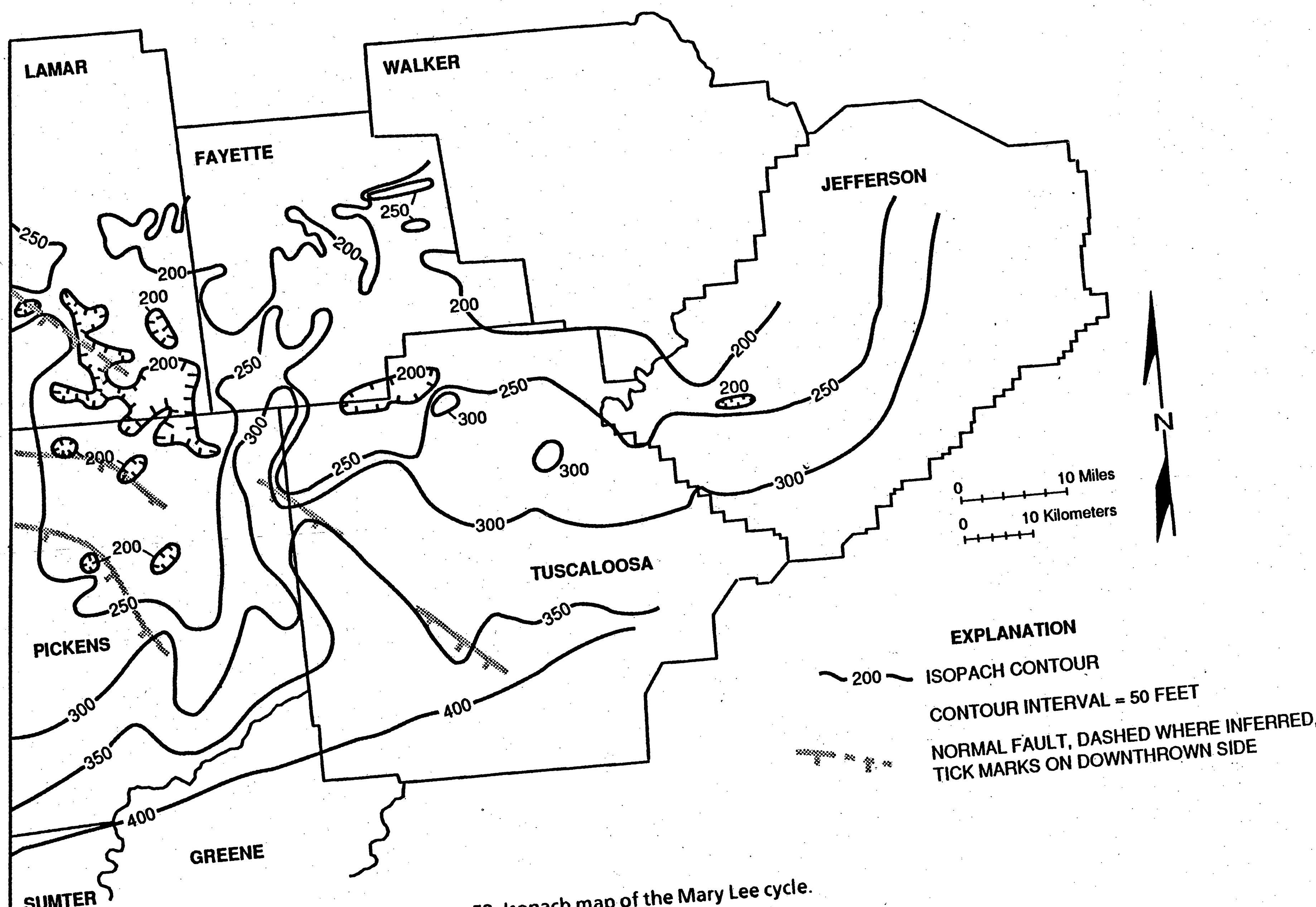



Figure 52. Isopach map of the Mary Lee cycle.

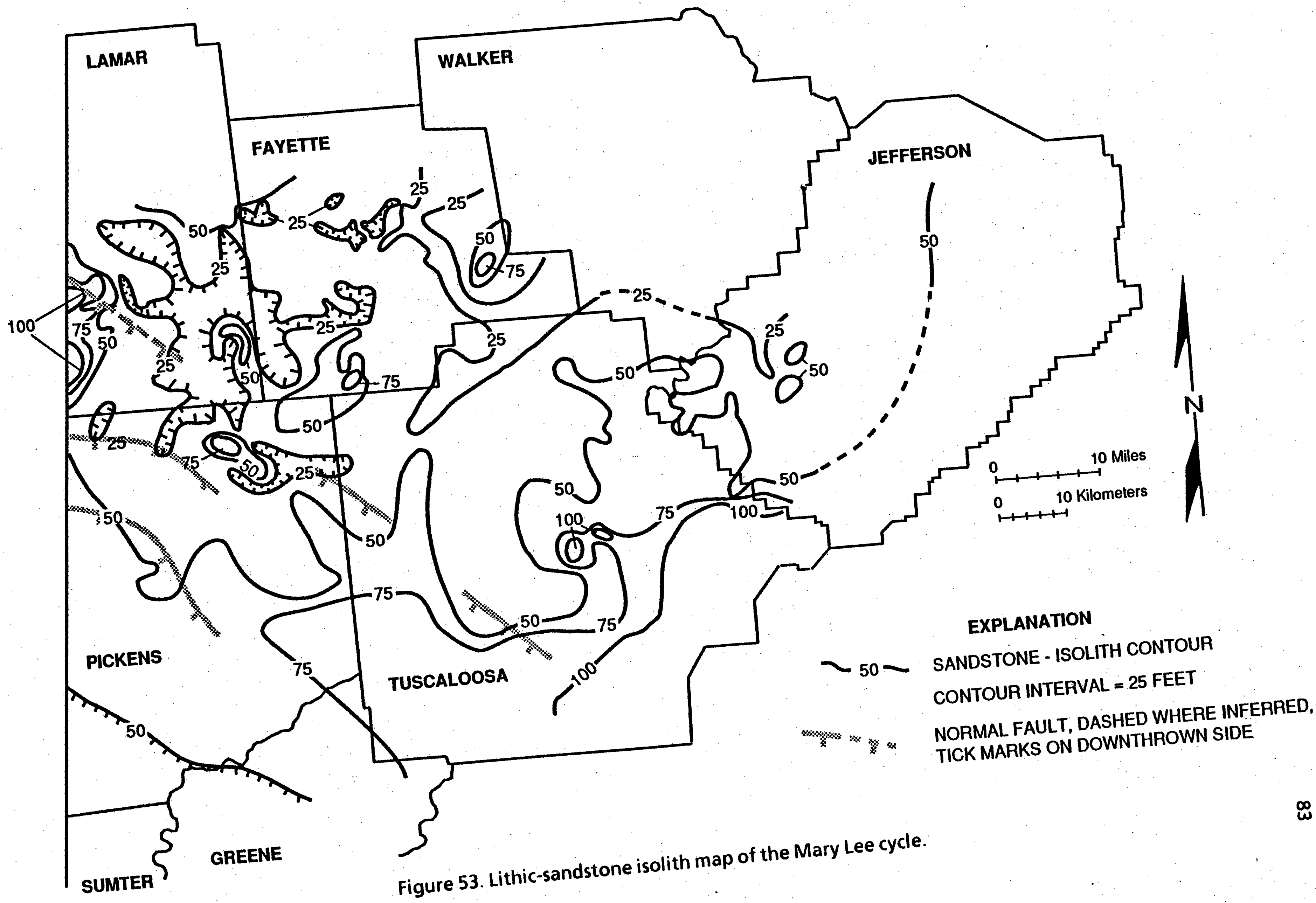



Figure 53. Lithic-sandstone isolith map of the Mary Lee cycle.

more than 100 feet in westernmost Lamar County where sandstone and coal are absent in the Black Creek cycle (figs. 50, 53).

Several quartzose sandstone bodies are present in the Mary Lee cycle of Lamar, Fayette, and Pickens Counties (fig. 54). Cross sections show that the eastern margin of the body in central Fayette County is traceable into thick lithic sandstone and coal in the eastern part of the County (figs. 4, 40, 45). The isolated body in the Mary Lee of central Pickens County coincides with 100-foot-thick sandstone in the Black Creek cycle, and 50-foot-thick sandstone in the Mary Lee of eastern Fayette County also coincides with thick Black Creek quartzose sandstone (figs. 50, 54). In contrast, the area defined by the 50-foot contour in southwest Fayette County is located between the two Black Creek quartzose sandstone bodies, and quartzose sandstone is present in the area lacking Black Creek quartzose sandstone and containing thick Mary Lee lithic sandstone.

Coal-abundance trends in the Mary Lee cycle (fig. 55) are similar to those in the Black Creek cycle (fig. 52). Ten beds are present in the Mary Lee cycle of southern Tuscaloosa County, and more than 4 beds occur throughout much of Tuscaloosa and western Jefferson Counties (fig. 55). Coal beds in eastern Tuscaloosa County are traceable well beyond the lobate lithic-sandstone body and are interspersed with that sandstone (figs. 39, 45). No coal is present in Sumter County, nor does coal occur in significant areas of Lamar and northern Pickens Counties where lithic sandstone and quartzose sandstone are commonly thick. However, 4 to 6 coal beds occur in eastern Fayette County. The southeast part of the area lacks quartzose sandstone in the Mary Lee cycle and contains thick quartzose sandstone in the Black Creek cycle. The northwest part of the area with 4 to 6 beds contains thin quartzose sandstone in both cycles.

## Interpretation

The regional thickness pattern of the Mary Lee cycle (fig. 50) indicates that the Black Creek depocenter had spread toward the west and had evolved into a southwestwardly narrowing trough of subsidence. Thickening of the cycle south of a fault in western Tuscaloosa County indicates that synsedimentary faulting may also have been a control on cycle thickness; however, data are scarce in

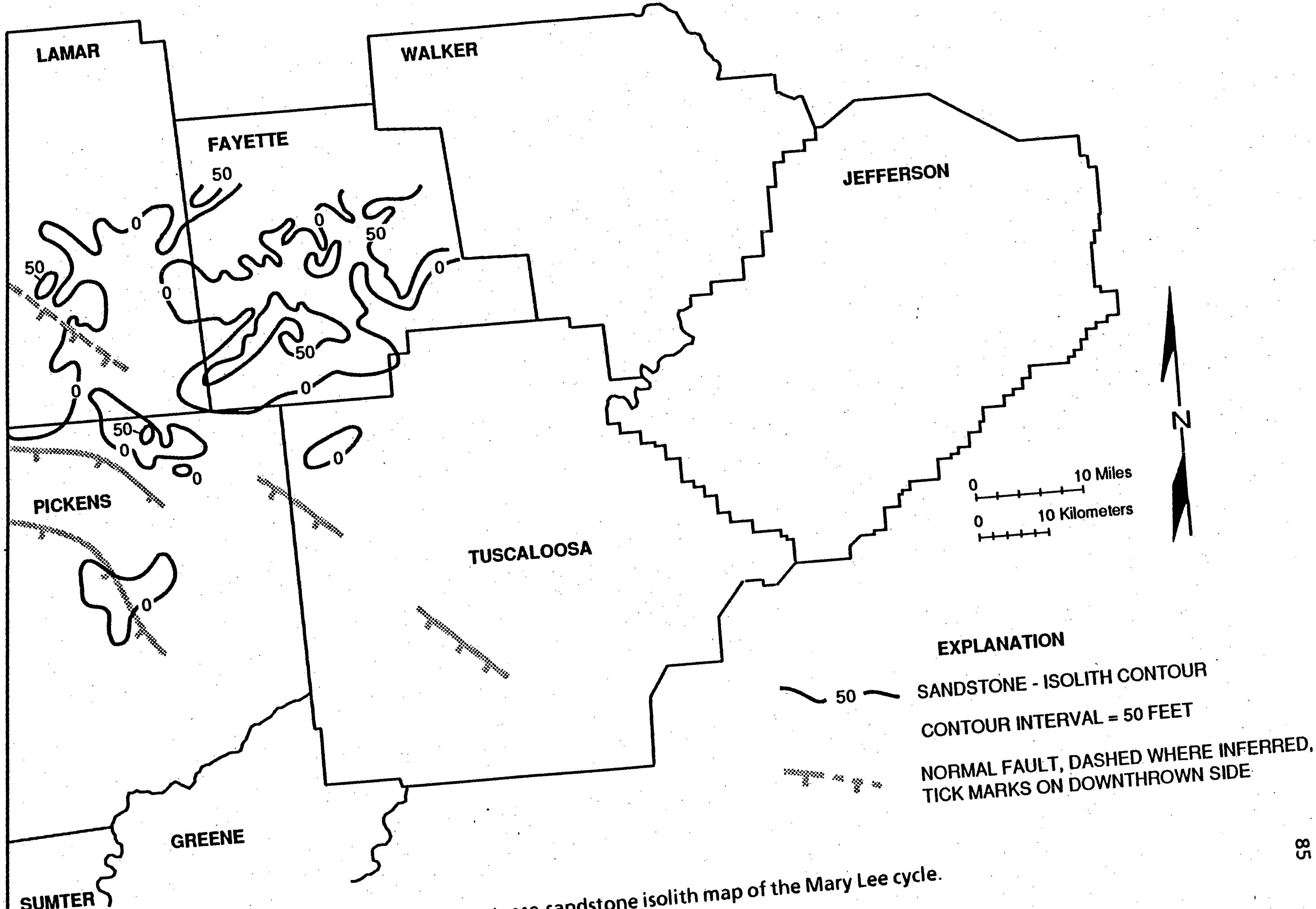



Figure 54. Quartzose-sandstone isolith map of the Mary Lee cycle.

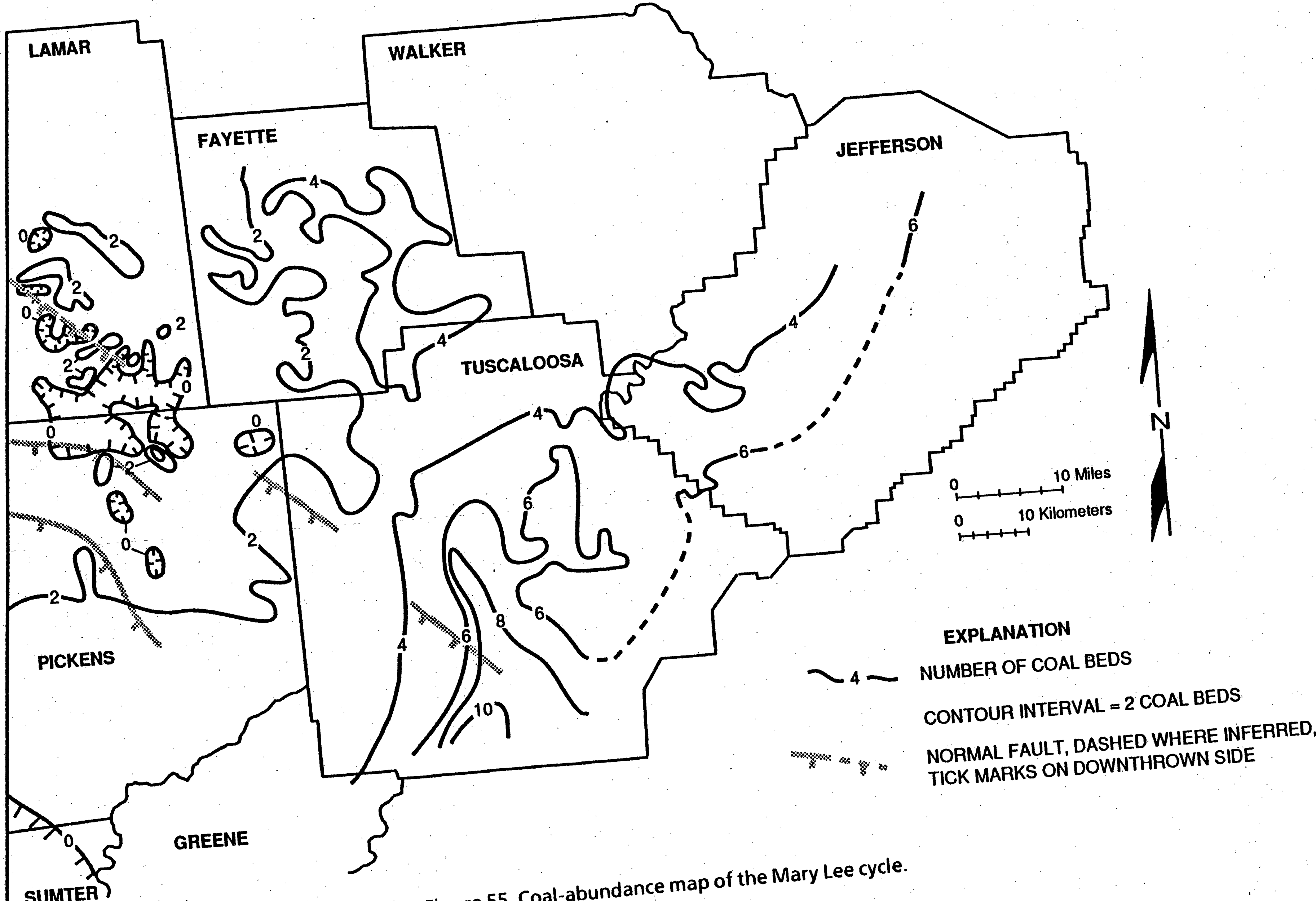



Figure 55. Coal-abundance map of the Mary Lee cycle.

this area. Differential compaction and relict topography evidently had a strong effect on the configuration of the Mary Lee cycle as indicated by coincidence of thick Mary Lee sediment with thin Black Creek quartzose sandstone in southern Fayette County (figs. 50, 52).

The distribution of lithic sandstone and coal in southern Tuscaloosa County is similar to that in the Black Creek cycle (figs. 49, 53). Therefore, the relationship between coal abundance and sandstone thickness appears to have remained unchanged despite the change in cycle thickness pattern. However, lithic sandstone tends to be thicker than 50 feet in the area circumscribed by the 350-foot cycle-isopach contour in western Tuscaloosa County (figs. 52, 53), indicating that thickening of the cycle in southwest Tuscaloosa County did influence the deposition of lithic sandstone.

Bifurcation of the thick sandstone body in western Tuscaloosa County may represent deltaic distributaries, although data are too sparse to justify detailed interpretation. In eastern Tuscaloosa County, the general lobate form outlined by the 50-foot contour also is suggestive of a delta. Because coal beds are traceable well beyond the limits of the lobate sandstone body and are interspersed with that sandstone, a deltaic interpretation based on sandstone-body geometry alone is probably incorrect. Alternatively, the main lobate body may represent a major fluvial system, and the numerous sub-lobes may represent crevasse-splay and associated flood-basin deposits which have been identified in nearby highwalls and cores (Epsman and others, 1988; Pashin and Sarnecki, 1990). Comparison of the cycle-isopach map and the lithic-sandstone isolith map (figs. 54, 55) indicates that the general lobate geometry of the sandstone body is an artifact of southward thickening caused by differential subsidence. Coal is most abundant between the two thick lithic sandstone bodies, so most peat beds evidently accumulated in alluvial interfluves.

Because quartzose sandstone typically underlies coal in the Mary Lee cycle (figs. 41, 44, 45), the sandstone is interpreted mainly as a regressive deposit. Nesting and stacking of quartzose sandstone in the Mary Lee cycle with that in the Black Creek cycle (figs. 50, 54) demonstrates the importance of relict topography in determining quartzose-sandstone distribution. Stacked sandstone bodies, such as the sandstone patch in central Pickens County and the body defined by the 50-foot contour in eastern Fayette County, are ostensibly the result of shoaling on inherited topographic highs. Nested sandstone, like the elongate body defined by the 50-foot contour in southern Fayette County, may represent shoals formed by currents that were confined to topographic lows.

The Mary Lee quartzose sandstone in western Lamar County lacks persuasive evidence for structural control by the predicted fault. Nevertheless, lithic sandstone thickens by more than 75 feet across the conjectured fault scarp (fig. 53), and cycle thickness increases across the scarp as well (fig. 52). The sandstone in western Lamar County evidently represents distal delta-front sands derived from a major delta complex in Mississippi (Sestak, 1984), and traceability of quartzose sandstone into lithic sandstone and coal in eastern Fayette County verifies the hypothesis of Mack and others (1983) that quartzose sandstone is derived from the removal of labile grains by marine reworking.

## Gillespie/Curry Cycle

### Characteristics

The Gillespie/Curry cycle is thicker than 450 feet in southeast Tuscaloosa County (fig. 56). The 300-foot contour defines an extensive thick trend extending from Pickens County to southern Jefferson County. North of the 300-foot contour, cycle thickness is variable, and the cycle is locally thinner than 200 feet in central Fayette County.

Lithic sandstone was the only sandstone type identified in the Gillespie/Curry cycle (fig. 57); net sandstone thickness is greatest in southeast Tuscaloosa County (figs. 56, 57). Throughout the remaining area south of the 300-foot cycle-thickness contour, net sandstone thickness is less than 75 feet. Several elongate and bifurcating trends are visible in southeast Tuscaloosa and western Jefferson Counties. A major elongate trend outlined by the 50-foot contour extends northwest from Tuscaloosa County and bifurcates in north Pickens County (fig. 57). A curvilinear trend defined by the 75-foot contour in northeast Tuscaloosa County is oriented northeast from the bifurcating trend and turns toward the northwest near its termination.

As a rule, the Gillespie/Curry contains only 2 coal beds (fig. 58). Coal is absent at some places, but as many as 4 beds are present locally. The coal beds are generally less than 1 foot thick (McCalley, 1900) but are areally extensive. The lower bed (Gillespie coal of McCalley, 1900) caps the thickest part

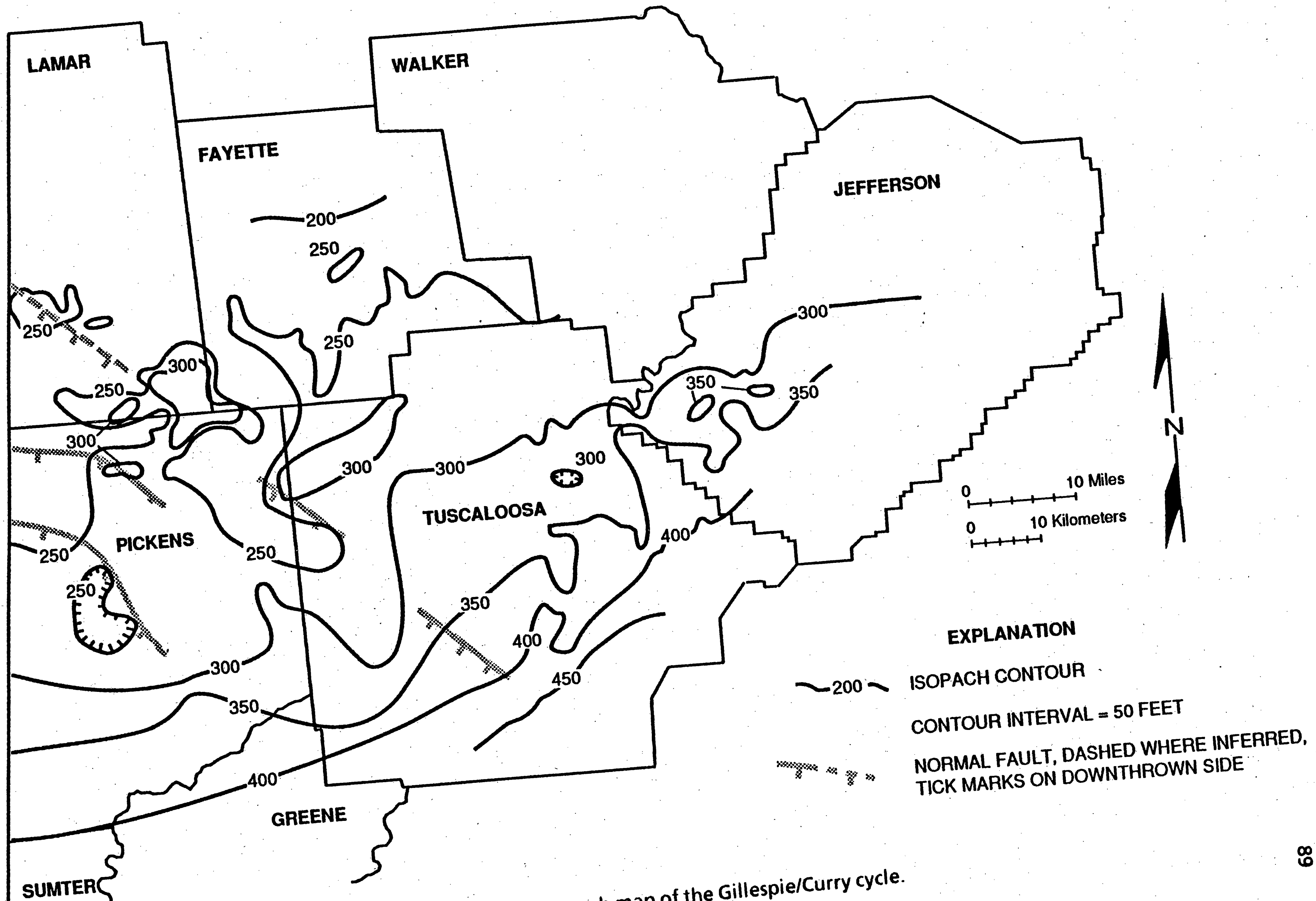



Figure 56. Isopach map of the Gillespie/Curry cycle.

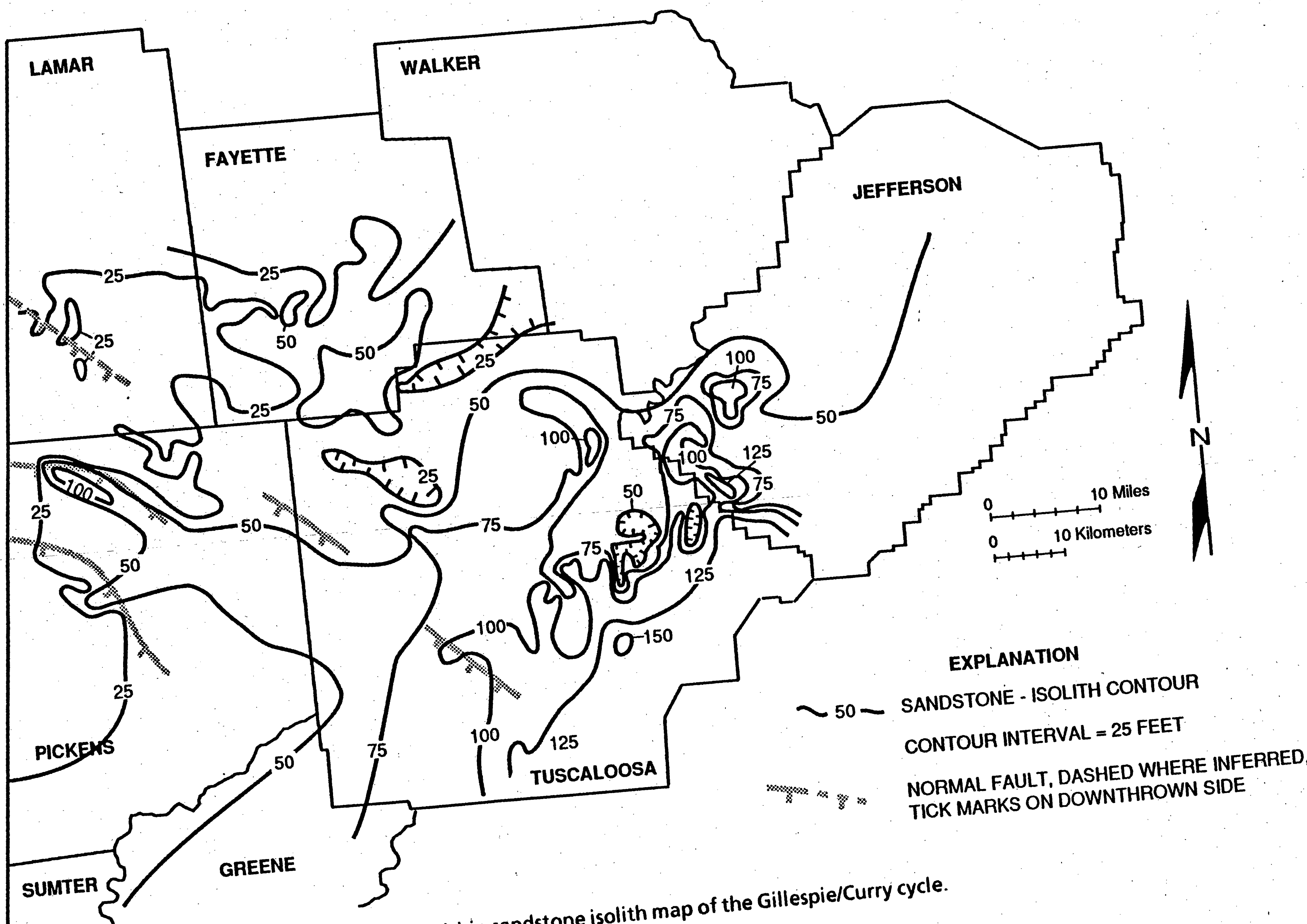



Figure 57. Lithic-sandstone isolith map of the Gillespie/Curry cycle.

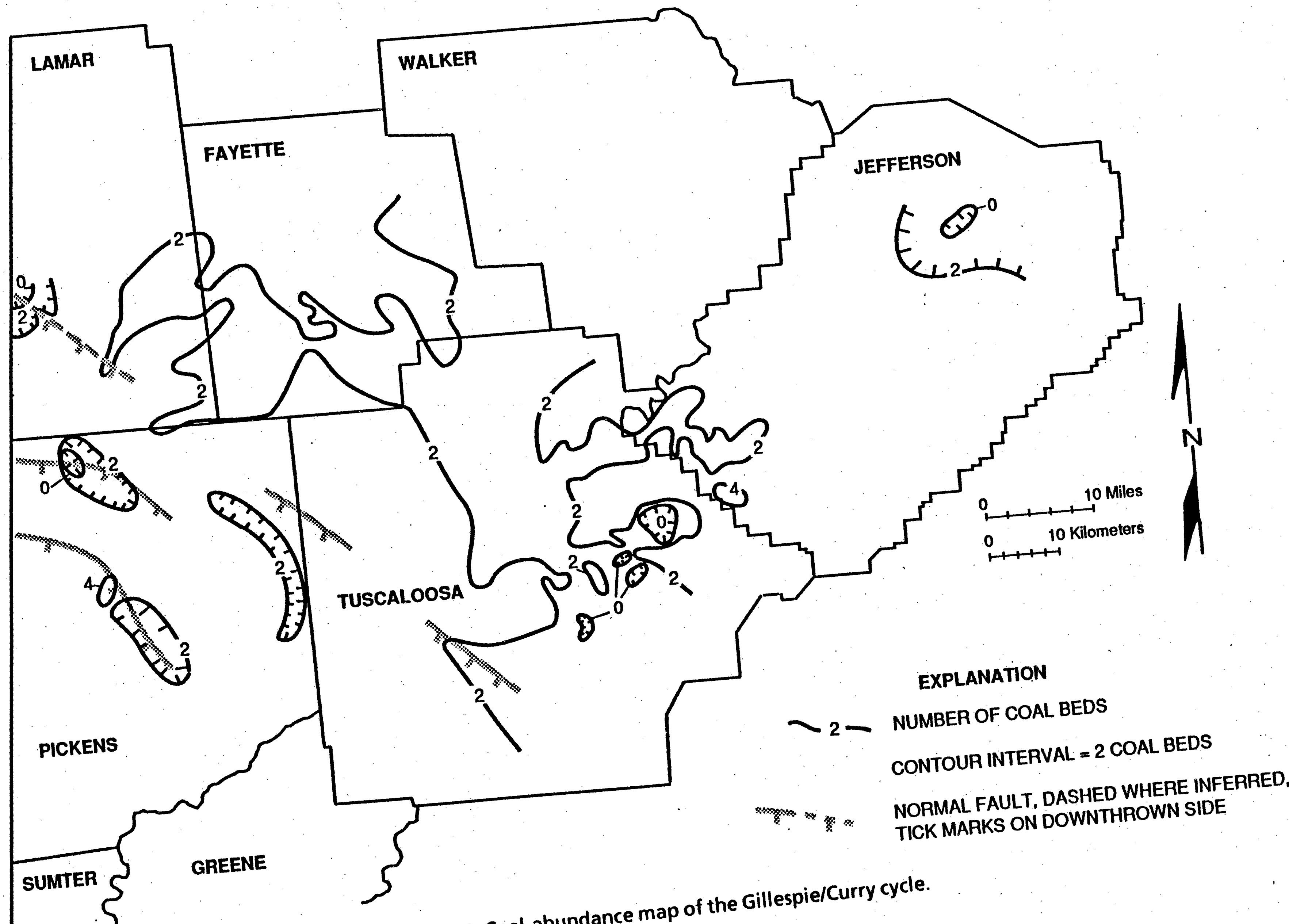



Figure 58. Coal-abundance map of the Gillespie/Curry cycle.

of the Gillespie/Curry cycle, and the upper bed (Curry coal of McCalley, 1900) caps a subcycle that is generally less than 80 feet thick (figs. 39, 45). Otherwise, it is difficult to relate coal distribution to other sedimentary patterns in the Gillespie/Curry cycle.

## Interpretation

The 300-foot contour ( fig. 56) defines the northwest margin of a trough of subsidence which had the same general trend as that developed during Mary Lee deposition (fig. 52). Whereas the Mary Lee trough narrowed toward the southwest, however, the Gillespie/Curry trough had a fairly uniform width. Thus, tectonic events leading to Gillespie/Curry deposition include westward expansion of the Black Creek depocenter and the development of a uniform trough of subsidence.

The numerous elongate and bifurcating trends on the sandstone-isolith map (fig. 57), some of which extend well beyond the trough of subsidence, suggest that deltaic environments predominated during Gillespie/Curry deposition. The elongate, bifurcating trend in Pickens County has the morphology of a trunk fluvial channel and two major distributaries; the overall geometry of the trend is analogous to the modern bird-foot lobe of the Mississippi Delta (Gould, 1970). The curvilinear trend in northeast Tuscaloosa County may represent a major distributary associated with the development of another delta lobe which is outlined by the 50-foot contour.

The trunk channel shows minor evidence for structural control by a known fault at the Pickens-Tuscaloosa County border (fig. 57). Much more convincing evidence of structural control by known structures can be demonstrated with regard to the distributaries. A known fault apparently confined the northern distributary; only the master fault of a modern-day graben (figs. 5, 6, 57) is shown. If both faults were shown, the distributary would lie directly in the graben. The southern distributary terminates at another master fault, which may have determined the site of mouth-bar development (fig. 57).

