GEOLOGICAL SURVEY OF ALABAMA

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

# FINAL REPORT

October 6, 2000-October 5, 2003

# GEOLOGIC SCREENING CRITERIA FOR SEQUESTRATION OF $CO_2$ IN COAL: QUANTIFYING POTENTIAL OF THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA

by

Jack C. Pashin[1], Richard E. Carroll[1], Richard H. Groshong, Jr.[2], Dorothy E. Raymond[1], Marcella McIntyre[2], and J. Wayne Payton[1]

[1]Geological Survey of Alabama
P.O. Box 869999
Tuscaloosa, AL 35486-6999

[2]Department of Geological Sciences
University of Alabama
Tuscaloosa, AL 35487

submitted to the
U.S. Department of Energy, National Energy Technology Laboratory

in partial fulfillment of contract
DE-FC26-00NT40927

January 2004

# DISCLAIMER

# ABSTRACT

Sequestration of $CO_2$ 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.

Coalbed methane reservoirs in the upper Pottsville Formation of the Black Warrior basin are extremely heterogeneous, and this heterogeneity must be considered to screen areas for the application of $CO_2$ sequestration and enhanced coalbed methane recovery technology. Major screening factors include stratigraphy, geologic structure, geothermics, hydrogeology, coal quality, sorption capacity, technology, and infrastructure. Applying the screening model to the Black Warrior basin indicates that geologic structure, water chemistry, and the distribution of coal mines and reserves are the principal determinants of where $CO_2$ can be sequestered. By comparison, coal thickness, temperature-pressure conditions, and coal quality are the key determinants of sequestration capacity and unswept coalbed methane resources.

Results of this investigation indicate that the potential for $CO_2$ sequestration and enhanced coalbed methane recovery in the Black Warrior basin is substantial and can result in significant reduction of greenhouse gas emissions while increasing natural gas reserves. Coal-fired power plants serving the Black Warrior basin in Alabama emit approximately 31 MMst (2.4 Tcf) of

$CO_2$ annually. The total sequestration capacity of the Black Warrior coalbed methane fairway at 350 psi is about 189 MMst (14.9 Tcf), which is equivalent to 6.1 years of greenhouse gas emissions from the coal-fired power plants.

Applying the geologic screening model indicates that significant parts of the coalbed methane fairway are not accessible because of fault zones, coal mines, coal reserves, and formation water with TDS content less than 3,000 mg/L. Excluding these areas leaves a sequestration potential of 60 MMst (4.7 Tcf), which is equivalent to 1.9 years of emissions. Therefore, if about10 percent of the flue gas stream from nearby power plants is dedicated to enhanced coalbed methane recovery, a meaningful reduction of $CO_2$ emissions can be realized for nearly two decades. If the fresh-water restriction were removed for the purposes of $CO_2$ sequestration, an additional 10 MMst (0.9 Tcf) of $CO_2$ could feasibly be sequestered. The amount of unswept coalbed methane in the fairway is estimated to be 1.49 Tcf at a pressure of 50 psi. Applying the screening model results in an accessible unswept gas resource of 0.44 Tcf. Removal of the fresh-water restriction would elevate this number to 0.57 Tcf. If a recovery factor of 80 percent can be realized, then enhanced recovery activities can result in an 18 percent expansion of coalbed methane reserves in the Black Warrior basin.

# TABLE OF CONTENTS


Disclaimer ..... ii
Abstract ..... iii
Table of contents ..... v
Introduction ..... 1
Executive summary ..... 7
Experimental ..... 12
Results and discussion ..... 23
Regional setting ..... 23
Stratigraphy and sedimentation ..... 26
Background ..... 26
Well-log cross sections ..... 31
Black Creek coal zone ..... 32
Ream coal zone ..... 34
Mary Lee coal zone ..... 35
Gillespy coal zone ..... 37
Curry coal zone ..... 38
Pratt coal zone ..... 38
Cobb coal zone ..... 39
Gwin coal zone ..... 41
Utley coal zone ..... 42
Net coal isolith maps ..... 43
Interpretations ..... 55
Structural geology ..... 63
Appalachian folds and thrust faults ..... 64
Horst and graben systems ..... 69
Cretaceous structure ..... 70
Pottsville fracture systems ..... 73
Geothermics ..... 82
Hydrogeology ..... 91
Permeability ..... 93
Water chemistry ..... 95
Reservoir pressure ..... 102
Coal quality ..... 113
Rank ..... 113
Grade ..... 120
Ash ..... 121
Sulfur ..... 125
Macerals ..... 129
Sorption capacity ..... 129
Gas content ..... 147
Gas and water production ..... 150
Background ..... 151
Production characteristics ..... 154
Production maps ..... 159
Controls on production performance ..... 168
Pottsville gas capacity ..... 177
Unswept methane ..... 182
Nitrogen capacity ..... 190
Carbon dioxide capacity ..... 197
Geologic screening model ..... 205
Stratigraphy ..... 207

Geologic Structure .......... 209
Geothermics .......... 210
Hydrogeology .......... 210
Coal quality .......... 212
Sorption capacity .......... 213
Technology and infrastructure .......... 214
Application of screening model to the Black Warrior coalbed methane fairway .......... 217
Stratigraphy .......... 217
Geologic Structure .......... 218
Geothermics .......... 221
Hydrogeology .......... 221
Coal quality .......... 223
Sorption capacity .......... 224
Technology and infrastructure .......... 225
Discussion: screening results .......... 229
Recommendations .......... 232
Technology transfer .......... 233
Conclusion .......... 236
References .......... 241

## Plates

Plate 1. Cross sections A-A' and B-B' of the Black Creek and Ream coal zones in the Black Warrior coalbed methane fairway, Alabama .......... pocket
Plate 2. Cross sections C-C', D-D' and E-E' of the Black Creek and Ream coal zones in the Black Warrior coalbed methane fairway, Alabama .......... pocket
Plate 3. Cross sections A-A' and B-B' of the Mary Lee coal zone in the Black Warrior coalbed methane fairway, Alabama .......... pocket
Plate 4. Cross sections C-C', D-D' and E-E' of the Mary Lee coal zone in the Black Warrior coalbed methane fairway, Alabama .......... pocket
Plate 5. Cross sections A-A' and B-B' of the Gillespy, Curry, and Pratt coal zones in the Black Warrior coalbed methane fairway, Alabama .......... pocket
Plate 6. Cross sections C-C', D-D' and E-E' of the Gillespy, Curry, and Pratt coal zones in the Black Warrior coalbed methane fairway, Alabama .......... pocket
Plate 7. Cross sections A-A' and B-B' of the Cobb and Gwin coal zones in the Black Warrior coalbed methane fairway, Alabama .......... pocket
Plate 8. Cross sections C-C', D-D' and E-E' of the Cobb and Gwin coal zones in the Black Warrior coalbed methane fairway, Alabama .......... pocket
Plate 9. Cross sections A-A' and B-B' of the Utley coal zone in the Black Warrior coalbed methane fairway, Alabama .......... pocket
Plate 10. Cross sections C-C' and D-D' of the Utley coal zone in the Black Warrior coalbed methane fairway, Alabama .......... pocket
Plate 11. Geologic screening model for $CO_2$ sequestration in coalbed methane reservoirs .......... pocket

## Tables


Table 1. Locality and stratigraphic information for coal samples analyzed during this project ... 18
Table 2. Adsorption data for coal at 50, 100, and 350 psi ... 133
Table 3. Results of proximate analysis ... 141
Table 4. Results of ultimate analysis ... 143
Table 5. Estimated gas capacity of the Black Warrior coalbed methane fairway ... 189
Table 6. Estimated tonnages of carbon dioxide and carbon that can be sequestered in the Black Warrior coalbed methane fairway ... 230


## Figures


Figure 1. Coalbed methane fields, coal-fired power plants, and deep underground coal mines in the Black Warrior basin of west-central Alabama ... 2
Figure 2. Well control in the Black Warrior coalbed methane fairway and locations of stratigraphic cross sections ... 5
Figure 3. Geologic factors affecting coalbed methane production and carbon sequestration in coal ... 6
Figure 4. Tectonic setting of the Black Warrior basin ... 24
Figure 5. Core log and geophysical well log of the Pottsville Coal Interval in Cedar Cove Field ... 25
Figure 6. Idealized depositional cycle in the Pottsville Formation, Black Warrior basin, Alabama ... 28
Figure 7. Generalized paleogeography of the Pottsville Formation in the Black Warrior basin of Alabama ... 30
Figure 8. Isopach map of the Ream through Gwin coal zones in the Black Warrior coalbed methane fairway ... 33
Figure 9. Net coal isolith of upper Pottsville Formation in the Black Warrior coalbed methane fairway ... 44
Figure 10. Net coal isolith of the Black Creek coal zone in the Black Warrior coalbed methane fairway ... 45
Figure 11. Net coal isolith of the Ream coal zone in the Black Warrior coalbed methane fairway ... 47
Figure 12. Net coal isolith of the Mary Lee coal zone in the Black Warrior coalbed methane fairway ... 48
Figure 13. Net coal isolith of the Gillespy coal zone in the Black Warrior coalbed methane fairway ... 50
Figure 14. Net coal isolith of the Curry coal zone in the Black Warrior coalbed methane fairway ... 51
Figure 15. Net coal isolith of the Pratt coal zone in the Black Warrior coalbed methane fairway ... 52
Figure 16. Net coal isolith of the Cobb coal zone in the Black Warrior coalbed methane fairway ... 53
Figure 17. Net coal isolith of the Gwin coal zone in the Black Warrior coalbed methane fairway ... 54
Figure 18. Net coal isolith of the Utley coal zone in the Black Warrior coalbed methane fairway ... 56
Figure 19. Net coal isolith of the Brookwood coal zone in the Black Warrior coalbed methane fairway ... 57
Figure 20. Generalized stratigraphic model of a Pottsville coal zone in the Black Warrior coalbed methane fairway ... 59

Figure 21. Generalized structural contour map of the top of the Pratt coal zone in the Black Warrior coalbed methane fairway ........ 65
Figure 22. Three-dimensional perspective view of the structure of the top of the Pratt coal zone in the Black Warrior coalbed methane fairway ........ 66
Figure 23. Structural model of the top of the Pratt coal zone in Cedar Cove and Peterson fields ........ 68
Figure 24. Balanced structural cross section of the Pottsville Formation in Deerlick Creek Field ........ 71
Figure 25. Structural contour map of the unconformity surface separating the Pottsville Formation and Tuscaloosa Group ........ 72
Figure 26. Photograph of a small normal fault and associated fracturing in an abandoned mine highwall, Brookwood coal zone, Brookwood Field ........ 74
Figure 27. Photograph of jointed shale above the Gwin coal zone in Oak Grove Field ........ 75
Figure 28. Photographs showing cleat systems in Alabama coal ........ 76
Figure 29. Generalized maps showing joint and cleat systems in the eastern Black Warrior basin of Alabama ........ 78
Figure 30. Generalized model of calcite mineralization in coal of the eastern Black Warrior basin ........ 80
Figure 31. Percentile plot showing the frequency of kinematic-aperture size classes for joints and fault-related shear fractures in five cores from Brookwood Field ........ 81
Figure 32. DFN and compartmentalization models showing relationship of a single coal bed to strata-bound joint networks ........ 83
Figure 33. Compartmentalization model of complete jointed DFN model showing development of first-order reservoir compartments around major coal zones and numerous second-order compartments in thick, shale-dominated intervals between coal zones ........ 84
Figure 34. Phase diagram for $CO_2$ showing relationship of the critical point to reservoir conditions in the Black Warrior coalbed methane fairway ........ 85
Figure 35. Relationship of methane sorption to temperature in bituminous coal of the Appalachian basin ........ 87
Figure 36. Temperature-depth plot for coalbed methane wells in the Black Warrior basin ........ 88
Figure 37. Histogram showing population distribution of geothermal gradients in the Black Warrior coalbed methane fairway ........ 89
Figure 38. Map of geothermal gradient in the Black Warrior coalbed methane fairway ........ 90
Figure 39. Map of temperature at the top of the Pratt coal zone in the Black Warrior coalbed methane fairway ........ 92
Figure 40. Plot of permeability versus depth for coal in the eastern Black Warrior basin ........ 94
Figure 41. Color-contoured DFN model showing transmissivity of coal and joints ........ 96
Figure 42. Pressure buildup test results showing permeability anisotropy in coalbed methane reservoirs of the Black Warrior basin ........ 97
Figure 43. Stiff diagrams showing the composition of formation water in the Pottsville Formation ........ 98
Figure 44. Generalized structural cross section showing meteoric recharge areas and subsurface flow patterns in the upper Pottsville Formation ........ 99
Figure 45. Relationship of fresh-water plumes in the Mary Lee coal zone along the southeast margin of the Black Warrior basin to geologic structure and Cretaceous cover ........ 101
Figure 46. Histogram showing bipolar distribution of hydrostatic pressure gradients in the Black Warrior coalbed methane fairway ........ 104
Figure 47. Pressure-depth plot based on water levels in the Black Warrior coalbed methane fairway ........ 105
Figure 48. Map of hydrostatic pressure gradient determined from water levels in the Black Warrior coalbed methane fairway ........ 107

