

**GEOLOGIC SCREENING CRITERIA FOR SEQUESTRATION OF  
CO<sub>2</sub> IN COAL: QUANTIFYING POTENTIAL OF THE BLACK WARRIOR  
COALBED METHANE FAIRWAY, ALABAMA**

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## ABSTRACT

Sequestration of CO<sub>2</sub> in coal has potential to reduce greenhouse gas emissions from coal-fired power plants while enhancing coalbed methane recovery. Data from more than 4,000 coalbed methane wells in the Black Warrior basin of Alabama provide an opportunity to quantify the carbon sequestration potential of coal and to develop a geologic screening model for the application of carbon sequestration technology. This report summarizes stratigraphy and sedimentation, structural geology, geothermics, hydrology, coal quality, gas capacity, and production characteristics of coal in the Black Warrior coalbed methane fairway and the implications of geology for carbon sequestration and enhanced coalbed methane recovery.

Coal in the Black Warrior basin is distributed among several fluvial-deltaic coal zones in the Lower Pennsylvanian Pottsville Formation. Most coal zones contain one to three coal beds that are significant targets for coalbed methane production and carbon sequestration, and net coal thickness generally increases southeastward. Pottsville strata have effectively no matrix permeability to water, so virtually all flow is through natural fractures. Faults and folds influence the abundance and openness of fractures and, hence, the performance of coalbed methane wells.

Water chemistry in the Pottsville Formation ranges from fresh to saline, and zones with TDS content lower than 10,000 mg/L can be classified as USDW. An aquifer exemption facilitating enhanced recovery in USDW can be obtained where TDS content is higher than 3,000 mg/L. Carbon dioxide becomes a supercritical fluid above a temperature of 88°F and a pressure of

1,074 psi. Reservoir temperature exceeds 88°F in much of the study area. Hydrostatic pressure gradients range from normal to extremely underpressured. A large area of underpressure is developed around closely spaced longwall coal mines, and areas of natural underpressure are distributed among the coalbed methane fields. The mobility and reactivity of supercritical CO<sub>2</sub> in coal-bearing strata is unknown, and potential exists for supercritical conditions to develop below a depth of 2,480 feet following abandonment of the coalbed methane fields.

High-pressure adsorption isotherms confirm that coal sorbs approximately twice as much CO<sub>2</sub> as CH<sub>4</sub> and approximately four times as much CO<sub>2</sub> as N<sub>2</sub>. Analysis of isotherm data reveals that the sorption performance of each gas can vary by a factor of two depending on rank and ash content. Gas content data exhibit extreme vertical and lateral variability that is the product of a complex burial history involving an early phase of thermogenic gas generation and an ongoing stage of late biogenic gas generation.

Production characteristics of coalbed methane wells are helpful for identifying areas that are candidates for carbon sequestration and enhanced coalbed methane recovery. Many geologic and engineering factors, including well construction, well spacing, and regional structure influence well performance. Close fault spacing limits areas where five-spot patterns may be developed for enhanced gas recovery, but large structural panels lacking normal faults are in several gas fields and can be given priority as areas to demonstrate and commercialize carbon sequestration technology in coalbed methane reservoirs.

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## INTRODUCTION

The amount of carbon dioxide (CO<sub>2</sub>) in the earth's atmosphere has risen from pre-industrial levels of 280 parts per million (ppm) to more than 365 ppm, and most of this increase has been within the last 60 years (Keeling and Whorf, 1998). This increase is attributed widely to the burning of fossil fuels, and if current trends in resource utilization continue, anthropogenic CO<sub>2</sub> emissions will triple during the 21<sup>st</sup> Century (IPCC, 1996). Recognizing the potential of global warming related to increased greenhouse gas emissions, the U.S. Department of Energy is seeking ways to offset industrial CO<sub>2</sub> emissions. Among the principal ways CO<sub>2</sub> emissions may be reduced is by sequestration in geologic formations, including coal. Coal is an especially attractive target for sequestration not only because it can store large quantities of gas, but because CO<sub>2</sub> can be used to enhance recovery of coalbed methane, thereby offsetting the costs associated with sequestration of CO<sub>2</sub> (Byrer and Guthrie, 1999; Gentzis, 2000; Hamelinck and others, 2001).

In a discussion of the state of carbon sequestration science, Reichle and others (1999) expressed the need for studies assessing the sequestration capacity of geologic formations and developing screening criteria for the demonstration and commercialization of CO<sub>2</sub> sequestration technology. In response to this and other needs articulated by Reichle and others (1999), the Geological Survey of Alabama, in partnership with the University of Alabama, Alabama Power Company, and Jim Walter Resources, Incorporated, is conducting a three-year study that assesses the CO<sub>2</sub> sequestration potential of coalbed methane reservoirs in the Black Warrior

basin (fig. 1) and develops geologic screening criteria that can be used to evaluate sedimentary basins and select sites for the demonstration and commercialization of sequestration technology.

The objectives of this study are (1) to develop a geologic screening model that is widely applicable, (2) to quantify the CO<sub>2</sub> sequestration potential of the coalbed methane fairway in the Black Warrior basin of Alabama, and (3) to apply the screening model to identify sites favorable for demonstration of enhanced coalbed methane recovery and mass sequestration of CO<sub>2</sub> emitted from coal-fired power plants. The coalbed methane fairway of the Black Warrior basin (fig. 1) is a logical location to develop screening criteria and procedures from numerous standpoints.

According to the U.S. Environmental Protection Agency, Alabama ranks 9<sup>th</sup> nationally in CO<sub>2</sub> emissions from power plants, and two coal-fired power plants are within the coalbed methane fairway (fig. 1). More than 1.2 Tcf (trillion cubic feet) of coalbed methane have been produced from the Black Warrior basin, which ranks second globally in cumulative coalbed methane production. Production is now leveling off, and enhanced coalbed methane recovery through carbon sequestration has the potential to offset impending decline and extend the life and geographic extent of the fairway far beyond current projections. Based on a preliminary assessment of sequestration potential in the Pottsville Formation of the Black Warrior basin, Pashin and others (2001a, b) indicated that, at current rates of emission, potential exists for sequestration of 35 to 72 years of emissions from coal-fired power plants adjacent to the Black Warrior coalbed methane fairway that serve the Birmingham and Tuscaloosa metropolitan areas. This number is promising, but Pashin and others pointed out that a more realistic appraisal

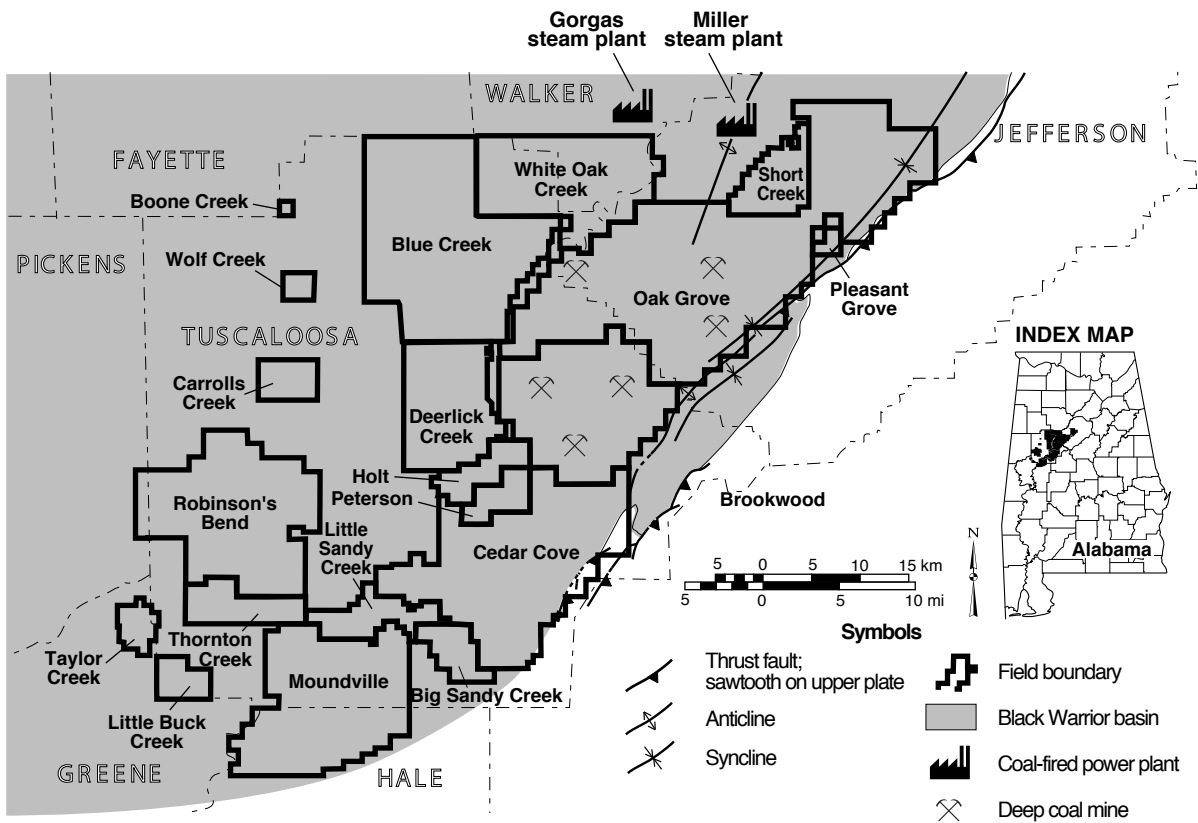


Figure 1.—Coalbed methane fields, coal-fired power plants, and deep underground coal mines in the Black Warrior basin of west-central Alabama (modified from Pashin and others, 2001a, b).

integrating the complexities and constraints imposed by geology, technology, and infrastructure is required to develop a plan for carbon sequestration and enhanced coalbed methane recovery in the Black Warrior basin.

The diverse depositional and structural styles in the Pottsville Formation of the Black Warrior basin have been central in the development of geologic models for Carboniferous coal-bearing strata (e.g., Thomas, 1988; Ferm and Weisenfluh, 1989; Gastaldo and others, 1993; Pashin and Groshong, 1998), which constitute nearly all the economic coal resources in the highly industrialized regions of eastern North America and Europe (Landis and Weaver, 1993; Bibler and others, 1998). For sequestration in coal to have a meaningful impact on greenhouse gas emissions, screening models and technologies must be tailored to take advantage of the numerous thin (< 6 ft), geometrically complex coal seams that abound in these areas. The Black Warrior basin is the most attractive of the Carboniferous coal basins for this purpose, because geologic data from more than 4,000 coalbed methane wells and exploration cores provide a unique, unparalleled database that is essential for developing screening models and quantifying sequestration potential (fig. 2).

Experience from more than 25 years of coalbed methane development in Alabama facilitates identification of screening criteria for sequestration of CO<sub>2</sub> in coal, because the geologic variables that determine the distribution and producibility of coalbed methane also influence sequestration capacity (fig. 3). Accordingly, the methods employed in our research draw heavily on the time-tested techniques used to evaluate coalbed methane reservoirs (e.g., Elder and Deul,

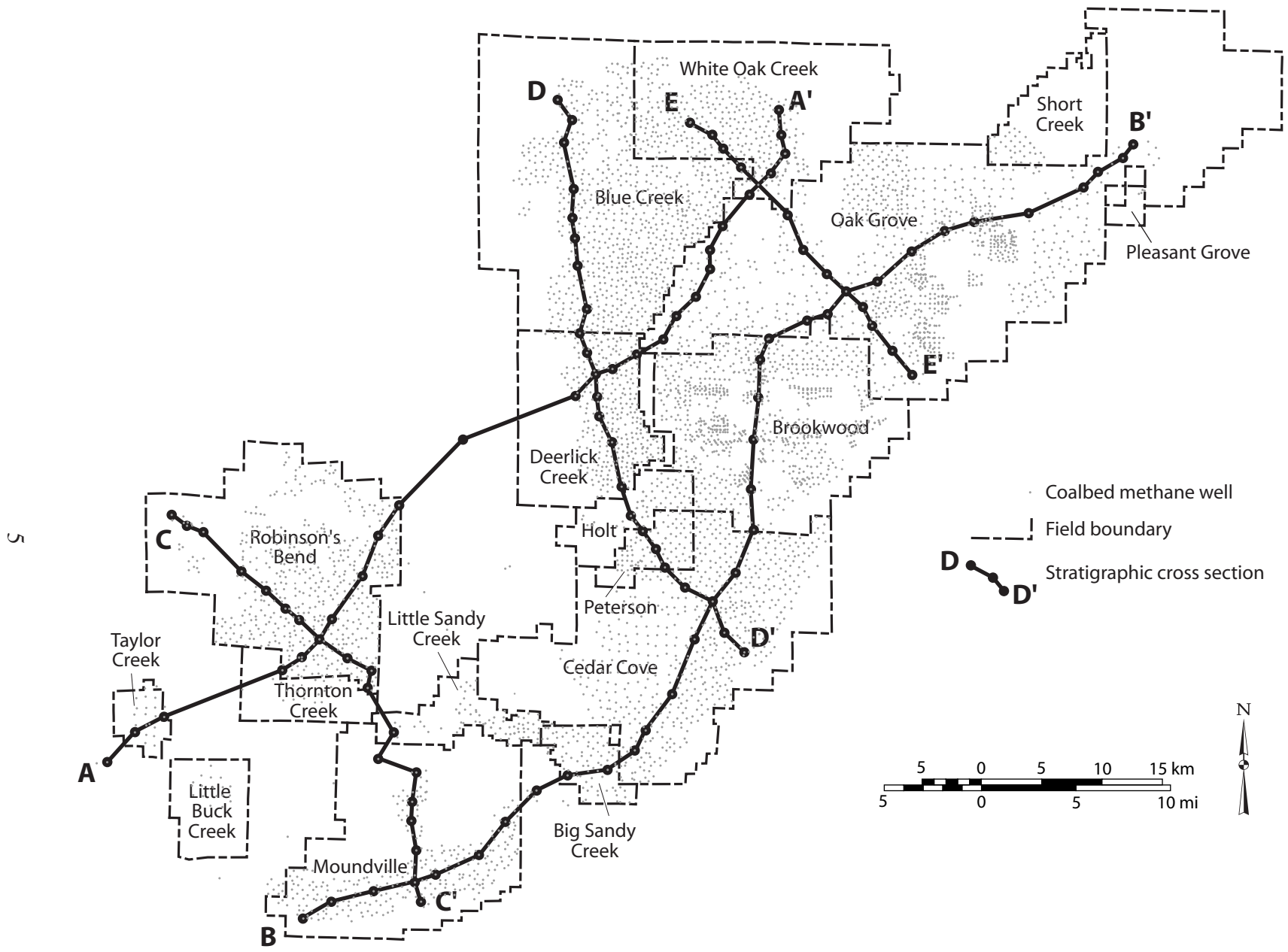


Figure 2.--Well control in the Black Warrior coalbed methane fairway and locations of stratigraphic cross sections (plates 1-8).

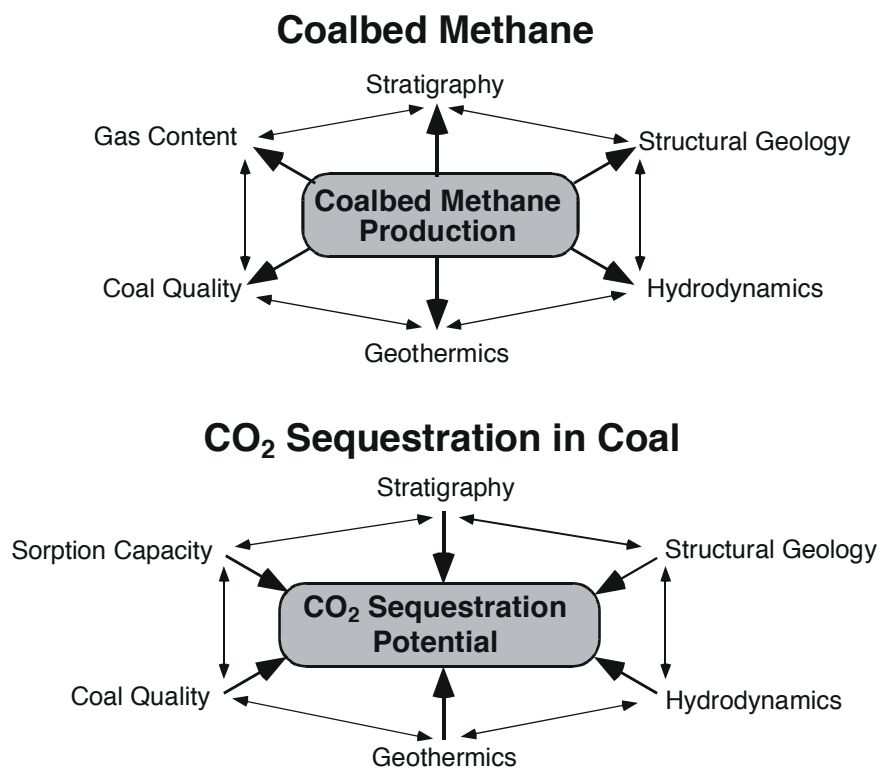


Figure 3.--Geologic factors affecting coalbed methane production and carbon sequestration in coal (modified from Pashin and others, 2001a, b).

1974; Pashin and others, 1991; Ayers and Kaiser, 1994; Kaiser and others, 1994). This report synthesizes results of the second year of our research, which focused on acquisition and interpretation of basic geologic data and is proceeding according to schedule. All data acquisition tasks are still in progress, but enough data have been collected to facilitate a preliminary characterization of stratigraphy, structural geology, hydrodynamics, geothermics, coal quality, and sorption capacity. This characterization is helping guide the project by identifying the strengths and pitfalls associated with each geologic screening criterion. We have also initiated a vigorous technology transfer program, which includes assembly of a project advisory committee, development of a project web page, publication of technical reports, and presentations at technical meetings.



## **EXECUTIVE SUMMARY**

Sequestration of CO<sub>2</sub> in coal has potential benefits for reducing greenhouse gas emissions from the highly industrialized Carboniferous coal basins of North America and Europe and for enhancing coalbed methane recovery. Hence, enhanced coalbed methane recovery operations provide a basis for a market-based environmental solution in which the cost of sequestration is offset by the production and sale of natural gas. The Black Warrior foreland basin of west-central Alabama contains the only mature coalbed methane production fairway in eastern North America, and data from this basin provide an excellent basis for quantifying the carbon sequestration potential of coal and for identifying the geologic screening criteria required to select sites for the demonstration and commercialization of carbon sequestration technology.

The Geological Survey of Alabama, in partnership with the University of Alabama, Jim Walter Resources, Incorporated, and Southern Company, has undertaken an intensive 3-year investigation aimed at quantifying the carbon sequestration potential of the Black Warrior coalbed methane fairway and developing a geologic screening model that is broadly applicable. This report summarizes results of the second year of this investigation, which has focused on geologic characterization. Key geologic variables analyzed include stratigraphy, structural geology, geothermics, hydrology, coal petrology, and production data.

Coalbed methane resources in the Black Warrior basin are distributed among multiple coal zones in the upper part of the Pottsville Formation (Lower Pennsylvanian). Pottsville coal zones are a series of fluvial-deltaic depositional cycles that are bounded by regionally extensive

flooding surfaces. Net coal thickness generally increases southeastward, and the greatest sequestration potential appears to be in the Black Creek, Mary Lee, Pratt, and Gwin coal zones. Most coal zones contain one to three coal beds thicker than 1 foot that are significant targets for coalbed methane production and carbon sequestration. Consequently, coalbed methane operations have relied heavily on the application of multi-seam completion technology, and similar approaches will be required for carbon sequestration.

Pottsville strata have effectively no matrix permeability to water, so virtually all flow is through natural fractures. Faults and folds of extensional and compressional origin influence the abundance and openness of natural fractures, and hence, the performance of coalbed methane wells. The Black Warrior coalbed methane fairway can be characterized as a southwest-dipping homocline that is broken by normal faults. Near the southeast margin of the coalbed methane fairway, frontal folds of the Appalachian thrust belt are superimposed on the faulted homocline. Fault-related fractures have significantly greater kinematic aperture than joints and have a much greater tendency to cut across bedding than other natural fractures in the Pottsville Formation. Therefore, fault zones constitute the most likely avenues along which injected CO<sub>2</sub> can leak from coal into the country rock or to the surface.

Temperature-pressure conditions have a strong influence on the carbon sequestration potential of coalbed methane reservoirs in the Black Warrior basin, because CO<sub>2</sub> becomes a supercritical fluid above a temperature of 88°F and a pressure of 1,074 psi. Under supercritical conditions, coal can contain more gas than is predicted by Langmuir adsorption theory, but the

mobility and reactivity of supercritical fluids in coal-bearing strata are poorly understood. The mean geothermal gradient in the coalbed methane fairway is about 9°F/1,000 feet, and reservoir temperature exceeds 88°F in much of the study area. Regional mapping indicates that localized areas of abnormally high reservoir temperature are superimposed on a southwest trend of increasing temperature that reflects the shape of the southwest-dipping homocline.

Water in the Pottsville Formation ranges from fresh to saline, and the coalbed methane reservoirs can be classified as USDW (TDS content <10,000 mg/L) in much of the production fairway. Fresh-water plumes formed by meteoric recharge of upturned strata along the southeast margin of the Black Warrior basin contain water with TDS content of less than 3,000 mg/L. In areas where producing reservoirs can be classified as USDW, enhanced coalbed methane recovery efforts will require an aquifer exemption to comply with Class II UIC requirements. However, where TDS content is less than 3,000 mg/L, this exemption is prohibited.

Hydrostatic pressure gradients range from normal (0.43 psi/ft) to extremely underpressured (0.05 psi/ft) and have a bipolar distribution in the Pottsville Formation. Normal to moderate underpressure is typical of most areas, and a large area of underpressure is developed around closely spaced longwall coal mines. However, other areas of underpressure are distributed among several coalbed methane fields and appear to be natural. Although dewatering related to mining and coalbed methane operations has given rise to subcritical reservoir conditions throughout the fairway, potential exists for supercritical conditions to develop as the hydrologic system equilibrates following the abandonment of the mines and gas fields. No potential for

supercritical conditions exists within coalbed methane reservoirs in the northern part of the coalbed methane fairway, whereas in the southwestern coalbed methane fields, potential exists for supercritical reservoir conditions to develop throughout this interval.

Coal quality parameters have a strong influence on the ability of coal to sorb gas. Rank in the coalbed methane fields ranges from high volatile B bituminous to low volatile bituminous, and virtually all coalbed methane production is from coal of high volatile A or higher rank. Mineral matter has minimal sorption capacity compared to the organic constituents of coal, and in the Pottsville Formation, ash is dominated by clay, quartz, and pyrite. High-pressure adsorption isotherms for CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub> confirm that coal sorbs approximately twice as much CO<sub>2</sub> as CH<sub>4</sub> and approximately four times as much CO<sub>2</sub> as N<sub>2</sub>. Comparison of isotherms reveals, however, that the sorption performance of coal for each gas can vary by a factor of two depending on coal quality.

Gas content data were compiled from numerous sources and exhibit extreme vertical and lateral variability that must be accounted for when assessing the potential for enhanced coalbed methane recovery. This variability is interpreted as the product of a complex burial history that involved thermogenic gas generation coincident with foreland basin subsidence and the early stages of post-orogenic unroofing. As the basin cooled during the late stages of unroofing, however, coal apparently became undersaturated with gas. However, development of a fresh-water recharge zone along the southeast margin of the basin has apparently facilitated late-stage

biogenic gas generation that has resulted locally in effectively complete isothermal methane saturation.

Production characteristics of coalbed methane wells are helpful for identifying areas that are candidates for carbon sequestration and enhanced coalbed methane recovery and for selecting which wells should be converted into injectors. Gas production from vertical wells typically exhibits exponential decline, whereas water production typically exhibits hyperbolic decline. Mapping peak and cumulative production indicates that many geologic and engineering factors, including well construction, well spacing, and regional structure influence well performance. Production patterns are affected significantly by extensional faults and fault-related folds and by compressional fold hinges. Close fault spacing limits areas where five-spot patterns may be developed for enhanced gas recovery, but large structural panels lacking normal faults are in several gas fields and can be given priority as areas to demonstrate and commercialize carbon sequestration technology in coalbed methane reservoirs.

The project team is conducting a vigorous technology transfer program, which includes assembly of a project advisory committee, development of a project web page, publication of technical reports, and presentations at technical meetings. The project is proceeding according to schedule and budget and work during the final year of this program is expected to continue according to plan. Next year's effort will focus on volumetric analysis of sequestration and enhanced recovery potential and development of a geologic screening model for carbon sequestration and enhanced coalbed methane recovery.

## EXPERIMENTAL

Information collected to evaluate the carbon sequestration potential of the Black Warrior coalbed methane fairway and develop geologic screening criteria includes stratigraphic, structural, geothermal, and hydrologic data. These data were collected from geophysical well logs available at the State Oil and Gas Board of Alabama. All wells in this report are identified by State Oil and Gas Board of Alabama permit numbers. Geological and engineering parameters are reported in a combination of linear and metric units, especially in geophysical well logs, and to ensure uniformity with previous investigations of the coalbed methane fairway, the units used in this report are those routinely used by operators and other stakeholders in the region. Coal quality data were compiled from the databases of the Geological Survey of Alabama, and new data were derived through analysis of cores and mine faces. To assess sequestration capacity, sorption isotherms for carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrogen (N<sub>2</sub>) were being run from coal samples throughout the coalbed methane fairway. Gas- and water-production data were derived from the databases of the State Oil and Gas Board of Alabama.

To determine the stratigraphic and structural architecture of the coalbed methane fairway, gamma-density logs were correlated along five lines of cross section spanning the coalbed methane fairway (fig. 2). These logs were used to identify regionally correlable stratigraphic markers and to determine the geometry and extent of the coal beds that constitute potential sequestration targets. Faults were also identified as wells were correlated. Normal faults were identified on the basis of missing section, whereas reverse faults were identified on the basis of

repeated section. After wells on the lines of cross section were correlated, one well per township section was correlated to develop a regional network of reference wells, and in turn, all wells were correlated to the reference wells.

Next, a series of stratigraphic cross sections was constructed showing the stratigraphic architecture of the target coal zones (plates 1-10). These cross sections depict gamma-density logs, major depositional cycles, subordinate parasequences, coal beds, and major sandstone units. Coal beds and associated organic-rich shale beds were classified according to thickness and density-log signature into primary resource targets, secondary resource targets, and thin marker beds. Primary resource targets are coal beds thicker than 2 feet and typically have a blocky log signature, whereas secondary resource targets are between 1 and 2 feet thick and log as a sharp spike reaching a recorded density of less than 1.5 g/cc (grams per cubic centimeter). Thin marker beds include coal and associated organic shale markers that are thinner than 1 foot and are too thin for the logging tool to record a density as low as 1.5 g/cc. After the coal beds were correlated, parasequences subordinate to the major depositional cycles were defined by correlating regionally extensive shale and coal markers. As the parasequences were defined, coal zones were subdivided into a series of subzones to facilitate identification and characterization of the major target coal beds.

To facilitate subsurface mapping, stratigraphic, structural, and well-location data from 4,998 wells were compiled into a spreadsheet. Well locations were computed from surveyed line calls on file at the State Oil and Gas Board of Alabama using the Wellbase module of the Geographix

Exploration System. Stratigraphic data include the depth of each cycle boundary and net coal thickness in each coal zone. Coal thickness was determined using high-resolution density logs, which typically have a scale of 1 inch equals 25 feet. Depending on the logging tool and recording apparatus, the accuracy of these logs ranges from 0.1 to 0.5 foot. Coal beds thinner than 1 foot are seldom completed for gas production and were thus excluded from the thickness determination to provide a reliable approximation of the quantity of coal available for sequestration. Structural data include bed elevation and fault-cut information. The elevation of each cycle boundary was computed by subtracting depth from the appropriate structural datum, which for coalbed methane wells is typically ground level or the elevation of the kelly bushing. The depth, elevation, and vertical separation of each fault cut identified was determined and compiled. Vertical separation was determined by the thickness of missing or repeated section. The uncertainty in the location of each fault cut was quantified, and the juxtaposed coal zones were identified and recorded.

Maps of coal thickness and geologic structure were made using Geographix Exploration System software. Maps were gridded and contoured using a minimum curvature algorithm in the Isomap module of Geographix. The map grids comprise 401 columns by 322 rows and have a cell size of 820 feet (about 15 acres), which provides the high resolution required to ensure that well data are honored. Net coal isolith maps for each target coal zone were made using a contour interval of 1 foot. A structural contour map of the top of the Pratt coal zone was made using a contour interval of 100 feet. Fault-cut information was used to determine bed-fault intersections,



but where well control is inadequate, fault and fold traces were compiled from the records of the Geological Survey of Alabama and the exhibits of the State Oil and Gas Board of Alabama.

To facilitate visualization of geologic structure, 3-D structural models of the coalbed methane fields have been constructed. In this report, a provisional 3-D model of Cedar Cove and Peterson fields is presented. Modeling faults is the most time-consuming aspect of well-based 3-D structural interpretation because most faults are undersampled. Model construction begins by importing and contouring a cycle boundary. Next, fault cuts are imported, and preliminary fault cut correlations are made based on trend. Where three or more fault cuts can be assigned to the same fault, the fault surface is contoured and extrapolated from just above the ground surface to an elevation of -3,000 ft. The lateral extent of the fault is based on a preliminary estimate of the length over which the cycle top shows an elevation change consistent with the fault dip. If less than three fault cuts are available for a fault, a plane of strike, dip, and extent consistent with fault relationships in the area is constructed and inserted into the model.

Locations of faulted wells, elevation changes of the cycle tops, and anomalous cycle thickness changes are all used in finding and extrapolating faults. Coal-zone thickness is generally consistent within a township, and local thickness anomalies generally indicate fault cuts. Once a fault plane has been placed into the interpretation, the map of the cycle boundary is cut along the fault trace so that it is no longer continuous across the fault. The cycle top is then extrapolated into a new intersection with the fault plane. The extrapolation of a cycle top to the fault is done with a projection tool in 3DMove, but the model typically must be conditioned so

that only one side at a time will be projected. Bedding cutoff lines are grouped with the other points on the cycle top and the surface is recontoured to form horizons that join perfectly with the fault. The contoured cycle surface is then adjusted to ensure agreement with the stratigraphic separations recorded in well logs. This process is repeated for every cycle top and for every fault to build the interpretation. The final stage of interpretation is to make numerous cross sections and check that all cycle variations are geologically realistic, again adjusting the interpretation if required. As the structural contour maps and 3-D interpretations are developed, new faults are found, and old faults may be moved or re-sized. Consequently, numerous iterations can be involved. The current maps represent an early stage of the 3-D interpretation process and so are likely to be revised in future reports.

Geothermic and hydrologic information required to determine temperature-pressure conditions in the coalbed methane fairway were obtained from geophysical well logs and compiled in a spreadsheet with the stratigraphic and structural data. Geothermic information was determined from bottom-hole temperatures recorded in the headers of well logs. The geothermal gradient for each well was determined by dividing the difference between average ground temperature (74°F) and bottom-hole temperature by total well depth. Wells penetrating units below the Pottsville Formation were excluded from evaluation, because high geothermal gradients in Cambrian-Mississippian carbonate rocks are not representative of the less thermally conductive, shale-rich Pottsville Formation. Extreme care was taken to eliminate anomalously low bottom-hole temperature readings on the bases of insufficient circulation time (less than 6

hours) and unrealistically low geothermal gradient (less than 6.0°F per 1,000 feet). The geothermal data population was then analyzed statistically, and contour maps of geothermal gradient and the temperature of the top of the Pratt coal zone were made using Isomap.

Minimum reservoir pressure was determined from well depth and water-level information recorded in the headers of well logs or interpreted from resistivity profiles. Fresh water exists at depth throughout much of the coalbed methane fairway (Pashin and others, 1991; Ellard and others, 1992), so reservoir pressure was estimated using a fresh-water hydrostatic gradient of 0.433 psi/ft (pounds per square inch per foot). Once data were compiled, the hydrostatic pressure gradient for each well and the pressure at the top of the Pratt coal zone were computed. The pressure-gradient population was analyzed statistically, and histograms and pressure-depth plots were made. Next, maps of hydrostatic pressure gradient and pressure at the top of the Pratt coal zone were mapped in Isomap using the same general gridding and contouring parameters discussed earlier.

Coal quality parameters, including rank and grade, may have a strong impact on the carbon sequestration capacity of coal-bearing strata. Rank and grade data were compiled from the databases of the Geological Survey of Alabama and U.S. Geological Survey (Bragg and others, 1998) and were augmented by new analyses of samples collected during this study. Coal rank was determined using volatile matter data (dry, mineral matter-free) and vitrinite reflectance data (mean-maximum reflectance in oil). To make a contour map of coal rank of the Mary Lee coal zone in the coalbed methane fairway, vitrinite reflectance values were converted to equivalent

Table 1. Locality and stratigraphic information for coal samples analyzed during this project.

Sample number	Thickness (in)	Coal zone	Coal Bed	Latitude	Longitude
AL-CU-TP1-2.0	21.0	Black Creek	Black Creek	33.89367	-87.03267
AL-JE-BCCFT-1.0	16.0	Pratt	Nickel Plate	33.58823	-87.06528
AL-JE-BCCFT-2.0	16.0	Curry	Curry	33.58823	-87.06528
AL-JE-MRM-1.0	16.0	Black Creek	Jefferson	33.75413	-86.91369
AL-JE-SCCH-0215.3	9.5	Gwin	Gwin	33.52520	-87.03282
AL-JE-TPLM-1.0	30.0	Mary Lee	Mary Lee	33.68605	-86.99623
AL-MA-LM1-1.0	8.0	Mary Lee	Blue Creek	33.93412	-87.66325
AL-MA-LM2-1.0	11.0	Mary Lee	Jagger	33.93652	-87.66788
AL-MA-MB2-1.0	10.0	Black Creek	Black Creek	34.07937	-87.74402
AL-TU-BWFM-1.0	15.0	Brookwood	Carter	33.22552	-87.41145
AL-TU-EPBC-1131.2	24.2	Pratt	□	33.42799	-87.51589
AL-TU-EPBC-1690.2	22.4	Mary Lee	□	33.42799	-87.51589
AL-TU-EPBC-2051.2	12.8	Black Creek	□	33.42799	-87.51589
AL-TU-JWR41-1.0	20.0	Mary Lee	Mary Lee	33.35614	-87.37737
AL-TU-JWR41-2.0	56.0	Mary Lee	Blue Creek	33.35614	-87.37737
AL-TU-JWR626-1400.0	32.5	Pratt	□	33.31167	-87.28118
AL-TU-JWR626-1947.5	23.0	Mary Lee	New Castle	33.31167	-87.28118
AL-TU-JWR628-2105.0	34.0	Mary Lee	Jagger	33.28205	-87.25115
AL-TU-JWR629-1695.1	21.0	Mary Lee	New Castle	33.35853	-87.25335
AL-TU-JWR630-0636.7	24.5	Gwin	Gwin	33.28477	-87.24127
AL-TU-JWR632-0986.9	22.0	Pratt	□	33.36762	-87.27253
AL-TU-JWR633-0613.7	20.0	Gwin	Gwin	33.29960	-87.26770
AL-TU-JWR633-1285.0	17.5	Pratt	□	33.29960	-87.26770
AL-TU-JWR633-1295.0	14.5	Pratt	□	33.29960	-87.26770
AL-TU-JWR633-1330.0	22.5	Pratt	□	33.29960	-87.26770
AL-TU-JWR633-1411.5	27.0	Pratt	□	33.29960	-87.26770
AL-TU-JWR633-1958.4	22.0	Mary Lee	New Castle	33.29960	-87.26770
AL-TU-JWR633-2041.0	25.5	Mary Lee	Jagger	33.29960	-87.26770
AL-TU-JWR638-0937.3	13.0	Cobb	Cobb	33.28377	-87.25077
AL-TU-JWR638-1406.8	11.0	Pratt	□	33.28377	-87.25077
AL-TU-JWR638-2104.0	27.0	Mary Lee	Jagger	33.28377	-87.25077
AL-TU-JWR639-2346.2	23.0	Black Creek	Black Creek	33.35645	-87.34957
AL-TU-JWR640-0688.8	36.0	Gwin	Gwin	33.28455	-87.25008
AL-TU-JWR640-1402.5	21.0	Pratt	□	33.28455	-87.25008
AL-TU-JWR640-2156.4	26.5	Mary Lee	Jagger	33.28455	-87.25008
AL-TU-JWR640-2541.8	15.5	Black Creek	Jefferson	33.28455	-87.25008
AL-TU-JWR640-2577.8	25.5	Black Creek	Black Creek	33.28455	-87.25008
AL-TU-JWR650-1724.5	27.5	Mary Lee	New Castle	33.37202	-87.36083

Table 1. Locality and stratigraphic information for coal samples analyzed during this project (continued).

Sample number	Thickness (in)	Coal zone	Coal Bed	Latitude	Longitude
AL-TU-JWR652-1141.6	17.0	Pratt	☐	33.37673	-87.35347
AL-TU-JWR652-1711.7	21.0	Mary Lee	New Castle	33.37673	-87.35347
AL-TU-JWR652-2190.0	18.0	Black Creek	Black Creek	33.37673	-87.35347
AL-TU-JWR653-2193.2	15.0	Black Creek	Black Creek	33.38955	-87.35997
AL-TU-JWR654-0227.7	21.0	Gwin	Gwin	33.38763	-87.36613
AL-TU-JWR654-1737.0	38.0	Mary Lee	New Castle	33.38763	-87.36613
AL-TU-JWR654-1994.0	18.5	Ream	5 combined beds	33.38763	-87.36613
AL-TU-JWR655-1168.6	22.0	Pratt	☐	33.38995	-87.36285
AL-TU-JWR655-1179.4	11.0	Pratt	☐	33.38995	-87.36285
AL-TU-JWR655-1205.3	23.0	Pratt	☐	33.38995	-87.36285
AL-TU-JWR655-2227.3	25.0	Black Creek	Black Creek	33.38995	-87.36285
AL-TU-JWR655-2229.4	25.0	Black Creek	Black Creek	33.38995	-87.36285
AL-TU-JWR656-2118.9	17.5	Black Creek	Black Creek	33.36310	-87.23923
AL-TU-JWR657-1208.3	16.5	Pratt	☐	33.38035	-87.36352
AL-TU-JWR657-1765.9	36.0	Mary Lee	New Castle	33.38035	-87.36352
AL-TU-MBR1-2.0	30.0	Mary Lee?	☐	33.19650	-87.26435
AL-TU-TRPM-3.0	39.0	Brookwood	Brookwood	33.27250	-87.30385
AL-TU-TRPM-4.0	13.0	Brookwood	Guide	33.27250	-87.30385
AL-WA-HV2-1.0	28.0	Mary Lee	Mary Lee	33.77603	-87.24593
AL-WA-NV-1.0	10.0	Black Creek	Black Creek	33.99678	-87.52083

volatile matter using the correlation scheme and rank classification of Stach and others (1982).

Ash and sulfur content were analyzed statistically to determine basic population characteristics.

These variables were also analyzed stratigraphically to determine if any systematic vertical trends in coal grade exist.

To determine the relationship between coal quality and gas sorption capacity, 58 coal samples were collected from exploration cores donated by Jim Walter Resources, Incorporated and El Paso Energy Corporation, and from active mine faces (table 1). The location, depth, and thickness of all sampled coal beds were recorded, and the samples were placed into air-tight plastic bags. Each sample was given a collection number, and the basic sample information was entered into a spreadsheet. Next, all samples were crushed to minus-10 mesh. A split of 50 to 200 grams was taken for archival collection purposes and stored in an airtight plastic bag. Another split of about 20 to 30 grams was crushed to -20 mesh and placed into paper coin envelopes. Each -20 split was used to make polished epoxy pellets for vitrinite reflectance and coal maceral analysis. Samples larger than 500 grams were sent to Alabama Power Company for proximate and ultimate analysis, and at least 300 grams of coal were sent to RMB Earth Science Associates for sorption isotherm analysis. Because of the quantity of coal required, only beds thicker than 18 inches were analyzed. Proximate and ultimate analysis was carried out according to ASTM standards except for moisture, which requires a minimum sample of 1,000 grams. Samples for isotherm analysis were crushed to -60 mesh and placed in a bath to bring the samples to equilibrium moisture. Equilibrium moisture and ash content were determined on a

two-gram split of each sample. Each sample was then split into three subsamples, and high-pressure sorption isotherms were run at 80°F using an apparatus and methodology similar to that described by Mavor and others (1990). A temperature of 80°F was chosen because it approximates reservoir temperature near the active coal-fired power plants. Data from the isotherms were extracted for pressures of 50, 100, and 350 psi and plotted against rank and grade parameters to quantify the influence of coal quality on sorption capacity.

Gas content data are useful for determining the potential for enhanced coalbed methane recovery in the Black Warrior coalbed methane fairway. Data were compiled from the published literature and have been derived mainly using the U.S. Bureau of Mines direct method and modified direct method (see Diamond and Schatzel, 1998). These data are augmented by proprietary analyses. In this report, some gas-content profiles are presented and interpreted to elucidate some of the challenges that must be met to realize enhanced coalbed methane recovery.

Production data were compiled from the databases of the State Oil and Gas Board to assess the performance of coalbed methane wells. Data compiled include cumulative gas and water production, peak gas and water production, and the number of days each well was on line. Production data are reported monthly to the Oil and Gas Board, thus the peak rates were calculated by dividing the volume of gas or water produced by the number of days the well was on line during the peak month. As with other types of data collected in this study, production data were analyzed statistically, and contour maps were made in Isomap.

# RESULTS AND DISCUSSION

## REGIONAL SETTING

The Black Warrior coalbed methane fairway is along the southeast margin of the Black Warrior basin in west-central Alabama (fig. 1). Twenty coalbed methane fields have been established in the Black Warrior basin, and in this study we are investigating 17 fields where closely spaced wells facilitate detailed study (fig. 2). Cumulative production of coalbed methane now exceeds 1.2 Tcf, and more than 3,000 wells are currently producing from coal in the Pottsville Formation. Vertical coalbed methane wells have been drilled in all fields, and mine-related coal degasification operations that include horizontal and gob wells are in Oak Grove and Brookwood fields. Coalbed methane resources have been estimated between 10 and 20 Tcf (Hewitt, 1984; McFall and others, 1986), and reserves have been estimated at slightly more than 2.5 Tcf (Rice, 1995; Lyons, 1997).

The Black Warrior basin is a late Paleozoic foreland basin that formed adjacent to the juncture of the Appalachian and Ouachita orogenic belts (e.g., Mellen, 1947; Thomas, 1985a, 1988, 1995) (fig. 4). The basin has a distinctive triangular plan and is bounded on the southeast by the Appalachian thrust belt, on the southwest by the Ouachita thrust belt, and on the north by the Nashville dome. The Pottsville Formation is exposed in the eastern third of the basin, and the western two thirds is concealed below Mesozoic strata of the Gulf Coastal Plain and the Mississippi Embayment (Mellen, 1947). Economic coal and coalbed methane resources in the Black Warrior basin are effectively restricted to the Pottsville Formation, which is of Early



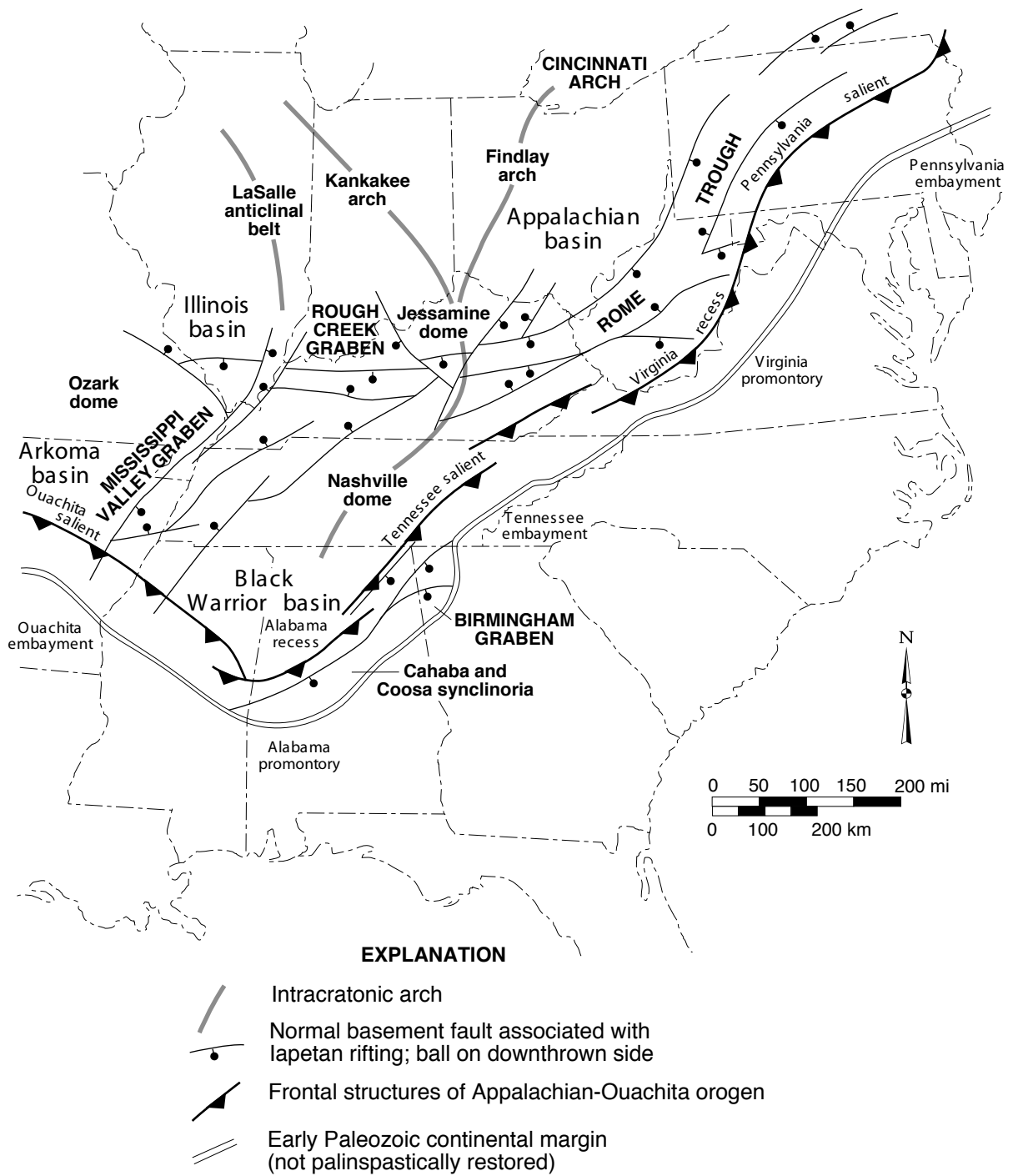


Figure 4.--Tectonic setting of the Black Warrior basin (modified from Thomas, 1988).

Pennsylvanian (Langsettian) age. The Pottsville Formation in Alabama is composed principally of shale, sandstone, and coal and is locally thicker than 6,000 feet (Thomas, 1988). Coal beds are bright-banded, are typically thinner than 9 feet, and have an average thickness of 1 foot (fig. 5). Economically significant coal beds are concentrated in the upper part of the Pottsville Formation in the Black Creek through Brookwood coal zones (McCalley, 1900; Butts, 1926). Virtually all coalbed methane production comes from the Black Creek through Utley coal zones, which have been designated formally as the Pottsville Coal Interval by the State Oil and Gas Board of Alabama (Hinkle and Sexton, 1984; Sexton and Hinkle, 1985; Pashin and Hinkle, 1997). New exploration is taking place in the lower Pottsville in some of the northern coalbed methane fields, but lower Pottsville coal was not considered in this study. The Pottsville Formation is overlain with angular unconformity by poorly consolidated sand and gravel of the Tuscaloosa Group (Upper Cretaceous), which is a major aquifer in the western coalbed methane fields (Pashin and others, 1991; Ellard and others, 1992; Pashin and Hinkle, 1997).

## **STRATIGRAPHY AND SEDIMENTATION**

The stratigraphy and sedimentology of coal-bearing strata must be considered when developing and implementing a carbon sequestration strategy because the thickness, continuity, and geometry of coal are determined in large part in the original depositional environment. In this section, we review the stratigraphy and sedimentology of the Pottsville Formation in the eastern Black Warrior basin. Following this, we present new stratigraphic cross sections and net

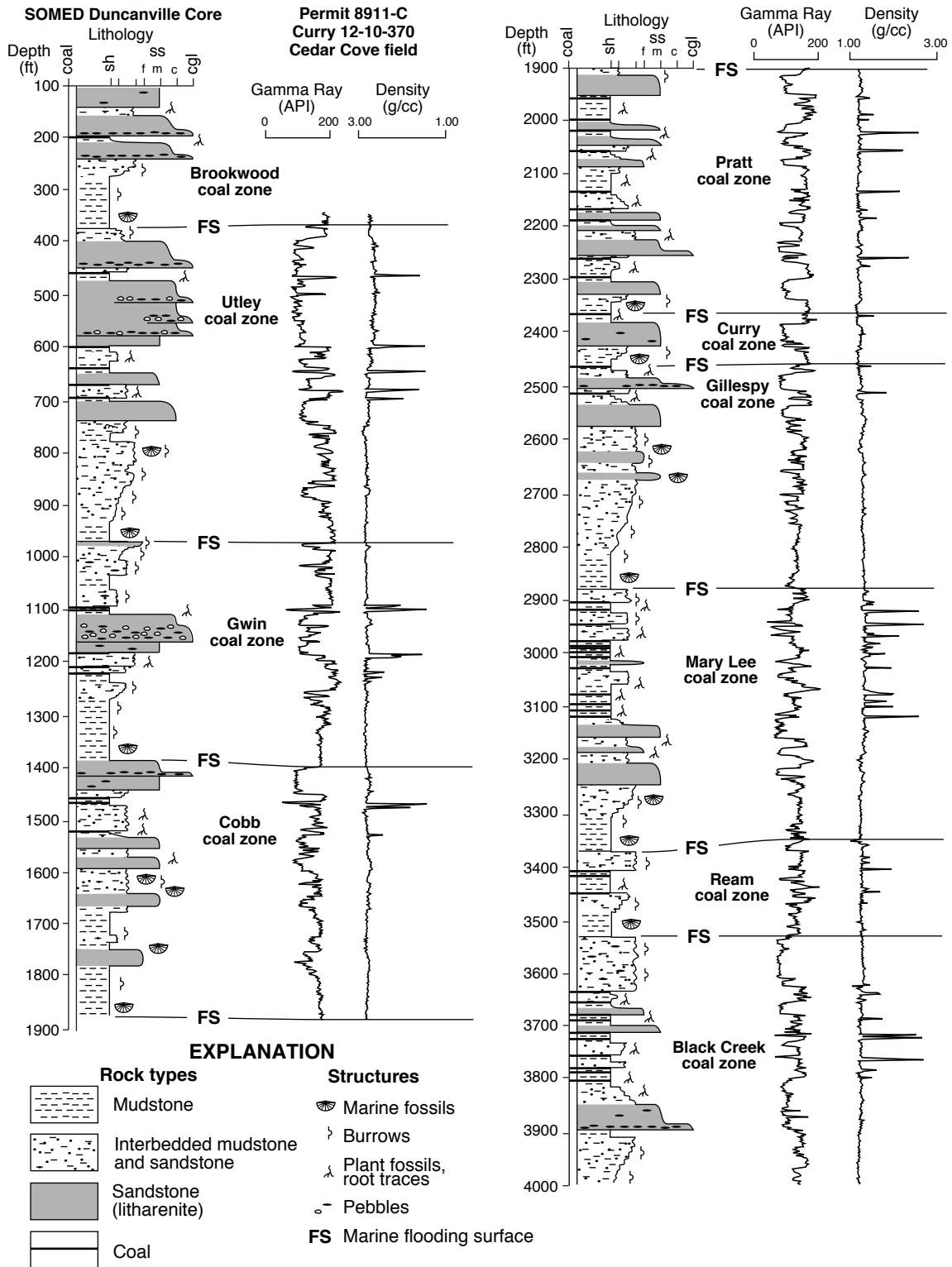


Figure 5.—Core log and geophysical well log of the Pottsville Coal Interval in Cedar Cove Field (modified from Pashin and Hinkle, 1997).

coal isolith maps and discuss the implications of these cross sections and maps for the application of carbon sequestration technology in the Black Warrior coalbed methane fairway.

## **Background**

Coal beds in the Pottsville Coal Interval were recognized by McCalley (1900) to form a series of stratigraphic clusters, or coal groups (fig. 5), that could be correlated throughout the eastern Black Warrior basin. These coal groups, which are properly termed coal zones to avoid confusion with formal stratigraphic terminology, have provided the basis for most later subdivisions of the Pottsville Formation in Alabama (Butts, 1910, 1926; Culbertson, 1964; Metzger, 1965). Butts (1926) was first to recognize the evidence for repeated marine transgressions and regressions during Pottsville deposition, and during the late 1960's and 1970's, the Alabama Pottsville played a central role in the development of facies models for Appalachian coal-bearing strata (Ferm and others, 1967; Horsey, 1981; Rheams and Benson, 1982; Ferm and Weisenfluh, 1989). Wanless (1976) made passing mention of cyclicity in the Pottsville Formation, but it was not until the intensive exploration for conventional hydrocarbons and coalbed methane in the 1980's that basinwide depositional cycles were confirmed (Sestak, 1984; Thomas, 1988; Pashin and others, 1991; Pashin, 1994a, b). The first cyclostratigraphic subdivision of the upper part of the Pottsville Formation was made by Pashin and others (1991), who defined a series of basinwide coarsening- and coaling-upward cycles. Pashin (1994a, 1998) suggested that high-frequency glacial eustasy in the Milankovitch long eccentricity band (~0.4

my) was the dominant causal mechanism of depositional cyclicity in the upper Pottsville Formation.

Pottsville cycles are internally heterogeneous (fig. 6). The basal surface of each cycle is typically sharp and locally truncates strata of the underlying cycle; marine fossils are concentrated above this surface. The shale above the fossil concentrations is typically between 30 and 300 feet thick; it contains burrows and scattered shells. Sandstone in the Pottsville Formation varies from litharenite containing low-grade metamorphic rock fragments to quartzarenite (Mack and others, 1983). Pottsville litharenite is dark and impermeable, or tight, whereas lighter colored, quartzose sandstone is permeable and of reservoir quality (Pashin and others, 1991). Tight sandstone is in places thicker than 150 feet and includes progradational foresets and a variety of channel fills. Reservoir-quality sandstone is basinward of tight sandstone and forms fining-upward successions 30 to 200 feet thick; reservoir sandstone in the Pottsville Coal Interval is restricted to areas northwest of the coalbed methane fairway. Each cycle is capped by a lithologically heterogeneous coal zone containing one or more coal beds of variable geometry and thickness that are intercalated with shale and sandstone.

The cycles are flooding surface-bounded depositional units that can be interpreted as parasequences in the terminology of Vail (1987) or genetic stratigraphic sequences in the terminology of Galloway (1989). The surfaces at the base of the Pottsville cycles are interpreted as transgressive surfaces of erosion, or ravinements, and the associated fossil concentrations are in condensed sections that rest directly on the ravinement surfaces (Liu and Gastaldo, 1992;

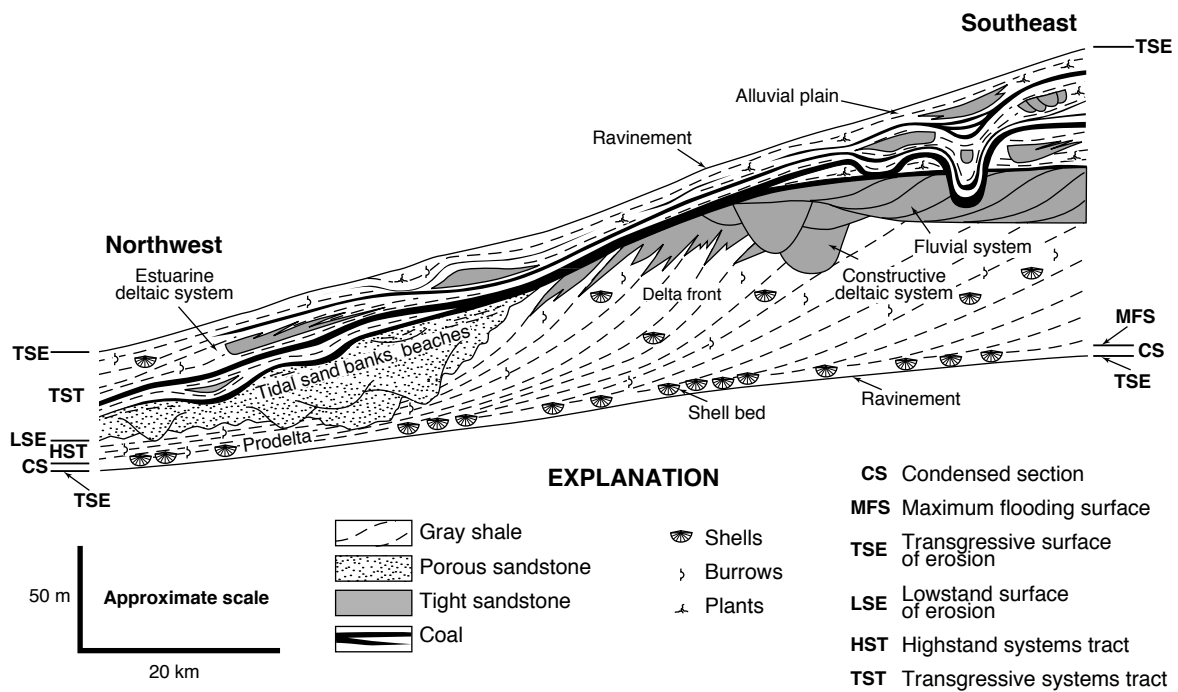


Figure 6.--Idealized depositional cycle in the Pottsville Formation, Black Warrior basin, Alabama (modified from Pashin, 1994b, 1998).

Pashin, 1998) (fig. 6). The coarsening-upward shale intervals above the fossil concentrations and litharenite foreset beds record deltaic progradation during highstand (e.g., Gastaldo and others, 1993), and each shale unit apparently rests on a maximum flooding surface (figs. 6, 7).

Quartzose sandstone was derived by marine reworking of lithic sand (Mack and others, 1983) and by transport of sand from distant sources (Pashin, 1994a); it was apparently deposited in tidal sand banks and beach-barrier systems northwest of the coalbed methane fields after lowstand (Hobday, 1974; Gastaldo and others, 1993; Pashin, 1998). Pottsville coal zones accumulated in diverse coastal-plain settings from highstand into the early stages of marine transgression (Pashin, 1998). The sandstone units associated with the coal beds include a broad range of fluvial and tidal-flat deposits, and the shale units include associated flood-basin and mudflat environments (Rheams and Benson, 1982; Pashin and others, 1991; Demko and Gastaldo, 1996). Coal beds are the products of peat swamps, and in the Pottsville Formation, coal beds represent a spectrum of domed and low-lying swamp types that spanned the coastal plain (Eble, 1990; Pashin, 1994a, c).

### **Well-Log Cross Sections**

Shale, sandstone, and coal are easily distinguished in gamma-density logs of the Pottsville Formation (fig. 5; plates 1-8). Shale can be identified as intervals with gamma count higher than 100 API units, whereas sandstone has a gamma count lower than 100 API units. Coal beds and

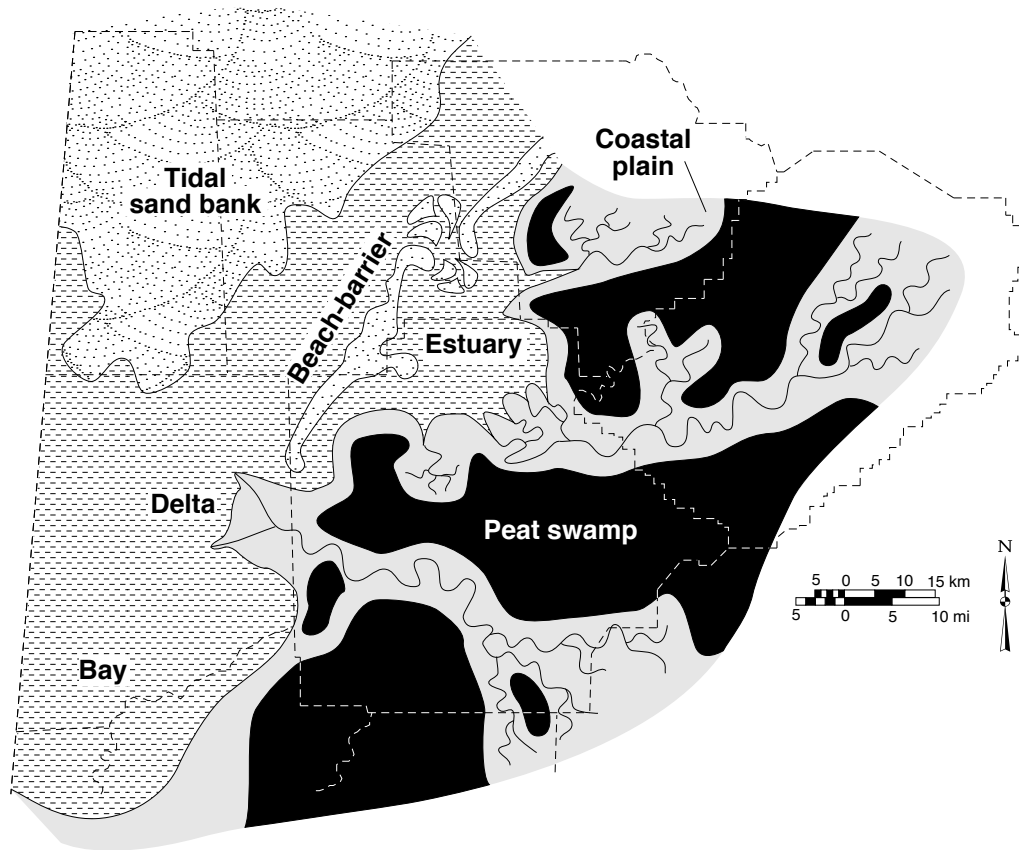


Figure 7.--Generalized paleogeography of the Pottsville Formation in the Black Warrior basin of Alabama (modified from Pashin and others, 1991).



associated organic shale beds form distinctive low-density markers and can also have a low gamma count similar to sandstone.

A network of stratigraphic cross sections shows the stratigraphic architecture of the Black Creek through Utley coal zones (plates 1-10). These cross sections were made to establish correlations of cycle-bounding flooding surfaces, coal beds, and aggradational sandstone units (i.e., sandstone with a blocky to fining-upward log signature). Cycle-bounding flooding surfaces can be identified at the base of the thick mudstone units and are overlain by shale with slightly higher radioactivity than adjacent shale units.