Because thick sandstone typically is below the stratigraphic level of the Gillespie coal bed, which is recognizable throughout most of the study area (figs. 39-45), the sandstone isolith map largely depicts sandstone distribution below the coal bed. Therefore, peat deposition evidently postdated deltaic progradation. Perhaps deltaic progradation in the Gillespie/Curry cycle represents a basin-filling episode that established an extensive alluvial plain where widespread peat deposition took place. Although evidence for deltaic environments exists in the Mary Lee and Gillespie/Curry cycles, coal occurrence is difficult to relate to those environments.

## Pratt Cycle

### Characteristics

The Pratt cycle generally varies in thickness from 150 to 250 feet throughout the northern part of the study area and thickens toward the south. The cycle attains a thickness of 500 feet in Sumter County but is only slightly more than 350 feet thick in southern Tuscaloosa County (fig. 59). In northern Pickens County, the 250-foot cycle-isopach contour reflects thickening along the Gillespie/Curry trunk channel, and the 200-foot cycle-isopach contour locally parallels faults (figs. 57, 59).

Like the Gillespie/Curry cycle, the only sandstone type in the Pratt cycle is lithic sandstone (fig. 60). Although the thickness pattern of the Pratt cycle differs from that of the Gillespie/Curry cycle, the distribution of lithic sandstone is similar (figs. 57, 60). Net-sandstone thickness in the Pratt cycle is more than 150 feet in southeast Tuscaloosa County, and numerous lobate and bifurcating trends are visible in east Tuscaloosa and west Jefferson Counties (fig. 60). Net sandstone thickness increases sharply across a fault in southern Tuscaloosa County, and a linear sandstone trend in Pickens County apparently coincides with a similar trend in the Gillespie/Curry cycle. Cross-section A-A' (fig. 39) shows that thick sandstone of the linear trend is within the coal-bearing interval. No evidence exists for bifurcation of the trend, but in northern Pickens County, thick Pratt sandstone is located immediately north of that in the Gillespie/Curry cycle (figs. 57, 60). In Lamar and Fayette Counties, the sandstone is generally less than 25 feet thick.

Coal abundance in the Pratt cycle increases toward the southeast (fig. 61). Fewer than 4 coal beds are present in Sumter and western Pickens Counties, and in parts of Lamar and Fayette Counties, less than 2 beds are present. More than 8 coal beds are present in the Pratt cycle of southwest Tuscaloosa

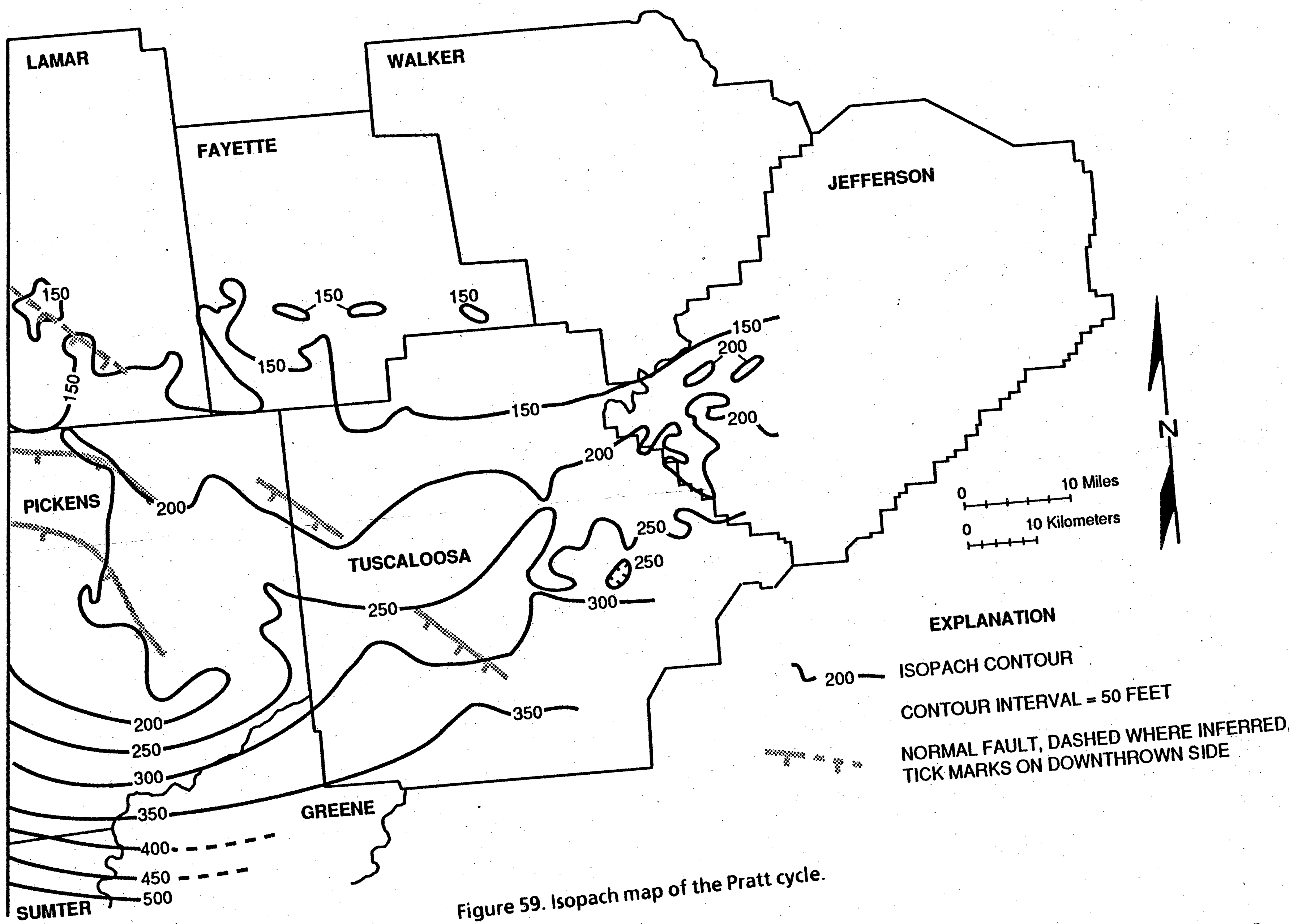



Figure 59. Isopach map of the Pratt cycle.

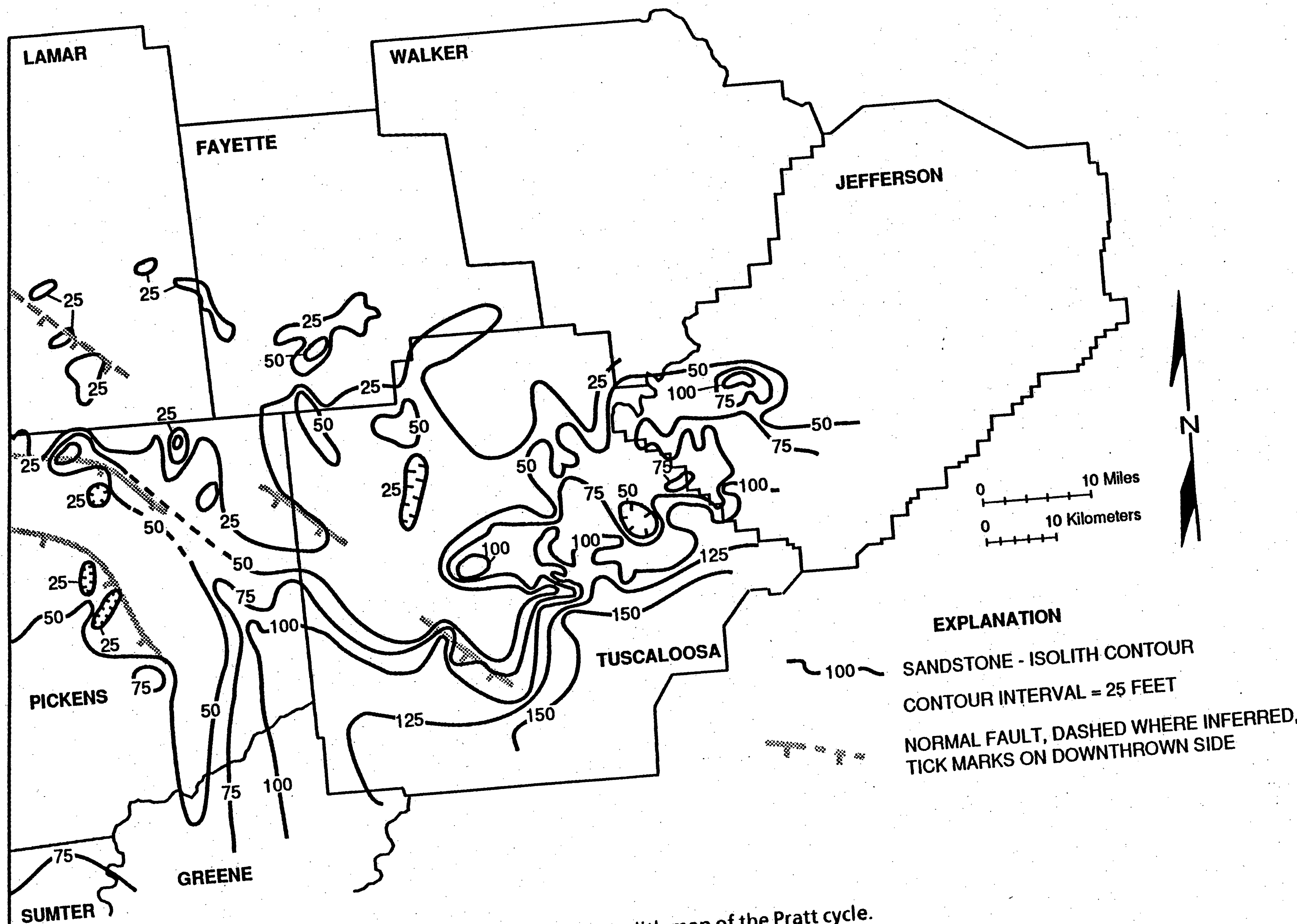



Figure 60. Lithic-sandstone isolith map of the Pratt cycle.

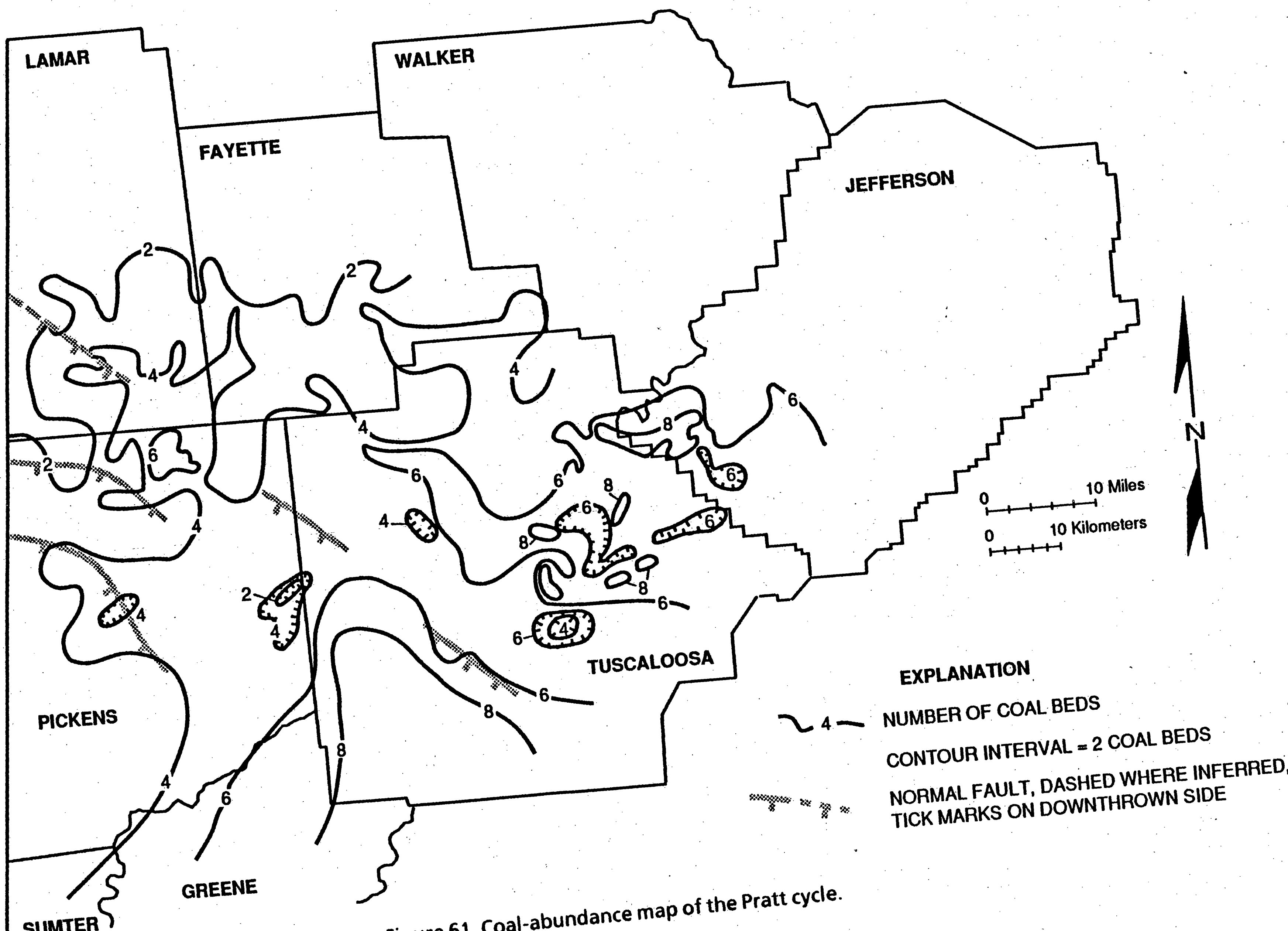



Figure 61. Coal-abundance map of the Pratt cycle.

County, and the 6-bed contour parallels a fault. Six to 8 coal beds are typically present in east Tuscaloosa and west Jefferson Counties, and 4 or more beds are present throughout most of the study area (fig. 61). In the Pratt cycle, abundant coal coincides with net sandstone thickness exceeding 75 feet (figs. 60, 61). As in the Mary Lee cycle, coal beds are traceable well beyond the limit of the lobate sandstone bodies and are interspersed with that sandstone (figs. 39, 45).

## Interpretation

The thickness pattern of the Pratt cycle (fig. 60) demonstrates a turnabout in basin configuration. The trough of subsidence in southern Tuscaloosa County was oriented more toward the east than during earlier cycles, and thickening of the Pratt cycle toward the southwest suggests that subsidence was much more rapid in Sumter County than in Tuscaloosa County. These changes in cycle-thickness trends reflect the increasing influence of the Ouachita orogen in controlling subsidence in Alabama. Thickening of the Pratt cycle along the trend of the Gillespie/Curry trunk channel indicates that the channel was slightly underfilled, so relict topography apparently was a local control on cycle thickness. Local parallelism of the 200-foot contour to the same faults that controlled Gillespie/Curry sandstone thickness suggests that synsedimentary fault movement also was a control on cycle thickness.

Sandstone-isolith patterns indicate that Pratt deposition included reactivation of the Gillespie/Curry trunk channel as evidenced by the elongate geometry outlined by the 50-foot contour (fig. 60). However, thick lithic sandstone north of the fault which controlled the position of the Gillespie/Curry distributary suggests diversion of the channel to the north by differential compaction. Because the relationship between sandstone distribution and coal distribution is similar in the Mary Lee and Pratt cycles, lobate and elongate sandstone trends in eastern Tuscaloosa and western Jefferson Counties may be partly a product of differential subsidence. Therefore, recognition of deltaic deposits is difficult, and most of the trends on the sandstone-isolith map probably represent fluvial systems on a differentially subsiding alluvial plain.

Although coal is most abundant between the two major lithic-sandstone trends in the Mary Lee cycle (figs. 53, 55), abundant coal in the Pratt cycle coincides with thick lithic sandstone (figs. 60, 61). Coal is most abundant along the southeast part of the linear channel trend in southwest Tuscaloosa County, so the channel apparently passed through an extensive wetland complex. Because sandstone in the Pratt cycle of eastern Tuscaloosa and western Jefferson Counties defines a wider lobate geometry than that in the Mary Lee cycle, the Pratt fluvial system evidently was less constrained along depositional strike. Therefore, coincidence of abundant coal and thick sandstone in the Pratt cycle of eastern Tuscaloosa and western Jefferson Counties evidently represents rapidly shifting fluvial environments in a peat-rich, wetland setting.

## Cobb Cycle

### Characteristics

The Cobb cycle is more than 450 feet thick at the Tuscaloosa depocenter and is more than 500 feet thick in Sumter County (fig. 62). South of the 350-foot contour, contours are closely spaced and define an arcuate trend of thick sediment similar to the one that is visible on the Black Creek-Cobb isopach map (fig. 46). North of the 350-foot contour, cycle thickness is fairly uniform and typically varies from 250 to 300 feet.

In the Cobb cycle, net-sandstone thickness exceeds 150 feet in southeast Tuscaloosa County and exceeds 100 feet along a trend extending from southwest Tuscaloosa County to west Jefferson County (fig. 63). Net sandstone thickness is less than 50 feet in west-central Tuscaloosa County and along a northeast trend that extends from northern Pickens County to southern Fayette County. However, sandstone is locally thicker than 100 feet in Lamar County.

In Lamar County, a body of quartzose sandstone is grossly delimited by the 100-foot contour, and the 50-foot contour probably represents the overall geometry of the sandstone body (fig. 63). The main axis of the quartzose sandstone body is located on the northern margin of the fault predicted on the basis of sandstone distribution in the Black Creek cycle; some linear trends outlined by the 100-foot contour are perpendicular to the postulated fault.

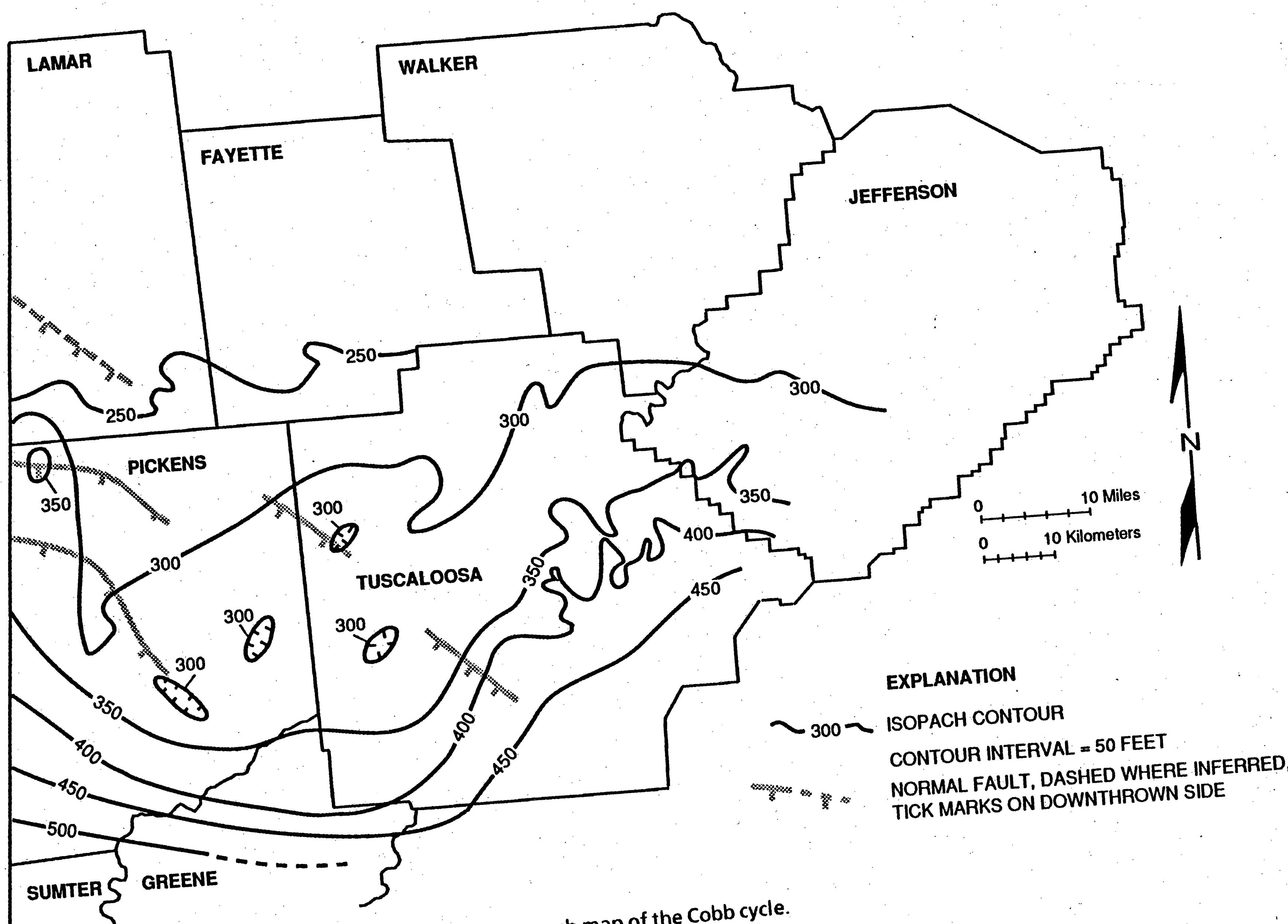



Figure 62. Isopach map of the Cobb cycle.

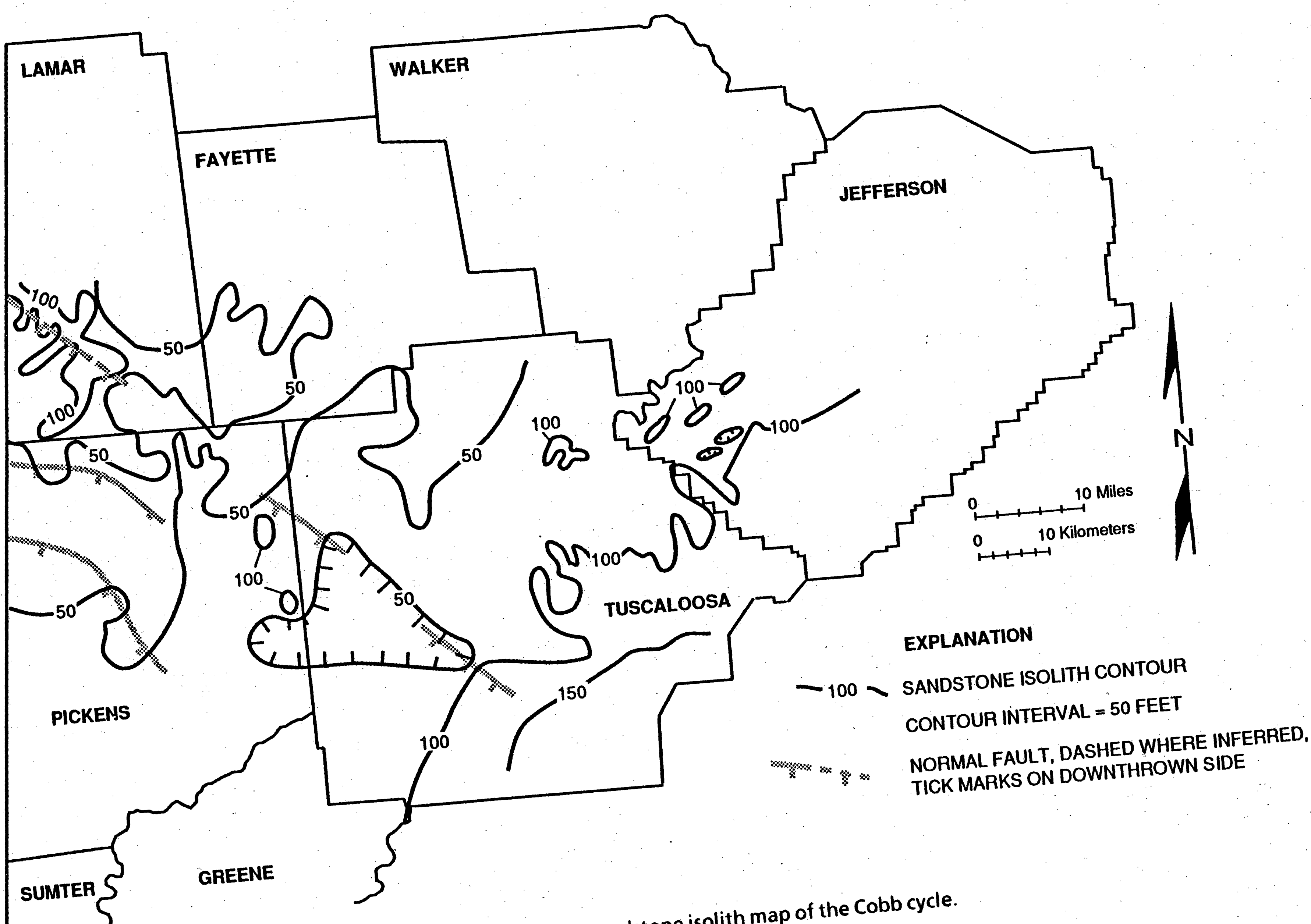



Figure 63. Sandstone isolith map of the Cobb cycle.

The Cobb cycle generally contains only 1 or 2 coal beds (fig. 64). Four coal beds are present in west-central Tuscaloosa County, and coal is lacking in the cycle in western Lamar County where the quartzose sandstone body is centered. Two to three coal beds are common in eastern Tuscaloosa County where the lithic sandstone is more than 100 feet thick.

## Interpretation

The arcuate trend of thick sediment defined by the 350-foot cycle-isopach contour (fig. 62) indicates that subsidence in Alabama occurred in response to a combination of Appalachian and Ouachita tectonics. In the eastern area, sediment thickness trends again were northeast, suggesting renewed thrust loading in the Appalachians, and the orientation of western part of the trend reflects continuation of the rapid subsidence that was evident during Pratt deposition. The uniformity of cycle thickness north of the 350-foot contour indicates an extensive platform area in the northern part of the study area.

Thickening of sandstone southeast of the 100-foot contour in southeastern Tuscaloosa and western Jefferson Counties (fig. 63) may be related to differential subsidence in that area and does not provide conclusive evidence for any depositional system. However, most sandstone is present below the coal-bearing part of the cycle (figs. 39-45), so both deltaic and alluvial environments may be represented. Absence of thick sandstone where the cycle is thicker than 400 feet in Greene and Sumter Counties is indicative of distal environments. Thickening of sandstone on the platform in the northern part of the study area and the deposition of quartzose sandstone in southwest Lamar County indicates the reestablishment of shoal-water conditions.

The thick quartzose sandstone body defined by the 100-foot contour appears to be controlled by the inferred fault in southwest Pickens County (fig. 63). The principal northwest sandstone trend parallels the fault, indicating shoaling at the top of the fault scarp. Perhaps the linear southwest trends that are oriented perpendicular to the main sandstone body represent channels or mass-flow bodies that traversed the fault scarp.

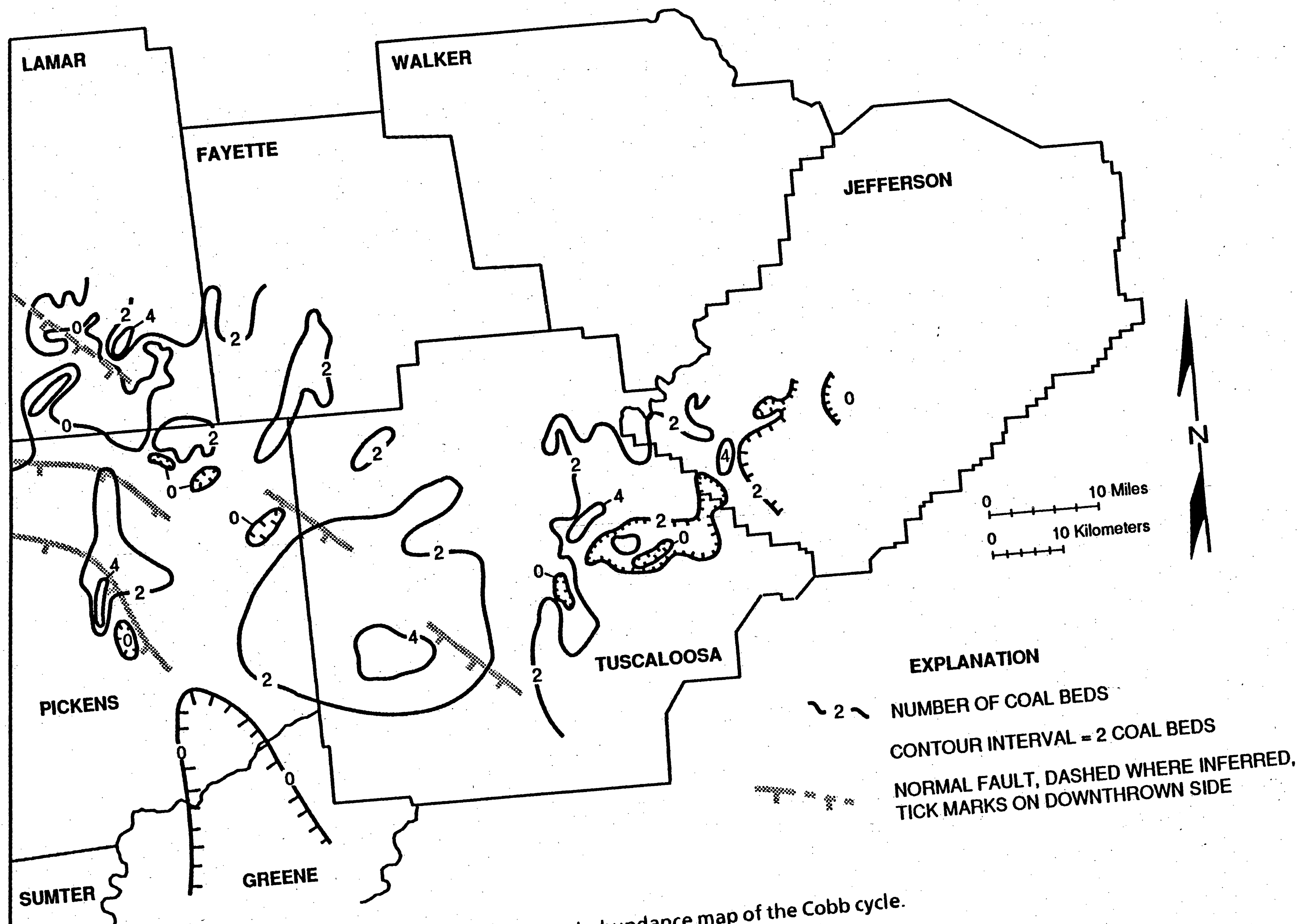



Figure 64. Coal-abundance map of the Cobb cycle.

# DEPOSITIONAL MODEL

The depositional model for the Black Creek-Cobb interval (fig. 65) was formulated using distinctive paleogeographic elements from the isopach and coal-abundance maps made for this study. Therefore, the model is an idealized composite of the architectural elements found in different cycles and is not a paleogeographic reconstruction. Ideally, a paleogeographic reconstruction depicts elements that are present at the same time. Because this study was based on subsurface data, interpretations from earlier outcrop studies were used to include in the model the nuances of sedimentary process that are not available from subsurface data.

Cross sections (figs. 39-45) demonstrate that cyclicity is the salient characteristic of the Black Creek-Cobb interval. This cyclicity can be related to relative sea-level variation. On the basis of isopach and isolith patterns, four major factors combine with the magnitude and periodicity of relative sea-level variation to control the geometry of each cycle package (1) subsidence, (2) synsedimentary fault movement, (3) relict topography, and (4) differential compaction.

Because mudstone is continuous at the base of each cycle, the entire study area was evidently inundated by marine water at the start of deposition of each cycle. According to Klein (1974), the thickness of marine strata from the base of a cycle to the lowermost shoreline strata of that cycle provides a minimum estimate of water depth. However, the model does not account for subsidence and compaction. Even so, some mudstone, such as that in the Black Creek and Gillespie/Curry cycles may have been deposited in water more than 300 feet deep. Hence, the thick, continuous mudstone units are interpreted to represent muddy, open-marine environments, such as shelf, slope, and prodelta (fig. 65).

Because coal groups generally are traceable throughout the study area, the sea had evidently retreated beyond the limits of the study area by the end of deposition of each cycle. On the basis of highwall and core descriptions (Epsman and others, 1988; Pashin and Sarnecki, 1990), regression culminated in the development of an alluvial plain which included fluvial systems, lakes, and peat

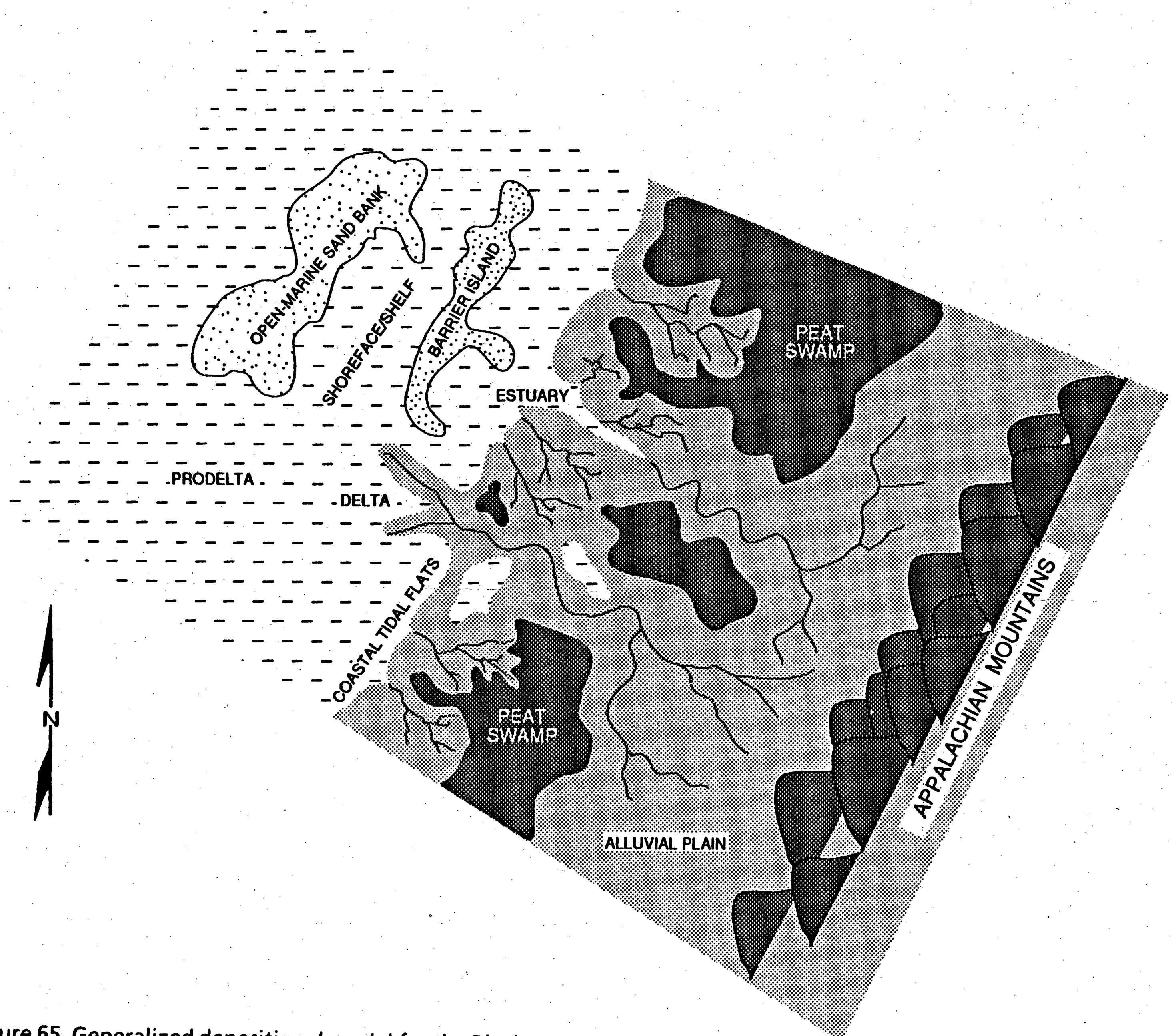



Figure 65. Generalized depositional model for the Black Creek-Cobb interval.

swamps (fig. 65). Therefore, the cycles of the Black Creek-Cobb interval represent a series of marine-terrestrial environmental continua.