Figure 49. Map of hydrostatic pressure at the top of the Pratt coal zone in the Black Warrior coalbed methane fairway ........ 108
Figure 50. Map showing shallowest unit where supercritical fluid conditions may develop for $CO_2$ in the Black Warrior coalbed methane fairway ........ 111
Figure 51. Coal rank in the Black Warrior coalbed methane fairway based on volatile matter and vitrinite reflectance data from the Mary Lee coal zone ........ 114
Figure 52. Cross sections showing the relationship of rank to structure in the Black Warrior coalbed methane fairway ........ 116
Figure 53. Generalized relationship between burial history and thermal maturation in the Black Warrior basin ........ 118
Figure 54. Histograms showing ash and total sulfur content in coal of the Black Warrior basin ........ 119
Figure 55. Relationship of ash and sulfur content to stratigraphy in the Black Warrior basin ........ 122
Figure 56. Maps showing variability of ash content in the Mary Lee and Utley coal beds in Blue Creek Field ........ 123
Figure 57. Histograms showing organic and pyritic sulfur content in coal of the Black Warrior basin ........ 126
Figure 58. Regression plots of sulfur forms versus total sulfur in coal of the Black Warrior basin ........ 127
Figure 59. Ternary plot showing maceral composition of coal samples used for sorption-isotherm, proximate, and ultimate analysis in this study ........ 130
Figure 60. Isotherm plots showing the capacity of coal in the Black Warrior basin to sorb carbon dioxide, methane, and nitrogen ........ 132
Figure 61. Comparison of isotherms calculated on different bases in coal of variable ash content and constant rank ........ 135
Figure 62. Scatterplots showing correlation between sorption capacity and volatile matter ........ 137
Figure 63. Scatterplots showing correlation between sorption capacity and volatile matter ........ 138
Figure 64. Scatterplots showing correlation between sorption capacity and ash content ........ 139
Figure 65. Scatterplots showing correlation between sorption capacity and ash content ........ 140
Figure 66. Scatterplots showing negative correlation between sorption capacity and ash content for samples with ash content between 5 and 21 percent ........ 145
Figure 67. Plots of gas content versus depth for two cores in the Black Warrior coalbed methane fairway ........ 148
Figure 68. Map showing years of reported production from vertical wells in the Black Warrior coalbed methane fairway ........ 152
Figure 69. Map showing generalized status of coalbed methane fields in the Black Warrior basin ........ 153
Figure 70. Decline curves for gas and water production from two wells in Deerlick Creek Field ........ 155
Figure 71. Histograms of cumulative and peak gas production from coalbed methane wells in the Black Warrior basin ........ 156
Figure 72. Histograms of cumulative and peak water production from coalbed methane wells in the Black Warrior basin ........ 157
Figure 73. Percentile plots of cumulative and peak water production from coalbed methane wells in the Black Warrior basin ........ 158
Figure 74. Scatterplots showing correlation between peak and cumulative production values from coalbed methane wells in the Black Warrior basin ........ 160
Figure 75. Scatterplot showing lack of correlation between peak water and gas production in the Black Warrior coalbed methane fairway ........ 161
Figure 76. Scatterplot showing modest correlation between water and gas production in Deerlick Creek Field ........ 162

Figure 77. Map of cumulative gas production from vertical wells in the Black Warrior coalbed methane fairway ........ 163
Figure 78. Map of cumulative water production from vertical wells in the Black Warrior coalbed methane fairway ........ 164
Figure 79. Map of peak gas production in the Black Warrior coalbed methane fairway for wells reporting data for 48 months or more ........ 165
Figure 80. Map of peak water production in the Black Warrior coalbed methane fairway for wells reporting data for 48 months or more ........ 166
Figure 81. Map showing relationship of peak gas production to structural traces in the Black Warrior coalbed methane fairway ........ 169
Figure 82. Map showing the relationship between peak water production and structural traces in the Black Warrior coalbed methane fairway........ 170
Figure 83. Map showing alignment of exceptionally productive gas wells along a synclinal fold hinge in Oak Grove Field........ 171
Figure 84. Map showing relationship of gas and water production to extensional structure in Deerlick Creek Field ........ 172
Figure 85. 3D computer model showing structural segmentation of coalbed methane reservoirs in Deerlick Creek Field and exceptionally poor production performance of wells penetrating normal faults and completed in the Mary Lee coal zone........ 174
Figure 86. Rank-estimated $CO_2$ capacity of the Mary Lee coal zone at 100 psi ........ 179
Figure 87. Plot of temperature correction factor versus temperature........ 180
Figure 88. Map of temperature correction factor used to estimate gas capacity in the Mary Lee coal zone at 100 psi ........ 181
Figure 89. Map of estimated unswept methane content in the Mary Lee coal zone at 50 psi ........ 183
Figure 90. Map of estimated unswept methane content in the Mary Lee coal zone at 100 psi ........ 184
Figure 91. Map of estimated unswept methane content in the Mary Lee coal zone at 350 psi ........ 185
Figure 92. Map of estimated unswept methane content in the upper Pottsville Formation at 50 psi ........ 186
Figure 93. Map of estimated unswept methane content in the upper Pottsville Formation at 100 psi ........ 187
Figure 94. Map of estimated unswept methane content in the upper Pottsville Formation at 350 psi ........ 188
Figure 95. Map of estimated nitrogen capacity in the Mary Lee coal zone at 50 psi ........ 191
Figure 96. Map of estimated nitrogen capacity in the Mary Lee coal zone at 100 psi ........ 192
Figure 97. Map of estimated nitrogen capacity in the Mary Lee coal zone at 350 psi ........ 193
Figure 98. Map of estimated nitrogen capacity in the upper Pottsville Formation at 50 psi ........ 194
Figure 99. Map of estimated nitrogen capacity in the upper Pottsville Formation at 100 psi ........ 195
Figure 100. Map of estimated nitrogen capacity in the upper Pottsville Formation at 350 psi ........ 196
Figure 101. Map of estimated carbon dioxide capacity in the Mary Lee coal zone at 50 psi ........ 198
Figure 102. Map of estimated carbon dioxide capacity in the Mary Lee coal zone at 100 psi ........ 199
Figure 103. Map of estimated carbon dioxide capacity in the Mary Lee coal zone at 350 psi ........ 200
Figure 104. Map of estimated carbon dioxide capacity in the upper Pottsville Formation at 50 psi ........ 201
Figure 105. Map of estimated carbon dioxide capacity in the upper Pottsville Formation

at 100 psi ........ 202
Figure 106. Map of estimated carbon dioxide capacity in the upper Pottsville Formation at 350 psi ........ 203
Figure 107. Geologic, technologic, and infrastructural factors that are useful for screening areas for the application of $CO_2$ sequestration and enhanced coalbed methane recovery technology in coal-bearing strata ........ 206
Figure 108. Areas where sequestration potential is limited by faulting, coal reserves, and fresh formation water ........ 219
Figure 109. Parts of the Black Warrior coalbed methane fairway where $CO_2$ sequestration is technically feasible ........ 220
Figure 110. Locations of gas-transmission pipelines and coal-fired power plants near the Black Warrior coalbed methane fairway ........ 226

# INTRODUCTION

The amount of carbon dioxide ($CO_2$) 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 $CO_2$ emissions will triple during the 21$^{st}$ 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 $CO_2$ emissions. Among the principal ways $CO_2$ 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 $CO_2$ can be used to enhance recovery of coalbed methane, thereby offsetting the costs associated with sequestration of $CO_2$ (Byrer and Guthrie, 1999; Gentzis, 2000; Hamelinck and others, 2001; White and others, 2003).

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 $CO_2$ 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, has completed a three-year study that assesses the $CO_2$ 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.

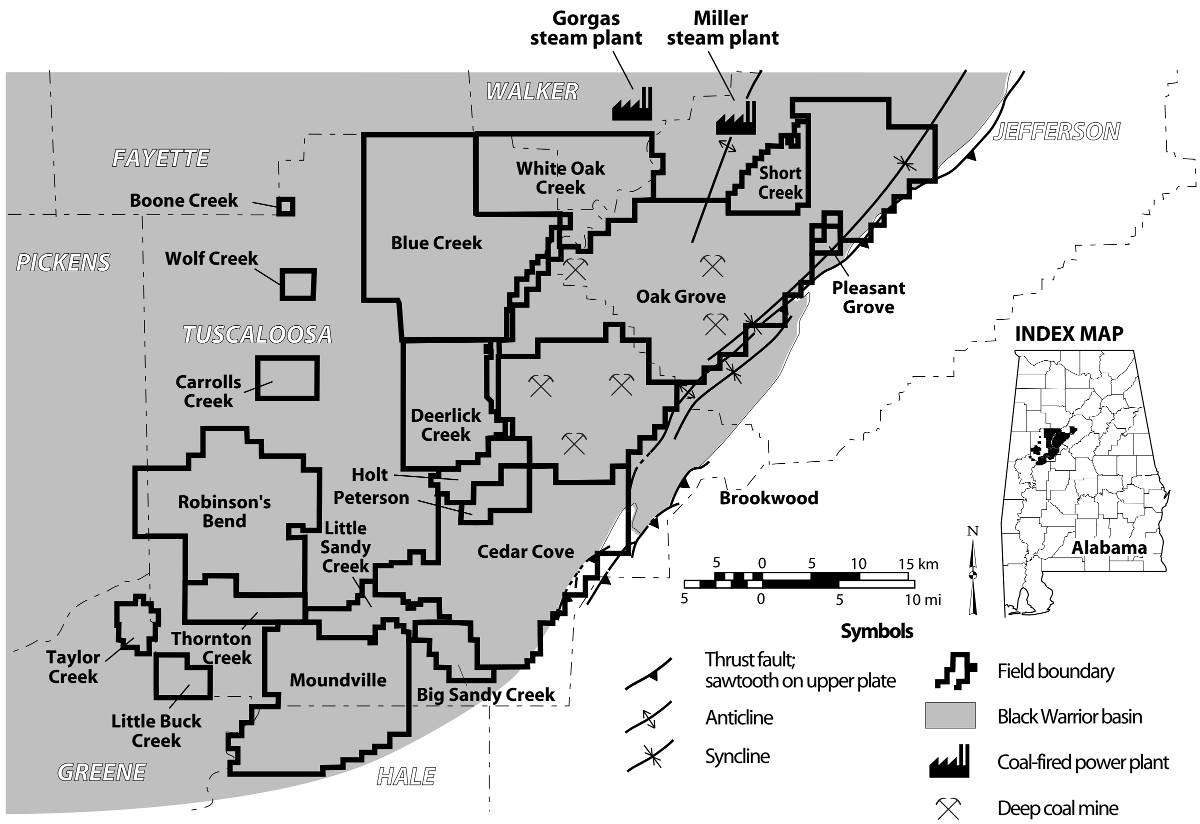



Figure 1.--Coalbed methane fields, coal-fired power plants, and deep underground coal mines in the Black Warrior basin of west-central Alabama (modified from Pashin and others, 2001a, b).

The objectives of this study are (1) to develop a geologic screening model that is widely applicable, (2) to quantify the $CO_2$ 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 $CO_2$ 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 $9^{th}$ nationally in $CO_2$ emissions from power plants, and two coal-fired power plants are within the coalbed methane fairway (fig. 1). More than 1.5 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 more than 35 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 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 5,000 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 $CO_2$ 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, 1974; Pashin and others, 1991; Ayers and Kaiser, 1994; Kaiser and others, 1994). This report presents the results of our research and characterizes the stratigraphy, structure, geothermics, hydrology, coal quality, sorption capacity, and production characteristics of coalbed methane reservoirs in the Black Warrior basin. The report also quantifies the $CO_2$ sequestration capacity of the Black Warrior coalbed methane fields and presents a conceptual geologic screening model that is then applied to the Black Warrior basin to help prioritize areas for the demonstration and commercialization of sequestration technology.

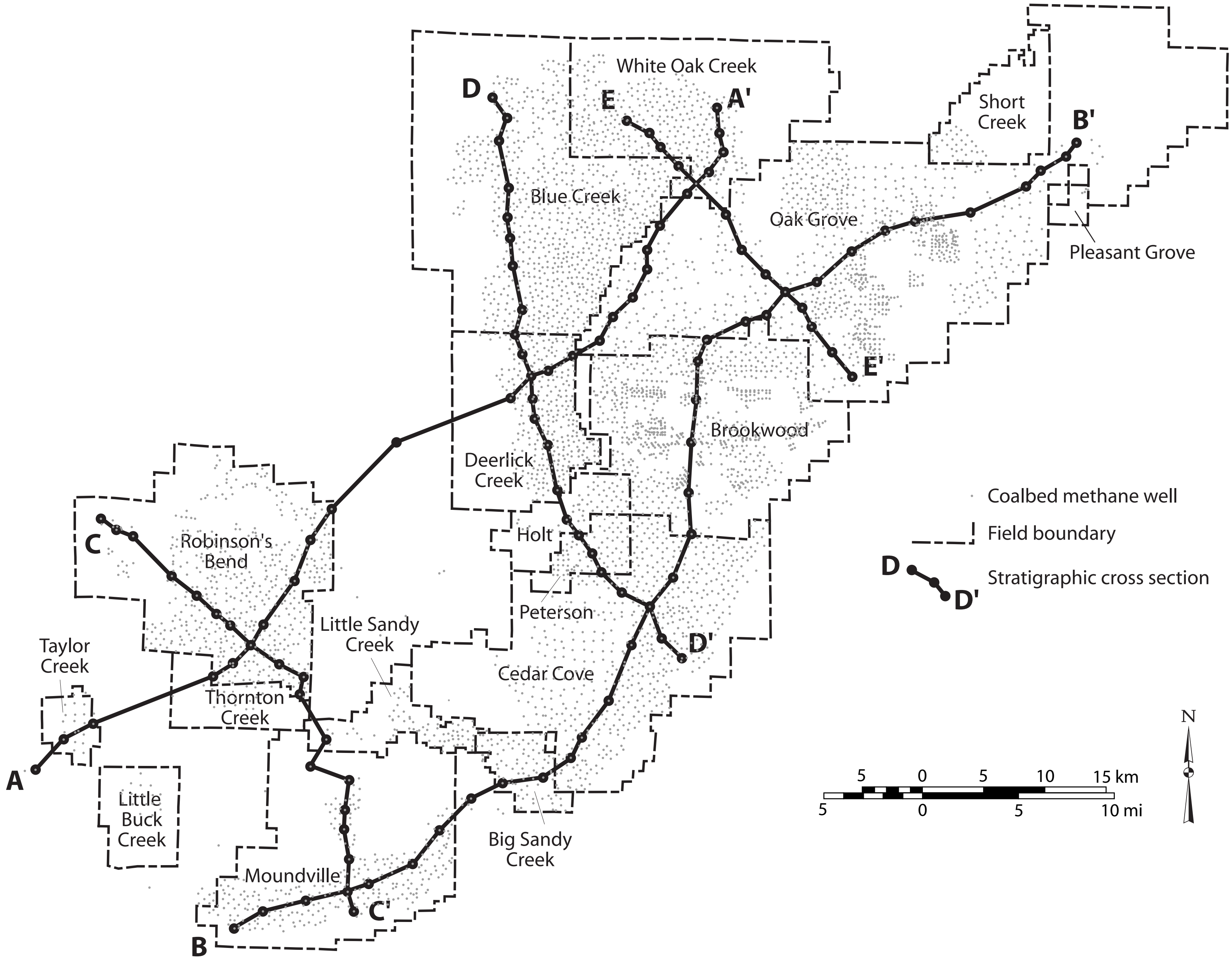



Figure 2.--Well control in the Black Warrior coalbed methane fairway and locations of stratigraphic cross sections (plates 1-10).