The cross sections confirm that cycle-bounding flooding surfaces are readily correlated throughout the study area and thus constitute important stratigraphic markers that can be used for subsurface mapping (plates 1-10). All cycles thicken toward the southwest in cross sections A-A' and B-B' and toward the southeast in cross sections C-C' through E-E', with the thickest sections in Moundville and Cedar Cove fields and the thinnest sections in Blue Creek, White Oak Creek, and Oak Grove fields. Isopach maps of selected cycles have been published by Pashin and others (1991) and Pashin (1994a) and confirm establishment of a persistent center of foreland-basin subsidence adjacent to the Appalachian orogen, which is referred to in this report as the Moundville-Cedar Cove depocenter (fig. 8). The density logs offer stratigraphic resolution that is sufficient to correlate coal beds over large areas, and even where beds merge, the well logs enable correlation at the bench scale (plates 1-10).

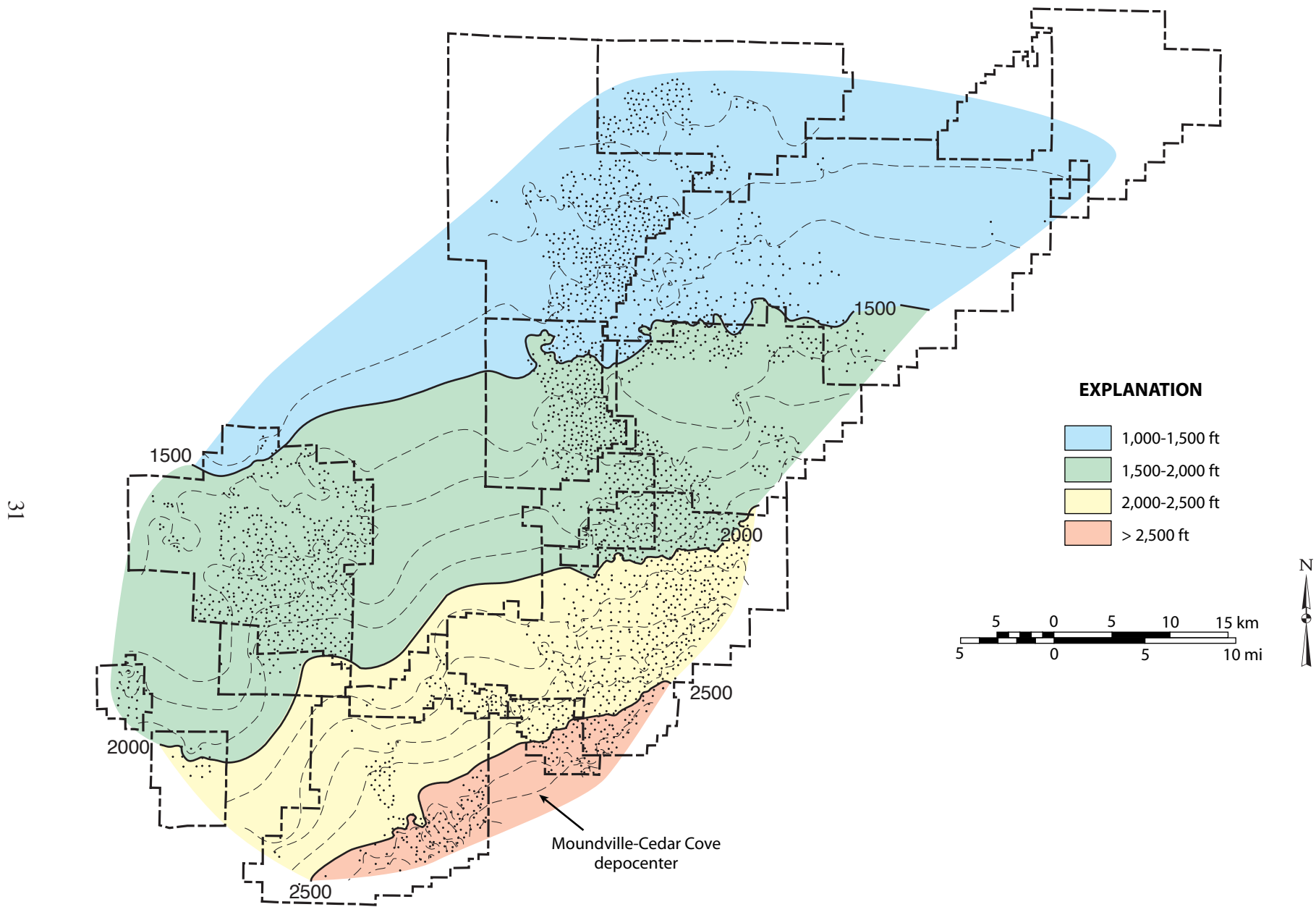


Figure 8.—Isopach map of the Ream through Gwin coal zones in the Black Warrior coalbed methane fairway.

## Black Creek Coal Zone

Correlation of coal beds indicates great variability of thickness, continuity, and geometry in the Pottsville Coal Interval (plates 1-10). The Black Creek coal zone, which forms the base of the Pottsville Coal Interval, has a distinctive log signature in which coal beds generally thin upward (fig. 5; plates 1, 2). The Black Creek coal zone contains several mineable coal beds near outcrop areas and is a significant coalbed methane reservoir throughout most of the production fairway. Coal beds are most numerous in the Moundville-Cedar Cove depocenter, where some well logs record more than 15 coal beds and organic-rich markers. By comparison, the coal zone contains 6 or fewer coal beds in parts of Oak Grove, White Oak Creek, Blue Creek, and Taylor Creek fields. Few wells in the coalbed methane fairway penetrate the basal flooding surface of the Black Creek depositional cycle.

Minor flooding surfaces within the cycle can be traced for large distances and help define three parasequences that are color-coded green, yellow, and brown (plates 1, 2). Subzones of the Black Creek zone correspond to the parasequences and are named after the major mineable coal beds. The Black Creek subzone is near the top of the green parasequence and is dominated by secondary resource targets (coal beds between 1 and 2 feet thick) and thin marker beds (coal and organic shale beds thinner than 1 foot). A primary resource target (coal thicker than 2 feet) was identified only in Oak Grove Field (plate 2; cross section E-E'). The Jefferson subzone (yellow parasequence) forms the middle of the Black Creek coal zone and contains an extensive primary resource target (Jefferson coal bed) that can be correlated throughout the study area. In northern

Brookwood and southern Oak Grove fields, exceptionally thick Jefferson coal is preserved in prominent stratigraphic sags (plates 1, 2; cross sections B-B', E-E'). Similar sags contain exceptionally thick coal in the Mary Lee coal zone and have been identified as channel fills (Pashin, 1994b). The Lick Creek subzone (brown parasequence) forms the top of the coal zone and contains mainly thin markers and secondary resource targets that are seldom completed for coalbed methane production.

Sandstone bodies within the Black Creek coal zone are highly discontinuous and are in places thicker than 120 feet (plates 1, 2). In the Jefferson subzone, thick, multistory sandstone bodies are concentrated in the Moundville-Cedar Cove depocenter. Higher in the section, however, single-story sandstone bodies are thinner than 30 feet. Primary and secondary resource coal beds have high continuity relative to the sandstone bodies, and only locally do the sandstone units appear to truncate or be in direct facies relationship with the coal beds.

### Ream Coal Zone

The Ream coal zone is thin in comparison to the Black Creek, and coal beds tend to be thin and discontinuous (fig. 5; plates 1, 2). The log signature of the Ream coal zone is highly variable, reflecting a heterogeneous distribution of shale, coal and sandstone. No regionally extensive parasequences were identified within the Ream coal zone because of this heterogeneity, and no subzones have been established. More than five beds are preserved in the Moundville-Cedar Cove depocenter, whereas coal is absent in northern Deerlick Creek and

southern Blue Creek fields. No regionally extensive subzones were identified, and the coal zone is dominated by thin coal markers and local secondary resource targets. However, primary resource targets are present in parts of Oak Grove and Taylor Creek fields (plate 1).

As in the Black Creek zone, sandstone bodies are markedly discontinuous (plates 1, 2). Single-story to multistory sandstone bodies are common and are in places thicker than 50 feet. In the lower part of the coal zone, thick, aggradational sandstone bodies are preserved just above the cycle boundary and thus appear to have incised the basal shale unit deeply. Coal beds within the Ream zone tend to be tightly clustered, and another series of sandstone bodies developed just below the terminal flooding surface appears to truncate coal beds in Cedar Cove Field.

### Mary Lee Coal Zone

The Mary Lee coal zone is economically the most important coal zone in the Pottsville Formation because it has been the primary focus of mining since the 19<sup>th</sup> Century (McCalley, 1990; Butts, 1926) and was the original focus of coal degasification efforts (Elder and Deul, 1974; Murrie and others, 1976; Diamond and others, 1976). In well logs, the Mary Lee zone can be distinctive because it contains multiple density spikes without any obvious vertical trend in size (fig. 5; plates 3, 4). The Mary Lee coal zone is thicker than the Ream coal zone and is subdivided into four parasequences (blue, green, yellow, and brown) and three subzones called the Jagger, Mary Lee-Blue Creek, and New Castle (plates 3, 4).

The blue parasequence forms the base of the Mary Lee depositional cycle, is dominated by a coarsening-upward shale-sandstone succession, and lacks significant coal (plates 3, 4). The Jagger subzone corresponds with the green parasequence. This subzone contains coal beds of variable continuity and is dominated by secondary resource targets. As many as five beds constitute the Jagger subzone in the Moundville-Cedar Cove depocenter, and the Jagger coal is the extremely widespread bed at or near the top of the green parasequence (plate 4; cross section D-D').

The Mary Lee-Blue Creek subzone is in the lower part of the yellow parasequence and contains the most important mining and degasification targets in the basin. In much of the coalbed methane fairway, this subzone contains two beds, specifically the Blue Creek coal and the Mary Lee coal. The Blue Creek is the thicker and older of the two beds. In Oak Grove Field, the Blue Creek bed thickens to more than 9 feet in channels as deep as 60 feet (Pashin and others, 1991; Pashin, 1994c). In the northeastern part of cross section B-B', one of the channel complexes is interpreted to truncate the upper part of the green parasequence, including the Jagger coal (plate 3), and similar channel complexes are developed in other parts of the study area (plates 3, 4). Although the Blue Creek and Mary Lee beds exhibit a high degree of continuity in most of the coalbed methane fairway, the beds split profusely in the Cedar Cove-Big Sandy Creek area (plates, 3, 4).

The New Castle subzone straddles the yellow and brown parasequences, and the economically important New Castle coal bed is in the upper part of the yellow parasequence. The

new Castle subzone is perhaps the most heterogeneous part of the Mary Lee coal zone and contains numerous primary resource targets, secondary resource targets, and thin marker beds (plates 3, 4). In general, coal beds tend to thin upward within the New Castle subzone. The minor flooding surface defining the top of the yellow parasequence can be traced for large distances above the New Castle coal bed, and only thin marker beds are present in the brown parasequence. Primary resource targets in the New Castle subzone are present mainly in Oak Grove, White Oak Creek, and Cedar Cove fields. In the Cedar Cove area, the New Castle subzone contains thicker coal than the Mary Lee-Blue Creek subzone.

Aggradational sandstone units in the Mary Lee coal zone are similar in thickness and lateral extent to those in the Black Creek coal zone (plates 1-4). Sandstone units are sparse in the blue and brown parasequences and are dispersed throughout the green and yellow parasequences (plates 3, 4). Throughout the coal zone, single-story sandstone bodies are dominant. Sandstone is typically absent within the Mary Lee-Blue Creek subzone in most coalbed methane fields, and less than 10 feet of mudstone typically separates the Blue Creek and Mary Lee coal beds. In Cedar Cove field, where the Blue Creek and Mary Lee beds split profusely, however, sandstone units thicker than 50 feet are common within the subzone (plate 3; cross section B-B').

### Gillespy Coal Zone

As in the Mary Lee coal zone, the Gillespy coal zone can be subdivided into four parasequences (plates 5, 6). The blue, green, and yellow parasequences are dominated by

coarsening-upward shale-sandstone successions and define a clinoform stratal pattern in which minor flooding surfaces descend northwestward. Aggradational sandstone bodies in the blue and green parasequences are exclusively single-story, whereas single-story and multistory sandstone bodies are developed in the yellow parasequence. The oldest coal in the Gillespy zone is near the top of the yellow parasequence, and only thin marker beds are present at this stratigraphic level. The brown parasequence forms the top of the Gillespy coal zone and contains the most widespread aggradational sandstone units of the four parasequences, and as a whole, the Gillespy coal zone can be characterized as a progradational parasequence set. The Gillespy coal is a widespread bed near the top of the brown parasequence. This coal is typically expressed as a thin marker bed, although secondary resource targets are developed locally.

### Curry Coal Zone

The Curry coal zone constitutes the thinnest depositional cycle in the upper Pottsville Formation (fig. 5; plates 5, 6). The coal zone is similar in thickness to the parasequences within the enveloping Gillespy and Pratt coal zones, suggesting that the Curry depositional cycle may be of the same stratigraphic rank as the parasequences within the other depositional cycles. Coal beds are restricted to the upper half of the Curry zone, and only thin markers and secondary resource targets are present.

Thick, aggradational sandstone bodies are most common below the coal beds, and single-story sandstone units predominate (plates 5, 6). None of the sandstone bodies traversed by the



cross sections truncate the basal flooding surface of the Curry coal zone. A second level of sandstone units is younger than the most widespread coal beds and is developed just below the terminal flooding surface of the depositional cycle.

### Pratt Coal Zone

The Pratt coal zone is second only to the Mary Lee in economic significance. Together, the Gillespy, Curry, and Pratt coal zones are distinctive in well logs because the density spikes associated with coal generally increase upward in size (fig. 5). As in the Black Creek coal zone, the Pratt coal zone contains numerous beds throughout most of the study area, and beds are most abundant in the Moundville-Cedar Cove depocenter (plates 5, 6). The Pratt coal zone was divided into three parasequences (green, yellow, and brown) and contains two subzones named after the American and Pratt coal beds. The American subzone spans the green and yellow parasequences, whereas the Pratt subzone is in the brown parasequence.

The American subzone is dominated by secondary resource targets and thin marker beds (plates 5, 6). In cross section D-D' (plate 6), coal beds are arranged in a progradational pattern in which successively younger beds extend farther northwest. Most coal beds in the American subzone are in the yellow parasequence, and major resource beds are developed in parts of Oak Grove and White Oak Creek fields. The Pratt subzone is dominated by a major resource bed in the northern part of the coalbed methane fairway, and in much of this area, the subzone has a distinctive log signature consisting of three closely spaced density spikes. Beds within the

subzone diverge toward the Moundville-Cedar Cove depocenter, which contains numerous secondary resource beds and thin markers.

Sandstone bodies in the Pratt coal zone include a complex array of single-story and multistory sandstone bodies similar to those lower in section (plates 5, 6). Aggradational sandstone bodies have a sporadic distribution in the green and yellow parasequences. The brown parasequence contains little sandstone in the distal parts of the basin where the Pratt subzone is dominated by major resource beds. By contrast, numerous multistory sandstone bodies are preserved in the Moundville-Cedar Cove depocenter, and cross sections B-B', C-C', and D-D' show a marked retrogradation of sandstone deposition toward the depocenter after deposition of the yellow parasequence.

### Cobb Coal Zone

The Cobb coal zone is one of the thickest depositional cycles in the Pottsville Coal interval and is distinctive in geophysical logs because it contains only one or two prominent density spikes (fig. 5; plates 7, 8). The coal zone is divided into four parasequences (blue, green, yellow, and brown) that generally thin upward. As in most other upper Pottsville cycles, coal beds are most abundant in the Moundville-Cedar Cove depocenter. Coal is concentrated in the upper half of the depositional cycle, and the coal zone contains three subzones named the Thomas, Cobb, and upper Cobb subzones.

Parasequence-bounding flooding surfaces in the lower part of the Cobb coal zone have a clinoform geometry in cross sections B-B' and C-C', indicating that the depositional cycle is a progradational parasequence set similar to that identified in the Gillespy coal zone (plates 5-8). The blue parasequence forms about half of the thickness of the Cobb coal zone and constitutes the basal mudstone of the Cobb depositional cycle (plates 7, 8). The mudstone coarsens upward into a widespread sandstone interval near the top of the parasequence. Coal is absent in the blue parasequence, save for some isolated wells with thin marker beds near the top of the interval.

The Thomas subzone is developed within the green parasequence, which is another coarsening-upward interval, and the most widespread coal marks the top of the subzone (plates 7, 8). The subzone is dominated by thin marker beds, although a secondary resource target is developed in part of Moundville Field (plate 1; cross section B-B'). The Cobb subzone spans the yellow parasequence and is capped by the Cobb coal bed, which is the principal resource target in this depositional cycle. Although the Cobb bed forms a prominent marker, it can be classified as a secondary resource target throughout most of the coalbed methane fairway. Beds thick enough to be considered primary targets are developed mainly in Cedar Cove, Moundville, and Robinson's Bend fields. The upper Cobb subzone is in the brown parasequence and is characterized mainly by thin coal beds and organic-rich shale markers. In the southwestern coalbed methane fields, however, the upper Cobb contains a prominent secondary resource target.

Aggradational sandstone units in the Cobb coal zone generally are thinner than 75 feet and contain only one or two stories (plates 7, 8). Major sandstone units in the blue and green parasequences cap coarsening-upward successions, and sandstone units in the green parasequence tend to be significantly thicker than those in the blue parasequence. Sandstone bodies in the yellow parasequence are similar in thickness and distribution to those in the parasequence below. In Robinson's Bend Field (cross sections B-B' and C-C'), sandstone of the yellow parasequence caps a coarsening-upward interval, whereas in the other fields, yellow-parasequence sandstone bodies frequently truncate strata of the green parasequence. The distribution of sandstone in the brown parasequence is highly sporadic, and sandstone units generally are less widespread than those in the older parasequences.

### Gwin Coal Zone

The Gwin coal zone is nearly as thick as the Cobb coal zone throughout much of the coalbed methane fairway (plates 7, 8). The log signature of the Gwin zone is inconsistent because of discontinuous coal beds and sandstone units, but most well logs in the southwestern coalbed methane fields contain two prominent coal markers (fig. 5). Like the Cobb coal zone, the Gwin zone is subdivided into four parasequences (blue, green, yellow, and brown). Two subzones called the Thompson Mill and Gwin subzones are named after the mineable coal beds.

Coal is restricted mainly to the green and yellow parasequences, and beds are most numerous in the Moundville-Cedar Cove depocenter (plates 7, 8). The Thompson Mill subzone is in the

green parasequence, and major resource target bed at the top of the parasequence in parts of Cedar Cove, Big Sandy, Moundville, Holt, and Peterson fields. The Gwin subzone spans the yellow and brown parasequences and contains widespread primary resource targets in the same general areas where primary targets are developed in the Thompson Mill subzone. The thickest coal beds tend to be in the upper part of the yellow parasequence, whereas the brown parasequence contains only localized thin marker beds.

Parasequences in the Gwin coal zone have a clinoform geometry similar to that in the Gillespy through Cobb coal zones (plates 5-8). Aggradational sandstone units in the blue parasequence are mainly single-story bodies developed in the southeastern part of the coalbed methane fairway (plates 7, 8). Sandstone units in the green parasequence are in locally thicker than 100 feet and form a widespread array of single-story and multistory sandstone bodies. In parts of Deerlick Creek and Blue Creek fields, these sandstone units have incised deeply into the basal mudstone of the blue parasequence (cross section D-D'; plate 8). Widespread multistory sandstone bodies are characteristic of the yellow parasequence, and these sandstone bodies also are incised deeply into subjacent strata. The brown parasequence commonly has a coarsening-upward log signature and contains relatively little aggradational sandstone. This parasequence thins northeastward and is extremely thin or absent in parts of Oak Grove Field (cross sections B-B', E-E'; plates 7, 8).

## Utley Coal Zone

The Utley is the youngest coal zone that is logged consistently enough to make regional cross sections (plates 9, 10). Well logs of the Utley coal zone contrast markedly with those of the Cobb and Gwin coal zones because numerous coal beds of variable thickness are distributed throughout the upper half of the depositional cycle (fig. 5, plates 9, 10). As in many of the older coal zones, the Utley coal zone was subdivided into four parasequences (blue, green, yellow, and brown). The Clements subzone includes coal beds in the blue and green parasequences, whereas the Utley subzone includes beds in the yellow and brown parasequences.

Most beds within the Utley coal zone can be correlated easily for large distances, and secondary resource beds and thin marker beds predominate (plates 9, 10). The oldest beds are developed in the Moundville-Cedar Cove depocenter, whereas younger beds tend to extend progressively farther away from the depocenter. The geometry and stacking pattern of the four parasequences resemble those in the Cobb and Gwin coal zones. Multistory sandstone bodies are characteristic of the Utley coal zone, although single-story sandstone bodies are typical of the green parasequence. Sandstone bodies in the yellow parasequence are in places thicker than 100 feet and are the most widespread of the aggradational sandstone units in the Utley coal zone.

### **Net Coal Isolith Maps**

Net coal isolith maps show the total thickness of coal in beds thicker than 1 foot in each upper Pottsville coal zone. In the Black Creek coal zone, beds thicker than 1 foot are present

throughout nearly the entire coalbed methane fairway (fig. 9), thus the Black Creek coal zone has significant potential for carbon sequestration and enhanced coalbed methane recovery. As much as 14 feet of coal is available in Cedar Cove Field, and a large area where coal thickness exceeds 5 feet encompasses most of Cedar Cove field as well as adjacent areas. Other notable areas where net coal thickness exceeds 5 feet include parts of Oak Grove and Brookwood fields. Stratigraphic cross sections indicate that the greatest resource potential is in the Black Creek and Jefferson subzones (plates 1, 2).

Whereas the Black Creek coal zone has at least some sequestration potential in all of the fields studied, coal beds within the Ream zone are thinner than 1 foot throughout most the study area (fig. 10). In eastern Oak Grove Field and southeastern Brookwood Field, however, net coal thickness locally exceeds 3 feet. In eastern Oak Grove Field, thick coal is in one bed, indicating high sequestration potential (plate 1; cross section B-B'). Thick coal is also present in part of Little Sandy Creek Field, and some sequestration potential may also exist in southern Deerlick Creek, Taylor Creek, and Little Buck Creek fields.

The Mary Lee coal zone contains coal beds thicker than 1 foot everywhere but a pair of small areas in Little Sandy Creek, Thornton Creek, and Moundville fields (fig. 11). Net coal thickness exceeds 5 feet in a belt expanding northeastward from Moundville Field into the northern coalbed methane fields. Importantly, parts of Brookwood field where net coal thickness is less than 5 feet are where gob wells reach total depth within the Mary Lee coal zone, so the Mary Lee-Blue Creek and New Castle subzones were not recorded in well logs. Patches with coal

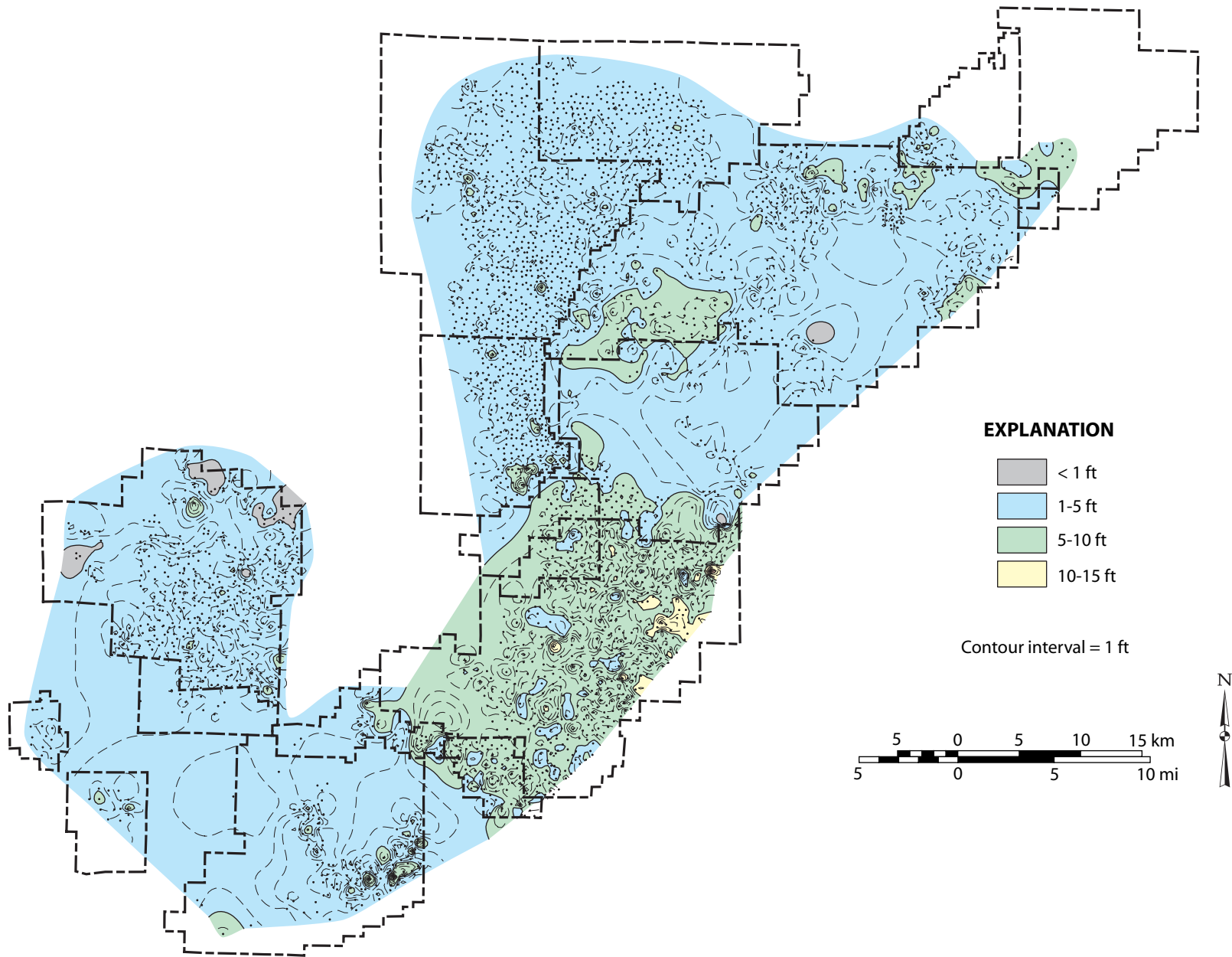


Figure 9.--Net coal isolith of the Black Creek coal zone in the Black Warrior coalbed methane fairway.



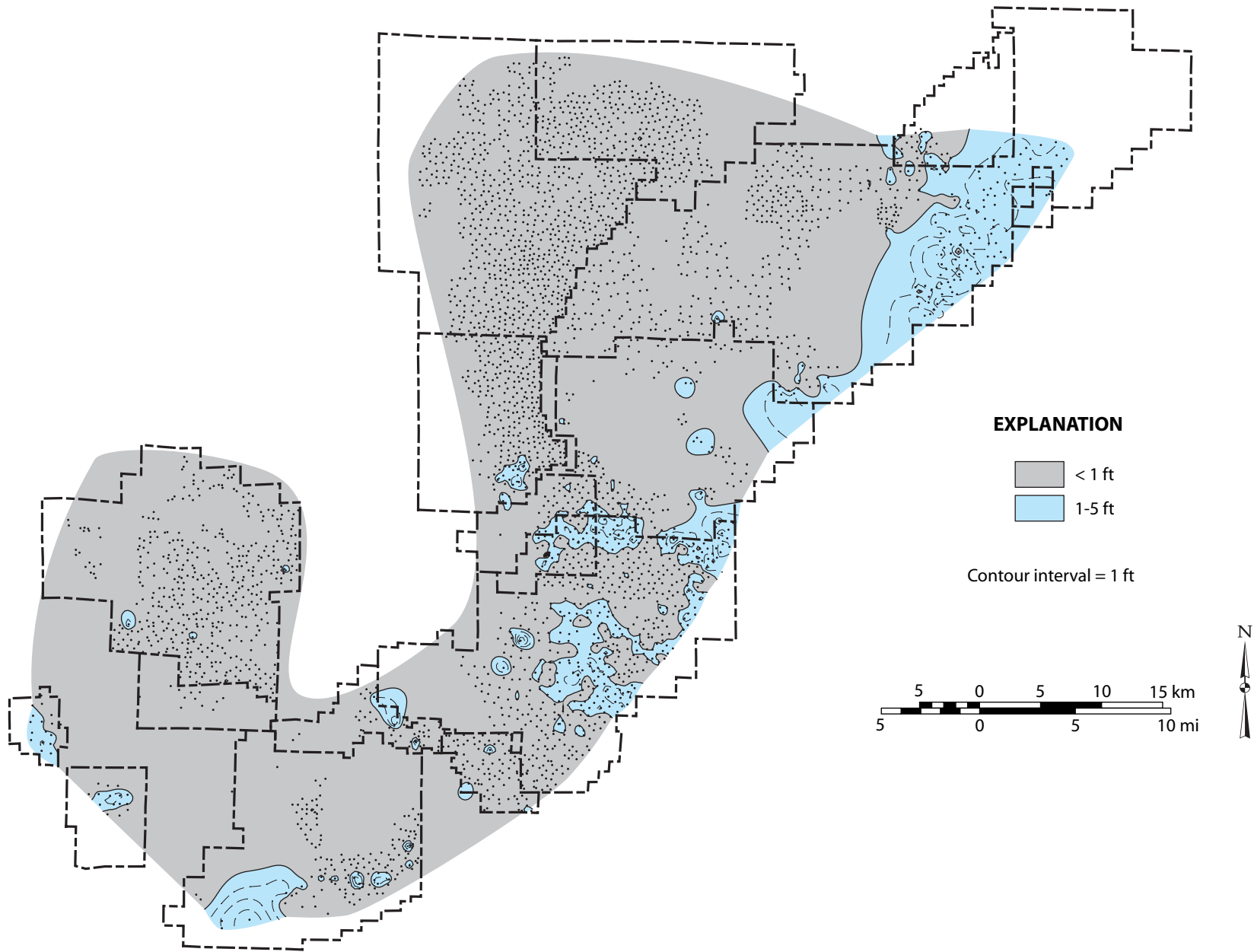


Figure 10.--Net coal isolith of the Ream coal zone in the Black Warrior coalbed methane fairway.

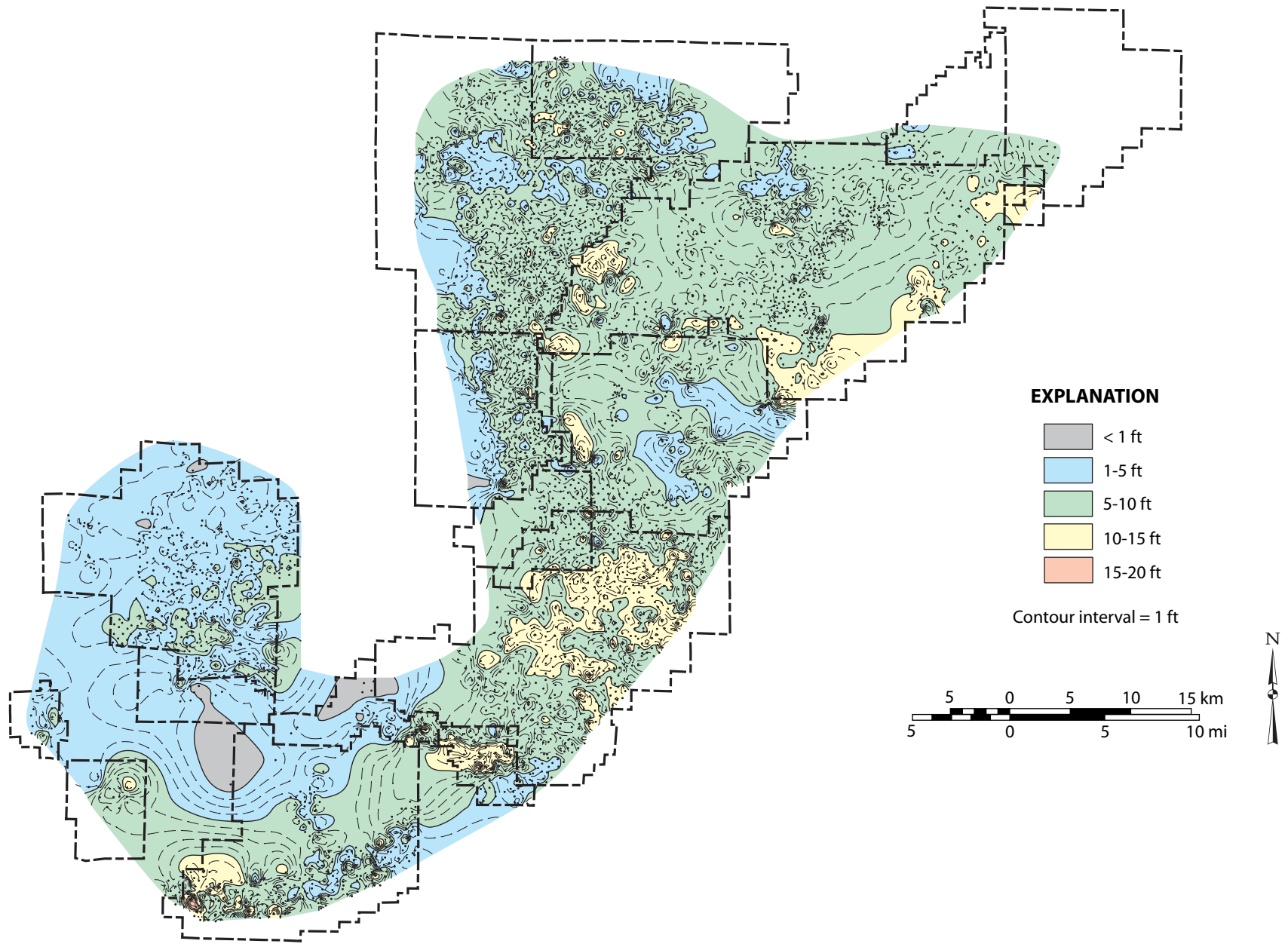


Figure 11.--Net coal isolith of the Mary Lee coal zone in the Black Warrior coalbed methane fairway.

thicker than 10 feet are distributed throughout the northeast trend, and near the southern end of the fairway, coal thickness exceeds 15 feet. Significant sequestration potential exists in all the Mary Lee subzones; the Mary Lee-Blue Creek zone is most important in the northern part of the fairway, whereas the New Castle and Jagger subzones are most important in the southern part (plates 3, 4).

Coal beds in the Gillespy and Curry zones are generally thinner than 1 foot and are thus of limited significance for coalbed methane production and carbon sequestration in most of the coalbed methane fairway (figs. 12, 13). In the Gillespy zone, however, several wells penetrate coal with net thickness greater than 2 feet in southeastern Cedar Cove Field and in much of Little Buck Creek Field (fig. 12). In the Curry zone, more than 2 feet of coal is available for sequestration in northeastern Oak Grove Field and in southern Moundville Field (fig. 13).

Along with the Black Creek and Mary Lee coal zones, the Pratt coal zone is one of the most important targets for mining and degasification in the Black Warrior basin. Net coal thickness in the Pratt zone increases southeastward from less than 1 foot in parts of Robinson's Bend Field to more than 10 feet along the southeast margin of the coalbed methane fairway (fig. 14). A large area containing coal thicker than 10 feet is in eastern Oak Grove Field. Thickness varies considerably in Cedar Cove, Big Sandy, and Moundville fields, where net coal thickness locally exceeds 10 feet. Both subzones of the Pratt coal zone contain target beds for carbon sequestration and enhanced coalbed methane recovery, and the Pratt zone contains the bulk of the primary resource targets in the northern part of the fairway (plates 5, 6).

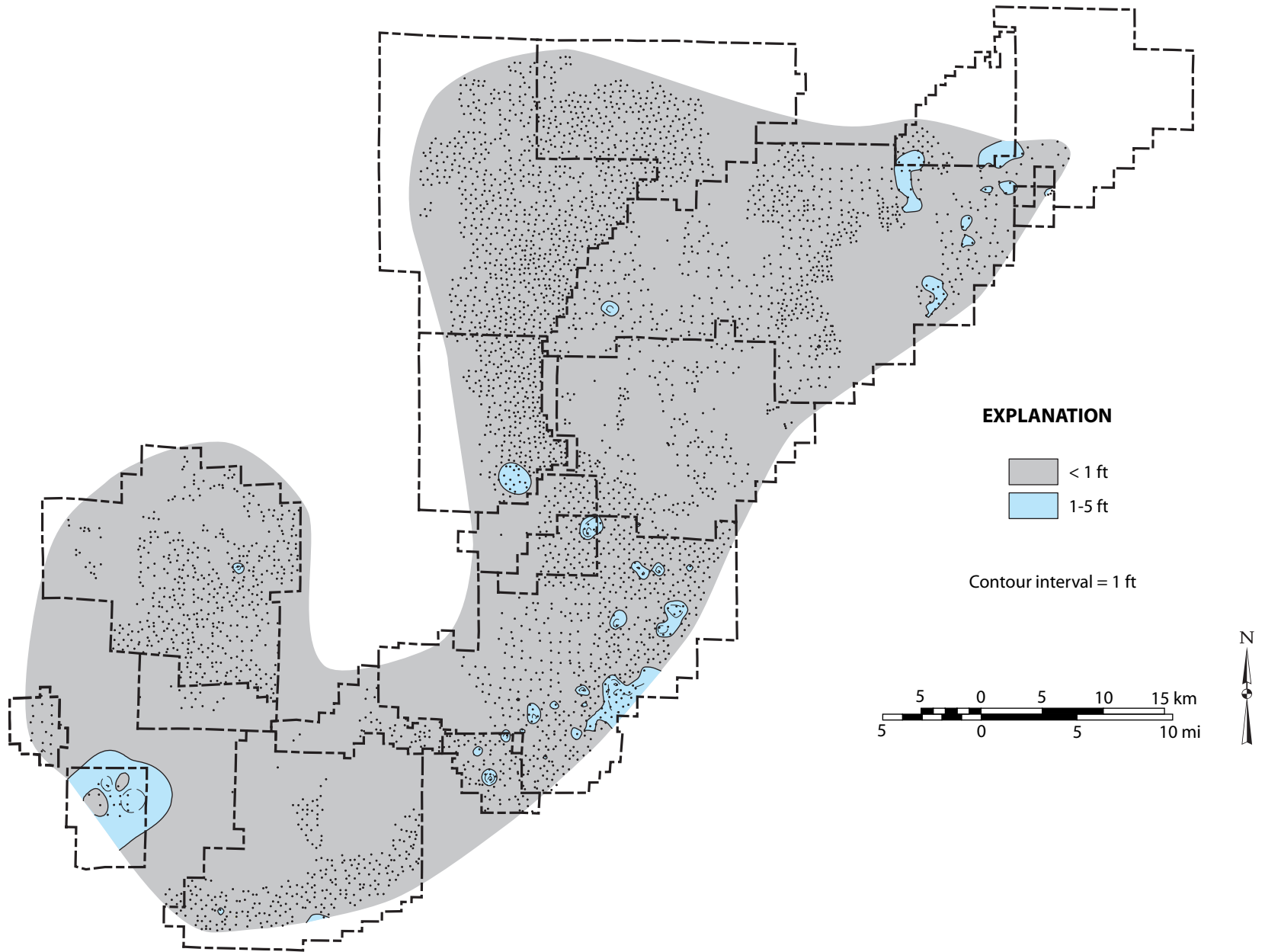


Figure 12.--Net coal isolith of the Gillespie coal zone in the Black Warrior coalbed methane fairway.

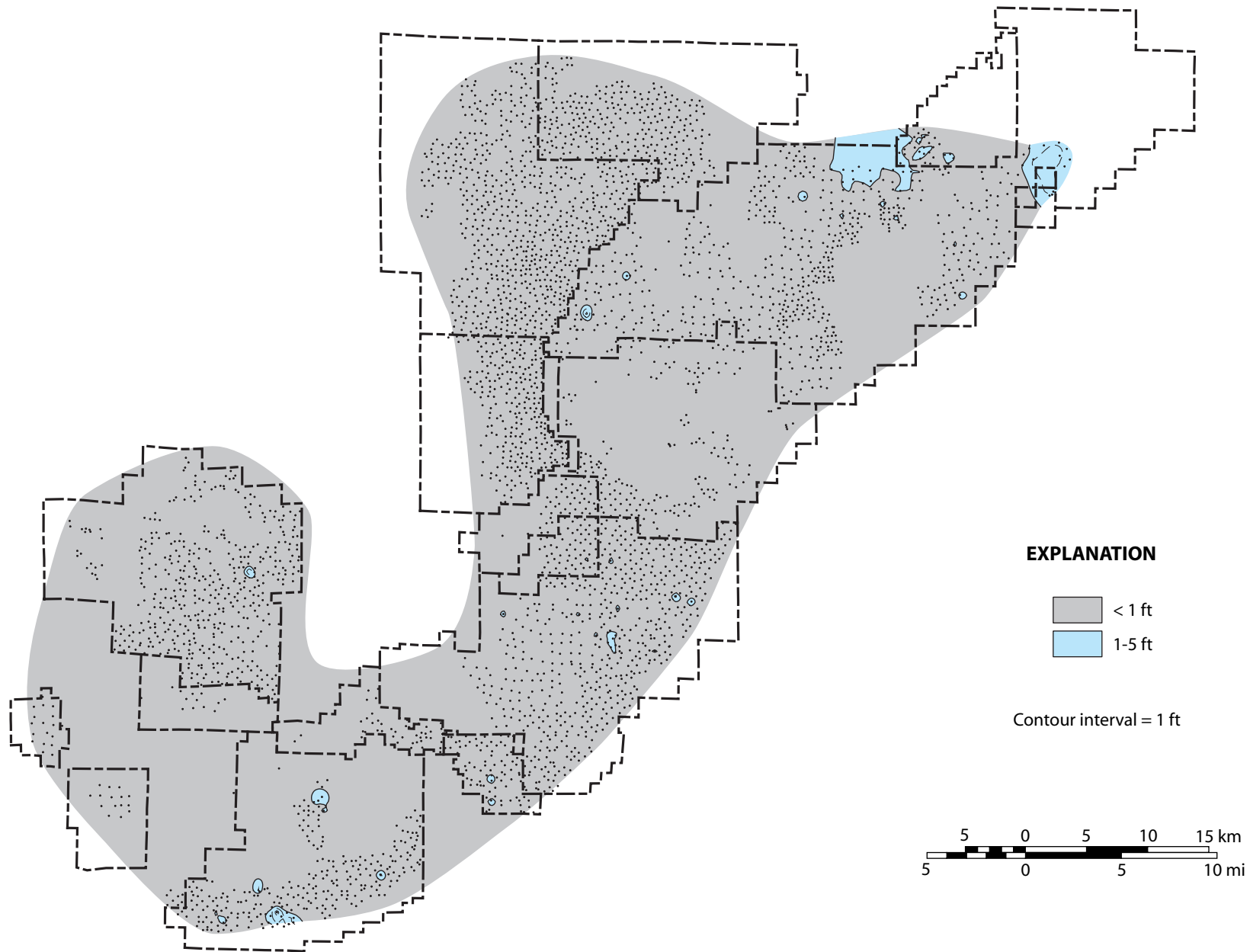


Figure 13.--Net coal isolith of the Curry coal zone in the Black Warrior coalbed methane fairway.

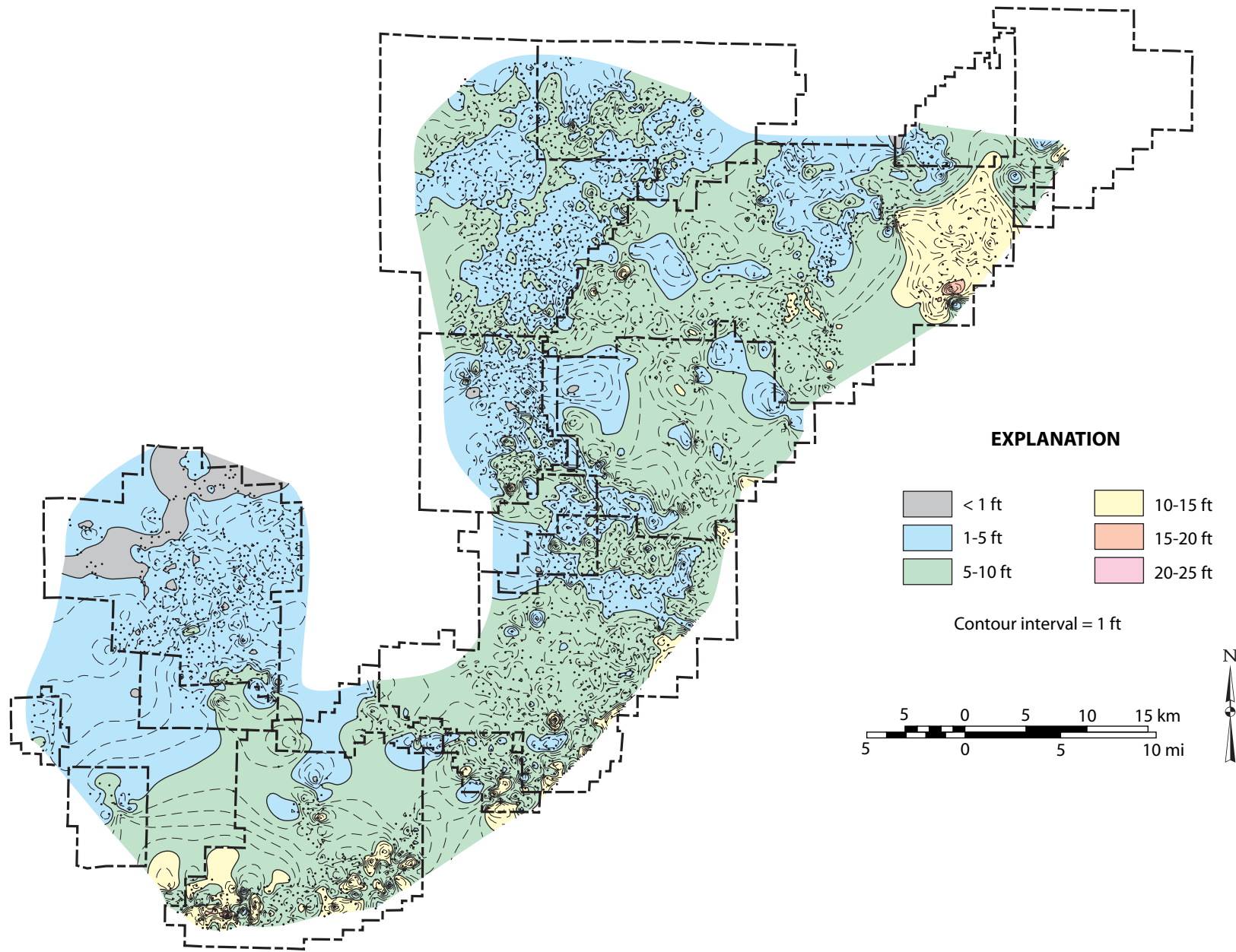


Figure 14.--Net coal isolith of the Pratt coal zone in the Black Warrior coalbed methane fairway.

As in most other coal zones, net coal thickness in the Cobb zone increases southeastward (fig. 15). Net coal is thinner than 1 foot in substantial parts of several coalbed methane fields and is locally thicker than 5 feet in a corridor extending from eastern Cedar Cove Field to southwestern Moundville Field. The Cobb subzone contains the dominant sequestration targets in this coal zone, and some potential sequestration targets are in the upper Cobb subzone within the Moundville-Cedar Cove depocenter (plates 7, 8).

In the Gwin coal zone, net coal thickness increases southeastward from less than 1 foot to more than 20 feet (fig. 16). A belt of coal thicker than 5 feet extends along the southeast margin of the basin from Moundville Field into central Cedar Cove Field. Both the Thompson Mill and Gwin subzones contain significant sequestration targets in this area, and the thickest coal beds are in the Gwin subzone (plates 7, 8).

The Utley coal zone is relatively shallow and thus is absent or not logged in coalbed methane wells in the northern part of the coalbed methane fairway (fig. 17). Net coal thickness generally increases southeastward from less than 1 foot in parts of Robinson's Bend Field. More than 5 feet of coal is present in Moundville and Cedar Cove Fields and is dispersed among numerous widely spaced coal beds (fig. 5; plates 9, 10). In parts of Moundville Field, net coal thickness exceeds 20 feet, suggesting that significant sequestration capacity exists in this area.

The Brookwood coal zone is deep enough to be considered as a carbon sequestration target only in the southwestern part of the coalbed methane fairway (fig. 18). Less than 5 feet of coal is present in most of Robinson's Bend Field, whereas more than 25 feet is present in parts of

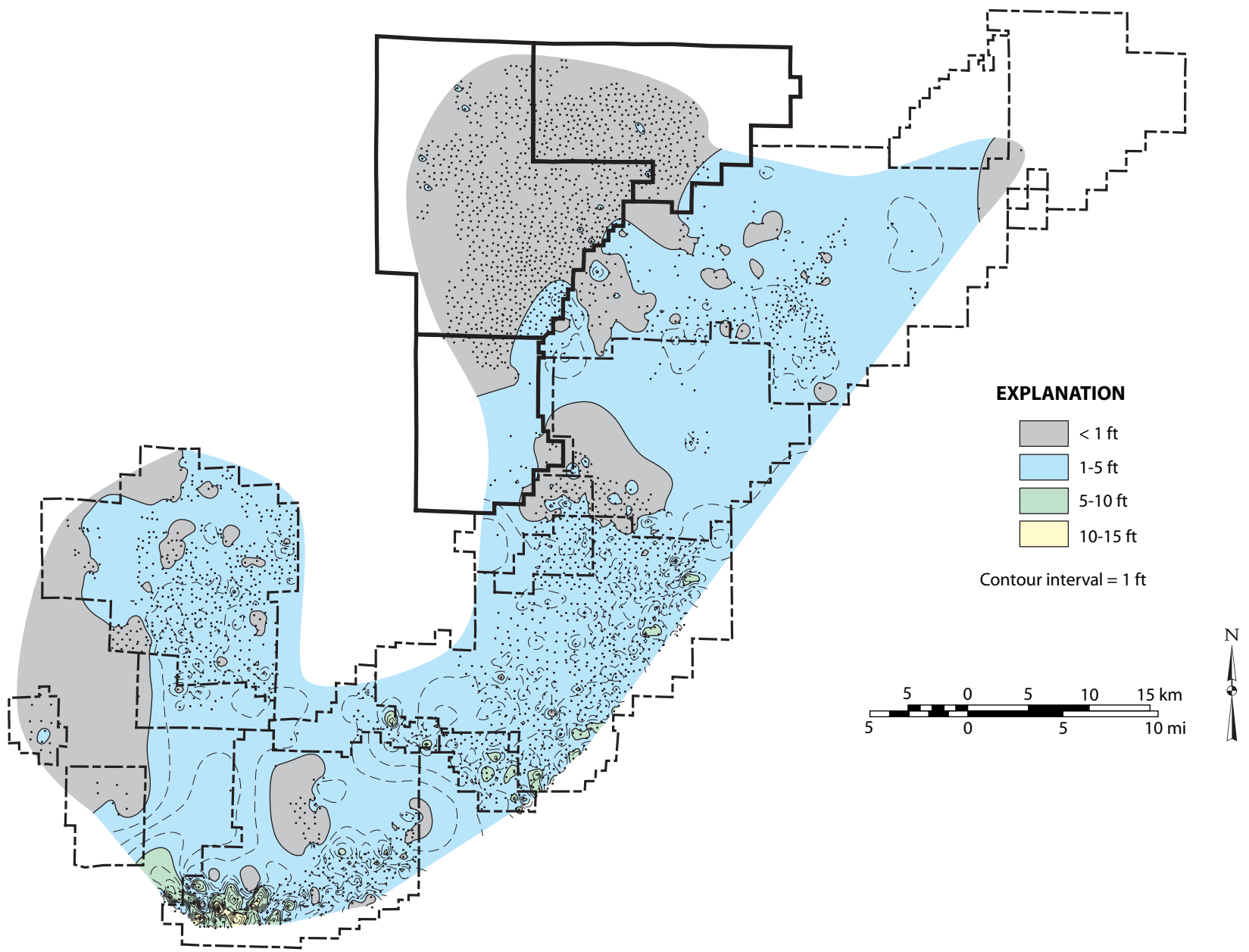


Figure 15.--Net coal isolith of the Cobb coal zone in the Black Warrior coalbed methane fairway.



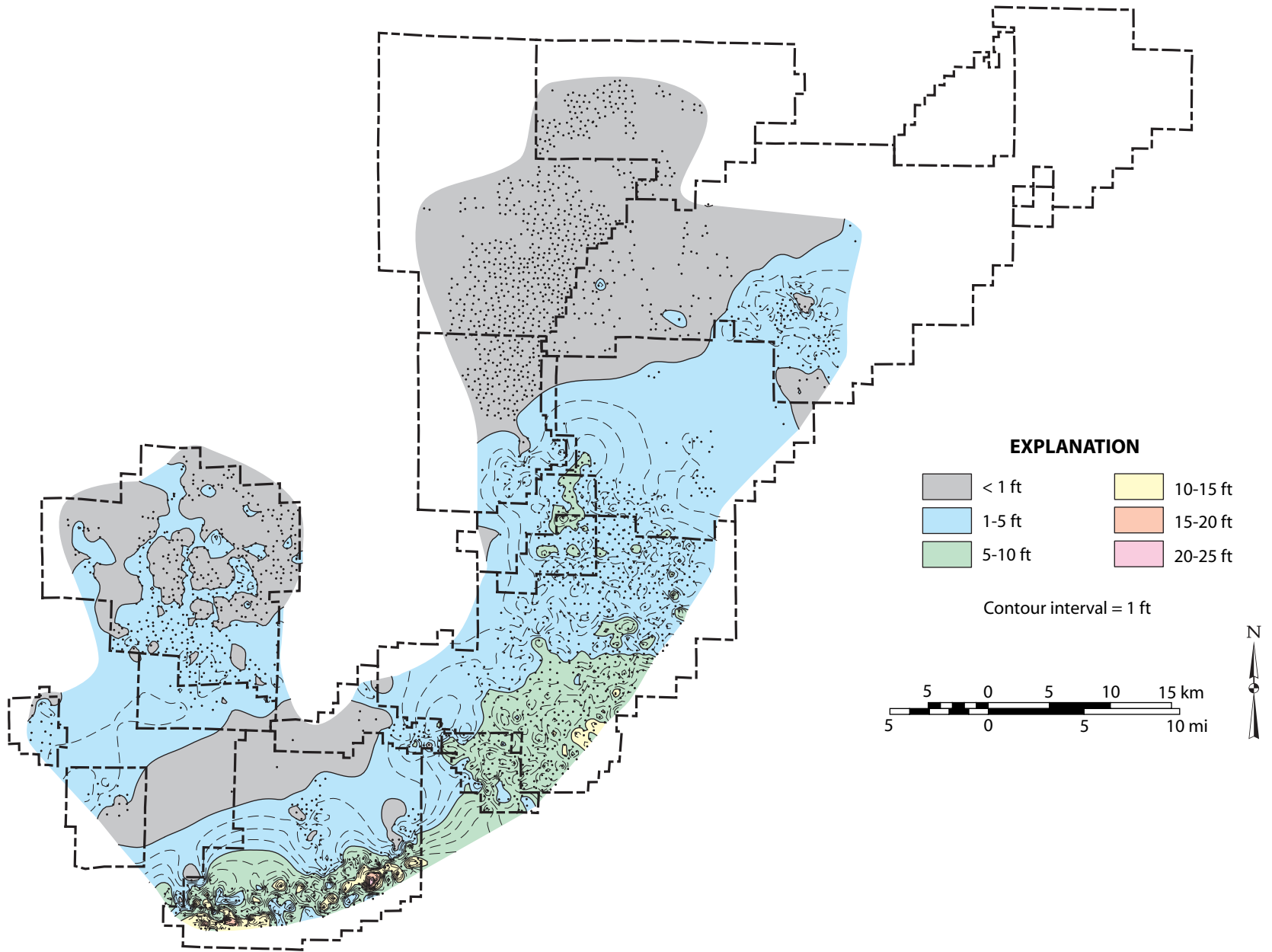


Figure 16.--Net coal isolith of the Gwin coal zone in the Black Warrior coalbed methane fairway.

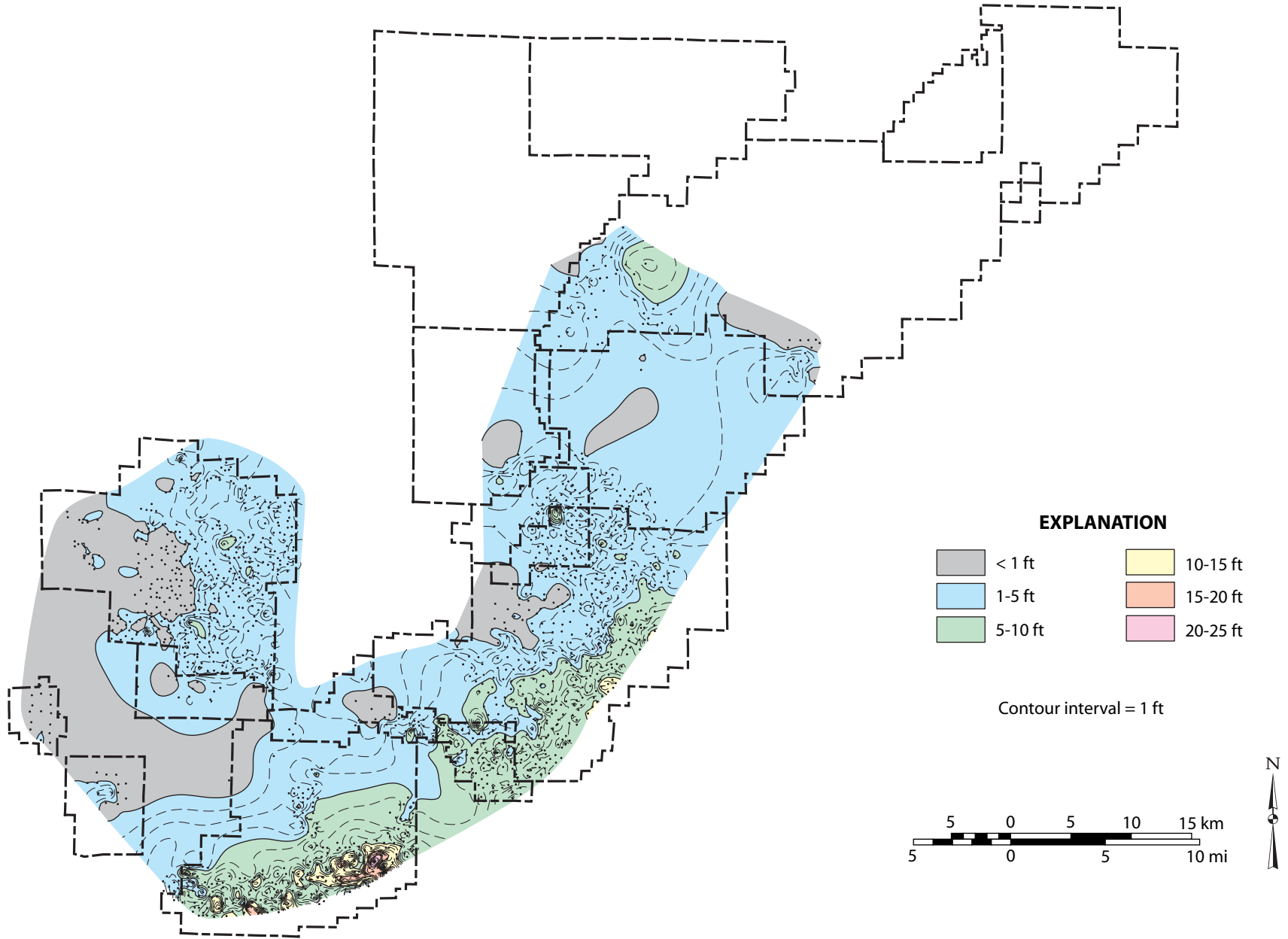


Figure 17.--Net coal isolith of the Utley coal zone in the Black Warrior coalbed methane fairway.

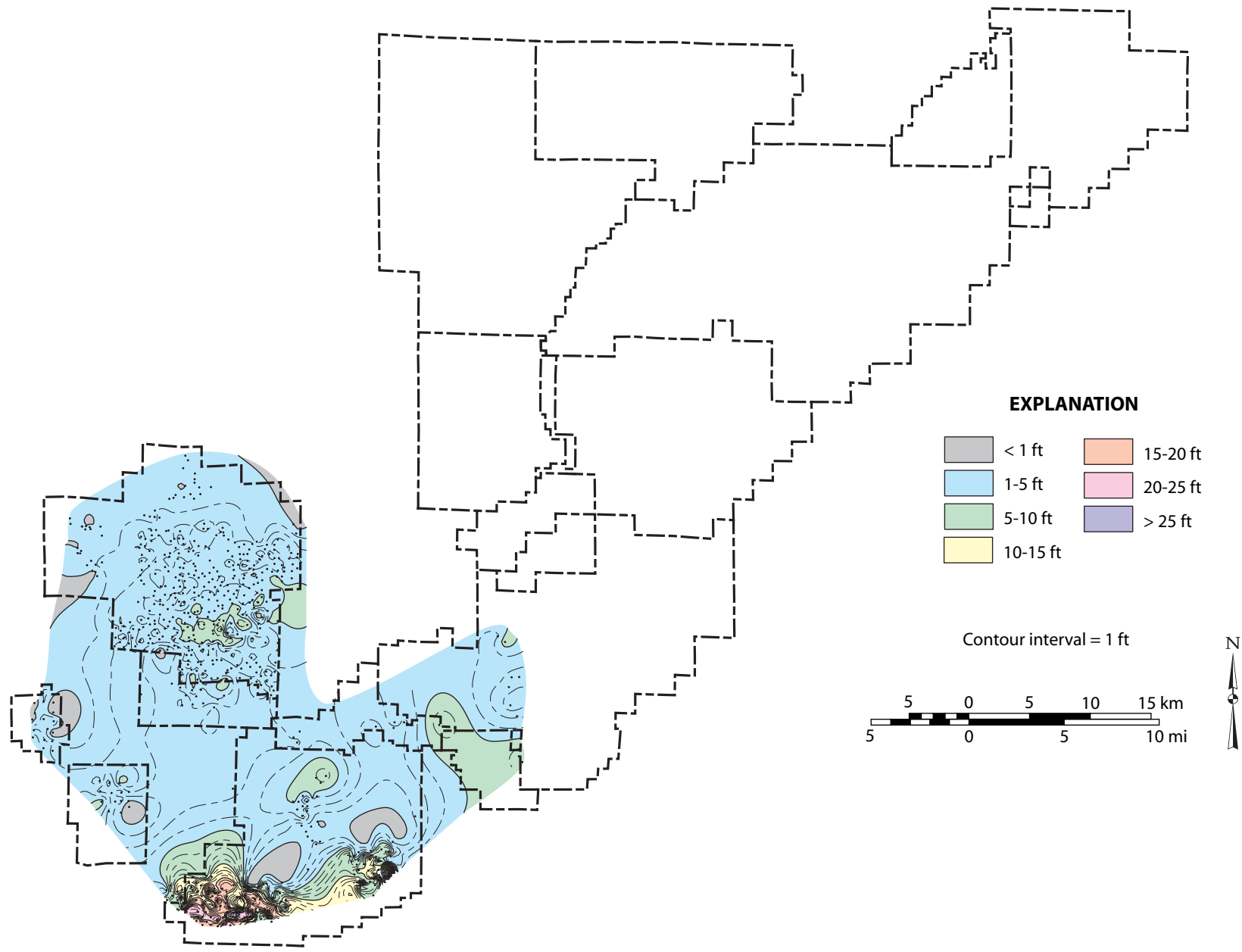


Figure 18.--Net coal isolith of the Brookwood coal zone in the Black Warrior coalbed methane fairway.