These continua present difficulty in interpreting subsurface maps. One difficulty is that sandstone-isolith patterns represent a composite of several depositional systems. Another difficulty is the overprint of subsidence on sandstone-isolith patterns. In the Black Creek-Cobb interval, the greatest problem is recognizing shore-zone deposits, particularly deltaic deposits which have been documented in outcrop (Ferm and others, 1967; Horne and others, 1976; Benson, 1979). The Gillespie/Curry is the only cycle in which subsurface deltaic deposits are easily recognized. Quartzose sandstone, which is interpreted to represent beach-barrier and open-marine sand bodies (fig. 65), provides the best criterion for recognizing shore-zone environments, particularly in the Black Creek and Mary Lee cycles where quartzose sandstone can be traced laterally into lithic sandstone and coal. Tidal-flat deposits have been recognized in the Pottsville (Hobday, 1974), and parts of the shoreline were evidently affected by mesotidal conditions (Horne, 1979). Therefore, muddy shore-zone environments, which include tidal flats and estuaries that are difficult to recognize in the subsurface, were included in the model (fig. 65).

Using modern analogs as a guide, coal beds in the Black Creek-Cobb interval probably have a diverse origin. Marginal-marine peat domes are known from the Klang-Langat delta of Malaysia (Coleman and others, 1970), and similar bodies may be present in the Black Creek-Cobb interval (fig. 65). However, marginal-marine peat bodies tend to be geographically restricted and thin, and their importance as precursors to economic coal bodies is controversial (McCabe, 1984, 1987; Jones and Cameron, 1988). Thick, widespread peat deposits are known from alluvial plains in Indonesia (Anderson, 1964, 1983; Anderson and Müller, 1975) and are considered viable analogs for Carboniferous coal (McCabe, 1984, 1987). The geographically extensive, mineable coal beds of the Black Creek-Cobb interval may have formed in such a setting, although outcrop evidence suggests that peat accumulated in low-lying swamps as opposed to raised swamps (Pashin and Sarnecki, 1990). Low-ash peat is presently forming between Pleistocene beach ridges in Georgia that are as much as 70 miles inland (Cohen, 1974); such peat may be an analog for coal beds associated with quartzose sandstone in the Black Creek and Mary Lee cycles.

Cycle-isopach maps indicate that the regional subsidence pattern varied with time in response to tectonic activity in the Appalachian and Ouachita orogens. However, net lithic-sandstone thickness in each cycle is greatest in southeast Tuscaloosa County regardless of the cycle thickness pattern. Therefore, regional sandstone dispersal was independent of subsidence, and the persistence of thick lithic sandstone in southeast Tuscaloosa County indicates a major sand source to the southeast of the study area in the Appalachian orogen (fig. 65). Only in the Mary Lee cycle of Lamar County, where lithic sandstone has been traced into deltaic deposits in Mississippi (Sestak, 1984), is an Ouachita source for lithic sandstone in Alabama probable.

The distribution of quartzose sandstone is more varied than that of lithic sandstone. However, the quartzose sandstone may have the same source as lithic sandstone, because quartzose sandstone probably formed by the removal of labile grains by marine reworking (Mack and others, 1983). Therefore, quartzose sandstone was probably derived from both the Appalachian and Ouachita orogens. However, southwest crossbed orientations have consistently been recorded from quartzose sandstone in Alabama (Metzger, 1965; Shadroui, 1986), indicating that southwest currents, such as tides and longshore drift, moved the sand. Because quartzose sandstone with southwest-dipping crossbeds is widespread throughout the Appalachian region (Horne, 1979), some sand may have been transported into the basin from the northeast.

## HYDROLOGIC AND HYDROCHEMICAL ANALYSIS

### INTRODUCTION

Hydrology is of fundamental importance in coalbed-methane exploration and production because of the need to reduce reservoir pressure and dispose of produced water. A significant amount of water must be removed from the reservoir to reduce fluid pressure, thereby facilitating the desorption of methane from coal. Coalbed-methane wells typically are drilled to a depth of 1,000 feet or more below the land surface of the Black Warrior basin (Sexton and Hinkle, 1985) and produce from 5 to 1,175 barrels of water per day (bpd) (0.1 to 29 gallons per minute). Produced water ranges from fresh to saline. Hence, drilling in areas of low-salinity water is desirable to avoid environmental problems related to water disposal.

The primary objective of hydrologic analysis was to identify hydrologic controls on the occurrence and producibility of coalbed methane. A secondary objective was to determine water-chemistry associations. Water-level, water-yield, water-pressure, and water-chemistry data were interpreted to evaluate hydrologic conditions in coal beds and associated strata of the Black Creek-Cobb interval. The data also were analyzed to determine the hydrodynamics of the coalbed-methane reservoir.

## METHODS

Hydrologic information used in the research was derived from the following sources (1) water-resource reports and file data of the Geological Survey of Alabama, the State Oil and Gas Board, the U.S. Geological Survey, and other agencies, (2) water-analysis and water-level information determined for wells in 1987-88, (3) coal-mine operators, and (4) coalbed-methane operators. The sources and types of available information are shown in table 4.

Table 4. Types and sources of hydrologic information and water-analysis data

| Source | Hydrologic information | | Water analyses | |
|---|---|---|---|---|
| | Records/files | Hydrologic tests | Partial | Standard |
| Water or test well | 1,000 + | 14 | 100 | 62 |
| Oil and gas exploration well | 30 | -- | 30 | -- |
| Coalbed degasification well | 442 | 27 | 59 | 70 |
| Surface runoff (unmined area) | 32 | -- | -- | 32 |
| Surface runoff (mined area) | 24 | -- | -- | 24 |

Water-analysis and hydrologic data were analyzed and plotted using statistical and graphic software packages. The critical values for regression coefficients presented in Rohlf and Sokal (1969) were used to determine the statistical correlation of data and specific parameters at the 95 percent or higher confidence level. Data plots that appear in this chapter include pressure-depth plots, the trilinear "Piper" diagram (Piper,1944) and the polygon-shaped "Stiff" diagram (Stiff, 1951).

## Water-Sample Analysis

The source of the surface-water data used in this report is Dyer (1982), and numerous water-resource reports provided data on ground-water chemistry. Hydrologic information includes water-level data and hydrologic well-test data to determine well yield and the water-transmitting ability of strata. This information is on file at the Water Resources Division of the Geological Survey of Alabama. The location of wells for which water-analysis data were used is shown in figure 66.

Water samples were collected from 59 coalbed-methane wells and 13 water wells in Tuscaloosa and Jefferson Counties in 1988. Standard analyses of the water samples were made in the Geochemical Laboratory of the Geological Survey of Alabama. The procedures described in Brown and others (1970), Skougstad and others (1979), and the U.S. Environmental Protection Agency (1979) were used to analyze the samples. The trilinear diagram (fig. 67) was used to plot chemical data and to determine water type, and the U.S. Geological Survey classification of water salinity (Swenson and Baldwin, 1965) was used to classify water according to total-dissolved-solids (TDS) content, or degree of mineralization. A subsurface salinity map was prepared by using the available water-analysis data and an interpretation of electric well logs (Epsman and others, 1983).

The analyses of water samples include a determination of silica, calcium, magnesium, sodium, potassium, sulfate, chloride, bicarbonate, carbonate, nitrate, selected trace-metal contents, and the physical properties of water. The pH of water samples was measured with an Orion Model 407-A pH meter with an associated specific-ion electrode. Specific conductance was measured in micromhos per centimeter with a model MCI, Mark IV portable meter or Curtin Matheson Scientific Inc. digital conductivity meter that was calibrated using standard solutions. Temperature was determined in the field by using a thermometer calibrated in degree-centigrade (°C) increments between -10 °C and 110 °C. For some samples, carbonate and bicarbonate contents were determined in the field by titrating 50 milliliters (ml) of well water with a standard sulfuric acid solution to end-point pH values of 8.4 and 4.5. Trace-metal content of the samples was determined using a Perkin-Elmer 2380 atomic-adsorption spectrophotometer.

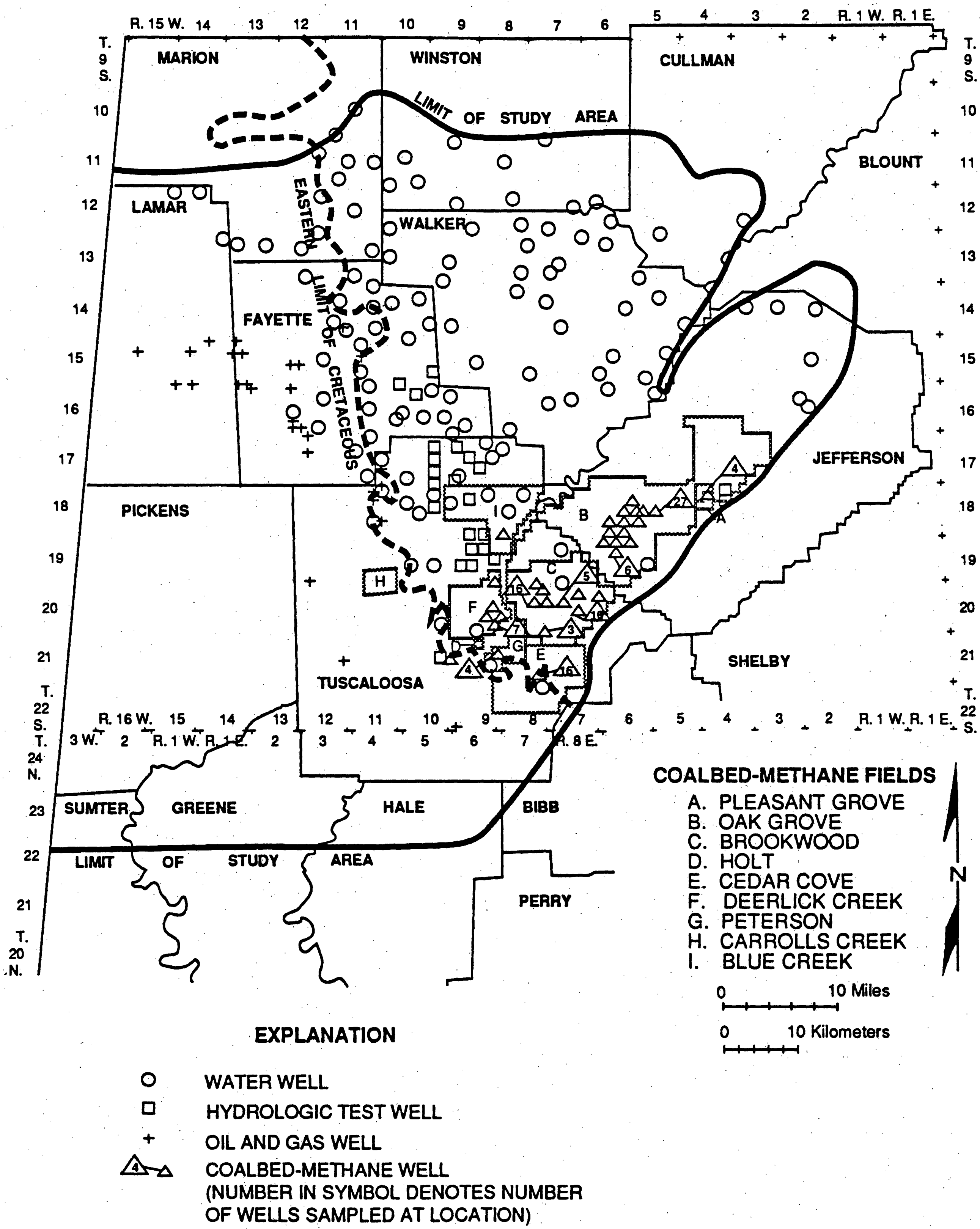



Figure 66. Location of wells used for water-analysis data.

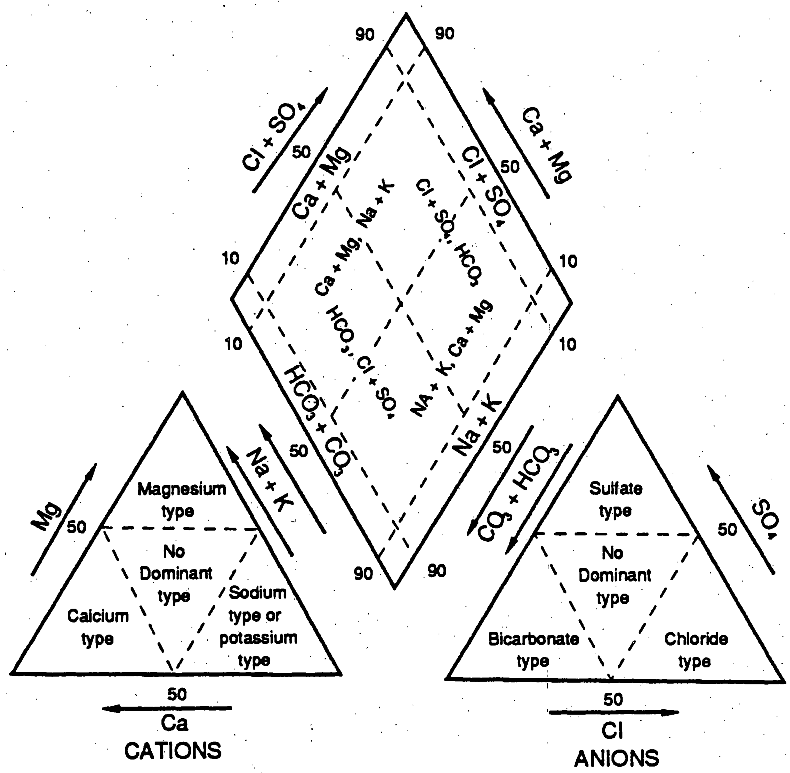



Figure 67. Hydrochemical classification of water using the trilinear Piper diagram.

## Water-Level Measurement

Water level was measured in 46 coalbed-methane wells in Tuscaloosa and Jefferson Counties in 1987 and 1988. The data were used for computing reservoir pressure and hydraulic head of coal-bearing intervals. The instrument used is a battery-operated Powers Well Sounder. Water level was determined to the nearest 0.1 ft. The potentiometric-surface map is based on water-level measurements for wells referenced to a datum, the National Geodetic Vertical Datum of 1929, which commonly is known as mean sea level (msl). The potentiometric-surface map for the upper Pottsville Formation was prepared using water-level data from more than 1,000 water, test, and oil-and-gas wells.

Pressure-depth quotients were determined from available water-level and construction information for wells to determine the current pressure regimes in the coalbed-methane fields. To determine pressure-depth quotient values, bottom-hole pressure was calculated (fluid column length times 0.433 psi/ft) and then divided by total well depth. Pressure-depth quotients were determined for intervals more than 1,000 ft below the land surface. The 1,000-foot depth criterion was selected because Diamond and others (1976) have determined that the highest potential for coalbed-methane production occurs below that depth. Pressure-depth plots were used in the evaluation of subsurface water-circulation patterns in areas of active coal degasification.

## GEOLOGIC AND HYDROLOGIC FRAMEWORK

The Pottsville Formation is a fractured rock system characterized by low transmissivity, low capacity for retention and storage of water, and normally low and erratic water yield to wells (Hinkle, 1976). Lithic sandstone has limited effective porosity (Tucker and Kidd, 1973), although quartzose sandstone has enough porosity and permeability to be potential petroleum reservoirs (Epsman, 1987). These low-permeability rocks of the Pottsville yield a limited quantity of water to wells. Although the permeability of upper Pottsville coal is low, it exceeds that of other rock types and is commonly highest along the face cleat (Gas Research Institute, 1985). Therefore, fractures play a significant role in ground-water flow, and coal beds are viable aquifers (fig. 68).

The Pottsville Formation is overlain by unconsolidated siliciclastics in the western part of the study area. The unconsolidated units include Quaternary terrace deposits and alluvium and Cretaceous sand, clay, and gravel. The basal Cretaceous sand is a major aquifer that appears to be locally interconnected hydrologically with the Pottsville Formation.

The mineralogy of strata in the Pottsville Formation evidently effects water-bearing properties and water chemistry. Although Pottsville strata are composed mainly of quartz, mica, and clay, other minerals of geochemical importance include pyrite ($FeS_2$), siderite ($FeCO_3$), and calcite ($CaCO_3$); these minerals commonly occur in bands or in fractures. The underclay and mudstone associated with the coal-bearing intervals contain kaolinite and illite (Rheams and others, 1987) which may play an important role in ion-exchange processes.

The occurrence and movement of water in the Pottsville, particularly in the degasification fields where permeability is low, is dependent on the type, openness, extent, and density of fractures in the

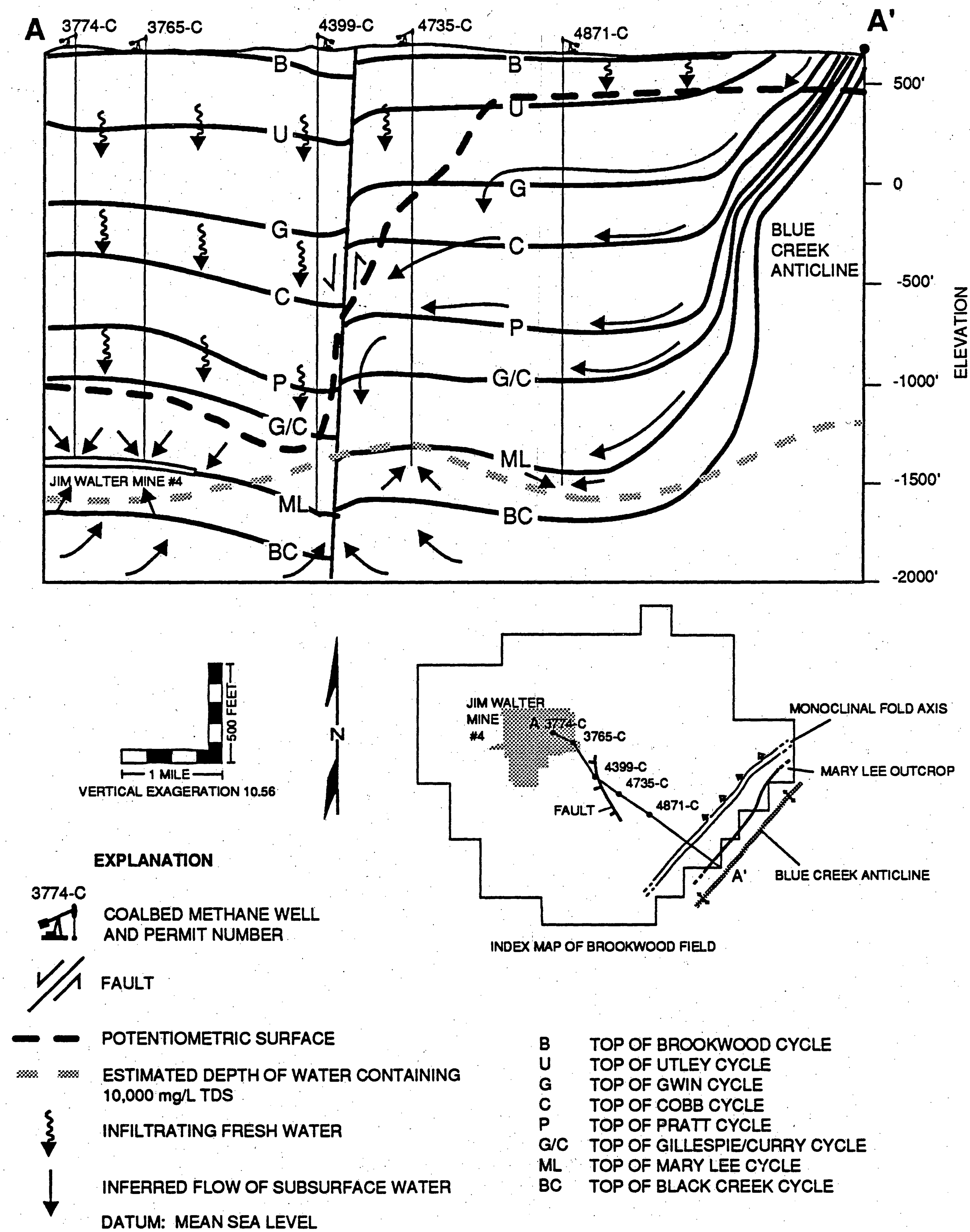



Figure 68. Idealized hydrogeologic cross section for an Alabama coalbed-methane field.

rocks. The occurrence and movement of ground water also is dependent on hydrologic conditions such as the position of the water table and potentiometric surface relative to the land surface (Harkins and others, 1980; Epsman and others, 1988) (fig. 68). The principal source of recharge to the Pottsville Formation is considered to be rainfall, but some recharge by streams is possible (Harkins and others, 1980). In some coalbed-methane fields, mine dewatering may accelerate fresh-water recharge (Epsman and others, 1988).

Hydrologic studies indicate that ground-water recharge through rainfall infiltration is nearly 5 percent of the average annual precipitation in the study area, which is approximately 54 inches per year (Harkins and others, 1980; Lineback and others, 1974). A low rate of recharge is indicated by the low median annual 7-day low flow of minor streams, which is 0.05 million gallons per day per square mile or less (Peirce, 1967). Additionally, the Pottsville has a limited ability to transmit water to streams during dry weather. Hinkle (1976) indicated that the upper 300 feet of the Pottsville in Alabama contains approximately $2.02 \times 10^7$ million gallons of water. The water typically has a low mineral content and is of acceptable chemical quality for drinking. However, some water contains an excessive amount of iron and manganese and has a low pH.

Water movement in the upper Pottsville is multidirectional due to the complex geometry of fracture systems (fig. 68). Flow generally is toward topographically low areas where natural discharge of water takes place (Harkins and others, 1980). Movement of deep water may mimic this pattern to some extent; however, where withdrawal of formation water caused by mine dewatering has produced low hydraulic head, vertical movement of water along fractures is possible. This condition is apparent in Oak Grove field (Epsman and others, 1988).

## POTENTIOMETRIC SURFACE

Water in the Pottsville Formation is unconfined in the shallow subsurface and is either semiconfined or confined at depth. Where an unconfined unit is involved, the potentiometric surface is traditionally referred to as the water table. Because a potentiometric-surface map is a composite of water-level measurements, the map can also be used to determine the downgradient direction of subsurface water movement. The general flow direction is perpendicular to the contours shown on the potentiometric map. Point values used in preparing a potentiometric-surface map can be used to determine the hydraulic gradient, or change in hydraulic head, that occurs over a specified flow-path distance.

The direction of shallow ground-water movement generally is toward surface drainage features, which include the Black Warrior River, Mulberry Fork, Sipsey Fork, and Locust Fork (fig. 69). In areas where the Pottsville is overlain by Cretaceous strata, the dominant direction of ground-water movement generally is downgradient to the southwest. The potentiometric surface ranges from more than 1,000 feet above msl in the northeasternmost upland area to less than 200 feet above msl at the Cretaceous overlap. Areas where the water table has been depressed by mine dewatering occur in Brookwood and Oak Grove fields. High potentiometric-surface values that occur along the Cretaceous overlap may be the result of recharge from outliers of Cretaceous sand. Hydraulic-gradient values in the horizontal direction, which were estimated from water-level data for water wells, range from 0.0001 in the northeast upland areas to 0.14 along bluffs of the Black Warrior River.

## WATER-TRANSMITTING CHARACTERISTICS

Hydraulic conductivity and transmissivity values were determined from hydrologic test data for 14 wells completed in the upper part of the Pottsville Formation (table 5). Hydraulic-conductivity values indicate that the water-transmitting ability of Pottsville strata decreases as depth increases (fig. 70). The hydraulic conductivity values below a depth of 150 feet typically are less than 0.1 feet per day (ft/d), and the associated transmissivity values, which were determined by multiplying the saturated thickness of rock in open well bores by hydraulic conductivity, also are very low (table 5). Storativity values, where determined, generally are 0.001 or less, indicating semi-confined to confined conditions. Water-transmitting values approximate those cited for coal-bearing zones in other regions (Fetter, 1980).

Hydrologic test data for wells in Cedar Cove, Brookwood, and Oak Grove fields also indicate that permeability decreases with depth (McKee and others, 1986). The permeability-versus-depth graph

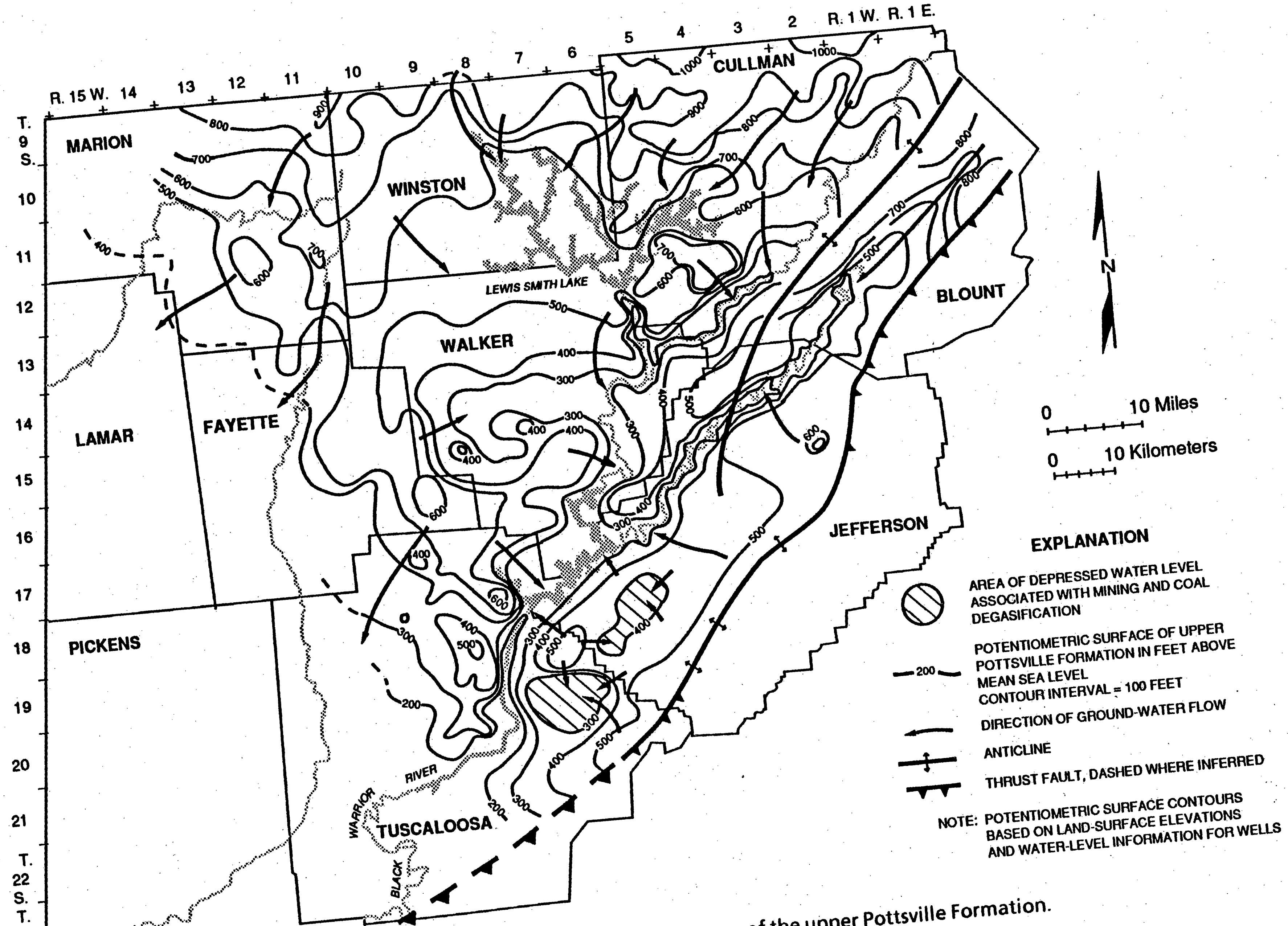



Figure 69. Generalized potentiometric-surface map of the upper Pottsville Formation.

Table 5. Hydrologic test data for wells

| Well no. | County | Hydraulic conductivity (ft/d) | Estimated transmissivity ($ft^2/d$) | Storativity | Well depth (ft) | Base, open zone (ft, msl) |
|---|---|---|---|---|---|---|
| Mar-1 | Marion | 0.001 | 0.27 | -- | 520 | -68 |
| TW-5 | Tuscaloosa | 3.24 | 48.6 | $10^{-2}$ | 60 | -459 |
| TW-7 | Tuscaloosa | .068 | 4.64 | $10^{-4}$ | 150 | -306 |
| TW-8 | Tuscaloosa | .115 | 12.3 | $10^{-4}$ | 150 | -332 |
| TW-10 | Tuscaloosa | .001 | .134 | $10^{-10}$ | 200 | -318 |
| TW-12 | Tuscaloosa | .025 | 4.82 | $10^{-4}$ | 267 | -317 |
| TW-13 | Tuscaloosa | .017 | 2.41 | $10^{-3}$ | 166 | -415 |
| TW-17 | Tuscaloosa | .044 | 4.34 | $10^{-4}$ | 170 | -432 |
| TW-18 | Tuscaloosa | .015 | 2.18 | $10^{-3}$ | 226 | -298 |
| TW-25 | Tuscaloosa | 1.28 | 1.31 | $10^{-3}$ | 150 | -332 |
| TW-26 | Tuscaloosa | 1.64 | 174 | -- | 124 | -271 |
| TW-27 | Tuscaloosa | 0 | .01 | $10^{-7}$ | 268 | -293 |
| TW-28 | Tuscaloosa | .007 | 1.00 | $10^{-5}$ | 248 | -360 |
| TW-30 | Tuscaloosa | .126 | 10.1 | $10^{-3}$ | 124 | -285 |

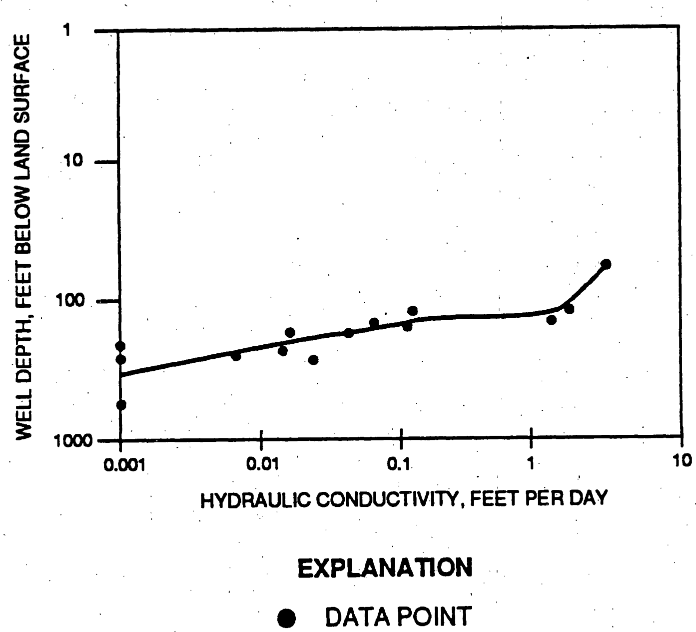



Figure 70. Plot of hydraulic conductivity versus well depth, upper Pottsville Formation.

presented in McKee and others (1986) shows that the rock permeability in these fields is on the order of 100 millidarcies (md) (~0.24 ft/d) at a depth of 100 feet and decreases to less than 10 md (~0.027 ft/d) at a depth of 1,000 feet or more. Low permeability values of 0.06 to 54 md (~0.01 to 0.13 ft/d) were reported by Epsman and others (1988) for the Mary Lee coal group at a depth of more than 1,000 feet in Oak Grove field. As already mentioned, the permeability of coal generally exceeds that of other upper Pottsville rock types.

## RESERVOIR PRESSURE

Water contained in reservoir rocks occurs under pressure termed reservoir pressure, formation pressure, or fluid pressure (Tucker and Kidd, 1973). Two types of conditions can exist in a water-bearing unit (1) hydrostatic conditions in which there is no flow, and (2) hydrodynamic conditions in which there is flow. Hydrodynamic conditions are typical for a hydrologic unit such as the Pottsville Formation.

The upper Pottsville can be classified as a low-pressure reservoir relative to the vertical fresh-water hydrostatic gradient (0.433 psi/ft). The pressure-depth data indicate that reservoir pressure is at or less than hydrostatic (fig. 71). Quotients less than 0.32 psi/ft are associated with active dewatering in underground coal mines and in coalbed-methane fields (fig. 72). The largest area of low reservoir pressure (pressure-depth quotient less than 0.32 psi/ft) is approximately 40 square miles and is centered near active mine-dewatering operations in Brookwood field that have been under way since the early 1970's. Data from Oak Grove field (fig. 71) plot near the hydrostatic pressure line and are the only data obtained from wells that had been on line for less than 3 months at the time of analysis. Hence, the Oak Grove data may represent natural, near-hydrostatic conditions in the Black Warrior basin. All other pressure-depth data indicate that pressure is not a function of depth owing to extensive hydrologic perturbation caused by mine and well dewatering.