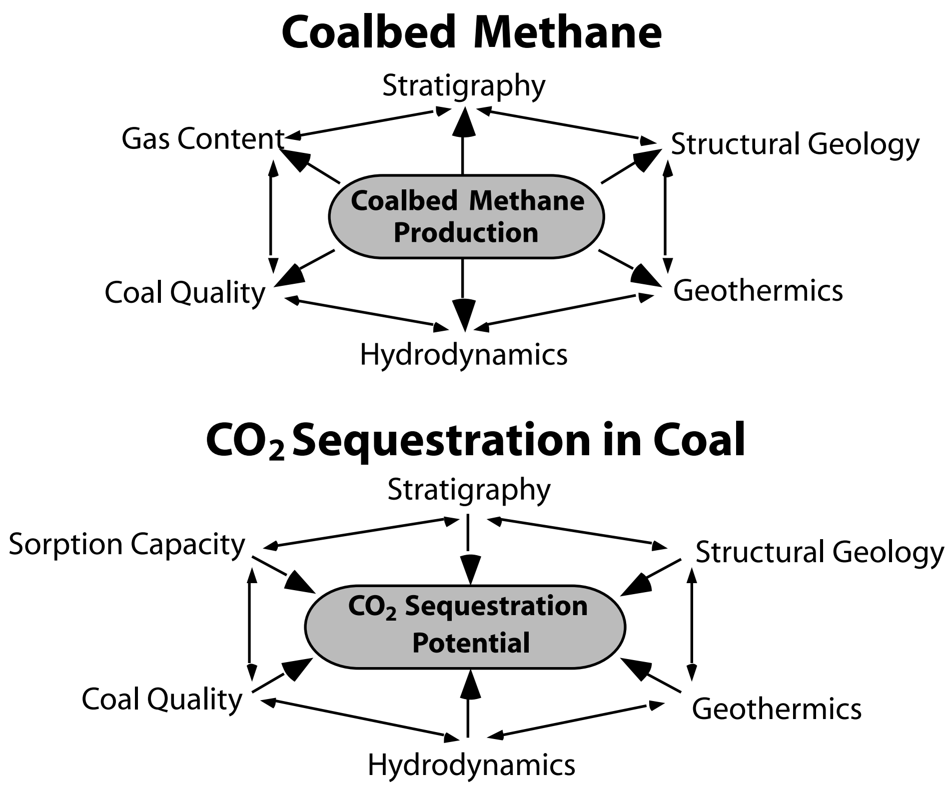



Figure 3.--Geologic factors affecting coalbed methane production and carbon sequestration in coal (modified from Pashin and others, 2001a, b).

# EXECUTIVE SUMMARY

Sequestration of $CO_2$ 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.

Coalbed methane reservoirs in the upper Pottsville Formation of the Black Warrior basin are extremely heterogeneous, and this heterogeneity must be considered to screen areas for the application of $CO_2$ sequestration and enhanced coalbed methane recovery technology. Major screening factors include stratigraphy, geologic structure, geothermics, hydrogeology, coal quality, sorption capacity, technology, and infrastructure. Applying the screening model to the Black Warrior basin indicates that geologic structure, water chemistry, and the distribution of coal mines and reserves are the principal determinants of where $CO_2$ can be sequestered. By comparison, coal thickness, temperature-pressure conditions, and coal quality are the key determinants of sequestration capacity and the quantity of coalbed methane that can be accessed through enhanced recovery operations.

Upper Pottsville coal beds are preserved in a series of flooding-surface-bounded depositional cycles of fluvial-deltaic origin that span 1,500 to more than 4,000 feet of section. More than 20 coal beds have been completed in some wells. Coal beds as thin as 1 foot are commonly

completed, and net completable coal thickness ranges from about 10 to more than 70 feet. Because coal and coalbed methane resources are dispersed widely through a thick section, multiple zone technology will need to be developed and applied to realize the potential of upper Pottsville strata for $CO_2$ sequestration and enhanced coalbed methane recovery.

Compressional folds and extensional faults are abundant in the Black Warrior basin, and these structures have a significant effect on the production performance of coalbed methane wells. Normal faults are major reservoir discontinuities, and trans-stratal fracture systems associated with these faults pose potential leakage risks. Therefore, $CO_2$ sequestration and enhanced recovery operations should avoid fault zones. Strata-bound joint and cleat systems are developed between the fault zones, and these fracture systems tend to favor the development of reservoir compartments around individual coal zones that favor bed-parallel flow over cross-formational flow.

Permeability, water chemistry, and temperature-pressure conditions are the key hydrologic and geothermal variables to be considered when screening coalbed methane reservoirs. Permeability-depth relationships in the Pottsville Formation favor sequestration and enhanced recovery efforts in coal shallower than 2,000 feet. Water chemistry is a fundamental control on where sequestration technology can be applied because of UIC regulations. Fresh-water plumes along the southeast margin of the Black Warrior basin contain water with TDS content less than 3,000 mg/L, and current UIC regulations prohibit underground injection into water that fresh. Most of the coalbed methane fields contain water with 3,000 to 10,000 mg/L TDS, and an aquifer exception can be obtained to facilitate enhanced hydrocarbon recovery programs (Class II UIC). Water with TDS content higher than 10,000 mg/L is common in some of the southwestern coalbed methane fields, and in these areas, $CO_2$ can be injected into coal without enhanced hydrocarbon recovery (Class I UIC).

Coalbed methane reservoirs  in the Black Warrior basin are normally pressured to underpressured, and geothermal gradients are generally between 8 and 15°F per 1,000 feet. Temperature correlates negatively and significantly with the sorption capacity of coal and must therefore be considered in regional estimates of sequestration capacity. Reservoir pressure has been depleted by prolonged dewatering associated with coalbed methane production. Beyond a depth of 2,480 feet, $CO_2$ will become a supercritical fluid if the reservoir returns to a normal hydrostatic pressure gradient. Supercritical $CO_2$ can weaken and react with coal, and rapid volumetric changes at the critical point raise some concerns about reservoir integrity and wellbore integrity. However, coal has stored supercritical $CO_2$ under natural conditions over geologic time.

The most important coal quality parameters determining how much gas can be stored in coal are ash content and rank. Ash content correlates negatively with sorption capacity, but the utility of ash content for regional assessment of sequestration and enhanced recovery potential is limited because ash data are too variable to predict between data points. Coal rank correlates highly with gas sorption capacity and is a regionalized variable that can be projected between data points with confidence. For these reasons, rank and reservoir temperature are key variables required to quantify the sequestration potential of coalbed methane reservoirs in the Black Warrior basin.

The sorption capacity per unit weight of coal in the Black Warrior coalbed methane fairway is influenced strongly by rank and reservoir temperature, whereas the sorption capacity per unit area of coal in the upper Pottsville Formation is influenced strongly by coal thickness. At 100 to

350 psi, upper Pottsville coal can adsorb between 250 and 700 scf/t and between 5 to 80 MMcf/ac of $CO_2$ on an as-received basis. Estimated at a modest pressure of 50 psi, unswept coalbed methane resources range from 40 to 100 scf/t and 1 to 7 MMcf/ac.

Numerous technological and infrastructural variables must be examined to screen areas for $CO_2$ sequestration and enhanced coalbed methane recovery. Critical variables for the Black Warrior coalbed methane fairway include proximity to coal-fired power plants, the design and maturity of coalbed methane fields, and pipeline infrastructure. Identifying the locations of underground coal mines, coal reserves, unplugged core holes, and communities are also important components of a screening strategy. Two coal-fired power plants are at the northern margin of the coalbed methane fairway, and a new plant is planned for the central part of the fairway. Most of the fairway is reaching maturity, although infill drilling and recompletion programs in some fields limit where demonstration and enhanced recovery programs should be sited. Coal mines and coal reserves are scattered through the northern part of the coalbed methane fairway and should be protected from sequestration activities.

Coal-fired power plants serving the Black Warrior basin in Alabama emit approximately 31 MMst (2.4 Tcf) of $CO_2$ annually. The total sequestration capacity of the Black Warrior coalbed methane fairway at 350 psi is about 189 MMst (14.9 Tcf), which is equivalent to 6.1 years of greenhouse gas emissions from the coal-fired power plants. Applying the geologic screening model indicates that significant parts of the coalbed methane fairway are not accessible because of fault zones, coal mines, coal reserves, and formation water with TDS content less than 3,000 mg/L. Excluding these areas leaves a sequestration potential of 60 MMst (4.7 Tcf), which is equivalent to 1.9 years of emissions. Therefore, if  about10 percent of the flue gas stream from nearby power plants is dedicated to enhanced coalbed methane recovery, a meaningful reduction of $CO_2$ emissions can be realized for nearly two decades. If the fresh-water restriction were removed for the purposes of $CO_2$ sequestration, an additional 10 MMst (0.9 Tcf) of $CO_2$ could feasibly be sequestered. The amount of unswept coalbed methane in the fairway is estimated to be 1.49 Tcf at a pressure of 50 psi. Applying the screening model results in an accessible unswept gas resource of 0.44 Tcf. Removal of the fresh-water restriction would elevate this number to 0.57 Tcf. If a recovery factor of 80 percent can be realized, then enhanced recovery activities can result in an 18 percent expansion of coalbed methane reserves in the Black Warrior basin.

Results of this investigation indicate that the potential for $CO_2$ sequestration and enhanced coalbed methane recovery in the Black Warrior basin is substantial and can result in significant reduction of greenhouse gas emissions while increasing natural gas reserves. Application of the geologic screening model to the Black Warrior coalbed methane fairway indicates that sequestration and enhanced recovery operations are possible in nearly all coalbed methane fields, and the only areas that appear to be technically infeasible within those fields are areas with coal reserves and fault systems. Future work should focus on the development and implementation of demonstration programs that focus on determination of optimal $CO_2$ injection rates, quantification of sequestration and enhanced gas recovery efficiency, and monitoring and verification of sequestration activities.

# 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 those reported in geophysical well logs. 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 ($CO_2$), methane ($CH_4$) and nitrogen ($N_2$) were run on coal samples from the coalbed methane fairway. Gas- and water-production data were derived from the databases of the State Oil and Gas Board of Alabama. Sorption data and other geologic information were used to calculate the $CO_2$ sequestration capacity of the coalbed methane reservoirs and to quantify the amount of unswept methane remaining in the reservoirs. Finally, a conceptual geologic screening model was formulated and applied to the Black Warrior basin to prioritize areas for the application and commercialization of sequestration technology.

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 5,052 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 were determined and recorded for each fault cut identified. 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, and a net coal isolith map of the Black Creek through Brookwood coal zones was made using a contour interval of 10 feet. 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 were constructed. Modeling faults is the most time-consuming aspect of well-based 3-D structural interpretation because most faults are undersampled. Model construction began by importing and contouring a cycle boundary. Next, fault cuts were imported, and preliminary fault cut correlations were made based on trend. Where three or more fault cuts could be assigned to the same fault, the fault surface was contoured and extrapolated from just above the ground surface to an elevation of –3,000 ft. The lateral extent of the fault was 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 were available for a fault, a plane of strike, dip, and extent consistent with fault relationships in the area was constructed and inserted into the model.

Locations of faulted wells, elevation changes of the cycle tops, and anomalous cycle thickness changes were all used to find and project faults. Coal-zone thickness is generally consistent within a township, and local thickness anomalies generally indicate fault cuts. Once a fault plane was placed into the interpretation, the map of the cycle boundary was cut along the fault trace so that it was no longer continuous across the fault. The cycle top was then extrapolated into a new intersection with the fault plane. A projection tool was used to project the cycle top to the fault plane in 3DMove, and the model typically had to be conditioned so that only one side at a time will be projected. Bedding cutoff lines were grouped with the other points on the cycle top, and the surface was recontoured to form horizons that join seamlessly with the fault. The contoured cycle surface was then adjusted to ensure agreement with the stratigraphic separations recorded in well logs. This process was repeated for every cycle top and for every fault to build the interpretation. The final stage of interpretation was to make numerous cross sections and check that all cycle variations are geologically realistic, again adjusting the interpretation if required.