Moundville Field. As in the Utley zone, coal resources of the Brookwood coal zone are dispersed widely in several beds.

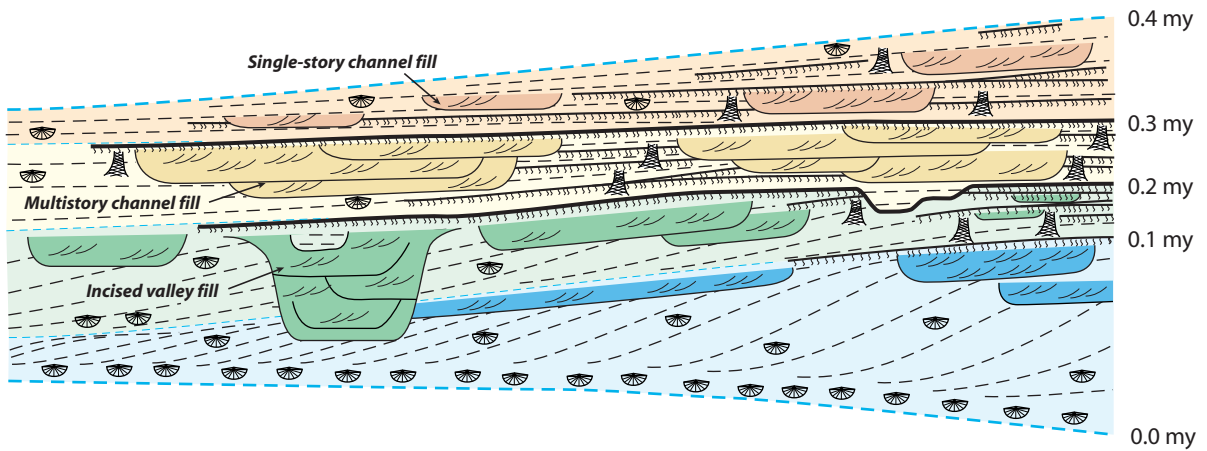
### **Interpretations**

Most Pottsville coal zones contain one to three widespread resource beds with potential for carbon sequestration and enhanced coalbed methane recovery (fig. 5; plates 1-10). Because prospective beds are dispersed through 1,500 to 4,500 feet of section, operators have developed multi-zone completion techniques to isolate and produce gas simultaneously from multiple coal beds (Graves and others, 1983), and similar multi-zone completion techniques can be applied to enhanced coalbed methane recovery operations. Experience has further dictated that completion technology be tailored to the mechanical and thermal challenges posed by coal beds at different depths (Elder and Deul, 1975; Lambert and others, 1980; Holditch and others, 1989), and conversion of production wells to injectors will probably require similar attention to detail. Cross sections and net coal isolith maps establish that the number and thickness of coal beds in the Pottsville Coal Interval increase toward the Moundville-Cedar Cove depocenter, but different coal zones and subzones are prospective in different parts of the coalbed methane fairway (figs. 9-18; plates 1-8). In the Black Creek coal zone, the Jefferson subzone contains a target bed with significant potential throughout the coalbed methane fairway, whereas the Ream subzone is prospective mainly along the southeastern margin of Oak Grove and Brookwood fields. Similarly, the Mary Lee and Pratt coal zones contain major target beds throughout the fairway,

whereas sequestration potential in the Gillespy and Curry zones is highly localized. In the Cobb through Brookwood coal zones, thick coal beds are concentrated along the southeastern margin of the basin in the Moundville-Cedar Cove depocenter, and although the coal thins northwestward, significant resource potential remains in Robinson's Bend Field.

Regional cross sections confirm that facies patterns in the Pottsville Formation are highly heterogeneous, reflecting a complex interplay among the fluvial-deltaic processes that deposited siliciclastic strata and the biological processes that favored peat accumulation (figs. 7, 19; plates 1-10). The flooding surfaces bounding each cycle are readily correlated among well logs and have proven useful for structural modeling (Wang and others, 1993; Smith, 1995; Pashin and Groshong, 1998).

Correlation of minor flooding surfaces within the depositional cycles indicates that many coal zones, specifically the Mary Lee, Gillespy, Cobb, Gwin, and Utley zones, each comprise sets of four parasequences (plates 3-10; fig. 19). The Curry and Pratt coal zones, moreover, can be considered together as another set of four parasequences (plates 5,6). Accordingly, if most upper Pottsville cycles are considered to have formed in response 4<sup>th</sup>-order changes of relative sea level driven by the long eccentricity cycle (~0.4 my), then each subordinate parasequence can be interpreted as the product of 5<sup>th</sup>-order sea-level changes driven by the short eccentricity cycle (~0.1 my) (fig. 19). Although an orbital eccentricity interpretation is applicable to the Mary Lee-Utley interval, interpretation of stratigraphic architecture in the Black Creek and Ream coal zones is less certain.



### EXPLANATION

- |      |  |  |  |                                 |
|------|--|--|--|---------------------------------|
| Coal |  | Primary resource target  |  | Cycle-bounding flooding surface |
|      |  | Secondary resource target  |  | Minor flooding surface          |
|      |  | Aggradational sandstone<br>(color-coded by parasequence)         |  | Shells and burrows              |
|      |  | Interbedded shale and sandstone<br>(color-coded by parasequence) |  | Plants                          |

Figure 19.—Generalized stratigraphic model of a Pottsville coal zone in the Black Warrior coalbed methane fairway.  
No scale intended.

Comparing cross sections of the Mary Lee through Utley cycles indicates that parasequences of the same color code have some common tendencies (plates 3-10; fig. 19). For example, blue-coded parasequences are developed mainly in the basal marine mudstone of most depositional cycles and are expressed mainly as coarsening-upward successions containing little coal. Green and yellow parasequences typically contain most of the economic coal beds, including major resource targets. Deeply incised, aggradational sandstone units are also common in the green- and yellow-coded intervals. In the northwestern coalbed methane fields, however, the yellow and green parasequences can form coarsening-upward intervals resembling the blue parasequences. The brown parasequences generally lack major resource coal beds and contain less aggradational sandstone than the green and yellow parasequences. A notable exception, however, is coal in the Pratt subzone, which is one of the most important drilling objectives in the Black Warrior coalbed methane fields. Core logs further establish that marine burrows and shells are more common near the upper contacts of the depositional cycles than in the main coal-bearing intervals (for example, see fig. 5).

The four-part parasequence sets can be classified as progradational, but the stratigraphic expression of the brown-coded parasequences is variable. In the Gillespy coal zone, for example, all four parasequences compose a progradational stacking pattern. Alternatively, the distribution of sandstone and marine fossils in the brown parasequences of the Mary Lee, Pratt, Cobb, Gwin, and Utley coal zones indicates retrogradation relative to the blue, green, and yellow-coded intervals (plates 3-10; fig. 19).

Sandstone has an extremely heterogeneous distribution within the Pottsville Coal Interval, and thick, aggradational sandstone bodies record numerous episodes of channel or valley incision and aggradation (plates 1-10). Single-story sandstone units apparently represent a spectrum of channel networks ranging from incised valley fills, braidplains, and distributary systems that were part of a drainage network that transported sediment from sources in the Appalachian orogen (Pashin and others, 1991; Pashin 1994a, c) (figs. 8, 19). These sandstone units are generally thinner than 50 feet and thus record only modest changes of base level or the autocyclic processes inherent in fluvial-deltaic systems.

By contrast, many of the multistory sandstone units, like those in the green and yellow parasequences of the Gwin coal zone (plates 7, 8), are in places more than 100 feet thick and appear to be deeply incised into older deltaic and coastal plain deposits or are a composite of multiple shallower incision events (fig. 19). Incised valley fill and braidplain sandstone bodies are common in Pennsylvanian strata of the Appalachian region and are thought to record lowstands associated with 3<sup>rd</sup>- and 4<sup>th</sup>-order changes of sea level (Chesnut, 1994; Aitken and Flint, 1994, 1995; Heckel and others, 1998). In the Black Warrior basin, however, incised valley fills and braidplain deposits are developed at multiple stratigraphic levels, particularly in the green and yellow parasequences (plates 5-10). This suggests that major erosional events in the Black Warrior coalbed methane fairway were a response to 5<sup>th</sup>-order sea-level changes and that development of individual sandstone stories was a response to even higher frequency stratigraphic processes (fig. 19).



Although few coal beds can be traced effortlessly through the coalbed methane fairway, the major resource beds nevertheless have great lateral extent, especially compared to the sandstone bodies (plates 1-10). This relationship indicates that peat pure enough to form coal accumulated after most channels and paleovalleys had aggraded completely (fig. 19). According to Diessel (1992, 1998), aggradation of valleys and channels is commonly required to support the high water table necessary to paludify large regions and support widespread peat accumulation. As many as three major resource coal beds are developed in some cycles, and one possibility is that regional paludification was at least partly a response to base level rises driven by the short eccentricity cycle, especially in the Mary Lee, Cobb, and Gwin coal zones (plates 3, 4, 7, 8). An everwet, equatorial climate prevailed in the Appalachian region during the Early Pennsylvanian (Cecil, 1990), and conditions were apparently humid enough to support swamp development in the underfilled paleovalley system that contains thick Blue Creek coal (plates 3, 4).

Roof strata in the coalbed methane fairway are dominated by mudstone (plates 1-10), suggesting that swamps were inundated with mud as base level continued rising. Inundation of peat swamps can take place by a variety of mechanisms depending on the local depositional environment, including marine flooding, overbank flooding, crevassing, channel avulsion, and deflation of water-laden peat bodies (e.g., Ferm, 1970; McCabe, 1984; Diessel, 1992). Between accumulation of major peat beds and downcutting of major valleys and channels, sedimentation was dominated by deposition of mudstone, thin sandstone units, and thin coal beds that have been preserved as secondary resource targets and organic-rich marker beds.

Three or more thin coal beds are between the significant resource beds in the Black Creek, Mary Lee, Pratt, and Gwin coal zones, especially in the Moundville-Cedar Cove depocenter, where rapid subsidence arguably facilitated preservation of the most complete stratigraphic successions (plates 1-8). Accumulation of thin coal beds may be controlled in large part by autocyclic processes like channel avulsion. Nonetheless, the thin coal beds and organic-rich shale markers represent high-frequency stratigraphic events within the general time frame of Milankovitch obliquity (40 ky) and precession (20 ky), so extreme high-frequency allocyclic control of sedimentation cannot be ruled out (fig. 19).

These results indicate that many factors have contributed to extreme facies heterogeneity in the Pottsville Coal Interval. Although the Pottsville is heterogeneous, our research suggests that high-resolution stratigraphic models help explain this heterogeneity and the distribution of potential targets for carbon sequestration. However, stratigraphic and sedimentologic studies provide only part of the information required to characterize coalbed methane reservoirs, and investigation of structural geology is required to provide a full picture of the geometry of coal-bearing strata.

## **STRUCTURAL GEOLOGY**

Folding, faulting, and fracturing modify the geometry, continuity, and hydraulic conductivity of coal beds and associated strata during and after deposition. Tectonic deformation of Pottsville strata began in the depositional environment and continued after deep burial (Weisenfluh and

Ferm, 1984; Thomas, 1988; Pashin, 1994c, 1998; Pashin and Groshong, 1998). Strata in the Pottsville Coal Interval lack matrix permeability to water, thus virtually all flow is through natural fractures (Pashin and others, 1991). Natural fractures in the Pottsville Formation include joints, cleats, and fault-related shear fractures (Ward and others, 1984; Pashin and others, 1991, 1999; Pashin, 1998).

Pashin and others (1995a) and Pashin and Groshong (1998) suggested that large-scale folds and faults influence coalbed methane production by determining the abundance and openness of natural fractures. Accordingly, it follows that these same structures will impact carbon sequestration capacity and the applicability of sequestration technology. In this section, we review the geologic structure of the Black Warrior coalbed methane fairway.

### **Appalachian Folds and Thrust Faults**

The coalbed methane fairway can be characterized most simply as a homocline that dips southwest toward the Ouachita orogenic belt and contains numerous superimposed folds and faults (Thomas, 1988) (figs. 20, 21). Folds of the Appalachian thrust belt are superimposed on the southeast margin of this homocline and include the Sequatchie anticline, the Coalburg syncline, and the Blue Creek anticline. The Sequatchie anticline is a prominent frontal structure of the Appalachian orogen in Alabama and Tennessee; it plunges southwestward, terminating in northern Oak Grove Field. The anticline is detached above crystalline basement in Cambrian shale and provided the basis for the first thin-skinned structural models of the Appalachian

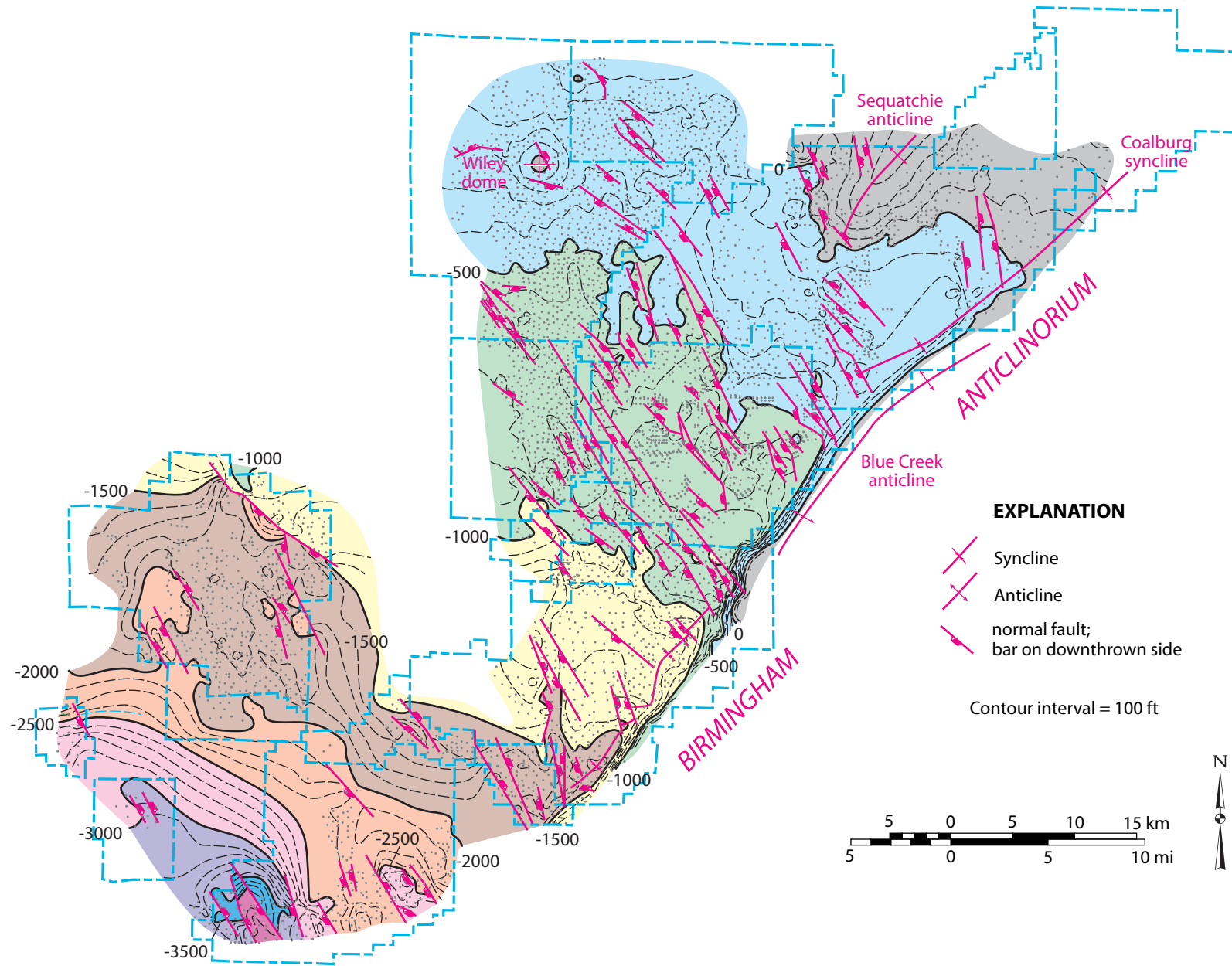


Figure 20.—Generalized structural contour map of the top of the Pratt coal zone in the Black Warrior coalbed methane fairway.

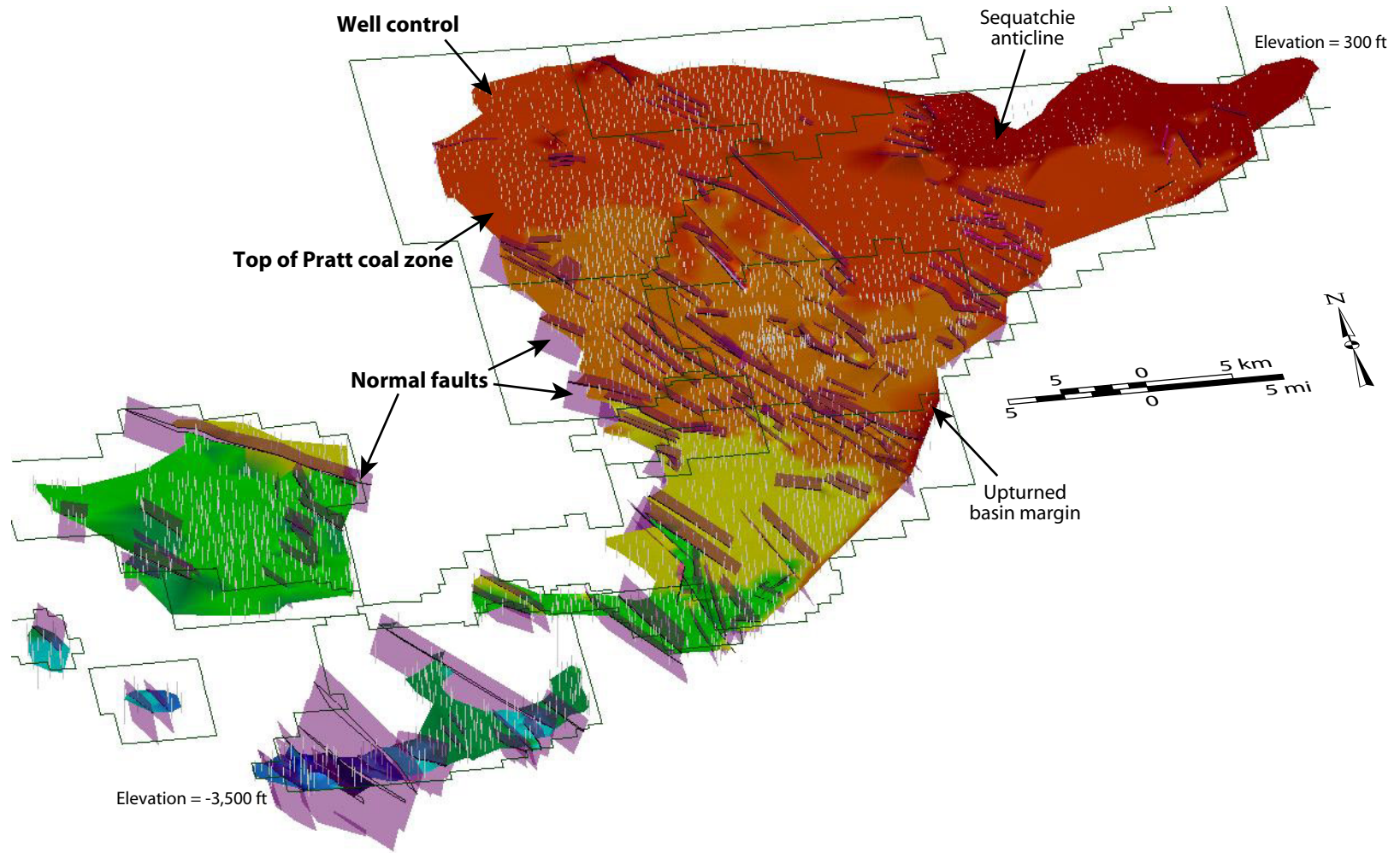


Figure 21.--Three-dimensional perspective view of the structure of the top of the Pratt coal zone in the Black Warrior coalbed methane fairway.

orogen (Rodgers, 1950). In Oak Grove Field, the Sequatchie anticline is a broad, open detachment fold with about 400 feet of structural relief and an interlimb angle of  $178^{\circ}$  (Pashin, 1994c; Pashin and Groshong, 1998).

Structures along the southeast margin of the coalbed methane fairway include a series of northeast-striking folds associated with the forelimb of the Birmingham anticlinorium (fig. 20). The Birmingham anticlinorium is a broad anticlinal structure that brings Cambrian-Ordovician carbonate rocks to the surface and is detached in Cambrian shale (Osborne and others, 1989; Thomas, 2001). The Coalburg syncline is a flat-bottomed structure that shares a common limb with the Sequatchie anticline (Semmes, 1929) and has an axial trace that follows the southeast margin of the coalbed methane fairway (fig. 20). The southeast flank of the Coalburg syncline is nearly vertical and has been overthrust in part by Cambrian-Ordovician carbonate rocks (Butts, 1910, 1927; Osborne and others, 1989) and is thus a footwall syncline in the forelimb of the Birmingham anticlinorium.

The Blue Creek anticline is an arcuate structure that strikes northeast, following the southeast boundaries of Oak Grove and Brookwood fields (fig. 20). The forelimb of the structure locally dips steeper than  $50^{\circ}$  NW and is thought to be a major recharge zone that has fed fresh water deep into the Pottsville Formation through coal beds and fractures exposed on the flank (Pashin and others, 1991; Ellard and others, 1992; Pashin and Hinkle, 1997). The Blue Creek anticline is thought to have formed above a blind detachment developed at least partly within Mississippian siliciclastic rocks (Thomas, 1985b; Cates and Groshong, 1999). Pottsville strata can be traced

across the anticline, and the Mary Lee coal zone is exposed on both flanks of the structure within a mile of where it is degassed at depth (Semmes, 1929; Pashin and others, 1991).

Southwest of the Blue Creek anticline in Cedar Cove Field, numerous coalbed methane wells penetrate a northwest-dipping fold limb (Ellard and others, 1992; Sparks and others, 1993).

Many of these wells have been drilled through a thrust-fault complex that juxtaposes Cambrian-Ordovician carbonate rocks with the Pottsville Formation (fig. 22). In this area, the upturned southeast margin of the Black Warrior basin is a footwall syncline that is analogous to the Coalburg syncline in Oak Grove Field. However, dip of the upturned limb in Cedar Cove Field is generally less than  $10^{\circ}$  NW.

The frontal thrust fault of the Appalachian orogen curves westward through Moundville Field, following the edge of the coalbed methane fairway. In this area, however, few wells penetrate structure directly associated with the Appalachian thrust belt. Instead, wells penetrate a horst-and-graben system that is similar to other extensional structures found throughout the eastern Black Warrior basin.

### **Horst and Graben Systems**

Throughout the coalbed methane fairway, the southwest-dipping homocline of the Black Warrior basin is broken by normal faults that generally strike northwest (figs. 20-22). Trace length of the subsurface-mappable faults ranges from about 1 to 8 miles. Fault strike averages about N.  $30^{\circ}$  W. and ranges from N.  $7^{\circ}$  W. in eastern Oak Grove Field to N.  $54^{\circ}$  W. in

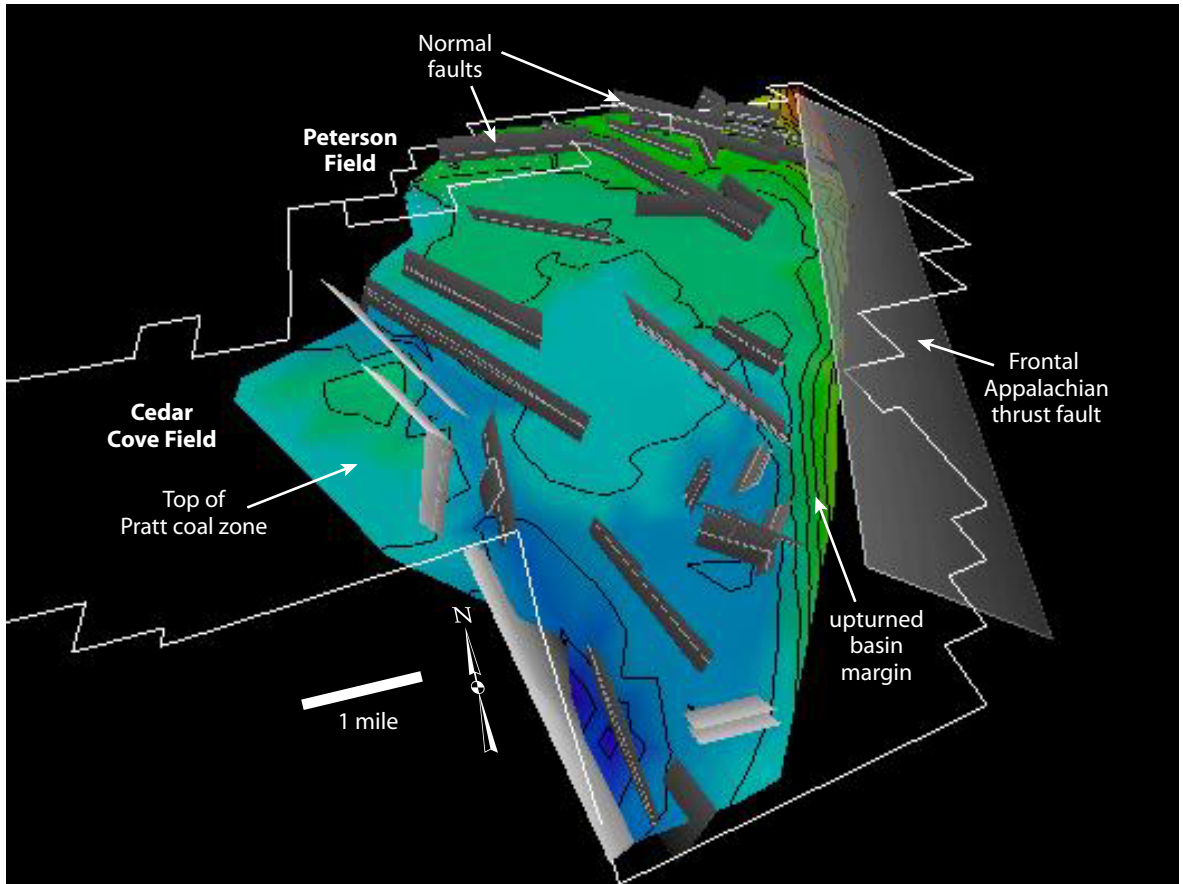


Figure 22.--Structural model of the top of the Pratt coal zone in Cedar Cove and Peterson fields.



Robinson's Bend Field. Dip of the faults is generally between 50 and 70°, and the faults form a horst-and-graben system in which about 60 percent of the mapped faults dip southwest and the remaining faults dip northeast. The faults tend to be planar or are composed of planar segments with sharp bends (figs. 20-22). Vertical separation of the faults is typically less than 250 feet, but displacement exceeds 750 feet along a fault in northeastern Robinson's Bend Field and approaches 1,000 feet along a fault in southwestern Moundville Field.

Structural style changes across the coalbed methane fairway (figs. 20, 21) and is thought largely to be the product of flexural extension related to overthrust loading in the Ouachita orogen (Wang and others, 1993; Cates and Groshong, 1999). The major fault in northeastern Robinson's Bend Field marks the edge of a large half graben and extends into crystalline basement, apparently joining with a mid-crustal detachment (Hawkins and others, 1999). The normal faults compose subparallel horsts and grabens in a corridor stretching from Moundville Field to Brookwood and Deerlick Creek fields. From Deerlick Creek Field northeastward, balanced structural modeling and surface mapping indicate that the horst and graben system is thin-skinned, having formed above a basal detachment near the base of the Pottsville Formation (Wang and others, 1993; Smith, 1995; Cates and Groshong, 1999) (fig. 23).

From Deerlick Creek Field northeastward, fault patterns become increasingly en echelon, forming right-stepping patterns that indicate a component of left-lateral shear (Butts, 1910, 1927; Pashin, 1994c) (figs. 20, 21). The Sequatchie anticline terminates at a north-south trending swarm of en echelon normal faults in central Oak Grove Field, which Pashin (1994c) interpreted

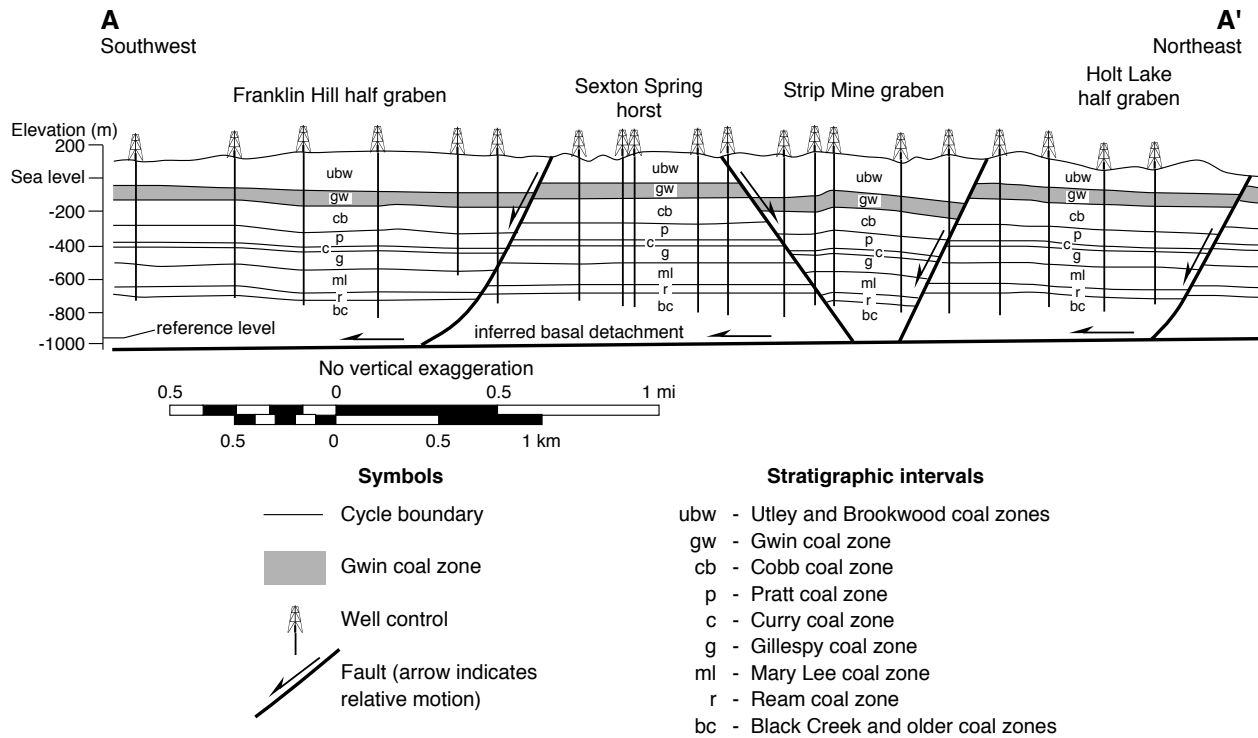


Figure 23.—Balanced structural cross section of the Pottsville Formation in Deerlick Creek Field (modified from Wang and others, 1993).

as a transtensional tear fault system marking the edge of the Sequatchie detachment block. Thus, the northeastward trend toward an echelon faulting is interpreted to be the product of a progressive kinematic linkage between regional flexural extension in the Black Warrior basin and the Appalachian thrust belt.

The population distribution of partially calcite-filled fracture apertures in shale and sandstone of the upper Pottsville Formation can be characterized by exponential functions based on data from five cores in Brookwood Field (fig. 24). Percentile plots indicate that about 60 percent of the joints sampled are hairline fractures with kinematic aperture smaller than 0.1 millimeters, whereas less than 35 percent of the fault-related shear fractures are hairline fractures.

Accordingly, fault-related fractures have greater potential to transmit fluid than do joints. Joints in the Pottsville Formation tend to be stratabound (i.e., concentrated in discrete beds) whereas fault zones cut across bedding and commonly extend from the reservoir zone to the surface.

Clayton and others (1994) identified a significant methane seep along a normal fault in Oak Grove Field, and faults should be treated cautiously as potential leakage hazards for sequestered CO<sub>2</sub>. Although faults may pose leakage hazards, large structural panels lacking significant faults exist in most coalbed methane fields, and perhaps these panels should be given priority for the demonstration of carbon sequestration and enhanced coalbed methane recovery technology.

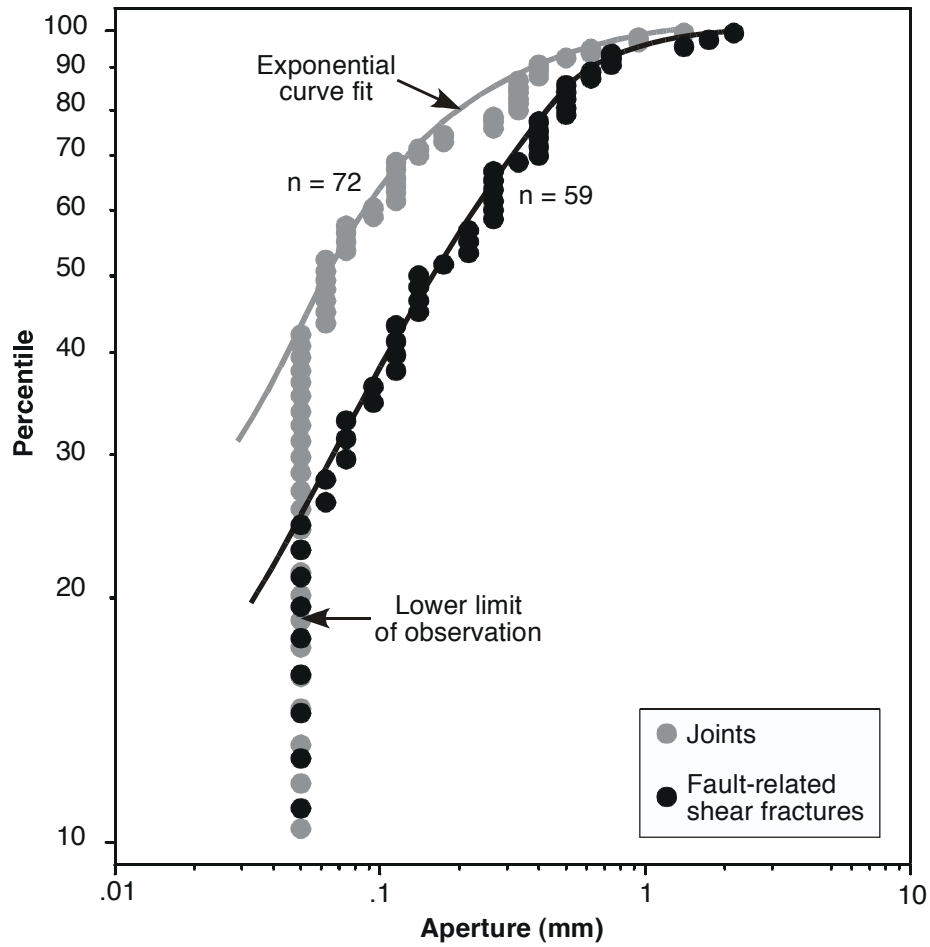


Figure 24.--Percentile plot showing the frequency of kinematic-aperture size classes for joints and fault-related shear fractures in five cores from Brookwood Field.

## **Regional Tilting**

A structural contour map of the base of the Tuscaloosa Group demonstrates that the unconformity surface separating the Pottsville Formation from the Mesozoic-Cenozoic cover of the Gulf Coastal Plain and Mississippi Embayment dips southwest (Kidd, 1976) (fig. 25).

Cretaceous strata are absent northeast of Brookwood and Blue Creek Fields. Contour patterns indicate that the unconformity surface strikes N. 38° W. in Brookwood and Blue Creek fields and strikes about N. 46° W. along the southwest edge of the coalbed methane fairway.

Between an elevation of 300 and 600 feet above sea level, outliers of Cretaceous strata predominate. A short distance southwest of the 300 foot contour, the Pottsville Formation is effectively buried below poorly consolidated Cretaceous cover. In the southwestern coalbed methane fields, the Mesozoic section is locally thicker than 900 feet, and the top of the Pottsville Formation lies more than 600 feet below sea level. Dip of the unconformity surface increases southwestward and is less than 1 degree throughout the study area.

All normal faults in the Black Warrior basin terminate at the regional unconformity marking the base of the Mesozoic-Cenozoic cover sequence in the Gulf Coastal Plain and the Mississippi Embayment (Thomas, 1988). Therefore, no structural reactivation of the faults has taken place since before the Tuscaloosa Group was deposited during the Late Cretaceous. Instead, the increasing southwest dip indicates that structural movement following Late Cretaceous reburial of the Black Warrior basin was dominated by southwestward tilting and flexure related to

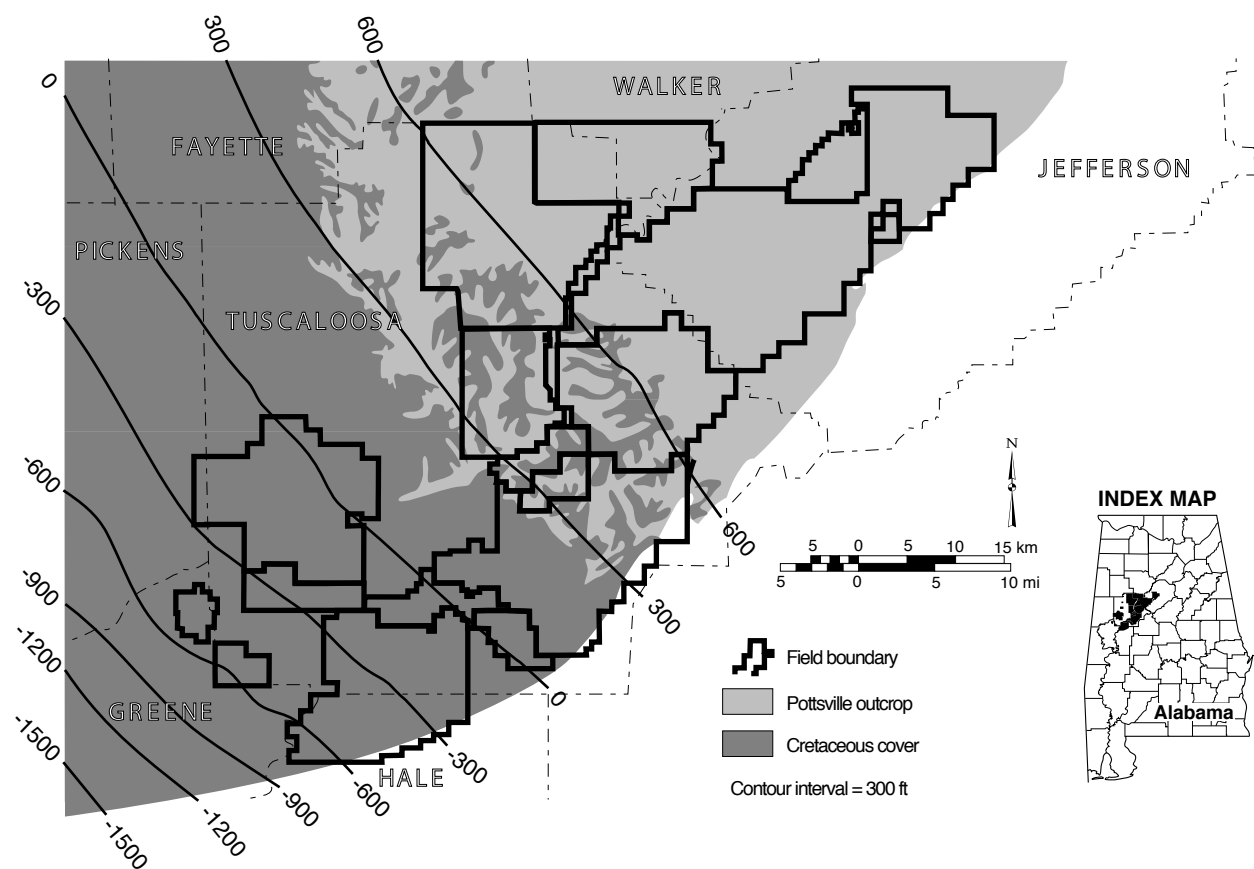


Figure 25.—Structural contour map of the unconformity surface separating the Pottsville Formation and Tuscaloosa Group (modified from Kidd, 1976).

development of the Gulf of Mexico passive margin and subsidence of the Mississippi Embayment.

## **GEO THERMICS**

Understanding temperature and pressure conditions in coal-bearing strata is important from two major standpoints. The first is that sorption of gas on coal, including methane and carbon dioxide, is sensitive to temperature and pressure (e.g., Jüntgen and Karweil, 1966; Yang and Saunders, 1985; Kroos and others, 2002) The second is that phase relationships dictate that carbon dioxide becomes a supercritical fluid above a temperature of 88°F and a pressure of 1,074 psi, which is well within reservoir conditions (fig. 26). In this section, we discuss reservoir temperature and geothermal gradient in the coalbed methane fairway, and in the following section on hydrogeology, we characterize reservoir pressure.

Bottom-hole temperature in the Pottsville Formation ranges from less than 80°F to more than 140°F in wells reaching total depth between 1,000 and 6,000 feet (fig. 27). Temperature and depth correlate with a coefficient of determination ( $r^2$ ) of 0.72, reflecting significant variation of the modern geothermal gradient. The regression line projects to a y-intercept of 74°F, which is about 10° above the current mean annual surface temperature in west-central Alabama.

Statistical analysis of the geothermal gradient calculations establishes a normal distribution with a strong central tendency around a mean gradient of 9.0°F/1,000 feet (fig. 28). This distribution

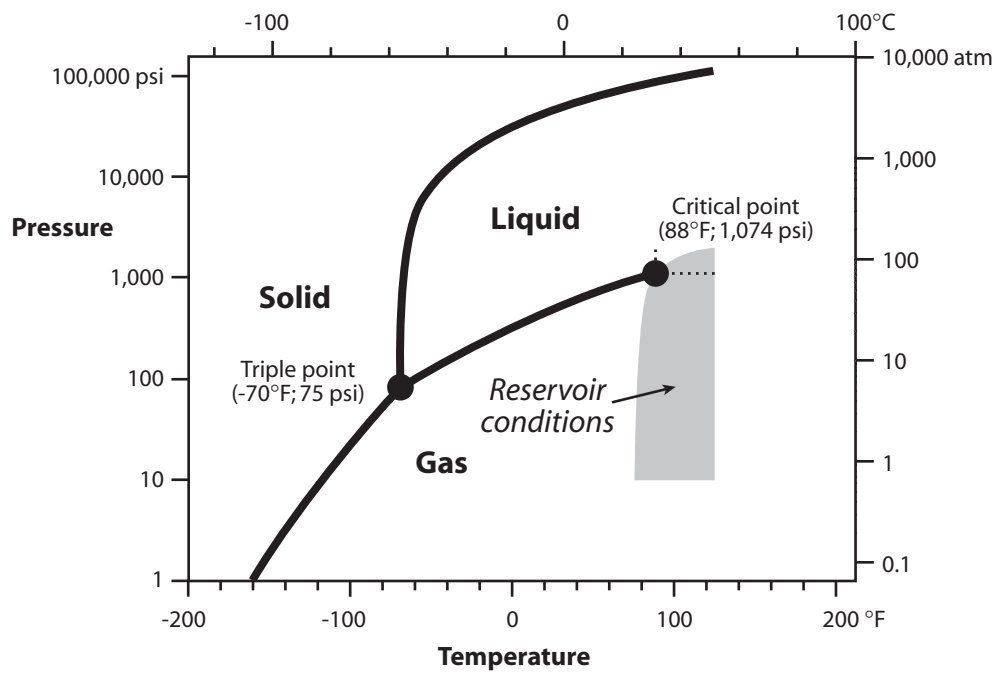


Figure 26.--Phase diagram for CO<sub>2</sub> showing relationship of the critical point to reservoir conditions in the Black Warrior coalbed methane fairway.



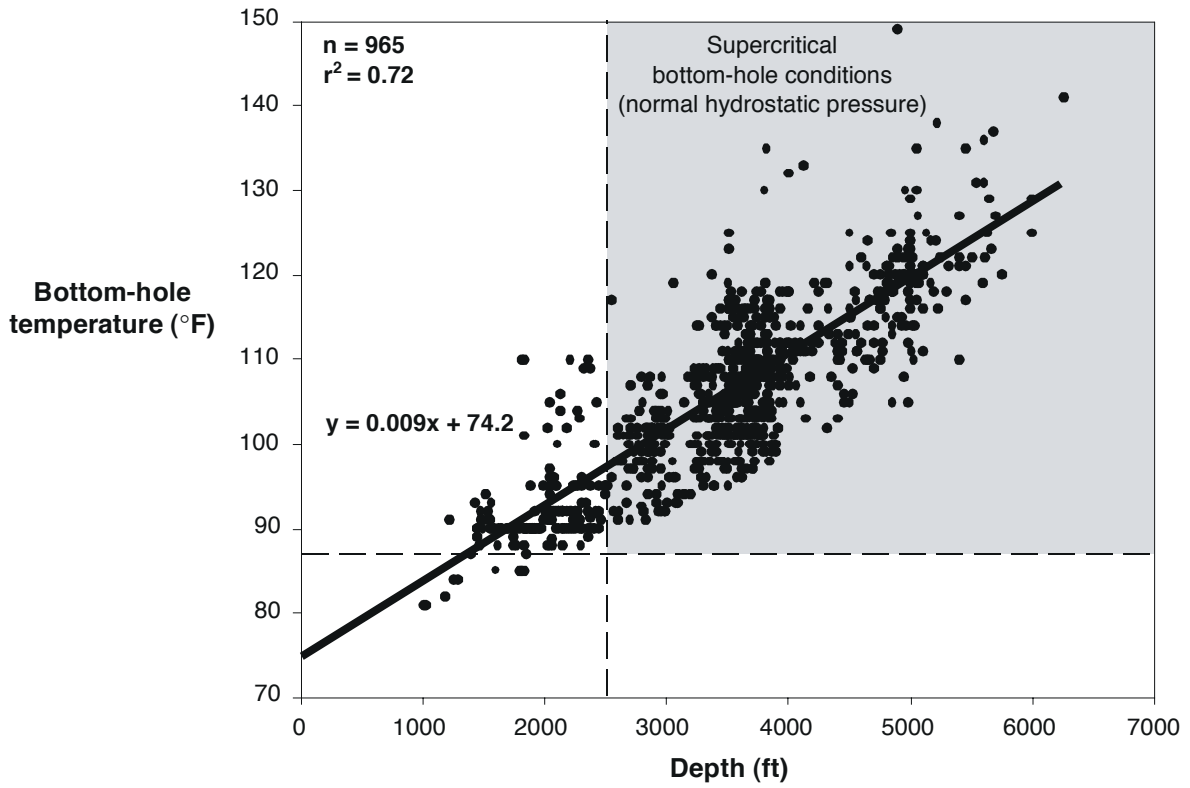


Figure 27.--Temperature-depth plot for coalbed methane wells in the Black Warrior basin.

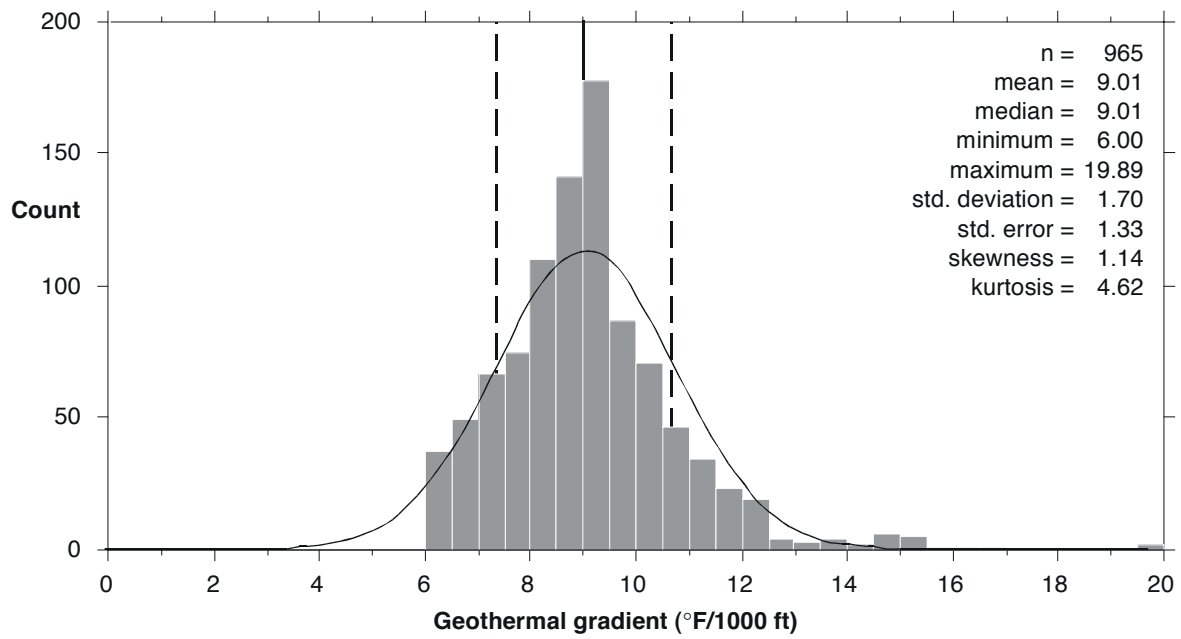


Figure 28.--Histogram showing population distribution of geothermal gradients in the Black Warrior coalbed methane fairway.

is positively skewed, and geothermal gradient ranges regionally from about 6.0°F/1,000 feet to nearly 20.0°F/1,000 feet.

Mapping confirms that geothermal gradient in the coalbed methane fairway is typically between 6 and 12°F/1,000 feet, although data are sparse in Deerlick Creek, Blue Creek, and White Oak Creek fields (fig. 29). Areas with geothermal gradient higher than 12°F/1,000 feet are distributed among several gas fields and are most common in western Oak Grove Field. No obvious correlation exists between geothermal gradient and structure, and the origin of areas with exceptionally elevated geothermal gradient remain a matter for speculation.

A map of estimated reservoir temperature at the top of the Pratt coal zone demonstrates that temperature increases southwestward from less than 80°F in the northeastern part of the coalbed methane fairway to more than 110°F in the southwestern part (fig. 30). The overall temperature pattern reflects the geologic structure of the coalbed methane fairway, and contours parallel the major normal faults in Cedar Cove, Robinson's Bend, and Moundville fields, as well as the western flank of the Blue Creek anticline in Cedar Cove Field. Local topographic relief is less than 250 feet in most of the coalbed methane fairway and is thus only a minor control on reservoir temperature. Areas with increased geothermal gradient are superimposed on the regional structure-dominated pattern in western Oak Grove Field and in parts of several other fields (figs. 28-30). The Pratt coal zone reaches the critical reservoir temperature of 88°F in Cedar Cove, Holt, and Robinson's Bend fields (fig. 30). However, reservoir pressure must be

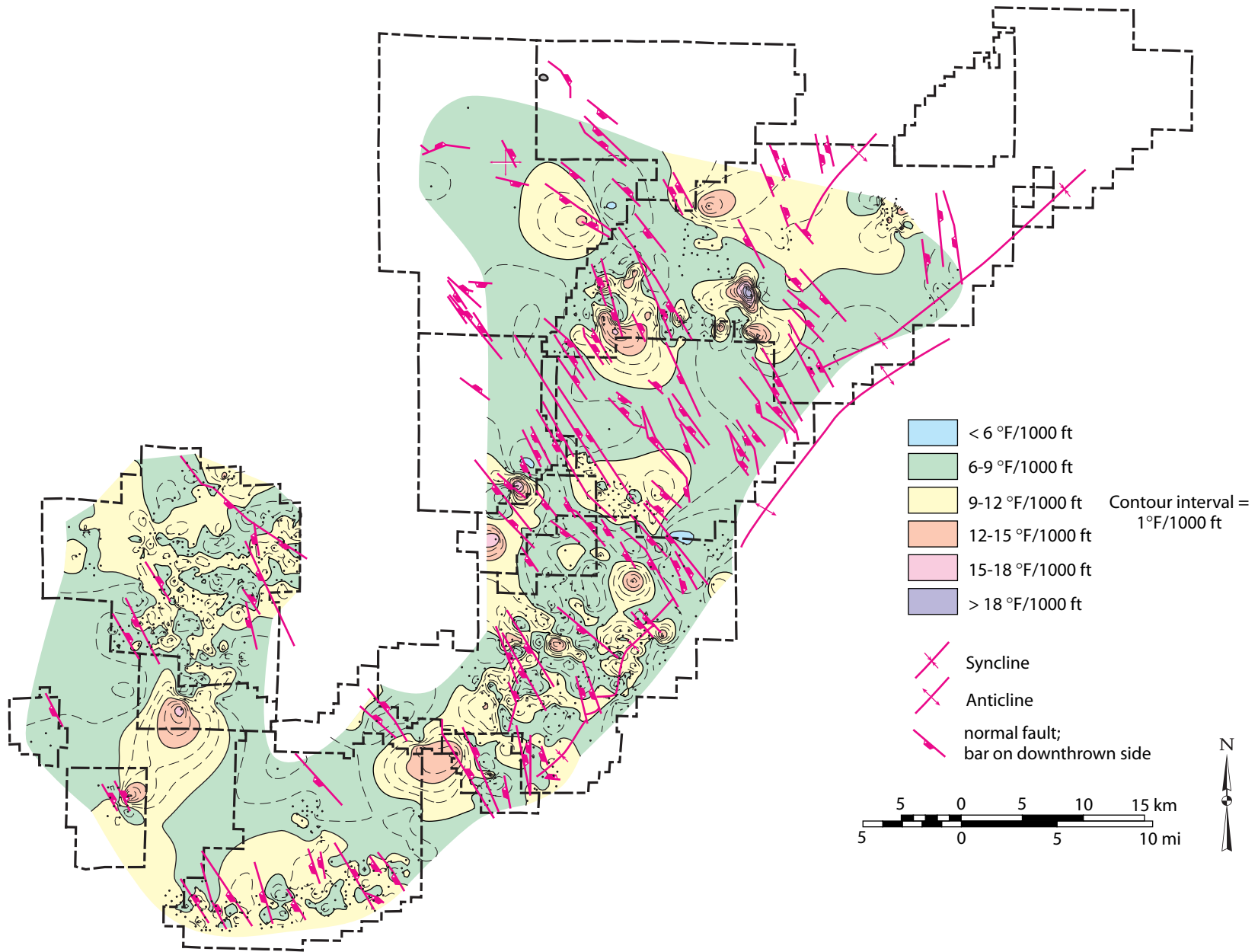


Figure 29.--Map of geothermal gradient in the Black Warrior coalbed methane fairway.

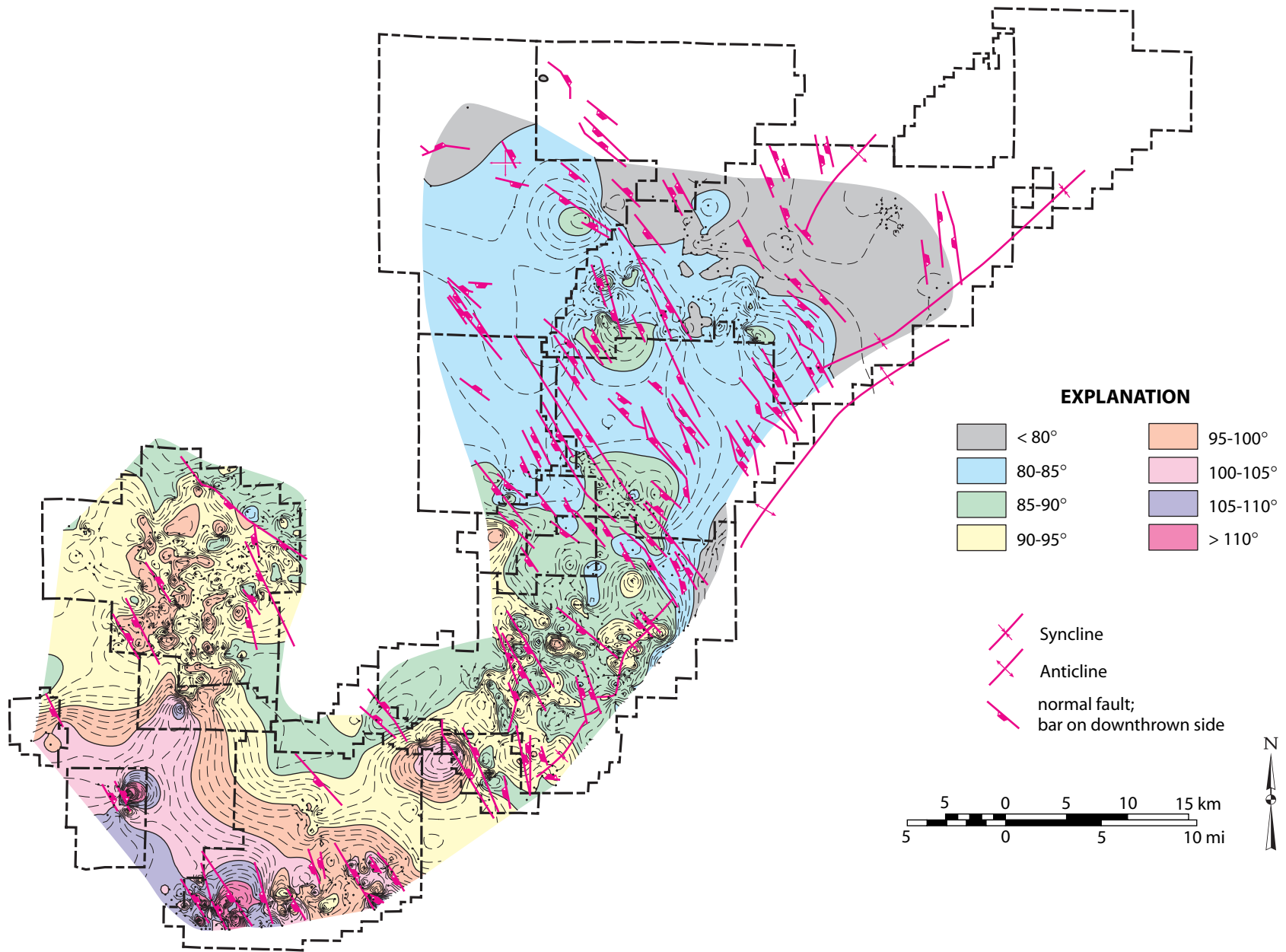


Figure 30.—Map of temperature at the top of the Pratt coal zone in the Black Warrior coalbed methane fairway.

determined and mapped to predict where supercritical fluid conditions may affect carbon sequestration and enhanced coalbed methane recovery operations.

## **HYDROGEOLOGY**

Two aspects of hydrogeology that are critical screening criteria for carbon sequestration and enhanced coalbed methane recovery are water chemistry and reservoir pressure. Water chemistry is important because injection of carbon dioxide into coal may sweep a large volume of formation water that must be disposed inexpensively and in an environmentally sound manner and because of underground injection control (UIC) regulations protecting underground supplies of drinking water (USDW). Reservoir pressure is a basic limiting factor on gas content, and in primary coalbed methane production, reservoir pressure must be lowered sufficiently by dewatering for gas to desorb from coal. In this section we review the permeability and water chemistry of coalbed methane reservoirs in the Black Warrior basin and present a new analysis of reservoir pressure in the Pottsville Formation.

### **Permeability and Water Chemistry**

Strata of the Pottsville Coal Interval in the Black Warrior coalbed methane fairway have effectively no matrix permeability. For example, sandstone in the coalbed methane fields has permeability of only 0.03 to 0.06 md (millidarcy), which approaches the permeability of shale (Pashin and Hinkle, 1997). For this reason virtually all flow of water through the Pottsville Coal

Interval takes place through natural fractures. The close spacing of cleats in coal relative to joints in shale and sandstone gives coal the best aquifer and reservoir properties of any rock type in the Pottsville Formation. On the basis of slug tests, the Pottsville can be considered a poorly transmissive system with permeability between 10 and 100 md at reservoir depth (McKee and others, 1988). McKee and others found that permeability in coal of the Pottsville Formation is highly stress-sensitive and decreases downward from nearly a darcy at the ground surface to tens of millidarcies or less below 1,000 feet.

Stiff diagrams demonstrate that subsurface waters in the Black Warrior coalbed methane fairway contain variable concentrations of sodium bicarbonate and sodium chloride (Pashin and others, 1991) (fig. 31). Water containing about 30 equivalents per million of sodium bicarbonate is typical of subsurface water shallower than 1,500 feet in the coalbed methane fields. However, water containing significant concentrations of sodium chloride has been identified as shallow as 1,000 feet. Bicarbonate concentration is effectively constant regardless of depth, and increasing concentrations of sodium chloride dominate the water chemistry below 1,500 feet. Disposal of saline formation water is a major concern in much of the coalbed methane fairway, and current practice is in-stream disposal augmented by some deep well disposal (Raymond, 1991; Ortiz and others, 1993; Pashin and Hinkle, 1997).