The flow of water caused by differences in reservoir pressure can be characterized as lateral flow that occurs due to a difference in pressure within the same interval and upward or downward flow that occurs as the result of a vertical head difference. Pressure in producing intervals ranges from 0 to

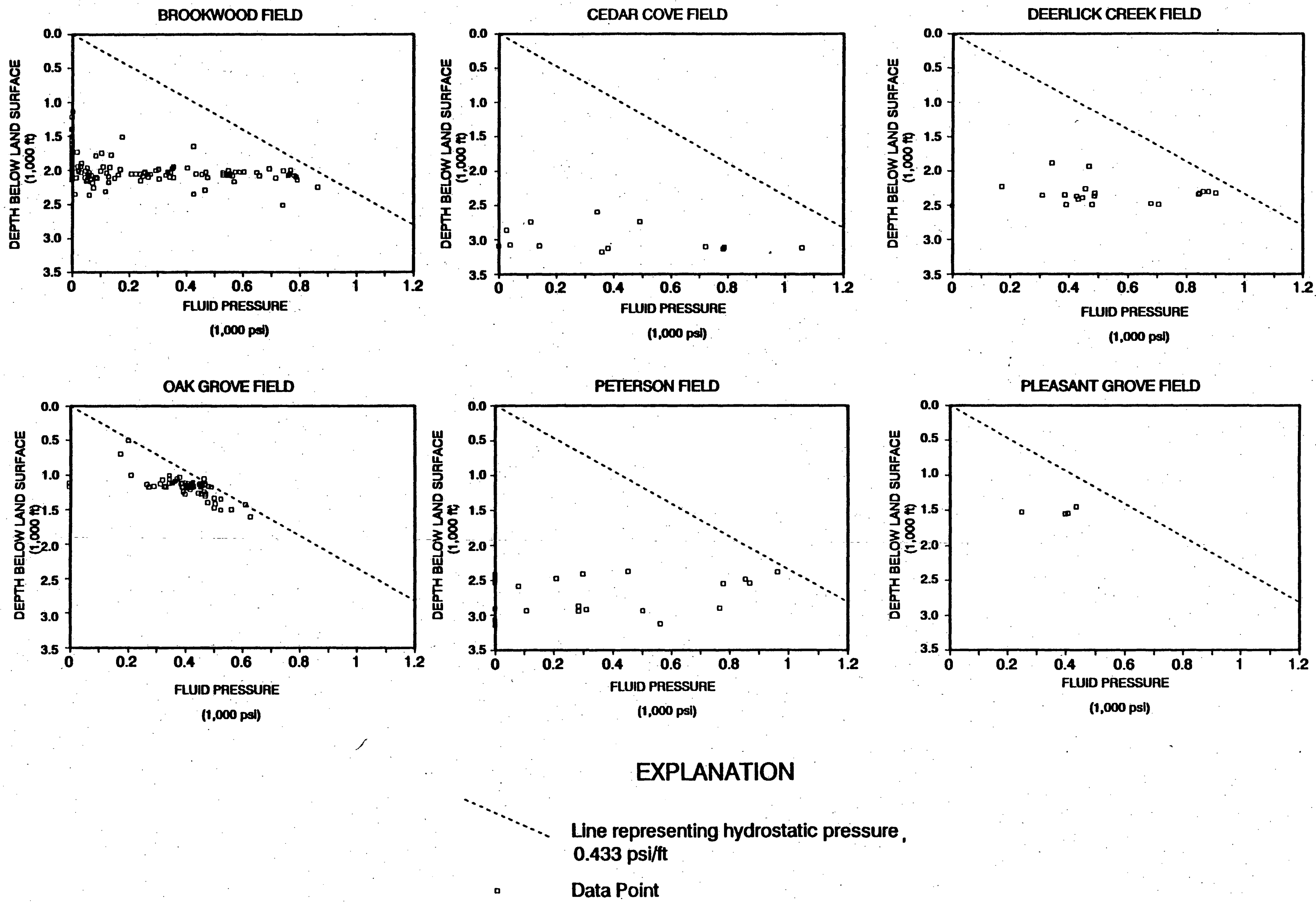



Figure 71. Pressure-depth plots for selected coalbed-methane fields.

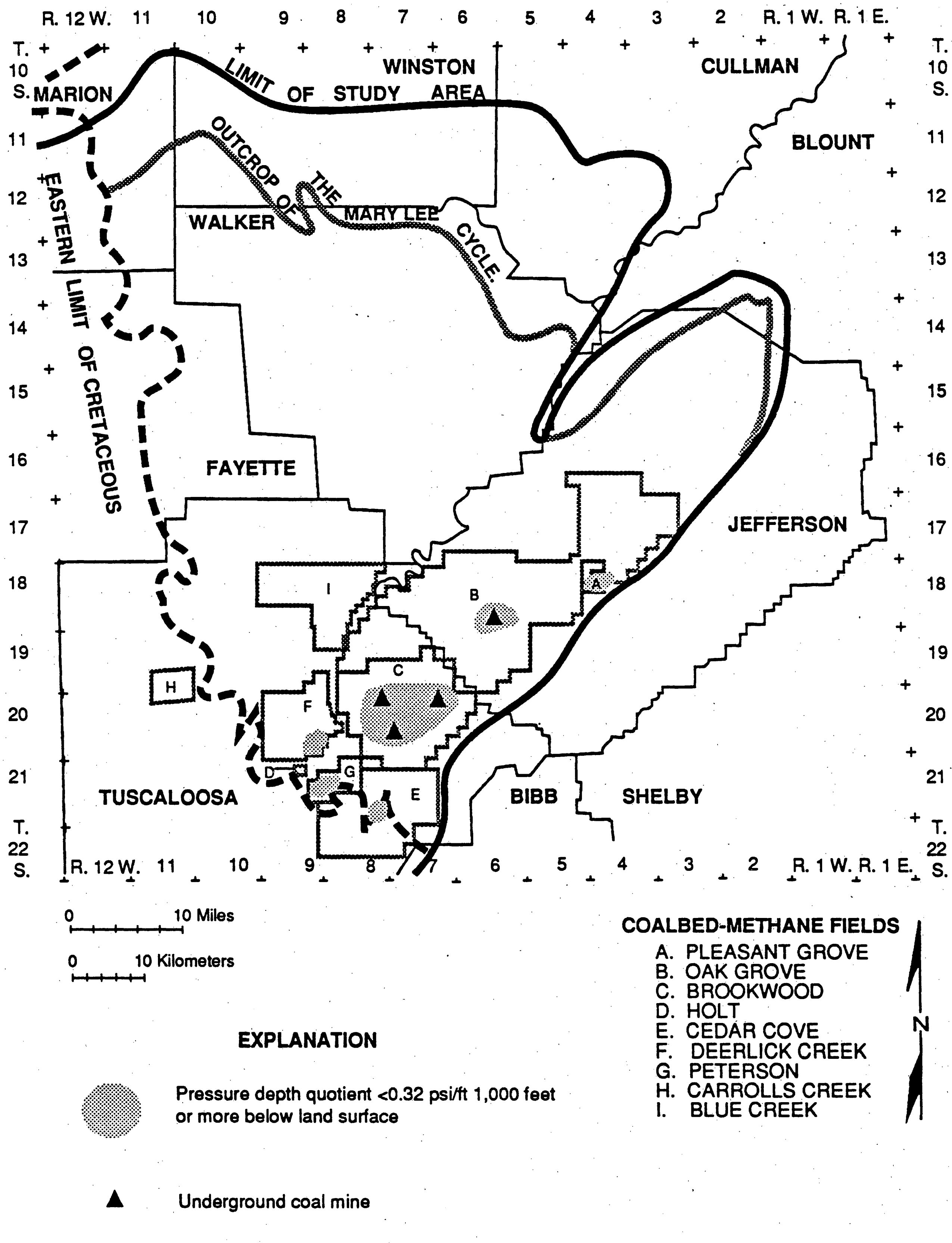



Figure 72. Areas with low pressure-depth quotient in the Upper Pottsville Formation.

700 psi or more at about the same level in Brookwood, Cedar Cove, Deerlick Creek, Holt, and Peterson fields and reflects potential for lateral movement of water toward low-pressure zones. This variablilty of pressure indicates considerable potential for flow in most coalbed-methane fields (fig. 71).

Potential for limited upward movement of water in coalbed-methane fields is indicated by pressure data available for coal beds at the Rock Creek site (Gas Research Institute, 1989) and by drill-stem-test data for deep formations at a test well site in western Jefferson County (table 6). The data indicate a pressure differential in the subsurface that would be conducive to the upward movement of mineralized water along fractures (fig. 68). At the western Jefferson site, a considerable pressure difference exists between shut-in intervals of the Mississippian Hartselle Sandstone and Bangor Limestone and the lower Pottsville Formation, reflecting potential for upward flow.

Table 6. Drill-stem-test data for a deep test well (DD-02), western Jefferson County, Alabama

[Well completed - March 1970; test conducted - February 1970; total depth - 6,060 feet. Interval tested (ft, kb) - feet below kelly bushing.]

| Test no. | Formation name | Interval tested (ft, kb) | | Fluid recovery (ft) | Depth of gage (ft) | Measured pressure | | | Estimated pressure gradient (psi/ft) |
|---|---|---|---|---|---|---|---|---|---|
| | | From | To | | | Initial (psi) | Final (psi) | Condition | |
| 1 | Pottsville (lower) | 2,810 | 2,975 | 120 | 2,971 | 102<br>376 | 131<br>296 | flowing<br>shut-in | 0.10 |
| 2 | Bangor Limestone | 3,343 | 3,551 | 245 | 3,547 | 161<br>880 | 193<br>880 | flowing<br>shut-in | 0.25 |
| 4 | Hartselle Sandstone | 3,570 | 3,724 | 140 | 3,720 | 791<br>1,492 | 1,511<br>1,520 | flowing<br>shut-in | 0.41 |
| 5 | Red Mountain | 4,300 | 4,416 | 150 | 4,412 | 100<br>431 | 130<br>615 | flowing<br>shut-in | 0.14 |

Note: Drill stem tests were performed to determine productivity, reservoir pressure, and water salinity at different depths. The results of test no. 3 are not shown because of their inconclusive nature (leak in drill stem). Pressure gradient was determined for each test interval by using gage depth and final shut-in pressure. Fluid recovery was not adequate for determination of water salinity. Information from files of the Water Resources Division of the Geological Survey of Alabama.

## WATER YIELD OF WELLS

Water wells typically are completed in the near-surface part of the Pottsville at an average depth of 150 feet. Water yield from these wells 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 commonly completed in unweathered rock at a depth exceeding 1,000 feet and have initial water-yield values ranging from 17 bpd to 1,175 bpd on the basis of a 420-well data set (fig. 73); average yield is only 103 bpd. Initial production rates are based on the results of 24-hour tests given on form OGB-9, First Production or Retest Report, for each well on file with the State Oil and Gas Board.

The initial-test water yield of coalbed-methane wells approximates the peak water-production rate according to data submitted to the State Oil and Gas Board. This is due in part to the decline in water yield with time that is associated with dewatering of coal beds. This aspect of water yield was recognized by Ancell and others (1980) in a 20-year production projection for 17 coalbed-methane wells in the Warrior basin and also is readily apparent in production-decline curves (Epsman and others, 1988). Low yield (0 to 50 bpd) may be attributed to low formation pressure in areas of active dewatering for coal mining and coal degasification (Pashin and others, 1989).

The water yield of coalbed-methane wells in the Black Warrior basin is typically less than 250 bpd. More than 70 percent of the well-yield values are between 0 and 250 bpd. Values higher than 250 bpd are associated with structural features, such as some faults and lineaments, where permeability of the strata is increased. Sixteen areas of high initial water production (>250 bpd per well) were identified during hydrologic evaluation. Although data are scarce, these areas coincide partly with areas having peak gas production of more than 200 Mcfd (fig. 74). Areas with high water yield occur in Brookwood, Deerlick Creek, Cedar Cove, Holt, Peterson, and Oak Grove fields. In three of the identified areas in Brookwood and Cedar Cove fields, the water yield per well exceeded 1,000 bpd.

## WATER CHEMISTRY

In the Black Warrior basin of Alabama, water chemistry is affected by the processes of oxidation, carbonation, hydration, and ion exchange associated with the weathering of rock and soil. In coalbed-methane fields, different water types may mix. These processes produce characteristic water species (fig. 75). Within the zone of active water circulation, pyrite in the Pottsville Formation apparently undergoes dissolution to form the soluble sulfate ($SO_4^{2-}$) and ferrous ($Fe^{2+}$) ions. Sulfate appears to undergo reduction with depth to form hydrogen sulfide ($H_2S$) which is noticeable in the

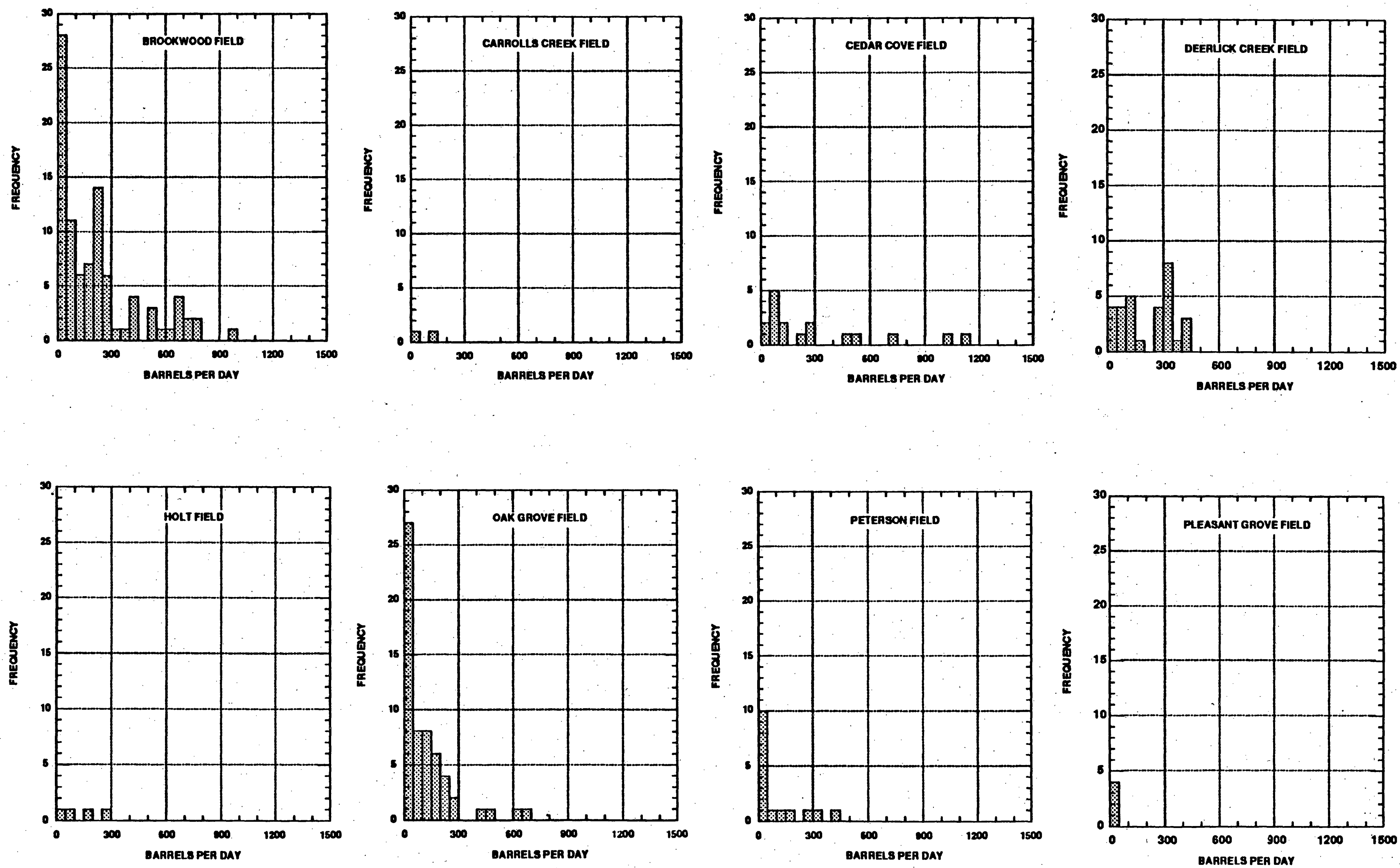



Figure 73. Frequency histograms of initial water yield of wells in coalbed-methane fields.

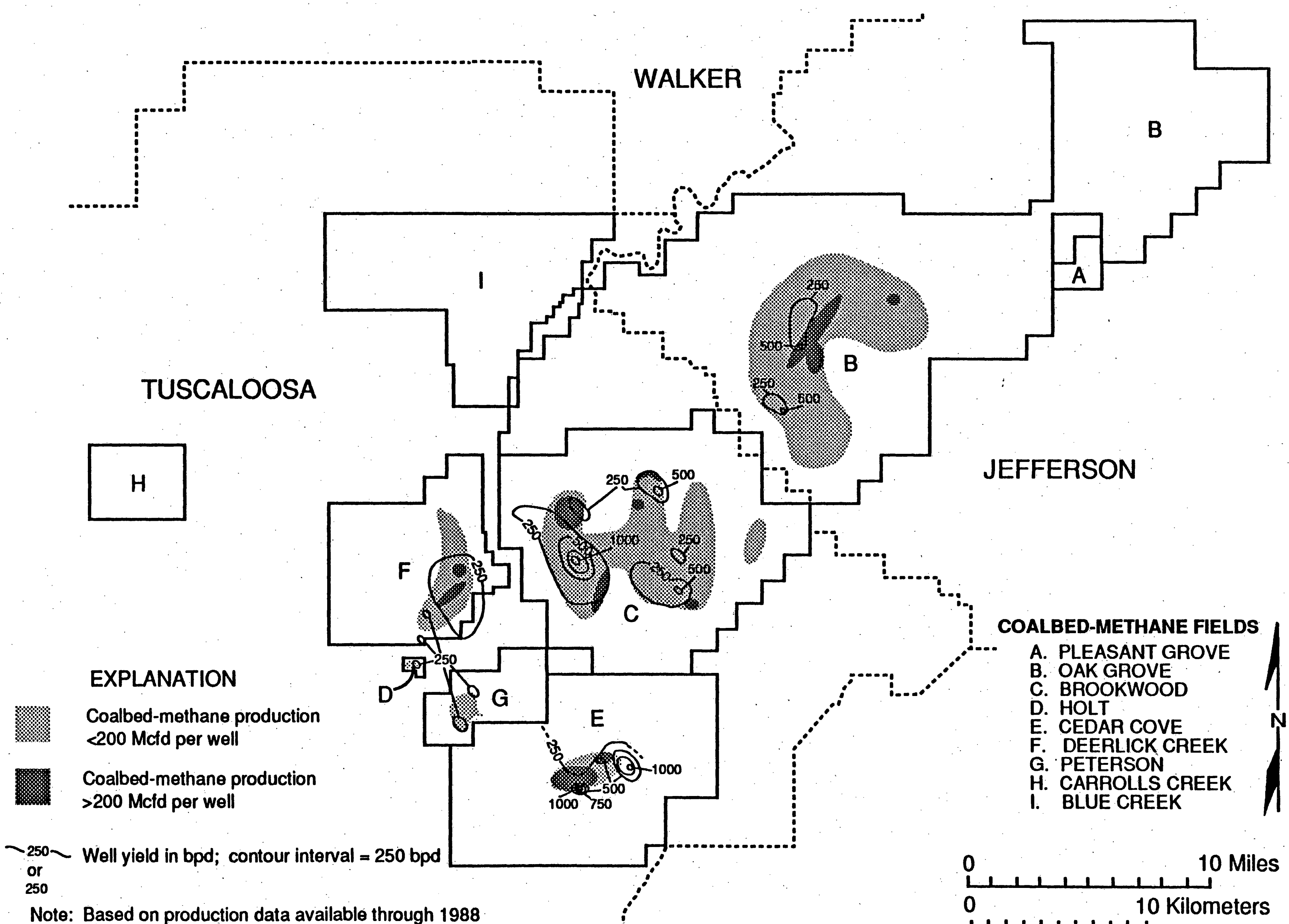



Figure 74. Map of water yield and peak methane production in coalbed-methane fields.

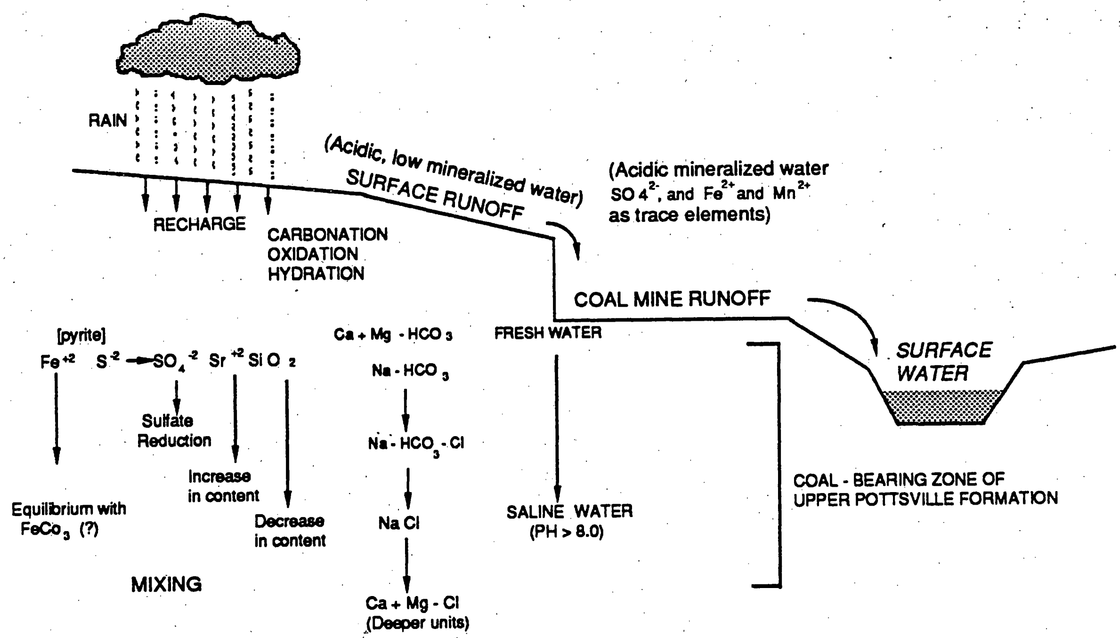



Figure 75. Idealized evolution of water species, Black Warrior basin.

foul, "rotten-egg" odor of some well-water samples. The ferrous ion apparently reaches equilibrium with siderite ($FeCO_3$) occurring in the subsurface. The chloride and strontium content of the water increases with depth and TDS content; silica content tends to decrease with regard to the same factors. The sodium and/or calcium and magnesium content tends to increase with depth.

Changes in the iron, bicarbonate, and sulfate content of water are probably caused by redox reactions and pH changes that occur in the subsurface and along the flow path (fig. 75). Similar changes have been observed in other water-bearing units (Lawrence and others, 1976; Langmuir, 1969). Sulfate-reducing bacteria may also cause a depletion of sulfate and an increase in pH (Langmuir, 1969). Decker and others (1987) indicated that the source of bicarbonate ($HCO_3^-$) in water from the Pratt and Mary Lee coal groups at the Rock Creek site in Oak Grove field is the reaction of $SO_4^-$ with organic matter to form, in part, $HCO_3^-$. However, another possible source of the $HCO_3^-$ is dissolution of calcite that occurs in fractures; according to the available data, calcite may reprecipitate at depth. The source of the sodium and chloride in deep subsurface water may be either connate water or ion exchange with rock constituents.

Linear-regression analysis of water-analysis data from coalbed-methane fields (table 7) was performed to determine which parameters correlate at a level of 95 percent or higher. Differences in correlations of water analysis parameters for coal and siliciclastic strata are shown in figure 76. The common associations for water in both types of strata include: (1) total well depth with initial water yield, specific conductance, water temperature, sodium content, and chloride content; and (2) specific conductance with calcium, magnesium, sodium, potassium, bicarbonate, carbonate, chloride, mercury, strontium, and TDS content. There also is a statistical correlation of specific conductance with sulfate and fluoride content of water from sandstone and mudstone. Water pH correlates positively with bicarbonate, carbonate, and iron content. Trace elements that correlate with the TDS content of water from coal beds are silver, arsenic, barium, cadmium, cobalt, chromium, iron, mercury, lithium, manganese, nickel, lead, selenium, strontium, and zinc.

Water salinity tends to increase markedly with depth in the Black Warrior basin, as demonstrated by vertical trends in sodium, chloride, and TDS content (fig. 77). The estimated depth to water containing 10,000 milligrams per liter (mg/L) TDS on the basis of geophysical logs and water-quality data is shown in figure 78. In some cases, measured specific-conductance or resistivity values of water samples were used to estimate TDS content. The map indicates that water containing 10,000 mg/L TDS occurs 500 to 2,500 feet below msl within the Black Warrior basin and 1,500 to 2,000 feet below msl in the coalbed-methane fields. The irregular pattern of the contours is interpreted to be an effect of surface-water infiltration and mixing. In some areas, the contours reflect shallow occurrence of saline water along faults and below Cretaceous cover. Along the southeast margin of the basin, very saline water occurs much deeper than in adjacent areas. This deep occurrence may be related to intense fracturing along the Blue Creek anticline and associated Alleghanian structures.

Trilinear (Piper) diagrams were made to illustrate the relationship between water type and drilling depth (fig. 79), subsurface stratigraphy (fig. 80), and water salinity (fig. 81). Trilinear diagrams show the relative percentage of the major cations (Ca, Mg, Na, K) and anions ($SO_4$, Cl, $CO_3$, $HCO_3$) in water; they can be used to show the chemical evolution of water as it moves along a flow path and to show differences in water chemistry. The diagrams reflect a transition from slightly mineralized

# Table 7. Water-analysis data for coalbed-methane fields

| Constituent | Field (number of analyses) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Blue Creek (1) | | | Brookwood (40) | | | Cedar Cove (16) | | |
| | Minimum | Maximum | Mean | Minimum | Maximum | Mean | Minimum | Maximum | Mean |
| Depth (ft) | -- | -- | 2,066 | 1,625 | 2,347 | 2,048 | 2,593 | 3,176 | 2,984 |
| Initial gas (mcf/d) | -- | -- | -- | 1 | 396 | 78.1 | 3.1 | 261 | 113.5 |
| Initial water (bpd) | -- | -- | -- | 0 | 800 | 201 | 15 | 1,000 | 259 |
| Specific conductance (µmhos/cm) | -- | -- | 10,500 | 1,698 | 28,200 | 6,640 | 2,750 | 26,000 | 10,400 |
| Temperature (°C) | -- | -- | 22 | 17 | 28 | 24 | 21 | 27 | 24 |
| pH (units) | -- | -- | 7.4 | 6.7 | 9.2 | 8.2 | 6.5 | 8.7 | 7.7 |
| $SiO_2$ (mg/L) | -- | -- | 2 | 0.2 | 13 | 6.7 | 3.2 | 14 | 9.6 |
| Ca (mg/L) | -- | -- | 250 | 0 | 390 | 48 | 2.5 | 620 | 140 |
| Mg (mg/L) | -- | -- | 69 | 0.9 | 420 | 50 | 1.1 | 200 | 48 |
| Na (mg/L) | -- | -- | 3,440 | 0 | 6,200 | 1,760 | 570 | 6,200 | 2,490 |
| K (mg/L) | -- | -- | 13 | 0.9 | 12 | 3.6 | 1.5 | 19 | 6.8 |
| $HCO_3$ (mg/L) | -- | -- | 770 | 76 | 1,200 | 690 | 170 | 1,100 | 660 |
| $CO_3$ (mg/L) | -- | -- | 0 | 0 | 57 | 12 | 0 | 0 | 0 |
| $SO_4$ (mg/L) | -- | -- | 12 | 0 | 650 | 56 | 0 | 83 | 6.6 |
| Cl (mg/L) | -- | -- | 10,200 | 140 | 11,000 | 2,180 | 430 | 11,000 | 3,610 |
| F (mg/L) | -- | -- | 0 | 0 | 12.8 | 3.5 | 0 | 6.2 | 2.1 |
| $NO_3$ (mg/L) | -- | -- | 10 | 0 | 23.16 | 3.11 | 0 | 6.24 | 0.45 |
| Ag (µg/L) | -- | -- | -- | 1 | 3 | 1 | -- | -- | 2 |
| Al (µg/L) | -- | -- | -- | 0 | 170 | 70 | -- | -- | 0 |
| As (µg/L) | -- | -- | -- | 1 | 475 | 98 | 1 | 17 | 9 |
| Ba (µg/L) | -- | -- | -- | 1,200 | 37,000 | 10,500 | -- | -- | 870 |
| Cd (µg/L) | -- | -- | -- | 1 | 26 | 10 | 0 | 6 | 1 |
| Cu (µg/L) | -- | -- | -- | 0 | 5 | 2 | 0 | 4 | 1 |
| Cr (µg/L) | -- | -- | -- | 0 | 7 | 3 | 0 | 4 | 1 |
| Co (µg/L) | -- | -- | -- | 10 | 20 | 18 | -- | -- | 10 |
| Fe (µg/L) | -- | -- | 1,000 | 5 | 35,000 | 7,560 | 20 | 41,000 | 7,300 |
| Hg (µg/L) | -- | -- | -- | 0 | 1 | .22 | 0 | 0.9 | 0.28 |
| Li (µg/L) | -- | -- | -- | 250 | 3,300 | 1,120 | -- | -- | 360 |
| Mn (µg/L) | -- | -- | 360 | 10 | 520 | 140 | 30 | 490 | 190 |
| Ni (µg/L) | -- | -- | -- | 8 | 500 | 140 | -- | -- | 2 |
| Pb (µg/L) | -- | -- | -- | 0 | 660 | 200 | 0 | 70 | 13 |
| Se (µg/L) | -- | -- | -- | 0 | 198 | 50 | -- | -- | 10 |
| Sr (µg/L) | -- | -- | 11,000 | 0 | 56,000 | 6,300 | 0 | 48,000 | 10,000 |
| Va (µg/L) | -- | -- | -- | 0 | 10 | 5 | -- | -- | 5 |
| Zn (µg/L) | -- | -- | 330 | 0 | 30 | 12 | 10 | 240 | 50 |
| TDS (mg/L) | -- | -- | 14,400 | 1,160 | 26,700 | 5,250 | 1,470 | 23,000 | 9,050 |

## Table 7. Water-analysis data for coalbed-methane fields--Continued

| Constituent | Field (number of analyses) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Deerlick Creek (11) | | | Holt (1) | | | Oak Grove (45) | | |
| | Minimum | Maximum | Mean | Minimum | Maximum | Mean | Minimum | Maximum | Mean |
| Depth (ft) | 2,103 | 2,813 | 2,401 | -- | -- | 2,608 | 697 | 1,602 | 1,169 |
| Initial gas (mcf/d) | 3 | 247 | 57.4 | -- | -- | 19 | 2.4 | 719 | 74.0 |
| Initial water (bpd) | 6 | 411 | 159 | -- | -- | 300 | 0 | 605 | 54 |
| Specific conductance (µmhos/cm) | 1,930 | 28,700 | 13,300 | -- | -- | 19,800 | 825 | 7,800 | 2,590 |
| Temperature (°C) | 20 | 27 | 24 | -- | -- | -- | 16 | 25 | 21 |
| pH (units) | 6.8 | 8.4 | 7.6 | -- | -- | 7.0 | 7.7 | 9.1 | 8.4 |
| $SiO_2$ (mg/L) | 3.2 | 11 | 6.8 | -- | -- | -- | 4.1 | 13 | 8.7 |
| Ca (mg/L) | 6.5 | 370 | 120 | -- | -- | -- | 0.8 | 43 | 9.6 |
| Mg (mg/L) | 1.7 | 120 | 36 | -- | -- | -- | 0.3 | 18 | 3.7 |
| Na (mg/L) | 480 | 6,800 | 2,700 | -- | -- | -- | 210 | 1,800 | 690 |
| K (mg/L) | 1.6 | 24 | 7.6 | -- | -- | -- | 0.3 | 2.4 | 1.2 |
| $HCO_3$ (mg/L) | 270 | 930 | 630 | -- | -- | 330 | 130 | 1,100 | 643 |
| $CO_3$ (mg/L) | 0 | 13 | 1 | -- | -- | 0 | 0 | 59 | 12 |
| $SO_4$ (mg/L) | 0.6 | 11 | 4.4 | -- | -- | -- | 0 | 130 | 7.2 |
| Cl (mg/L) | 250 | 15,000 | 6,600 | -- | -- | 13,000 | 25 | 2,700 | 560 |
| F (mg/L) | 0 | 20 | 3.3 | -- | -- | -- | 0.3 | 11 | 3.6 |
| $NO_3$ (mg/L) | 0 | 7.60 | 2.30 | -- | -- | -- | 0 | 12.5 | 1.21 |
| Ag (µg/L) | -- | -- | 1 | -- | -- | -- | 0 | 1 | 1 |
| Al (µg/L) | -- | -- | 0 | -- | -- | -- | 30 | 200 | 130 |
| As (µg/L) | -- | -- | 30 | -- | -- | -- | 1 | 40 | 12 |
| Ba (µg/L) | -- | -- | 870 | -- | -- | -- | 200 | 3,000 | 1,360 |
| Cd (µg/L) | -- | -- | 10 | -- | -- | -- | 0 | 4 | 2 |
| Cu (µg/L) | -- | -- | 0 | -- | -- | -- | 0 | 0 | 0 |
| Cr (µg/L) | -- | -- | 7 | -- | -- | -- | 0 | 4 | 2 |
| Co (µg/L) | -- | -- | 10 | -- | -- | -- | 10 | 40 | 20 |
| Fe (µg/L) | 10 | 246,000 | 38,000 | -- | -- | -- | 20 | 99,000 | 5,820 |
| Hg (µg/L) | -- | -- | 0 | -- | -- | -- | 0 | 0.1 | 0.02 |
| Li (µg/L) | -- | -- | 420 | -- | -- | -- | 180 | 930 | 440 |
| Mn (µg/L) | 30 | 3,800 | 620 | -- | -- | -- | 5 | 880 | 80 |
| Ni (µg/L) | -- | -- | 2 | -- | -- | -- | 0 | 2 | 1 |
| Pb (µg/L) | -- | -- | 44 | -- | -- | -- | 0 | 90 | 16 |
| Se (µg/L) | -- | -- | 40 | -- | -- | -- | 1 | 70 | 25 |
| Sr (µg/L) | 530 | 17,000 | 7,000 | -- | -- | -- | 0 | 1,900 | 390 |
| Va (µg/L) | -- | -- | 5 | -- | -- | -- | 0 | 5 | 5 |
| Zn (µg/L) | 70 | 360 | 220 | -- | -- | -- | 0 | 60 | 17 |
| TDS (mg/L) | 1,150 | 17,300 | 8,840 | -- | -- | -- | 545 | 4,870 | 1,790 |