Geothermic and hydrologic information required to determine temperature-pressure conditions in the coalbed methane fairway were obtained from geophysical well logs and were 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 calculated by dividing the difference between average near-surface 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 bottom-hole temperature values in Cambrian-Mississippian carbonate rocks are inconsistent with geothermal gradients within the 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 each 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 each 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 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

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 |

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.

The potential for $CO_2$ sequestration and enhanced coalbed methane recovery in the Black Warrior basin was estimated using basic grid-math techniques in Isomap. Sorption-rank correlations were used to grid the capacity of coal to hold $CO_2$, $CH_4$, and $N_2$ in scf/t (standard cubic feet per ton) at a temperature of 80°F and pressures of 50, 100, and 350 psi. Next, sorption-temperature correlations were used to make a grid that can be used to correct sorption capacity for reservoir temperature. The tonnage of coal for each coal zone was then calculated by multiplying grids of coal thickness by 1,800 short tons per foot per acre to derive short tons per acre following the procedures for used estimating bituminous coal resources in the Black Warrior basin (Ward, 1984). Next, total sorption capacity in scf/ac (standard cubic feet per acre) was calculated for each gas in each coal zone at 50, 100, and 350 psi by multiplying the appropriate coal tonnage, sorption capacity, and temperature correction grids. The total gas capacity of the upper Pottsville Formation at these pressures was then calculated in scf/ac by adding the total sorption capacity grids for each coal zone.

A screening model was developed to help identify and prioritize areas for the demonstration and commercialization of $CO_2$ sequestration technology. The screening model was developed as a procedural workflow in which stratigraphy, geologic structure, geothermics, coal quality, sorption capacity, production performance, and regional infrastructure are evaluated systematically to identify areas that are favorable for $CO_2$ sequestration. The screening model was then applied to the Pottsville Formation to pinpoint priority areas and to refine estimates of sequestration capacity and enhanced recovery potential, and our intention was to develop a general workflow that could be applied to other coal basins.

# 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 1.5 Tcf, and more than 4,000 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 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).

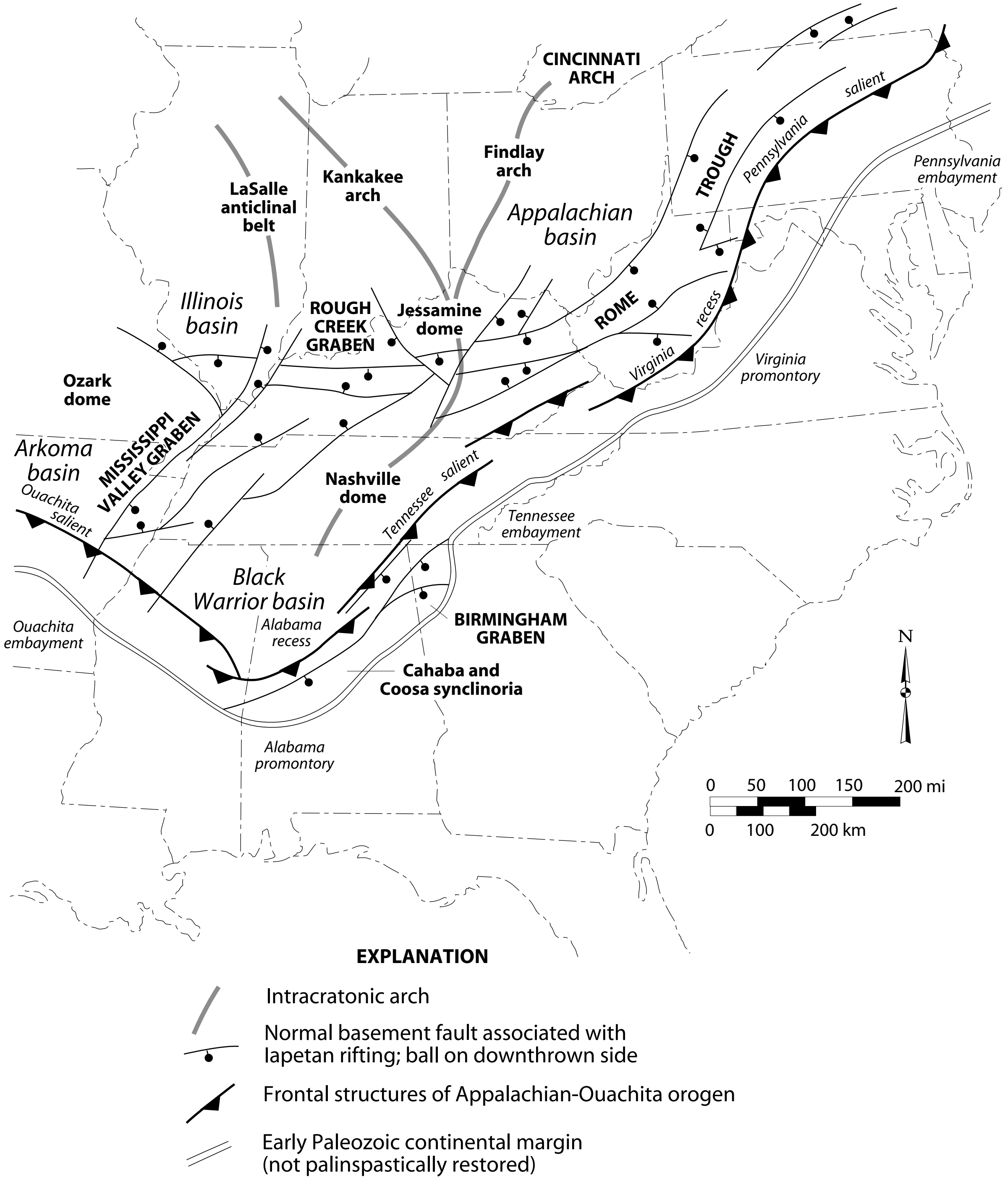



Figure 4.--Tectonic setting of the Black Warrior basin (modified from Thomas, 1988).

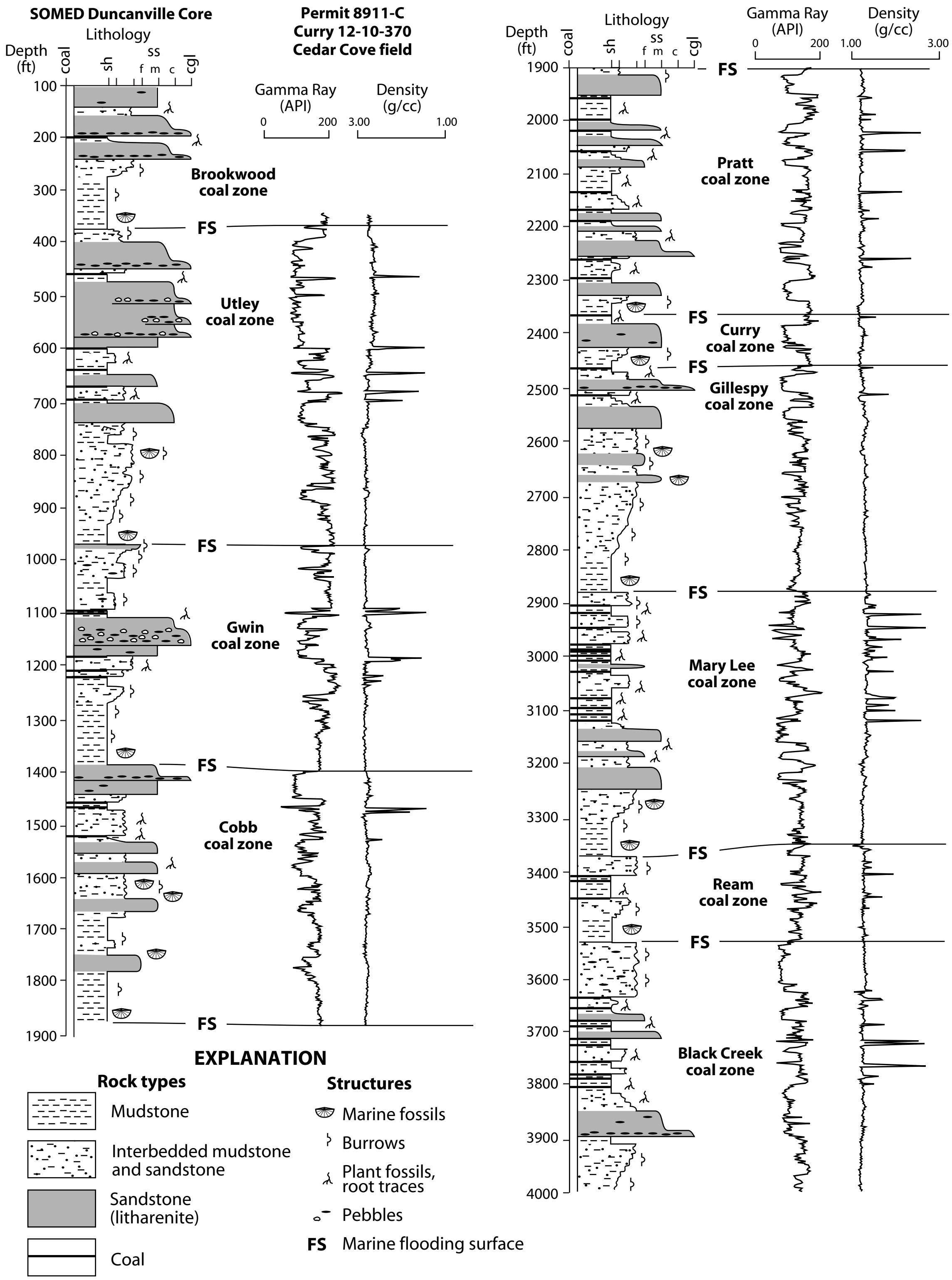



Figure 5.--Core log and geophysical well log of the Pottsville Coal Interval in Cedar Cove Field (modified from Pashin and Hinkle, 1997).

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 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

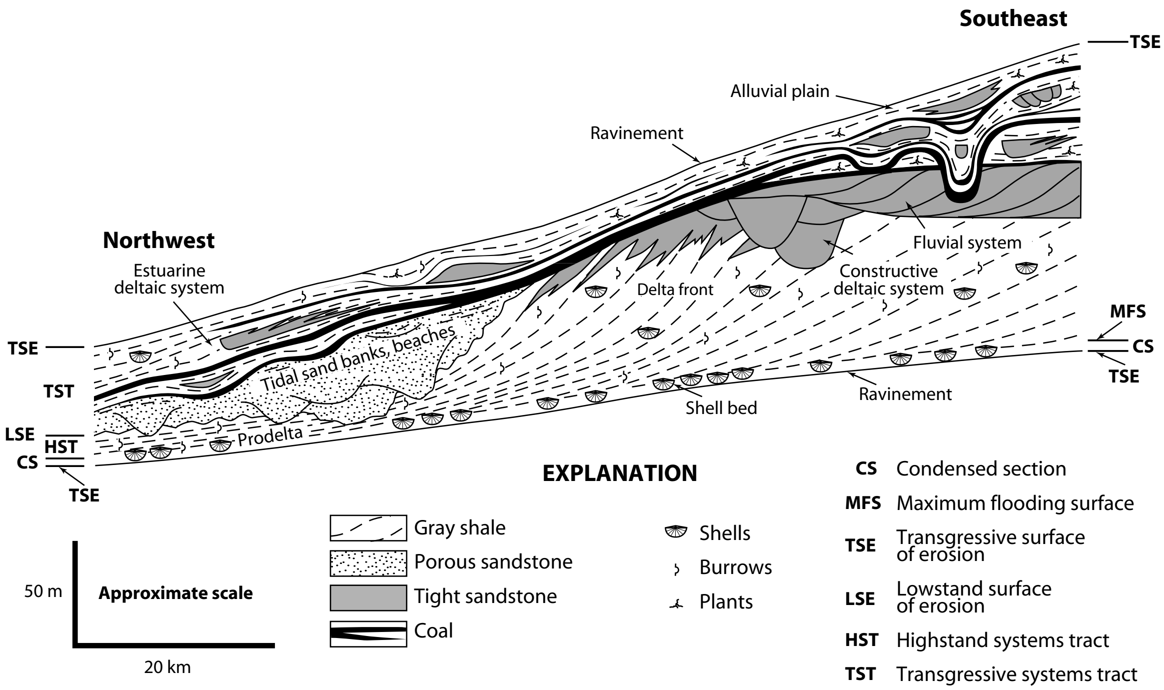



Figure 6.--Idealized depositional cycle in the Pottsville Formation, Black Warrior basin, Alabama (modified from Pashin, 1994b, 1998).