Shallow bicarbonate water in the Pottsville Formation apparently formed by meteoric recharge of the phreatic zone. The similar amount of bicarbonate in deep, saline water suggests a genetic linkage with the shallow water, but the increased chlorinity indicates that this water is

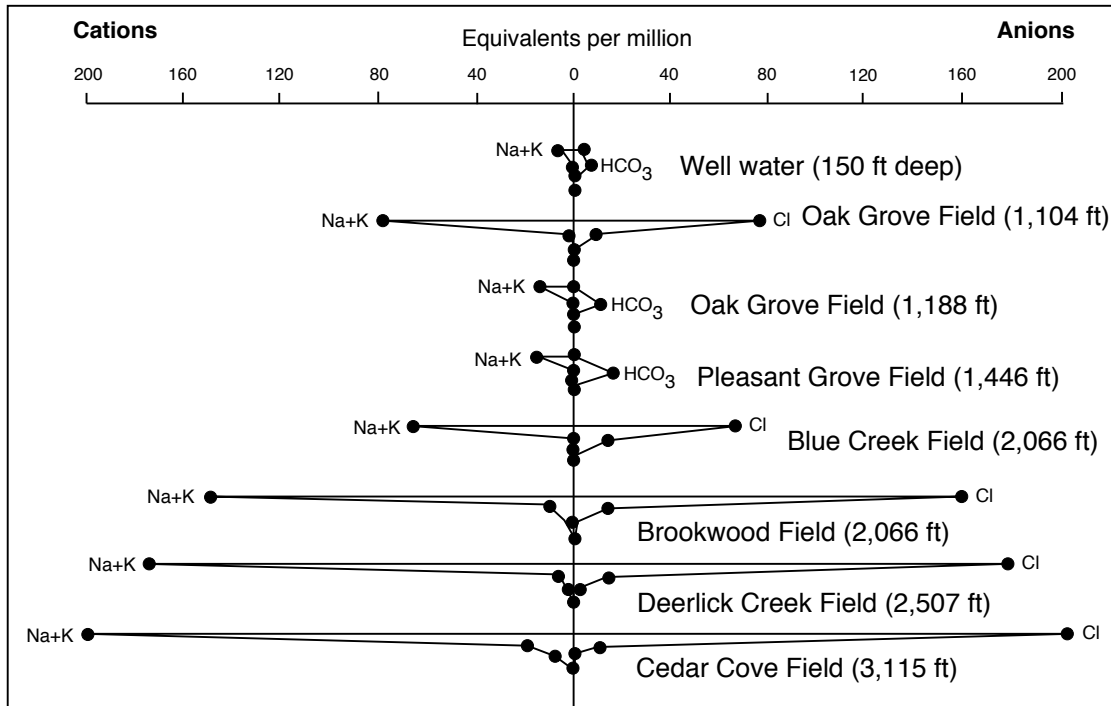


Figure 31.--Stiff diagrams showing the composition of formation water in the Pottsville Formation (modified from Pashin and others, 1991).



sufficiently old to have equilibrated with brine below the Pottsville Coal Interval. Presence of contrasting bicarbonate and chloride waters between 1,000 and 1,500 feet indicates mixing within the productive reservoir zone.

Total dissolved solids (TDS) content is less than 10,000 mg/L (milligrams per liter) in most of the coalbed methane fairway (Pashin and others, 1991; Ellard and others, 1992, 1997; Sparks and others, 1993), thus many parts of the Pottsville Coal Interval can be classified as a USDW. Along the southeastern margin of the basin, water in the Mary Lee coal zone consistently has TDS content lower than 3,000 mg/L, and in places, TDS content is less than 1,000 mg/L (Pashin and others, 1991) (fig. 32). Upturned and fractured strata in the forelimb of the Birmingham anticlinorium form a recharge zone in which the coal beds that produce coalbed gas at depth are at or near the surface. Accordingly, water with TDS content less than 3,000 mg/L has been interpreted to define a series active fresh-water water plumes that extend from the forelimb of the Birmingham anticlinorium deep into the Black Warrior basin (Pashin and others, 1991). Termination of the fresh-water plumes at the edge of Cretaceous cover suggests that poorly consolidated strata of the Tuscaloosa Group intercept recharge in the southwestern coalbed methane fields.

The TDS content of water in the Pottsville Formation has important implications for the applicability of carbon sequestration and enhanced coalbed methane recovery. Carbon sequestration in the absence of enhanced gas recovery can be considered as a Class I UIC process, which is prohibited in USDW under current regulations. Enhanced coalbed methane

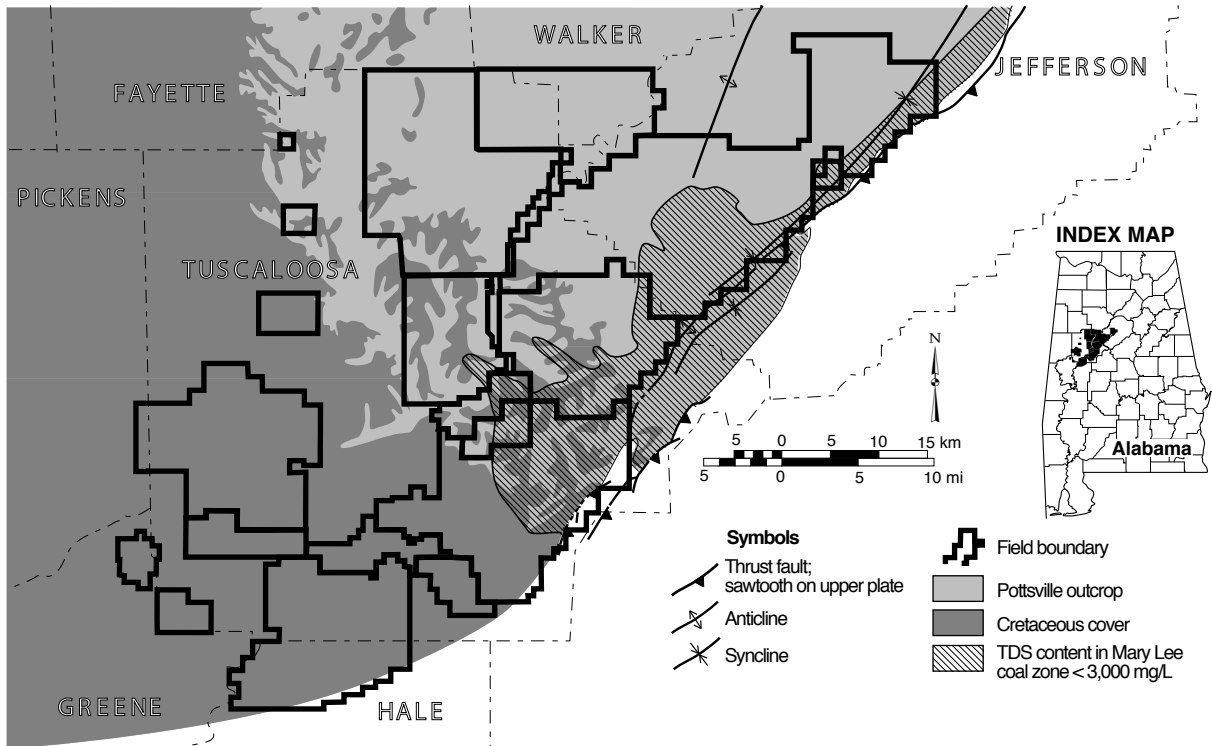


Figure 32.—Map showing freshwater plumes in the Mary Lee coal zone adjacent to the forelimb of the Birmingham anticlinorium (modified from Pashin and others, 1991).

recovery, alternatively, is a Class II UIC process. According to Class II UIC regulations, an aquifer exemption may be granted for enhanced recovery of hydrocarbons in USDW provided that the TDS content of the formation water exceeds 3,000 mg/L. According to these regulations, enhanced coalbed methane recovery would be prohibited in the fresh-water plumes along the southeast margin of the Black Warrior basin.

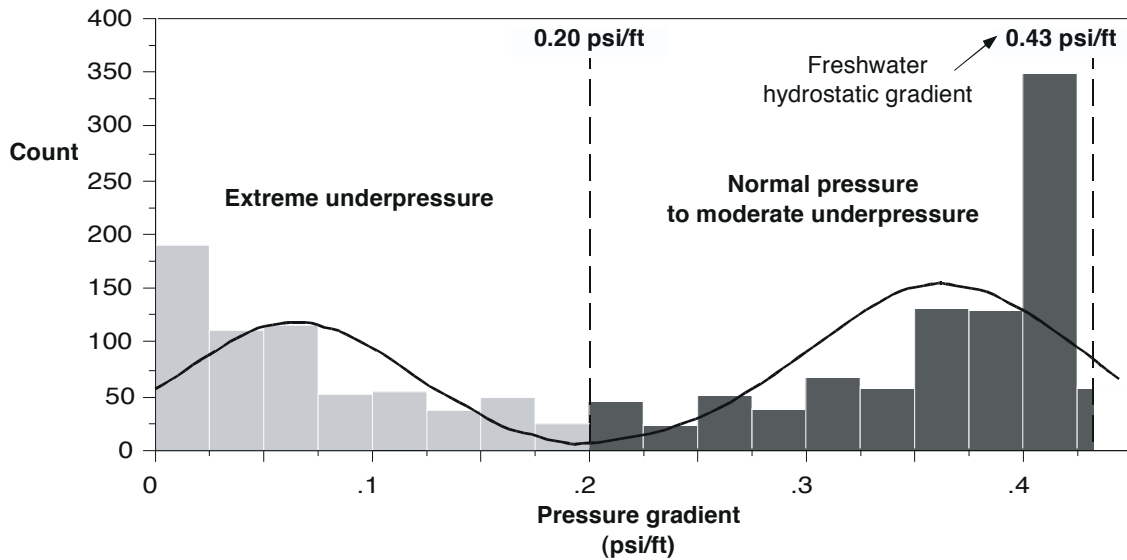
Water chemistry also has direct operational implications for carbon sequestration and enhanced coalbed methane recovery operations. Formation water in the Pottsville Formation is saturated with calcium carbonate, which can lead to precipitation of calcite scale on perforations during gas production. Ellard and others (1997) indicated that scaling is enhanced in wells where the salinity of produced formation fluids decreases over time. Injection of CO<sub>2</sub> into the Pottsville Formation will increase the acidity of the formation water, thus preventing scale and helping to dissolve fracture-filling calcite. Near production wells, however, reduced pressure may facilitate precipitation of calcite scale, thus further research is needed on the potential of enhanced coalbed methane recovery operations on water chemistry and mineral precipitation.

### **Reservoir Pressure**

Reservoir pressure includes lithostatic and hydrostatic components, and each of these components is of critical concern in coalbed methane production and carbon sequestration. Lithostatic and hydrostatic stress combine to influence macroporosity and permeability in coal, which are much more stress-sensitive than in other rock types (McKee and others, 1988).

Moreover, coalbed methane production is induced by dewatering, and therefore, lowered hydrostatic pressure is the principal mechanism by which gas flows to the wellbore. Examination of bulk density logs indicates that lithostatic pressure gradients in the Pottsville Formation are about 1.1 psi/ft and in the Tuscaloosa Group are about 1.0 psi/ft. Salinity of formation water in the Pottsville Formation is typically well below that of sea water, so hydrostatic pressure can be estimated readily from water-level data using a freshwater hydrostatic gradient of 0.43 psi/ft, and effective stress can be estimated by subtracting the hydrostatic pressure gradient in a given well from the lithostatic gradient (McKee and others, 1988).

Water-level data indicate that the hydrostatic pressure gradient in the Black Warrior coalbed methane fairway varies from normal (0.43 psi/ft) to abnormally low ( $<0.05$  psi/ft) (figs. 33, 34). A histogram and pressure-depth plot indicate that pressure gradient has a nearly bipolar population distribution, and wells with a hydrostatic pressure gradient less than 0.20 psi/ft can be classified as extremely underpressured; those with a higher gradient can be classified as normally pressured to moderately underpressured. Extremely underpressured wells cluster about a median of 0.05 psi/ft and form a positively skewed subpopulation, and normally pressured to moderately underpressured wells cluster about a median of 0.39 psi/ft and form a negatively skewed subpopulation. A pressure-depth plot reveals that wells with normal pressure to moderate underpressure exist at all bottom-hole depths, whereas extremely underpressured wells are clustered between 1,500 to 2,000 feet (fig. 34).



Basic statistics	Extreme underpressure mode	Normal pressure mode
Mean	.07	.37
Standard deviation	.05	.06
Standard Error	.00	.00
Variance	.00	.00
Count	629	940
Minimum	.00	.20
Maximum	.19	.43
Median	.05	.39
Mode	.01	.42
Skewness	.82	-1.09
Kurtosis	-.48	.18

Figure 33.--Histogram showing bipolar distribution of hydrostatic pressure gradients in the Black Warrior coalbed methane fairway.

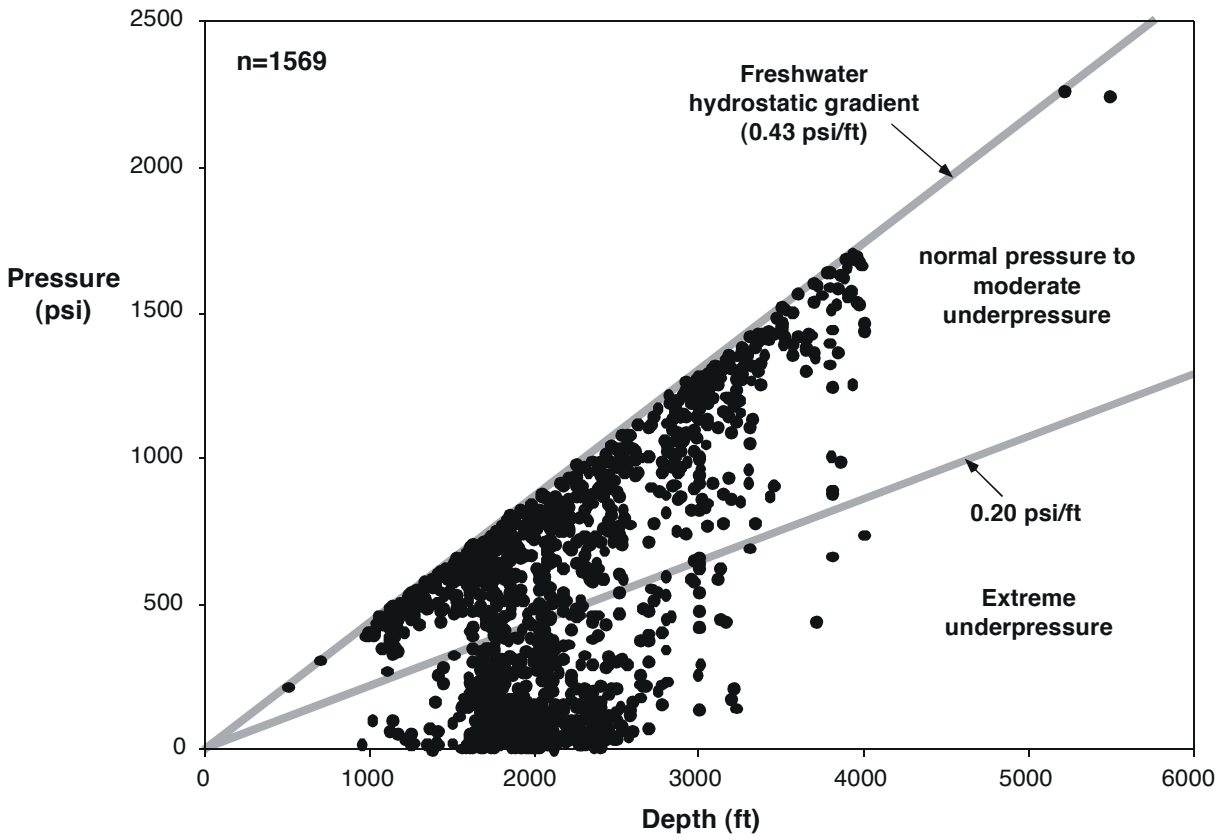


Figure 34.--Pressure-depth plot based on water levels in the Black Warrior coalbed methane fairway.

Water-level data are available from Little Sandy Creek Field northeastward and can be used to map minimum hydrostatic pressure gradient and minimum pressure prior to degasification in the northeastern part of the coalbed methane fairway (figs. 35, 36). Wells with near-normal hydrostatic pressure gradients span large areas of Cedar Cove, Deerlick Creek, Blue Creek, and Oak Grove Fields, and hydrostatic pressure at the top of the Pratt coal zone is in places higher than 700 psi. Large areas of extreme underpressure are in Brookwood, Oak Grove, Blue Creek, and White Oak Creek fields. In these areas, hydrostatic pressure at the top of the Pratt coal zone is projected to be less than 100 psi. Other pockets of extreme underpressure exist in parts of Holt, Peterson, Deerlick Creek, Blue Creek, and White Oak Creek fields. Although pressure gradient is mappable, in some areas, the gradient can change from less than 0.1 psi/ft to more than 0.3 psi/ft across a 40-acre drilling unit.

Bimodal pressure gradients are typical of compartmentalized hydrologic systems (Bradley and Powley, 1994), and the extreme bimodality of hydrostatic pressure gradients in the Pottsville Formation reflects a combination of anthropogenic and natural factors. Dewatering associated with longwall mining may be a major cause of underpressure in Brookwood and Oak Grove fields. In Brookwood Field, the Blue Creek coal of the Mary Lee zone is mined at a depth of about 2,000 feet, which explains the clustering of extremely underpressured wells at this level (fig. 34). Indeed, caution must be exercised when interpreting water levels, especially in mined areas, because bottom-hole pressure may not be representative of the shallow hydrologic system, where a water table may remain perched above the depressurized zone (Pashin and others, 1991;

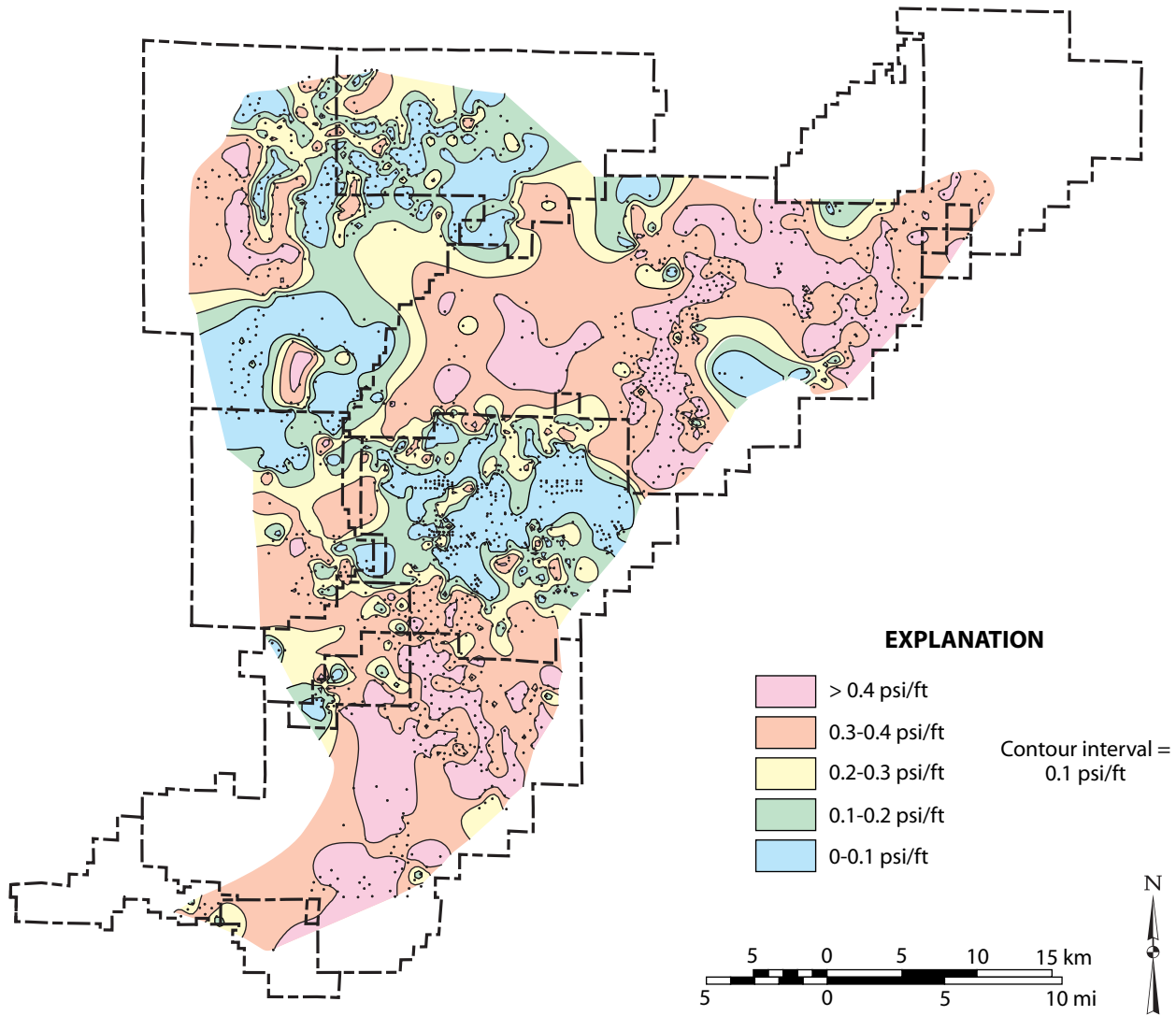


Figure 35.—Map of hydrostatic pressure gradient determined from water levels in the Black Warrior coalbed methane fairway.



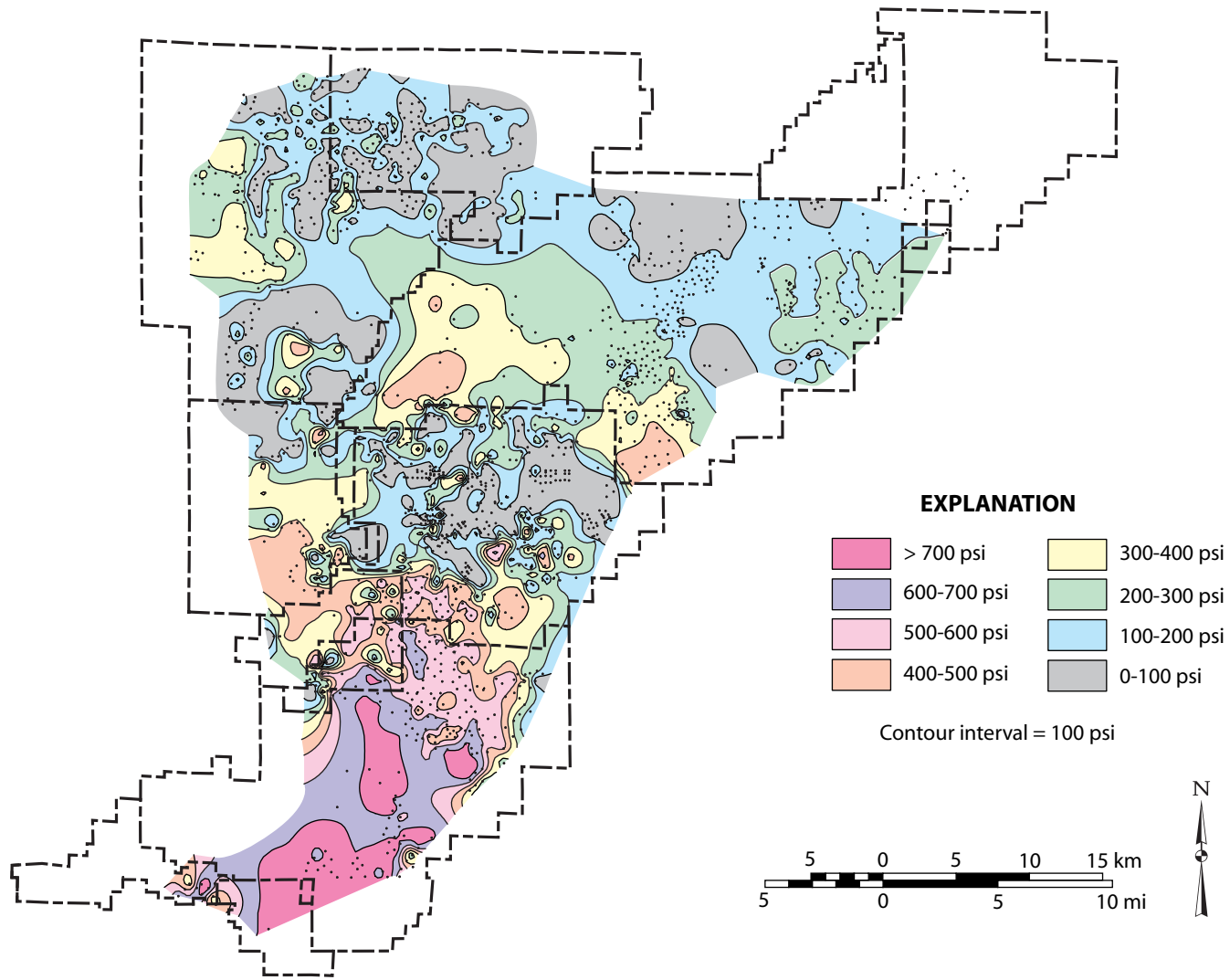


Figure 36.—Map of hydrostatic pressure at the top of the Pratt coal zone in the Black Warrior coalbed methane fairway.

Pashin and Hinkle, 1997). Pockets of extreme underpressure in Holt, Peterson, Deerlick Creek, Blue Creek, and White Oak Creek fields are far removed from the underground coal mines and thus appear to be natural.

Some degree of underpressure is typical of geologically old sedimentary basins like the Black Warrior basin because fluids contract thermally and fractures dilate during regional unroofing and associated cooling (Bradley, 1975; Kreitler, 1989). Kaiser (1993) suggested that normal pressure in coalbed methane reservoirs indicates hydrologic connection to recharge areas, and the large areas of near-normal reservoir pressure in Oak Grove and Cedar Cove fields (fig. 35) accordingly appear to reflect connection to the recharge area along the forelimb of the Birmingham anticlinorium. However, in a low-permeability system like the Pottsville Formation, this connection probably developed over geologic time, and dewatering of coal beds during gas production can reduce head quite rapidly as gas evolves into open fractures and flow is disconnected from the regional recharge system.

The extreme natural underpressure in parts of Blue Creek and White Oak Creek fields (fig. 35) may indicate isolation from recharge areas, free gas in the available pore space, or a tight reservoir condition in which water is unable to flow into the wellbore in the time between drilling and logging. Of the three possibilities, a tight borehole condition is doubtful because coalbed methane production has been highly successful in these fields (Levine and others, 1997). Isolation from recharge is feasible at least locally, because major changes in hydrostatic pressure across drilling units provides evidence for compartmentalization. Another factor that should be

considered in these areas, however, is that significant gas pressure may exist that must be detected by gauges rather than by analysis of water levels.

The heterogeneity of hydrostatic pressure in the Pottsville Formation has significant implications for the distribution of effective stress and permeability. In normally pressured reservoirs, vertical effective stress increases downward at a rate of about 0.7 psi/ft, whereas in completely underpressured reservoirs, coal must bear the full lithostatic load of 1.0 to 1.1 psi/ft. Increased lithostatic load will decrease the closure depth of fractures and can decrease the ability of coal matrix to transmit gas (Bustin, 1997), thereby potentially degrading reservoir quality and inhibiting the ability to effectively inject CO<sub>2</sub>. This effect may be mitigated by shrinkage of the coal matrix as gas is desorbed or may be exacerbated by swelling as CO<sub>2</sub> and other gases are adsorbed (Harpalani and Schraufnagel, 1990; Levine, 1996; Kroos and others, 2002). Furthermore, if extreme hydrostatic underpressure is related to free gas in fractures and the gas content in coal is high, minimal dewatering may be required for economic gas production during the primary production phase, and little water may be produced during the enhanced recovery phase.

Although lithostatic stress affects the permeability of coal, the flow of gas from the coal matrix into fractures is induced by changes in hydrostatic pressure. The most obvious evidence for this is that gas is produced as hydrostatic stress is reduced and effective stress is increased. Although fracture aperture and coal fabric respond to effective stress, the internal surface area, or Langmuir volume, of coal is relatively insensitive to stress (Bustin, 1997). Diffusion of gas

through the coal structure along concentration gradients to free surfaces, such as fractures, apparently is a fundamental control on sorption and desorption (Gamson and others, 1993; Harpalani and Ouyang, 1999), and changing hydrostatic pressure by dewatering apparently stimulates diffusion toward the open spaces where darcian flow operates.

As already mentioned, carbon dioxide has potential to become a supercritical fluid where reservoir temperature exceeds 88°F and pressure exceeds 1,074 psi (fig. 26). In a normally pressured hydrostatic system, critical pressure is reached at a depth of 2,480 feet. Critical bottom-hole temperature is exceeded well above this depth in nearly all coalbed methane wells, so supercritical fluid conditions are potentially widespread in the Pottsville Coal Interval (fig. 37). However, one must keep in mind that active coalbed methane reservoirs are in a depressurized state, so supercritical conditions can only be reached in most cases as the reservoir equilibrates to the natural system after abandonment. Furthermore, if supercritical conditions are eventually met, coal will be significantly undersaturated with CO<sub>2</sub>.

Subcritical conditions prevail throughout the Pottsville Coal Interval northeast of a line running through Brookwood and Deerlick Creek fields (fig. 37). The Black Creek coal zone exceeds critical depth south of this line, and potentially supercritical conditions may develop at higher stratigraphic intervals toward the structurally deepest parts of the coalbed methane fairway. In the footwall block of the half graben in Robinson's Bend Field, supercritical conditions are restricted to the Black Creek and Ream coal zones, whereas in the hanging-wall

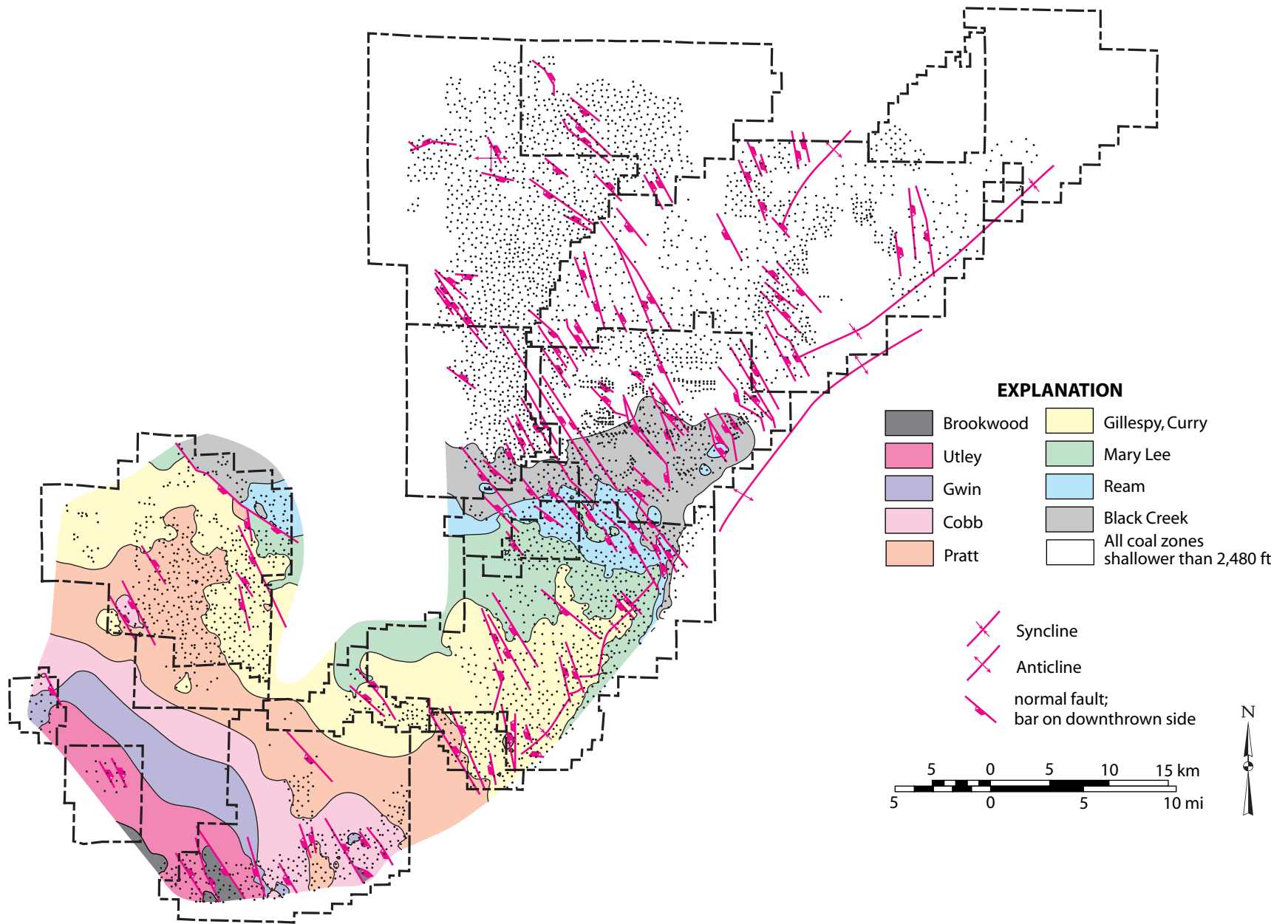


Figure 37.--Map showing shallowest unit where supercritical fluid conditions may develop for CO<sub>2</sub> in the Black Warrior coalbed methane fairway.

block, supercritical conditions may exist in the Pratt coal zone. In southwestern Moundville Field, moreover, the complete Pottsville Coal Interval exceeds critical depth.

The precise significance of critical depth in the Black Warrior coalbed methane fairway is unclear. Abnormally low pressure in Brookwood field may give rise to subcritical conditions at depth, but the long-term stability of underpressured areas in the Pottsville Formation is unknown. Few water levels have been recorded in the southwest part of the coalbed methane fairway, so it is unclear whether significant pockets of natural underpressure exist in this area. Sorption isotherms for Carboniferous coal under supercritical pressure and temperature indicate that coal can hold significantly more CO<sub>2</sub> than is predicted by Langmuir adsorption theory (Kroos and others, 2002), so potential exists for enhanced sequestration potential below a depth of 2,480 feet. However, the mobility of excess CO<sub>2</sub> in coal, the reactivity of CO<sub>2</sub> with formation fluids, and the sweep efficiency of enhanced coalbed methane operations under supercritical conditions need to be researched. Additionally, the CO<sub>2</sub>-N<sub>2</sub>-CH<sub>4</sub> chemical system is poorly understood, and it is possible that mixtures of gases in this system reach a state of nonideality under different temperature-pressure conditions than is predicted for single gases (Horita and others, 2001).

## **COAL QUALITY**

Coal quality parameters, which include rank, grade, and maceral composition, have a significant effect on the petroleum source rock and reservoir characteristics of coal (e.g., Levine, 1993; Lamberson and Bustin, 1993; Bustin and Clarkson, 1998). Coal quality varies significantly

in the Black Warrior basin, and analysis of coal quality parameters have played an important role in coalbed methane development (Winston, 1990a, b; Levine and Telle, 1991). In this section, we discuss rank and grade in the Black Warrior basin to help lay the foundation for analysis of sorption capacity and gas content.

### **Rank**

Major rank parameters in coal include volatile matter content, fixed carbon content, calorific value, moisture, and vitrinite reflectance. Moisture content in bituminous coal is generally lower than 3 percent and is of limited value as a rank parameter. The other rank parameters have been mapped for each Pottsville coal zone by Winston (1990a, b), and most recent work has relied on mapping and interpretation of volatile matter and vitrinite reflectance data (Telle and others, 1987; Winston, 1990a, b; Levine and Telle, 1991; Pashin and others, 1999).

Coal rank in the study area ranges from high volatile B bituminous to low volatile bituminous (Semmes, 1929; Winston, 1990a, b) (fig. 38), and to date, virtually all coalbed methane production in Alabama is from coal of high volatile A bituminous rank or higher. In the Mary Lee coal zone, high volatile B bituminous coal is in the western part of the fairway in a corridor between Robinson's Bend and Deerlick Creek fields, extending northward along the western margin of Blue Creek Field. Most coal in the gas production fairway is of high volatile A bituminous rank, and an elliptical area containing medium volatile and low volatile bituminous coal of metallurgical quality is centered near the southeast margin of the basin in Oak Grove and

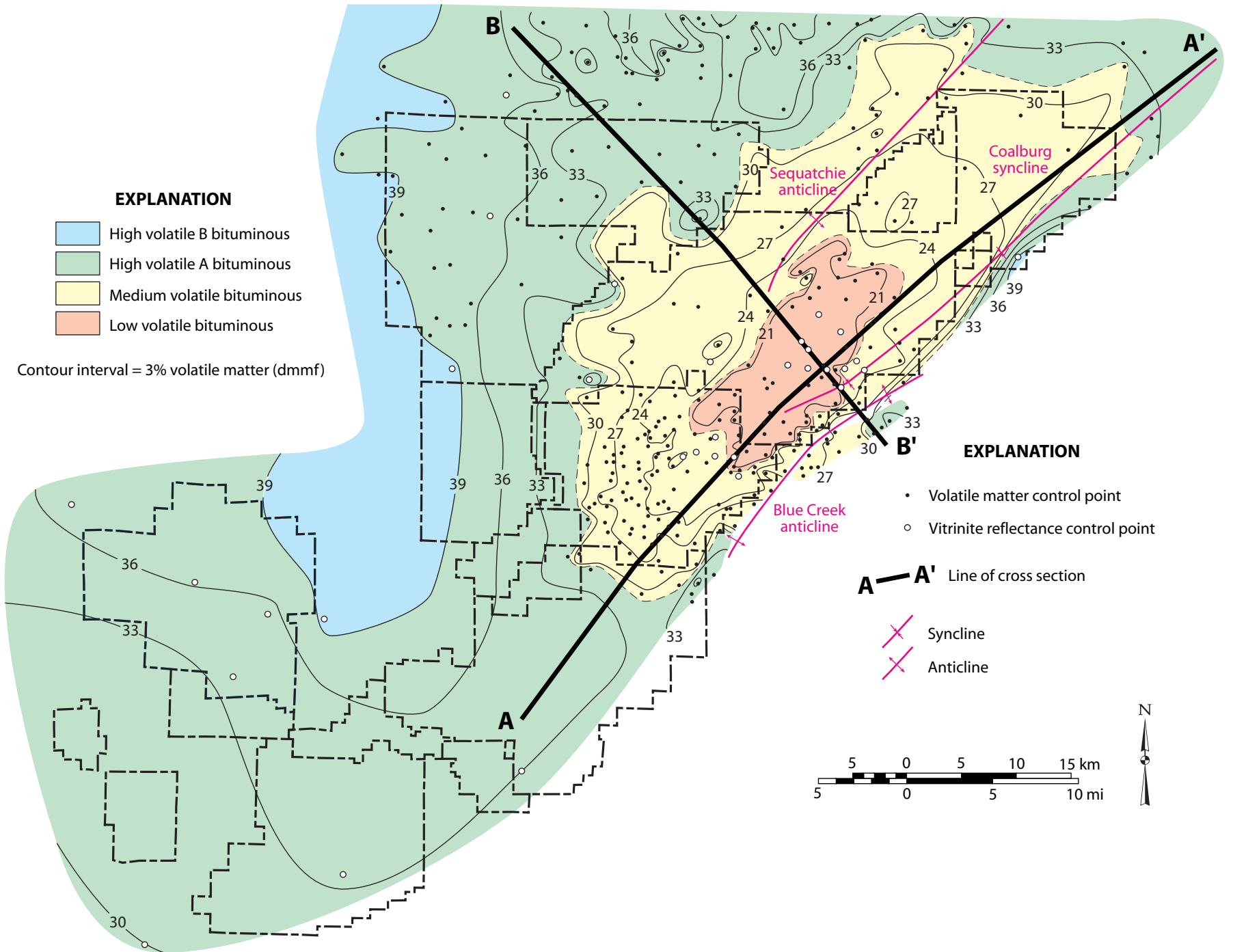


Figure 38.—Coal rank in the Black Warrior coalbed methane fairway based on volatile matter and vitrinite reflectance data from the Mary Lee coal zone.



Brookwood fields. Volatile matter content increases asymmetrically from a minimum of 18 percent in southern Oak Grove field to more than 30 percent along the margins of the rank anomaly. The southeast margin of the anomaly is marked by the upturned northwest limb of the Birmingham anticlinorium, where volatile matter content in the Mary Lee zone increases updip by as much as 12 percent.

Generalized structural cross sections through the rank anomaly indicate that coal rank decreases upsection, and the Cobb and younger coal zones reach a maximum of medium volatile bituminous rank (Winston, 1990a; Pashin and others, 1999) (fig. 39). At a given depth, rank decreases more rapidly toward the southwest and northwest than to the northeast. In both cross sections, isovols cut across bedding, and in cross section B-B', isovols cut squarely across the forelimb of the Blue Creek anticline.

The rank pattern in the Black Warrior coalbed methane fairway does not reflect thickening of the Pottsville Coal Interval into the Moundville-Cedar Cove depocenter (figs. 8, 38). Similarly, isovols in most areas are oblique or even perpendicular to strike of the southwest-dipping homocline of the Black Warrior basin (figs. 20, 38). From Robinson's Bend Field southwest, however, isovols more closely parallel strike of the regional homocline. The relationship between rank and normal faults has yet to be determined because vertical separations are too small in the Pottsville outcrop area, where numerous proximate analyses are available. Extensional faults in Robinson's Bend and Moundville fields, where displacement is between

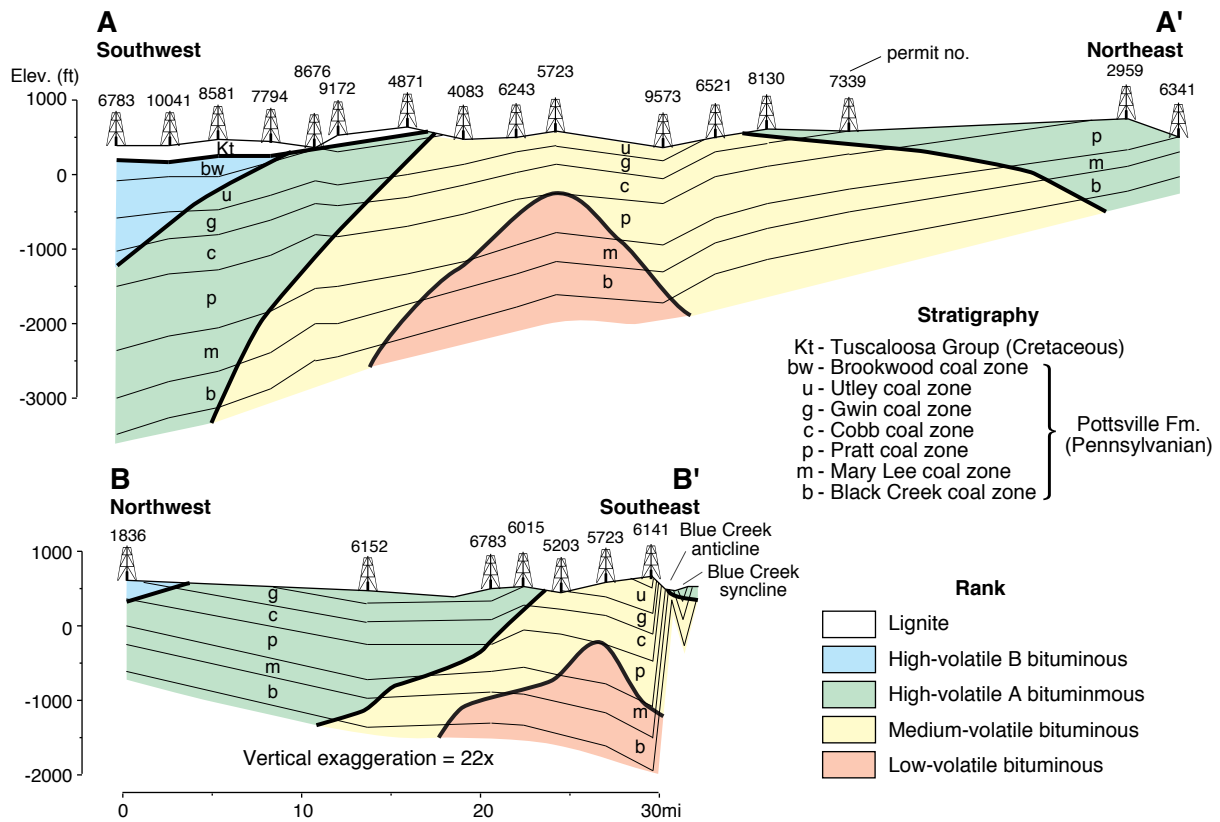


Figure 39.—Cross sections showing the relationship of rank to structure in the Black Warrior coalbed methane fairway (modified from Pashin and others, 1999).

500 and 1,000 feet, provide the best opportunity to determine if a relationship exists and should be the object of future research.

An obvious relationship between rank pattern and thrust belt structure is the strong parallelism of isovols to the forelimb of the Birmingham anticlinorium (fig. 38). Farther northwest in north-central Oak Grove Field, the Sequatchie anticline has only 400 feet of relief and predictably has little effect on the rank pattern. Relief of the anticline increases up-plunge to the northeast, and in this area, rank of the Mary Lee coal zone decreases slightly across the axial trace.

Lopatin modeling west of the coalbed methane fairway provides evidence for a complex burial and thermal history and enables some generalizations to be made about burial and gas generation (Telle and others, 1987; Hines, 1988; Carroll and others, 1995) (fig. 40). Major maturation apparently took place during rapid burial associated with Appalachian-Ouachita orogenesis, and the Pottsville Formation attained a rank of high volatile A bituminous near maximum burial. Importantly, major thermogenic gas generation is thought to begin as coal reaches this rank (Jüntgen and Karweil, 1966). According to the Lopatin models, minor thermogenic gas generation may have continued during post-orogenic unroofing but was effectively complete by Late Cretaceous reburial as the Gulf Coastal Plain and Mississippi Embayment formed. Indeed, Cretaceous strata of the Tuscaloosa Group contain only lignitic plant material (Stephenson, 1926; Carroll and others, 1995).

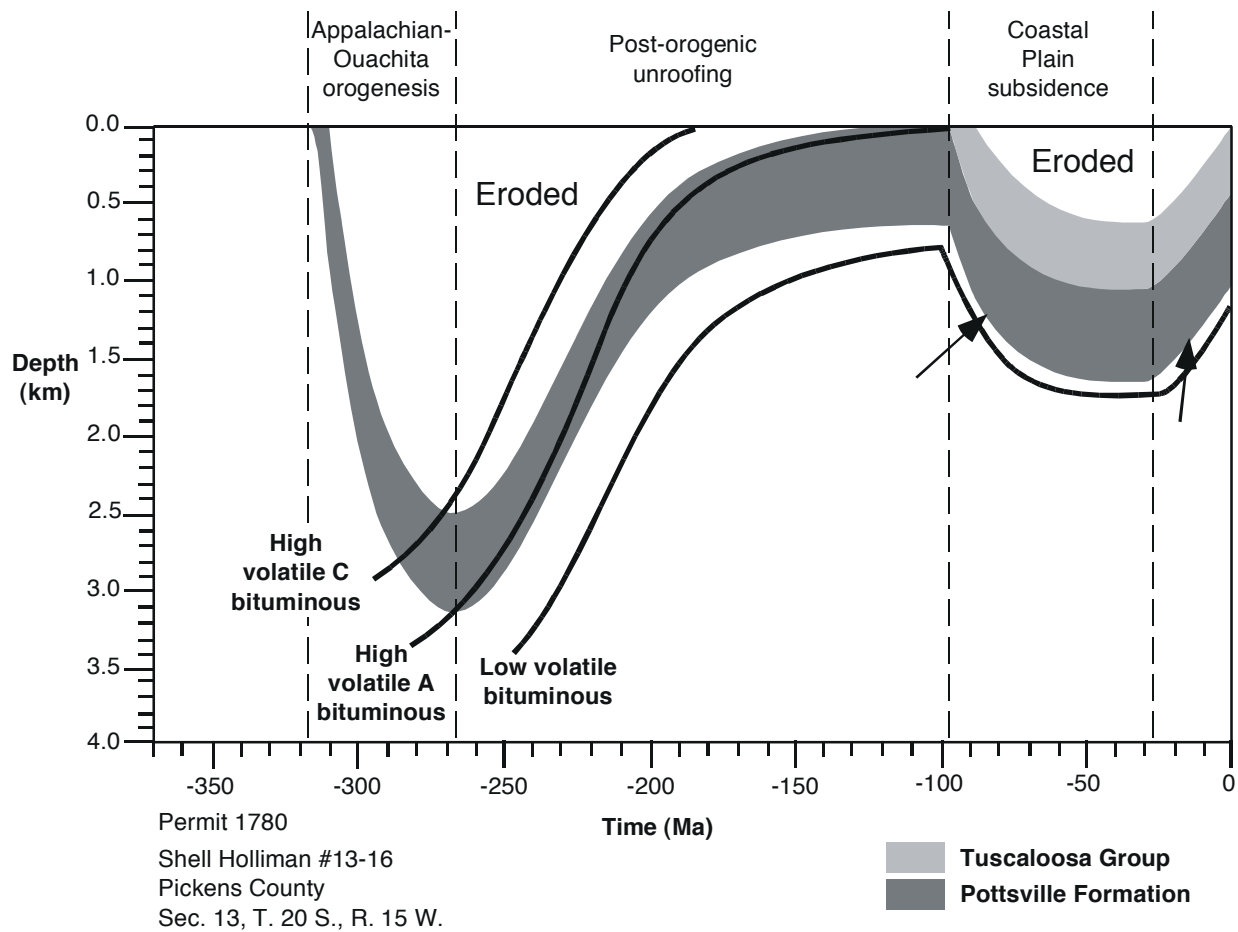


Figure 40.--Generalized relationship between burial history and thermal maturation in the Black Warrior basin (after Carroll and others, 1995).

Although burial associated with foreland basin subsidence may have been an important mechanism of thermal maturation, rank anomalies not related to the regional isopach and structural contour patterns (figs. 8, 20, 38) indicate that burial maturation was overprinted strongly by spatial and temporal changes in the paleogeothermal gradient (Telle and others, 1987; Winston, 1990a, b; Levine and Telle, 1991). Accordingly, the paleogeothermal gradient is thought to have been lowest in the area containing thermally immature coal of high volatile B bituminous rank and is thought to have been highest in the elliptical area containing medium volatile and low volatile bituminous coal. The origin of the elevated geothermal gradient is unclear, and the best hypothesis to date is tectonic expulsion of warm fluid from the Appalachian orogen (Winston, 1990a, b).

Although the mechanism of enhanced maturation remains unclear, structural relationships in the Appalachian thrust belt provide some constraint on the timing of coalification and underscore the special nature of rank anomalies in the Black Warrior basin. In an overturned fold limb southeast of the Birmingham anticlinorium, isovols are incompletely folded with bedding, indicating a dominant synkinematic coalification signature (Pashin and others, 1999; Carroll and Pashin, 1999). In the Blue Creek anticline and nearby parts of the forelimb of the Birmingham anticlinorium, by contrast, isovols are clearly not folded with bedding (Pashin and others, 1999) (fig. 39). Therefore, the elliptical rank anomaly is apparently post-kinematic relative to the forelimb of the anticlinorium. If orogenic fluid expulsion was the mechanism upgrading rank in Oak Grove and Brookwood fields, then orogenic movements at that time must have been

principally in the hinterland relative to the Birmingham anticlinorium. Several out-of-sequence structural elements have been identified in the Appalachian thrust belt of Alabama (Thomas and others, 1989), which helps support this hypothesis.

### **Grade**

The major grade parameters affecting the sorption capacity and gas content of bituminous coal are mineral matter content and maceral composition. The dominant forms of mineral matter in Alabama coal are clay minerals, quartz, pyrite, and calcite. A database containing more than 850 proximate and ultimate analyses of coal is available to analyze key grade parameters (Bragg and others, 1998). These analyses report ash, which includes the non-combustible residue of mineral matter, and sulfur forms, which include pyrite, organic sulfur, and sulfate.

### **Ash**

By definition, the ash content of coal is less than 50 percent by weight, and in the Pottsville Formation of Alabama, ash content is characteristically between 2 and 30 percent (Shotts, 1956, 1960; Winston, 1990a). A histogram of ash content confirms this and demonstrates that ash values can be characterized as a normal population with positive skewness (fig. 41). Mean ash content is 12 percent, and values between 6 and 18 percent fall within one standard deviation of the mean.

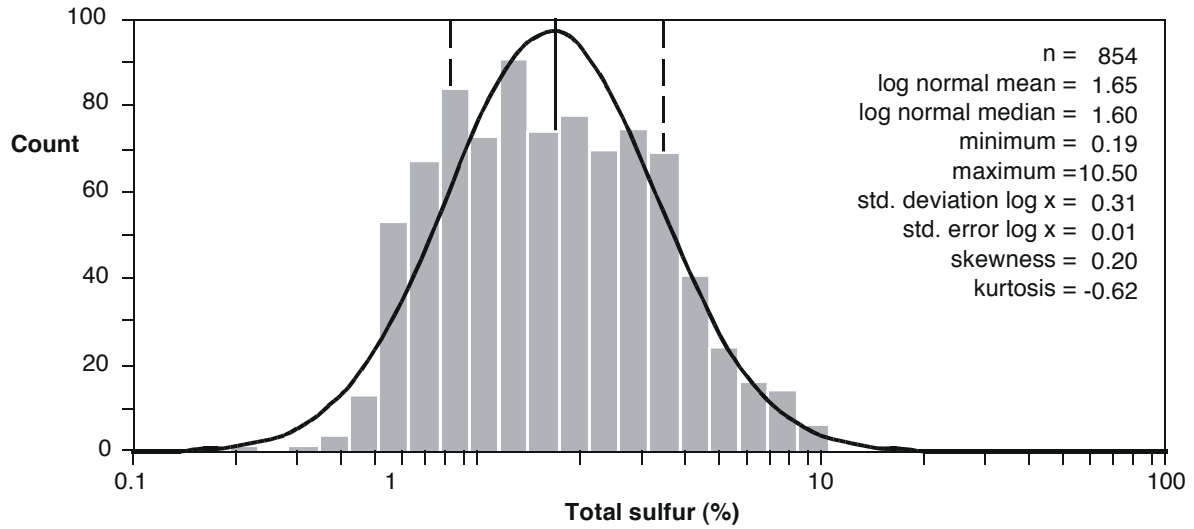
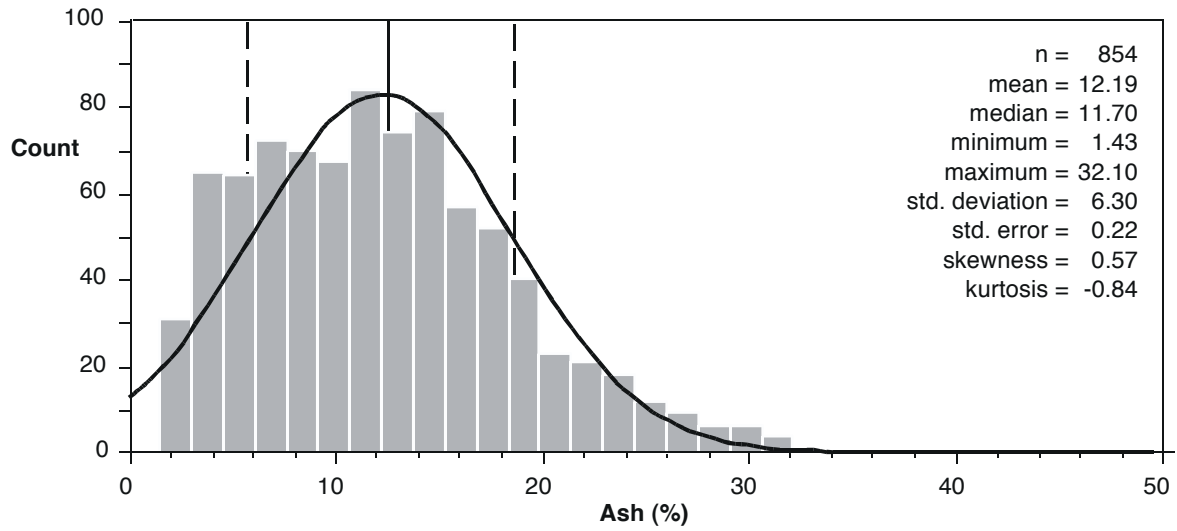


Figure 41.--Histograms showing ash and total sulfur content in coal of the Black Warrior basin.

Some stratigraphic trends of ash content are apparent in the Pottsville Formation (fig. 42). Mean ash content increases from a mean of 7 percent in the Black Creek coal zone to about 15 percent in the Mary Lee coal zone. Few analyses are available for the Gillespy and Curry zones, but the available data indicate that ash content is highly variable. Ash data show no distinctive stratigraphic trend in the Pratt through Utley coal zones, although ash content in the Nickel Plate subzone is markedly lower than in the American and Pratt subzones. As in the Black Creek and Mary Lee coal zones, ash content in the Brookwood coal zone tends to increase upward.

Whereas rank can be interpolated between data points with a high degree of confidence, grade parameters are highly variable. Comparison of ash content in the Mary Lee and Utley coal beds in Blue Creek Field, for example, underscores the variability of coal quality within and among coal beds (fig. 43). Although density logs can potentially be used to estimate ash content, most beds in the Black Warrior basin are thin, and caving of coal results in inconsistent contact between the sonde and the borehole. Therefore, proximate analyses should be used to quantify ash content in the Black Warrior coalbed methane fairway, although density logs can be helpful to identify unusually high ash beds.

Little research has been performed on the composition of ash-forming clay minerals in coal of the Black Warrior basin. In the associated underclay beds, however, clay minerals are dominated by kaolinite, illite, and chlorite (Metzger, 1964; Rheams and others, 1987). Metzger (1964) noted that kaolinite content tends to decrease upward as the concentration of other clay minerals increases, and similar trends may be present in coal. Quartz and clay minerals are



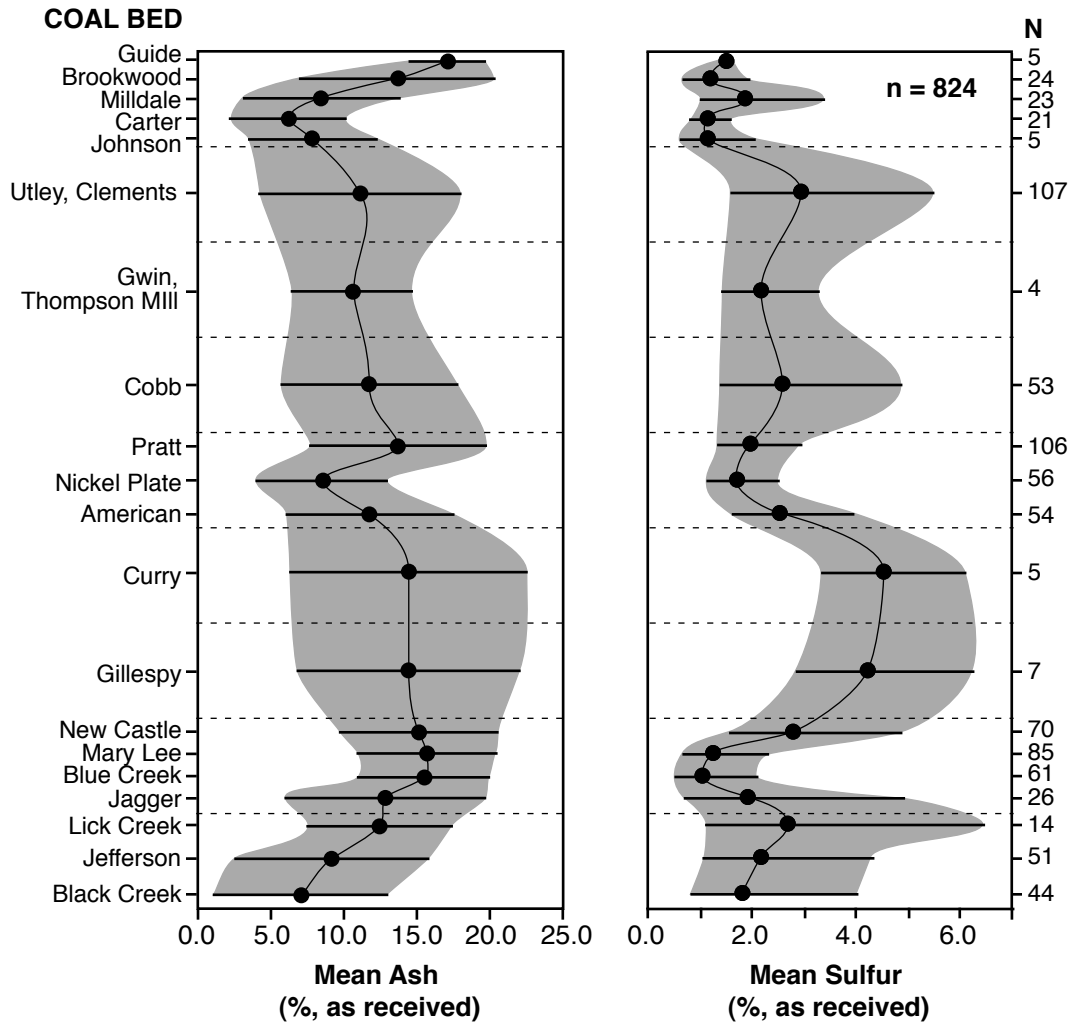


Figure 42.—Relationship of ash and sulfur content to stratigraphy in the Black Warrior basin. Dots mark mean, and shaded area marks values within one standard deviation from the mean.