# Table 7. Water-analysis data for coalbed-methane fields--Continued

| Constituent | Field (number of analyses) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Peterson (4) | | | Pleasant Grove (4) | | | Wildcat (3) | | |
| | Minimum | Maximum | Mean | Minimum | Maximum | Mean | Minimum | Maximum | Mean |
| Depth (ft) | 2,474 | 3,132 | 2,907 | 1,446 | 1,548 | 1,515 | 902 | 2,289 | 1,711 |
| Initial gas (mcf/d) | 7.8 | 111 | 45.1 | 11.1 | 17 | 14.1 | -- | -- | 9 |
| Initial water (bpd) | 3 | 171 | 58 | 25 | 40 | 31 | -- | -- | 491 |
| Specific conductance (µmhos/cm) | 6,200 | 40,380 | 26,320 | 1,420 | 1,663 | 1,520 | 2,880 | 9,000 | 4,990 |
| Temperature (°C) | -- | -- | -- | 19 | 21 | 20 | -- | -- | -- |
| pH (units) | 6.4 | 7.0 | 6.6 | 7.0 | 9.0 | 8.2 | 7.5 | 8.4 | 8.0 |
| $SiO_2$ (mg/L) | -- | -- | -- | 8.5 | 11 | 10 | -- | -- | -- |
| Ca (mg/L) | -- | -- | -- | 0.8 | 2.5 | 1.5 | -- | -- | 54 |
| Mg (mg/L) | -- | -- | -- | 0.5 | 1.2 | 0.7 | -- | -- | 24 |
| Na (mg/L) | -- | -- | -- | 360 | 470 | 400 | -- | -- | 1,859 |
| K (mg/L) | 18 | 21 | 20 | 0.6 | 1.4 | 0.9 | -- | -- | 8.8 |
| $HCO_3$ (mg/L) | -- | -- | -- | 880 | 1,100 | 963 | -- | -- | 86 |
| $CO_3$ (mg/L) | -- | -- | -- | 0 | 14 | 5 | -- | -- | 0 |
| $SO_4$ (mg/L) | -- | -- | -- | 0.5 | 8.3 | 2.9 | -- | -- | 1.5 |
| Cl (mg/L) | 2,530 | 18,400 | 12,300 | 19 | 57 | 36 | 660 | 2,526 | 1,390 |
| F (mg/L) | -- | -- | -- | 0.6 | 3.0 | 2.1 | -- | -- | 0.7 |
| $NO_3$ (mg/L) | -- | -- | -- | 0.03 | 2.64 | 1.10 | -- | -- | -- |
| Ag (µg/L) | -- | -- | -- | -- | -- | 0.5 | -- | -- | -- |
| Al (µg/L) | -- | -- | -- | -- | -- | 0 | -- | -- | -- |
| As (µg/L) | -- | -- | -- | 0 | 5 | 2 | -- | -- | -- |
| Ba (µg/L) | -- | -- | -- | -- | -- | 300 | -- | -- | -- |
| Cd (µg/L) | -- | -- | -- | 0 | 3 | 2 | -- | -- | -- |
| Cu (µg/L) | -- | -- | -- | 0 | 0 | 0 | -- | -- | -- |
| Cr (µg/L) | -- | -- | -- | 0 | 4 | 2 | -- | -- | -- |
| Co (µg/L) | -- | -- | -- | -- | -- | 10 | -- | -- | -- |
| Fe (µg/L) | -- | -- | -- | 320 | 15,000 | 5,230 | -- | -- | 4,150 |
| Hg (µg/L) | -- | -- | -- | 0 | 0 | 0 | -- | -- | -- |
| Li (µg/L) | -- | -- | -- | -- | -- | 120 | -- | -- | -- |
| Mn (µg/L) | -- | -- | -- | 50 | 140 | 90 | -- | -- | -- |
| Ni (µg/L) | -- | -- | -- | -- | -- | 2 | -- | -- | -- |
| Pb (µg/L) | -- | -- | -- | 0 | 3 | 2 | -- | -- | -- |
| Se (µg/L) | -- | -- | -- | -- | -- | 0 | -- | -- | -- |
| Sr (µg/L) | -- | -- | -- | 40 | 70 | 50 | -- | -- | -- |
| Va (µg/L) | -- | -- | -- | -- | -- | 5 | -- | -- | -- |
| Zn (µg/L) | -- | -- | -- | 20 | 30 | 25 | -- | -- | -- |
| TDS (mg/L) | -- | -- | -- | 876 | 1,090 | 979 | -- | -- | 4,694 |

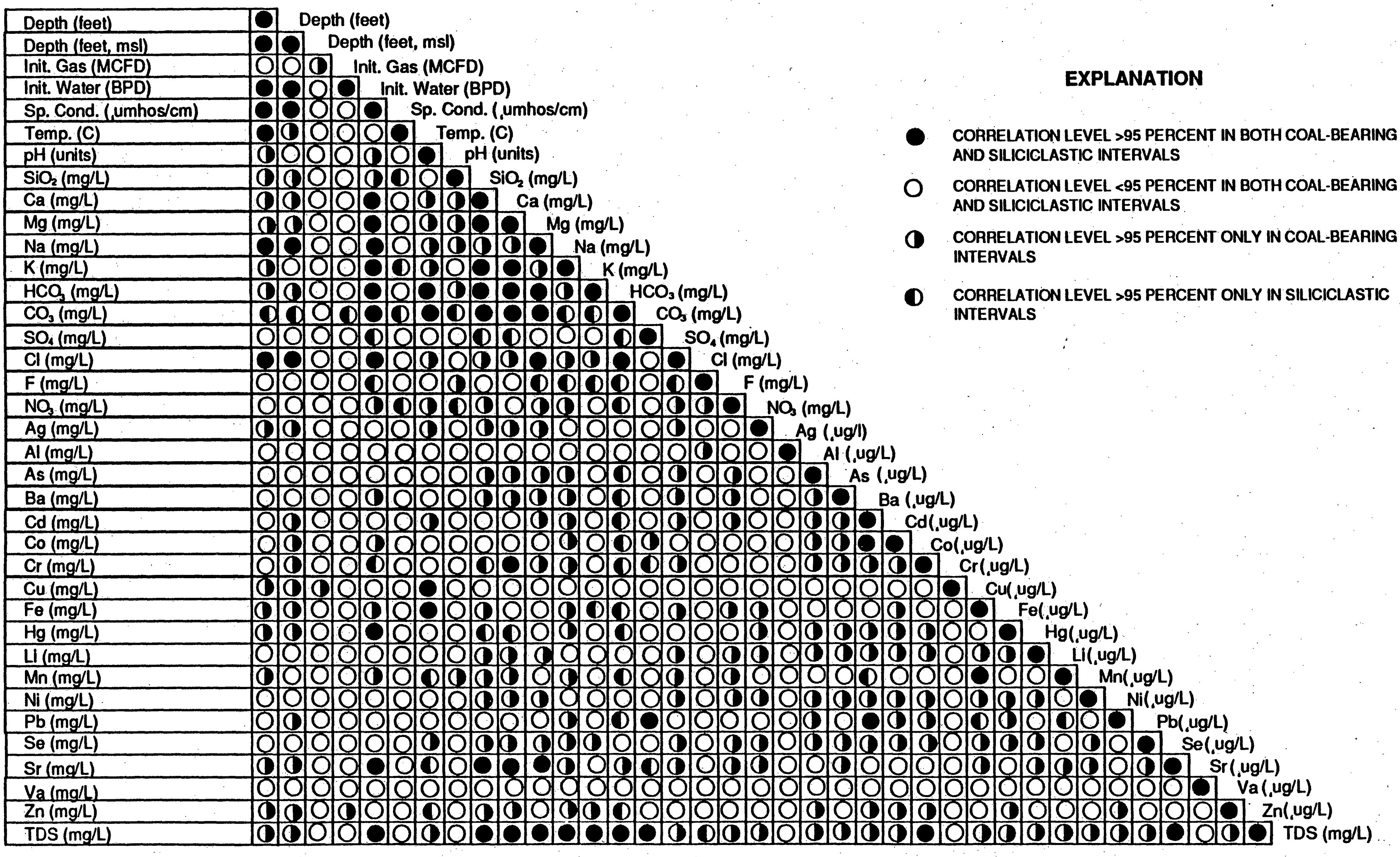



Figure 76. Correlation chart of water-analysis parameters for coal-bed and sandstone-mudstone intervals.

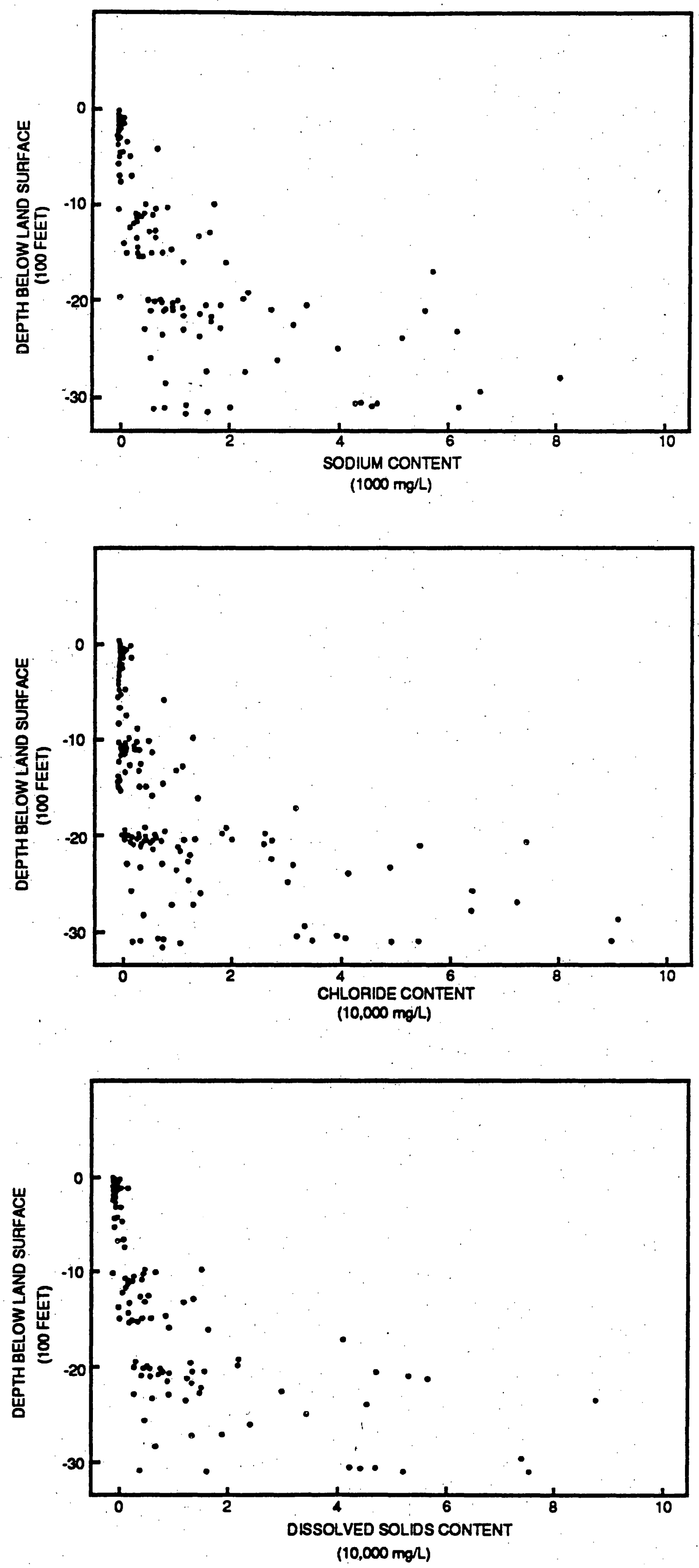
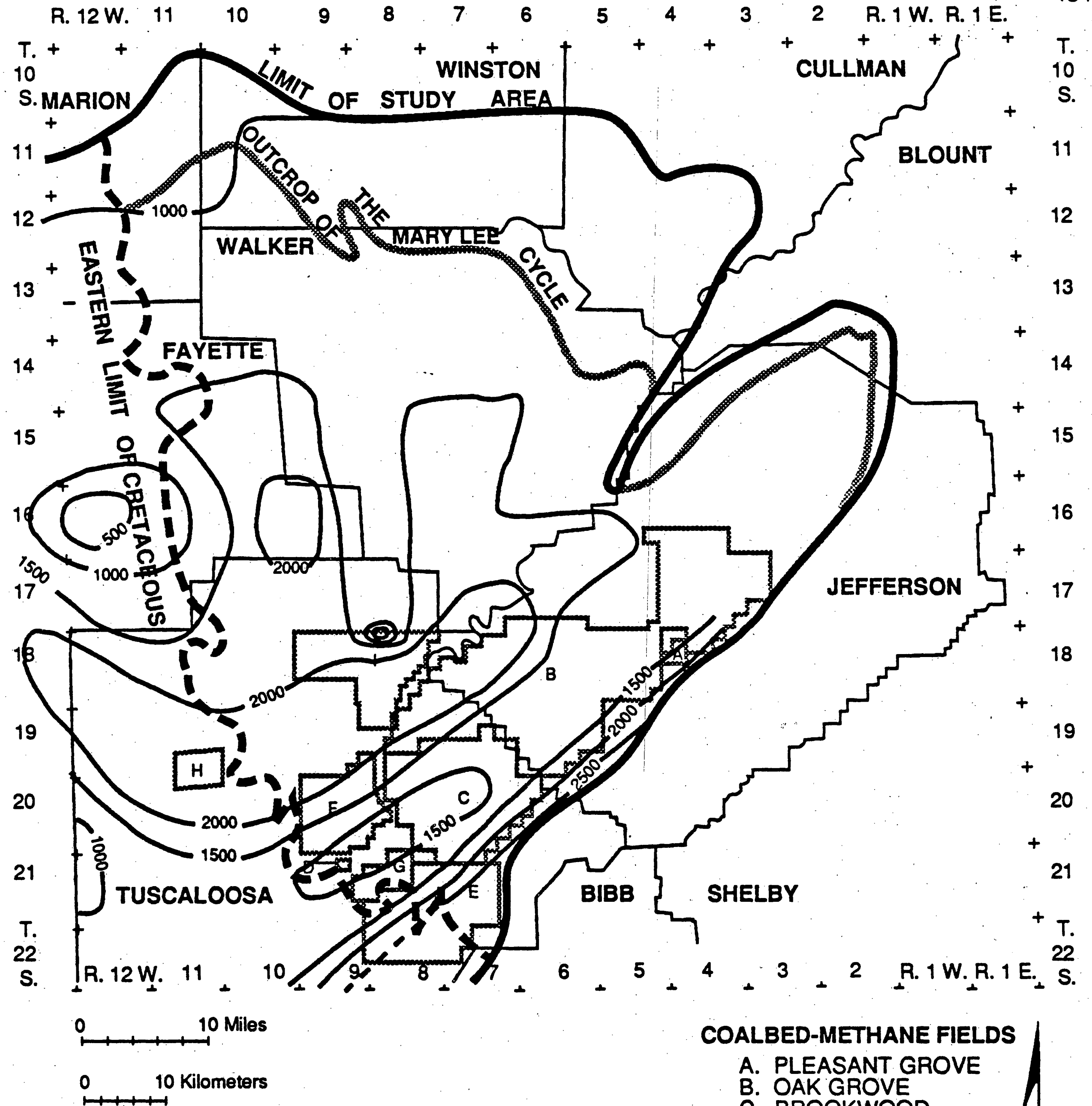



Figure 77. Selected scattergrams showing relationship between salinity and depth.




**COALBED-METHANE FIELDS**

A. PLEASANT GROVE
B. OAK GROVE
C. BROOKWOOD
D. HOLT
E. CEDAR COVE
F. DEERLICK CREEK
G. PETERSON
H. CARROLLS CREEK
I. BLUE CREEK

**EXPLANATION**

1000 — Estimated elevation (feet below msl) of water containing 10,000 mg/L TDS, line dashed where inferred
Contour interval = 500 feet

Note: Map based on water-analysis data and interpretation of electric logs for wells (Epsman and others, 1983)

Figure 78. Estimated elevation of water containing more than 10,000 milligrams per liter of total dissolved solids (very saline water).

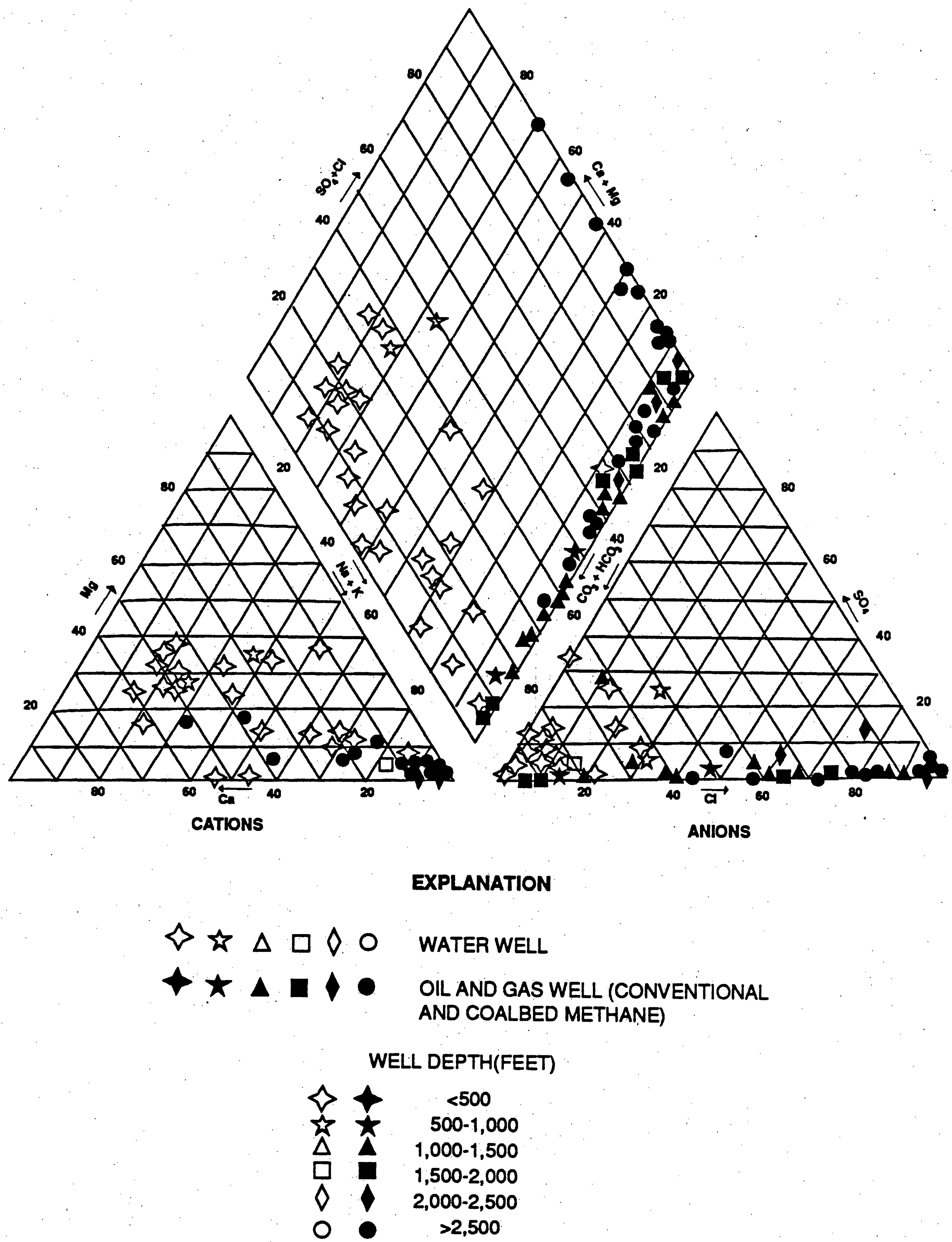
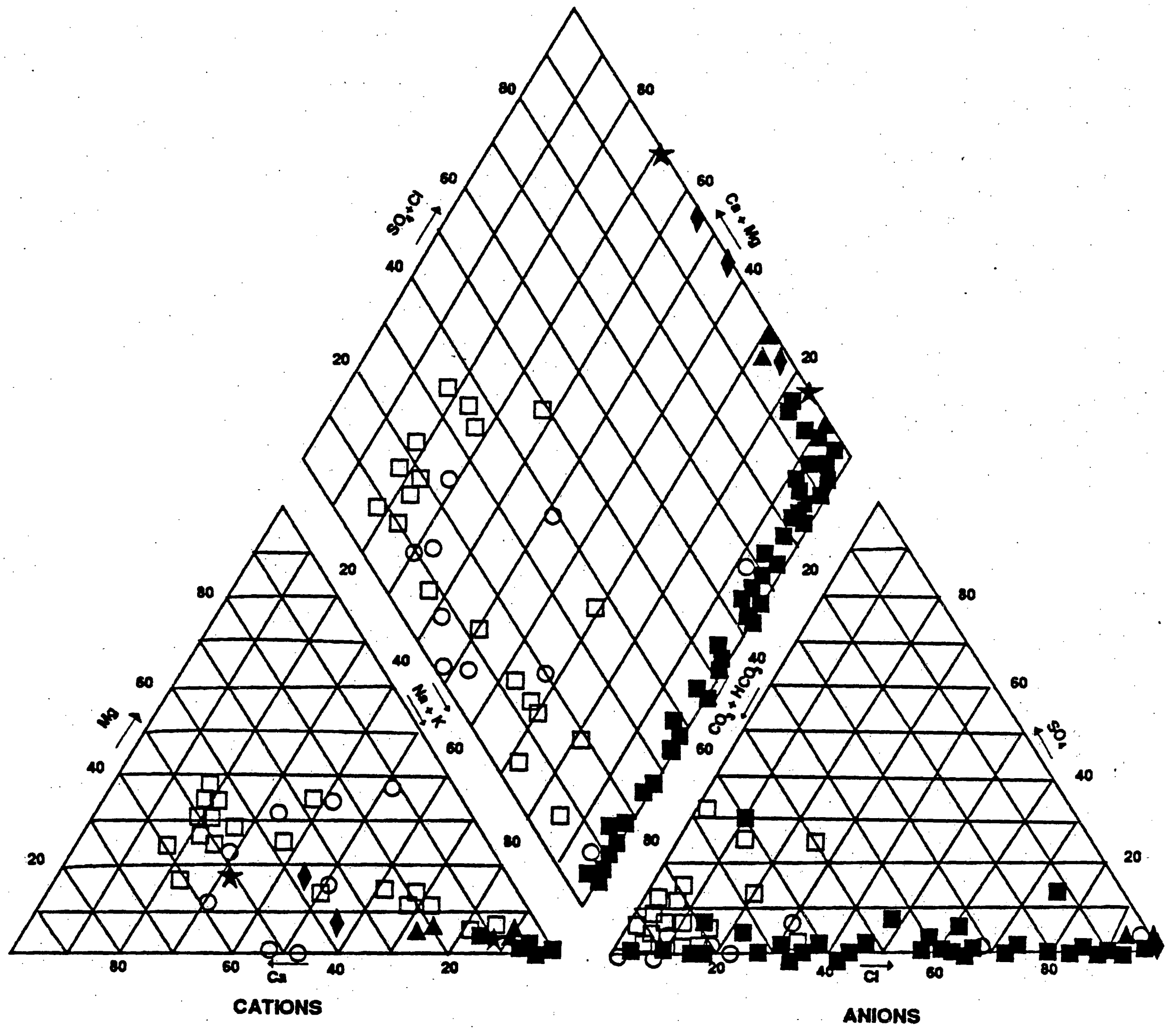



Figure 79. Piper diagram showing well depth in relation to water type.

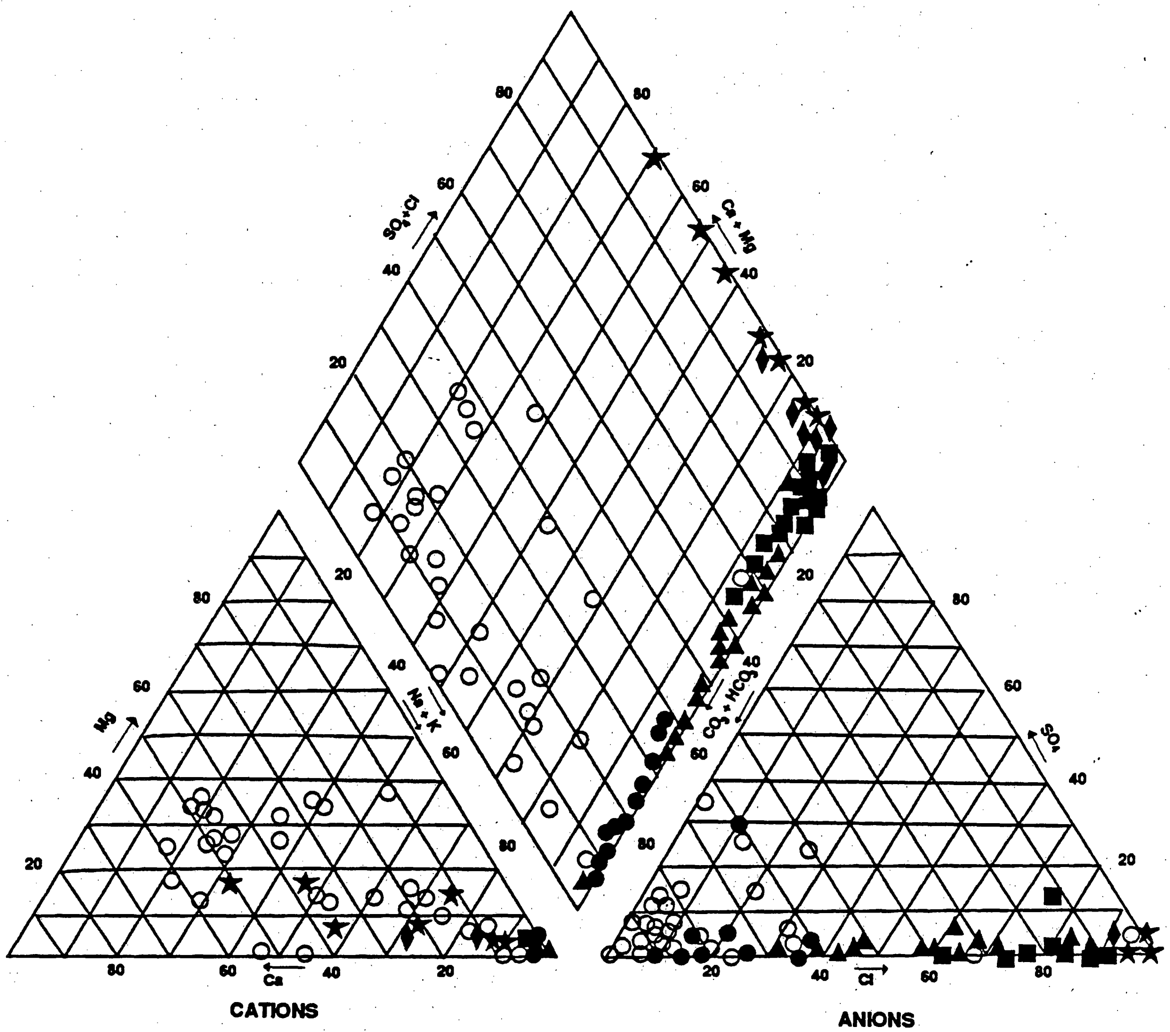



**EXPLANATION**

| | |
|---|---|
| ○ □ ☆ △ ◊ | WATER WELL |
| ● ■ ★ ▲ ♦ | OIL AND GAS (CONVENTIONAL AND COALBED METHANE) |

| | GEOLOGIC UNIT | AGE |
|---|---|---|
| ○ ● | COKER FORMATION | CRETACEOUS |
| □ ■ | POTTSVILLE FORMATION (UPPER PART) | PENNSYLVANIAN |
| ☆ ★ | POTTSVILLE FORMATION (LOWER PART) | PENNSYLVANIAN |
| △ ▲ | MISSISSIPPIAN UNDIFFERENTIATED | MISSISSIPPIAN |
| ◊ ♦ | DEVONIAN UNDIFFERENTIATED | DEVONIAN |

Figure 80. Piper diagram showing stratigraphic units in relation to water type.




**EXPLANATION**

○ △ □ ◊ ☆ WATER WELL

● ▲ ■ ♦ ★ OIL AND GAS WELL (CONVENTIONAL AND COALBED METHANE

| TOTAL DISSOLVED SOLIDS CONTENT (mg/L) | | | CLASSIFICATION |
|---|---|---|---|
| ○ | ● | <1,000 | FRESH |
| △ | ▲ | 1,000-3,000 | SLIGHTLY SALINE |
| □ | ■ | 3,000-10,000 | MODERATELY SALINE |
| ◊ | ♦ | 10,000-35,000 | VERY SALINE |
| ☆ | ★ | >35,000 | BRINE |

Figure 81. Piper diagram showing water salinity in relation to water type.

sodium- or calcium-bicarbonate water associated with Cretaceous sand and the upper Pottsville; to moderately to highly mineralized sodium-bicarbonate-chloride type water in the Black Creek-Cobb interval; and to moderately to highly mineralized sodium-calcium-magnesium-chloride type water in the deep Devonian and Mississippian strata that occur more than 2,500 feet below the land surface. Typically, the water becomes more mineralized and alkaline (pH $>$ 8) with depth, and the concentration of some trace metals, including strontium and iron, increases.

Water chemistry varies among the coalbed-methane fields (table 7) and can be illustrated using Stiff diagrams (fig. 82). Stiff diagrams are made by plotting cation and anion concentration in equivalents per million relative to a vertical axis and commonly are used to compare water from different locations. Surface water and shallow subsurface water typically are low in mineral content and are of the calcium-magnesium or sodium-bicarbonate type. However, runoff water from mines is highly mineralized and has high sulfate content. Water associated with coal-bearing intervals and with coal degasification typically is mineralized and is of a sodium-bicarbonate or sodium-chloride type. Downward and lateral movement of weakly mineralized, sodium-bicarbonate water within permeable coal-beds may account for the difference in water type.

The salinity and isochlor maps of the Mary Lee coal group (figs. 83-85) indicate that northwest lateral and downward movement of weakly mineralized water has taken place at the southeast edge of the basin (fig. 68). Several fresh-water protrusions extend northwest from the Blue Creek anticline, suggesting that the structure has played a major role in recharge and the development of head along the basin margin. The protrusions terminate sharply immediately northeast of the Cretaceous overlap, reflecting the increased depth of Pottsville strata and the ability of Cretaceous strata to store and transmit meteoric water (figs. 83-85). Fresh-water protrusions only correspond with a few underground mines, so they apparently are natural rather than an artifact of mine dewatering and induced underpressure.

Very saline water (TDS 10,000-35,000 mg/L) occurs in the Mary Lee coal group in the interior part of the Black Warrior basin (fig. 85). Several locations of high TDS content (10,000 mg/L) in the Mary Lee coal group are shown on the salinity map; the water is sodium chloride in type. The high mineral

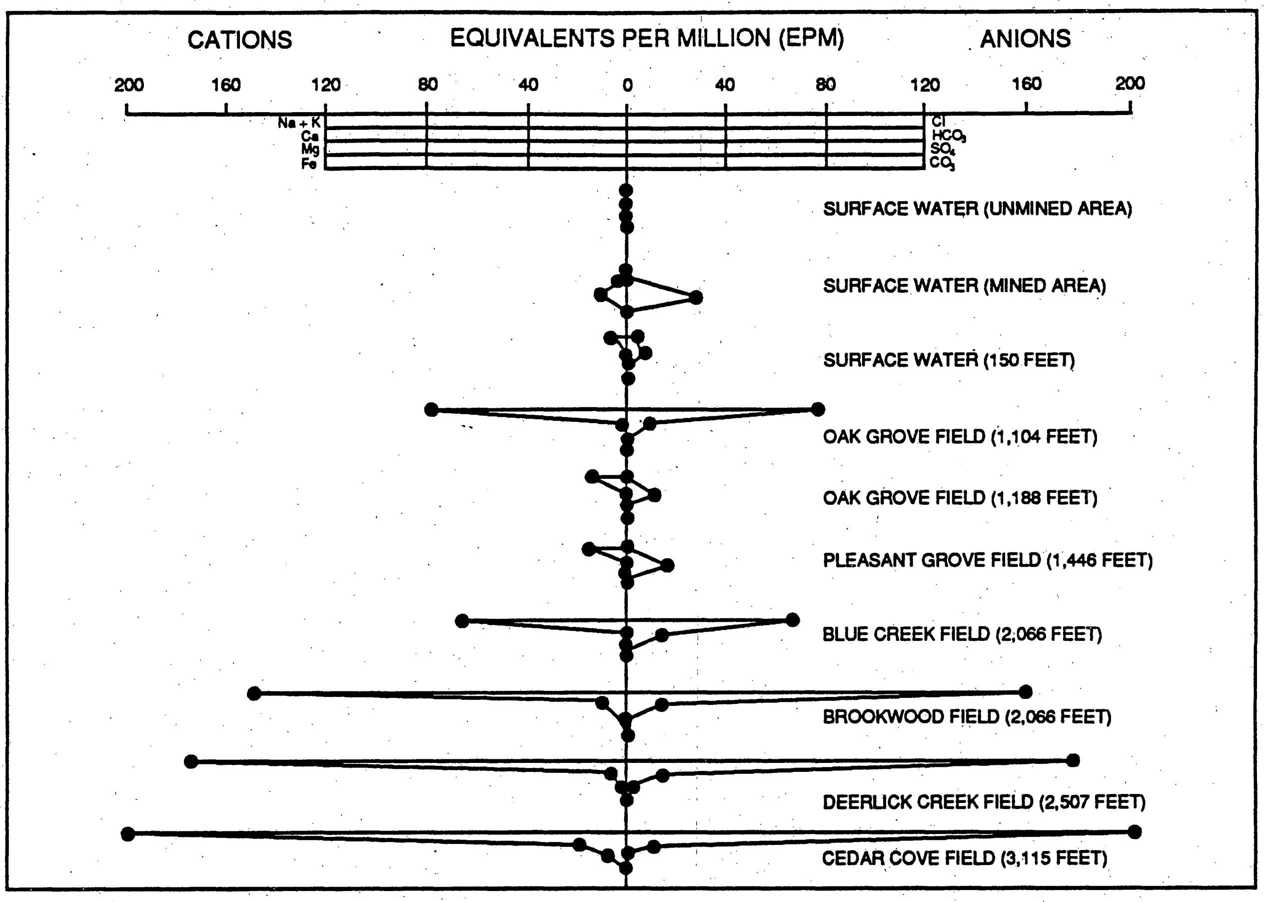



Figure 82. Stiff diagrams for representative water, Black Warrior basin.

content may indicate a combination of upward movement of mineralized water and restriction from recharge related to the northwest limb of the Blue Creek anticline. Water movement along fault planes may be restricted owing to closure by the modern tectonic stress field, and clay-rich gouge and termination of coal beds at fault planes probably inhibits lateral flow. Many areas having saline water contain numerous northwest-striking, normal faults. The faults apparently act in places as a barrier to lateral flow that helps define the fresh-water protrusions.