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; 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,

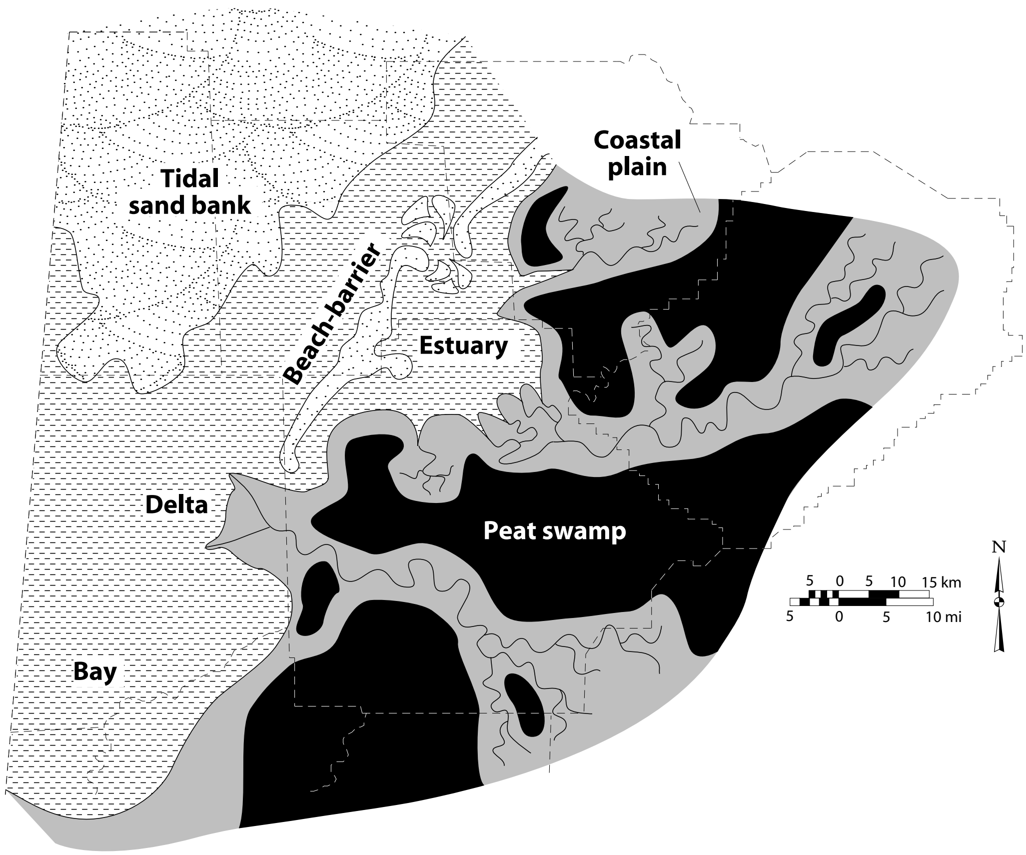



Figure 7.--Generalized paleogeography of the Pottsville Formation in the Black Warrior basin of Alabama (modified from Pashin and others, 1991).

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 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).

## 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

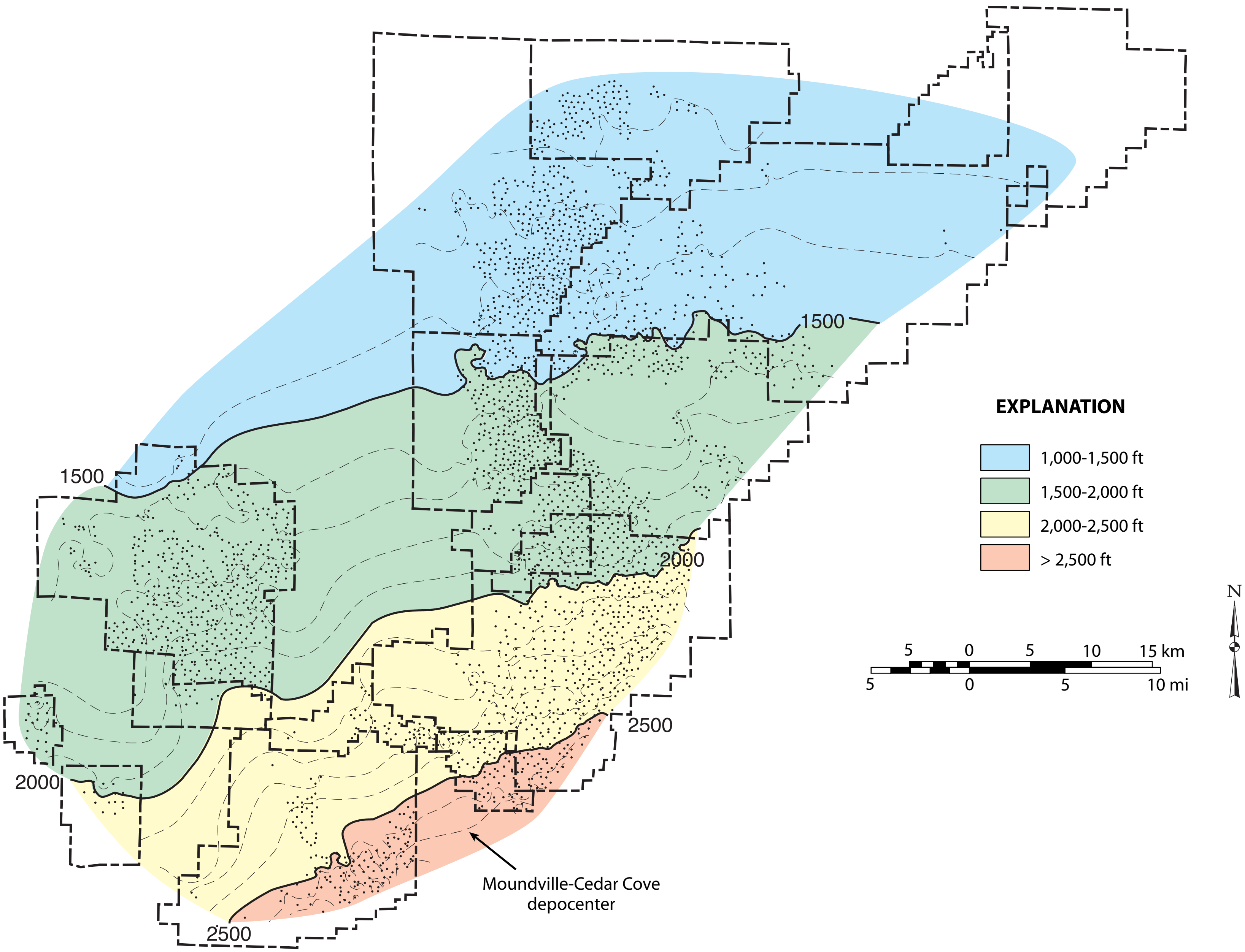



Figure 8.--Isopach map of the Ream through Gwin coal zones in the Black Warrior coalbed methane fairway.

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, 1994c). 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 19th 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 adjacent 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 associated with coal (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 the upper Pottsville Formation and in each upper Pottsville coal zone. Net coal thickness in the Black Creek through Brookwood coal zones increases toward the southeast (fig. 9). Less than 10 feet of coal is present in parts of White Oak Creek, Robinson’s Bend, and Taylor Creek fields. Net coal thickness exceeds 40 feet in much of the Moundville-Cedar Cove depocenter, and in parts of Moundville Field, net coal thickness is greater than 70 feet.

In the Black Creek coal zone, beds thicker than 1 foot are present throughout nearly the entire coalbed methane fairway (fig. 10), 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

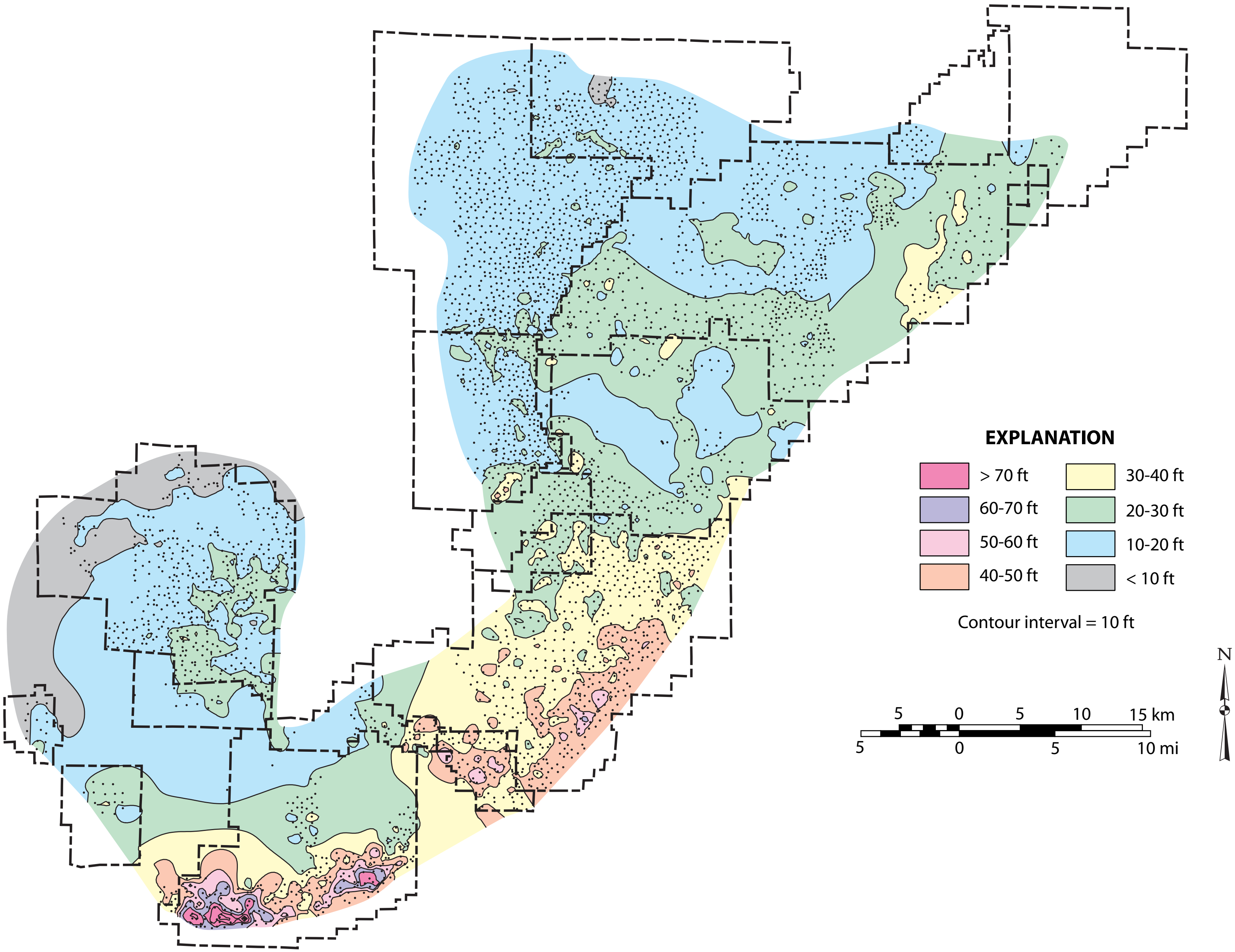



Figure 9.--Net coal isolith of upper Pottsville Formation in the Black Warrior coalbed methane fairway.

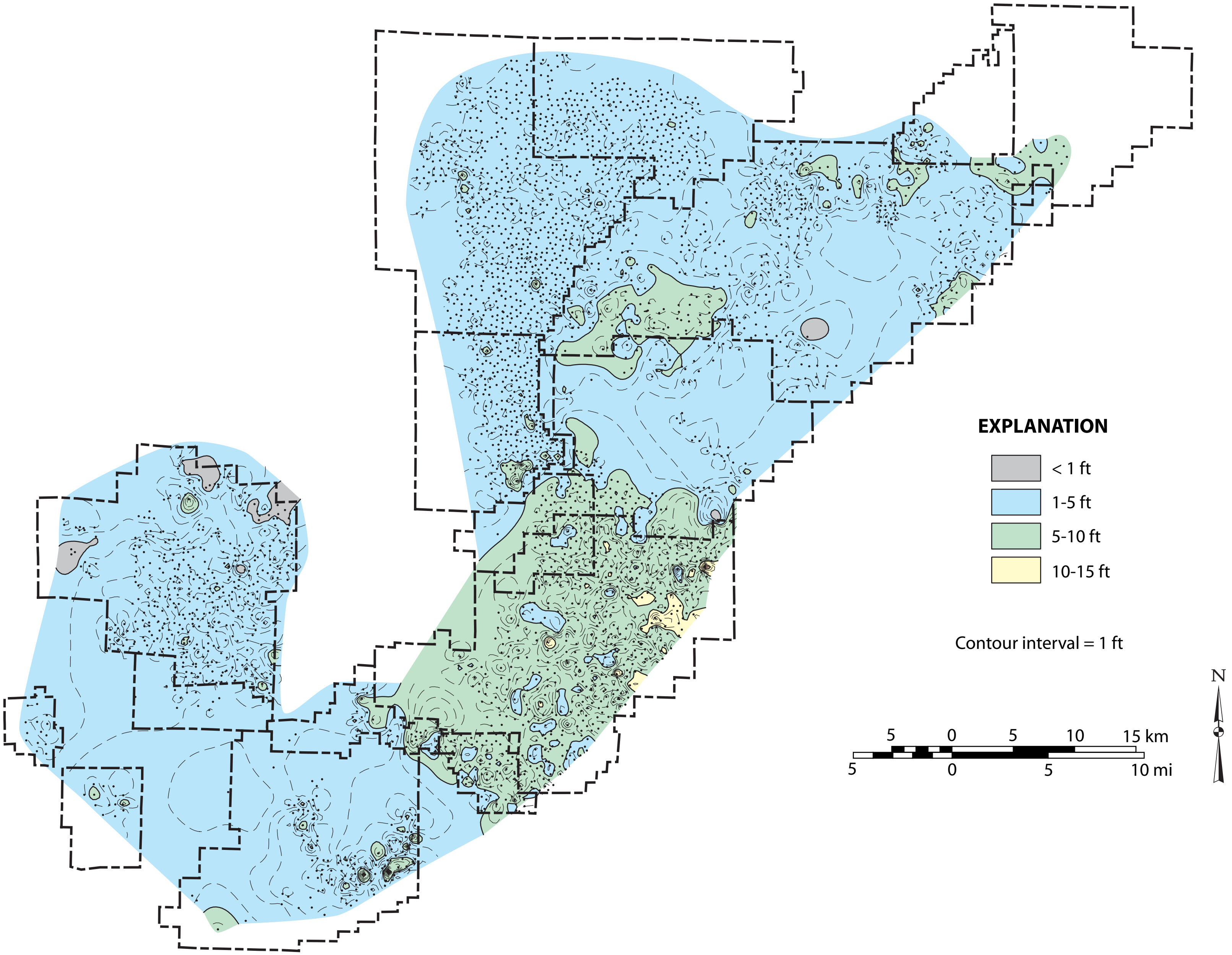



Figure 10.--Net coal isolith of the Black Creek coal zone in the Black Warrior coalbed methane fairway.