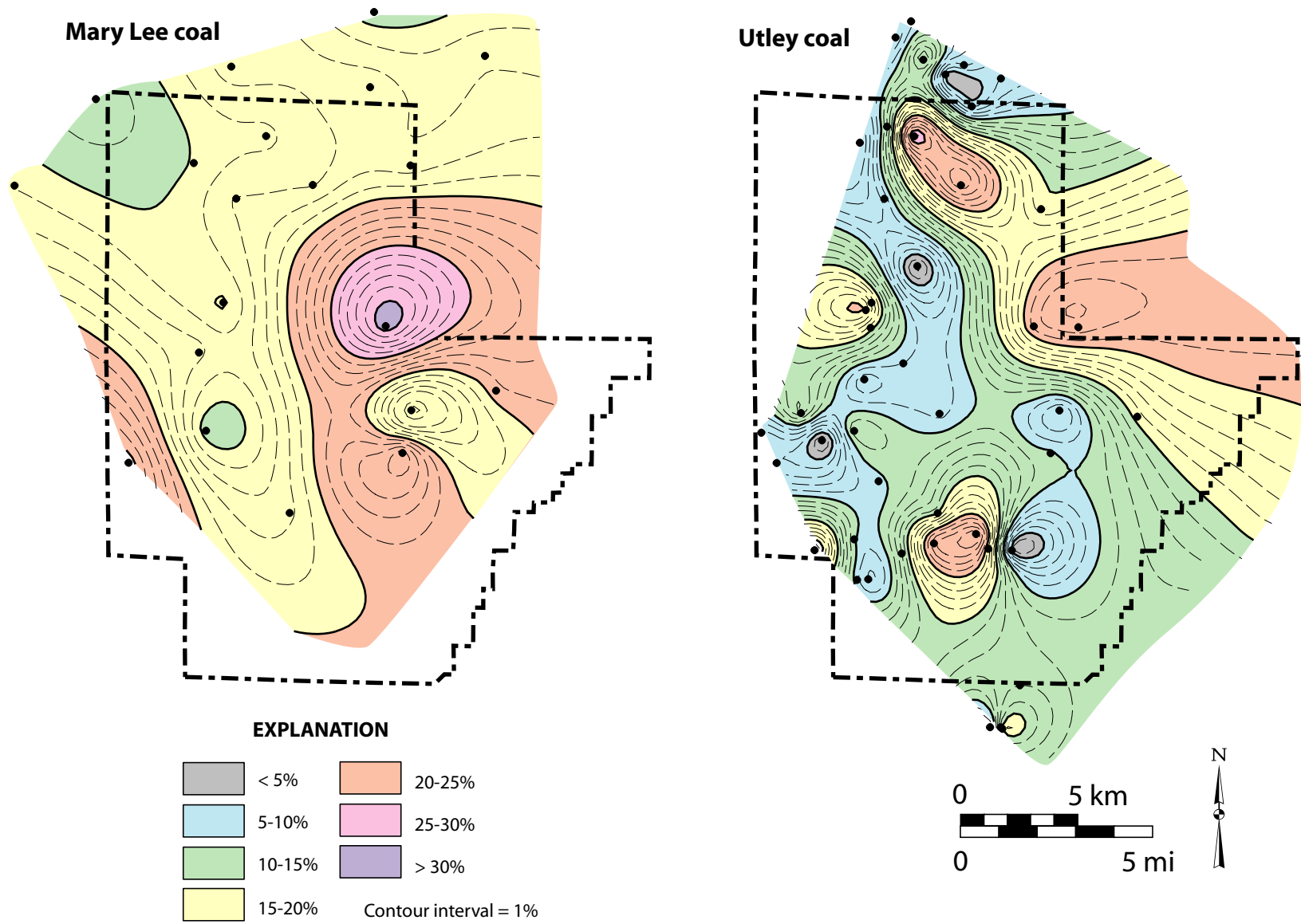


Figure 43.--Maps showing variability of ash content in the Mary Lee and Utley coal beds in Blue Creek Field.

concentrated in partings, and pyrite forms framboids and nodules. The dominant cleat-filling minerals in the Black Warrior basin are calcite and pyrite (Pashin and others, 1999).

Quartz and clay are mainly detrital mineral matter, whereas pyrite is of chemical origin. Silicate minerals may be derived from overbank flooding, (McCabe, 1984), degradation of peat (Spears, 1987), plant phytoliths (Renton and Cecil, 1979), and eolian processes, including volcanic ash falls (Spears, 1970). Siliciclastic partings in Pottsville coal appear detrital and are interpreted to represent intermittent flooding of low-lying swamp areas and perhaps episodic concentration of inorganic material by degradation of peat. Dispersed clay and quartz within coal may represent dilute flooding events and may also have been transported into swamps by wind; phytoliths cannot be ruled out without rigorous petrographic analysis. An eolian interpretation may be most applicable to dispersed mineral matter in domed parts of swamps. Kaolinized ash-fall beds, or tonsteins, have been identified in coal beds of the Appalachian region (Lyons, 1992) but have yet to be discovered in Alabama.

## Sulfur

Although the relative proportions of clay and quartz in the mineral matter fraction of coal cannot be determined from proximate and ultimate analyses, ultimate analysis enables quantification of sulfur and pyrite content in coal. Total sulfur content determined from coal of the Black Warrior basin ranges from 0.2 to 10.5 percent, and sulfur values form a log-normal distribution with weak positive skewness (fig. 41). Mean sulfur content calculated on a log-

normal basis is 1.65 percent, and values between 0.8 and 2.3 percent fall within one standard deviation from the mean.

In the Black Creek coal zone, mean sulfur content typically ranges from 1 to 6 percent and tends to increase upsection (fig. 42). In the Mary Lee coal zone, by comparison, mean sulfur content typically is between 1 and 5 percent in the Jagger and New Castle beds and between 1 and 2 percent in the Blue Creek and Mary Lee beds. Gillespy and Curry coal consistently contain more than 2 percent sulfur, whereas sulfur content in the Pratt coal zone is generally between 1 and 3 percent. Sulfur content ranges considerably in the Cobb through Utley coal zones, whereas the Brookwood coal zone is dominated by beds with low sulfur rivaling the Blue Creek and Mary Lee beds. Maps of sulfur content by Winston (1990a) reveal that sulfur content within each coal zone increases toward the northwest.

Sulfatic sulfur content in the analyses published by Bragg and others (1998) is negligible, indicating that the samples were fresh at the time of analysis. Organic sulfur content has a negatively skewed log-normal distribution with a strong central tendency about a log-normal mean of 0.6 percent (fig. 44). Regression analysis indicates that organic sulfur content is nearly invariant with respect to total sulfur (fig. 45). Pyritic sulfur, by contrast, has a much wider range of values than organic sulfur (fig. 44). Pyritic sulfur content has a log normal mean of 0.7 percent and a range of less than 0.1 percent to 9.1 percent; values between 0.1 percent and 2.0 percent fall within the standard deviation. Regression analysis indicates that pyritic sulfur is the primary determinant of total sulfur content ( $r^2=0.95$ ) and that pyritic sulfur forms the majority of sulfur in

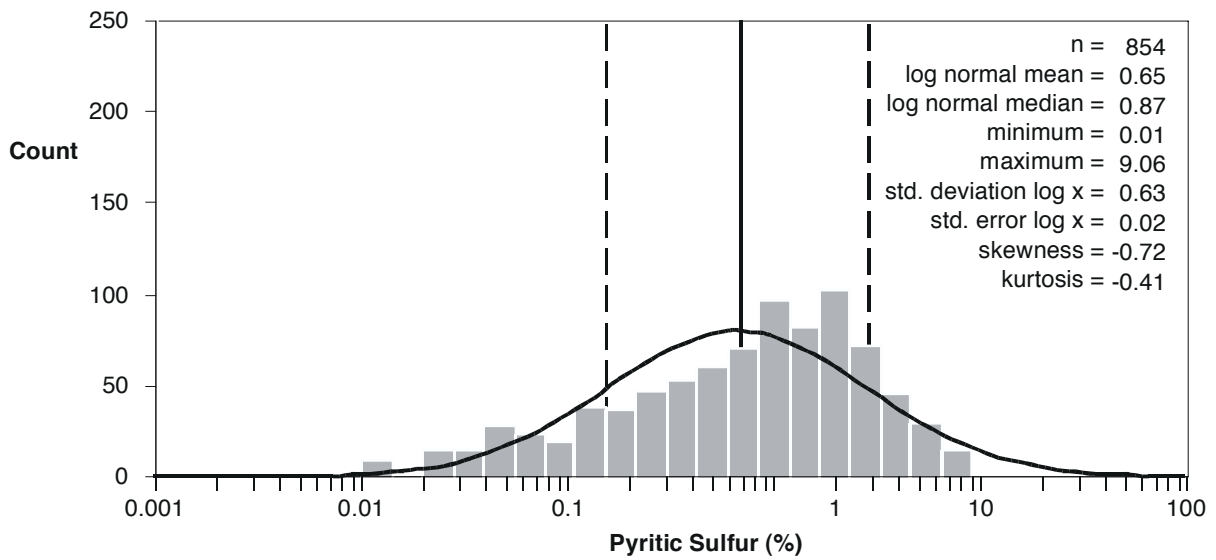
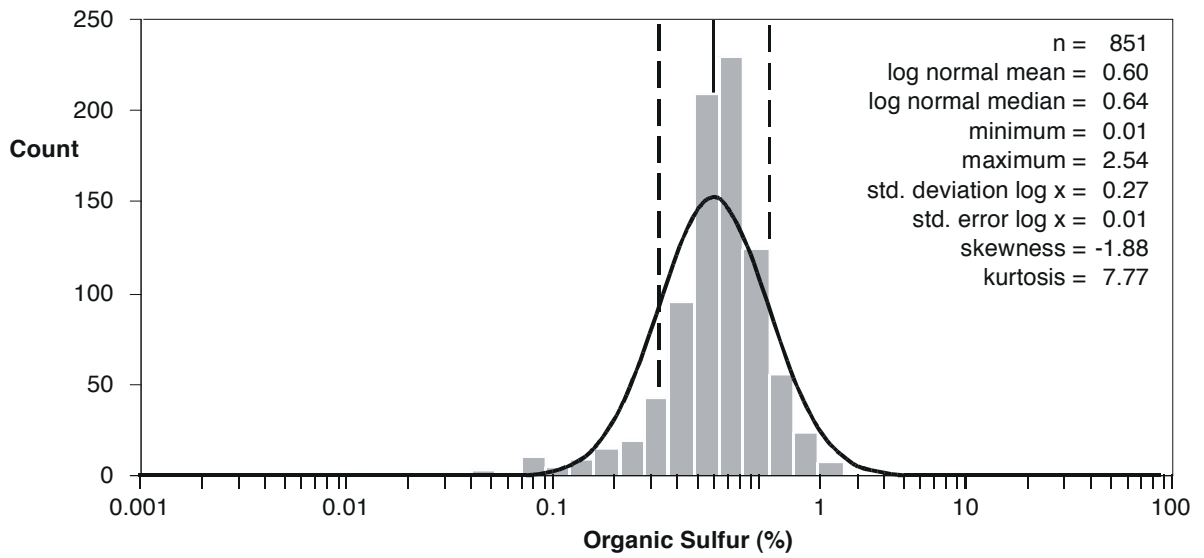


Figure 44.--Histograms showing organic and pyritic sulfur content in coal of the Black Warrior basin.

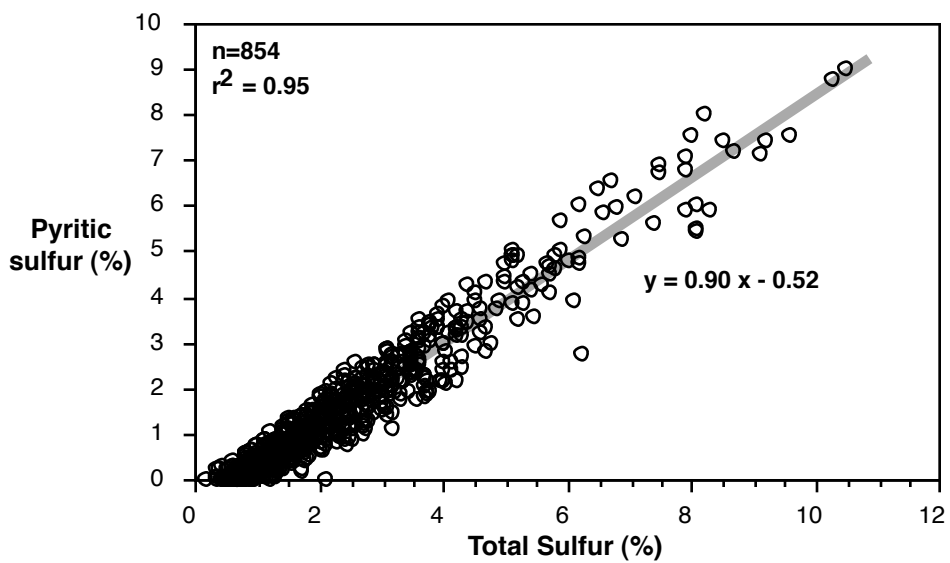
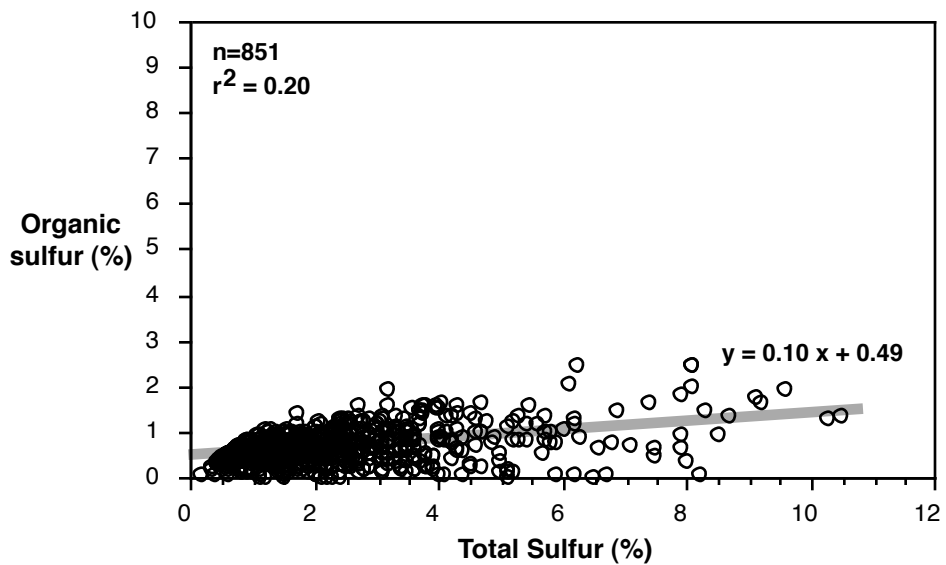


Figure 45.--Regression plots of sulfur forms versus total sulfur in coal of the Black Warrior basin.

Black Warrior basin coal at concentrations above 0.6 percent (fig. 45). An important point to consider is that the specific gravity of pyrite is about 2.4 times as great as that of elemental sulfur, thus pyrite makes a proportionally greater contribution to total coal and ash composition than pyritic sulfur as reported in ultimate analyses.

The major forms of sulfur in coal are present at the peat stage (Casagrande, 1987). Some sulfate is present in plant tissue and can also form by microbial oxidation of organically bound, sulfurous functional groups to sulfate (Casagrande and Siefert, 1977). Under anoxic and acidic conditions deeper in the peat profile, facultative anaerobic bacteria reduce the sulfate to hydrogen sulfide and, ultimately, hydrogen is replaced with iron to form pyrite. The negligible sulfate values in coal of the Black Warrior basin suggest that, not only were the analyzed samples fresh, but that sulfate reduction during sedimentation was highly efficient. Marine water contains abundant sulfate that can be incorporated into peat and can also be reduced to pyrite. Indeed, studies of sulfur content in coal have established a fundamental correlation between high sulfur content (greater than 2 percent) and marine roof rock (Williams and Keith, 1963; Gluskoter and Simon, 1968). Winston (1990a) attributed the northwest increase in sulfur content to indicate more frequent development of marginal-marine swamps prone to flooding by saline, sulfate-laden water in distal parts of the Black Warrior basin.

## Macerals

The bright-banded coal beds of the Black Warrior basin are rich in vitrinite (70-95 percent) and contain subordinate amounts of inertinite (5-35 percent) and liptinite (0-5 percent). The coal can be classified as bimacerite, or more specifically, vitrinertite (fig. 46), and petrologic analyses of coal from the cores sampled in this study are consistent with other analyses of Alabama coal (e.g., Telle and Thompson, 1987). Macerals are the coalified organic remains of plants, and useful reviews of the diagnosis and origin of macerals are available in Stach and others (1982) and Papp and others (1998).

Vitrinite is formed by the coalification of woody material and is a gas-prone form of kerogen. Inertinite includes oxidized plant remains, including the products of swamp fires and is thought to have little hydrocarbon source potential. Liptinite represents waxy organic matter and includes the remains of spores, leaves, cuticles, and algae. Accordingly, liptinite macerals constitute oil-prone kerogen.

The high vitrinite content and extremely low liptinite content of coal in the Black Warrior basin (fig. 46) confirms that it is a gas-prone source rock with limited potential for oil generation. Indeed, oil-prone kerogen can adversely affect the ability of coal to adsorb and transmit gas (Levine, 1993). Vitrinite is generally thought to be the principal gas-sorbent maceral in coal, although Levine (1993) indicated that the relationship of gas sorption to maceral composition can be difficult to predict.



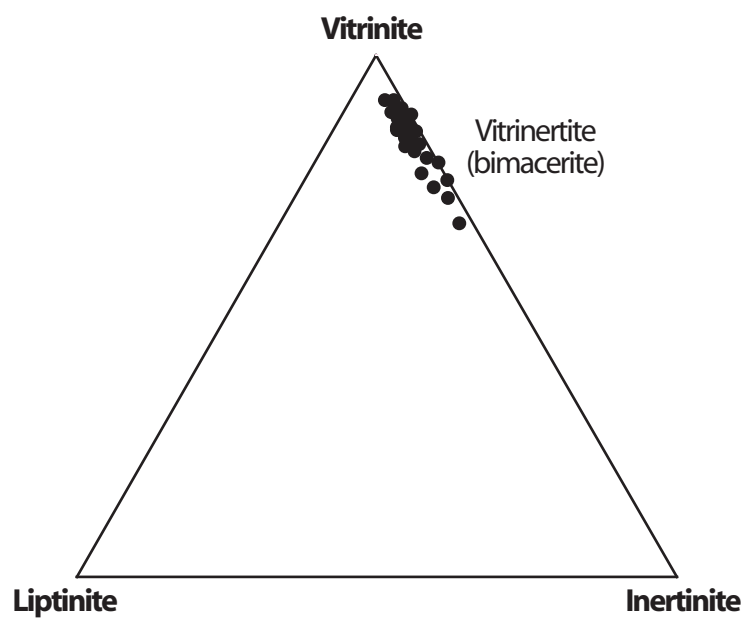


Figure 46.--Ternary plot showing maceral composition of coal samples used for sorption-isotherm, proximate, and ultimate analysis in this study.

## SORPTION CAPACITY

Understanding the gas sorption capacity of coal is perhaps more important in carbon sequestration than in primary coalbed methane production. This is because injection operations may result in complete isothermal saturation of coal with CO<sub>2</sub>, and exceeding the sorption capacity may result in leakage of gas into the country rock and ultimately back to the surface. The three gases that come into play in carbon sequestration and enhanced coalbed methane recovery are CO<sub>2</sub>, which is the greenhouse gas to be sequestered, CH<sub>4</sub>, which is the objective of enhanced coalbed methane recovery, and N<sub>2</sub>, which is the dominant constituent of the gas emission stream from coal-fired power plants. Importantly, both CO<sub>2</sub> and N<sub>2</sub> both have potential to drive enhanced coalbed methane recovery (Puri and Yee, 1990).

Isotherms for all three gases indicate that the sorption performance of coal for each gas studied can vary by a factor greater than 2 on as-received and mineral-matter-free bases (fig. 47; table 2). Isotherms for CO<sub>2</sub> were terminated at about 600 psi because of condensation. Isotherm results are in keeping with those of previous investigators, who found that coal sorbs significantly more CO<sub>2</sub> than CH<sub>4</sub> or N<sub>2</sub> (Arri and others, 1992; Harpalani and Pariti, 1993; Hall and others, 1994). Interestingly, the three gases show little overlap in overall sorption performance.

Isotherms from individual coal samples indicate that above 500 psi, coal holds about twice as much CO<sub>2</sub> as CH<sub>4</sub> and about twice as much CH<sub>4</sub> as N<sub>2</sub> (fig. 48). These isotherms also show the impact of calculating sorption capacity on different bases. The low moisture percentages in

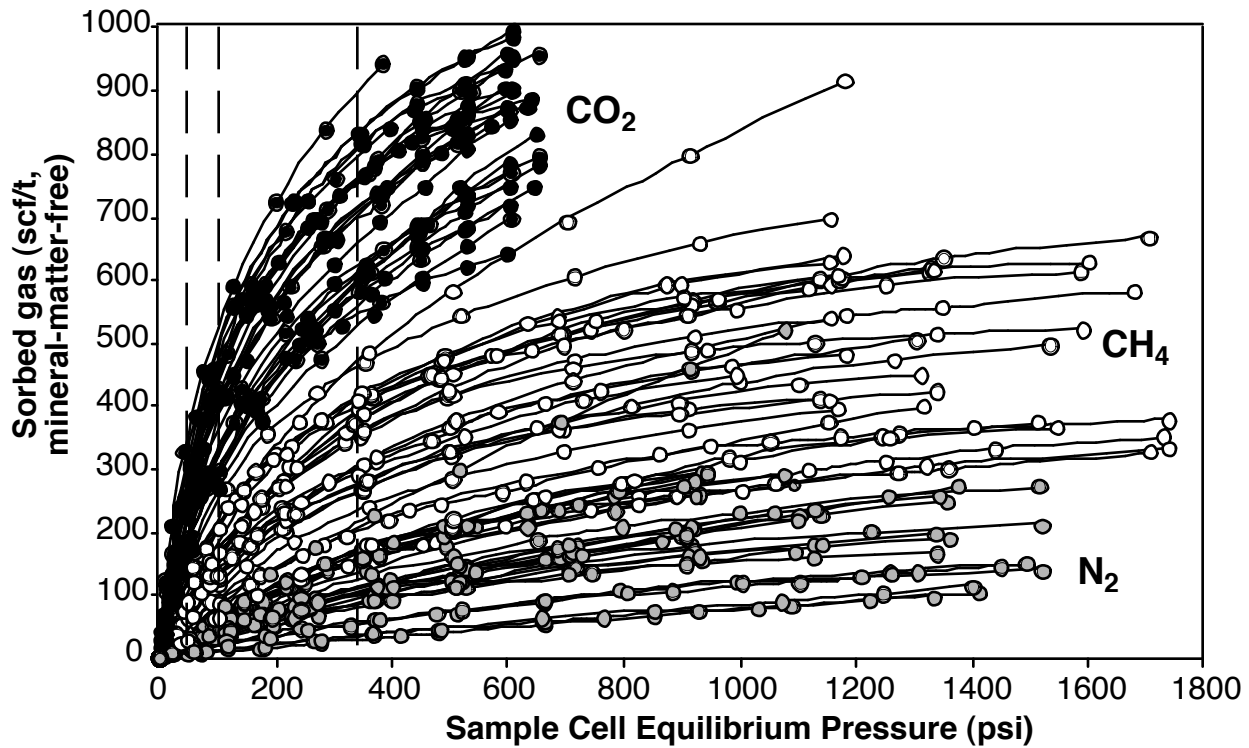
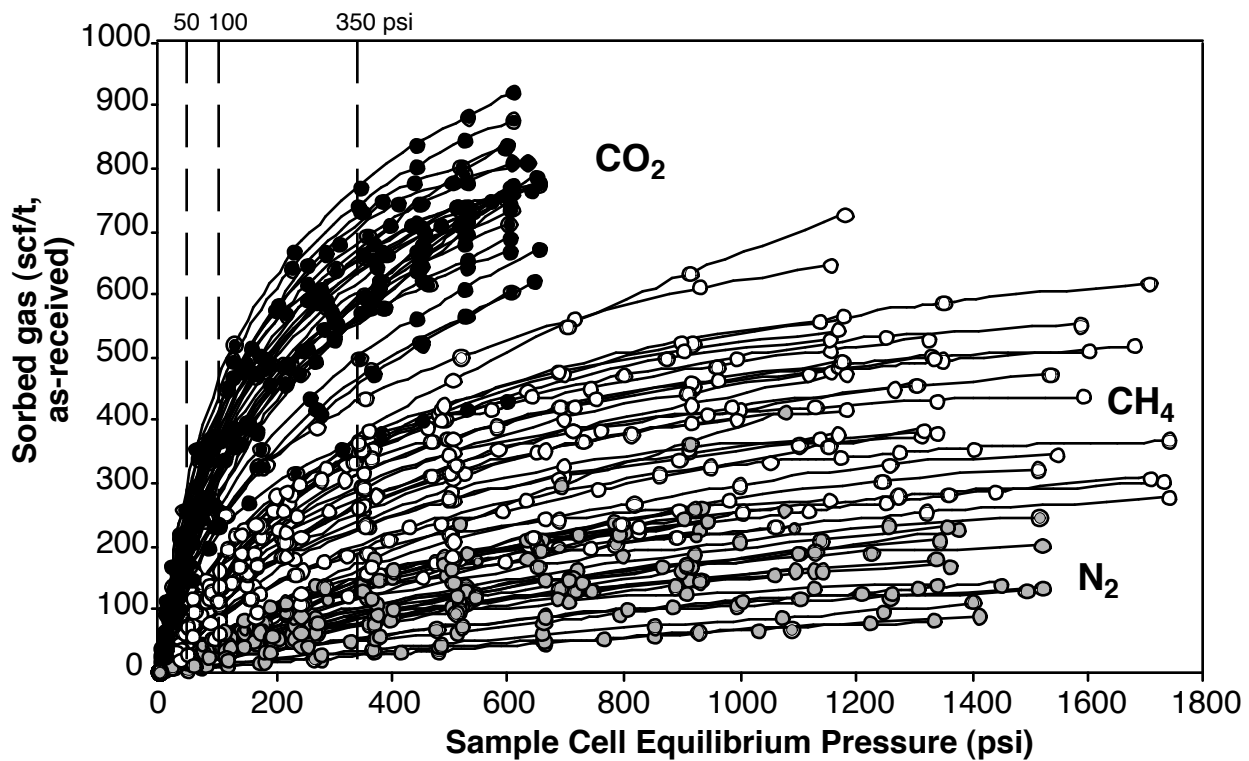


Figure 47.--Isotherm plots showing the capacity of coal in the Black Warrior basin to sorb carbon dioxide, methane, and nitrogen.

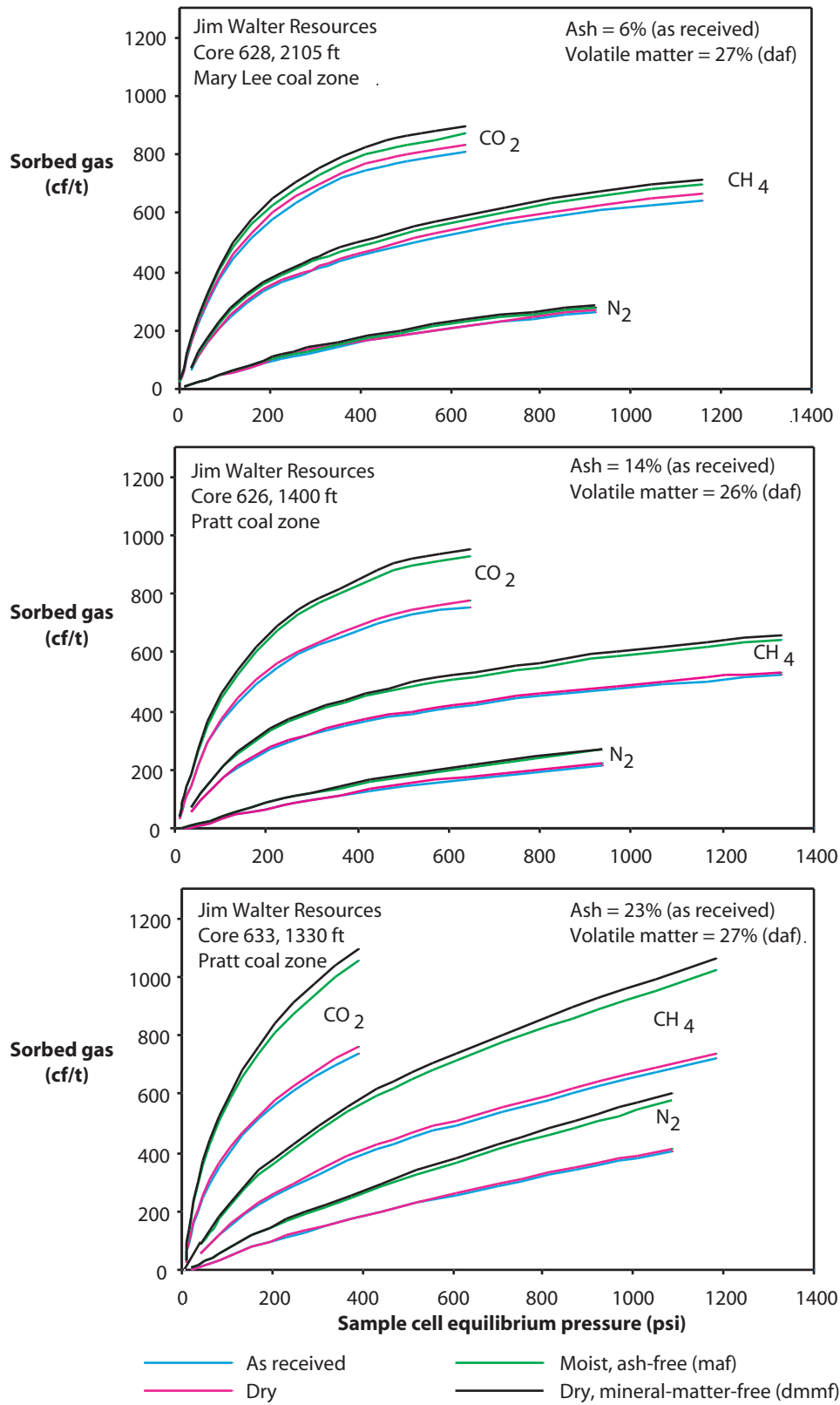


Figure 48.—Comparison of isotherms calculated on different bases in coal of variable ash content and constant rank.

bituminous coal have little effect on the calculation, whereas ash has an increasingly large effect as ash content increases. The sorption capacity of coal decreases with increasing temperature (Jüntgen and Karweil, 1966; Yang and Saunders, 1985; Scott, 2002). In general, the sorption capacity of coal at a given pressure in the Black Warrior basin can be expected to change by about 25 percent over the typical range of reservoir temperatures (75-125°F) in the Pottsville Coal Interval.

Sorption capacity correlates significantly with volatile matter and ash content (figs. 49-52; tables 2-4), and no significant correlations were found with maceral content. Correlating volatile matter with sorption capacity reveals a negative correlation for each gas at sample cell equilibrium pressures of 50, 100, and 350 psi, and correlations tend to be just slightly stronger when sorption capacity is calculated on a mineral-matter-free basis (figs. 49, 50). Interestingly, CO<sub>2</sub> ( $r = 0.62$  to  $0.70$ ) is more weakly correlated with volatile matter than the other gases that were investigated ( $r = 0.69$  to  $0.87$  for CH<sub>4</sub> and  $0.78$  to  $0.89$  for N<sub>2</sub>).

At sample cell equilibrium pressures of 50, 100, and 350 psi, weak positive correlations between ash content and as-received sorption capacity for the three gases studied are common (figs. 51, 52). On an as-received basis, CO<sub>2</sub> capacity is most poorly correlated with ash content ( $r = 0.00$  to  $0.14$ ), and N<sub>2</sub> capacity is most strongly correlated ( $r = 0.30$  to  $0.40$ ). When sorption capacity is calculated on a mineral-matter-free basis, these correlations tend to be stronger, and correlation coefficients range narrowly from  $0.36$  to  $0.41$  for all three gases (fig. 52).

Examination of the scatterplots indicates that data points tend to be widely scattered and that the

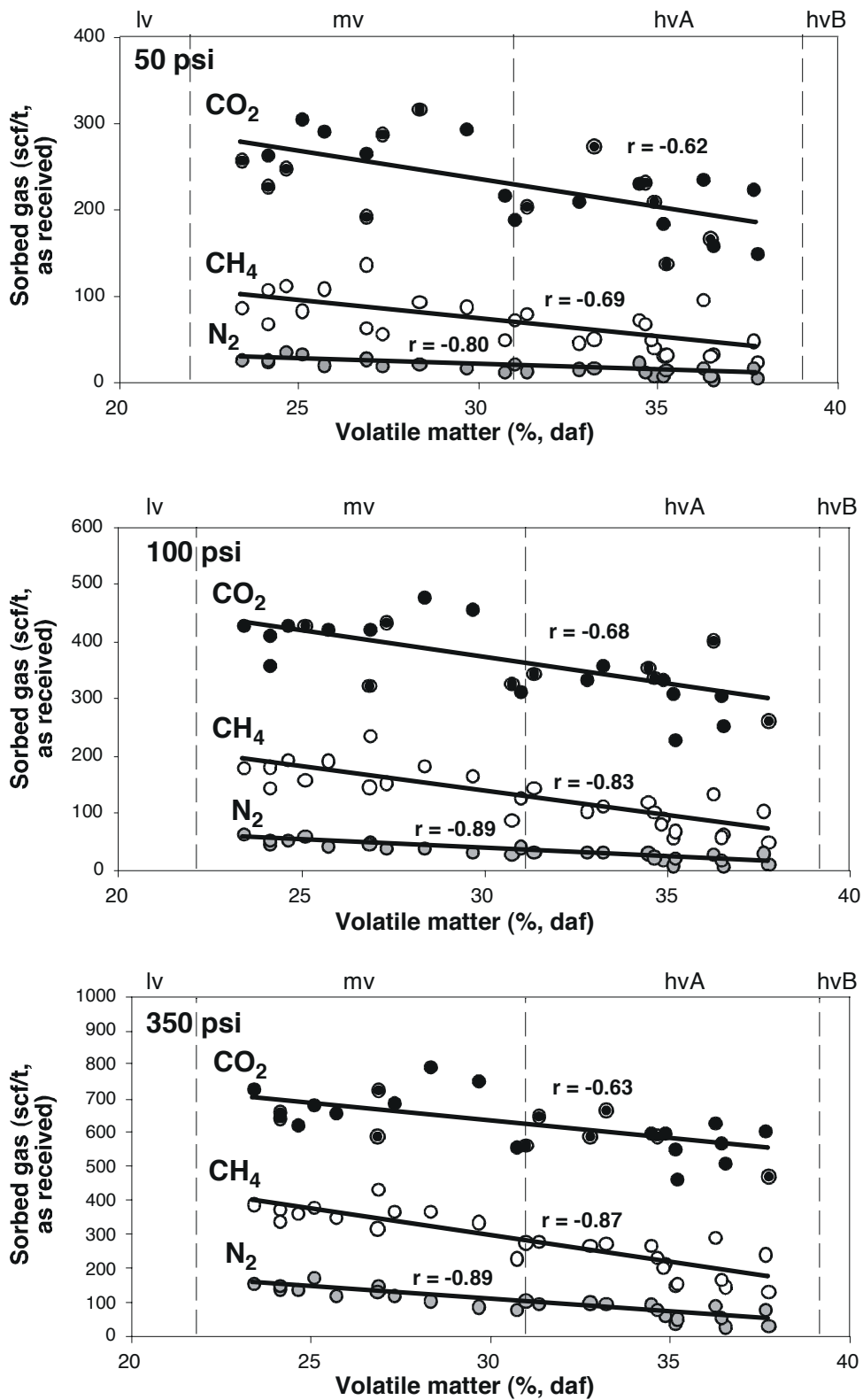


Figure 49.--Scatterplots showing correlation between sorption capacity (as-received) and volatile matter (daf)

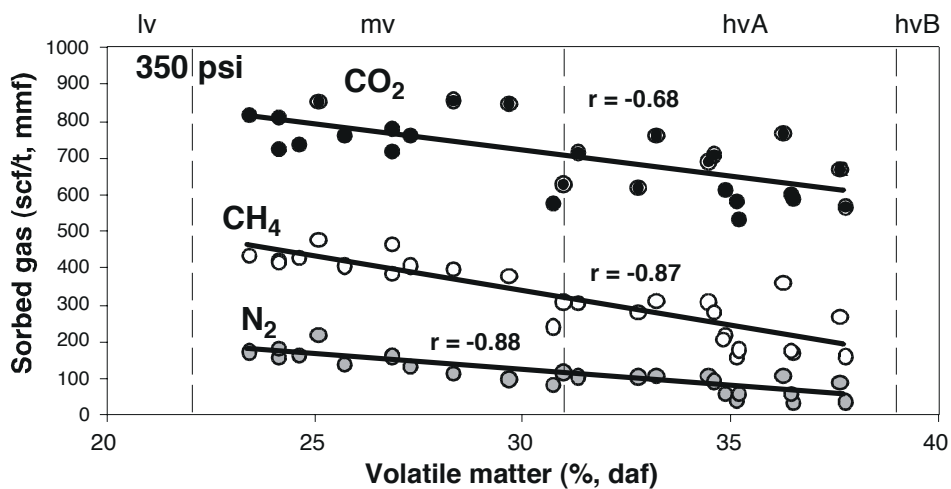
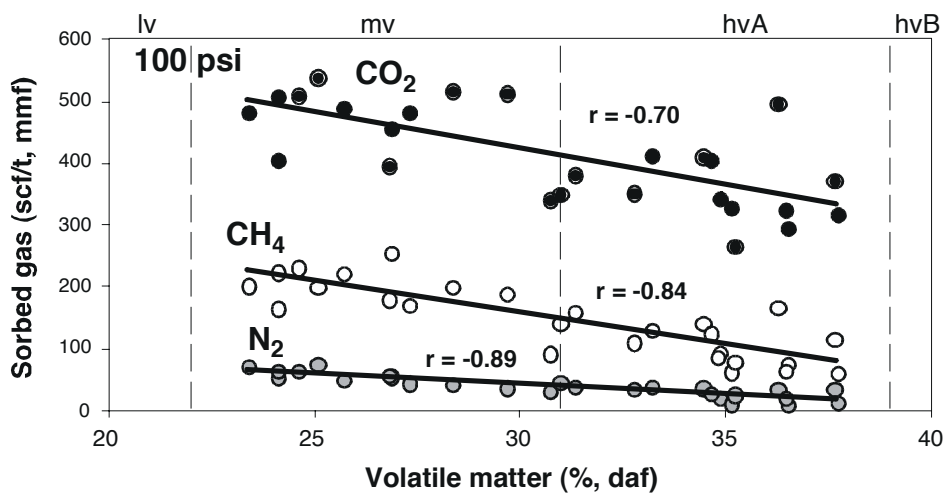
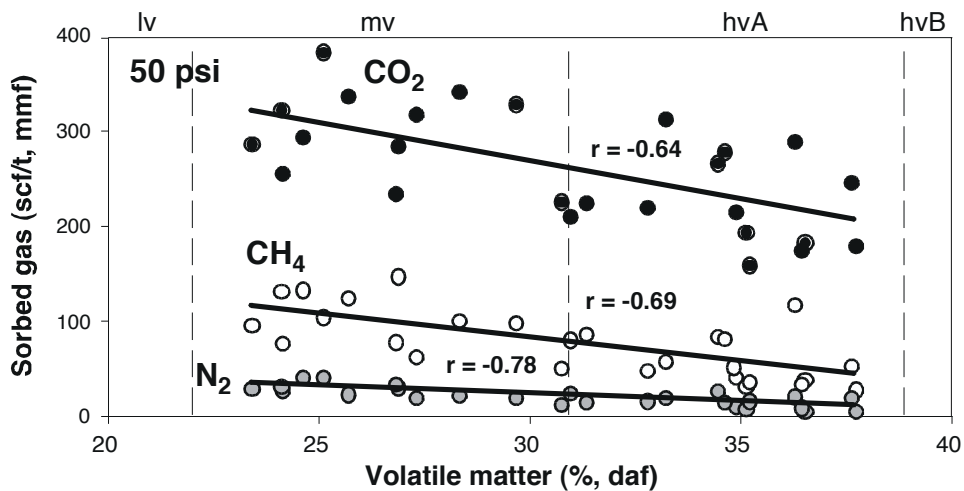


Figure 50.--Scatterplots showing correlation between sorption capacity (mmf) and volatile matter (daf)

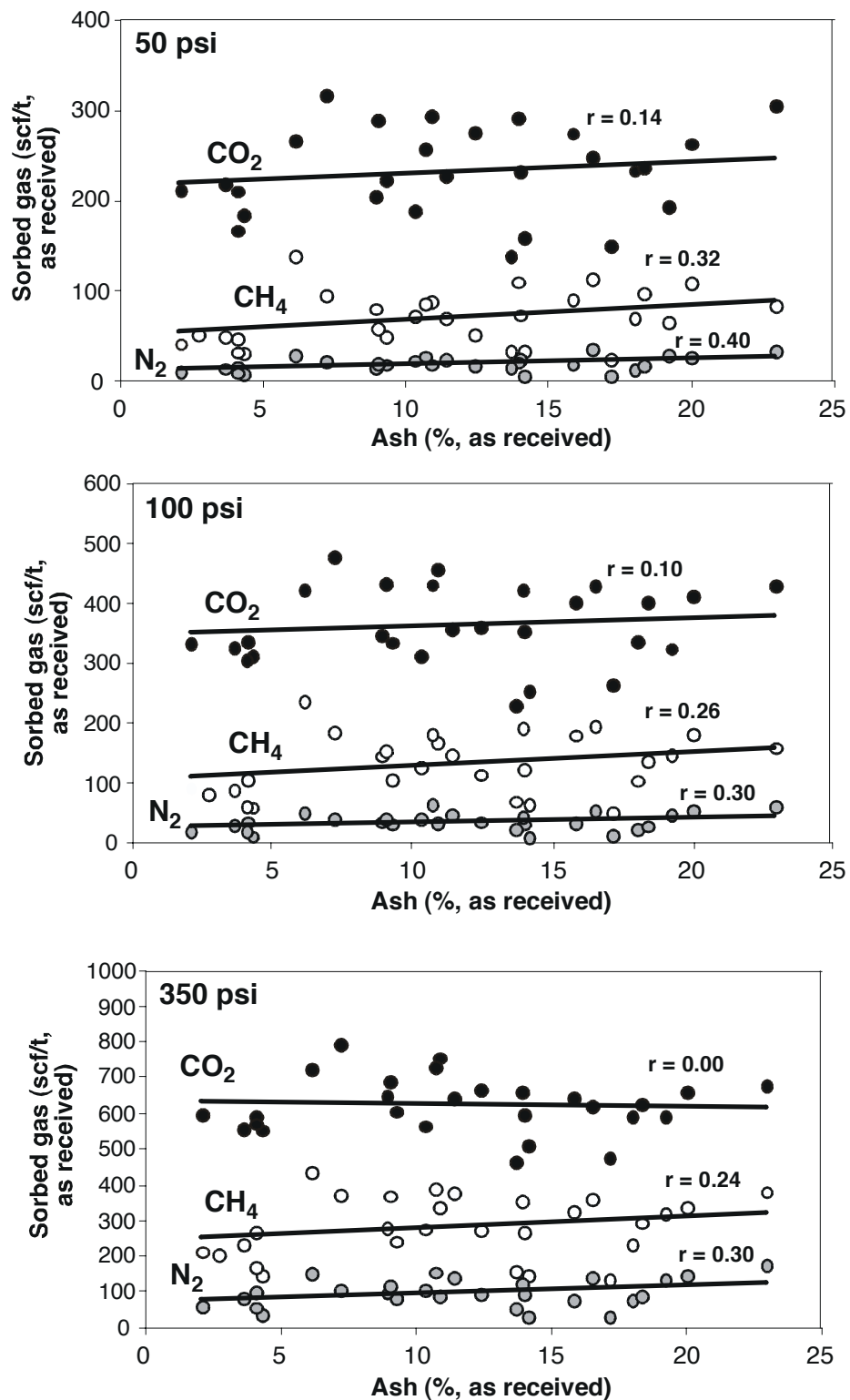


Figure 51.--Scatterplots showing correlation between sorption capacity (as-received) and ash content (as-received).



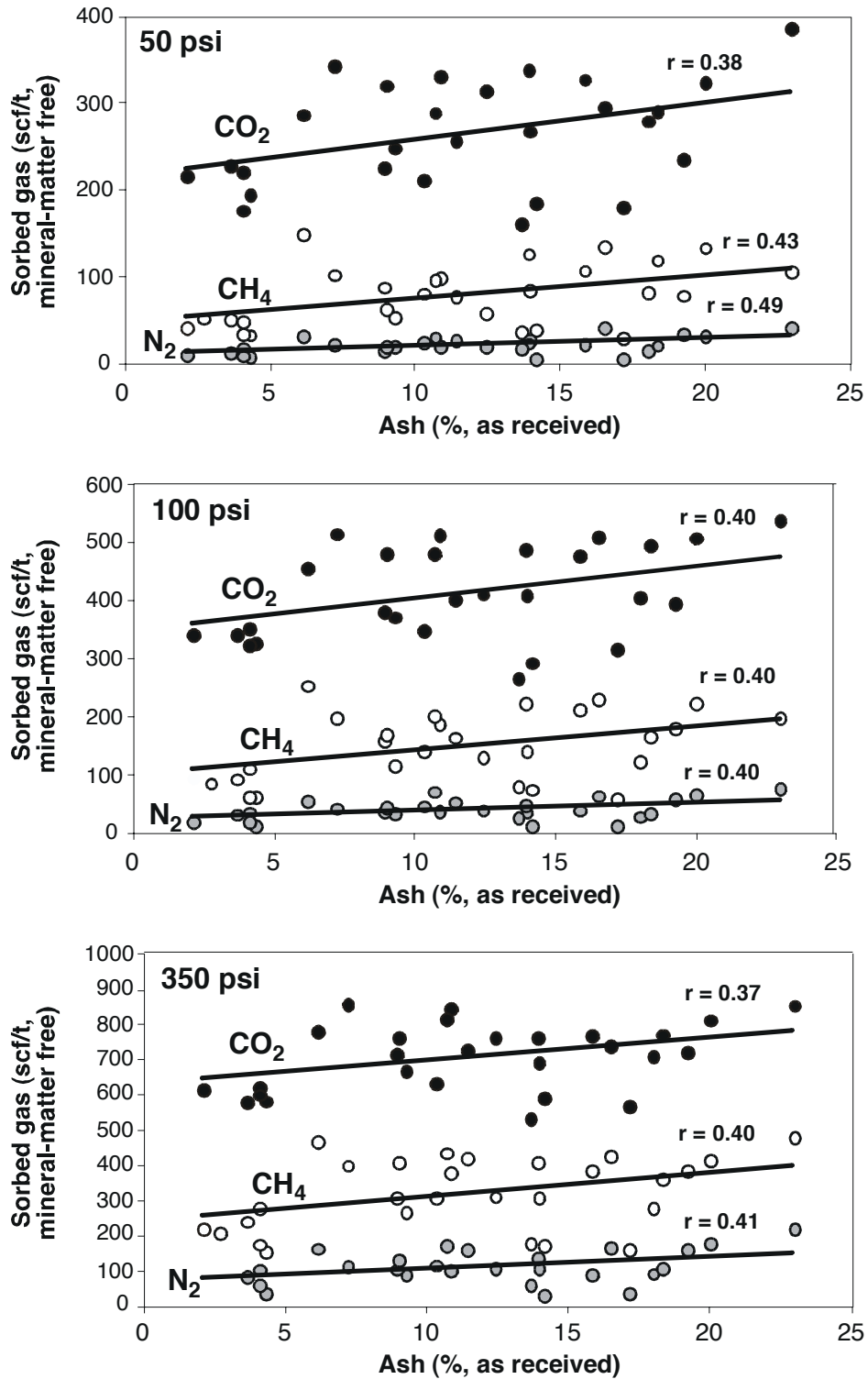


Figure 52.--Scatterplots showing correlation between sorption capacity (mmf) and ash content (as-received).

Table 2. Adsorption data for coal at 50, 100, and 350 psi.

Sample Number	Gas	Adsorption @ 50 psi			Adsorption @ 100 psi			Adsorption @ 350 psi		
		AR (scf/t)	MAF (scf/t)	DMMF (scf/t)	AR (scf/t)	MAF (scf/t)	DMMF (scf/t)	AR (scf/t)	MAF (scf/t)	DMMF (scf/t)
AL-CU-TP1-2.0	CH <sub>4</sub>	38.9	39.7	41.0	75.3	76.9	79.5	198.7	202.9	209.8
	CO <sub>2</sub>	184.5	188.4	194.8	300.2	306.6	317.1	595.4	608.2	628.9
	N <sub>2</sub>	8.5	8.7	8.9	16.3	16.6	17.2	51.9	53.1	54.8
AL-JE-BCCFT-1.0	CH <sub>4</sub>	49.3	51.2	52.3	86.3	89.5	91.4	225.8	234.1	239.2
	CO <sub>2</sub>	199.9	207.2	211.7	305.4	316.6	323.5	555.6	576.1	588.7
	N <sub>2</sub>	11.7	12.1	12.4	26.3	27.3	27.9	77.5	80.4	82.0
AL-JE-MRM-1.0	CH <sub>4</sub>	39.2	40.8	41.8	92.2	96.0	98.5	253.3	263.8	270.5
	CO <sub>2</sub>	176.0	183.3	188.0	299.0	311.4	319.4	586.8	611.0	626.7
	N <sub>2</sub>	15.3	15.9	16.4	32.0	33.3	34.2	96.1	100.0	102.6
AL-JE-TPLM-1.0	CH <sub>4</sub>	63.1	71.9	74.1	112.4	128.2	132.2	263.1	299.9	309.3
	CO <sub>2</sub>	212.9	242.7	250.4	329.7	375.9	387.7	602.7	687.1	708.6
	N <sub>2</sub>	19.9	22.7	23.4	29.9	34.1	35.1	87.5	99.8	102.9
AL-MA-LM1-1.0	CH <sub>4</sub>	29.7	33.9	35.7	56.2	64.2	67.5	142.1	162.3	170.9
	CO <sub>2</sub>	153.1	174.8	184.0	250.1	285.6	300.7	502.5	573.9	604.1
	N <sub>2</sub>	3.5	4.1	4.3	7.0	8.0	8.4	24.3	27.8	29.3
AL-MA-LM2-1.0	CH <sub>4</sub>	23.1	27.1	28.7	46.4	54.3	57.5	126.8	148.7	157.2
	CO <sub>2</sub>	147.5	172.9	182.9	235.3	275.8	291.7	467.5	547.9	579.7
	N <sub>2</sub>	4.5	5.2	5.6	8.9	10.4	11.1	28.4	33.4	35.3
AL-MA-MB2-1.0	CH <sub>4</sub>	28.5	29.8	31.6	53.3	55.6	59.0	143.4	149.7	158.7
	CO <sub>2</sub>	172.8	180.3	191.2	270.4	282.2	299.3	571.6	596.5	632.7
	N <sub>2</sub>	5.6	5.9	6.2	10.6	11.0	11.7	33.3	34.8	36.9
AL-TU-EPBC-1131.2	CH <sub>4</sub>	47.8	52.3	54.3	102.0	111.5	115.8	238.0	260.1	270.1
	CO <sub>2</sub>	191.1	208.9	216.8	311.0	340.0	353.0	597.4	653.0	678.1
	N <sub>2</sub>	16.9	18.4	19.1	28.8	31.5	32.7	77.8	85.1	88.3
AL-TU-EPBC-1690.2	CH <sub>4</sub>	58.5	69.0	71.7	101.4	119.7	124.3	228.6	269.8	280.4
	CO <sub>2</sub>	198.3	234.1	243.3	313.6	370.2	384.7	586.8	692.6	719.8
	N <sub>2</sub>	11.2	13.2	13.8	21.7	25.6	26.6	73.9	87.2	90.6
AL-TU-EPBC-2051.2	CH <sub>4</sub>	39.2	40.3	41.3	79.7	81.9	83.8	195.4	200.8	205.6
AL-TU-JWR41-1.0	CH <sub>4</sub>	74.8	82.9	85.1	136.7	151.6	155.6	314.9	349.2	358.4
	CO <sub>2</sub>	269.6	299.0	306.9	422.9	469.1	481.4	743.9	825.0	846.6
	N <sub>2</sub>	16.6	18.4	18.9	30.0	33.3	34.2	84.1	93.4	95.8
AL-TU-JWR41-2.0	CH <sub>4</sub>	79.2	85.0	86.8	148.3	159.1	162.6	342.9	367.7	375.9
	CO <sub>2</sub>	292.2	313.4	320.4	443.0	475.1	485.7	771.4	827.3	845.9
	N <sub>2</sub>	19.6	21.1	21.5	36.5	39.2	40.0	100.6	107.9	110.3
AL-TU-JWR626-1400.0	CH <sub>4</sub>	97.9	111.6	114.9	175.3	199.7	205.7	347.5	396.0	407.9
	CO <sub>2</sub>	232.4	264.9	272.8	374.5	426.8	439.6	656.3	747.9	770.3
	N <sub>2</sub>	18.4	21.0	21.6	38.6	44.0	45.3	118.0	134.5	138.6
AL-TU-JWR626-1947.5	CH <sub>4</sub>	65.5	73.0	75.0	130.6	145.5	149.6	351.2	391.4	402.4
	CO <sub>2</sub>	217.9	242.9	249.8	349.6	389.6	400.5	631.9	704.2	724.0
	N <sub>2</sub>	22.8	25.5	26.2	44.6	49.8	51.2	136.4	152.0	156.3

Table 2. Adsorption data for coal at 50, 100, and 350 psi (continued).

□ □ Sample Number	□ □ Gas	Adsorption @ 50 psi			Adsorption @ 100 psi			Adsorption @ 350 psi		
		AR (scf/t)	MAF (scf/t)	DMMF (scf/t)	AR (scf/t)	MAF (scf/t)	DMMF (scf/t)	AR (scf/t)	MAF (scf/t)	DMMF (scf/t)
AL-TU-TRPM-3.0	CH <sub>4</sub>	51.3	57.7	59.8	110.9	124.7	129.2	266.5	299.8	310.6
□	CO <sub>2</sub>	223.5	251.3	260.4	354.4	398.5	413.0	663.1	745.7	772.7
□	N <sub>2</sub>	15.9	17.9	18.6	31.2	35.0	36.4	90.0	101.3	104.9
AL-WA-HV2-1.0	CH <sub>4</sub>	27.6	31.4	32.7	54.7	62.1	64.7	151.2	172.0	179.0
□	CO <sub>2</sub>	133.9	152.2	158.5	226.9	257.9	268.6	458.0	520.8	542.4
□	N <sub>2</sub>	12.8	14.5	15.2	20.5	23.3	24.2	49.7	56.5	58.8
AL-WA-NV-1.0	CH <sub>4</sub>	26.1	27.2	28.5	56.7	59.0	62.1	162.3	168.9	177.7
□	CO <sub>2</sub>	165.2	172.0	180.9	273.0	284.3	298.9	564.7	588.0	618.3
□	N <sub>2</sub>	7.9	8.2	8.6	16.1	16.8	17.6	52.2	54.3	57.1

Table 3. Results of proximate analysis.

□ □ Sample Number	As Received				
	Moisture %	Ash %	Fixed Carbon %	Volatile matter %	Calorific value Btu
AL-CU-TP1-2.0	2.88	2.14	61.83	33.16	14,368
AL-JE-BCCFT-1.0	1.54	3.68	65.59	29.18	14,734
AL-JE-BCCFT-2.0	1.78	6.74	55.79	35.69	14,071
AL-JE-MRM-1.0	1.59	4.13	63.31	30.97	14,487
AL-JE-SCCH-0215.3	1.30	5.55	66.32	26.84	14,482
AL-JE-TPLM-1.0	1.71	14.01	54.63	29.65	12,887
AL-MA-LM1-1.0	3.88	14.19	51.33	30.60	11,929
AL-MA-LM2-1.0	3.54	17.20	48.35	30.92	11,543
AL-MA-MB2-1.0	5.28	4.35	58.55	31.83	13,056
AL-TU-BWFM-1.0	2.54	3.07	60.16	34.23	14,338
AL-TU-EPBC-1131.2	2.35	9.31	54.78	33.56	13,462
AL-TU-EPBC-1690.2	2.34	18.04	51.07	28.56	11,946
AL-TU-EPBC-2051.2	1.66	2.77	62.26	33.31	14,767
AL-TU-JWR41-1.0	1.42	10.91	61.32	26.35	13,575
AL-TU-JWR41-2.0	1.43	7.24	65.29	26.04	14,152
AL-TU-JWR626-1400.0	1.51	13.96	62.34	22.19	13,038
AL-TU-JWR626-1947.5	1.62	11.45	65.64	21.29	13,600
AL-TU-JWR628-2105.0	1.36	6.18	67.50	24.96	14,412
AL-TU-JWR629-1695.1	1.11	20.03	59.02	19.85	12,164
AL-TU-JWR630-0636.7	1.85	8.95	60.99	28.21	13,727
AL-TU-JWR632-0986.9	0.90	19.26	57.56	22.29	12,342
AL-TU-JWR633-0613.7	1.32	10.34	60.66	27.68	13,765
AL-TU-JWR633-1285.0	1.15	42.84	38.99	17.02	8,135
AL-TU-JWR633-1295.0	0.95	16.55	61.59	20.91	12,856
AL-TU-JWR633-1330.0	1.43	23.01	55.50	20.06	11,581
AL-TU-JWR633-1411.5	1.49	18.45	55.37	24.69	12,245
AL-TU-JWR633-1958.4	1.09	10.73	67.27	20.91	13,794
AL-TU-JWR633-2041.5	1.27	4.52	62.30	31.91	14,698
AL-TU-JWR639-2346.2	1.31	3.41	71.16	24.12	14,884
AL-TU-JWR640-0688.8	1.58	8.99	63.11	26.33	13,864
AL-TU-JWR640-1402.5	1.34	3.73	71.05	23.88	14,912
AL-TU-JWR640-2156.4	1.11	4.21	72.50	22.18	14,880
AL-TU-JWR640-2541.8	1.07	15.00	63.80	20.13	12,913
AL-TU-JWR640-2577.8	0.94	4.71	72.40	21.95	14,894
AL-TU-JWR650-1724.5	1.46	14.66	58.30	25.58	12,843
AL-TU-JWR652-1141.6	1.58	10.68	58.42	29.32	13,465

Table 3. Results of proximate analysis (continued).

□ □ Sample Number	As Received				
	Moisture %	Ash %	Fixed Carbon %	Volatile matter %	Calorific value Btu
AL-TU-JWR652-1711.7	1.30	15.32	58.74	24.65	12,819
AL-TU-JWR652-2190.0	1.22	9.05	65.01	24.72	13,971
AL-TU-JWR653-2193.2	1.41	10.46	62.94	25.19	13,628
AL-TU-JWR654-0227.7	1.53	13.55	55.46	29.46	12,894
AL-TU-JWR654-1737.0	1.30	15.87	48.29	34.54	12,800
AL-TU-JWR654-1994.0	1.15	18.39	50.23	30.24	12,360
AL-TU-JWR655-1168.6	1.29	15.80	55.28	27.63	12,722
AL-TU-JWR655-1179.4	1.47	13.86	45.77	38.90	12,911
AL-TU-JWR655-1205.3	1.45	6.43	63.07	29.05	14,226
AL-TU-JWR655-2227.3	1.13	10.45	64.02	24.40	13,669
AL-TU-JWR655-2229.4	1.15	5.96	66.68	26.21	14,514
AL-TU-JWR656-2118.9	0.85	7.49	73.56	18.10	14,411
AL-TU-JWR657-1208.3	1.32	4.85	59.08	34.76	14,569
AL-TU-JWR657-1765.9	1.13	17.24	52.25	29.37	12,540
AL-TU-MBR1-2.0	9.46	3.86	58.34	28.34	11,895
AL-TU-TRPM-3.0	2.03	12.45	56.65	28.87	13,068
AL-TU-TRPM-4.0	1.84	14.08	53.69	30.39	12,769
AL-WA-HV2-1.0	2.64	13.71	53.59	30.06	12,345
AL-WA-NV-1.0	3.82	4.12	58.44	33.62	13,528

Table 4. Results of ultimate analysis.

□ □ Sample Number	Dry Basis								
	C	H	N	O	Mineral Matter	Total S	Sulfatic S	Organic S	Pyritic S
	%	%	%	%	%	%	%	%	%
AL-CU-TP1-2.0	83.42	5.25	1.76	6.69	2.75	0.68	0.01	0.61	0.06
AL-JE-BCCFT-1.0	87.86	5.12	1.58	1.01	4.42	0.69	0.02	0.47	0.20
AL-JE-BCCFT-2.0	82.09	5.00	1.72	-0.30	9.96	4.63	0.21	1.16	3.27
AL-JE-MRM-1.0	84.16	5.05	1.81	3.56	5.21	1.22	0.01	0.92	0.29
AL-JE-SCCH-0215.3	84.70	4.74	1.79	2.47	6.44	0.68	0.01	0.60	0.07
AL-JE-TPLM-1.0	75.93	4.79	1.61	2.55	15.87	0.87	0.00	0.56	0.31
AL-MA-LM1-1.0	70.11	4.61	1.82	7.99	16.33	0.71	0.01	0.53	0.16
AL-MA-LM2-1.0	67.01	4.52	1.61	6.86	20.45	2.17	0.02	0.63	1.53
AL-MA-MB2-1.0	78.70	4.84	1.94	9.11	5.41	0.82	0.02	0.72	0.08
AL-TU-BWFM-1.0	84.29	5.36	1.60	4.41	4.06	1.19	0.06	0.81	0.34
AL-TU-EPBC-1131.2	79.67	5.11	1.64	2.49	11.15	1.56	0.03	0.83	0.70
AL-TU-EPBC-1690.2	71.58	4.59	1.61	3.07	20.32	0.68	0.02	0.51	0.15
AL-TU-EPBC-2051.2	87.50	5.36	1.75	1.61	3.57	0.96	0.02	0.87	0.08
AL-TU-JWR41-1.0	78.65	4.58	1.81	3.09	12.40	0.80	0.01	0.62	0.17
AL-TU-JWR41-2.0	82.58	4.72	1.95	2.87	8.22	0.54	0.02	0.47	0.04
AL-TU-JWR626-1400.0	77.30	4.19	1.29	2.04	15.86	1.01	0.07	0.59	0.36
AL-TU-JWR626-1947.5	80.39	4.52	1.60	1.15	12.96	0.70	0.03	0.56	0.11
AL-TU-JWR628-2105.0	85.61	4.63	1.49	-0.20	7.98	2.20	0.15	0.67	1.38
AL-TU-JWR629-1695.1	71.56	3.72	1.32	0.32	23.43	2.83	0.10	0.65	2.09
AL-TU-JWR630-0636.7	80.93	4.72	1.51	2.59	10.47	1.13	0.06	0.59	0.48
AL-TU-JWR632-0986.9	72.13	4.21	1.20	0.71	22.26	2.32	0.04	0.61	1.67
AL-TU-JWR633-0613.7	81.15	4.87	1.41	1.33	11.74	0.76	0.03	0.57	0.16
AL-TU-JWR633-1285.0	47.60	3.02	0.76	0.41	49.49	4.87	0.20	0.40	4.26
AL-TU-JWR633-1295.0	75.70	4.24	1.20	0.30	19.06	1.85	0.07	0.55	1.23
AL-TU-JWR633-1330.0	69.04	3.98	1.16	0.86	26.10	1.62	0.14	0.50	0.98
AL-TU-JWR633-1411.5	72.70	4.15	1.22	1.90	20.94	1.30	0.09	0.62	0.59
AL-TU-JWR633-1958.4	82.69	4.53	1.54	-0.43	12.17	0.82	0.04	0.58	0.19
AL-TU-JWR633-2041.5	88.39	4.61	1.65	-0.29	5.53	1.06	0.06	0.52	0.48
AL-TU-JWR639-2346.2	88.69	4.90	1.90	-0.34	4.50	1.39	0.04	0.98	0.37
AL-TU-JWR640-0688.8	82.59	4.87	1.53	1.17	10.25	0.71	0.03	0.62	0.07
AL-TU-JWR640-1402.5	86.02	4.96	1.51	2.76	4.62	0.97	0.05	0.65	0.28
AL-TU-JWR640-2156.4	87.68	4.75	1.50	0.67	5.23	1.14	0.03	0.45	0.65
AL-TU-JWR640-2541.8	75.10	4.16	1.46	-0.32	18.81	4.44	0.11	1.21	3.11
AL-TU-JWR640-2577.8	88.81	4.83	1.73	-1.80	6.05	1.68	0.05	0.84	0.79
AL-TU-JWR650-1724.5	75.67	4.55	1.62	1.86	16.85	1.42	0.04	0.69	0.69
AL-TU-JWR652-1141.6	76.94	4.63	1.57	2.94	13.41	3.07	0.08	1.06	1.93

Table 4. Results of ultimate analysis (continued).