## PRODUCTION ANALYSIS

### INTRODUCTION

The ability to accurately estimate the productivity of coalbed-methane wells is a critical factor in identifying areas of high production potential. Once potentially productive areas are identified,

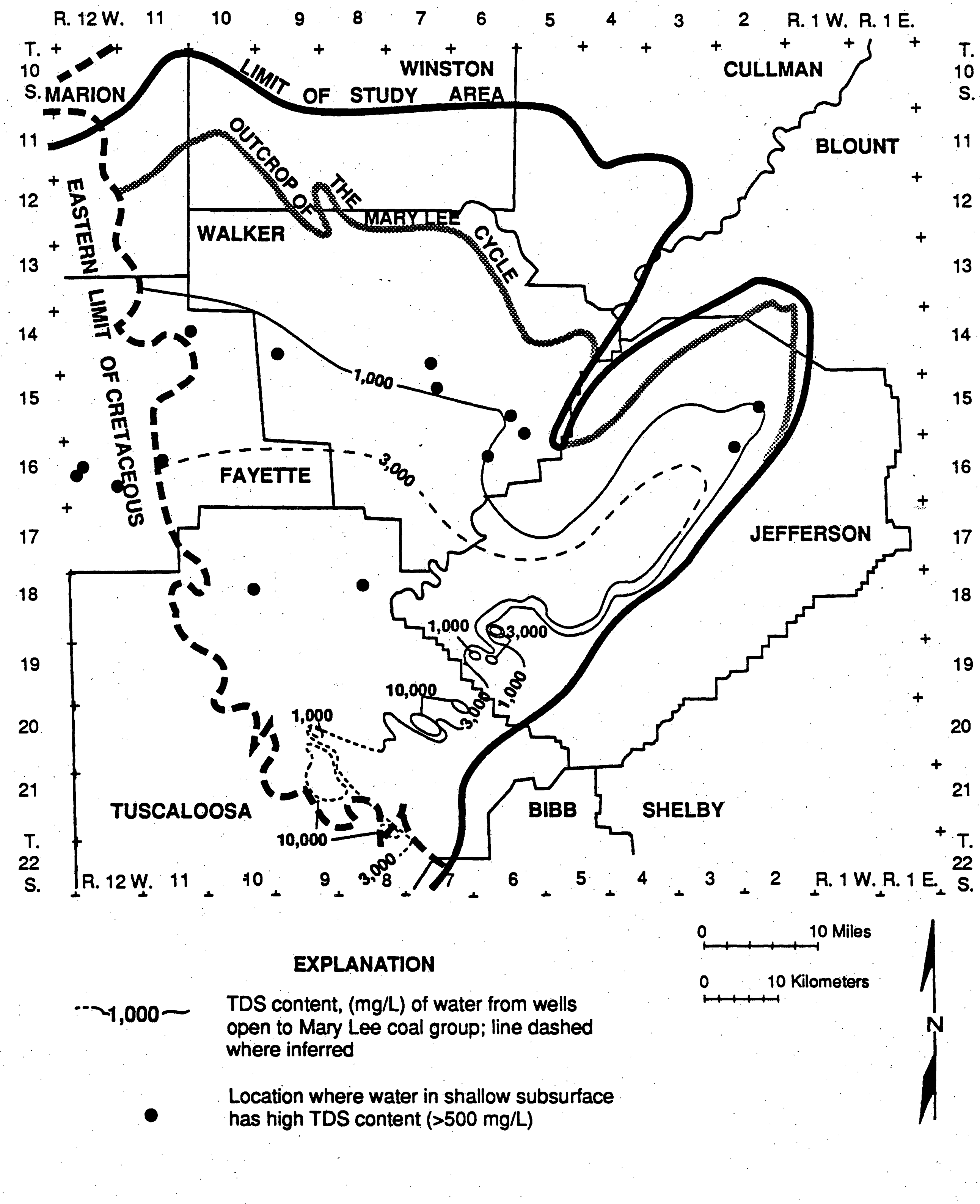
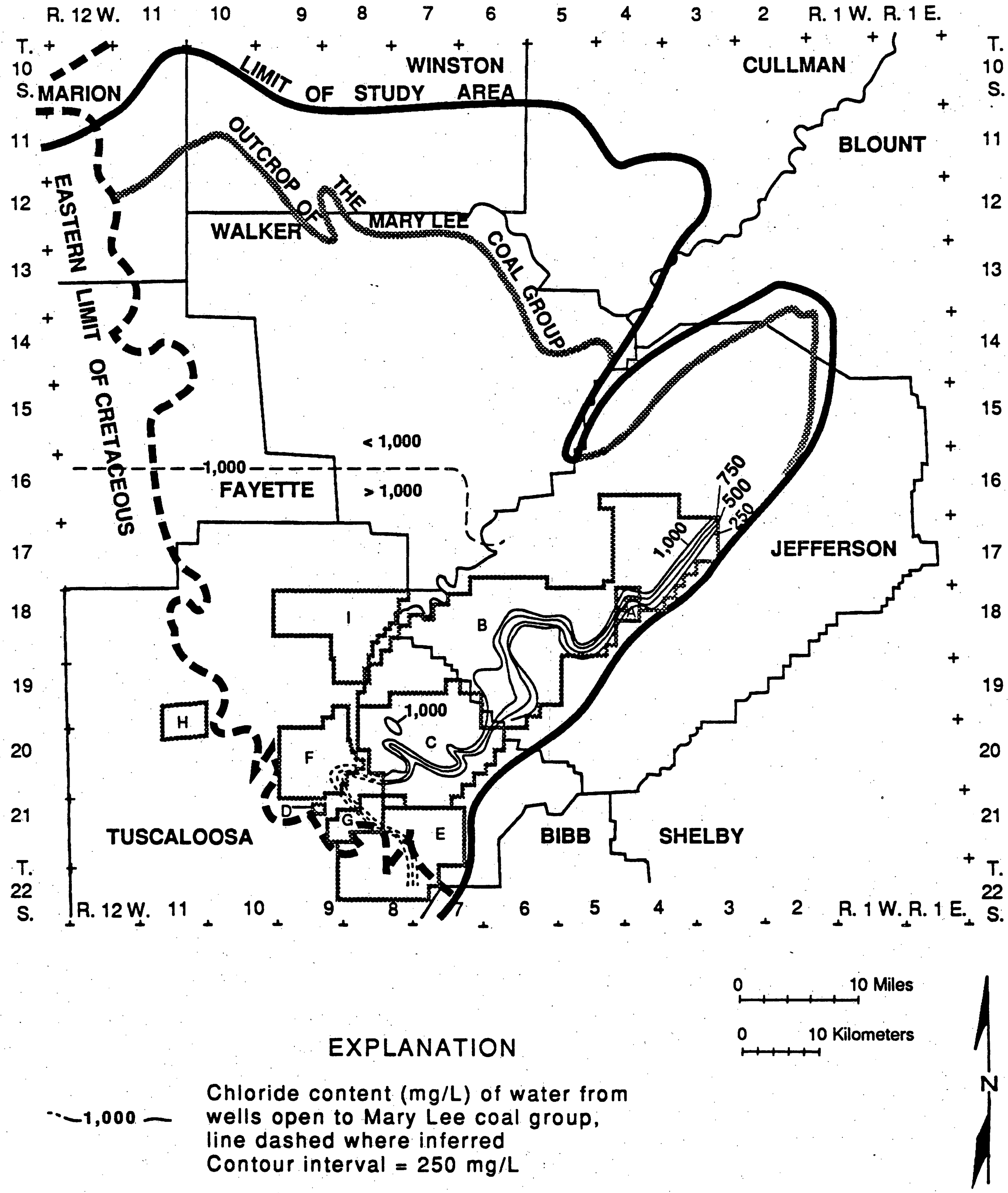



Figure 83. Salinity map of the Mary Lee cycle.




EXPLANATION

1,000 — Chloride content (mg/L) of water from wells open to Mary Lee coal group, line dashed where inferred
Contour interval = 250 mg/L

Figure 84. Isochlor map of the Mary Lee cycle.

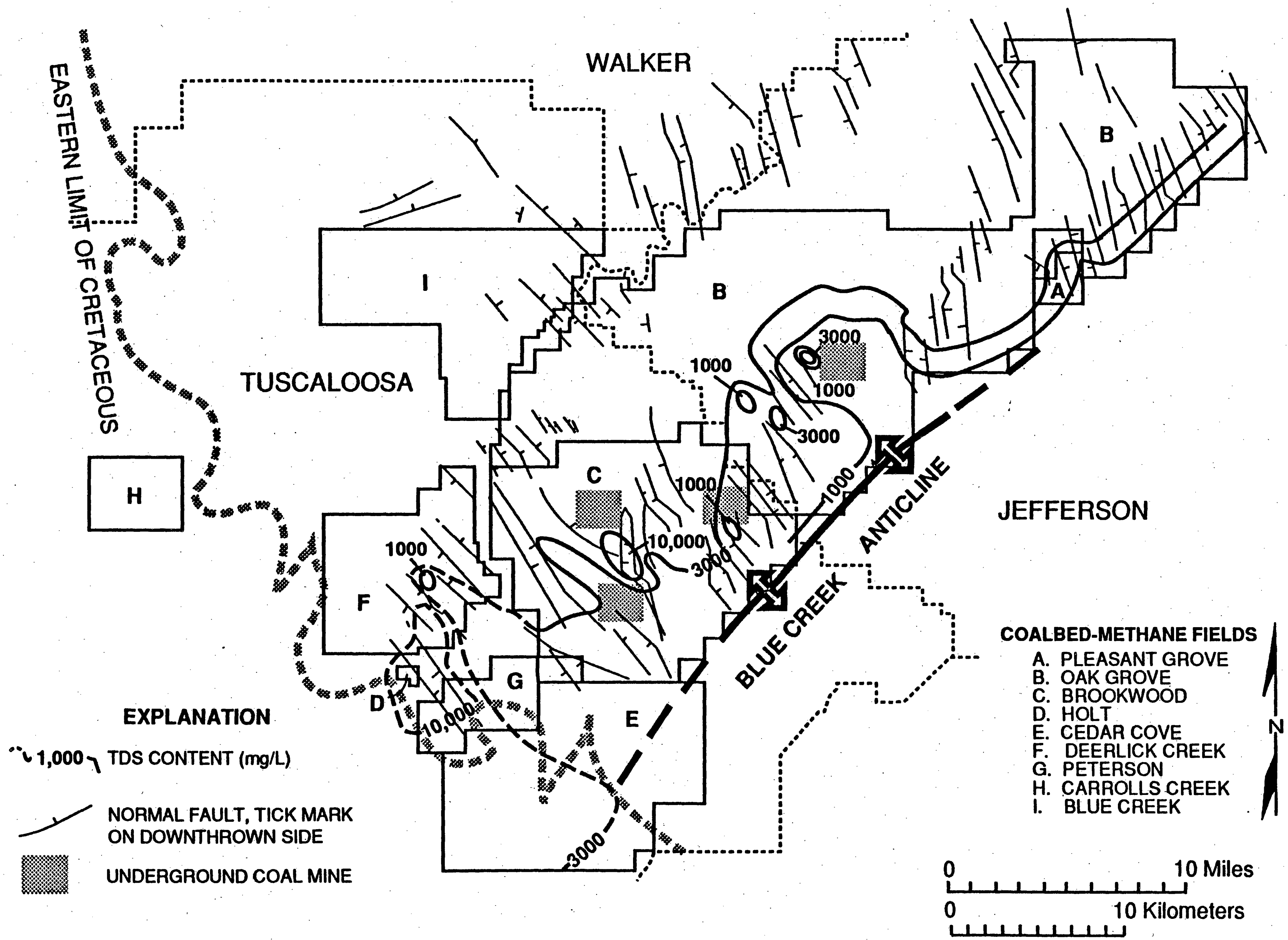



Figure 85. Relationships among water salinity, structural features, and underground mines.

geologic factors may be evaluated to determine those factors that control the production potential of the wells. However, a suitable measure of coalbed-methane productivity has not been identified in the Black Warrior basin. Therefore, the principal objectives were to first define well productivity and to then identify the impact of geology and well design on the producibility of coalbed methane.

## METHODS

Engineering and production data were compiled and computed from the files of the State Oil and Gas Board of Alabama. Completion evaluation included a review of Form OGB-7, Well Record and Completion or Recompletion Report, to determine the method of completion, such as open-hole, perforated casing, or slotted casing, that was used in each well. Stimulation evaluation included a review of Form OGB-6, Report of Well Treatment, to determine the type of stimulation used in the wells, such as water-sand and foam-sand-water techniques.

Production evaluation utilized initial-production data for gas and water obtained from Form OGB-9, First Production or Retest Report. The initial gas-production rate is generally based on the 24-hour test performed early in the life of each well. The peak gas-production rate was obtained from the Board's monthly production-history records for each well. The highest monthly gas volume was identified, and that volume was divided by the number of days in the month to generate a daily rate. The same procedure was used to calculate the peak water-production rate. The time to reach the peak gas-production rate was taken as the number of months that had elapsed since production was first reported to the Board.

Total production time is defined as the total number of months that production was reported to the Board. The average gas production rate was computed by dividing the cumulative gas production by the total production time; that number was then divided by 30 days per month to obtain an average daily rate. The decline time is defined as the number of months a well produces before the production ceases to be highly variable and a steady production decline trend is established. This value was determined from a plot of the production history and, for most wells, was found to occur at or shortly after the time of peak gas production.

Three other factors tested to determine their influence on the productivity of these wells are coal thickness, depth to the Mary Lee coal bed, and well spacing. Net coal thickness and depth were determined from expanded density logs. Well spacing is the number of acres assigned to the individual well as determined from the Board's records.

These data were summarized, and a computer database was generated. In order to analyze productivity, a variety of statistical procedures were employed. Types of statistical analysis used include statistical summaries, analysis of variance (ANOVA), and linear regression. Results of the statistical analysis were then evaluated and interpreted in order to determine the geologic significance and implications of the findings.

## WELL DESIGN

### Well Type and Production

Drillers have employed three major methods of producing coalbed methane (Sexton and Hinkle, 1985). The first and most common type is the vertically drilled well or borehole (fig. 86). As of December 31, 1988, more than 390 vertical wells had produced nearly 33 Bcf (billion cubic feet) of methane (fig. 87; table 8). The second method of production is from "gob" wells (fig. 88), which are vertical wells drilled into the collapsed roof rock of underground coal mines after mining. By the end of 1988, 104 gob wells had produced more than 34 Bcf of methane (fig. 88). The third method of coalbed-methane recovery is by drilling horizontal boreholes into the coal face in the underground mines. In horizontal boreholes, the produced methane is collected by an underground piping system that is connected to a vertical borehole which transmits the gas to the surface. As of December 31, 1988, 19 horizontal boreholes had produced a total of 3 Bcf of methane (fig. 87; table 8).

Although 76 percent of the wells in the degasification fields are vertical boreholes, 49 percent of the cumulative production has come from gob wells (fig. 87; table 8). Horizontal wells account for only 4 percent of the cumulative production; only 19 boreholes were on line at the end of 1988. The average cumulative production to date for a vertical well is 85 million cubic feet (MMcf) of methane, whereas the average cumulative production to date for a horizontal well is 158 MMcf, nearly twice as

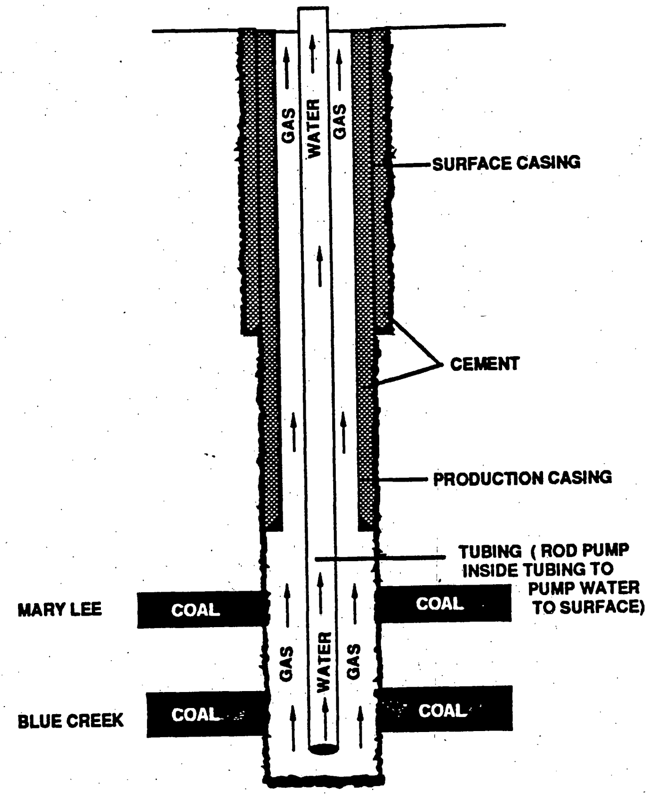
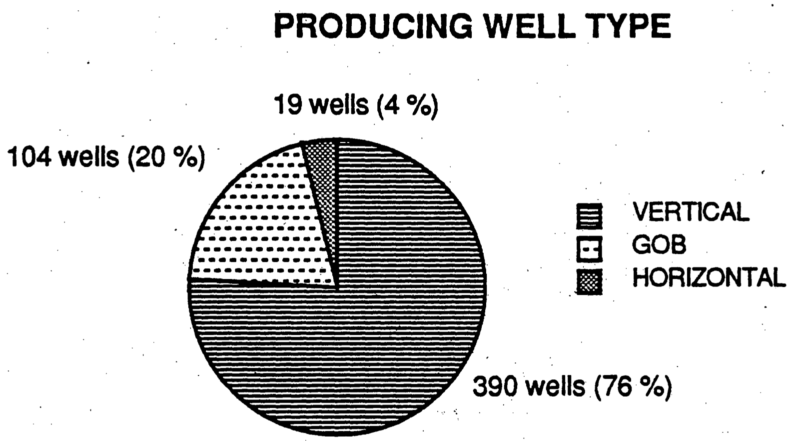
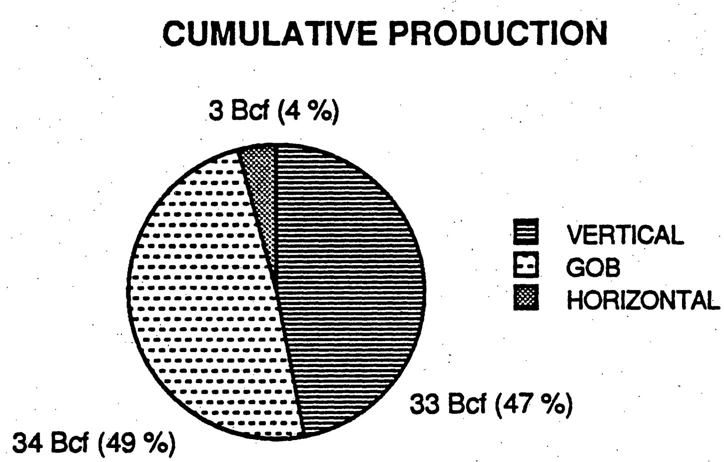



Figure 86. Schematic of a vertical well (not to scale).

much. In contrast, the average cumulative production to date for a gob well is 327 MMcf, nearly 4 times as much as a vertical well. However, gob and horizontal holes are restricted to areas of underground mining in Brookwood and Oak Grove fields and cannot be drilled on a regional basis.

Figure 89 depicts cumulative production through December 1988 for each coalbed-methane field. Table 8 depicts the producing method, the amount of production, and the number of wells for each field. With the exception of Carrolls Creek field, all fields have or will have vertical wells producing coalbed methane. Because Brookwood and Oak Grove are the only fields with active underground mines, production from gob and horizontal wells is restricted to those fields. Gob and horizontal boreholes have limited distribution and cannot be evaluated in the same way as vertical boreholes, which are present throughout the degasification area; only data from vertical boreholes were used in the regional production analysis.



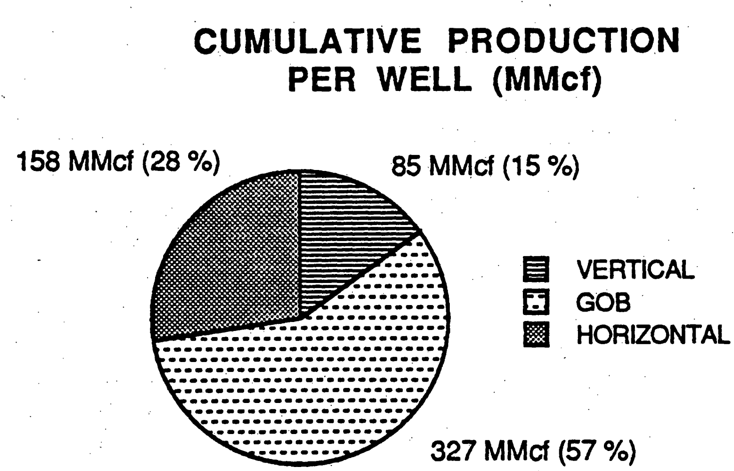




Figure 87. Methane production by well type through December 1988.

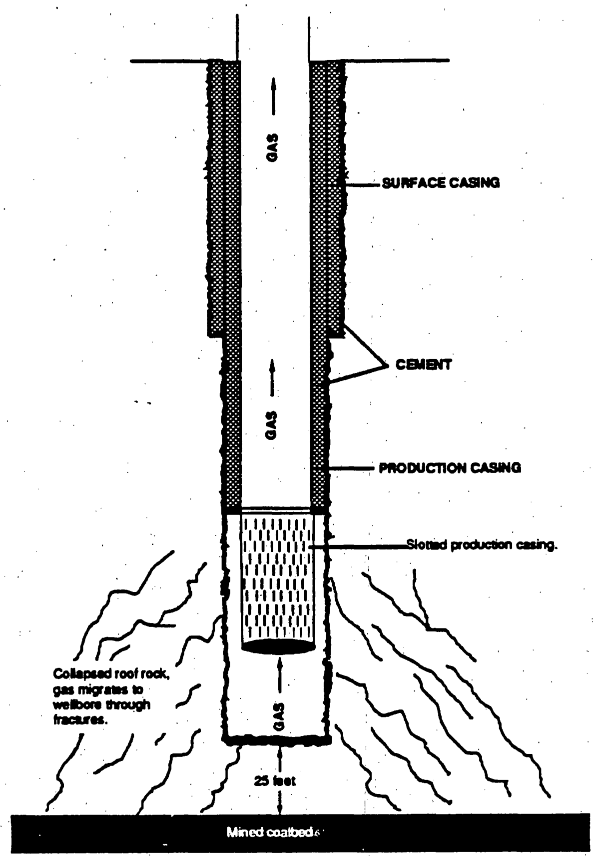



Figure 88. Schematic of a gob well.

## Completion

Of the 417 vertical wells evaluated for this study, 303 (73 percent) were completed open-hole. Using this method, production casing is cemented into place immediately above the uppermost coal bed that is to be produced. Wells completed with perforated casing or slotted casing numbered 106 (25 percent), and 8 wells (2 percent) were completed with a combination slotted-casing and open-hole technique. Although most vertical wells in the degasification fields have been completed open-hole (fig. 90), the most common completion procedure used by coalbed-methane operators at present is with slotted casing. The advantages of this method include better isolation of productive strata and elimination of problems associated with wellbore caving. Most wells in Brookwood and Oak Grove employ a single-zone completion in the Mary Lee coal group, whereas most of the wells in

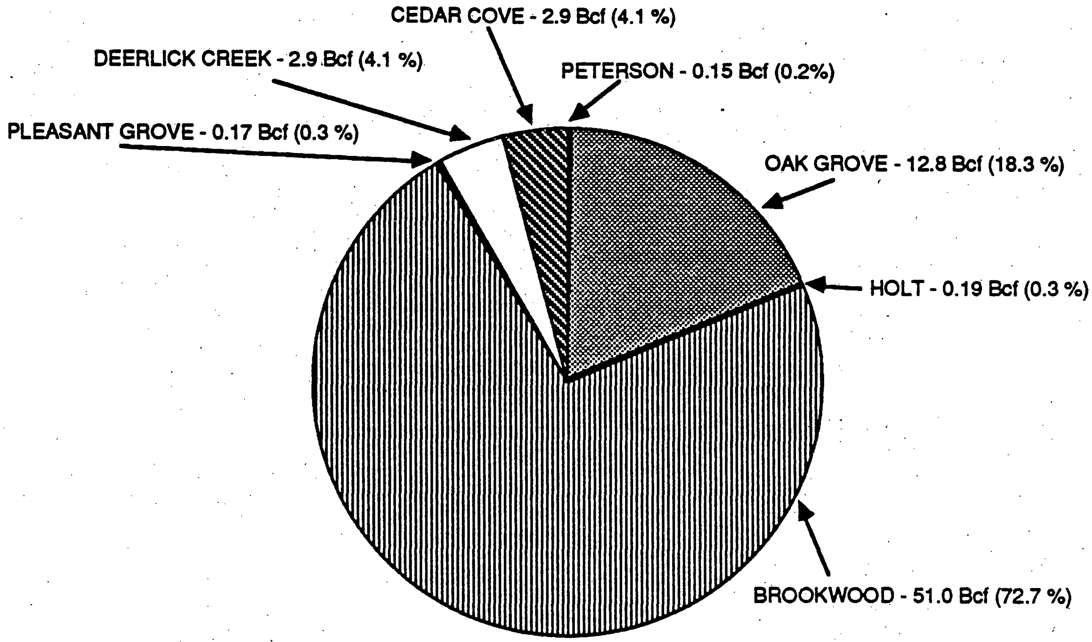



Figure 89. Cumulative methane production by field through December 1988.

Table 8. Cumulative production (Mcf) by well type through December 1988

| Field | Vertical | | GOB | | Horizontal | |
|---|---|---|---|---|---|---|
| | Production (Mcf) | Number | Production (Mcf) | Number | Production (Mcf) | Number |
| Oak Grove | 12,410,032 | 221 | 365,259 | 1 | 32,342 | 5 |
| Brookwood | 14,203,527 | 97 | 33,784,599 | 103 | 3,002,324 | 14 |
| Pleasant Grove | 171,191 | 4 | – | – | – | – |
| Holt | 191,132 | 5 | – | – | – | – |
| Cedar Cove | 2,852,066 | 18 | - | – | – | – |
| Deerlick Creek | 2,947,846 | 38 | – | – | – | – |
| Peterson | 150,367 | 6 | – | – | – | – |
| Carrolls Creek | 0 | 0 | – | – | – | – |
| Blue Creek | 0 | 0 | – | – | – | – |
| Unnamed field | 2,727 | 2 | – | – | – | – |
| Total | 32,928,888 | 391 | 34,149,858 | 104 | 3,034,666 | 19 |

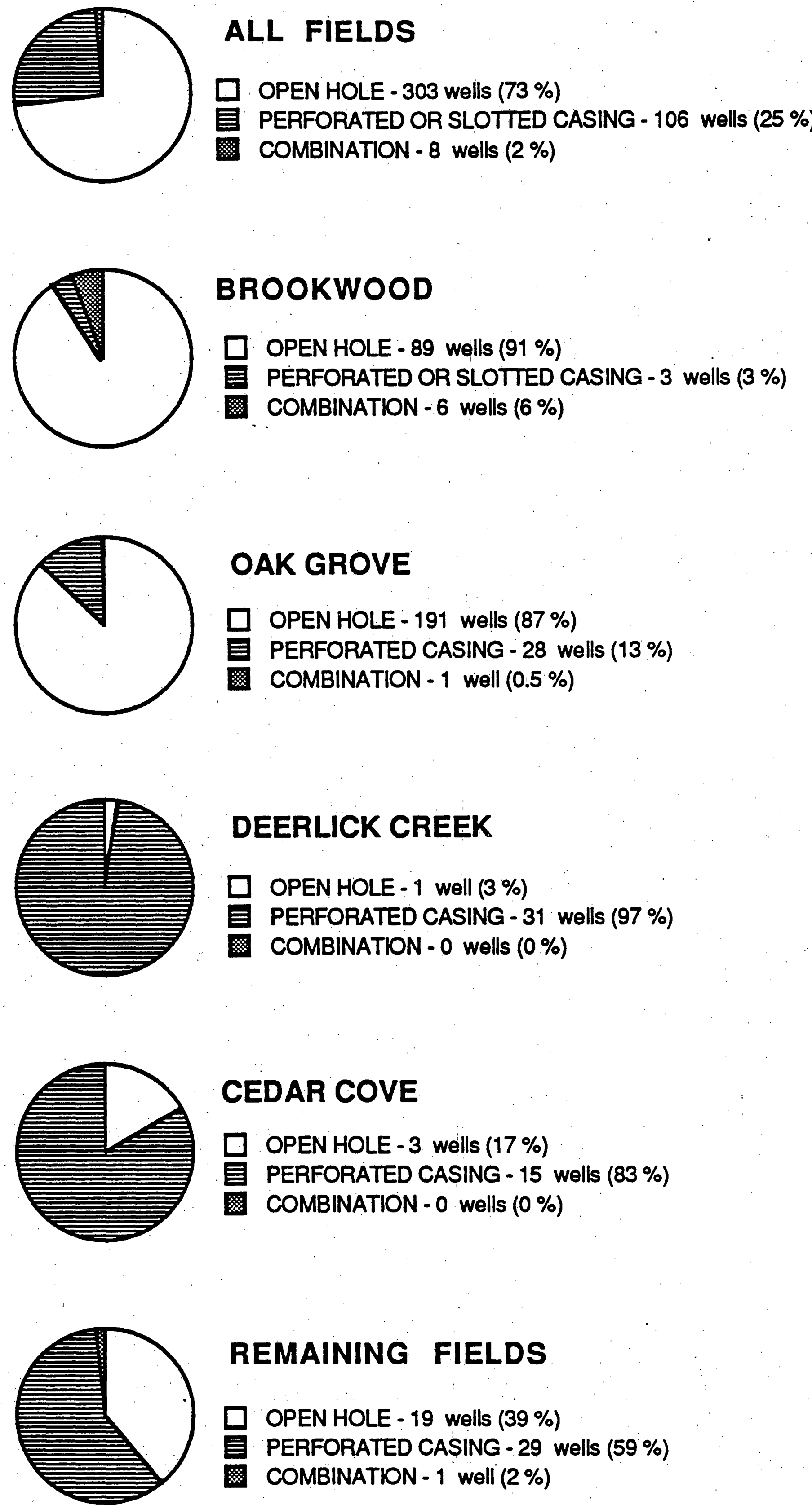



Figure 90. Completion methods by field through December 1988.

the remaining fields are multiple zone completions producing the coalbed-methane resources of the entire Black Creek-Cobb interval.

The preponderance of open-hole completions (fig. 90) reflects practice by operators in Brookwood and Oak Grove fields, which contain most of the wells analyzed. In the remaining fields, perforated casing predominates, although open-hole completions are common. In all of the fields, combination completions are few.

Stimulation technique varies, but most wells evaluated were stimulated using water as the injection fluid and sand as the propping agent. Wells were evaluated to determine the major fluid injected. The fluids used in well stimulation include water, foam, and gel; the fluids may be applied alone or in combination. Some wells in Brookwood field were not stimulated. Although more of the wells evaluated were stimulated with water and sand than with any other method (fig. 91), the current stimulation practice employed by most operators is the cross-linked gel-and-sand method. One operator continues to use water and sand for well stimulation (personal communication).

Of the 413 wells evaluated, 196 wells (47 percent) were stimulated with water as the major fluid (fig. 91). Foam, gel, and combination stimulations were used in fairly equal proportions ranging from 15 to 17 percent each. Deerlick Creek is the only field where the highest proportion of the wells have been stimulated by a method other than the water-and-sand fracture; combination stimulations comprise 81 percent of the stimulations in that field. All 17 wells that were not stimulated are in Brookwood field.

## WELL PRODUCTIVITY AND EFFECTS OF COMPLETION AND GEOLOGY

### 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. The average production rate is a long-term measure of a well's long-term ability to produce, whereas the initial and peak rates occur in the first year of production of wells drilled with a 40-acre or smaller

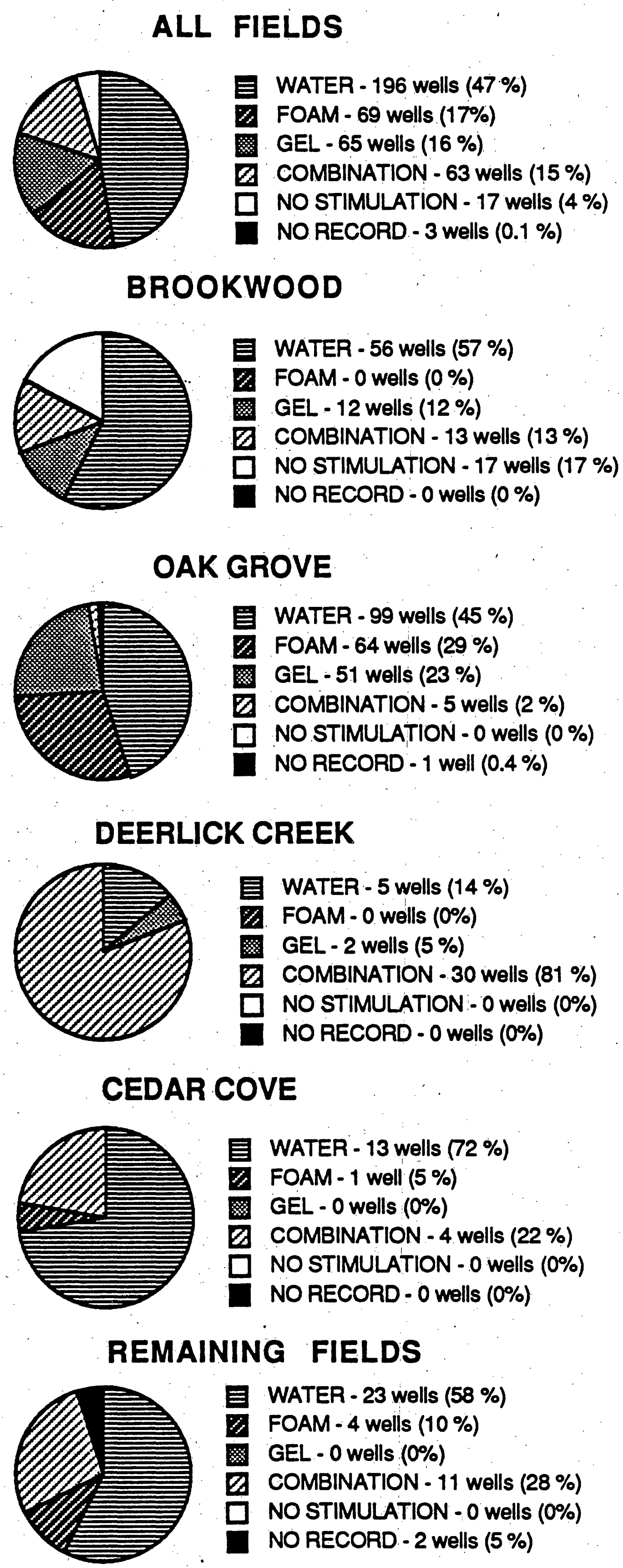



Figure 91. Stimulation methods by field through December 1988.

spacing. Results of linear regression indicate that both the initial and peak rates correlate positively and significantly with the average rate, but the peak rate correlates much more highly (fig. 92). Hence, the peak rate is a better short-term measure of a well's long-term performance. A least-squares regression of the data is defined by the following equation that enables computation of expected long-term production performance:

$$AGR = 0.45\,(PGR) + 10.5$$

in which AGR represents average production, and PGR represents peak production.