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. 11). 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. 12). 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 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

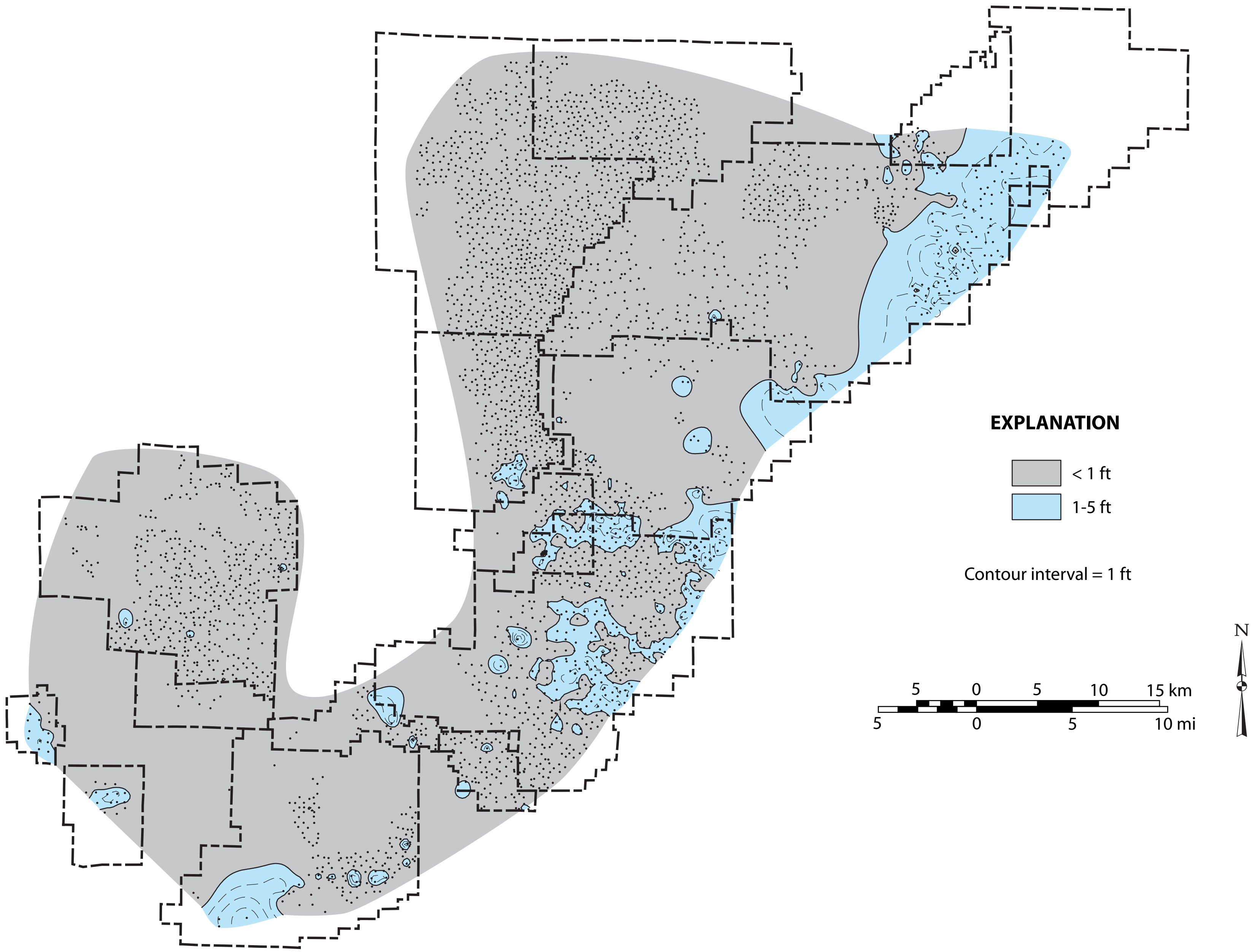



Figure 11.--Net coal isolith of the Ream coal zone in the Black Warrior coalbed methane fairway.

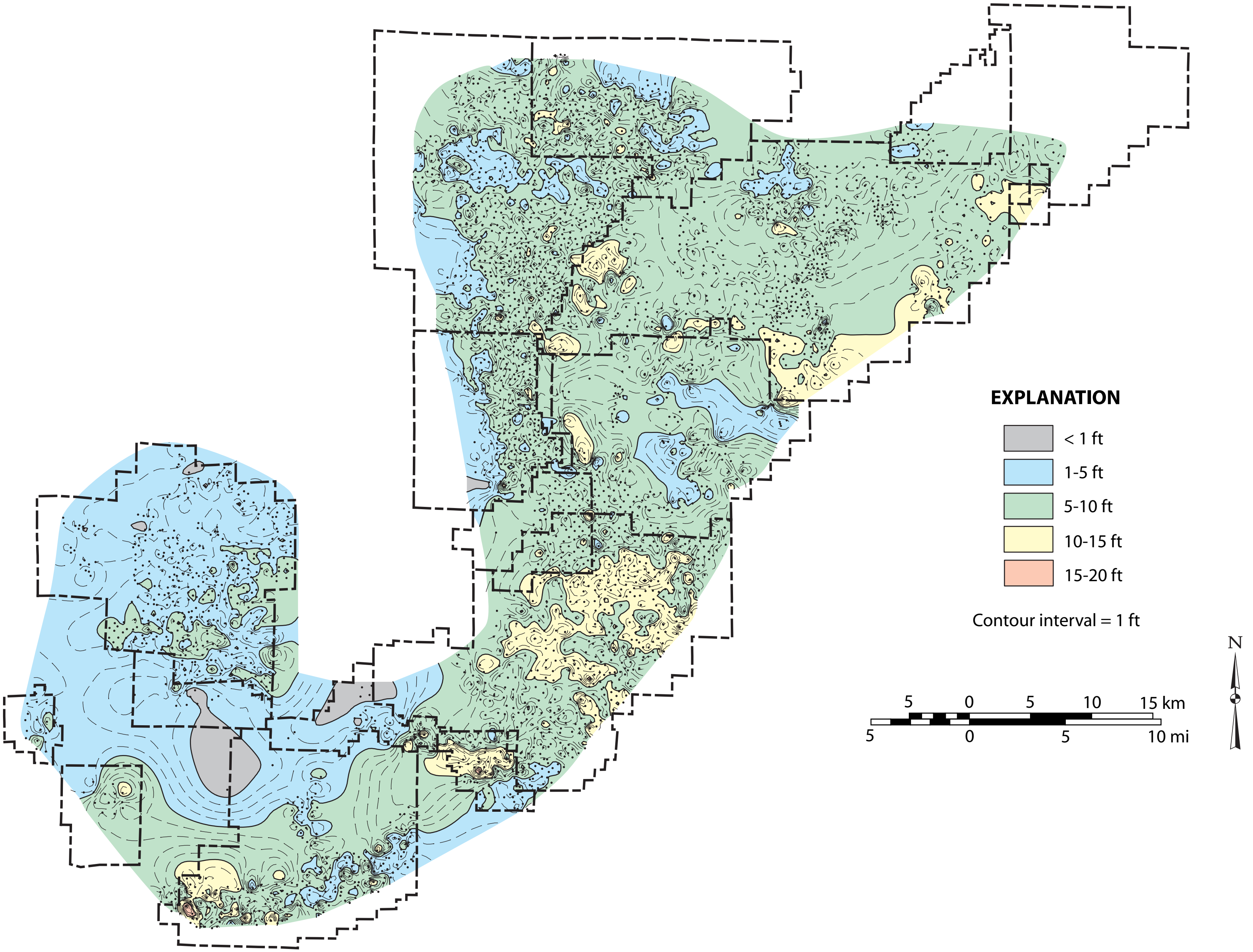



Figure 12.--Net coal isolith of the Mary Lee coal zone in the Black Warrior coalbed methane fairway.

coalbed methane fairway (figs. 13, 14). 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. 13). 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. 14).

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. 15). 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).

As in most other coal zones, net coal thickness in the Cobb zone increases southeastward (fig. 16). 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. 17). 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

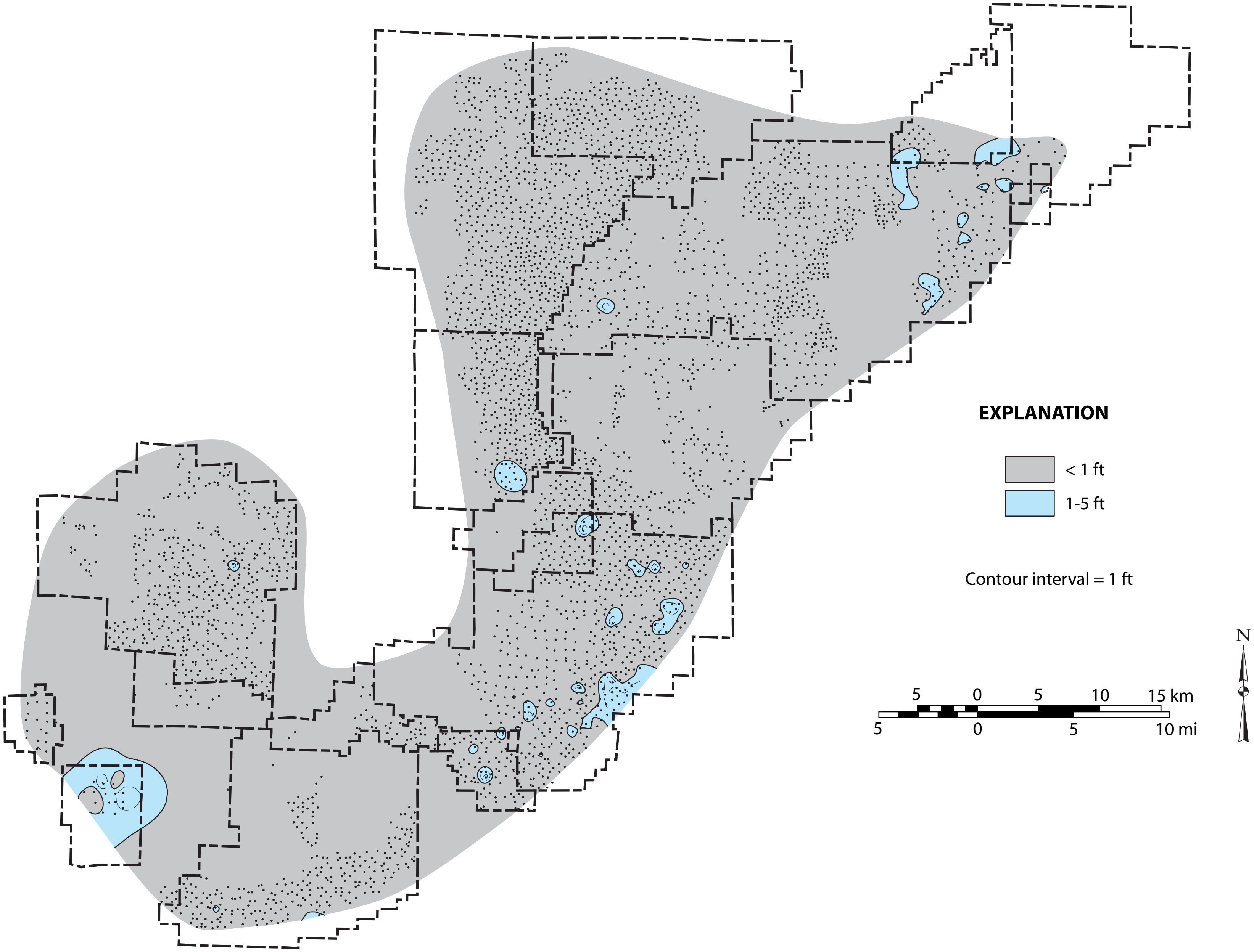



Figure 13.--Net coal isolith of the Gillespy coal zone in the Black Warrior coalbed methane fairway.