□ □ Sample Number	Dry Basis								
	C	H	N	O	Mineral Matter	Total S	Sulfatic S	Organic S	Pyritic S
	%	%	%	%	%	%	%	%	%
AL-TU-JWR652-1711.7	73.26	4.57	1.44	3.85	17.51	1.36	0.04	0.65	0.68
AL-TU-JWR652-2190.0	80.50	4.47	1.69	2.18	10.99	2.00	0.05	0.67	1.28
AL-TU-JWR653-2193.2	79.36	4.45	1.56	1.43	12.88	2.59	0.09	0.74	1.76
AL-TU-JWR654-0227.7	76.41	4.49	1.65	-0.37	17.09	4.06	0.07	1.28	2.72
AL-TU-JWR654-1737.0	73.18	4.35	1.56	1.22	19.35	3.61	0.06	0.97	2.58
AL-TU-JWR654-1994.0	70.32	4.19	1.51	-0.37	23.25	5.75	0.09	1.16	4.50
AL-TU-JWR655-1168.6	72.52	4.34	1.53	1.81	19.38	3.79	0.06	1.27	2.45
AL-TU-JWR655-1179.4	73.55	4.56	1.50	1.43	17.89	4.89	0.08	2.04	2.77
AL-TU-JWR655-1205.3	82.59	4.83	1.66	2.50	8.09	1.90	0.04	0.95	0.92
AL-TU-JWR655-2227.3	78.51	4.40	1.66	1.56	13.23	3.30	0.04	1.14	2.12
AL-TU-JWR655-2229.4	83.36	4.66	1.78	1.42	8.02	2.75	0.02	1.15	1.58
AL-TU-JWR656-2118.9	84.48	4.20	1.75	0.48	9.00	1.54	0.01	0.70	0.83
AL-TU-JWR657-1208.3	83.81	5.02	1.74	2.38	6.48	2.14	0.02	0.97	1.15
AL-TU-JWR657-1765.9	72.72	4.28	1.57	1.86	20.01	2.13	0.00	0.81	1.32
AL-TU-MBR1-2.0	78.18	4.37	1.78	10.43	5.14	0.98	0.03	0.89	0.05
AL-TU-TRPM-3.0	77.20	4.83	1.60	2.25	14.50	1.41	0.01	0.75	0.65
AL-TU-TRPM-4.0	74.65	4.78	1.50	1.21	17.42	3.52	0.15	1.29	2.08
AL-WA-HV2-1.0	72.37	4.65	1.78	6.08	15.78	1.04	0.01	0.51	0.52
AL-WA-NV-1.0	79.90	5.13	1.99	6.79	5.67	1.91	0.03	0.76	1.12

positive correlation is chiefly a function of poor sorption performance below 5 percent ash and exceptional performance of one sample with 23 percent ash. If regression analysis is performed only on samples between 5 and 21 percent ash, no correlations or negative correlations ( $r = 0.00$  to  $-0.48$ ) exist between sorption capacity and ash content, and correlations are strongest when the data are analyzed at high pressure on an as-received basis (fig. 53).

Mineral matter and moisture have minimal surface area compared to the microporous organic constituents of coal (Gan and others, 1972; Clarkson and Bustin, 1996). Accordingly, the adsorption capacity of coal would be expected to decrease proportionally with increasing ash and moisture content. Pore volume also increases with increasing rank (i.e., decreasing volatile matter) (Gan and others, 1972; Clarkson and Bustin, 1997; Bustin and Clarkson, 1998), so rank parameters should correlate with sorption capacity.

Although results from the Black Warrior basin follow the expected rank-sorption capacity relationship (figs. 49, 50), the positive correlation between ash content and sorption capacity is counterintuitive (figs. 51, 52). Although isolating data between 5 and 21 percent ash yields the expected negative correlation (fig. 53), coal with extremely low ash content ( $< 5$  percent) nevertheless has retarded sorption potential (figs. 51, 52). The reasons for the poor performance of low-ash coal are unclear and may be related to a couple of factors. One possibility is that mineral matter helps provide structural support that decreases the sensitivity of the organic matrix to effective stress. Another possibility is that porosity in mineral matter provides permeable conduits for gas to enter parts of the organic matrix that are otherwise inaccessible.



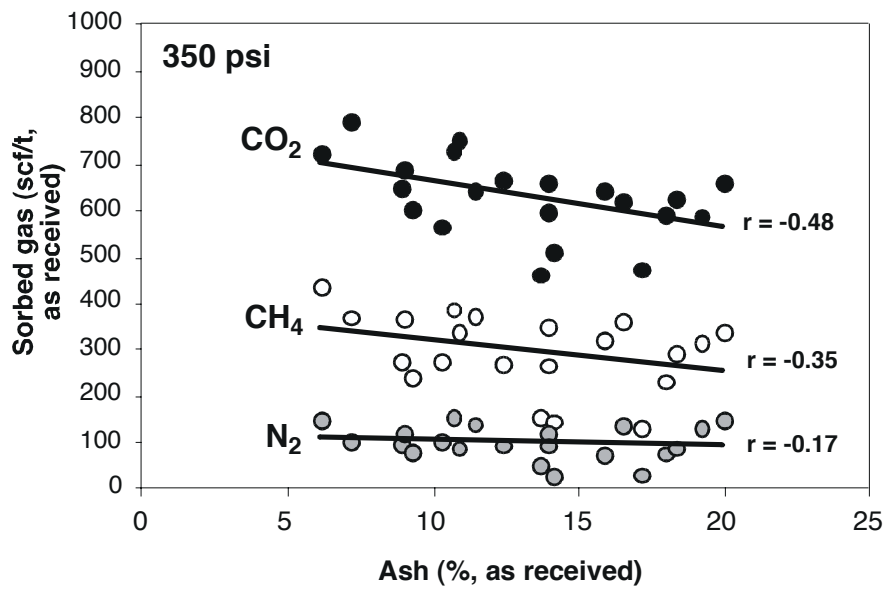


Figure 53.--Scatterplots showing negative correlation between sorption capacity (as-received) and ash content (as-received) for samples with ash content between 5 and 21 percent.

Interestingly, Bustin (1997) noted a positive correlation between ash content and gas content in Australian coal, so ash-enhanced sorption may not be unique to the Black Warrior basin.

Other relationships between sorption and other coal quality parameters also may not be straightforward. In a comparison of dried and moisture-equilibrated coal of bituminous rank, for example, Joubert and others (1973, 1974) found that moisture content suppresses sorption capacity far more than would be expected on the basis of weight percentages or volumetrics. Their finding confirms that isotherms should be run on moisture-equilibrated coal to accurately characterize gas sorption under reservoir conditions. Regardless, these types of findings demonstrate that basic relationships between sorption capacity and coal quality need to be derived empirically rather than by relying on simple volumetric relationships.

In mature coalbed methane reservoirs, which have been dewatered for several years, hydrostatic pressure in places can be depleted to 50 psi or lower. The isotherms indicate that Pottsville coal can hold an average of 80 scf/t (standard cubic feet per ton) of CH<sub>4</sub> at 50 psi and 128 scf/t at 100 psi, so a large gas resource appears to remain untapped (fig. 47). At these same pressures, coal holds an average of 230 to 361 scf/t of CO<sub>2</sub>, so large volumes of CO<sub>2</sub> may be required to fully saturate coal and recover all of the remaining coalbed methane. By contrast, coal typically adsorbs only about 18 to 33 scf/t of N<sub>2</sub> at these pressures, so relatively little N<sub>2</sub> may be required for enhanced coalbed methane recovery. Little research has been done on the sorption selectivity of coal relative to these three gases, but experiments in the San Juan basin suggest that N<sub>2</sub> breaks through early (Stevens and others, 1999a, b), whereas early breakthrough

of CO<sub>2</sub> has not been observed. This research further indicates that coal does not need to be fully saturated with CO<sub>2</sub> to drive enhanced coalbed methane recovery. Perhaps an optimal mix of CO<sub>2</sub> and N<sub>2</sub> is attainable that provides for efficient enhanced coalbed methane recovery while minimizing the cost of refining CO<sub>2</sub> derived from power-plant flue gas streams.

### **GAS CONTENT**

To help determine the economic viability of a coalbed methane reservoir the original gas content of the coal must be known. Gas content data are potentially of similar value in screening areas for enhanced coalbed methane recovery because enough of the original resource must remain unrecovered to justify the expense of separating, transporting, and injecting CO<sub>2</sub>.

Original gas content is highly variable in coal beds of the Black Warrior basin, ranging from almost 0 to more than 600 scf/t on an ash-free basis (fig. 54). Published results of desorption tests show that gas content typically increases with depth. However, that increase is commonly erratic, and gas content may vary by more than 300 scf/t within a single coal zone. In addition to vertical variation of gas content, local variation also exists within coal beds, and some beds at depth are effectively degassed (Diamond and others, 1976; Malone and others, 1987a). Gas content higher than 400 scf/t is common in Oak Grove and Brookwood fields, whereas lower gas content is typical of other areas. Comparison of gas-content data with results of adsorption experiments suggests that most coal in the Alabama coalbed methane fields is undersaturated with methane, but some beds have effectively complete isothermal gas saturation (Kim, 1977).

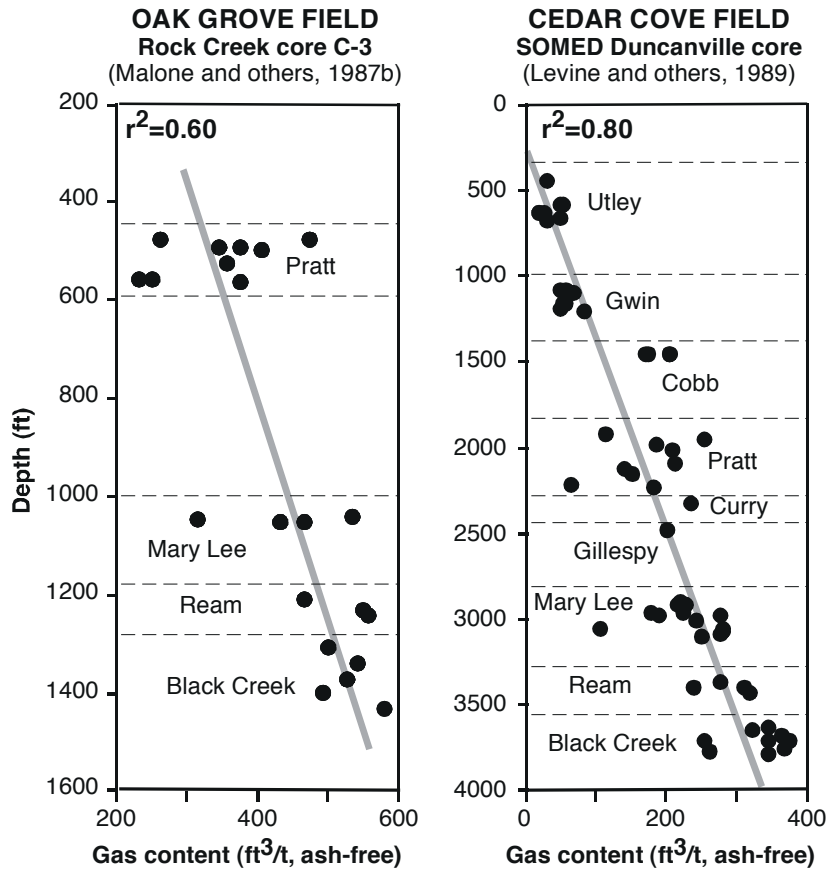


Figure 54.--Plots of gas content versus depth for two cores in the Black Warrior coalbed methane fairway.

Explaining why gas content is so variable is difficult because numerous factors affect the ability of coal to generate and retain gas. Those factors include analytical error, coal quality, reservoir pressure, and basin hydrodynamics. Perhaps the most important causes of variable gas content in Pottsville coal relate to burial history and the hydrodynamics of the Black Warrior basin. During active subsidence and coalification, coal generates many times more methane than it can hold (Levine, 1993). During regional unroofing, however, active thermogenic gas generation effectively ceases, and decreasing temperature causes coal to become undersaturated with methane (Scott and others, 1994).

Although post-orogenic cooling explains undersaturated coal in the Black Warrior basin, it does not explain why saturated coal is present in some areas. Rice (1993) noted that carbon in the produced gas is isotopically too light to have been generated strictly by thermogenic means and is thus probably mixed with late-stage biogenic gas. Late biogenic gas is thought to form in areas affected by fresh-water recharge (Rice, 1993; Scott, 1993), so it is not surprising that coal with high gas saturation is developed in the Oak Grove-Brookwood area, where freshwater plumes extend from the northwest flank of the Birmingham anticlinorium deep into the Black Warrior basin (fig. 32). Burial history analysis suggests that plume development may have begun during the late stages of Mesozoic unroofing (fig. 40).

Subsequent reburial below coastal plain strata (fig. 40) may have intercepted recharge across much of the basin, but today, this situation is restricted to the western part of the coalbed methane fairway. As Pottsville strata have approached modern depths, where sorption capacity is

most sensitive to pressure, pockets of extreme underpressure may have begun to develop. The dynamic subsurface flow system and pressure regime in the Black Warrior basin today may be promoting desorption and migration of gas in some areas and resorption in others, thus giving rise to a heterogeneous distribution of coalbed methane resources.

Many desorption analyses underestimate gas content by not accounting fully for lost gas and reservoir temperature, and for this reason, gas recovery from many wells in the Black Warrior basin greatly exceeds estimates of original gas in place (Mavor and Nelson, 1997). Besides underestimating the gas content of coal, additional gas may be produced from organic-rich shale units enveloping the coal (Lamarre and others, 2001). For these reasons, estimating the volume of gas remaining in mature reservoirs should ideally be based on new direct measurements of gas content. Perhaps the most practical indirect approach is to determine ambient reservoir pressure with shut-in tests and to use the pressure data in combination with sorption isotherms to estimate remaining coalbed methane resources.

## **GAS AND WATER PRODUCTION**

Production data are useful not only for characterizing the performance of coalbed methane reservoirs, but for screening areas for sequestration and enhanced recovery efforts. These data are also useful for determining which wells to convert into injectors and which ones to leave as producers as enhanced recovery efforts commence. In this section, we review the production characteristics of vertical coalbed methane wells in the Black Warrior basin and review the basic geologic controls on well performance.

## Background

Three types of coalbed methane wells are drilled in the Black Warrior basin, namely vertical wells, gob wells, and horizontal wells. Gob and horizontal wells are drilled in association with underground mining operations in Brookwood and Oak Grove Fields and are thus of limited relevance to CO<sub>2</sub> sequestration and enhanced gas recovery. Vertical wells are similar to conventional petroleum wells, have no dependence on mining operations, and are drilled in all coalbed methane fields. Therefore, vertical wells are the focus of this discussion.

The Black Warrior coalbed methane fairway has had a steady development history which began in 1980, and most wells have been producing between 9 and 15 years (fig. 55). The earliest wells, which were drilled between 1975 and 1980 are in extreme close-spaced patterns (~15 acres) in eastern Oak Grove Field and in Pleasant Grove Field. Subsequent development has utilized chiefly 40- and 80-acre well spacing. Most wells were drilled between 1988 and 1991 prior to expiration of the Section 29 tax credit. The vast majority of these wells remain on line today, although the wells in the southwestern (Little Buck Creek, Taylor Creek, and Little Sandy Creek) and northwestern fields (Carrolls Creek, Wolf Creek, and Boone Creek) have been plugged and abandoned (fig. 56). Most wells in Moundville Field are listed by the State Oil and Gas Board of Alabama as temporarily abandoned, and efforts are currently underway to revive production in that field. Active exploration is focused in the parts of Blue Creek, White Oak Creek, and Short Creek fields where wells have reported less than 3 years of production. Most areas where wells have reported less than 6 years of production in Oak Grove and Brookwood

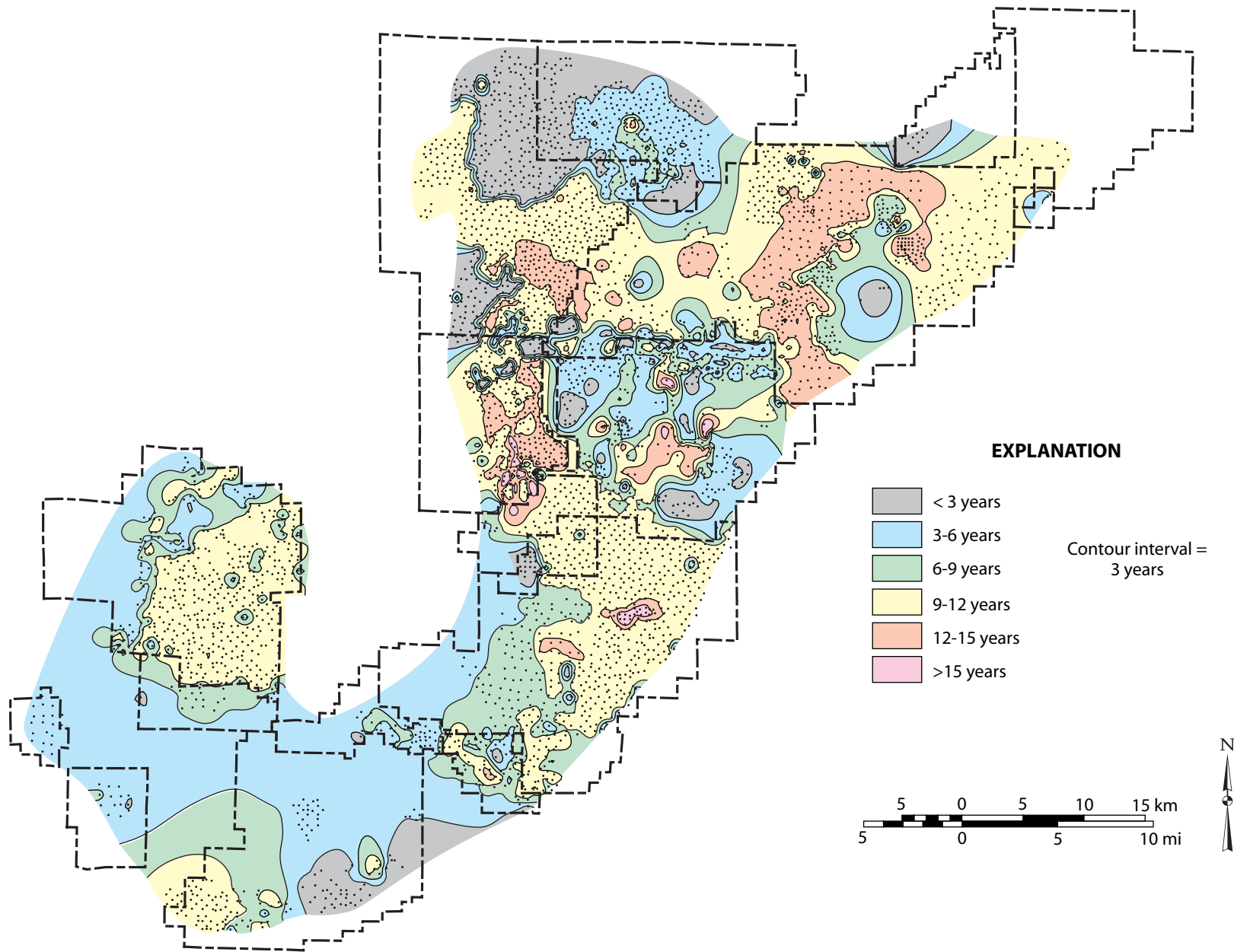


Figure 55.--Map showing years of reported production from vertical wells in the Black Warrior coalbed methane fairway.



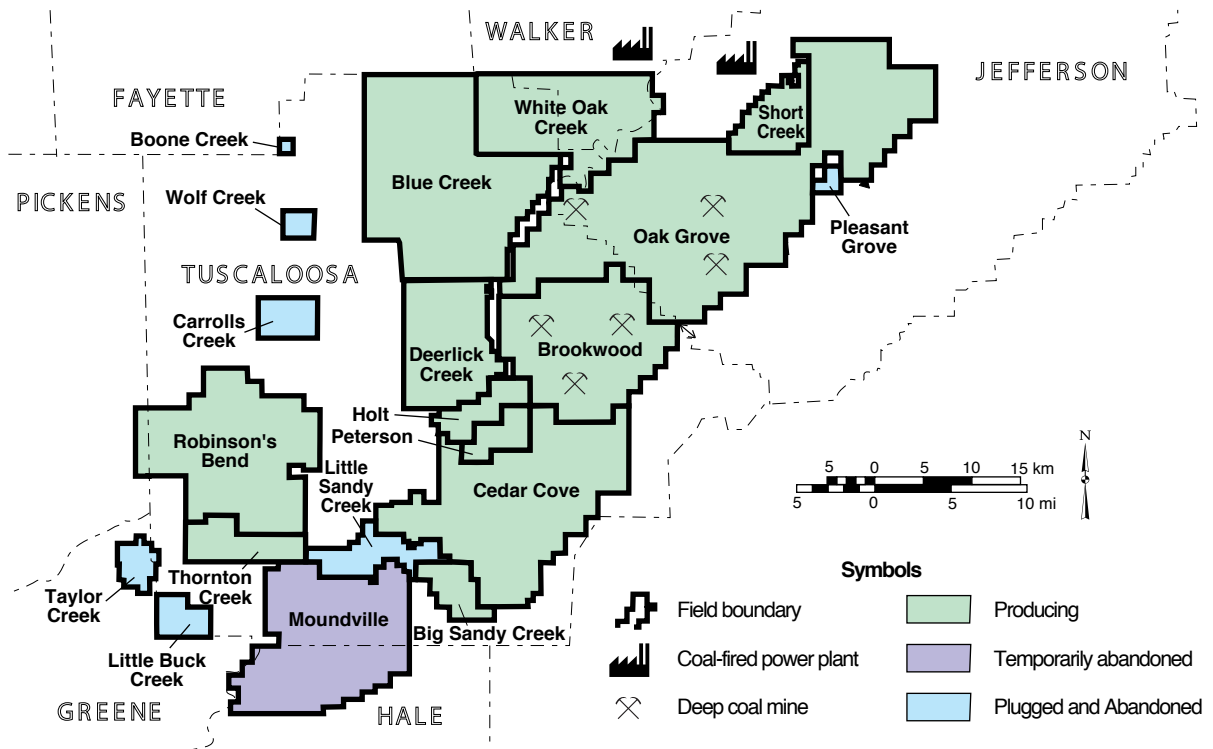


Figure 56.--Map showing generalized status of coalbed methane fields in the Black Warrior basin.

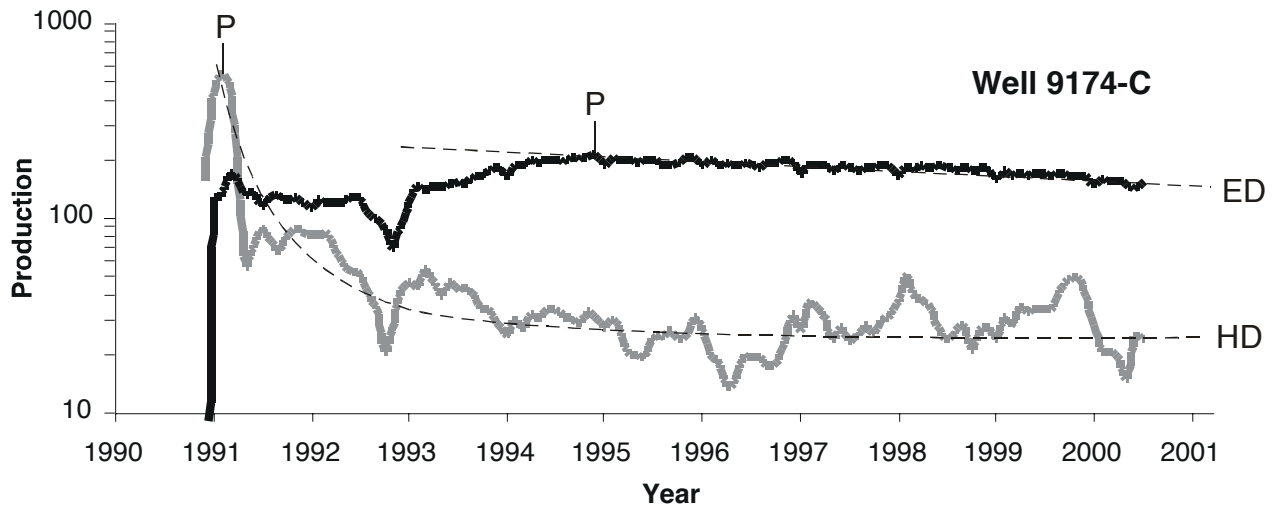
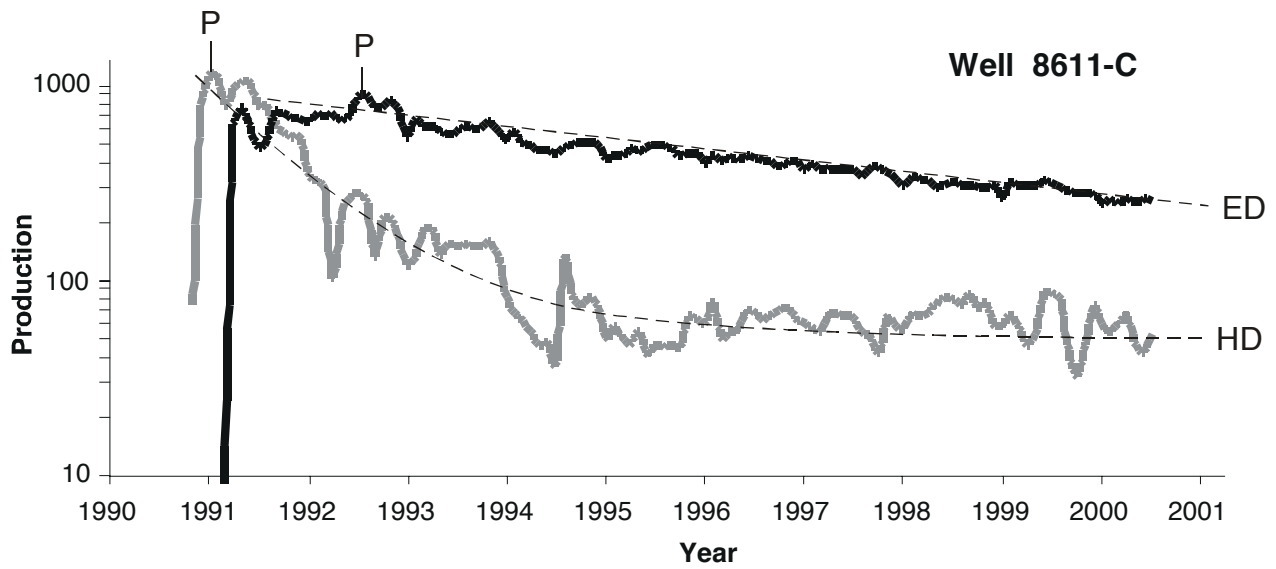
fields are where mining has passed through vertical wells and areas of recent development peripheral to the mines.

Completion practice in vertical wells varies considerably (e.g., Lambert and others, 1980; Holditch and others, 1989; Pashin and Hinkle, 1997). Many early wells were completed in open hole in single coal beds, whereas virtually all wells today are cased and perforated in multiple coal beds (Graves and others, 1983). Stimulation practice is also varied, and early wells were stimulated with water and sand, nitrogen foam, or cross-linked gel. Today, most vertical wells are stimulated with nitrogen foam.

#### Production Characteristics

Essentially all vertical wells produce at least some water and gas, and the volumes of fluid produced and the decline characteristics of these wells can be difficult to predict. Even so, some generalizations can be made. Gas and water production tend to peak during the first two years wells are on line, although it is not common for some wells to take more than 48 months to reach peak flow rates (Pashin and Hinkle, 1997) (fig. 57). Once peak production is reached, gas production tends to decline exponentially (i.e., constant rate of decline), whereas water production tends to decline hyperbolically (i.e., decreasing rate of decline).

Cumulative and peak gas and water production data for wells that have produced longer than 48 months have log-normal population distributions (Pashin and Hinkle, 1997; Zuber and Boyer, 2001) (figs. 58-60). Cumulative gas production from vertical wells has a log-normal mean of 136



— Water (bpd)	P Peak production
— Gas (Mcf/d)	ED Exponential decline
	HD Hyperbolic decline

Figure 57.--Decline curves for gas and water production from two wells in Deerlick Creek Field (modified from Cox, 2002).

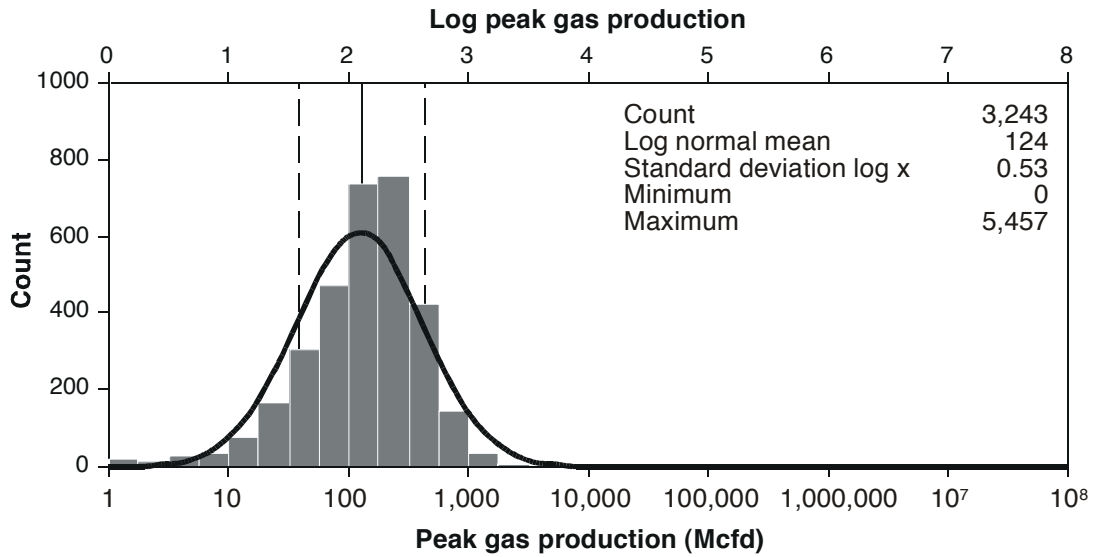
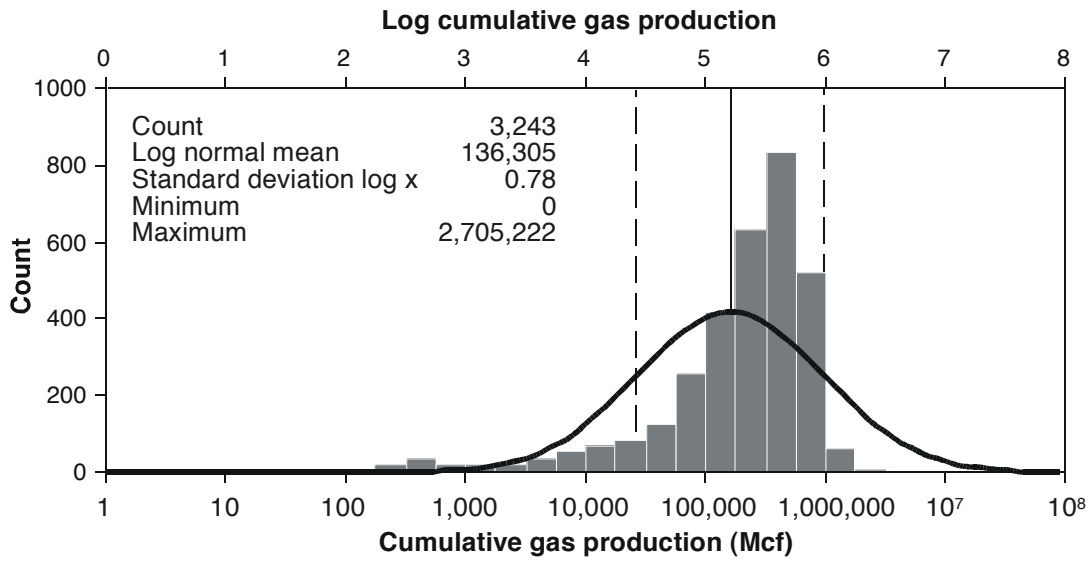


Figure 58.--Histograms of cumulative and peak gas production from coalbed methane wells in the Black Warrior basin.

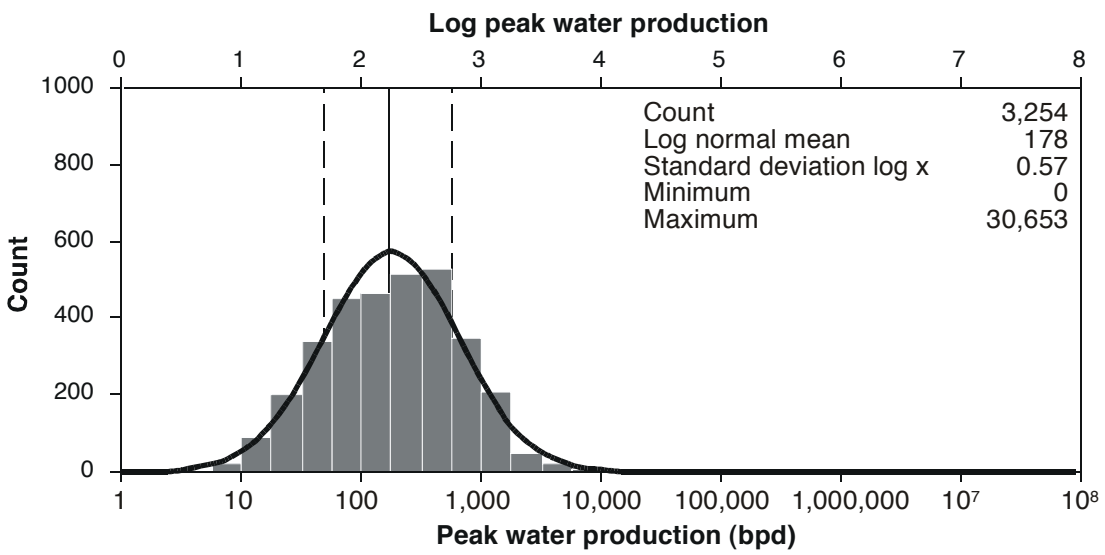
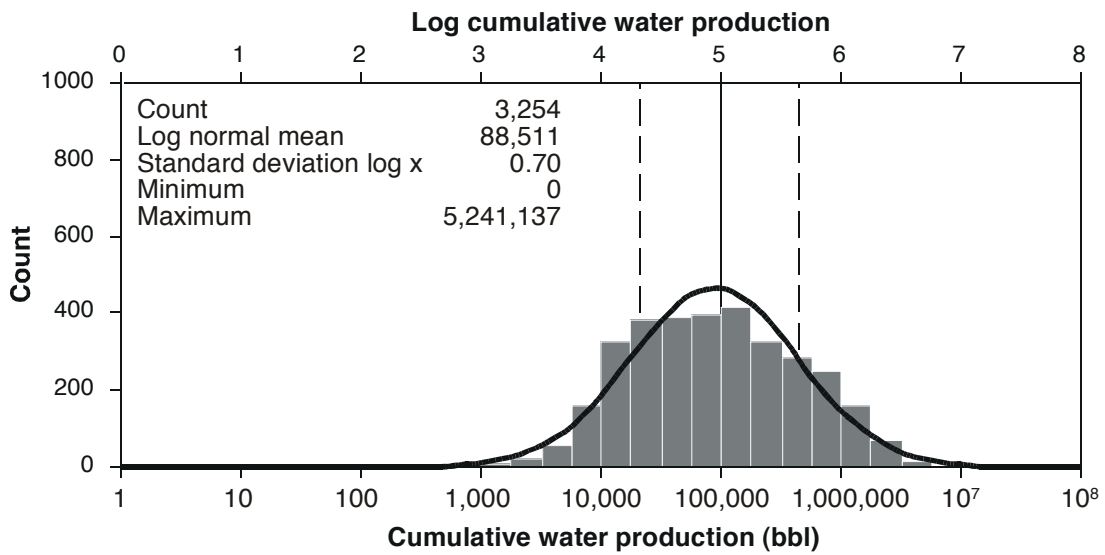


Figure 59.--Histograms of cumulative and peak water production from coalbed methane wells in the Black Warrior basin.

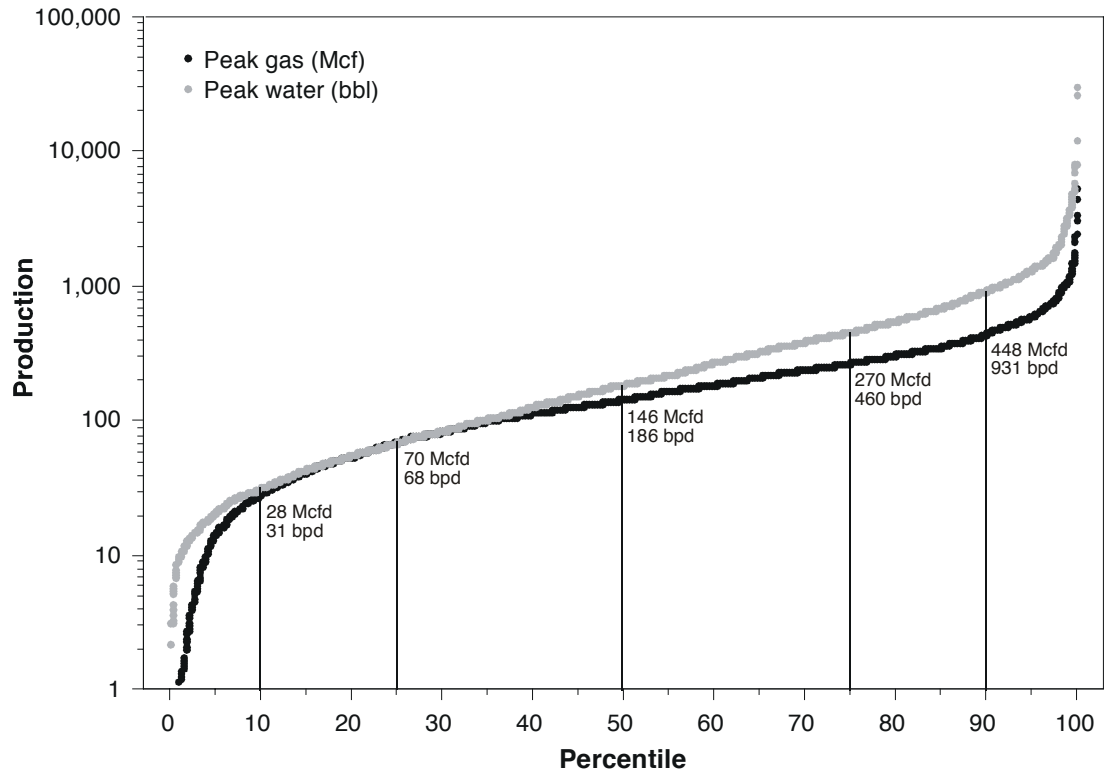
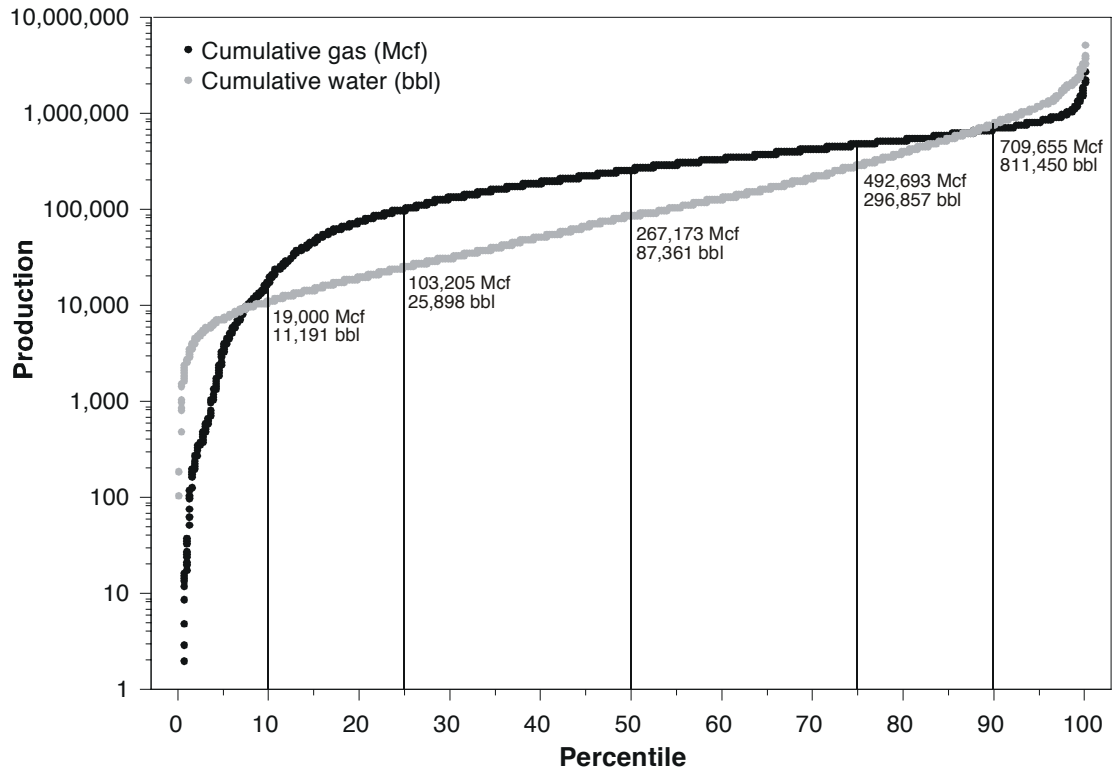


Figure 60.--Percentile plots of cumulative and peak water production from coalbed methane wells in the Black Warrior basin.

MMcf (million cubic feet), whereas cumulative water production has a log-normal mean of about 88,500 bbl (barrels). Importantly, most wells in the basin are still producing, so these numbers will increase in future years. Percentile plots establish that 80 percent of the vertical wells in the Black Warrior basin have produced between 19 and 710 MMcf of gas and between 11,000 and 811,000 bbl of water (fig. 60). Peak gas production for wells that have produced longer than 48 months has a log-normal mean of 124 Mcfd (thousand cubic feet per day), whereas peak water production has a log-normal mean of 178 bpd (barrels per day). Percentile plots demonstrate that 80 percent of the vertical wells have peaked between 28 and 448 Mcfd of gas and between 31 and 961 bpd of water.

Peak and cumulative production values correlate strongly for gas and water when analyzed on a logarithmic basis (Pashin and Hinkle, 1997) (fig. 61). Therefore, peak production rates are valuable indicators of long-term well performance than can be obtained early in the life of a well. However, basic population statistics dictate that meaningful predictions can only be made within the certainty of an order of magnitude. Although a strong correlation exists between peak and cumulative production values for each fluid, no global correlation exists between gas and water production (fig. 62). This indicates that the flow of gas and water are largely independent and also reflects contrasting gas production from virgin reservoirs and from reservoirs that have been dewatered by mining activity. In a recent study of Deerlick Creek Field, which has not been affected by mine dewatering, Cox (2002) found a modest positive correlation between peak gas and water production (fig. 63).

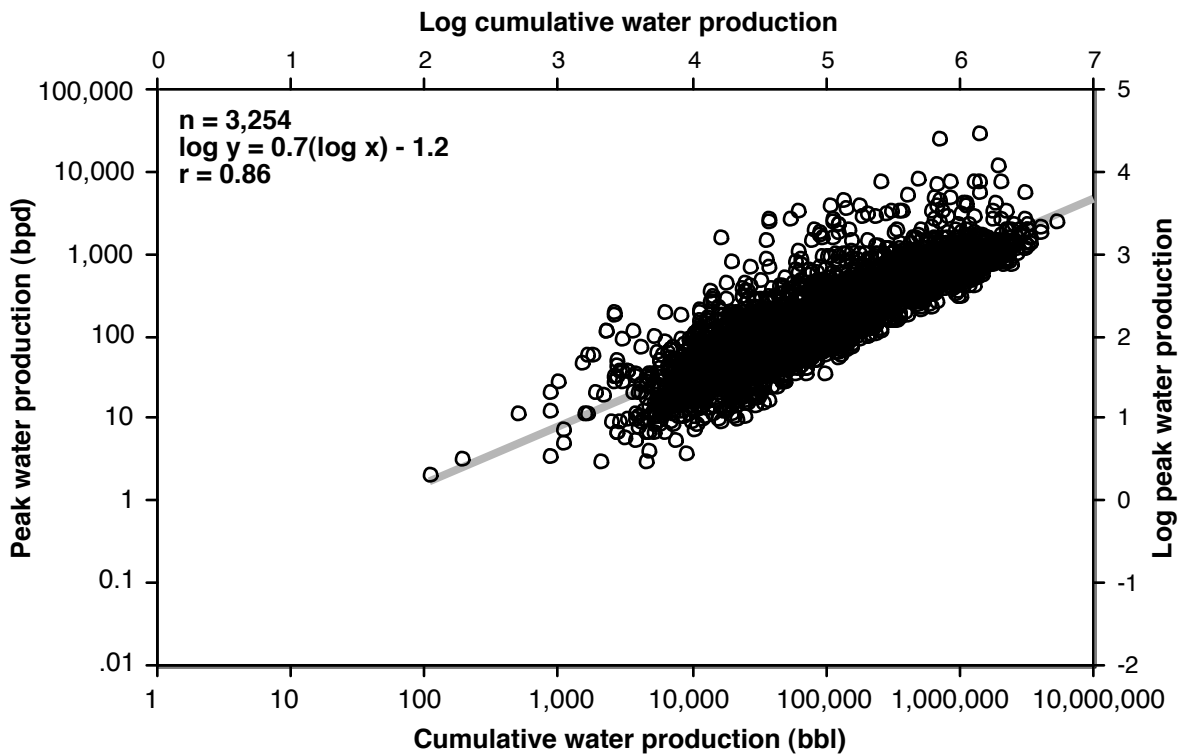
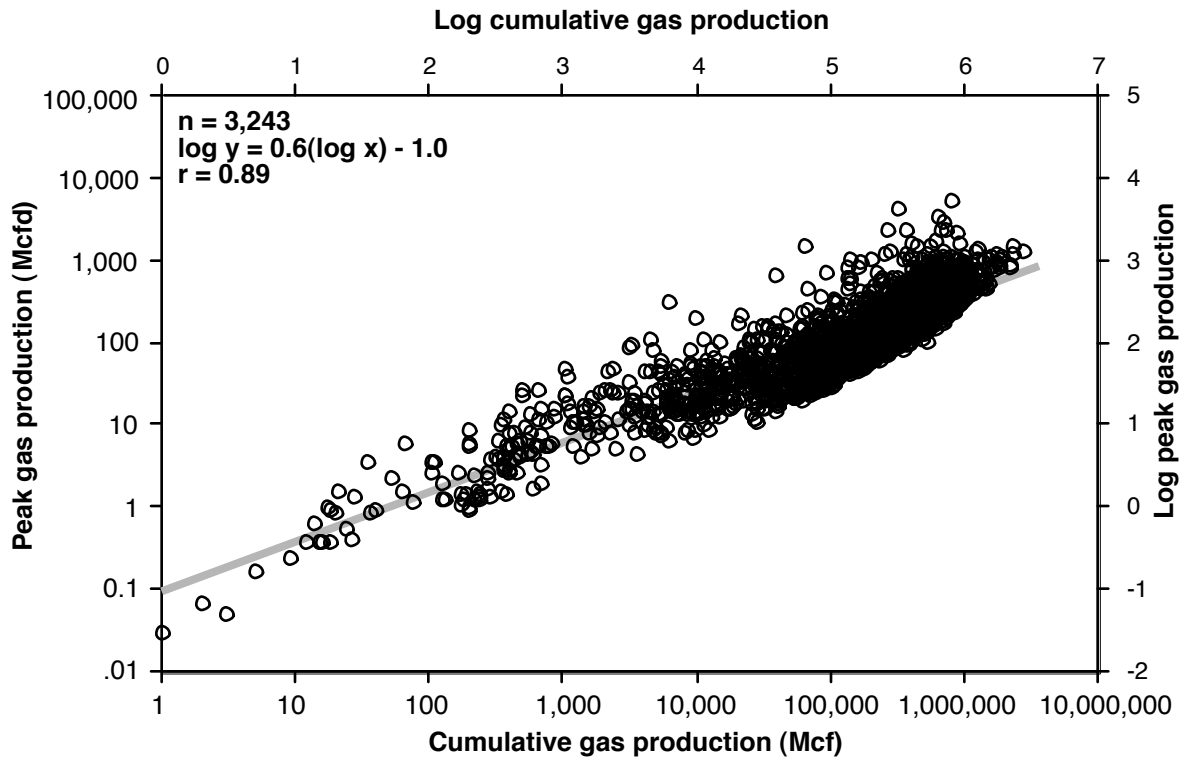


Figure 61.--Scatterplots showing correlation between peak and cumulative production values from coalbed methane wells in the Black Warrior basin.



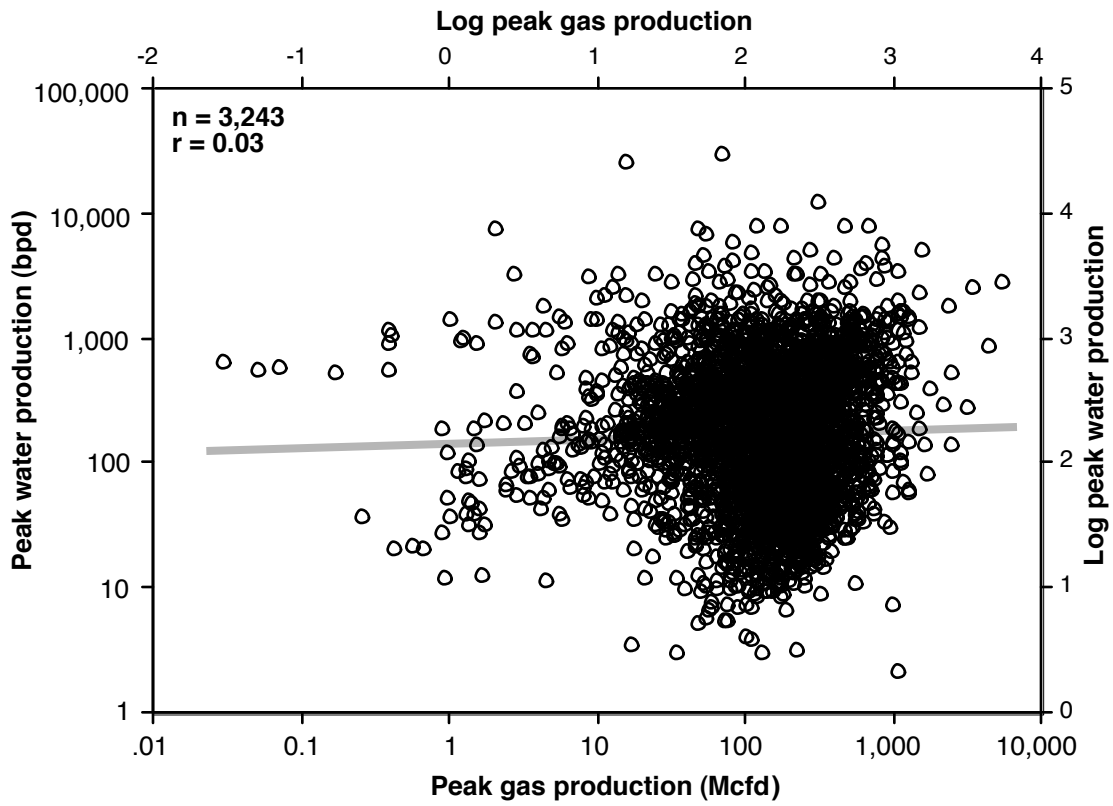


Figure 62.--Scatterplot showing lack of correlation between peak water and gas production in the Black Warrior coalbed methane fairway.

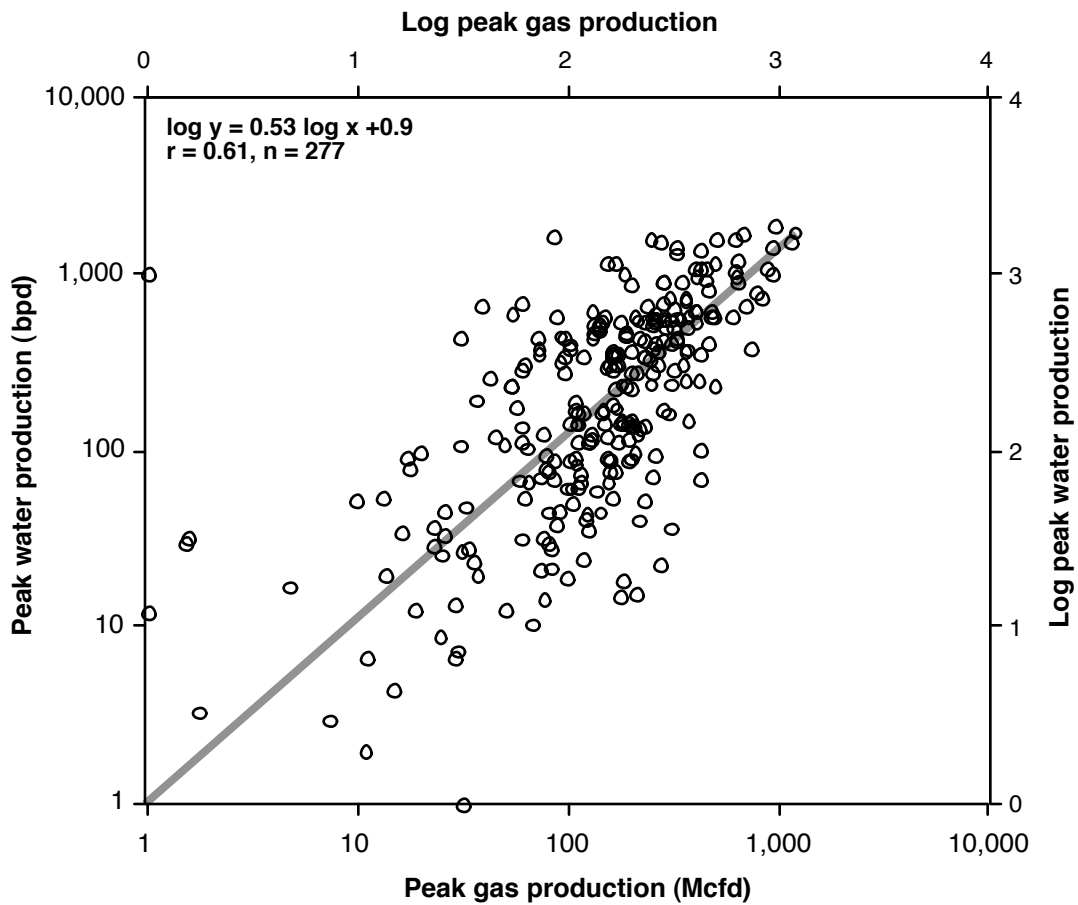


Figure 63.--Scatterplot showing modest correlation between water and gas production in Deerlick Creek Field (modified from Cox, 2002).

## Production Maps

Mapping cumulative and peak gas and water production demonstrates the variable performance of vertical coalbed methane wells (figs. 64-67). The cumulative gas map shows an arcuate trend of exceptional production where most wells have produced more than 300 MMcf that extends from Cedar Cove Field northward into White Oak Creek Field (fig. 64). Within this trend, many wells have had cumulative production exceeding 1 Bcf (billion cubic feet), and some wells in Cedar Cove Field have produced more than 1.5 Bcf of gas. Outside of this arcuate trend, cumulative production exceeding 300 MMcf has a patchy distribution, and in the southwestern coalbed methane fields, which are abandoned or temporarily abandoned, only one well has produced more than 100 MMcf of gas.

Cumulative water production has a more heterogeneous distribution than cumulative gas production (fig. 65). Wells have produced less than 100,000 bbl over large parts of the basin, yet wells with cumulative production exceeding 1,000,000 bbl exist in most fields. The largest areas where cumulative water production exceeds 100,000 bbl per well are in Robinson's Bend, Cedar Cove, and western Oak Grove fields. From northeastern Cedar Cove Field to southeastern Deerlick Creek Field, high water production generally corresponds with the arcuate trend of high gas production (figs. 64, 65). By contrast, less than 100,000 bbl of water has been produced from nearly all wells in the arcuate trend within the northern part of the arcuate trend of high gas production, which extends from northern Deerlick Creek Field into White Oak Creek Field.

Whereas maps of cumulative gas and water production are influenced significantly by the amount of time wells have been on line, maps of peak gas and water production provide a more

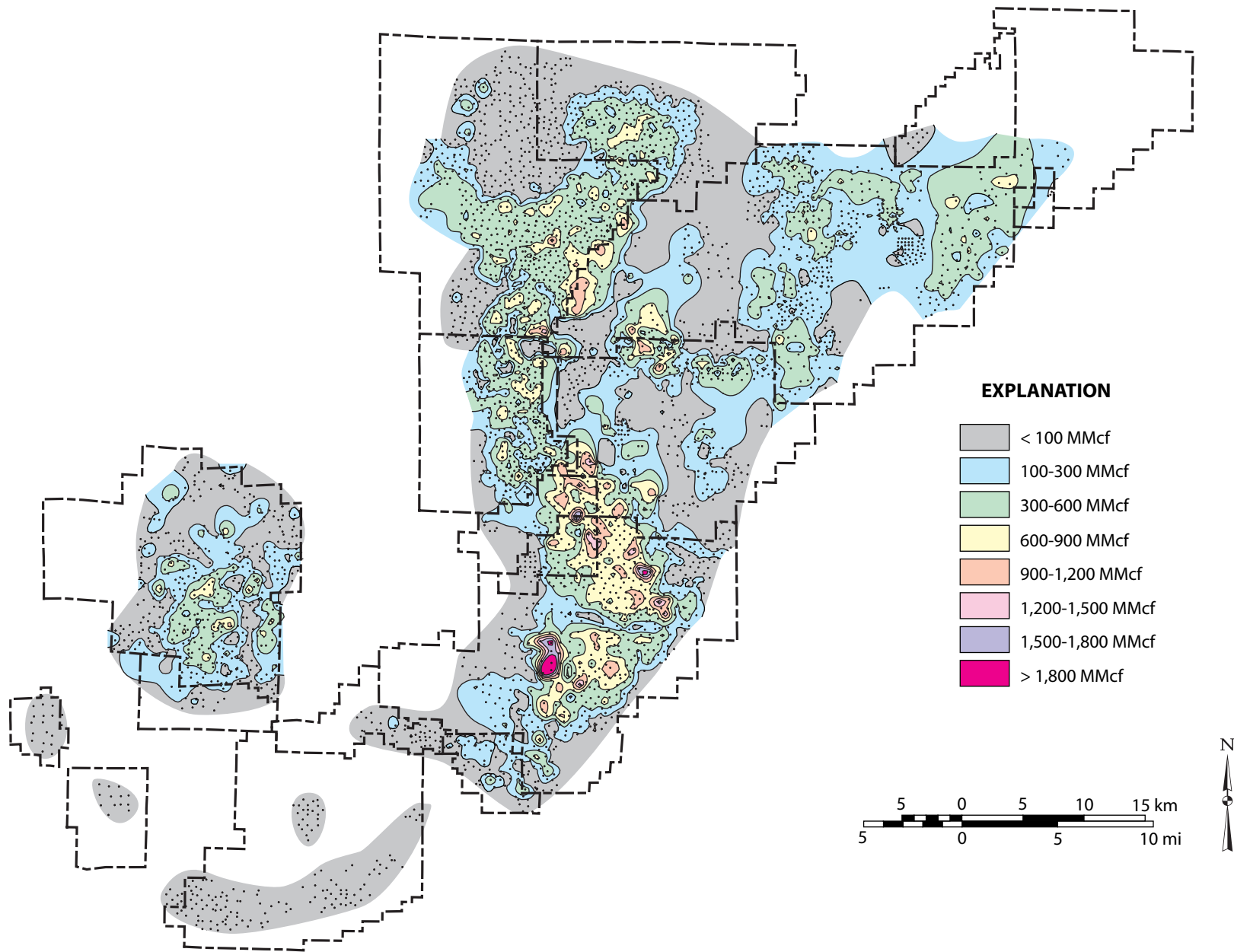


Figure 64.—Map of cumulative gas production from vertical wells in the Black Warrior coalbed methane fairway.