Cumulative relative-frequency values for peak gas-production values (fig. 93) indicate that 28 percent of the wells had peak production equal to or lower than 100 Mcfd, 52 percent had peak production equal to or lower than 100 Mcfd, and 70 percent had peak production equal to or lower than 150 Mcfd. By the end of 1988, only 21 percent of the coalbed-methane wells in the Black Warrior basin had produced more than 200 Mcfd. Observing the frequency graph, the 200 Mcfd peak rate appears to be a logical dividing point between low- and high-productivity wells. Using the 200 Mcfd value as a guide, a map depicting trends of high and low productivity was developed (fig. 94), and completion practices were evaluated.

## Completion and Geology

Completion practice has changed over the past few years. Whereas single-zone, open-hole completion was the standard method used by most operators, the present method is to complete multiple-zone wells with perforated or slotted casing. Whereas stimulation practice varied during the first four or five years, operators are currently stimulating most wells with a cross-linked gel-and-sand fracture or sand-and-water fracture. A statistical summary of coalbed-methane production parameters is provided in table 9.

Plotting peak production rate against well permit numbers is a means of determining whether production has changed over time. Results of this analysis (fig. 95) indicate that, in spite of changing completion practice, no correlation exists between production and time. Similarly, no significant correlation exists between peak production and well spacing, and no statistical relationship exists

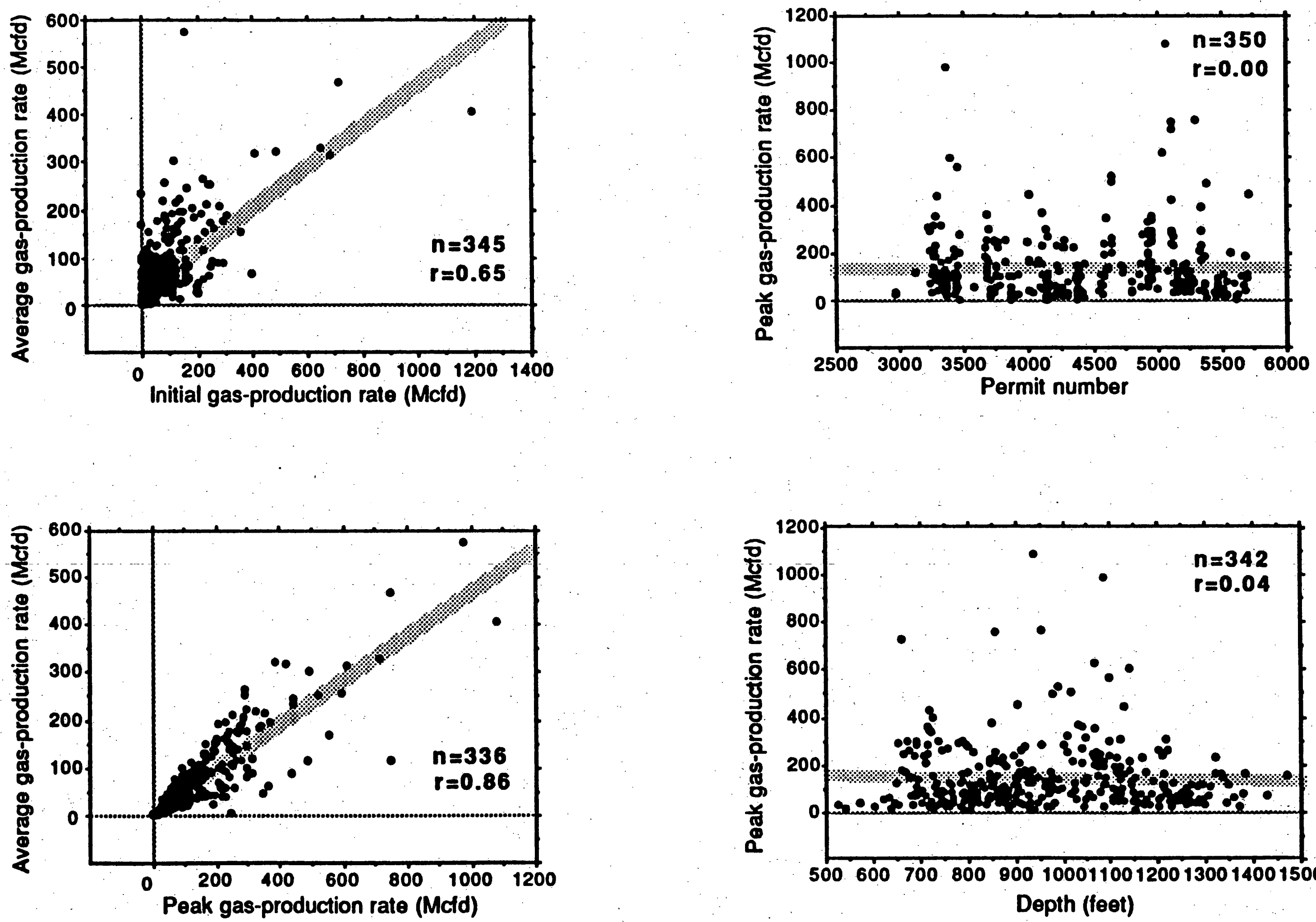



Figure 92. Results of statistical analysis of production parameters.

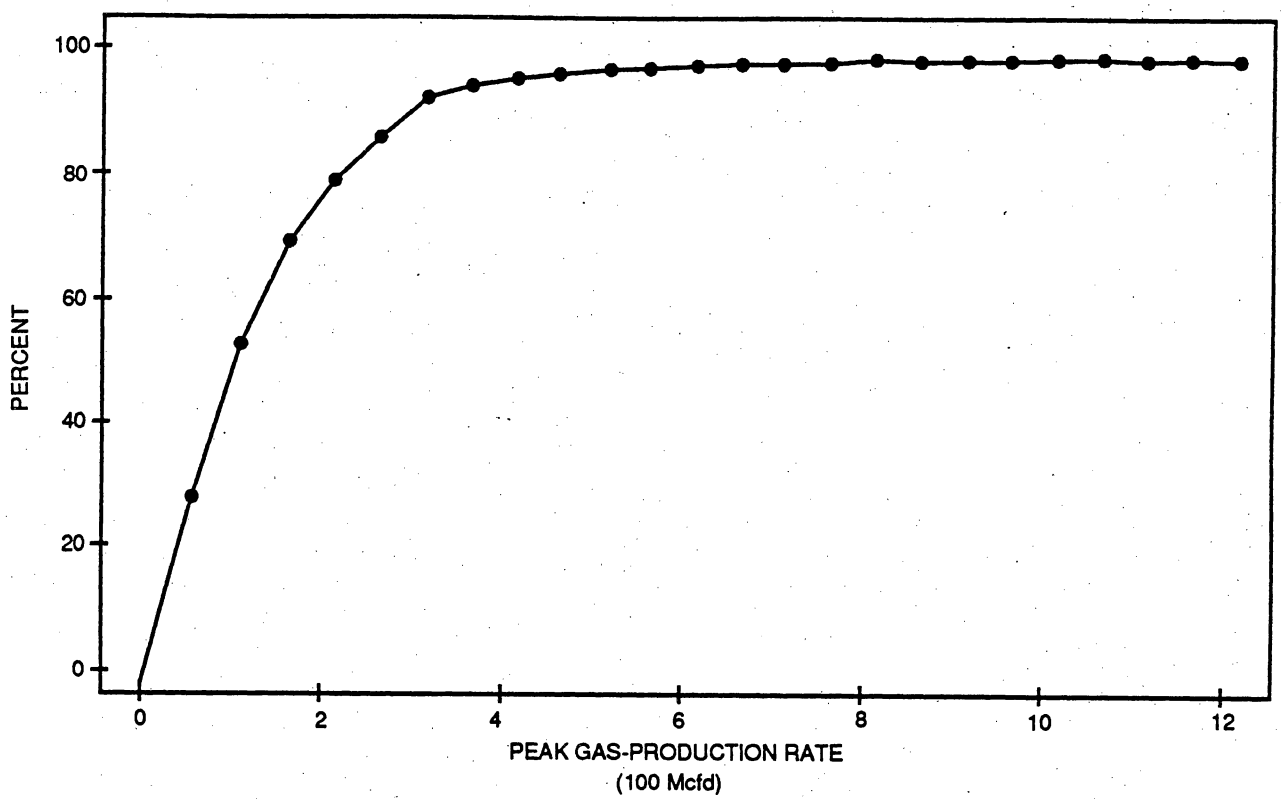



Figure 93. Cumulative-relation frequency, peak gas production.

between peak methane production and geologic and hydrogic factors like well depth and net completed coal thickness (figs. 92, 95). However, a weakly significant, positive correlation exists between water production and peak methane production.

Tables 10 and 11 were prepared for the evaluation of completion and stimulation data. Table 10 shows the number of wells in each field, the completion method, and the number that had a peak-production rate of more than 200 Mcfd, and the number that had a peak production rate of less than 200 Mcfd. The percentage of wells completed by a given method is basically the same whether the production is more or less than 200 Mcfd (table 10; fig. 96). On the basis of this comparison, completion method is apparently not a strong control on well productivity.

The number of wells in each field, the type of stimulation method employed, and the number of wells with peak production greater and less than 200 Mcfd are listed in table 11. As is the case for completion method, the percentage of wells producing more and less than 200 Mcfd is essentially the same regardless of stimulation method (table 11, fig. 97). However, only 5 percent of the wells

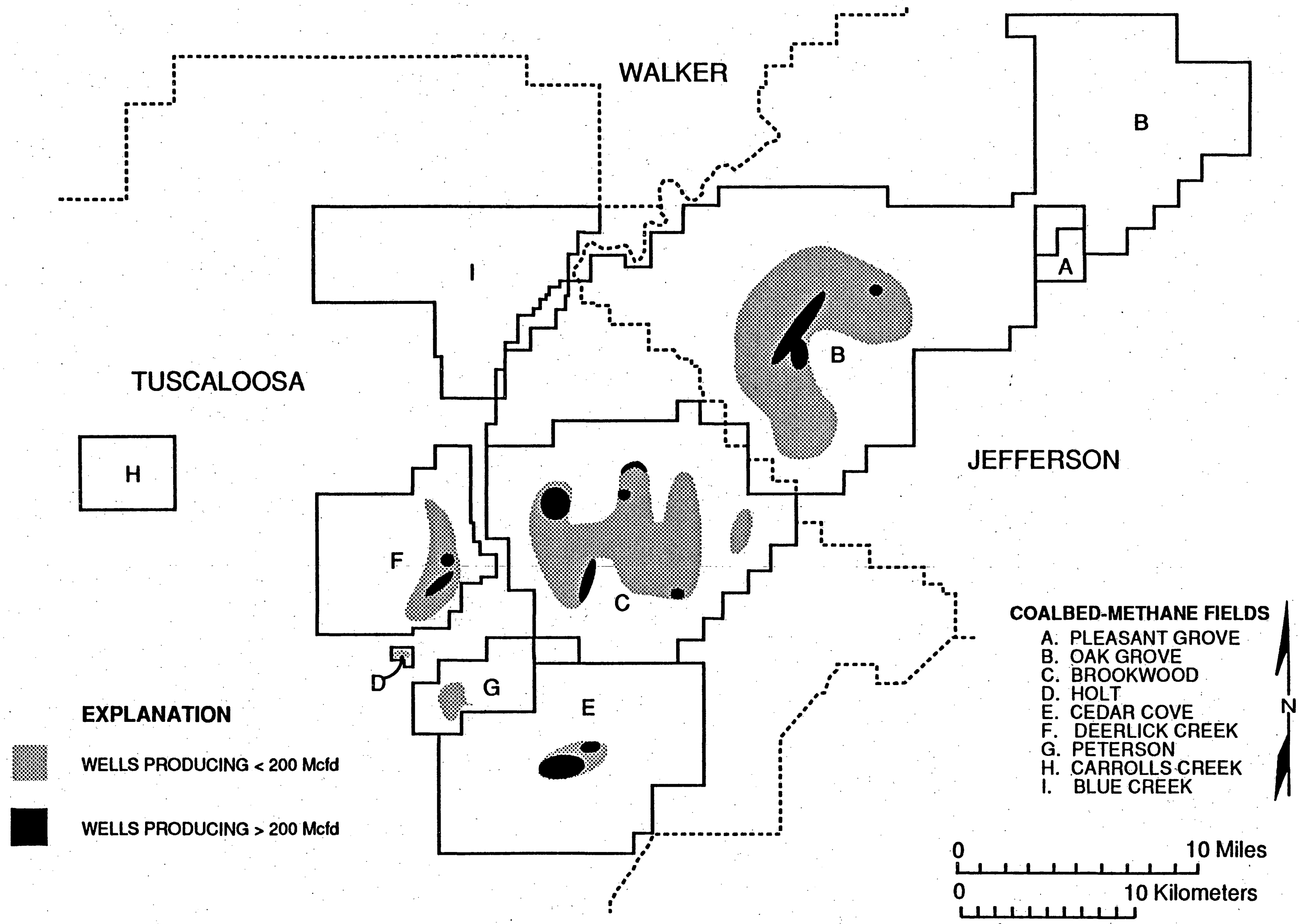



Figure 94. Coalbed-methane production trends in the Black Warrior basin.

Table 9. Statistical summary of production parameters

| Parameter | Number of observations | Mean | Median | Mode | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|---|---|---|
| Initial gas rate (Mcfd) | 397 | 81 | 55 | 17 | 105 | 1 | 1,191 |
| Initial water rate (bpd) | 396 | 132 | 64 | 6 | 171 | 0 | 1,176 |
| Peak gas rate (Mcfd) | 351 | 134 | 96 | 50 | 139 | 1 | 1,081 |
| Peak gas time (months) | 351 | 12 | 7 | 2 | 14 | 1 | 86 |
| Peak water rate (bpd) | 349 | 167 | 71 | 13 | 250 | 1 | 1,705 |
| Average gas rate (Mcfd) | 348 | 72 | 52 | 56 | 73 | 1 | 572 |
| Total production time (months) | 386 | 35 | 28 | 1 | 26 | 1 | 102 |
| Decline time (months) | 139 | 14 | 9 | 2 | 14 | 1 | 60 |
| Net coal thickness (ft) | 305 | 7 | 6.6 | 5 | 2.8 | 1.3 | 29.5 |
| Depth (ft) | 320 | 1,347 | 1,144 | 1,789 | 434 | 681 | 2,375 |
| Well spacing (acres) | 417 | 45 | 40 | 40 | 19 | 10 | 80 |

producing more than 200 Mcfd were stimulated with foam, whereas 19 percent of the wells producing less than 200 Mcfd were completed by that method. Additionally, 9 percent of the wells producing more than 200 Mcfd were not stimulated, whereas only 3 percent of the wells producing less than 200 Mcfd were not stimulated.

Several factors may account for the poor performance of wells stimulated by foam. Most foam wells are in the original Oak Grove pattern, which contains many of the oldest coalbed-methane wells in the Black Warrior basin. Low production may be attributed in part to unrefined engineering strategies, although peak production has not increased significantly with time and engineering advances. Wells in the Oak Grove pattern are the most closely spaced in the basin (approximately 25 acres), thus poor performance may reflect competition among closely spaced wells for a limited methane resource.

The surprisingly high performance of unstimulated wells can be related directly to geology. All unstimulated wells with initial or peak production higher than 200 Mcfd are located on productive lineament trends in Brookwood field similar to the one in Oak Grove field (fig. 12). The most notable unstimulated well is the "glory hole" of Brookwood field, which peaked higher than 1,000 Mcfd. Hence, wells drilled into natural fracture networks do not necessarily need to be stimulated. In fact,

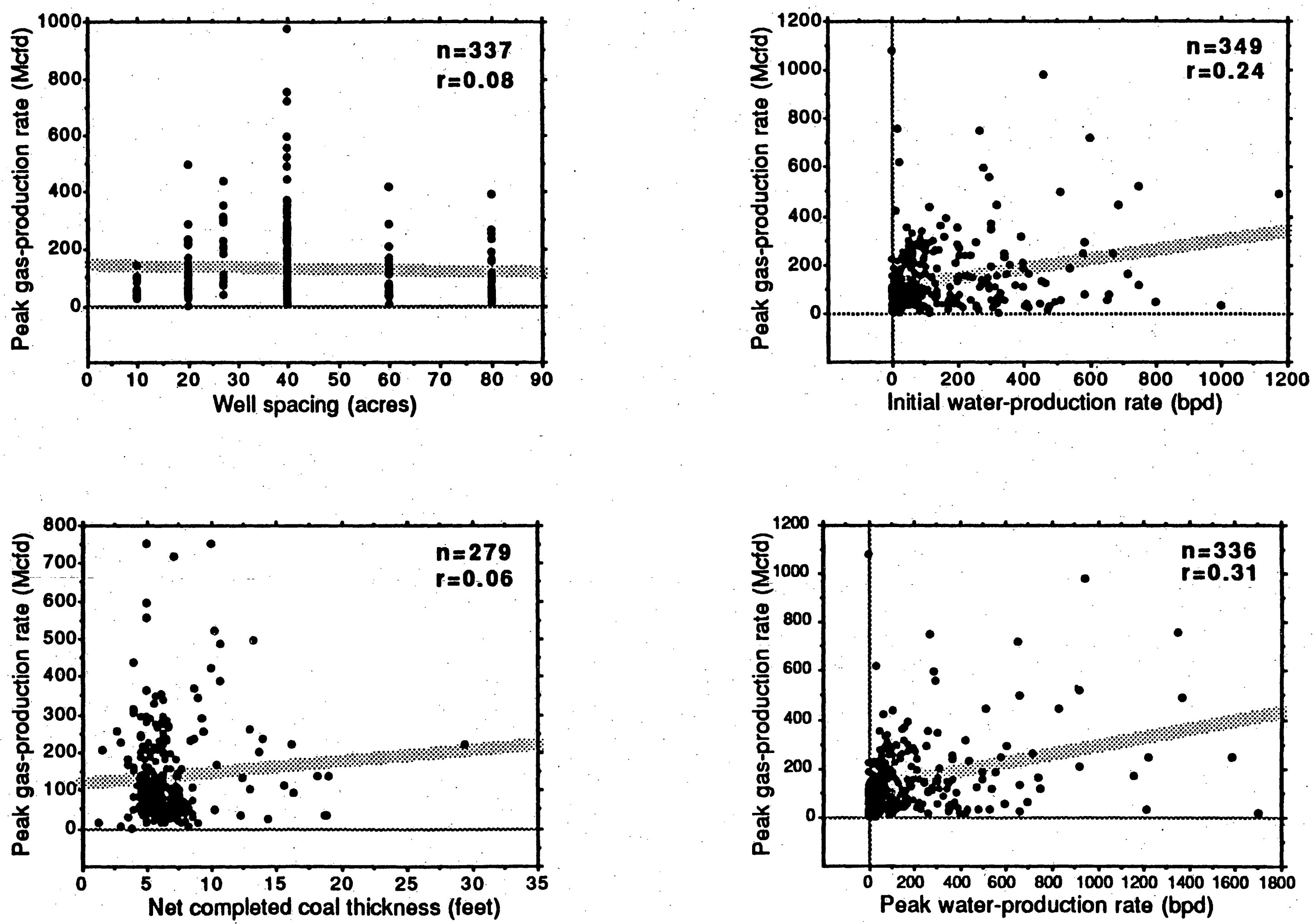



Figure 95. Results of statistical comparison of geologic and production parameters.

Table 10. Comparison of completion methods used in wells producing more and less than 200 Mcfd

| Field | Wells with peak production >200 Mcfd | | | Wells with peak production <200 Mcfd | | |
|---|---|---|---|---|---|---|
| | Open-hole | Perfed. casing | Both | Open-hole | Perfed. casing | Both |
| Brookwood | 30 | 1 | 1 | 59 | 2 | 5 |
| Oak Grove | 26 | – | 1 | 165 | 28 | – |
| Deerlick Creek | – | 4 | – | 1 | 27 | – |
| Cedar Cove | – | 11 | – | 3 | 4 | – |
| Peterson | – | – | – | 7 | 16 | 1 |
| Holt | – | – | – | 3 | 2 | – |
| Blue Creek | – | – | – | – | 9 | – |
| Pleasant Grove | - | – | – | 3 | 1 | – |
| Carrolls Creek | – | – | – | 4 | – | – |
| Unnamed field | – | – | – | 2 | 1 | – |
| Total | 56 | 16 | 2 | 247 | 90 | 6 |
| Percent of wells >200 Mcfd Total - 74 | 76 | 21 | 3 | | | |
| Percent of wells <200 Mcfd Total - 343 | | | | 72 | 26 | 2 |

Table 11. Comparison of stimulation methods used in wells producing more and less than 200 Mcfd

| Field | Wells with peak production >200 Mcfd | | | | | | Wells with peak production <200 Mcfd | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Water | Foam | Gel | Combo. | NS[1] | No 6[2] | Water | Foam | Gel | Combo. | NS[1] | No 6[2] |
| Brookwood | 14 | – | 6 | 5 | 7 | – | 42 | – | 6 | 8 | 10 | – |
| Oak Grove | 18 | 4 | 5 | – | – | 1 | 81 | 60 | 46 | 5 | – | – |
| Deerlick Creek | 1 | – | – | 3 | – | – | 4 | – | 2 | 27 | – | – |
| Cedar Cove | 9 | – | – | 2 | – | – | 4 | 1 | – | 2 | – | – |
| Peterson | – | – | – | – | – | – | 18 | – | – | 5 | – | 1 |
| Holt | – | – | – | – | – | – | 3 | 1 | – | 1 | – | – |
| Blue Creek | – | – | – | – | – | – | – | – | – | 2 | – | – |
| Pleasant Grove | – | – | – | – | – | – | – | 3 | – | 1 | – | – |
| Carrolls Creek | – | – | – | – | – | – | 2 | – | – | – | – | – |
| Unnamed field | – | – | – | – | – | – | – | – | – | 2 | – | 1 |
| Total | 42 | 4 | 11 | 10 | 7 | 1 | 154 | 65 | 54 | 53 | 10 | 2 |
| Percent wells >200 Mcfd Total - 75 | 56 | 5 | 15 | 13 | 9 | 1 | | | | | | |
| Percent wells <200 Mcfd Total - 338 | | | | | | | 46 | 19 | 16 | 15 | 3 | 1 |

[1]NS - Not stimulated.
[2]No 6 - No Form OGB-6 submitted.

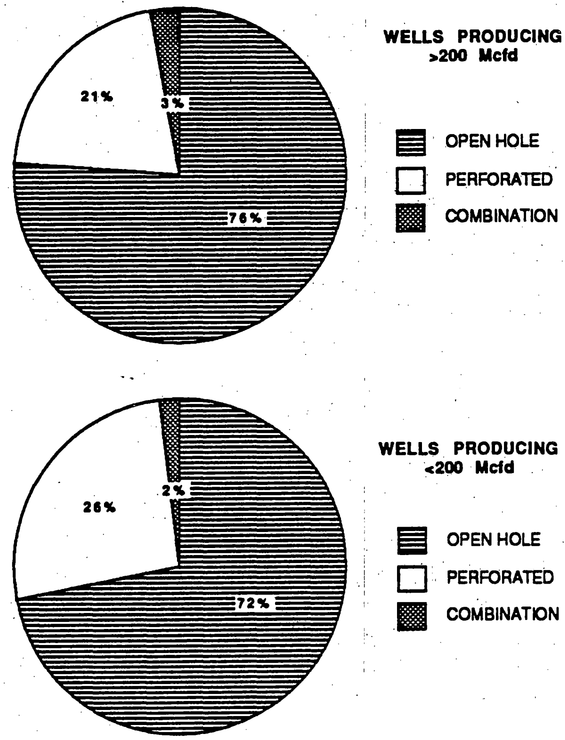



Figure 96. Comparison of completion methods used in wells producing more and less than 200 Mcfd.

more than 85 percent of the wells with peak production higher than 200 Mcfd are on the lineament trends. Additionally, fracture treatments for wells outside of productive lineament trends may be designed to duplicate geologic conditions in those trends.

# CONCLUSIONS

## GEOLOGIC CONTROLS ON COALBED-METHANE PRODUCTION

### Structural Geology

The productivity map (fig. 94) demonstrates that highly productive trends in the Black Warrior basin are localized and tend to be oriented northeast. Of all the geologic relationships discussed in this study, the clearest pattern with respect to coalbed-methane production is coincidence of highly productive wells with northeast-oriented lineaments. Hence, examination of lineament patterns may be the best method of locating prospective sites of exceptional productivity.

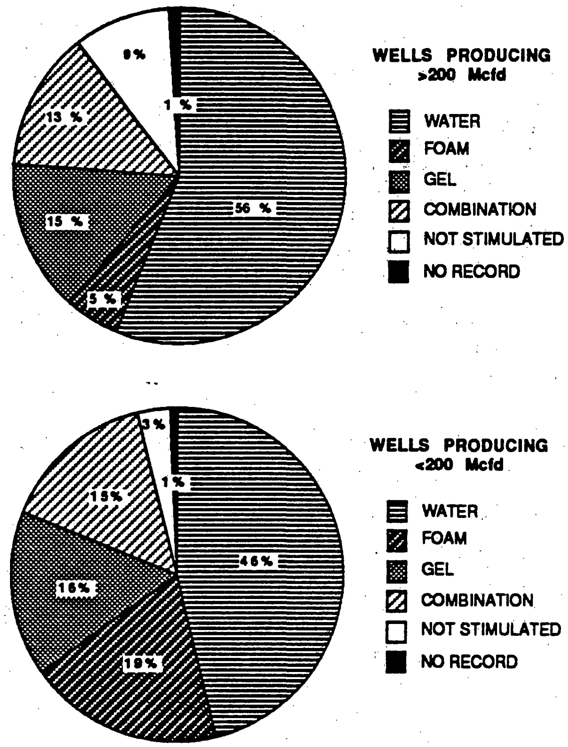



Figure 97. Comparison of stimulation methods used in wells producing more and less than 200 Mcfd.

In Oak Grove field, production is exceptionally high along northeast-striking structures (fig. 12), whereas methane production is low in an area containing numerous northwest-trending faults (Pashin and others, 1989). If highly productive trends are caused by northeast-oriented fracture systems, why are the abundant northwest fracture systems unproductive? One explanation is that the northeast-oriented compressive-stress (Engelder, 1982; Park and others, 1984) has closed fractures oriented perpendicular to the stress vector and has opened fractures oriented parallel to the vector. Hence, permeability may be higher along northeast-oriented fracture zones than along northwest-oriented fracture zones. For example, the "glory hole" of Brookwood field evidently penetrated a lineament-related fracture zone oriented with an azimuth of 82°, and gas production peaked after the advancing mine face intersected the fracture zone, thereby causing rapid dewatering (Epsman and others, 1988). Alignment of the producing fracture zone with the axis of maximum horizontal compression as determined by Park and others (1984) suggests that investigation of the relationship between current crustal stress and methane productivity on a site-specific basis may have merit.

Furthermore, some normal faults contain clay-rich gouge that may inhibit permeability, and fault discontinuities in coal beds limit the areal extent of the available coalbed-methane reservoir.

Because stains and fillings are locally present on the face cleat, the face cleat evidently conducted fluid and was thus open at one time. Engineering tests at the Rock Creek site revealed that the cone of depression developed by dewatering of the Pratt coal bed is elongate in the face-cleat direction, but other beds did not show a similar pattern (Boyer and others, 1986), perhaps due to interference by other fracture systems. Even so, the Rock Creek results demonstrate that the face cleat can be an important avenue of fluid transmission in coal, and some lineaments associated with high productivity are nearly parallel to the face cleat (figs. 12, 13). However, the northeast face cleat is essentially ubiquitous (fig. 10), whereas high-productivity trends are localized (fig. 94). Therefore, enhanced methane production is apparently related to locally increased permeability.

## Coal Quality and Gas Composition

Methane has been produced from the Mary Lee coal group in areas containing coal with less than 37 percent volatile matter, which coincides with the approximate lower limit of major catagenetic (thermal) methane generation (Jüntgen and Klein, 1975). However, biogenic and migrated gas may form a significant resource in areas where volatile-matter content is higher than 37 percent, and results of gas-composition analysis suggests that some methane may have migrated from Mississippian source rocks. Thus far, gas-content and gas-composition data are not available from coal Alabama with more than 37 percent volatile matter. Hence, the impact of coal rank on producibility is uncertain.

Coal grade may be an important consideration in the exploration of areas where coal has a high volatile-matter content. Because ash content is inversely related to methane content in coal (Wyman, 1984), high-ash resources may have reduced potential. The low-quality coal belt coincides partly with an area of high volatile-matter content, so resources may be limited in this area. The impact of sulfur content on the producibility of coalbed methane appears minimal. Although some operators have reported sulfurous odors emanating from some wellbores, no significant impact on the quality of methane and production water has been reported.

## Sedimentology

Statistical analysis indicates that coal thickness is not a control on coalbed-methane production (fig. 95). This result is surprising, considering that coal, which is the primary source rock and reservoir rock, is a prerequisite for production. Lack of a correlation between coal thickness and production is interpreted to reflect the influence of other factors, particularly permeability, on the producibility of coalbed methane. Therefore, coal occurrence should be considered a critical production parameter from the standpoint of locating a resource base that may be developed.

Why is coal most abundant in southern Tuscaloosa and western Jefferson Counties? In short, coal abundance can be related to depositional environment and 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 greatly as cycle thickness increases, and (3) in Greene and Sumter Counties, coal abundance and net lithic-sandstone thickness do not increase greatly as cycle thickness increases.

Restriction of the thickest 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 in southern Tuscaloosa and western Jefferson Counties helped maintain terrestrial environments conducive to peat accumulation. Channel and flood-basin sedimentation also caused splitting and proliferation of coal beds in this area (Epsman and others, 1988). The remaining parts of the study area were far from a sediment source and were dominated by marine sedimentation which is conducive to mudstone and quartzose sandstone deposition. Consequently, peat deposition only occurred in these areas late in each cycle when most or all of the region was emergent.

The increase in coal abundance and net lithic-sandstone thickness with cycle thickness indicates that subsidence acted in concert with fluvial sedimentation in the formation of abundant coal. Splitting of coal across faults onto downthrown fault blocks has been documented by Weisenfluh and

Ferm (1984), Epsman and others (1988), and Pashin and others (1989), and southern Tuscaloosa and western Jefferson Counties are part of a major trough of subsidence. Whether or not this subsidence occurred along faults, differential subsidence may result in the splitting of coal beds. However, in Greene and Sumter Counties, where the Black Creek-Cobb interval is locally thicker than 2,400 feet, subsidence was not near a sediment source, so environments conducive to peat deposition seldom were developed.

## Hydrology and Hydrochemistry

Pressure-depth quotients and water-level data suggest that natural reservoir pressure in the Black Warrior basin is near hydrostatic and that dewatering for mining and degasification has induced underpressure in large areas. Areas of enhanced permeability where reservoir pressure can be lowered rapidly by dewatering coal beds are important for the development of coalbed-methane fields. Simply stated, lowering of reservoir pressure is critical to methane desorption from coal. If reservoir pressure can be lowered by the rapid removal of subsurface water, a large proportion of the desorbed methane may be recoverable.

Areas containing water with low TDS content may be related to meteoric recharge of the upper Pottsville along the southeastern edge of the basin. Therefore, the fresh-water tongues in that area may be migrating along avenues of high permeability. For example, Pashin and others (1989) documented a fresh-water lens that occurs along the productive lineament trend in Oak Grove field. Hence, identification of areas containing low TDS water may be an important consideration in recognizing open fracture systems which may provide the best drilling sites.

New areas favorable for coalbed-methane drilling have been recognized southwest of the present coalbed-methane fields, and numerous wells have been drilled or at least permitted. Because the upper Pottsville is overlain by Cretaceous sediment, which apparently acts as a sink for meteoric water, low-TDS protrusions probably are not developed in the same way as in the coalbed-methane fields. Therefore, potential exists for production of water with TDS content well in excess of 3,000 mg/L, and drillers should perhaps economize their efforts to offset the added cost of producing coalbed methane from below Cretaceous cover.

## REGIONAL CHARACTERIZATION OF COALBED-METHANE POTENTIAL

Having identified geologic controls on the occurrence and producibility of coalbed methane, the Black Warrior basin of Alabama was divided into 6 distinct areas having different coalbed-methane potential (fig. 98; table 12). Essentially all parts of the study area have some coalbed-methane potential, but that potential is variable. The criteria used to define the areas include, coal rank, coal abundance, depth to the coal group, and water salinity. In order of increasing potential, the Black Warrior basin of Alabama was divided into areas A through F.

Area A (fig. 98) comprises parts of Tuscaloosa, Walker, Cullman, Marion, Winston, Fayette, Lamar, and Pickens Counties. At present, there is no coalbed-methane production in this area, although parts of Deerlick Creek and Blue Creek fields are within the area limits. The Mary Lee coal group in Area A has volatile-matter content ranging from 34 to 40 percent and vitrinite reflectance less than 0.8 percent (table 12), so little thermal methane generation evidently occurred in this area. However, migrated and biogenic methane may be an economic resource. Where data are available, fewer than 10 coal beds are present in the Black Creek-Cobb interval. Water salinity is low along the northeast rim of area A (<1,000 mg/L TDS), but thick Cretaceous overburden in the western part of the area may signify high TDS content in water of the upper Pottsville. In the eastern part of the area, target coal groups crop out, so thin overburden is a concern. However, the Mary Lee cycle is at a depth of 1,800 feet in the southern part of the area. Overall, the coalbed-methane potential of area A is questionable, particularly because coal rank is low.