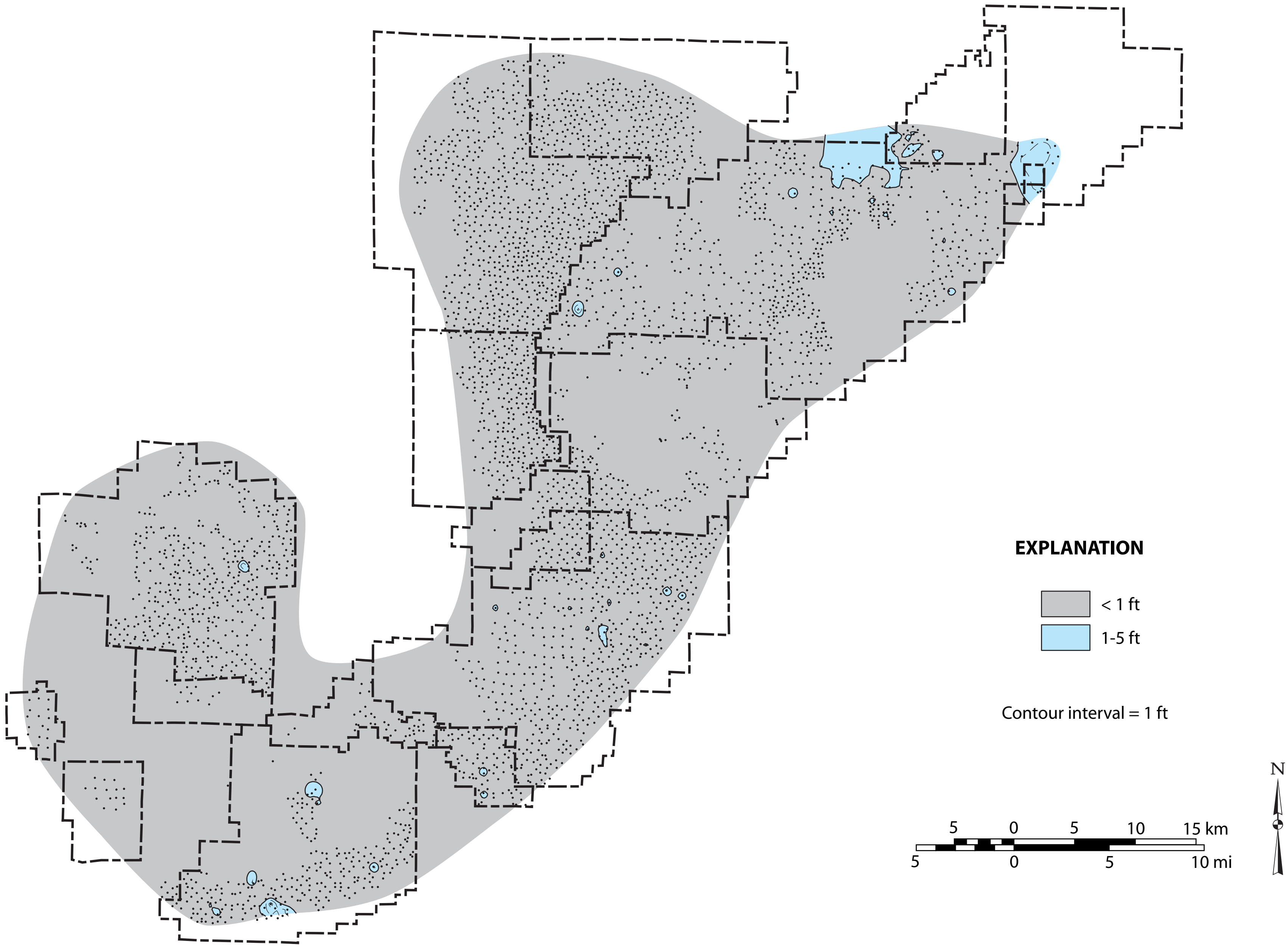



Figure 14.--Net coal isolith of the Curry coal zone in the Black Warrior coalbed methane fairway.

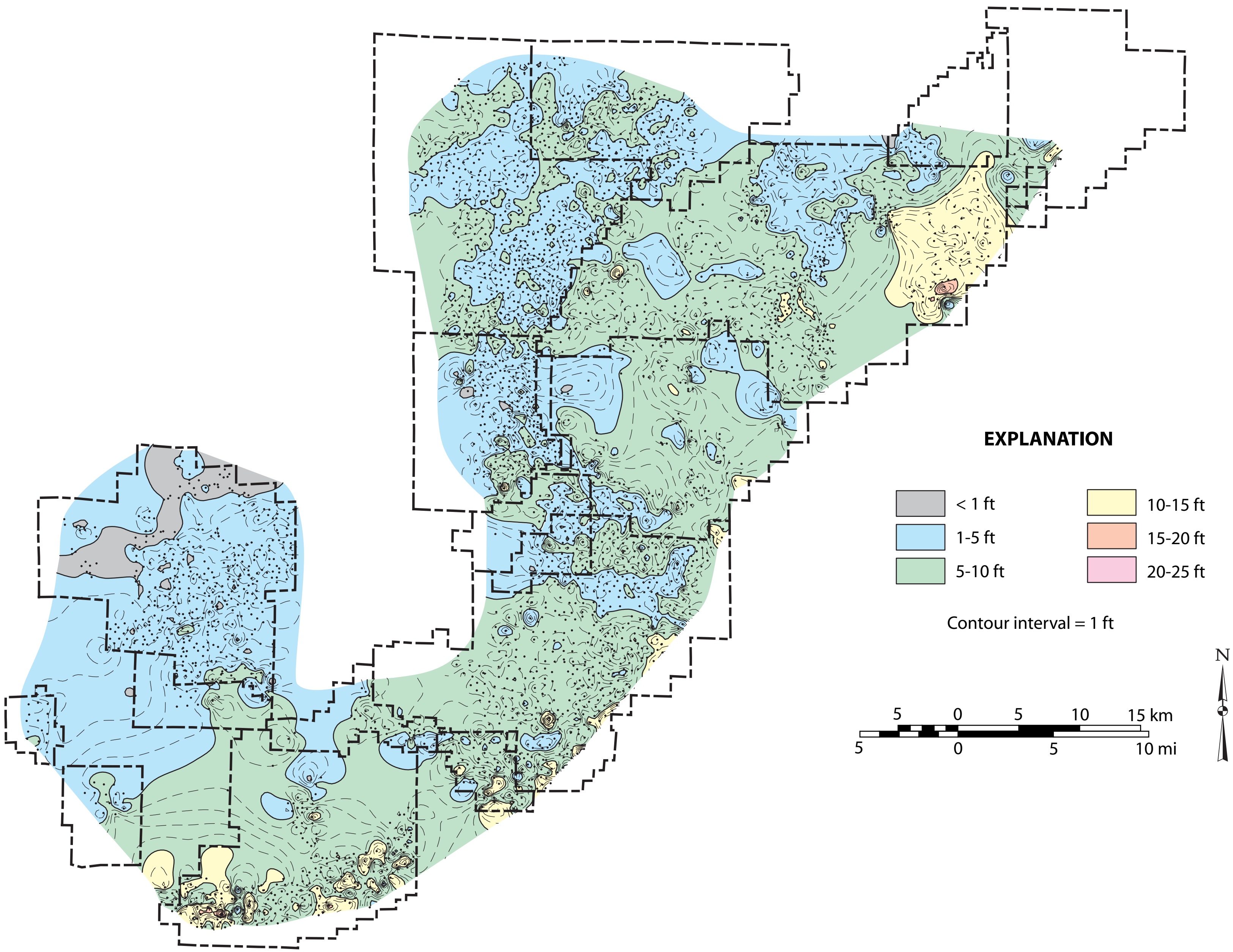



Figure 15.--Net coal isolith of the Pratt coal zone in the Black Warrior coalbed methane fairway.

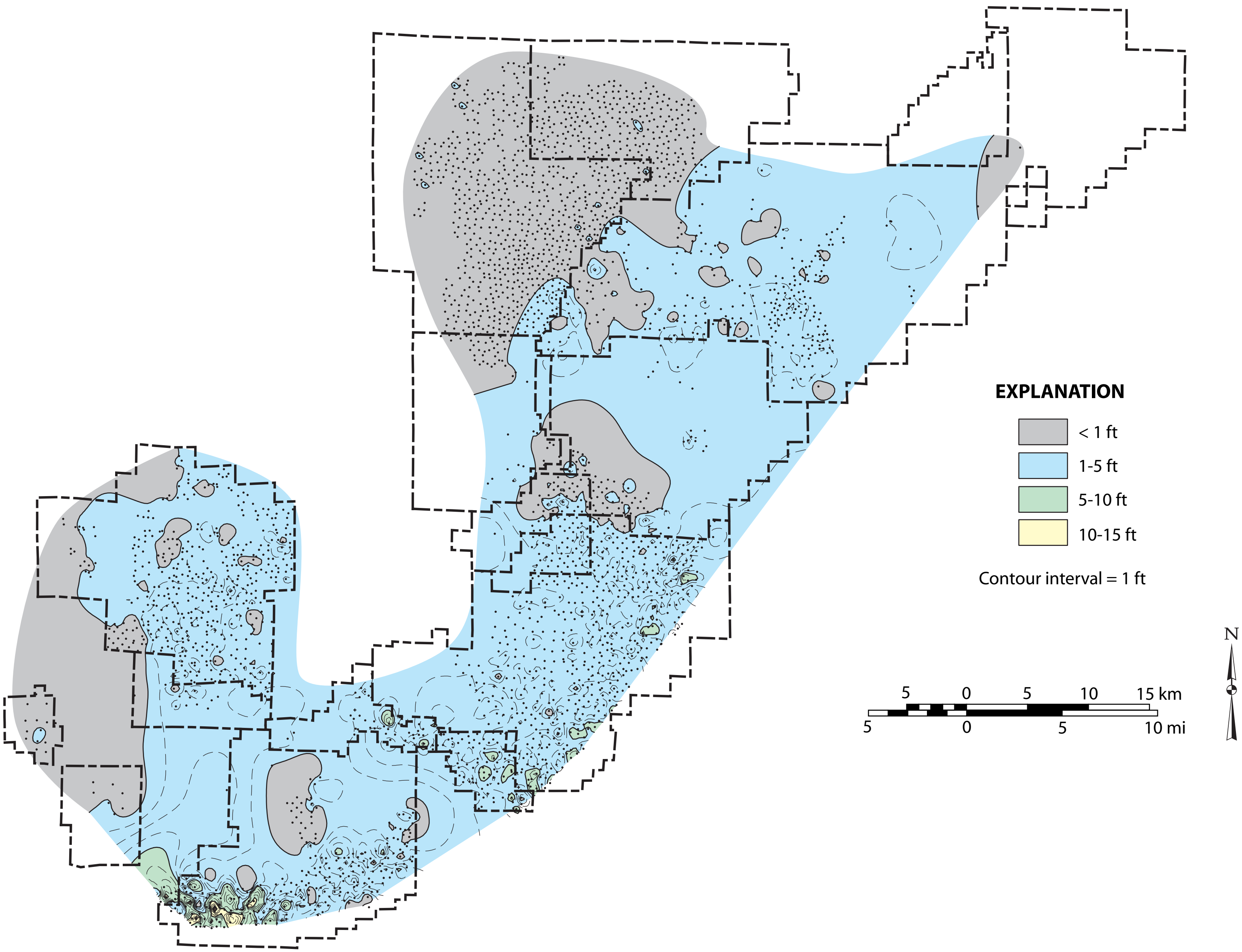



Figure 16.--Net coal isolith of the Cobb coal zone in the Black Warrior coalbed methane fairway.

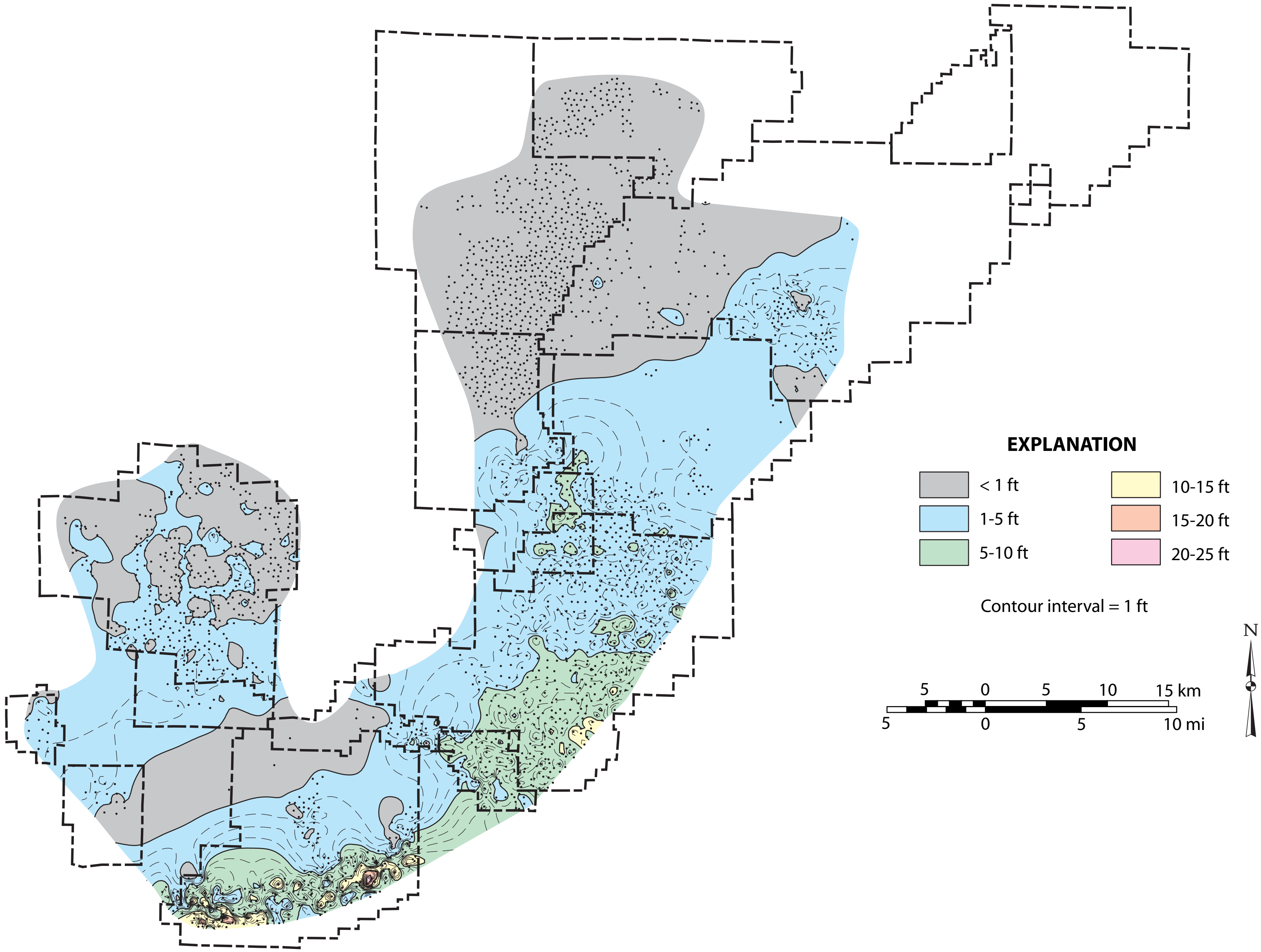



Figure 17.--Net coal isolith of the Gwin coal zone in the Black Warrior coalbed methane fairway.