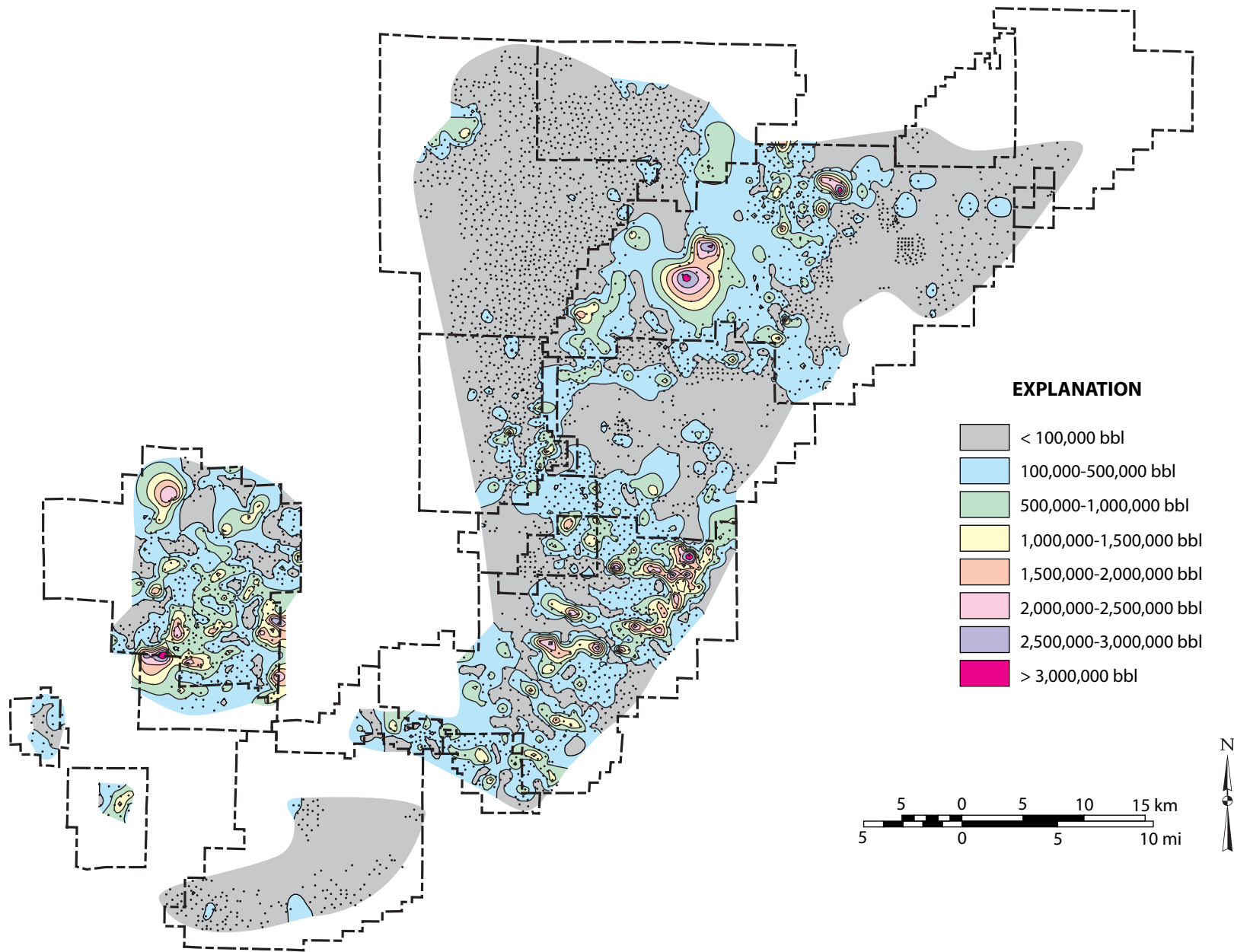


Figure 65.--Map of cumulative water production from vertical wells in the Black Warrior coalbed methane fairway.

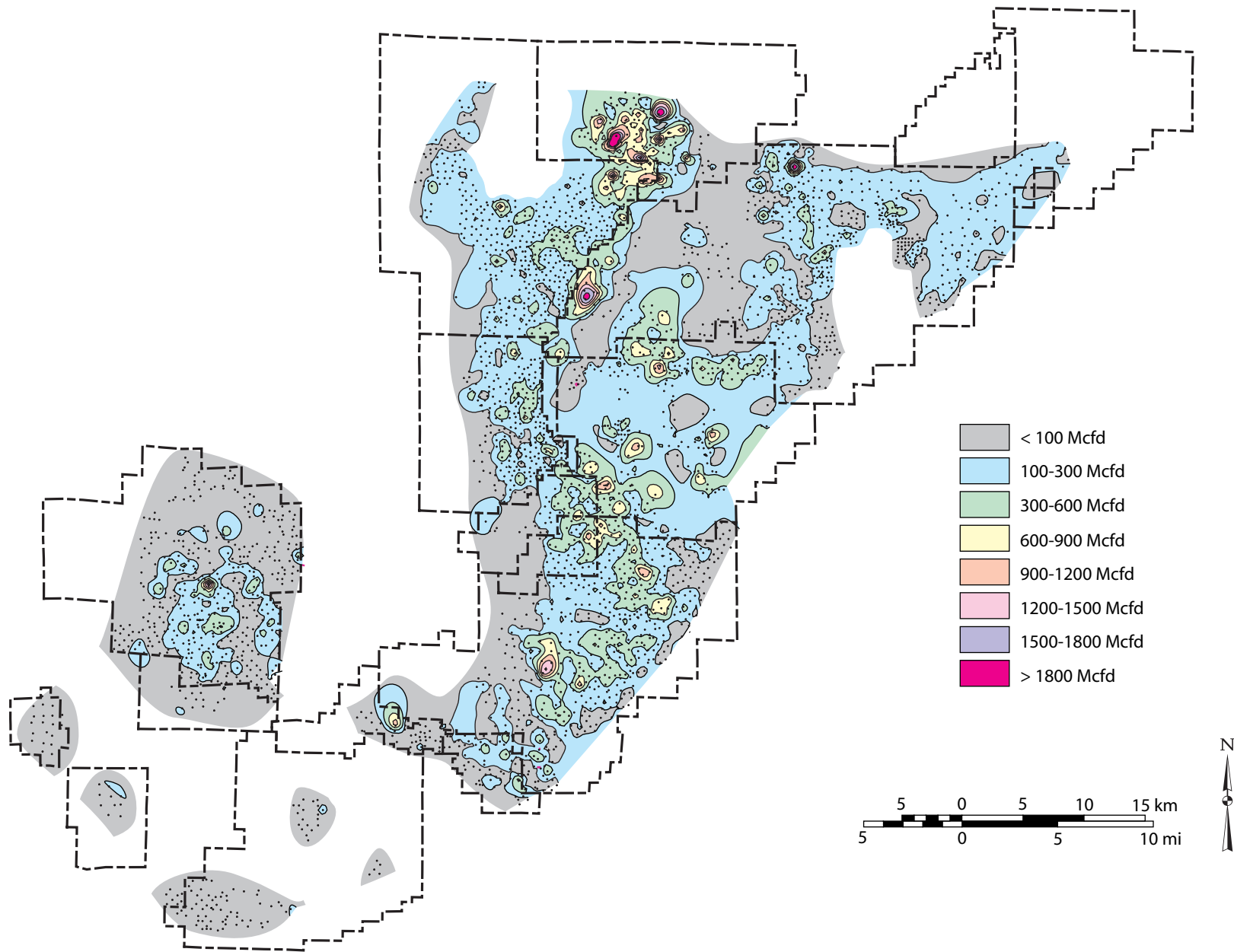


Figure 66.--Map of peak gas production in the Black Warrior coalbed methane fairway for wells reporting data for 48 months or more.

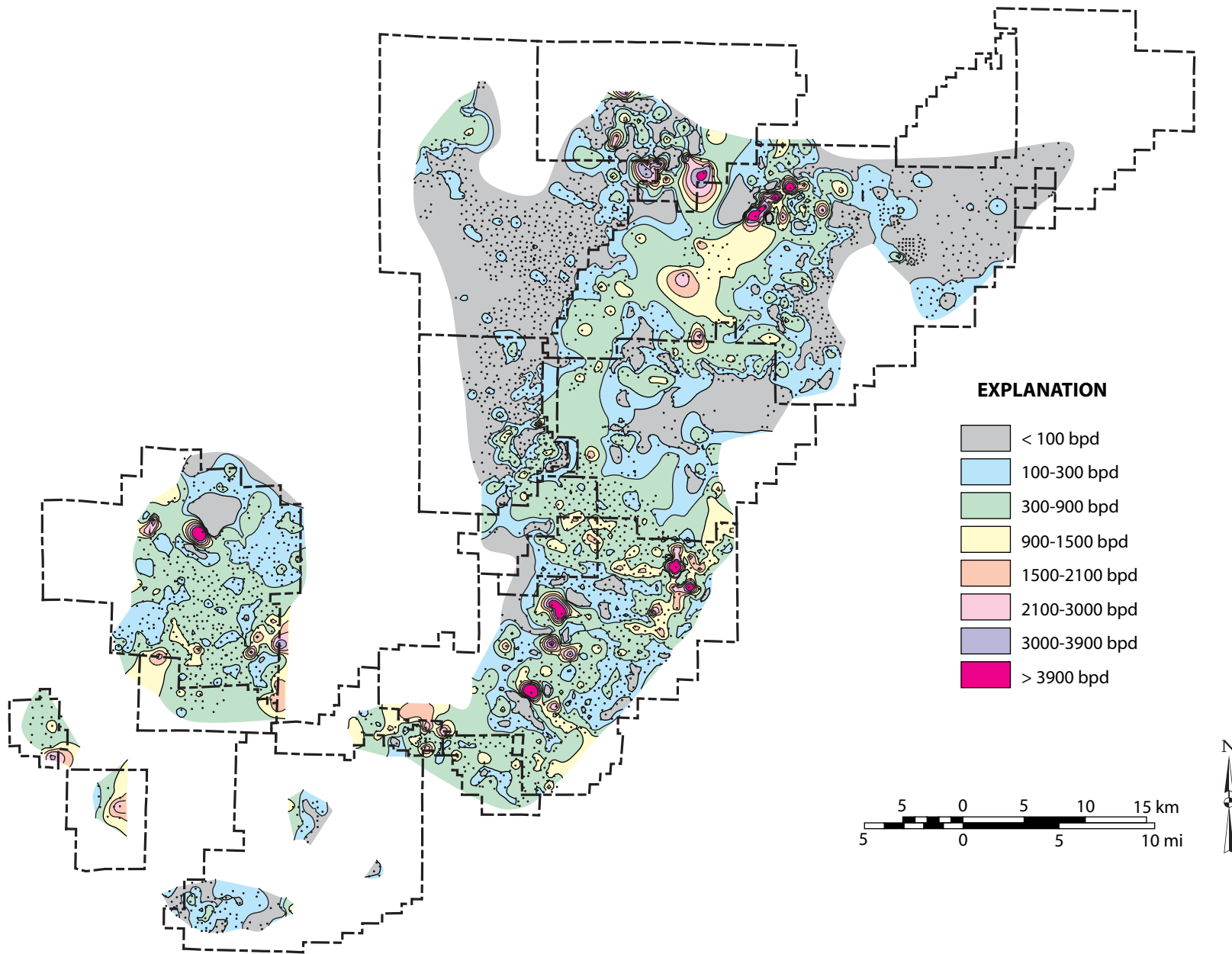


Figure 67.—Map of peak water production in the Black Warrior coalbed methane fairway for wells reporting data for 48 months or more.

even view of the productivity of coalbed methane wells in the Black Warrior basin (figs. 66, 67). Wells with peak gas production exceeding 300 Mcfd have a patchy distribution but follow the same basic geographic trends identified in the cumulative gas map (figs. 64, 66). This map shows a concentration of exceptionally productive wells in White Oak Creek Field, and many of these wells have achieved peak flow rates exceeding 1,000 Mcfd (fig. 66).

Peak water production trends also tend to follow those of cumulative water production (figs. 65, 67), as would be expected because of the high level of correlation between peak and cumulative production variables (fig. 61). Wells with peak water production exceeding 300 bpd are concentrated in an arcuate belt that is offset to the east of the belt of exceptional gas production (figs. 66, 67). Wells that have produced more than 300 bpd are also abundant from Robinson's Bend and Big Sandy fields to the southwestern limit of the production fairway. Wells that have peaked higher than 3,000 bpd are distributed throughout the water-productive areas and are aligned in northern Oak Grove Field. Of all the fields, peak water production rates are most variable in White Oak Creek Field.

### Controls on Production Performance

Many factors influence the productivity of coalbed methane wells in the Black Warrior basin, including well construction, well spacing, coal thickness, gas content, and the abundance and openness of natural fractures (Pashin and others, 1991; Pashin and Hinkle, 1997). Regional mapping provides some insight into the mechanisms that control production in the Black Warrior coalbed methane fairway (figs. 68, 69), but in many places, a more localized approach to



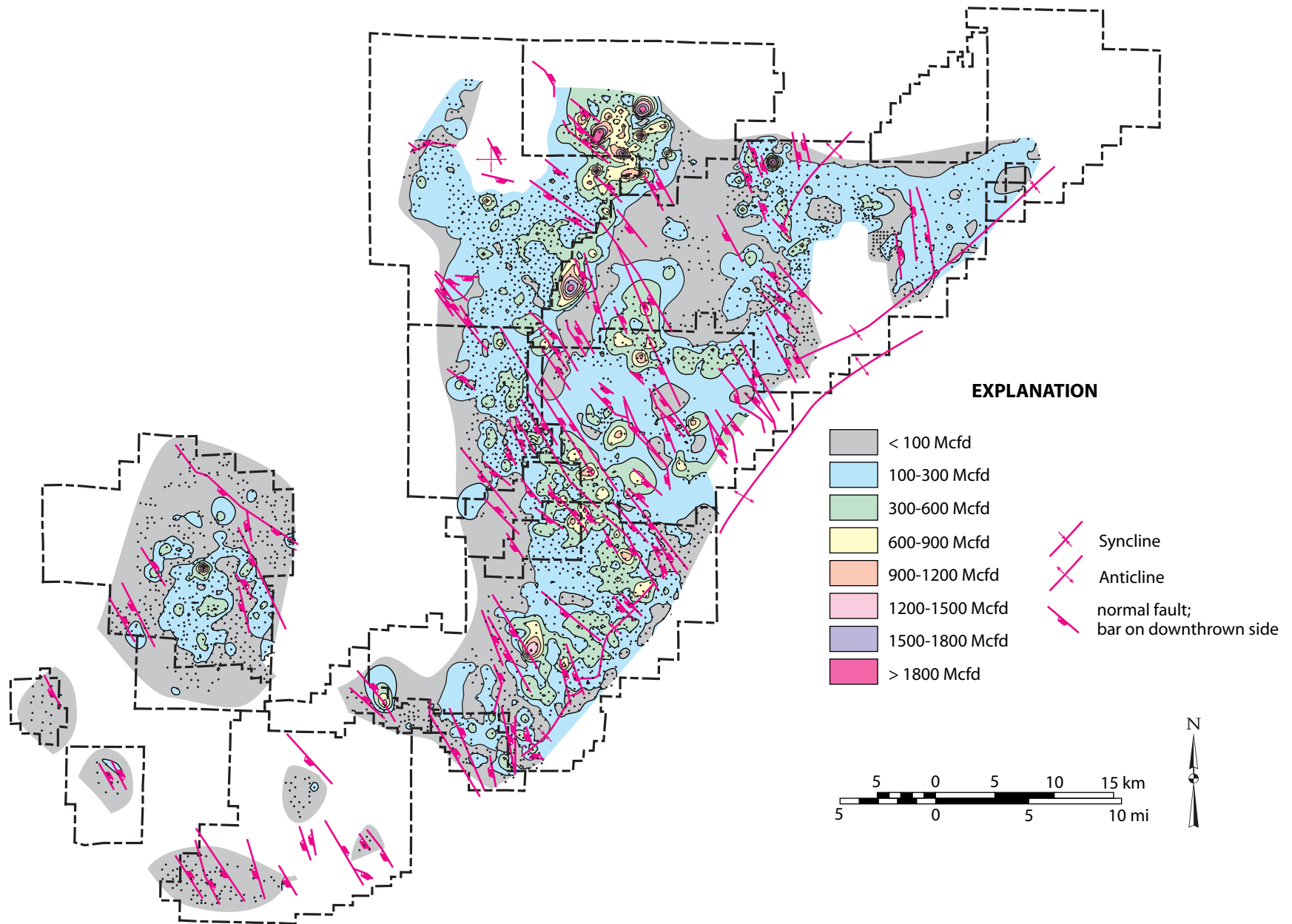


Figure 68.—Map showing relationship of peak gas production to structural traces in the Black Warrior coalbed methane fairway.

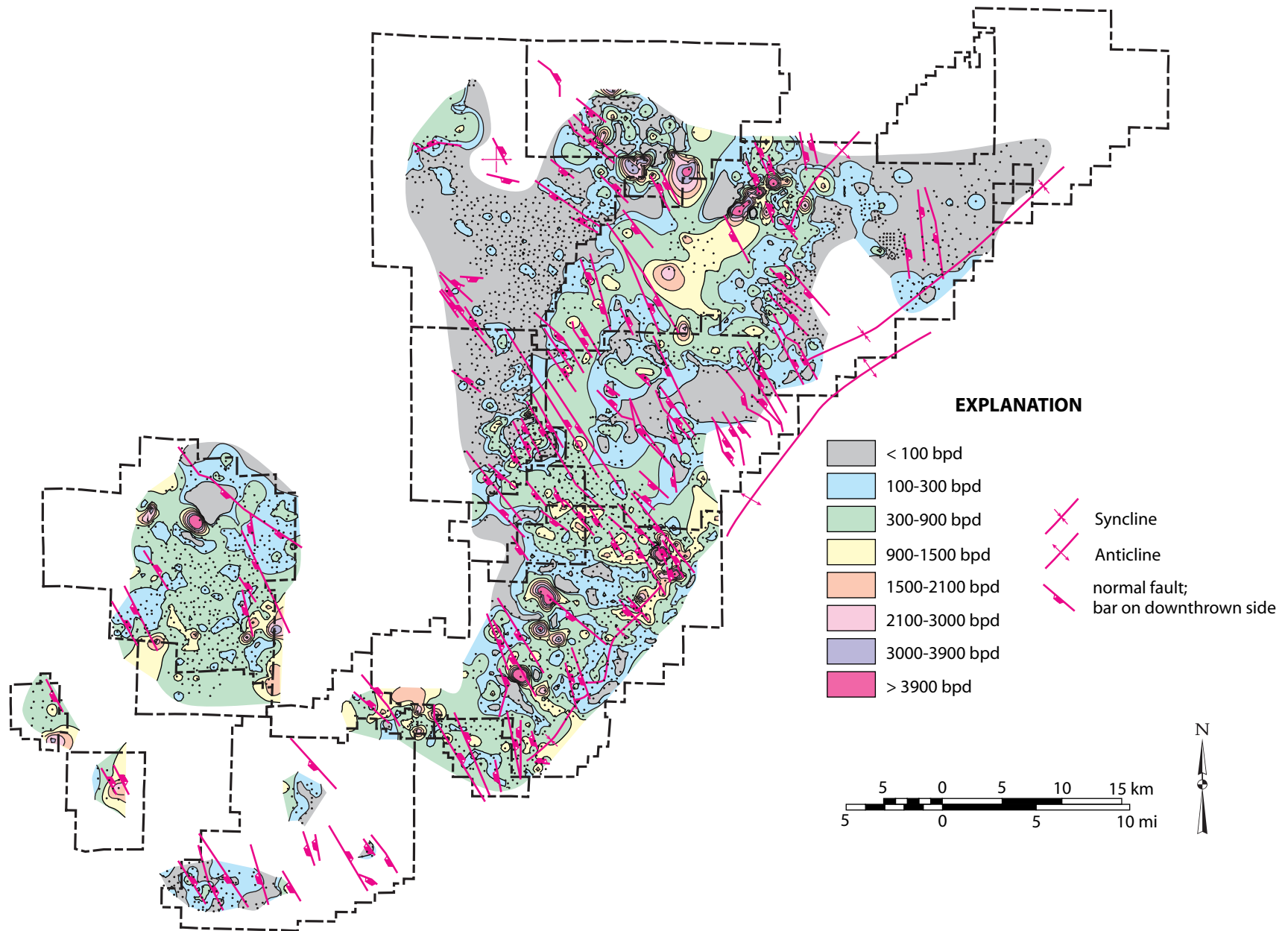


Figure 69.—Map showing the relationship between peak water production and structural traces in the Black Warrior coalbed methane fairway.

geological characterization is required to diagnose the controls on well performance (figs. 70, 71). In this section, we review the basic geologic controls on coalbed methane production in the Black Warrior basin and discuss the implications of these controls for carbon sequestration and enhanced coalbed methane recovery.

Pashin and others (1991) found an extremely poor correlation between net completed coal thickness and peak gas and water production and concluded that coal thickness and gas content were key determinants of the resource base but are not the primary determinants of well performance. Detailed studies of have been useful for identifying structural controls on well performance (Pashin and others, 1991, 1995; Pashin and Groshong, 1998). In Oak Grove Field, for example, exceptionally productive gas wells are aligned along the axial trace of a small syncline that defines a structural hinge separating the crestal uplift of the Sequatchie anticline from the more gently dipping northwest limb of the Coalburg syncline (Pashin and others, 1991) (fig. 70). In northeastern Cedar Cove Field, exceptional water production follows the axial trace of the footwall syncline near the southeast margin of the Black Warrior basin and thus provides another example of increased fluid production associated with a compressional fold hinge (Sparks and others, 1993; Pashin and Groshong, 1998) (fig. 69).

Control of gas and water production by normal faults is not obvious in the regional maps, but detailed mapping in southeastern Deerlick Creek Field provides evidence for control of gas and water production by extensional structures (fig. 71). Here, highly productive coalbed methane wells (peak gas production >300 Mcfd, peak water production >750 bpd) are concentrated in a pair of half grabens and are effectively absent from in intervening half graben and full graben

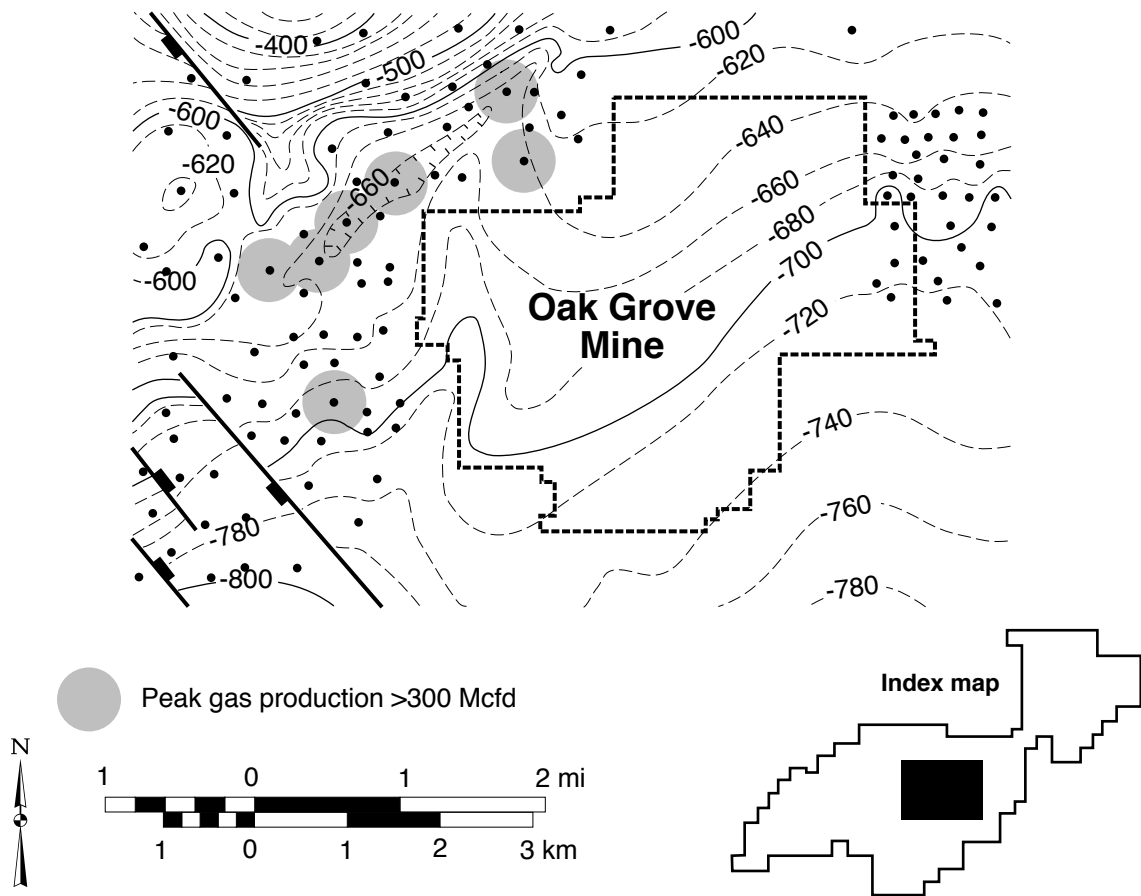
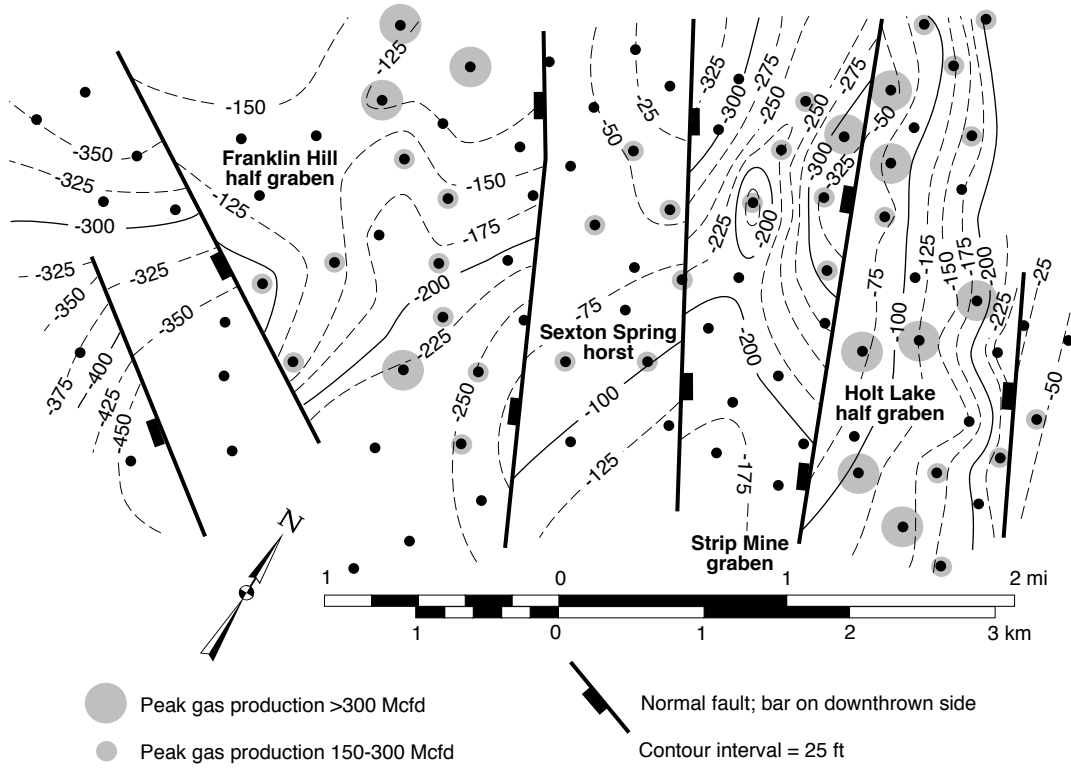


Figure 70.—Map showing alignment of exceptionally productive gas wells along a synclinal fold hinge in Oak Grove Field (modified from Pashin and others, 1991).

**A. Gas production and structure**



**B. Water production and structure**

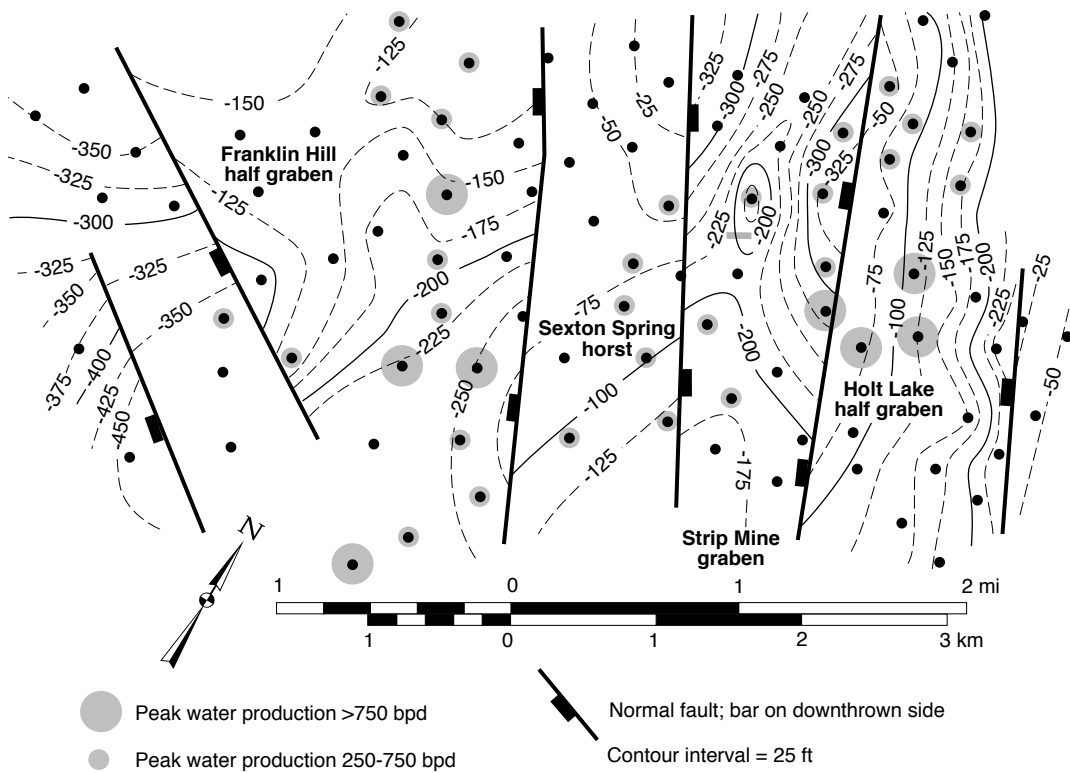


Figure 71.—Map showing relationship of gas and water production to extensional structure in Deerlick Creek Field (modified from Pashin and others, 1995).

(Pashin and others, 1995; Pashin and Groshong, 1998). Indeed, the exceptionally productive wells that map within the Strip Mine graben penetrate the bounding fault and are completed within the Holt Lake half graben. Importantly, well performance within the half grabens is extremely variable, and Pashin (1998) and Pashin and Groshong (1998) attributed this variability to hidden interwell heterogeneity. This interwell heterogeneity is thought to influence the abundance and openness of natural fractures, thereby determining the effectiveness with which wells can dewater and depressurize the reservoir.

Another example of structurally influenced gas production is in Robinson's Bend Field, where wells with peak production higher than 100 Mcfd are concentrated in the hanging-wall block of a large-scale half graben (figs. 20, 68). In northeastern Cedar Cove Field and adjacent parts of Brookwood, Holt, and Peterson fields, areas of exceptional gas and water production are associated with a major fault swarm that extends northwestward from the upturned structural margin of the Black Warrior basin (figs. 68, 69). Near the margin of the basin in Cedar Cove Field, large volumes of water are produced from the fault swarm, whereas the most productive gas wells are concentrated southwest of the fault swarm in what can again be interpreted as the hanging-wall complex of a half-graben structure (Pashin and Groshong, 1998). Farther northwest, however, exceptional gas and water production tend to coincide with the fault swarm.

An interesting feature of the basin is a northeast-elongate area of exceptional gas production that follows the boundary between Oak Grove and Blue Creek fields (fig. 64). In this area, the field boundaries follow the valley of the Black Warrior River. Accordingly, one possibility is

that dilation of fractures related to incision and concomitant isostatic rebound of the river valley are facilitating enhanced gas production.

Comparison of the regional maps of peak and cumulative water production with the map of minimum hydrostatic pressure gradient suggests that a significant relationship exists between water production and water levels in coalbed methane wells (figs. 35, 65, 67). Limited water production in much of Brookwood and Eastern Oak Grove Fields corresponds in large part with areas of active longwall coal mining and may therefore reflect the effects of prolonged dewatering associated with coal extraction. Low water production values and high gas production values in large parts of Deerlick Creek and Blue Creek fields help corroborate the hypothesis of gas-filled fractures in parts of the basin distal to the recharge area along the structurally upturned southeast margin of the Black Warrior basin. The Pottsville Formation in Big Sandy Creek, Little Sandy Creek and Robinson's Bend fields is concealed completely below Cretaceous cover (fig. 25), and high water production rates in these fields may indicate filling of fractures with water through hydraulic communication with poorly consolidated Cretaceous aquifers over geologic time.

Some tangible effects of reservoir engineering are also apparent in the regional production maps. The original coalbed methane wells in eastern Oak Grove Field, which are arranged in an extremely tight, rectilinear grid known as the Oak Grove pattern (figs. 66, 70), are single-zone wells that not only were subjected to early drilling and completion practices, but were drilled so closely (~15-acre spacing) that they apparently competed for a limited gas resource. Marginally productive wells in western Oak Grove Field were drilled on an effective 160-acre spacing,

which may have been too wide to effectively depressurize and drain the reservoir. To address this issue, an infill drilling program is now underway. Last, but not least, the exceptional peak gas production rates in White Oak Creek Field, which was developed mainly after drillers could take advantage of the Section 29 tax credit, can be attributed in part to improved engineering technology and hindsight of the rapid development of the late 1980s and early 1990s that resulted in the industry's current concept of best management practice.

Production data have many potential uses in the application of carbon sequestration and enhanced coalbed methane recovery technology. Decline curves can be analyzed to identify the wells that are reaching the end of their economically productive life and to determine which wells should be converted into injectors and which wells are best left as producers. Injecting CO<sub>2</sub> into coal changes the balance of relative permeability between gas and water, and the high viscosity of CO<sub>2</sub> relative to CH<sub>4</sub> may sweep water that would otherwise remain in the reservoir. Therefore, water production data may provide insight into the volumes of water that may be swept during enhanced recovery operations. Well spacing information can also provide important information regarding when and how to apply carbon sequestration technology. For example, areas that are currently candidates for infill drilling, such as those in the western part of Oak Grove Field, may not be candidates for enhanced gas recovery for many years.

Gas and water production data indicate that coalbed methane reservoirs have enhanced permeability along compressional fold hinges and are segmented by normal faults. Strata in compressional fold hinges may be intensely fractured and may present hazards for cross-formational leakage of injected CO<sub>2</sub>. Fault zones may also provide conduits for cross-



formational flow of gas and also raise issues for the applicability of enhanced recovery technology on the simple grounds that faults limit the continuity of coal beds. For example, within the major fault arrays, faults are spaced too closely to develop classic five-spot patterns of injectors and producers. Therefore, efforts to demonstrate the potential for carbon sequestration and enhanced coalbed methane recovery in the Black Warrior basin should focus at least initially on large structural panels that lack significant normal faults. Indeed, large tracts of land that can accommodate multiple five-spot patterns are in Oak Grove, White Oak Creek, Deerlick Creek, Cedar Cove, and Robinson's Bend fields, and smaller tracts have potential elsewhere (fig. 72). In the southern coalbed methane fields, where part of the Pottsville Coal Interval is within the supercritical CO<sub>2</sub> window, coal zones deeper than 2,480 feet should be approached with caution until a more complete understanding of the behavior of supercritical gas in coal is realized (figs. 37, 72).

## **TECHNOLOGY TRANSFER**

The Geological Survey of Alabama and the University of Alabama have undertaken a vigorous technology transfer initiative to facilitate the participation of stakeholders and to disseminate the results of research. Thus far, technology transfer efforts include development of a web page, assembly of a project advisory group, technical publications, and public presentations.

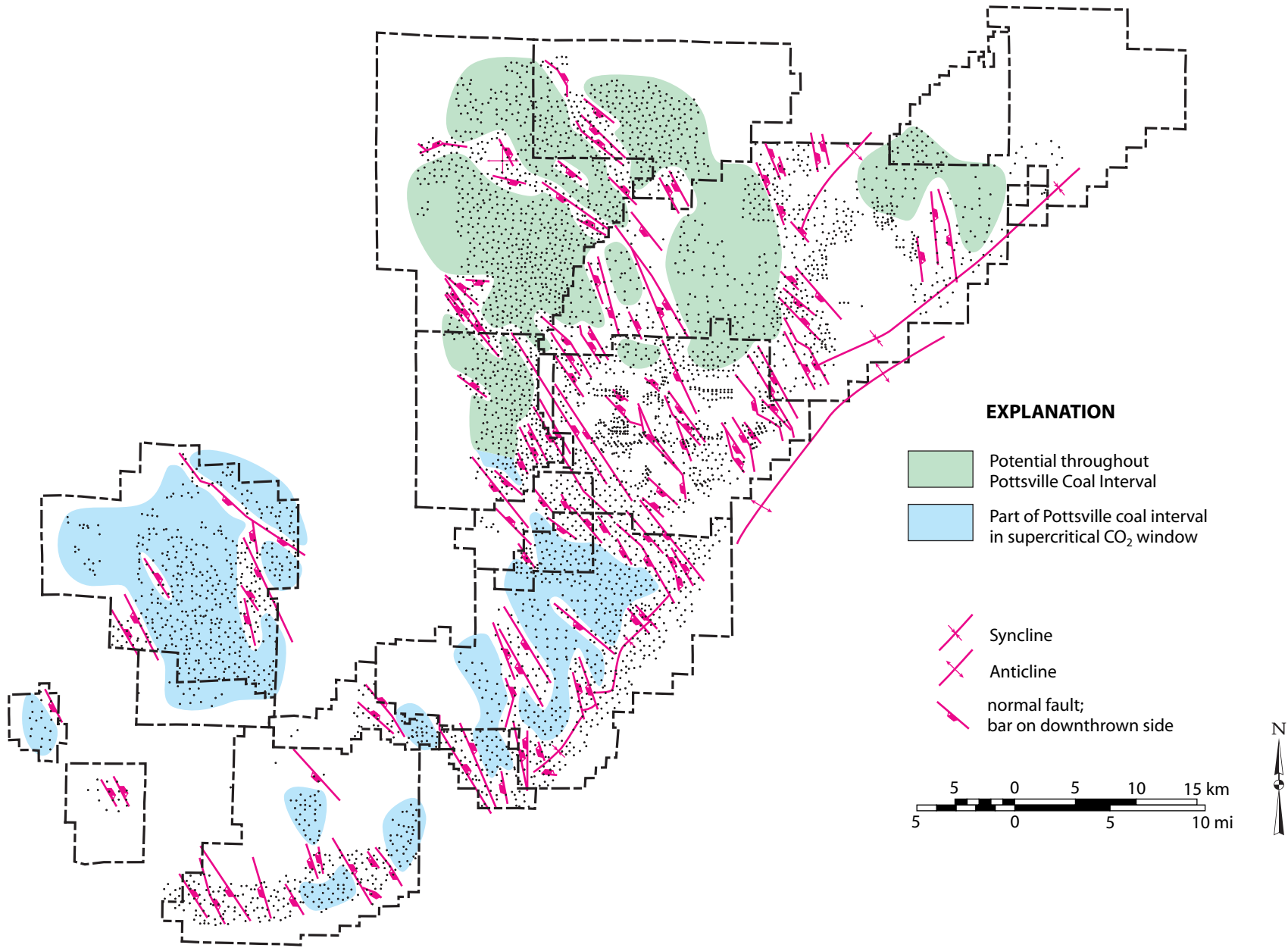


Figure 72.--Map showing structural panels that appear favorable for development of five-spot well patterns for carbon sequestration and enhanced coalbed methane recovery in the Black Warrior coalbed methane fairway.

A project web page is available at the following URL: <<http://www.gsa.state.al.us/gsa/CO2PAGE/CO2page.htm>>. This web page gives background on the research project, lists project team members and advisory committee members, and contains links to other relevant web pages. The web page has been and will continue to be updated periodically to highlight progress on the project and other breaking developments. Also, a PDF file of last year's technical progress report (Pashin and others, 2002) is available for download through the web page, and this report will also be made available through the page.

The project advisory committee comprises key stakeholders in the coalbed methane and electric power industries. A list of committee members and their affiliations is as follows:

Terry Burns, Geomet Operating Company  
Richard Chastain, Southern Company  
Gary Hart, Southern Company  
John Hollingshead, Geomet Operating Company  
Paul Mock, Chevron-Texaco  
Phil Malone, Geomet Operating Company  
Jerry Sanders, Black Warrior Methane Corporation  
Rhonda Tinsley, Southern Company  
John Wallace, Energen Resources Corporation

A meeting of the advisory committee was held on May 11, 2001, at the Geological Survey of Alabama in conjunction with the 2001 International Coalbed Methane Symposium, and another meeting is planned in conjunction with the 2003 International Coalbed Methane Symposium. These meetings are valuable for opening lines of communication between the coalbed methane producers and Southern Company, which is the largest electrical utility in the United States.

Southern Company is the parent company of Alabama Power Company, which operates the coal-fired power plants adjacent to the Black Warrior coalbed methane fairway.

During the last year, presentations related to the project were made at meetings of the Warrior Basin Section of the Society of Petroleum Engineers, the American Association of Petroleum Geologists Annual Meeting, the Coal-Seq I Forum, The annual meeting of The Society for Organic Petrology, the Southeastern Section of the Geological Society of America, the Alabama Mining Institute, and in a short course at the Gulf Coast Association of Geological Societies annual meeting. Our poster session at the American Association of Petroleum Geologists Annual Meeting (Pashin and Carroll, 2002) was awarded the President's Certificate of Excellence in Presentation from the Energy Minerals Division.

Additional presentations are planned for 2003, and Jack Pashin has been invited to deliver a keynote lecture on the carbon sequestration potential of coal-bearing strata at the XVth International Congress on Carboniferous and Permian Stratigraphy, which will be held in Utrecht, The Netherlands in August. A manuscript by Jack C. Pashin and Marcella R. McIntyre entitled, "Temperature-Pressure Conditions in Coalbed Methane Reservoirs of the Black Warrior Basin: Implications for Carbon Sequestration and Enhanced Coalbed Methane Recovery," has been accepted for publication pending minor revision in the International Journal of Coal Geology. Additional abstracts and papers by a variety of project members have been accepted for presentation and publication at the 2003 International Coalbed Methane Symposium, which will be held in Tuscaloosa during May.

## **FUTURE WORK**

Our research is moving ahead according to schedule and budget, and we anticipate this project to continue according to plan (fig. 73). Geologic characterization of the Black Warrior coalbed methane fairway (Tasks 1-3) is now complete, and all basic data required to complete the study have been compiled. For the remainder of the study, work will center on volumetric analysis (Task 5) and development of a geologic screening model (Task 6). Technology transfer activities will continue throughout the remainder of the project, and the final report is expected to be complete by January 5, 2004.

Year 1 (2000-01)									Year 2 (2001-02)									Year 3 (2002-03)																	
10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9
<b>Task 1. Subsurface geology</b>																																			
Task 1a. Stratigraphic analysis																																			
Task 1b. Structural analysis																																			
Task 1c. Hydrodynamics																																			
<b>Task 2. Sorption capacity</b>																																			
Task 2a. Sorption isotherms																																			
Task 2b. Gas content																																			
<b>Task 3. Production analysis</b>																																			
<b>Task 4. Volumetric analysis</b>																																			
<b>Task 5. Screening model</b>																																			
Task 5a. Development of model																																			
Task 5b. Application of model																																			
<b>Task 6. Technology Transfer</b>																																			
Advisory Committee																																			
Meetings and publications																																			
Web page																																			
Workshops																																			
<b>Deliverables</b>																																			
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Annual reports																																			
Final report																																			

Figure 73.--Chart showing progress to date (shaded) and research schedule for this project.

## CONCLUSION

Sequestration of CO<sub>2</sub> in coal has potential benefits for reducing greenhouse gas emissions from the highly industrialized Carboniferous coal basins of North America and Europe and for enhancing coalbed methane recovery. Hence, enhanced coalbed methane recovery operations provide a basis for a market-based environmental solution in which the cost of sequestration is offset by the production and sale of natural gas. The Black Warrior foreland basin of west-central Alabama contains the only mature coalbed methane production fairway in eastern North America, and data from this basin provide an excellent basis for quantifying the carbon sequestration potential of coal and for identifying the geologic screening criteria required to select sites for the demonstration and commercialization of carbon sequestration technology.

The Geological Survey of Alabama, in partnership with the University of Alabama, Jim Walter Resources, Incorporated, and Southern Company, has undertaken an intensive 3-year investigation aimed at quantifying the carbon sequestration potential of the Black Warrior coalbed methane fairway and developing a geologic screening model that is broadly applicable. This report summarizes results of the second year of this investigation, which has focused on geologic characterization. Key geologic variables analyzed include stratigraphy, structural geology, geothermics, hydrology, coal petrology, and production data.

Coalbed methane resources in the Black Warrior basin are distributed among multiple coal zones in the upper part of the Pottsville Formation (Lower Pennsylvanian). Pottsville coal zones are a series of fluvial-deltaic depositional cycles that are bounded by regionally extensive

flooding surfaces. Net coal thickness generally increases southeastward, and the greatest sequestration potential appears to be in the Black Creek, Mary Lee, Pratt, and Gwin coal zones. Most coal zones contain one to three coal beds thicker than 1 foot that are significant targets for coalbed methane production and carbon sequestration. Consequently, coalbed methane operations have relied heavily on the application of multi-seam completion technology, and similar approaches will be required for carbon sequestration.

Pottsville strata have effectively no matrix permeability to water, so virtually all flow is through natural fractures. Faults and folds of extensional and compressional origin influence the abundance and openness of natural fractures, and hence, the performance of coalbed methane wells. The Black Warrior coalbed methane fairway can be characterized as a southwest-dipping homocline that is broken by normal faults. Near the southeast margin of the coalbed methane fairway, frontal folds of the Appalachian thrust belt are superimposed on the faulted homocline. Fault-related fractures have significantly greater kinematic aperture than joints and have a much greater tendency to cut across bedding than other natural fractures in the Pottsville Formation. Therefore, fault zones constitute the most likely avenues along which injected CO<sub>2</sub> can leak from coal into the country rock or to the surface.

Temperature-pressure conditions have a strong influence on the carbon sequestration potential of coalbed methane reservoirs in the Black Warrior basin, because CO<sub>2</sub> becomes a supercritical fluid above a temperature of 88°F and a pressure of 1,074 psi. Under supercritical conditions, coal can contain more gas than is predicted by Langmuir adsorption theory, but the



mobility and reactivity of supercritical fluids in coal-bearing strata are poorly understood. The mean geothermal gradient in the coalbed methane fairway is about 9°F/1,000 feet, and reservoir temperature exceeds 88°F in much of the study area. Regional mapping indicates that localized areas of abnormally high reservoir temperature are superimposed on a southwest trend of increasing temperature that reflects the shape of the southwest-dipping homocline.

Water in the Pottsville Formation ranges from fresh to saline, and the coalbed methane reservoirs can be classified as USDW (TDS content <10,000 mg/L) in much of the production fairway. Fresh-water plumes formed by meteoric recharge of upturned strata along the southeast margin of the Black Warrior basin contain water with TDS content of less than 3,000 mg/L. In areas where producing reservoirs can be classified as USDW, enhanced coalbed methane recovery efforts will require an aquifer exemption to comply with Class II UIC requirements. However, where TDS content is less than 3,000 mg/L, this exemption is prohibited.

Hydrostatic pressure gradients range from normal (0.43 psi/ft) to extremely underpressured (0.05 psi/ft) and have a bipolar distribution in the Pottsville Formation. Normal to moderate underpressure is typical of most areas, and a large area of underpressure is developed around closely spaced longwall coal mines. However, other areas of underpressure are distributed among several coalbed methane fields and appear to be natural. Although dewatering related to mining and coalbed methane operations has given rise to subcritical reservoir conditions throughout the fairway, potential exists for supercritical conditions to develop as the hydrologic system equilibrates following the abandonment of the mines and gas fields. No potential for

supercritical conditions exists within coalbed methane reservoirs in the northern part of the coalbed methane fairway, whereas in the southwestern coalbed methane fields, potential exists for supercritical reservoir conditions to develop throughout this interval.

Coal quality parameters have a strong influence on the ability of coal to sorb gas. Rank in the coalbed methane fields ranges from high volatile B bituminous to low volatile bituminous, and virtually all coalbed methane production is from coal of high volatile A or higher rank. Mineral matter has minimal sorption capacity compared to the organic constituents of coal, and in the Pottsville Formation, ash is dominated by clay, quartz, and pyrite. High-pressure adsorption isotherms for CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub> confirm that coal sorbs approximately twice as much CO<sub>2</sub> as CH<sub>4</sub> and approximately four times as much CO<sub>2</sub> as N<sub>2</sub>. Comparison of isotherms reveals, however, that the sorption performance of coal for each gas can vary by a factor of two depending on coal quality.

Gas content data were compiled from numerous sources and exhibit extreme vertical and lateral variability that must be accounted for when assessing the potential for enhanced coalbed methane recovery. This variability is interpreted as the product of a complex burial history that involved thermogenic gas generation coincident with foreland basin subsidence and the early stages of post-orogenic unroofing. As the basin cooled during the late stages of unroofing, however, coal apparently became undersaturated with gas. However, development of a fresh-water recharge zone along the southeast margin of the basin has apparently facilitated late-stage

biogenic gas generation that has resulted locally in effectively complete isothermal methane saturation.

Production characteristics of coalbed methane wells are helpful for identifying areas that are candidates for carbon sequestration and enhanced coalbed methane recovery and for selecting which wells should be converted into injectors. Gas production from vertical wells typically exhibits exponential decline, whereas water production typically exhibits hyperbolic decline. Mapping peak and cumulative production indicates that many geologic and engineering factors, including well construction, well spacing, and regional structure influence well performance. Production patterns are affected significantly by extensional faults and fault-related folds and by compressional fold hinges. Close fault spacing limits areas where five-spot patterns may be developed for enhanced gas recovery, but large structural panels lacking normal faults are in several gas fields and can be given priority as areas to demonstrate and commercialize carbon sequestration technology in coalbed methane reservoirs.

The project team is conducting a vigorous technology transfer program, which includes assembly of a project advisory committee, development of a project web page, publication of technical reports, and presentations at technical meetings. The project is proceeding according to schedule and budget and work during the final year of this program is expected to continue according to plan. Next year's effort will focus on volumetric analysis of sequestration and enhanced recovery potential and development of a geologic screening model for carbon sequestration and enhanced coalbed methane recovery.

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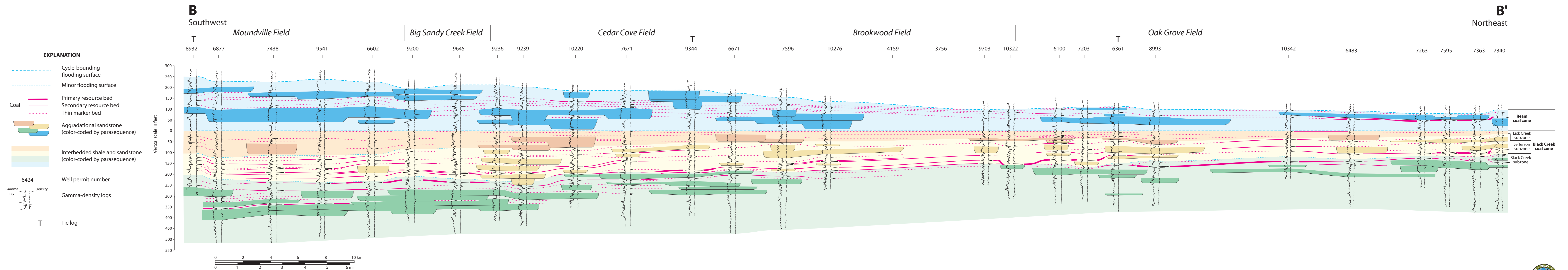
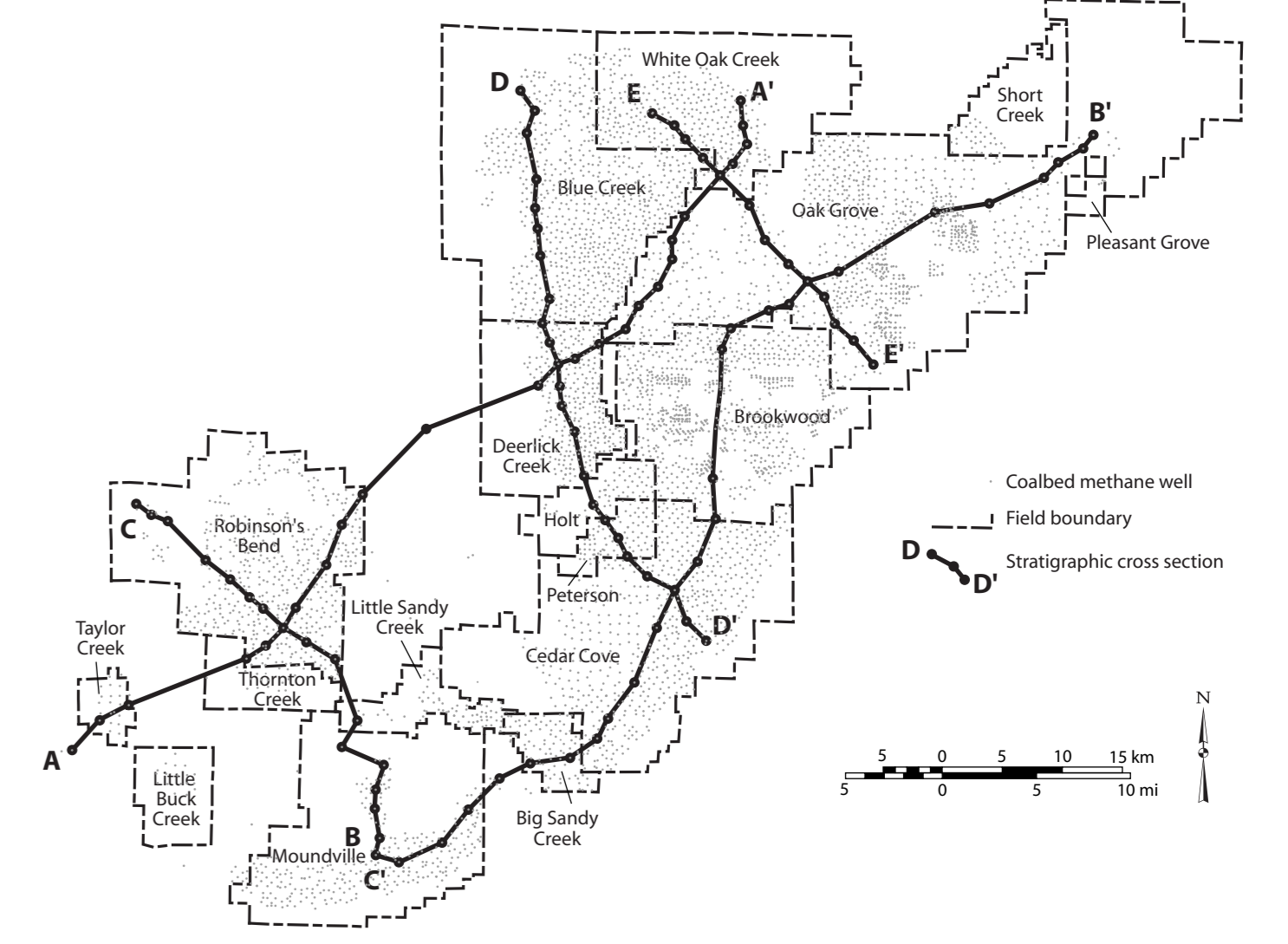
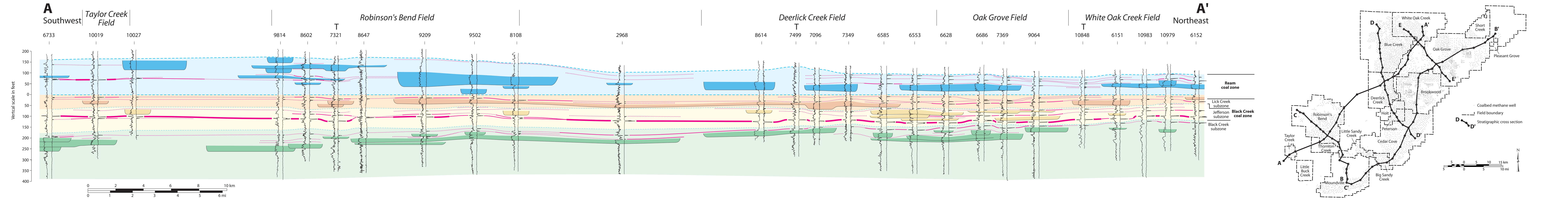
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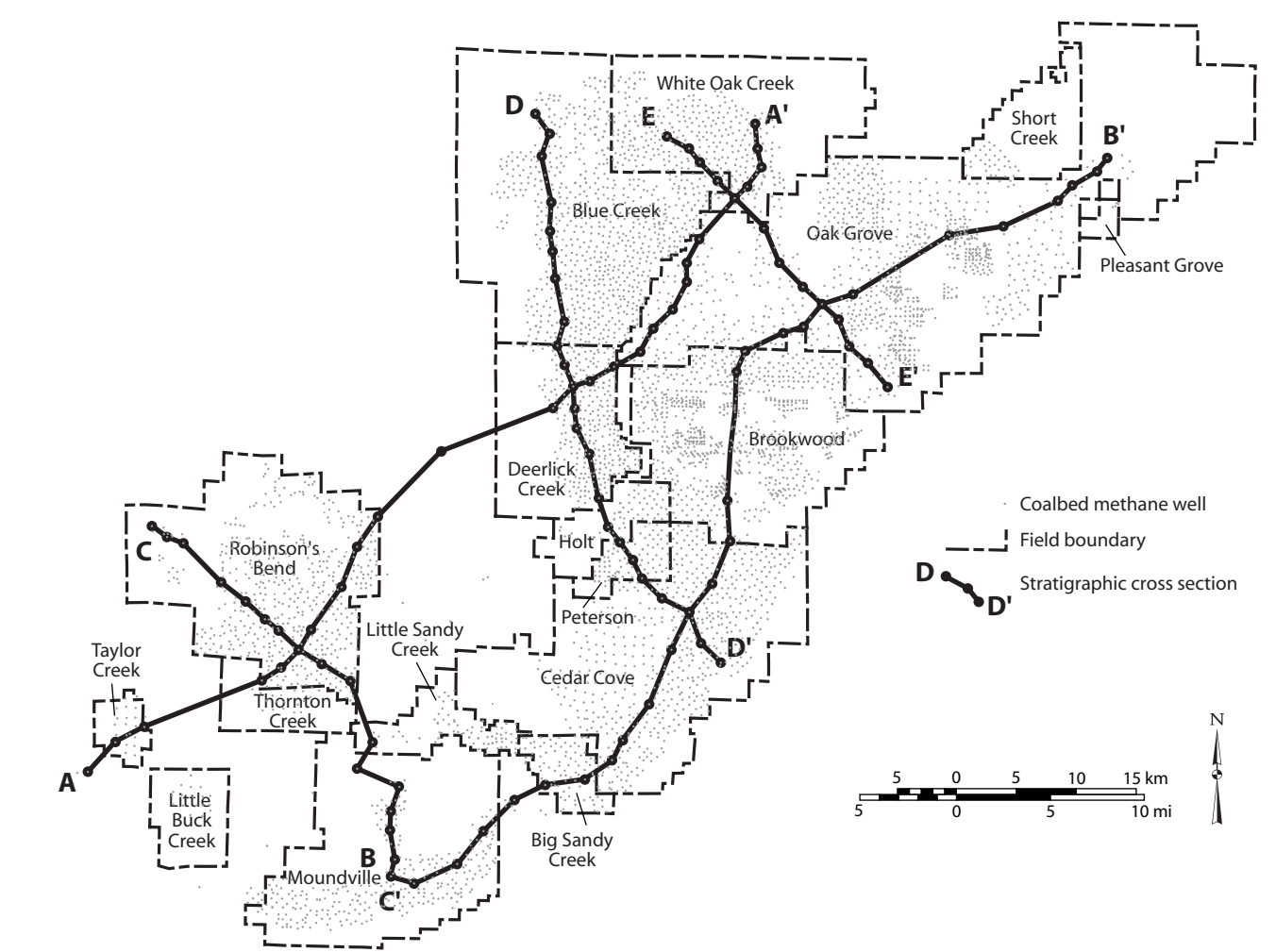
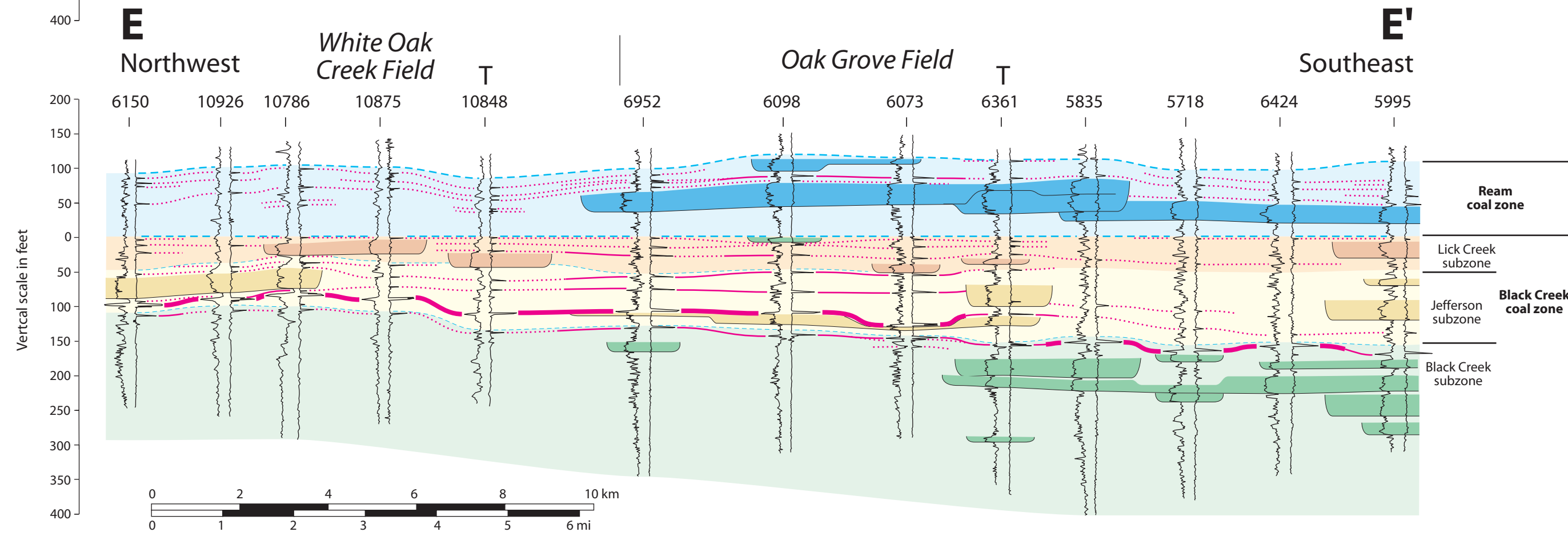
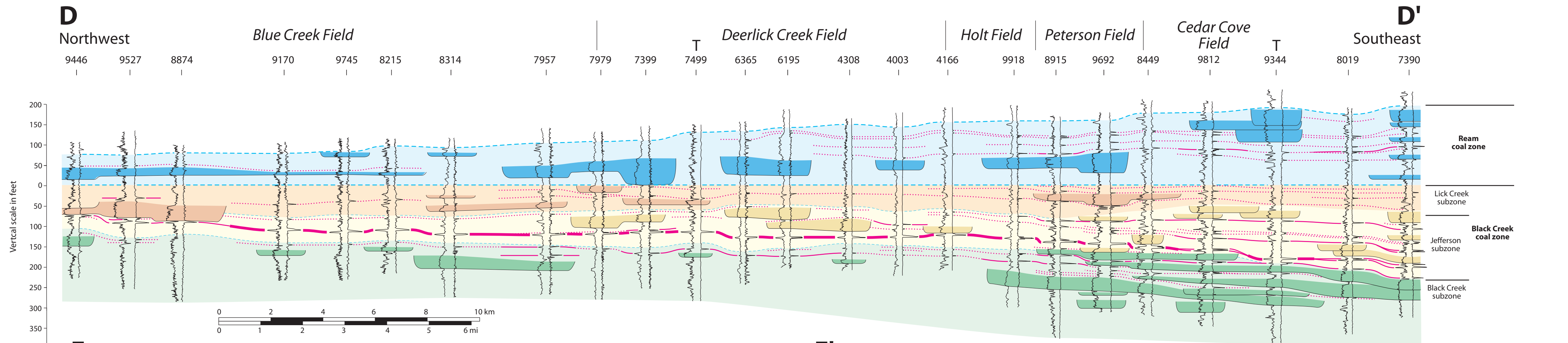
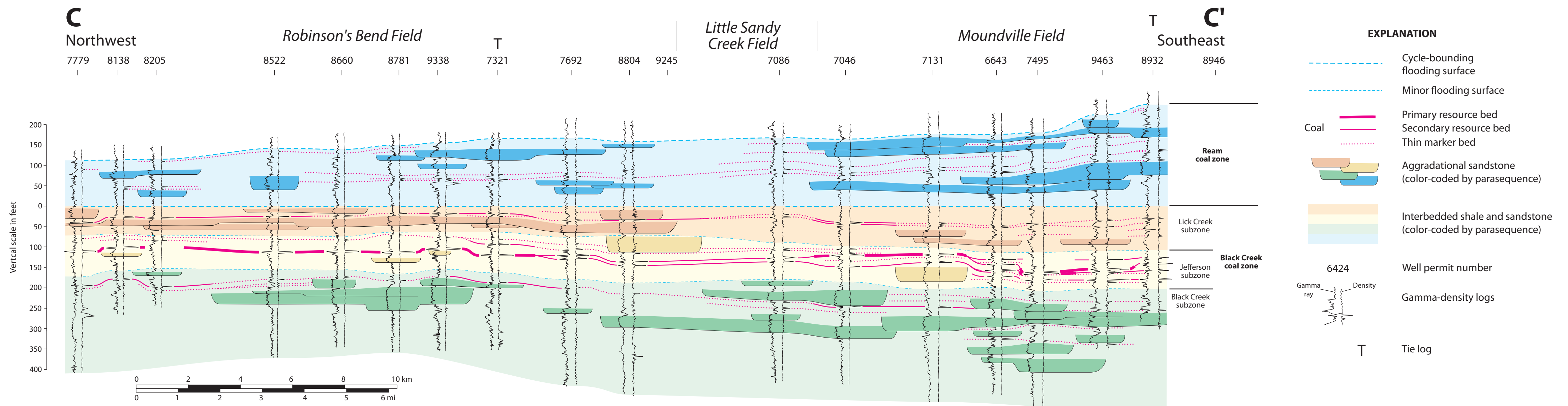
**CROSS SECTIONS A-A' AND B-B' OF THE BLACK CREEK AND REAM COAL ZONES IN THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA**