Area B, in southern Walker and central Jefferson Counties, contains the northeast part of Oak Grove field which has not been drilled (fig. 98). The Mary Lee coal group contains 28 to 37 percent volatile matter, and 15 to 25 coal beds are present in the Black Creek-Cobb interval (table 12). Therefore, coal abundance is favorable, but rank is variable. Hydrologic evidence indicates that area B has the potential to produce water with TDS values greater than 3,000 mg/L. Overburden is a concern

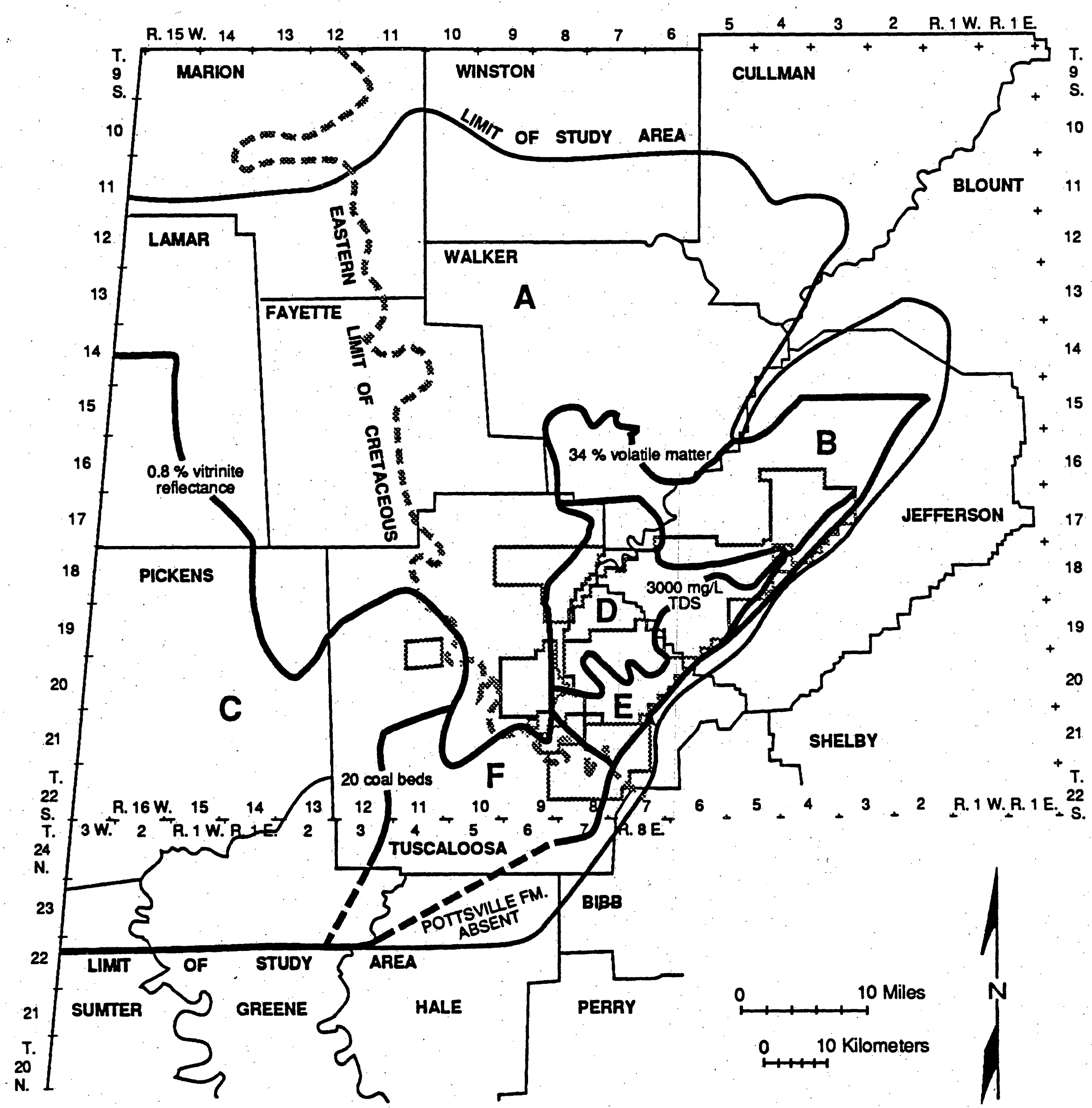



Figure 98. Regional characterization of coalbed-methane potential, Black Warrior basin, Alabama. See figure 1 for field names.

Table 12. Regional characterization of coalbed-methane potential

| Area | Coal rank of Mary Lee cycle (%) | | Coal abundance in Black Creek-Cobb interval | Depth to top of Mary Lee cycle (feet) | Water salinity (TDS) of Mary Lee Coal group (mg/L) | Proven production |
|---|---|---|---|---|---|---|
| | Volatile matter | Vitrinite reflectance | | | | |
| A | 34 to 40 | 0.6 to 0.8 | <10 beds | 600 to 1,800 | 1,000 to >3,000 | No |
| B | 28 to 37 | 0.8 to 1.0 | 15 to 25 beds | 0 to 600 | >3,000 | No |
| C | No data | 0.8 to 1.2 | <20 beds, locally <5 beds | 600 to 4,800 | no data, probably >3,000 | No |
| D | 22 to 34 | 0.8 to 1.4 | 15 to 30 beds | 600 to 1,500 | >3,000 | Yes |
| E | 19 to 34 | 1.0 to 1.4 | 20 to 30 beds | 600 to 2,100 | <3,000, locally <1,000 | Yes |
| F | No data | 0.8 to 1.0 | 20 to 40 beds | 2,700 to 3,300 | <3,000, locally >10,000 | Yes |

because the Mary Lee, Pratt, and Cobb cycles crop out in the northeast part of the area. However, the Mary Lee cycle is present at a depth of 600 feet in the western part of the area, and the Black Creek cycle is deeper than 1,000 feet. Hence, the coalbed-methane potential of area B increases toward the west.

Area C is in southwest Lamar, most of Pickens, west-central Tuscaloosa, and northernmost Sumter and Greene Counties (fig. 98). Carrolls Creek field is the only coalbed-methane field in this area. A vitrinite-reflectance measurement of 0.86 from that field corresponds to a volatile-matter content of about 37 percent, which suggests that only migrated and biogenic gas are preserved in the reservoir. Two coalbed-methane wells completed in the Mary Lee coal group in Carrolls Creek field produced only 9 and 39 Mcfd of gas in initial tests. However, vitrinite reflectance is greater than 0.8 percent throughout Area C and is 1.2 percent in Sumter County, indicating that some medium-volatile bituminous coal may be present (table 12). The target coal groups have thick overburden, and the Mary Lee cycle is at a depth of 4,800 feet. Fewer than 20 coal beds are present in the study interval throughout most of the area, and fewer than 5 beds are present locally. However, more than four closely spaced coal beds occur in the Pratt cycle in parts of Pickens County. Another concern in developing Area C is the possibility of high TDS water related to deep burial of the Pottsville below Cretaceous cover. Hence, Area C has variable coalbed-methane potential.

Area D includes parts of Tuscaloosa, Jefferson, and Walker Counties and contains large portions of Brookwood, Oak Grove, and Blue Creek fields (fig. 98); this area has been the site of extensive development. Volatile-matter content ranges from 22 to 34 percent (table 12), indicating that coal rank ranges from high-volatile A bituminous to medium-volatile bituminous. In area D, 15 to 20 coal beds are common, and the area locally contains more than 30 beds. Area D has proven production along its southeast margin where TDS content is much less than 10,000 mg/L. However, several parts of the area contain formation water with TDS content greater than 10,000 mg/L. The Mary Lee cycle is at a depth between 600 and 1,500 feet, so overburden is not a major concern. On the basis of high-rank coal and proven production, Area D has good coalbed-methane potential.

Area E is located in western Jefferson and eastern Tuscaloosa Counties and contains parts of Oak Grove, Brookwood, and Cedar Cove fields (fig. 98); it contains abundant coalbed-methane wells. The area is similar in many respects to area D, but area E contains low-volatile bituminous coal with less than 19 percent volatile matter (table 12); this is the highest rank coal known from the Black Warrior basin. The northwest margin of area E is defined by fresh-water tongues related to recharge along the Blue Creek anticline, so TDS content is locally less than 1,000 mg/L. Area E has proven production along its northwestern margin and has excellent coalbed-methane potential.

Area F is in the southern Tuscaloosa County area and includes part of Cedar Cove field and an undrilled part of Deerlick Creek field (fig. 98). More than 20 coal beds occur in the area, and more than 40 coal beds occur locally (table 12), although coal-thickness data are scarce. Vitrinite reflectance is higher than 0.8 percent, and area F contains a proven high-productivity trend in Cedar Cove field. However, potential for producing high-TDS water (more than 10,000 mg/L) exists because coal-bearing strata are overlain by thick Cretaceous sediment, and the Mary Lee cycle is as deep as 3,300 feet. On the basis of geologic factors, areas D, E, and F offer the best coalbed-methane potential in the Black Warrior basin of Alabama. Areas D and E already have numerous producing coalbed-methane wells, so area F may be the most promising frontier area in Alabama.

However, results of this investigation indicate that abundant, high-rank coal is not enough to ensure economic methane production. High-productivity trends are localized (fig. 94), and geologic data suggest that these trends are predictable. Several highly productive trends occur along northeast-oriented lineaments. These lineaments evidently are the surface expression of zones of enhanced permeability that apparently are related to fractures. Productive trends also are associated with areas of low reservoir pressure, and salinity maps indicate that fresh water has migrated toward these areas from the southeast margin of the basin. The available data indicate that structure and hydrology are critical production parameters that may be used to identify favorable well sites within regions containing significant coal resources.

## FUTURE NEEDS

Future studies of structural geology should concentrate on detailed, site-specific analysis of lineament and fracture patterns. In this study, only a basic correlation between northeast-oriented lineaments and exceptional methane production has been identified. Methodology must be developed that may be used to identify which lineaments have the greatest potential and to determine how geology, permeability, and production potential vary along lineament trends.

Perhaps the biggest remaining questions regarding coal quality and gas composition pertain to the relationship of gas content to coal rank. Does coal with volatile-matter content higher than 37 percent contain a significant quantity of biogenic gas? Has gas migrated from high-rank coal into lower rank coal and into areas with exceptional permeability? If so, future gas-content and gas-composition studies should include parts of the basin that have been overlooked because of low coal rank. Vitrinite-reflectance data are still so scarce that each new data point alters the map pattern significantly. Hence, detailed rank maps of the western part of the basin may reveal unforeseen areas with significant coalbed-methane potential.

This study focused only on the regional aspects of sedimentology and coal occurrence in the Black Warrior basin. Future research should focus on the geologic controls of coal-body geometry and the criteria that may be used to predict the occurrence of thick coal bodies. How does coal-body geometry vary, and what are the sedimentologic and structural controls on that geometry? Do facies changes coincide with productive lineament trends as is the case in Oak Grove field?

Hydrologic investigation suggests that pumping of coalbed-methane wells has induced underpressuring in large areas, thereby facilitating methane desorption. However, the rate at which underpressuring can be induced and the area which a given well or set of wells may effectively depressurize have not been addressed. Site-specific hydrochemical studies may also have merit. For example, the fresh-water lens that occurs along the productive lineament trend in Oak Grove field indicates connection with a fresh-water protrusion, and possibly, downward percolation of surface water. Do only fresh-water lenses coincide with productive lineaments, or can salinity anomalies in general be used to identify zones of permeability?

A major implication of this research is that well and field design may be tailored to specific geologic settings. Although much of this study emphasizes highly productive lineament trends, the areas between those trends also offer significant economic potential. Perhaps the most important avenue of research remaining is the development of a strategic well-siting and well-design plan. For example, wells may be distributed along prospective lineament-related fracture zones, and some of those wells may not need to be stimulated. Additionally, fracture treatments may be developed that duplicate geologic conditions in natural fracture zones, and a well-spacing strategy needs to be developed for areas between lineament trends that will optimize reservoir drainage.

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## REFERENCES CITED

Ancell, K. L., Lambert, S., and Johnson, F. S., 1980, Analysis of the coalbed degasification process at a seventeen well pattern in the Warrior Basin of Alabama: Society of Petroleum Engineers/U.S. Department of Energy, First Annual Symposium on Unconventional Gas Recovery, Pittsburgh, Pennsylvania 1980, Proceedings, p. 355-370.

Anderson, J. A. R., 1964, The structure and development of the peat swamps of Sarawak and Brunei: Journal of Tropical Geography, v. 18, p. 7-16.

______1983, The tropical peat swamps of western Malesia, *in* Gore, A. J. P., ed., Ecosystems of the world, 4B, mires swamp, bog, fen, and moor: Amsterdam, Elsevier, p. 188-199.

Anderson, J. A. R., and Müller, J., 1975, Palynological study of a Holocene peat and a Miocene coal deposit from NW Borneo: Review of Palaeobotany and Palynology, v. 19, p. 291-351.

Beaumont, C., Quinlan, G., and Hamilton, J., 1988, Orogeny and stratigraphy numerical models of the Paleozoic in the eastern interior of North America: Tectonics, v. 7., p. 389-416.

Benson, D. J., 1979, Criteria for the recognition of depositional environments of coal-bearing strata in the Warrior basin: Tuscaloosa, Alabama, Alabama Mining and Mineral Resources and Research Institute, Final Report, Project 5194001, 66 p.

Boyer, C. M., II, Briscoe, F. H., Camp, B. S., Koenig, R. A., Malone, P. G., and Stubbs, P. B., 1986, Geologic and reservoir characterization for the multiple coal seams completion project at Rock Creek, v. 2: Chicago, Illinois, Gas Research Institute Topical Report contract no. 5083-214-0847.

Brown, Eugene, Skougstad, M. W. Fishman, M. J. 1970, Method for collection and analysis of water samples for dissolved minerals and gases: U.S. Geological Survey Technical Water-Resources Investigation 5, Chapter A1, 160 p.

Butts, Charles, 1910, Description of the Birmingham quadrangle, Alabama: U.S. Geological Survey Atlas, Folio 175, 24 p.

_____ 1926, The Paleozoic rocks, *in* Adams, G. I., Butts, C., Stephenson, L. W., and Cooke, W., Geology of Alabama: Geological Survey of Alabama Special Report 14, p. 41-230.

Cleaves, A. W., 1981, Resources of Lower Pennsylvanian (Pottsville) depositional systems of the western Warrior coal field, Alabama and Mississippi: Mississippi Mineral Resources Institute Technical Report 81-1, 125 p.

Cleaves, A. W., and Broussard, M. C., 1980, Chester and Pottsville depositional systems, outcrop and subsurface, in the Black Warrior basin of Mississippi and Alabama: Gulf Coast Association of Geological Societies Transactions, v. 30, p. 49-60.

Cohen, A. D., 1974, Petrography and paleoecology of some Holocene peats from the Okefenokee swamp-marsh complex of southern Georgia: Journal of Sedimentary Petrology, v. 44, p. 716-726.

Coleman, J. M., Gagliano, S. M., and Smith, W. G., 1970, Sedimentation in a Malaysian high tide tropical delta: Society of Economic Paleontologists and Mineralogists Special Publication 15, p. 185-197.

Culbertson, W. C., 1964, Geology and coal resources of the coal-bearing rocks of Alabama: U.S. Geological Survey Bulletin 1182-B, 79 p.

Damberger, H. H., Harvey, R. D., Ruch, R. R., and Thomas, J., 1984, Coal characterization, *in* Cooper, B. R., and Ellingson, W. A., eds., The science and technology of coal utilization: Plenum Press, New York, New York, p. 7-45.

Decker, A. D., Klusman, R., and Horner, D. M., 1987, Geochemical techniques applied to the identification and disposal of connate coal water: Tuscaloosa, Alabama, Eastern Region Coalbed Methane Resource Center, Proceedings 1987 Coalbed Methane Symposium, p. 229-242.

Diamond, W. P., Murrie, G. W., and McCulloch, C. M.,1976, Methane gas content of the Mary Lee Group of coalbeds, Jefferson, Tuscaloosa, and Walker counties, Alabama: U.S. Bureau of Mines Report of Investigations 8117, 9 p.

Dyer, K. L., 1982, Stream water quality in the coal region of Alabama and Georgia: U.S. Department of Agriculture General Technical Report NE-73, 109 p.

Engelder, Terry, 1982, Is there a genetic relationship between selected regional joints and contemporary stress within the lithosphere of North America?: Tectonics, v. 1., p. 161-177.

______1985, Loading paths to joint propagation during a tectonic cycle an example from the Appalachian Plateau, U.S.A.: Journal of Structural Geology, v. 7, p. 459-476.

Epsman, M. L., 1987, Subsurface geology of selected oil and gas fields in the Black Warrior basin of Alabama: Geological Survey of Alabama Atlas 21, 255 p.

Epsman, M. L., Moffett, T. B., Hinkle, Frank, Wilson, G. V., and Moore, J. D., 1983, Depths to groundwaters with approximately 10,000 milligrams per liter of total dissolved solids in parts of Alabama: Geological Survey of Alabama Special Map 198.

Epsman, M. L., Wilson, G. V., Pashin, J. C., Tolson, J. S., Ward, W. E., Chandler, R. V., Winston, R. B., Richter, K. E., Hamilton, R. P., and Rheams, L. J., 1988, Geologic evaluation of critical production parameters for coalbed methane resources; part II, Black Warrior basin: Chicago, Illinois Gas Research Institute, Annual Report, Contract no. 5087-214-1544, 178 p.

Fanning, B. J., and Moore, R., 1989. Surface and underground mines producing Alabama coal: Montgomery, Alabama, Alabama Department of Economic and Community Affairs, Division of Science, Technology and Energy, 43 p.

Fieldner, A. C., Cooper, H. M., and Osgood, F. D., 1925, Analyses of mine samples: United States Bureau of Mines Technical Paper 347, p. 12-99.

Ferm, J. C., Ehrlich, R., and Neathery, T. L., 1967, A field guide to Carboniferous detrital rocks in northern Alabama: Geological Society of America, Guidebook, 1967 Coal Division field trip, 101 p.

Fetter, C. W., Jr., 1980, Applied hydrogeology: New York, New York, Charles E. Merrill Publishing Company, 488 p.

Gas Research Institute, 1985, Multiple coal seam project: Chicago, Illinois, Gas Research Institute Quarterly Review Of Methane From Coal Seams Technology, v. 3, no. 2, p. 39-48.

Gas Research Institute, 1989, Rock Creek methane from multiple coal seams completion projects, March 22, 1989: Chicago, Illinois, Gas Research Institute Test Planning Committee meeting report, 76 p.

Geochem Laboratories, 1986, southern overthrust regional studies area II Alabama data shipment Houston, Texas, Geochem Laboratories, unpublished.

Gould, H. R., 1970, The Mississippi Delta complex Society of Economic Paleontologists and Mineralogists Special Publication 15, p. 3-30.

Graham, S. A., Ingersoll, R. V., and Dickinson, W. R., 1976, Common provenance for lithic grains in Carboniferous sandstones from Ouachita Mountains and Black Warrior basin: Journal of Sedimentary Petrology, v. 46, p. 620-632.

Harkins, J. R., and others, 1980, Hydrologic assessment, Eastern Coal Province, Area 23, Alabama: U.S. Geological Survey open-file report 80-683, 76 p.

Heckel, P. H.,1984, Changing concepts of Midcontinent Pennsylvanian cyclothems, North America, *in* Congrés International de Stratigraphie et de Géologie du Carboniferé, 9th, Compte Rendu, Volume 3: Carbondale, Illinois, Southern Illinois University Press, p. 535-553.

Hildick, M. E., 1982, The petrology, rank, and correlation of the Lower Pennsylvanian Blue Creek and Mary Lee coal seams in Jefferson and Walker Counties, Alabama: Auburn, Alabama, Auburn University, unpublished Master's thesis, 162 p.

Hines, R. A., Jr., 1988, Carboniferous evolution of the Black Warrior foreland basin, Alabama and Mississippi: Tuscaloosa, Alabama, The University of Alabama, unpublished Ph.D. dissertation, 231 p.

Hinkle, Frank, 1976, The Pottsville Formation, *in* water content and potential yield of significant aquifers in Alabama: Geological Survey of Alabama open-file report, p. 10-1 - 10-9.

Hobday, D. K., 1974, Beach and barrier island facies in the Upper Carboniferous of northern Alabama: Geological Society of America Special Paper 148, p. 209-224.

Horne, J. C., 1979, The effects of Carboniferous shoreline geometry on paleocurrent distribution, *in* Ferm, J. C., and Horne, J. C., eds., Carboniferous depositional environments in the Appalachian region: Columbia, South Carolina, Carolina Coal Group, University of South Carolina, p. 509-516.

Horne, J. C., Ferm, J. C., Hobday, D. K., and Saxena, R. S., 1976, A field guide to Carboniferous littoral deposits in the Warrior basin: New Orleans, Louisiana, New Orleans Geological Society Guidebook, 80 p.

Horsey, C. A., 1981, Depositional environments of the Pennsylvanian Pottsville Formation in the Black Warrior basin of Alabama: Journal of Sedimentary Petrology, v. 51, p. 799-806.

Jones, J. R., and Cameron, B., 1988, Modern coastal back-barrier environment analog for coal basin or for carbonaceous black shale?: Geology, v. 16, p. 345-348.

Jordan, T. E., 1981, Thrust loads and foreland basin evolution, Cretaceous, western United States: American Association of Petroleum Geologists Bulletin, v. 65, p. 2506-2520.

Jüntgen, H., and Karweil, J., 1966, Gasbildung und Gasspeicherung in Steinkohlenflözen Parts I and II: Erdöl und Kohle, Erdgas Petrochemistrie, v. 19, p. 251-258, 339-344.

Jüntgen, H., and Klein, J., 1975, Entstehung von Erdgas aus kohligen Sedimenten: Erdöl und Kohle, Erdgas Petrochemistrie, Ergängsband 1, p. 52-69.

Kelafant, J. R., Wicks, D. E., and Kuuskraa, V. A., 1987, A geologic assessment of natural gas from coal seams of the northern Appalachian basin: Chicago, Illinois, Gas Research Institute, Topical Report, 88/0039.

Kidd, J. T., 1976, Configuration of the top of the Pottsville Formation in west-central Alabama: Alabama State Oil and Gas Board Map 1.

______1982, Structural Geology of the Black Warrior Basin in Alabama, *in* L. J. Rheams and D. J. Benson, eds., Depositional Setting of the Pottsville Formation in the Black Warrior basin: Tuscaloosa, Alabama, Alabama Geological Society Guidebook, p. 27-33.

Klein, G. deV., 1974, Estimating water depths from analysis of barrier-island and deltaic sequences: Geology, V. 2, p. 409-412.

Klein, G. deV., and Willard, D. A., 1989, Origin of the Pennsylvanian coal-bearing cyclothems of North America: Geology, v. 17, p. 152-155.

Klitgord, K. D., Dillon, W. P., and Popenoe, P., 1983, Mesozoic tectonics of the southeastern United States coastal plain and continental margin: U.S. Geological Survey Professional Paper 1313-P, 15 p.

Lambert, S. W., Beavers, C. D., Dobscher, F. X., Cook, C. O., Lanier, J. B., Saulsberry, J. L., Sheehy, L. D., Spafford, S. O., and Stubbs, P. B., 1988, Rock Creek methane from multiple coal seams completion project: Chicago, Illinois, Gas Research Institute semi-annual report (January 1988-June, 1988), contract no. 5087-214-1457, 366 p.

Langmuir, Donald, 1969, Geochemistry of iron in a coastal plain ground water of the Camden, New Jersey, area: U.S. Geological Survey Professional Paper 650-C, p. 224-235.

Lawrence, A. R., Lloyd, J. W., and Marsh, J. M., 1976, Hydrochemistry and ground water mixing in part of the Lincolnshire Limestone aquifer, England: Ground Water, v. 14, p. 320-327.

Lineback, N. G., Pierce, L. B., and Turnage, N. E., 1974, The map abstract of water resources, Alabama: Geological Survey of Alabama Map Abstract 2, 105 p.

Mack, G. H., Thomas, W. A., and Horsey, C. A., 1983, Composition of Carboniferous sandstones and tectonic framework of southern Appalachian-Ouachita orogen: Journal of Sedimentary Petrology, v. 54, p. 1444-1456.

McCabe, P. J., 1984, Depositional environments of coal and coal-bearing strata, *in* Rahmani, R. A., and Flores, R. M., eds., Sedimentology of coal and coal-bearing sequences: International Association of Sedimentologists Special Publication 7, p. 13-42.

______1987, Facies studies of coal and coal-bearing strata: Geological Society of London Special Publication 32, p. 51-66.

McCalley, Henry, 1900, Report on the Warrior coal basin: Geological Survey of Alabama Special Report 10, 327 p.

McCulloch, C. M., Deul, Maurice, and Jeran, P. W., 1974, Cleat in bituminous coal beds: U.S. Bureau of Mines Report of Investigations 7910, 25 p.

McFall, K. S., Wicks, D. E., and Kuuskraa, V. A., 1986, a geological assessment of natural gas from coal seams in the Warrior basin, Alabama—topical report (September 1985-September 1986):

Washington, D. C., Lewin and Associates, Inc., prepared for Gas Research Institute under contract 5084-214-1066, 80 p.

McKee, C. R., Bumb, A. C., Way, S. C., Koenig, R. A., Reverand, V. M., and Brandenburg, C. F., 1986, Using permeability vs depth correlations to assess the potential for producing gas from coal seams: Chicago, Illinois, Gas Research Institute Quarterly Review of Methane for Coal Seams Technology v. 4, no. 1, p. 15-26.

Metzger, W. J., 1965, Pennsylvanian stratigraphy of the Warrior basin, Alabama: Geological Survey of Alabama Circular 30, 80 p.

Murrie, G. W., Diamond, W. P., and Lambert, S. W., 1976, Geology of the Mary Lee group of coalbeds, Black Warrior coal basin, Alabama: United States Bureau of Mines Report of Investigations 8189, 49 p.

Nickelsen, R. P., and Hough, V. D., 1967, Jointing in the Appalachian Plateau of Pennsylvania: Geological Society of America Bulletin, v. 78, p. 609-630.

Park, D., Sanford, R. L., Simpson, T. A., and Hartman, H. L., 1984, Pillar stability and subsidence study at a deep longwall coal mine: University of Nevada, Reno, Proceedings Generic Minerals Technical Center, Nevada, 2nd Annual Workshop p. 17-50.

Pashin, J. C., and Ettensohn, F. R., 1987, An epeiric shelf-to-basin transition Bedford-Berea sequence, northeastern Kentucky and south-central Ohio: American Journal of Science, v. 287, p. 893-926.

Pashin, J. C., Chandler, R. V., and Mink, R. M., 1989, Geologic controls on occurrence and producibility of coalbed methane, Oak Grove field, Black Warrior basin, Alabama: Tuscaloosa, Alabama, Eastern Region Coalbed Methane Resource Center, Proceedings 1989 Coalbed Methane Symposium, p. 203-209.

Pashin, J. C., and Sarnecki, J. C., 1990, Coal-bearing strata near Oak Grove and Brookwood coalbed methane fields, Black Warrior basin, Alabama: Geological Survey of Alabama, Geological Society of America Annual Meeting, Southeastern Section, Tuscaloosa, Alabama, Guidebook V, 35 p.

Peirce, L. B., 1967, 7-day low flows and flow duration of Alabama streams: Geological Survey of Alabama Bulletin 87, 114 p.

Piper, A. M., 1944, A graphic procedure in the geochemical interpretation of water analyses: American Geophysical Union Transactions, v. 25, p. 914-923.

Potter, P. E., and Pettijohn, F. J., 1977, Paleocurrents and basin analysis: 2nd. ed., Berlin, Springer-Verlag, 425 p.

Quinlan, G. M., and Beaumont, C., 1984, Appalachian thrusting, lithospheric flexure, and the Paleozoic stratigraphy of the eastern interior of North America: Canadian Journal of Earth Sciences, v. 21, p. 973-996.

Raymond, D. E., Rheams, L. J., Osborne, W. E., Gillespie, W. H., and Henry, T. W., 1988, Surface and subsurface mapping for the establishment of a stratigraphic and biostratigraphic framework for the Pennsylvanian section in the Jasper Quadrangle of the Black Warrior basin of Alabama: Geological Survey of Alabama, open-file Report, 427 p.

Rheams, L. J., Barnett, R. L., and Smith, W. E., 1987, Underclays in the southeastern part of the Warrior Coal Field: Geological Survey of Alabama Circular 132, p. 140.

Rice, D. D., Epsman, M. L., and Mancini, E. A., 1989, Origin of conventional and coalbed gases in the Black Warrior basin region, northwestern Alabama: Tuscaloosa, Alabama, Eastern Region Coalbed Methane Resource Center, Proceedings 1989 Coalbed Methane Symposium, p. 321.

Rightmire, C. T., 1984, Coalbed methane resource, *in* Rightmire, C. T., Eddy, G. E., and Kirr, J. N., eds.), Coalbed methane resources in the United States: American Association of Petroleum Geologists Studies in Geology 17, p. 1-13.

Rightmire, C. T., Eddy, G. E., and Kirr, J. N. (eds.), 1984, Coalbed methane resources in the United States: Tulsa, Oklahoma, American Association of Petroleum Geologists Studies in Geology 17, 378 p.

Robertson Research (U.S.) Inc., 1985, Oil Generation in Black Warrior Basin Alabama, a geochemical study: Kingwood, Texas, Robertson Research (U.S.), Inc., California, 328 p.

Rohlf, F. J., and Sokal, R. R., 1969, Statistical tables: San Francisco, W.H Freeman, 253 p.

Semmes, D. R., 1920, Petroleum possibilities of Alabama, Part I, Northern Alabama: Geological Survey of Alabama Bulletin 22, p. 46-120.

______1929, Oil and gas in Alabama: Geological Survey of Alabama Special Report 15, 408 p.

Sestak, H. M., 1984, Stratigraphy and depositional environments of the Pennsylvanian Pottsville Formation in the Black Warrior basin Alabama and Mississippi: Tuscaloosa, Alabama, The University of Alabama, unpublished Master's thesis, 184 p.

Sexton, T. A., and Hinkle, Frank, 1985, Alabama's coalbed gas industry Alabama: State Oil and Gas Board Report 8B, 31 p.

Shadroui, J. M., 1986, Depositional environments of the Pennsylvanian Bremen Sandstone Member and associated strata, Pottsville Formation, north-central Alabama: Tuscaloosa, Alabama, The University of Alabama, unpublished Master's thesis, 172 p.

Shotts, R. Q., 1956, A compilation of complete analyses of Alabama coals published since 1925, Warrior and Plateau fields: Alabama State Mine Experiment Station Bulletin 6, 31 p.

______1960, Coal analyses made at the Alabama State Mine Experiment Station, 1944-60, and some other unpublished analyses: Alabama State Mine Experiment Station Bulletin 7, 39 p.

Skougstad, M. W., Fishman, M. J., Friedman, L. C., Erdmann, D. E., and Duncan, S. S., 1979, Techniques of water-resources investigation of the United States Geological Survey, methods for determination of inorganic substances in water and fluvial sediments: Washington, D.C., U.S. Govt. Printing Office, Book 5, Chapter A1, 626 p.

Stach, E., Mackowsky, M.-Th., Teichmüller, M. Taylor, G. H., Chandra, D., and, Teichmüller, R., 1982, Stach's textbook of coal petrology: 3rd edition, Berlin, Gebrüder Borntraeger, 535 pp.

Stephenson, L. W., 1926, The Mesozoic rocks, *in* Adams, G. I., Butts, C., Stephenson, L. W., and Cooke, W., Geology of Alabama: Alabama Geological Survey Special Report 14, p. 231-250.

Stiff, H.A., Jr., 1951, The interpretation of chemical water analysis by means of pattern: American Institute of Mining, Metallurgical and Petroleum Engineers Transactions, v. 192, p. 376-378.

Swenson, H. A., and Baldwin, H. L., 1965, A primer on water quality: Washington, U.S. Government Printing Office, 27 p.

Szabo, M. W., Osborne, W. E., Copeland, C. W., Jr., and Neathery, T. L, 1988, Geologic map of Alabama: Geological Survey of Alabama Special Map 220, scale 1 250,000.

Telle, W. R., Thompson, D. A., Lottman, L. K., and Malone, P. G., 1987, Preliminary burial - thermal history investigations of the Black Warrior Basin: implications for coalbed methane and conventional hydrocarbon development: Tuscaloosa, Alabama, Eastern Region Coalbed Methane Resource Center, Proceedings 1987 Coalbed Methane Symposium.

Thomas, W. A., 1973, Southwestern Appalachian structural system beneath the Gulf Coastal Plain: American Journal of Science, v. 273-A, p. 372-390.

______1985, The Appalachian-Ouachita connection Paleozoic orogenic belt at the southern margin of North America: Annual Review of Earth and Planetary Sciences, v. 13, p. 175-199.

______1988a, The Black Warrior basin, *in* Sloss, L. L., ed., Sedimentary cover North American craton: Geological Society of America, The Geology of North America, v. D-2, p. 471-492.

______1988b., Early Mesozoic faults of the northern Gulf Coastal Plain in the context of opening of the Atlantic Ocean, *in* Manspeizer, W., ed., Triassic-Jurassic Rifting: New York, New York, Elsevier, p. 463-476.

Thomas, W.A., and Bearce, D. N., 1986, Birmingham anticlinorium in the Appalachian fold-thrust belt, basement fault system, synsedimentary structure, and thrust ramp: Centennial Field Guide, Southeastern Section of the Geological Society of America, v. 6, p. 191-200.

Thomas, W. A., and Womack, S. H., 1983, Coal stratigraphy of the deeper part of the Black Warrior basin in Alabama: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 439-446.

Thompson, D. A., and Telle, W. A., 1987, Coalbed methane in the Black Warrior basin, Alabama—Geology, resources, and development: Chicago, Illinois, Gas Research Institute, Quarterly Review of Methane from Coal Seams Technology, v. 4, no. 3, p. 2-18.

Tucker, W. E., and Kidd, R. E., 1973, Deep-well disposal in Alabama: Alabama Geological Survey Bulletin 104, 230 p.

Udden, J. A., 1912, Geology and mineral resources of the Peoria quadrangle, Illinois: U.S. Geological Survey Bulletin 506, p. 1-103.

U.S. Environmental Protection Agency, 1979, Methods for chemical analysis of water and wastes: Cincinnati, Ohio, Environmental Monitoring and Support Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, EPA-600-4-79-020, 430 p.

Ward, W. E., II, 1977, Jointing in a selected area of the Warrior coal field: Tuscaloosa, Alabama, The University of Alabama, unpublished Master's thesis, 61 p.

______1984, Reserve base of bituminous coal and lignite in Alabama: Geological Survey of Alabama Circular 118, 102 p.

Ward, W. E., II, Drahovzal, J. A., and Evans, F. E., Jr., 1984, Fracture analyses in a selected area of the Warrior coal basin, Alabama: Geological Survey of Alabama Circular 111, 78 p.

Ward, W. E., II, Barnett, R. L., and Rheams, L. J., 1989, Coal resources of Walker County, Alabama: Geological Survey of Alabama Special Map 205, in press.

Weisenfluh, G. A., 1979, The Warrior basin, *in* Ferm, J. C., and Horne, J. C., eds., Carboniferous depositional environments in the Appalachian region: Columbia, South Carolina, Carolina Coal Group, University of South Carolina, p. 518-529.

Weisenfluh, G. A., and Ferm, J. C., 1984, Geologic controls on deposition of the Pratt seam, Black Warrior basin, Alabama, U.S. A., *in* Rahmani, R. A., and Flores, R. M., eds., Sedimentology of coal and coal-bearing sequences: International Association of Sedimentologists Special Publication 7, p. 317-330.

Weller, Stuart, 1930, Cyclic sedimentation of the Pennsylvanian Period and its significance: Journal of Geology, v. 38, p. 97-135.

Williams, E. G., and Keith, M. L., 1963, Relationship between sulfur in coals and the occurrence of marine roof beds: Economic Geology, v. 58, p. 720-729.

Wyman, R. E., 1984, Gas resources in Elmworth coal seams, *in* Masters, J. A. (ed.), Elmworth-case study of a deep basin gas field: American Association of Petroleum Geologists Memoir 38, p. 173-187.