By  
Jack C. Pashin and Dorothy E. Raymond  
2002



Berry H. (Nick) Tew, Jr.  
State Geologist



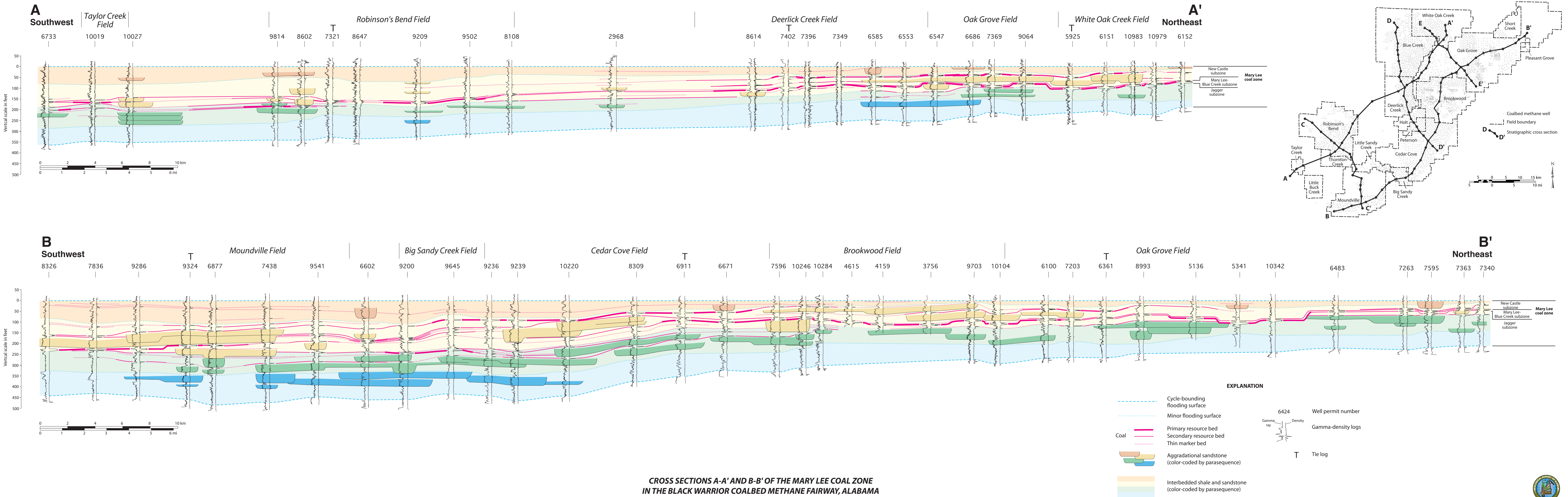


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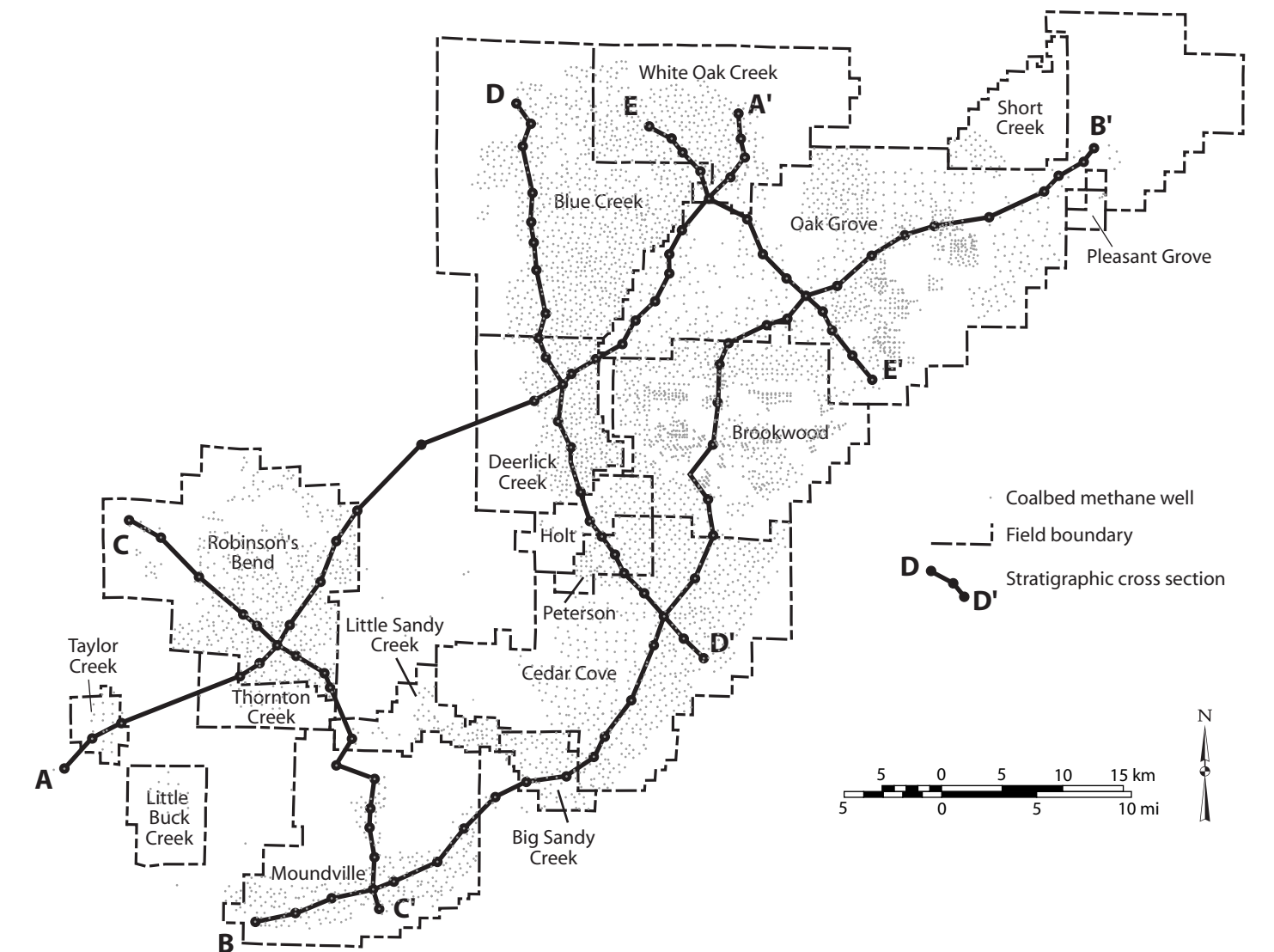
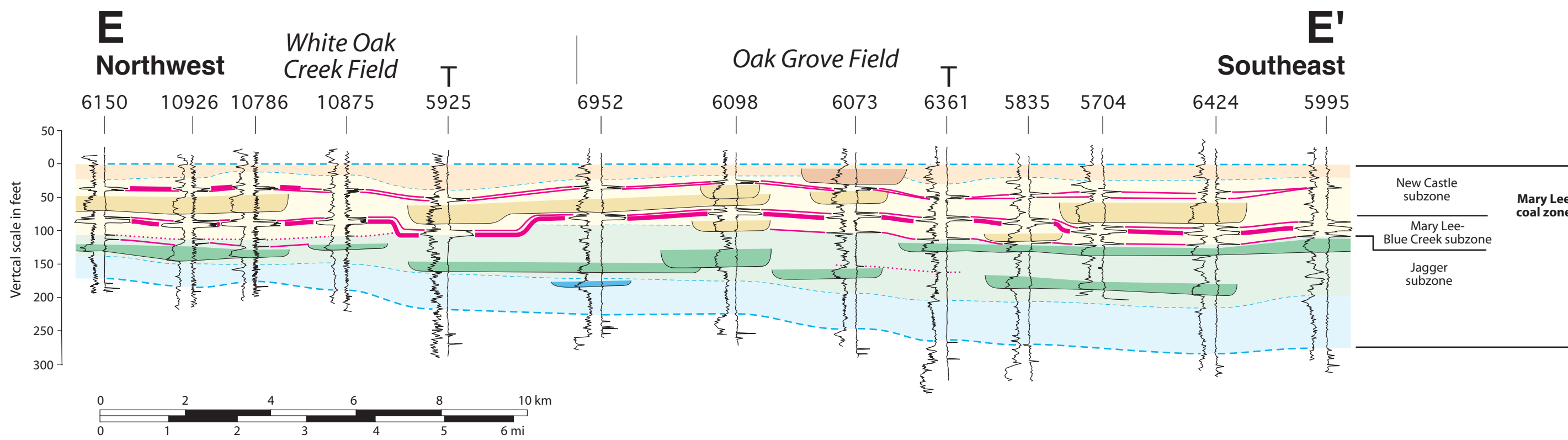
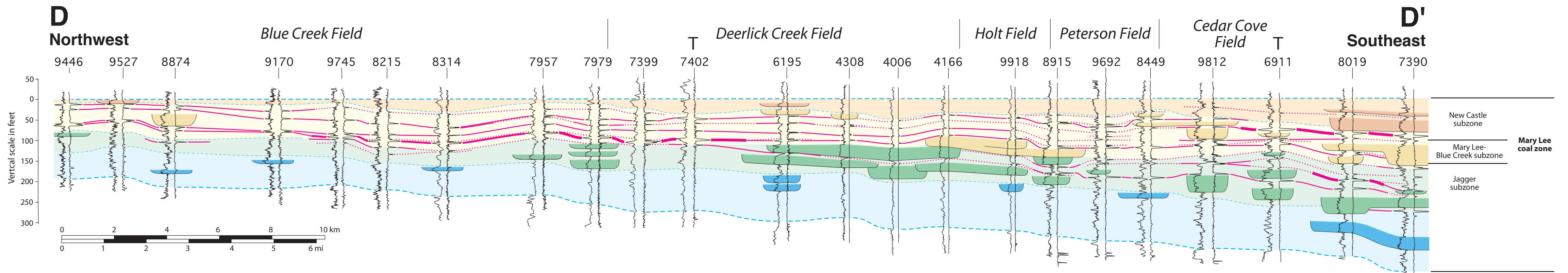
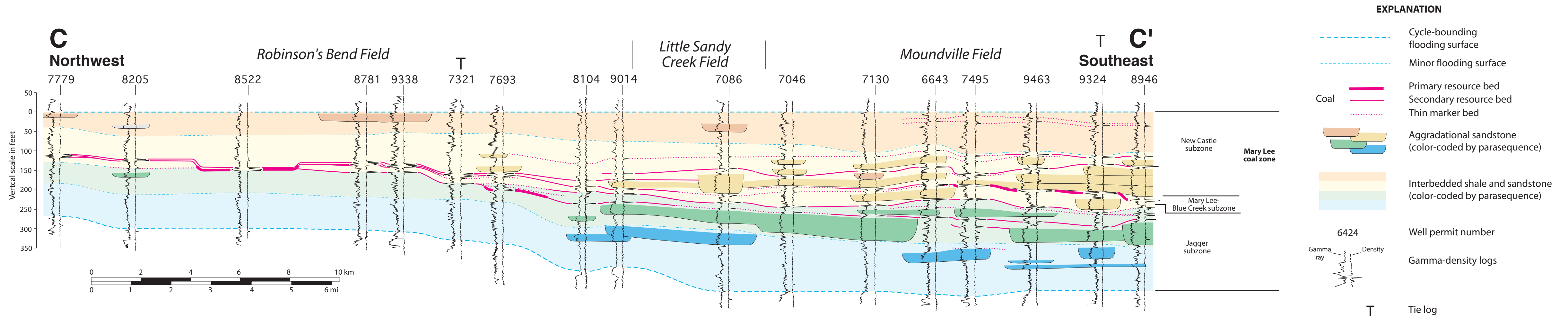


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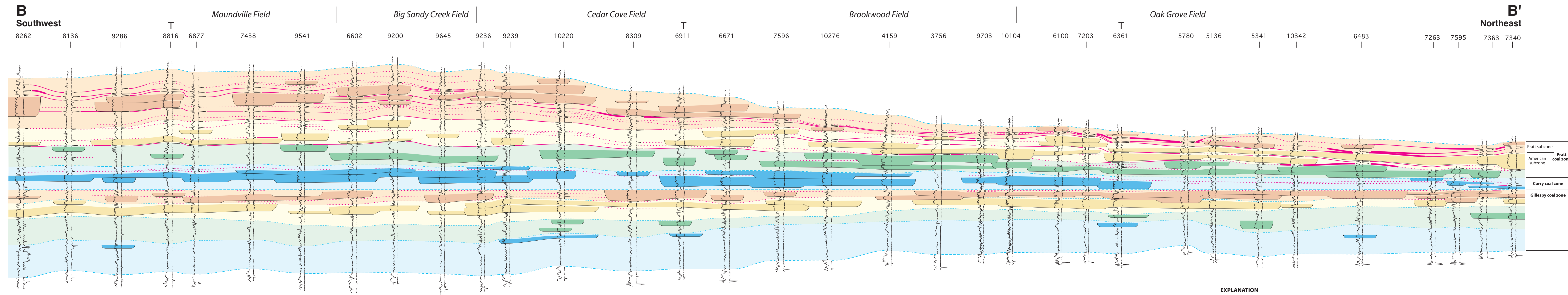
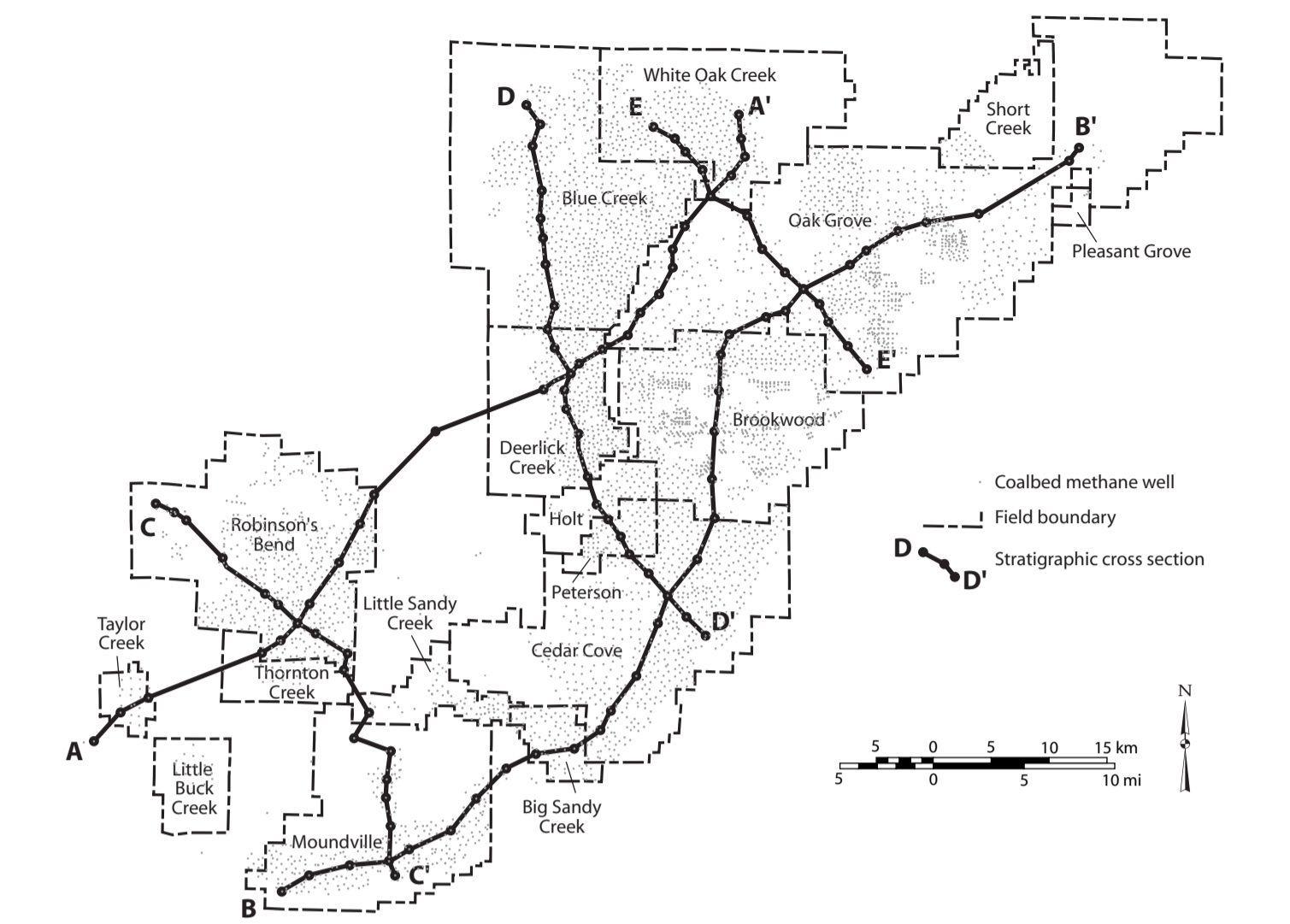
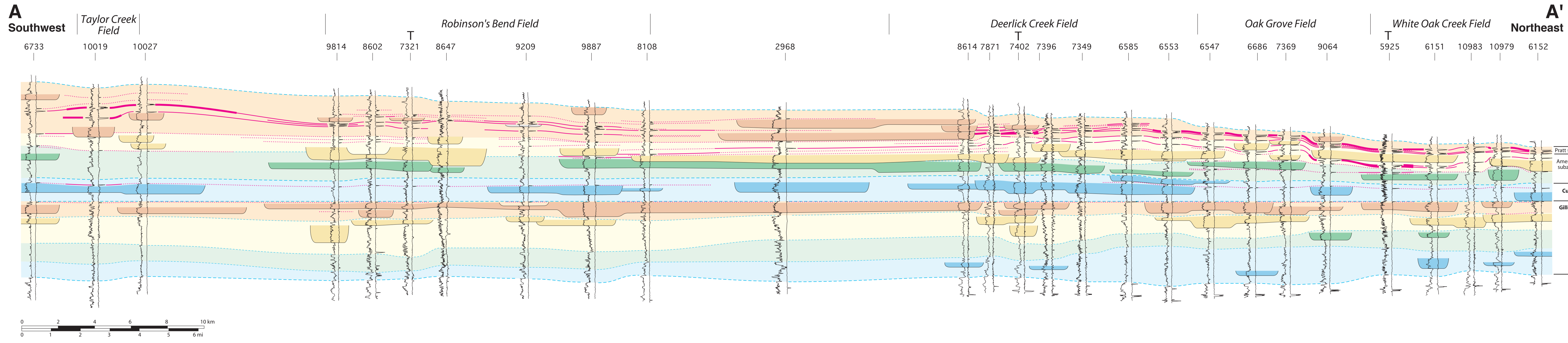


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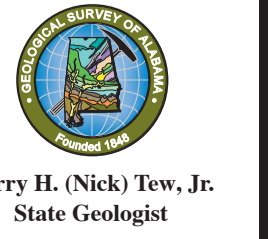
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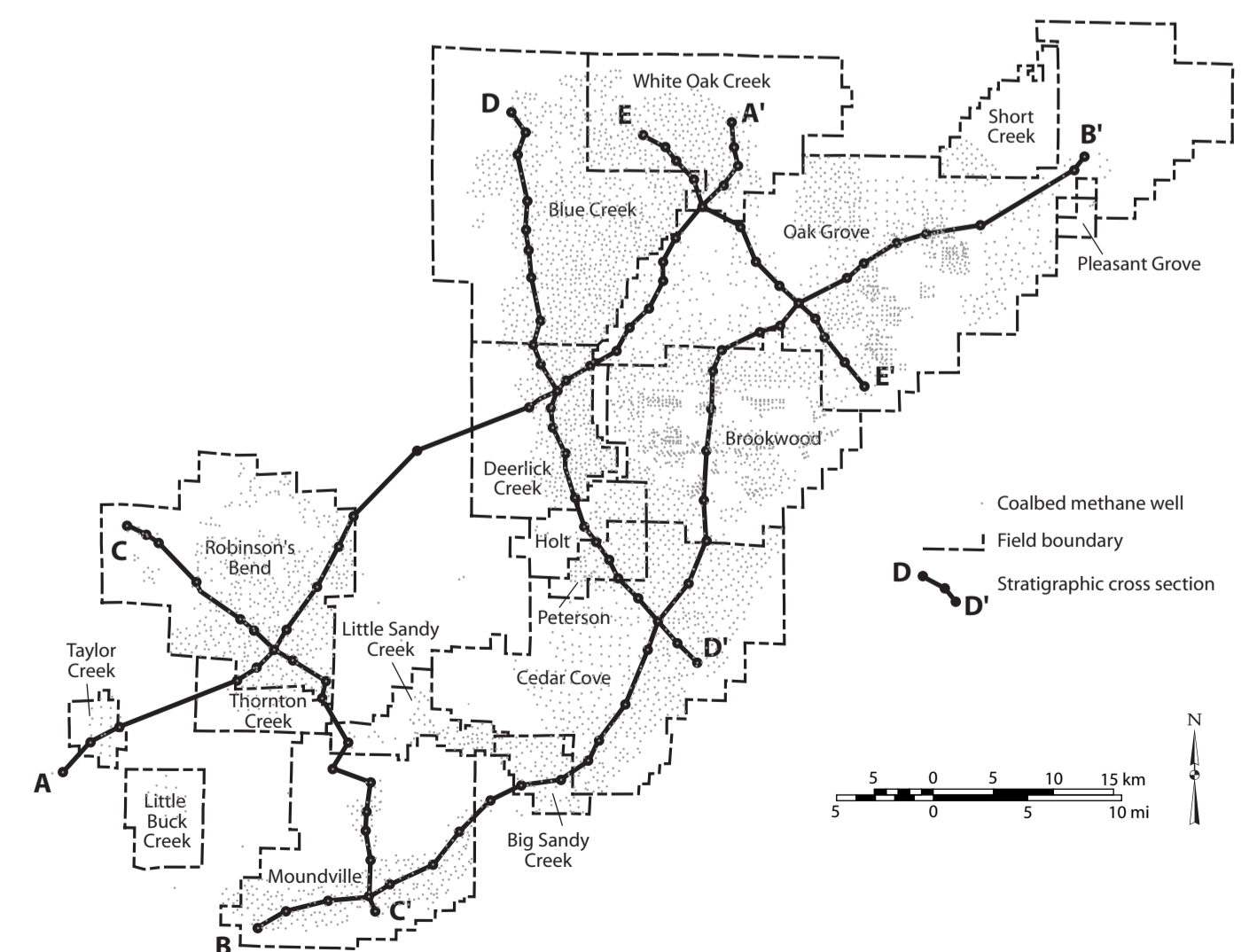
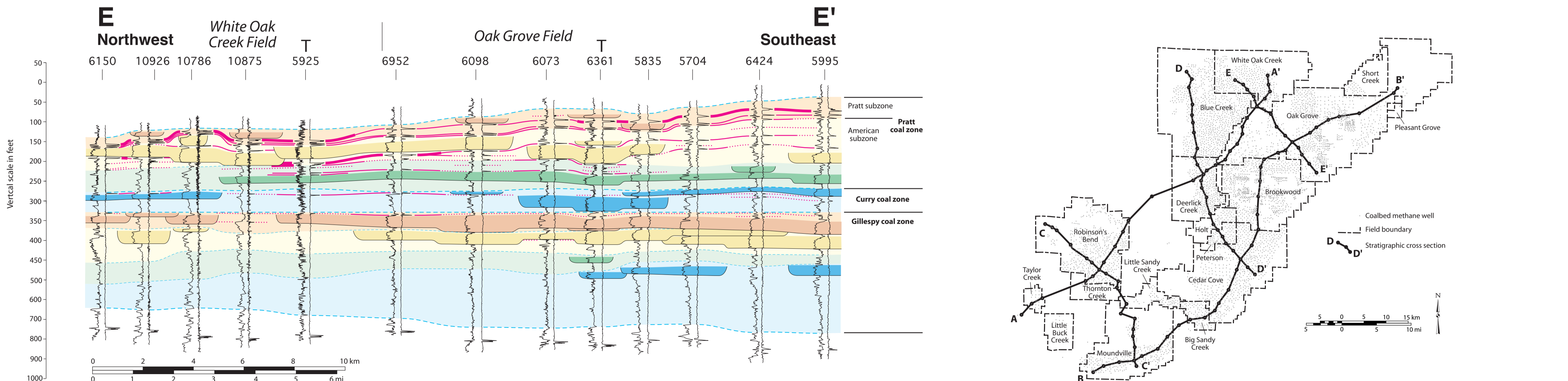
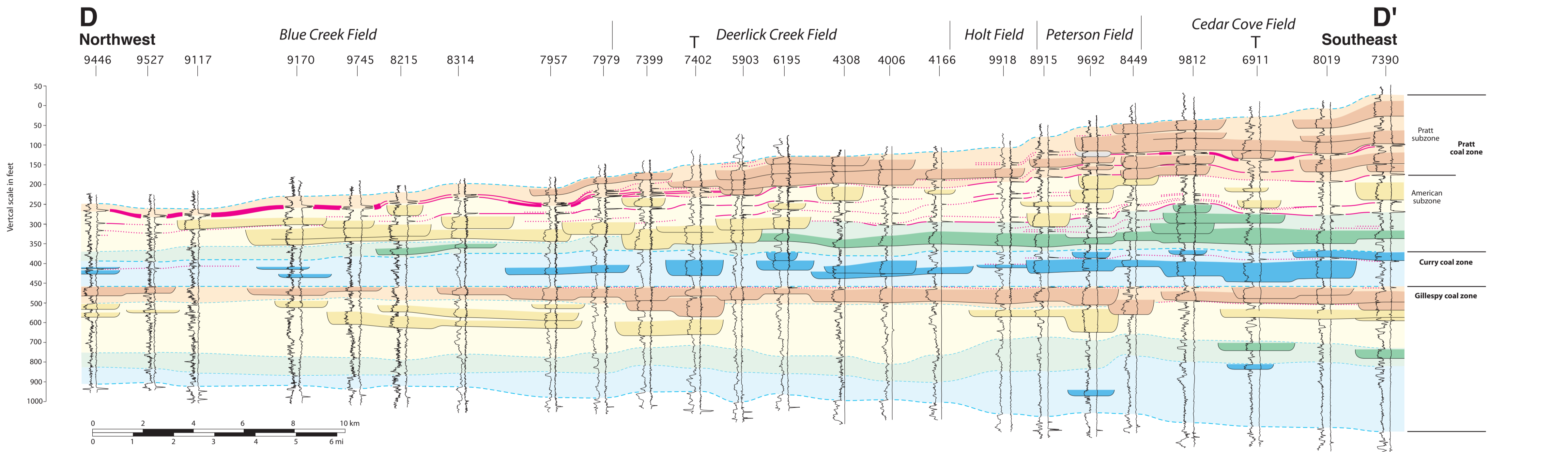
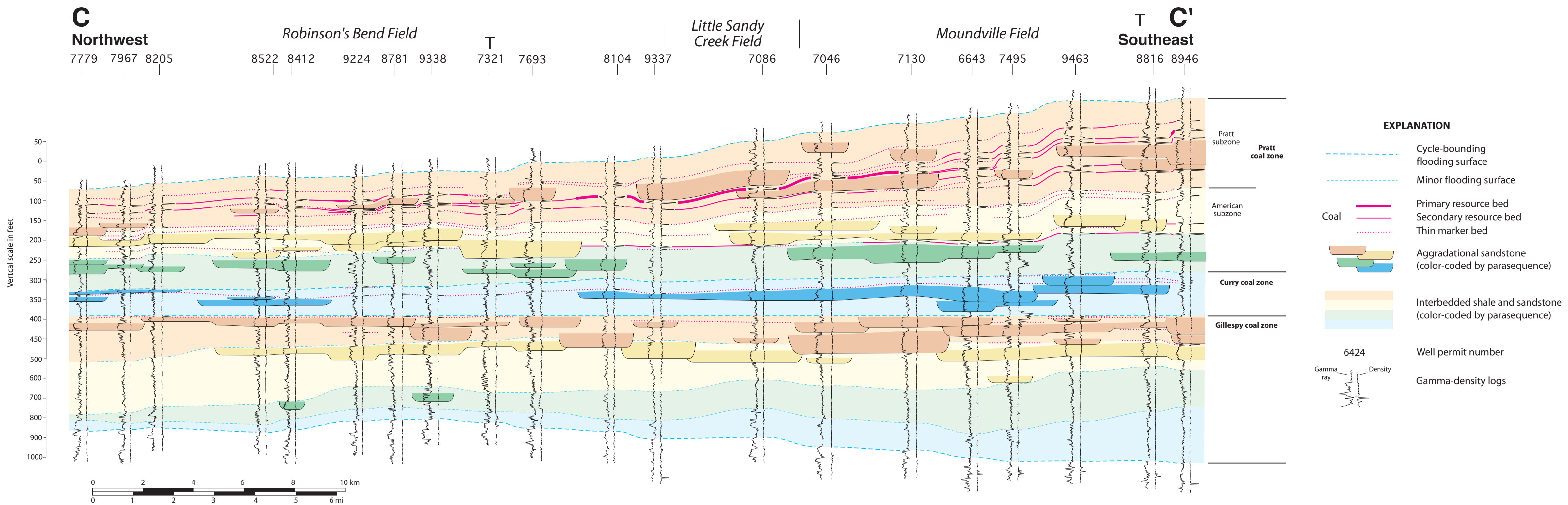
- Cycle-bounding flooding surface
- Minor flooding surface
- Coal:
  - Primary resource bed
  - Secondary resource bed
  - Thin marker bed
- Aggradational sandstone (color-coded by parasequence)
- Interbedded shale and sandstone (color-coded by parasequence)

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**CROSS SECTIONS A-A' AND B-B' OF THE GILLESPY, CURRY, AND PRATT COAL ZONES IN THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA**

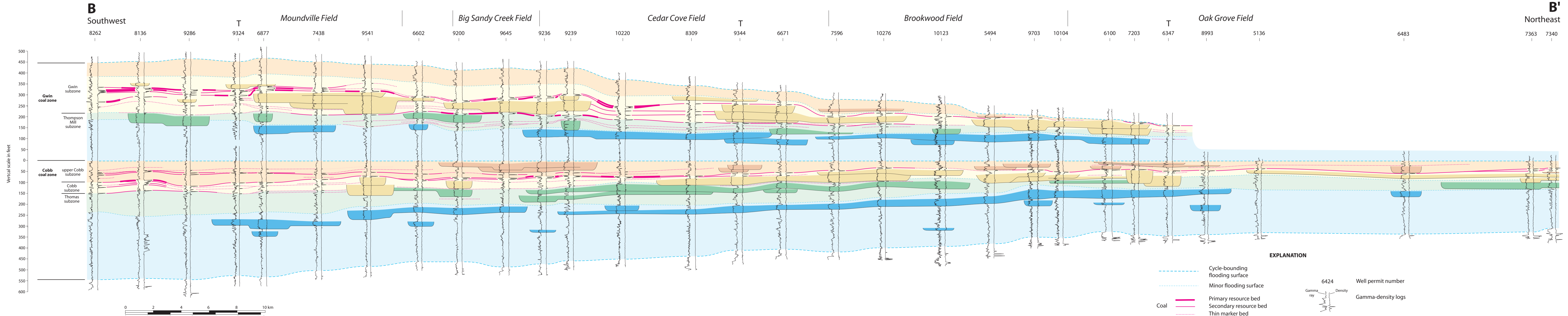
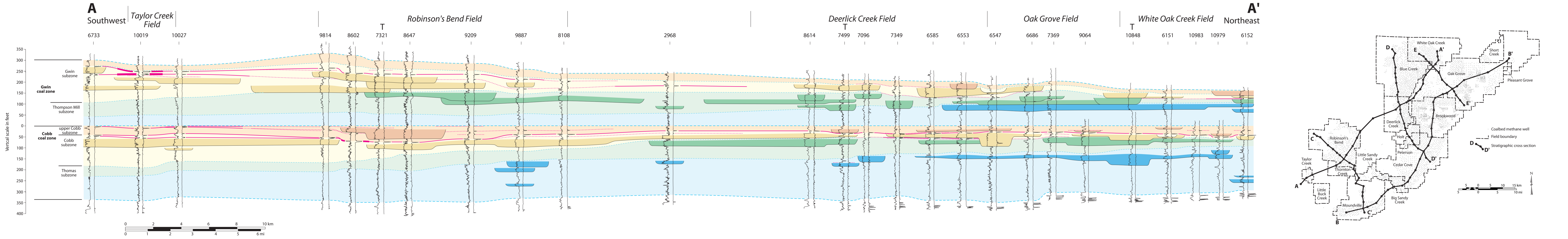
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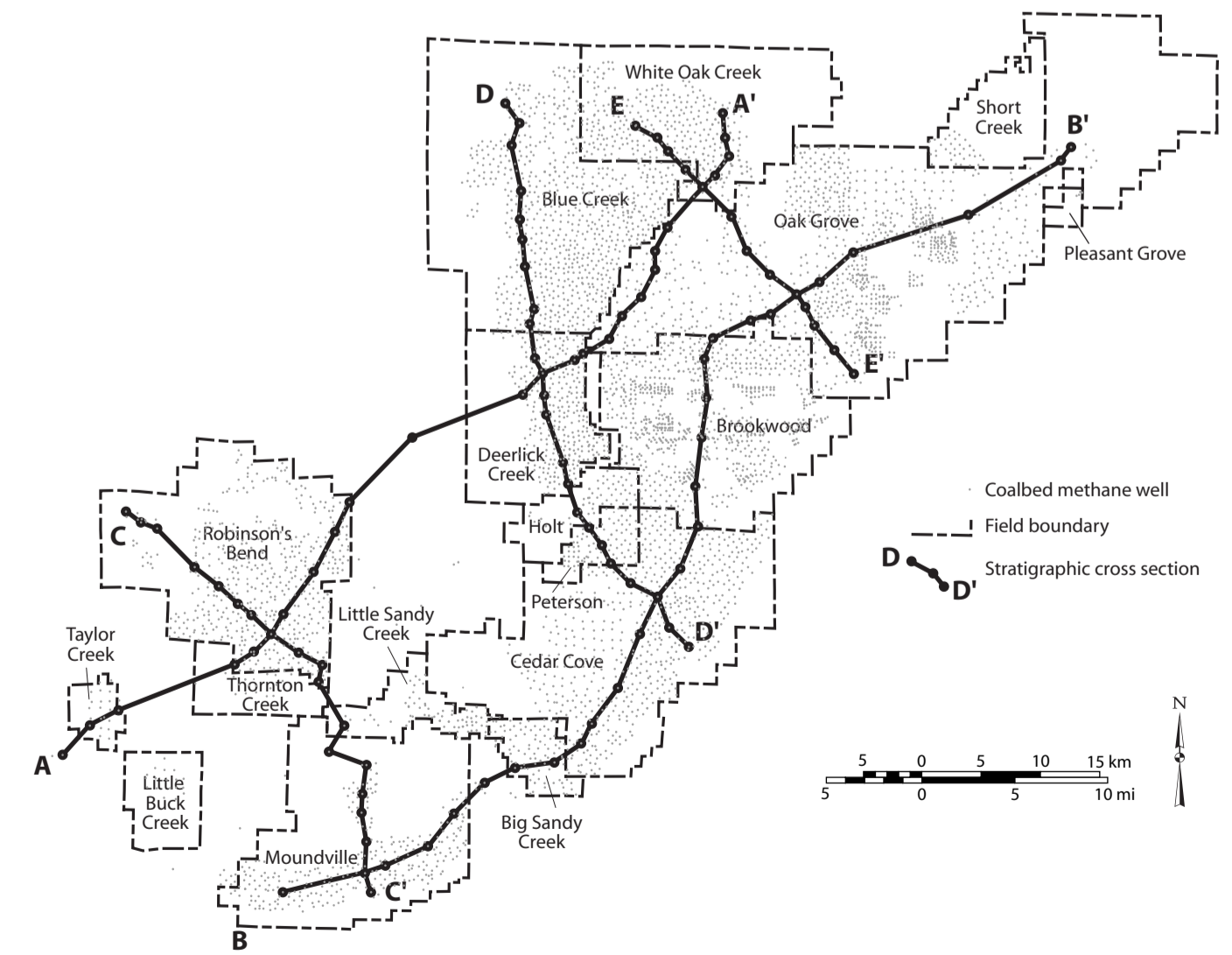
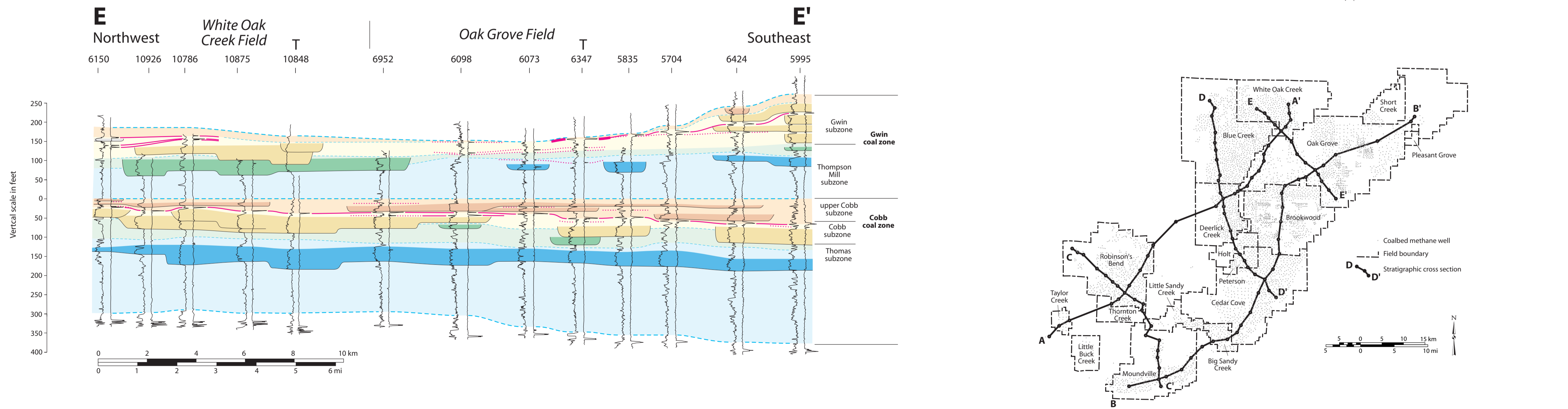
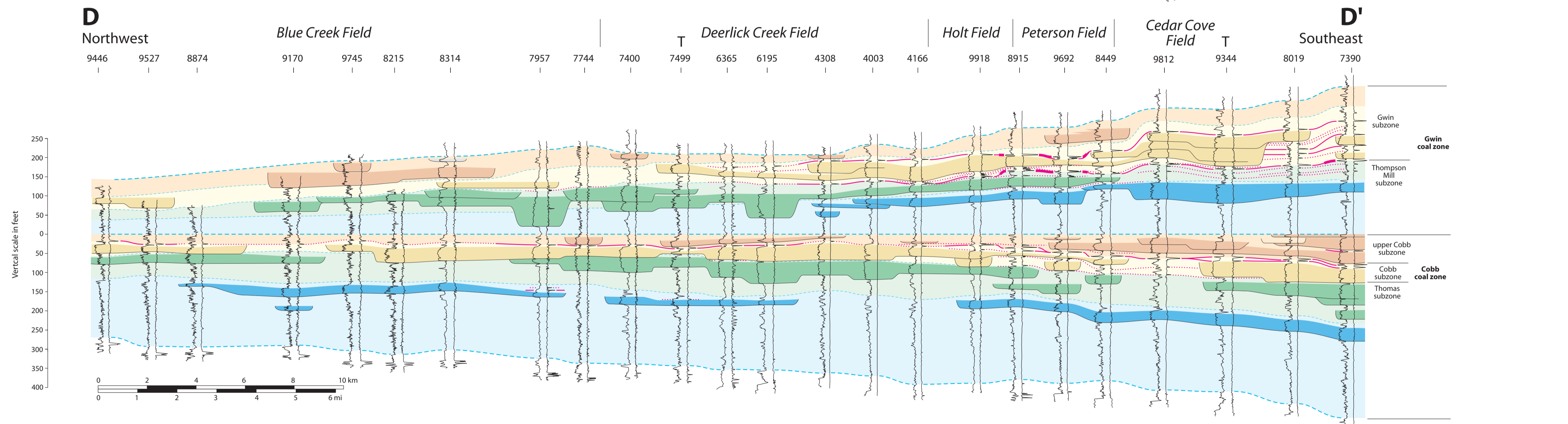
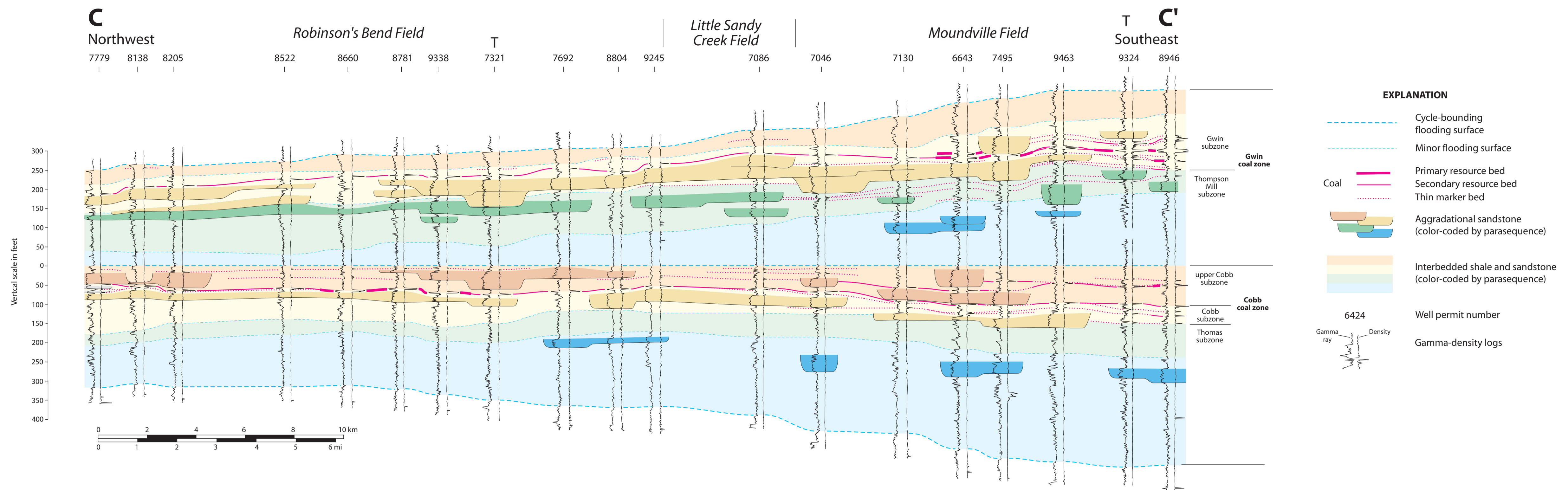


CROSS SECTIONS A-A', AND B-B' OF THE COBB AND GWIN COAL ZONES IN THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA

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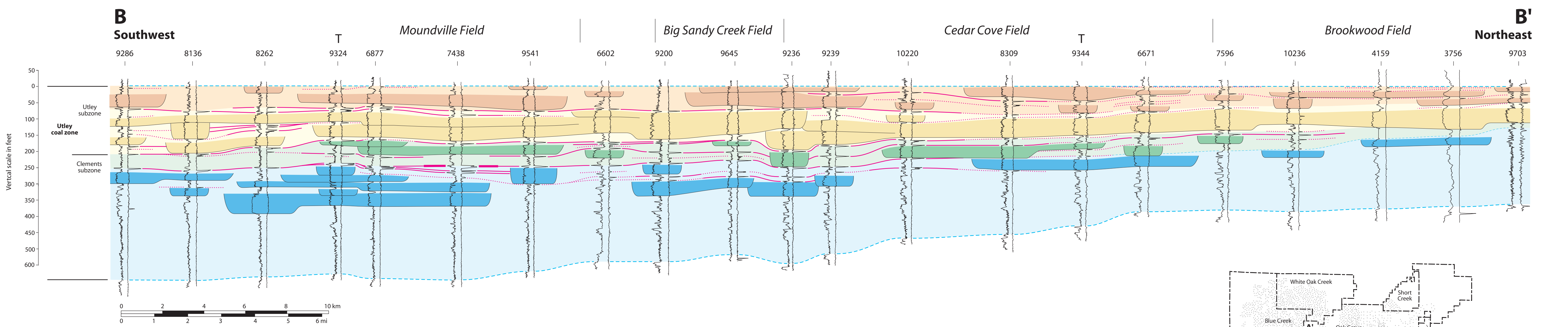
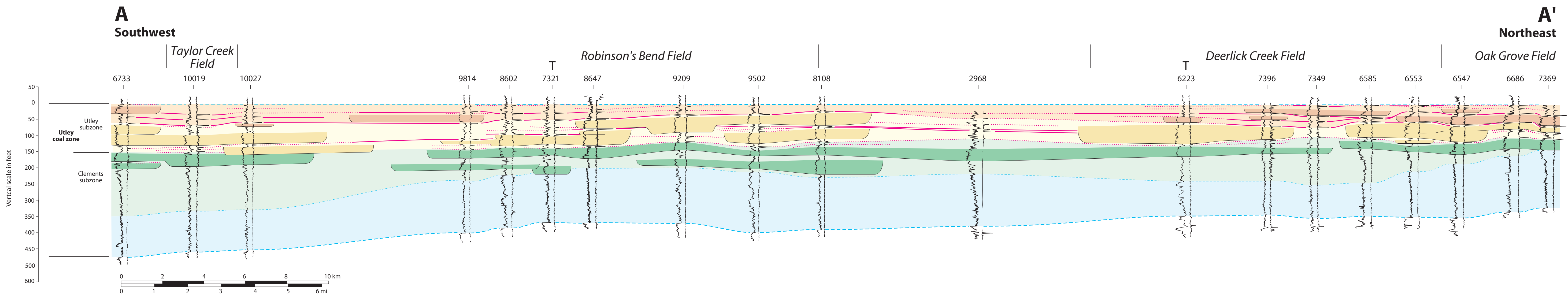


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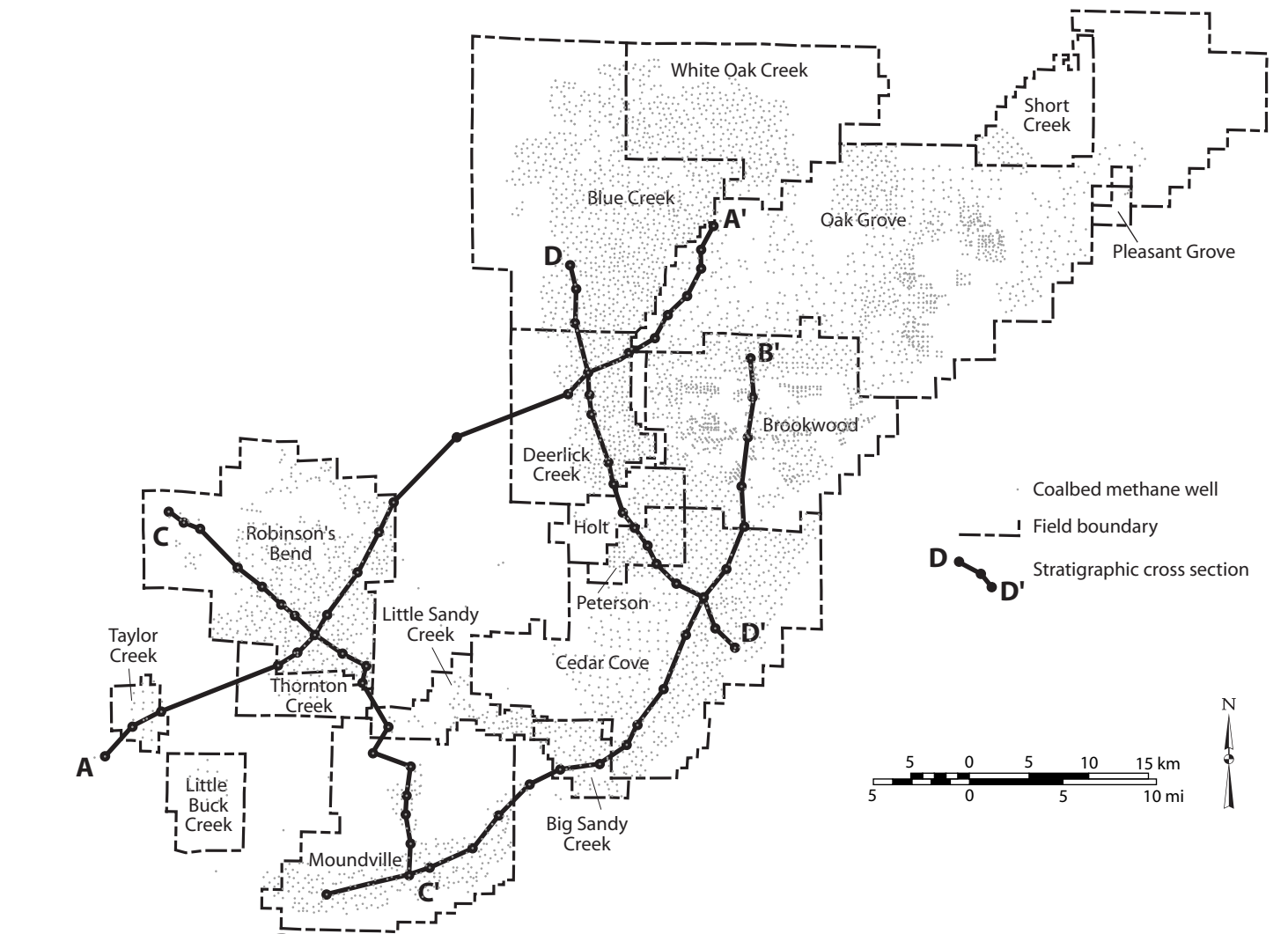


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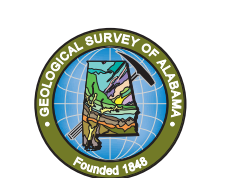
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- EXPLANATION**
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  - Gamma-density logs

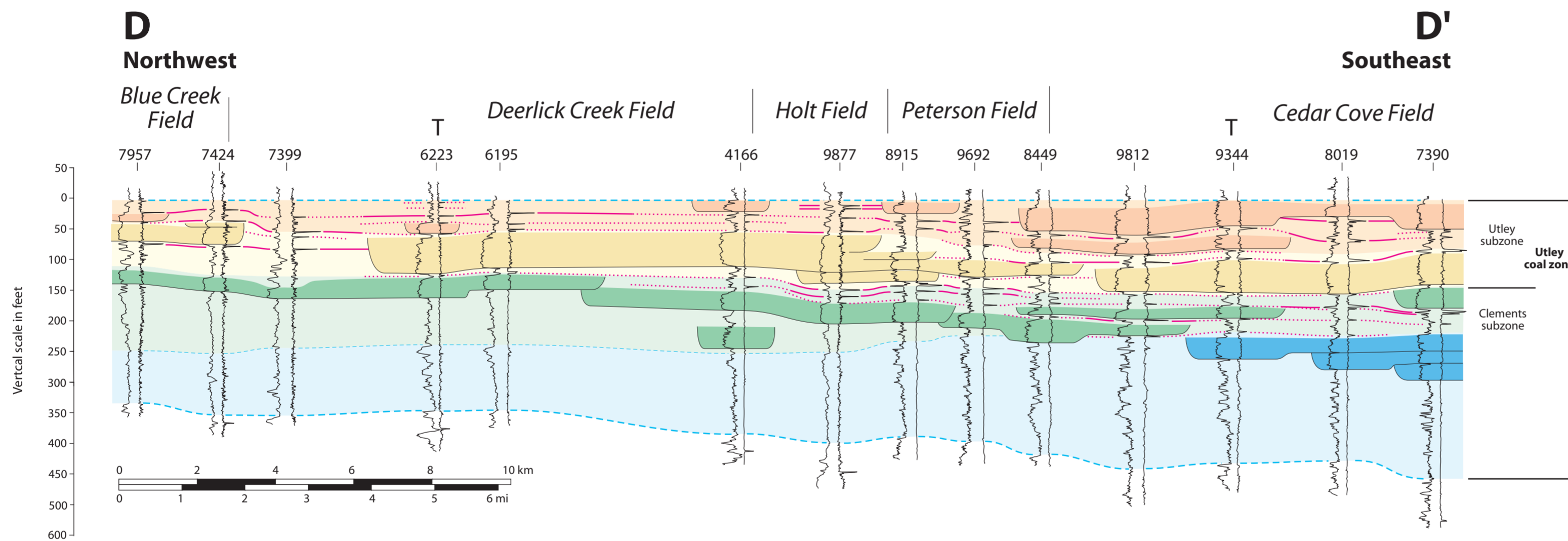
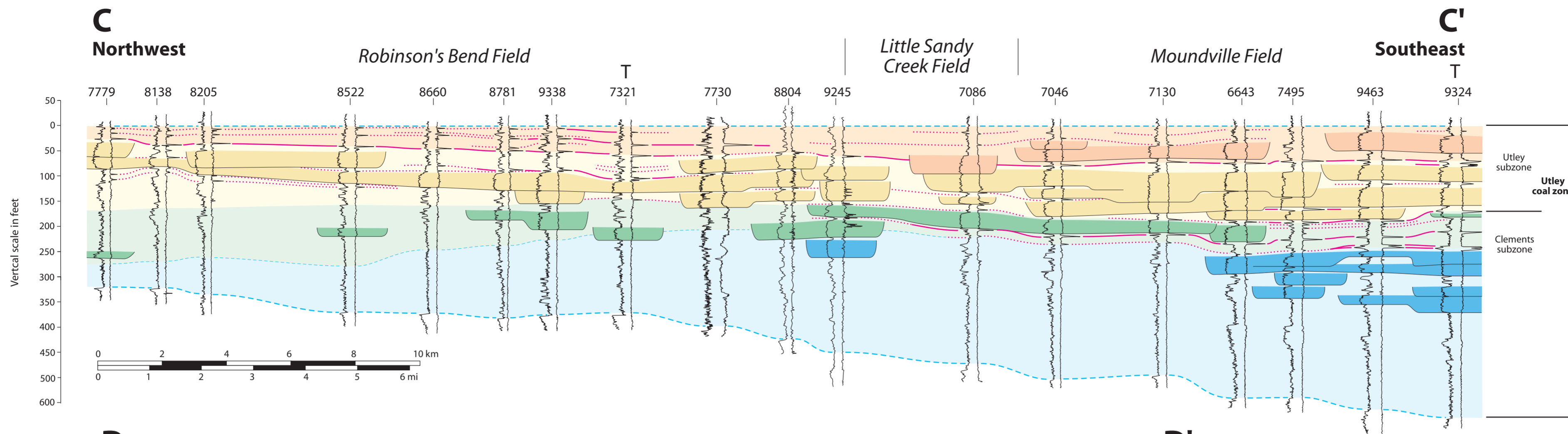


**CROSS SECTIONS A-A' AND B-B' OF THE UTLEY COAL ZONE  
IN THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA**  
By  
Jack C. Pashin and Dorothy E. Raymond  
2002



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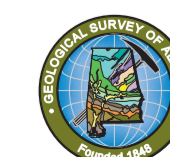
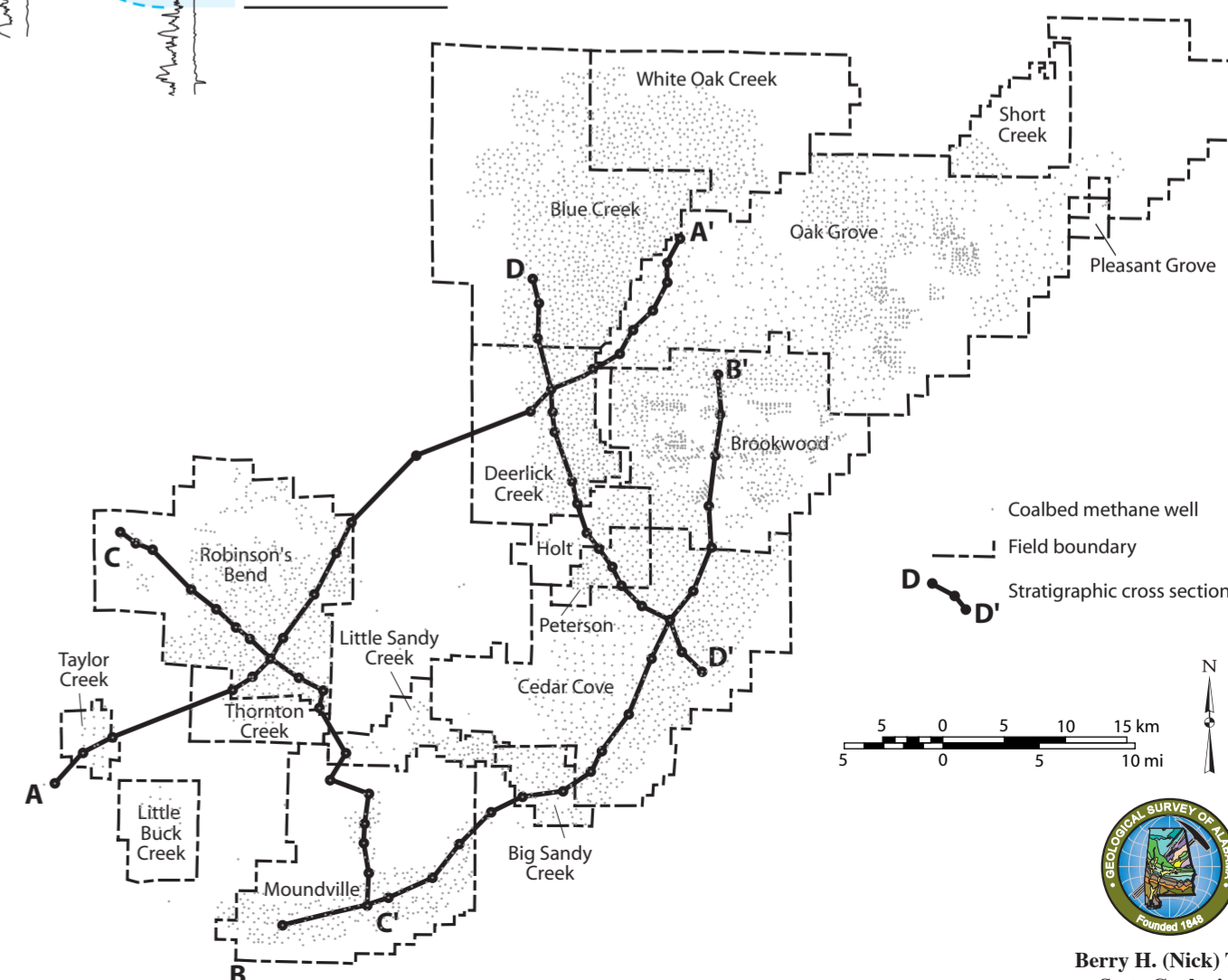


**EXPLANATION**

- Cycle-bounding flooding surface
- Minor flooding surface
- Primary resource bed
- Secondary resource bed
- Thin marker bed
- Aggradational sandstone (color-coded by parasequence)
- Interbedded shale and sandstone (color-coded by parasequence)
- Well permit number
- Gamma-density logs

**CROSS SECTIONS C-C' AND D-D' OF THE UTLEY COAL ZONE  
IN THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA**

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2002



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