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. 18). 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. 19). 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 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

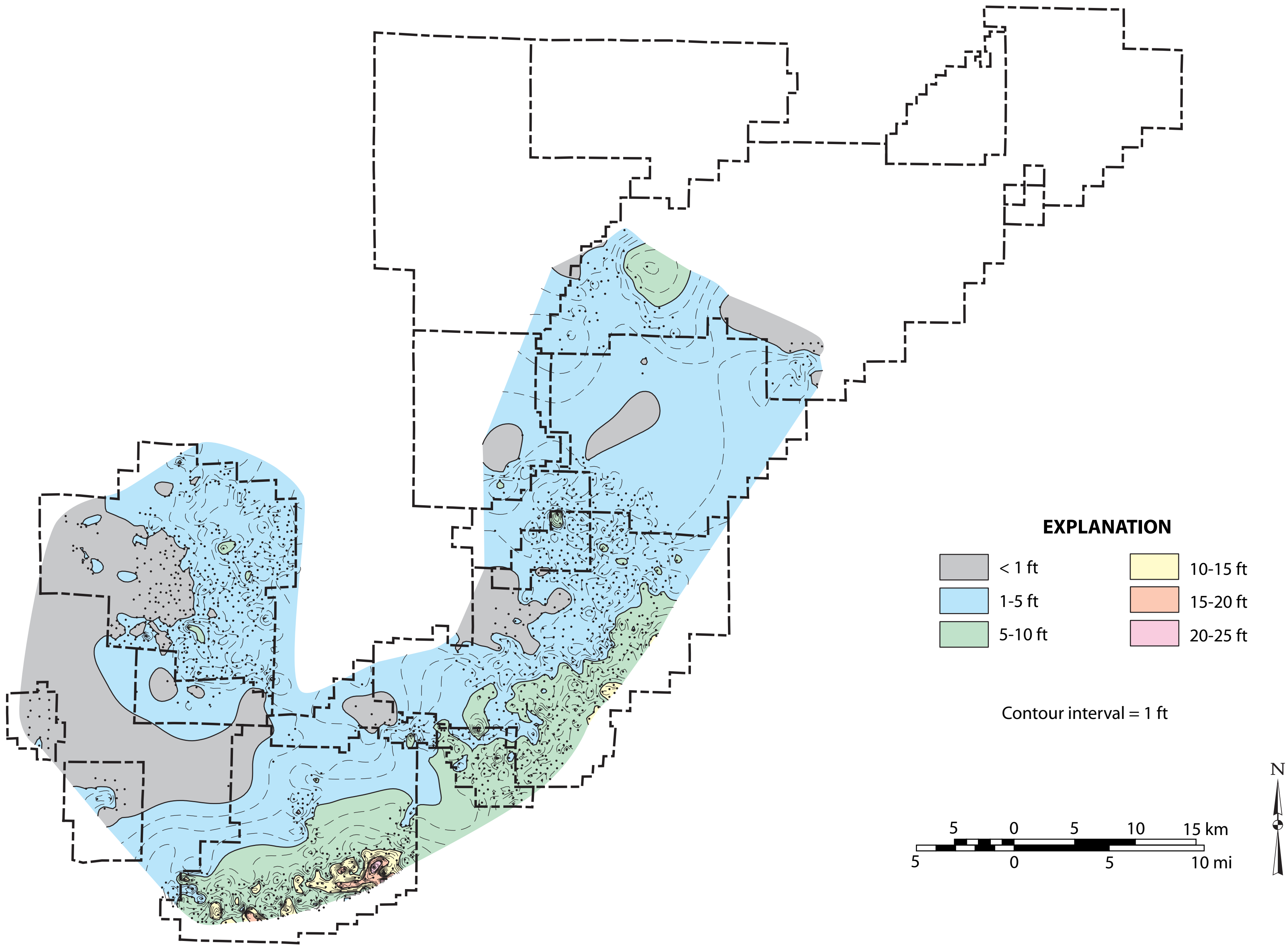



Figure 18.--Net coal isolith of the Utley coal zone in the Black Warrior coalbed methane fairway.

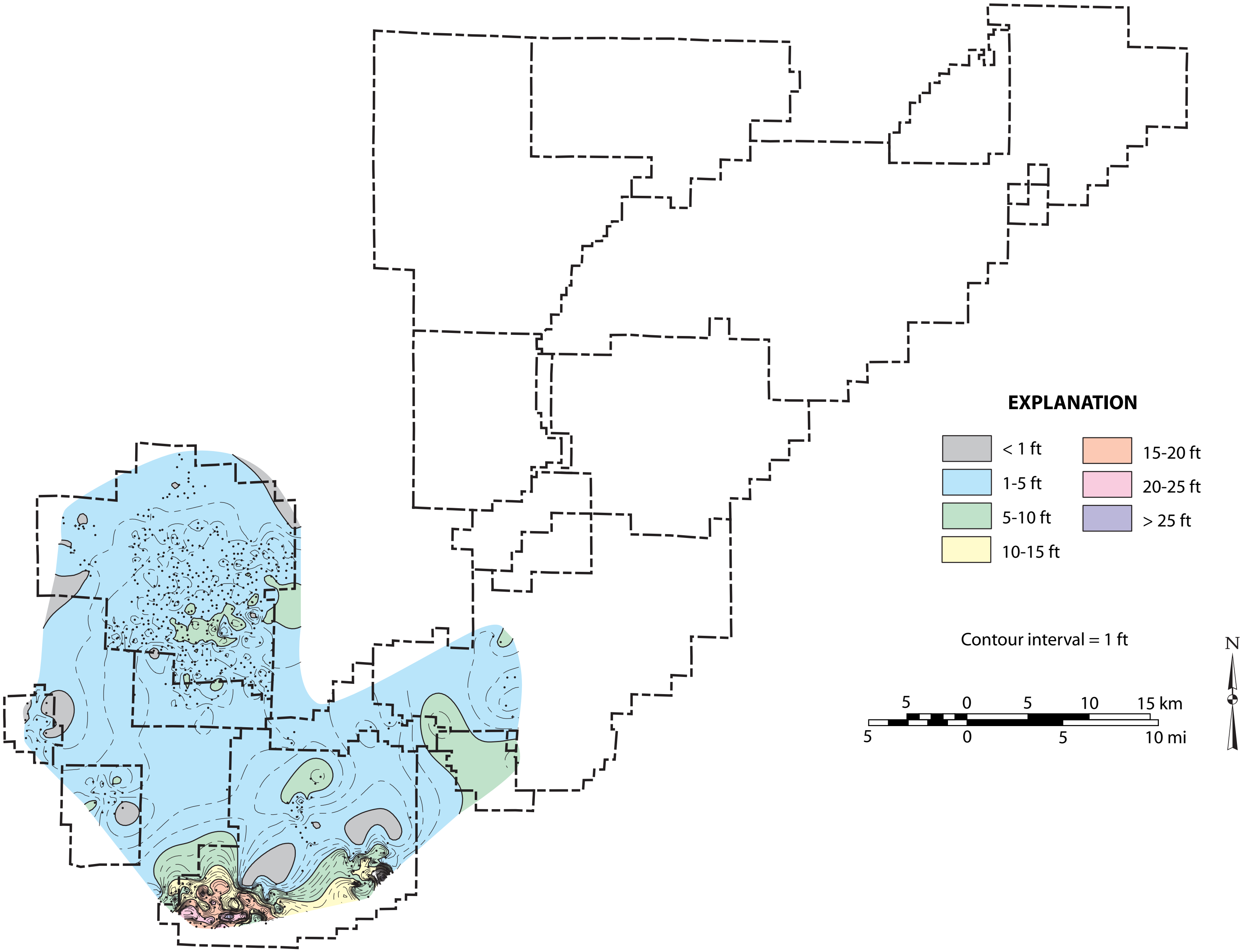



Figure 19.--Net coal isolith of the Brookwood coal zone in the Black Warrior coalbed methane fairway.

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. 10-19; 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, 20; 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. 20). 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 $4^{th}$-order changes of relative

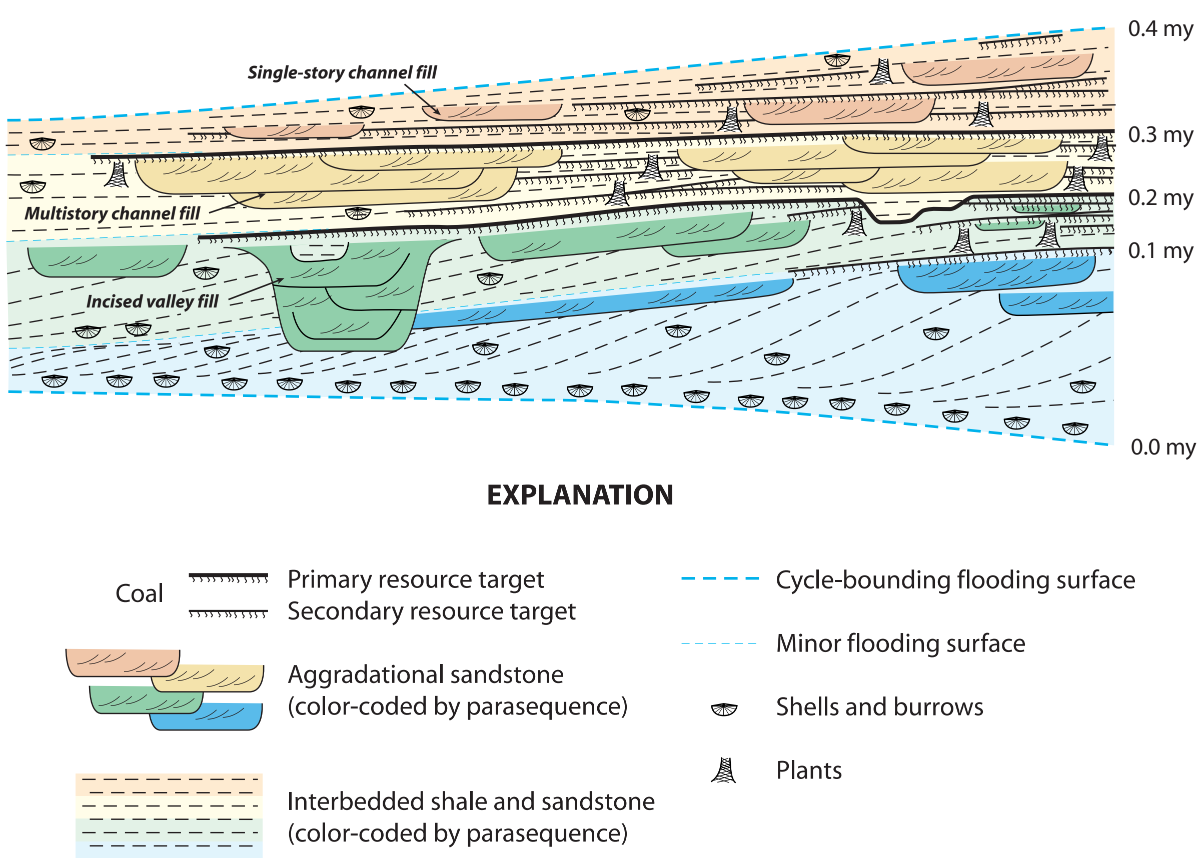



Figure 20.--Generalized stratigraphic model of a Pottsville coal zone in the Black Warrior coalbed methane fairway. No scale intended.

sea level driven by the long eccentricity cycle (~0.4 my), then each subordinate parasequence can be interpreted as the product of 5$^{th}$-order sea-level changes driven by the short eccentricity cycle (~0.1 my) (fig. 20). 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.

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. 20). 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, 20). 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. 20). Incised valley fill and braidplain sandstone bodies are common in Pennsylvanian strata of the Appalachian region and are thought to record lowstands associated with $3^{rd}$- and $4^{th}$-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 $5^{th}$-order sea-level changes and that development of individual sandstone stories was a response to even higher frequency stratigraphic processes (fig. 20).

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. 20). 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. 20).

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. 21, 22). 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 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° (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. 21). 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

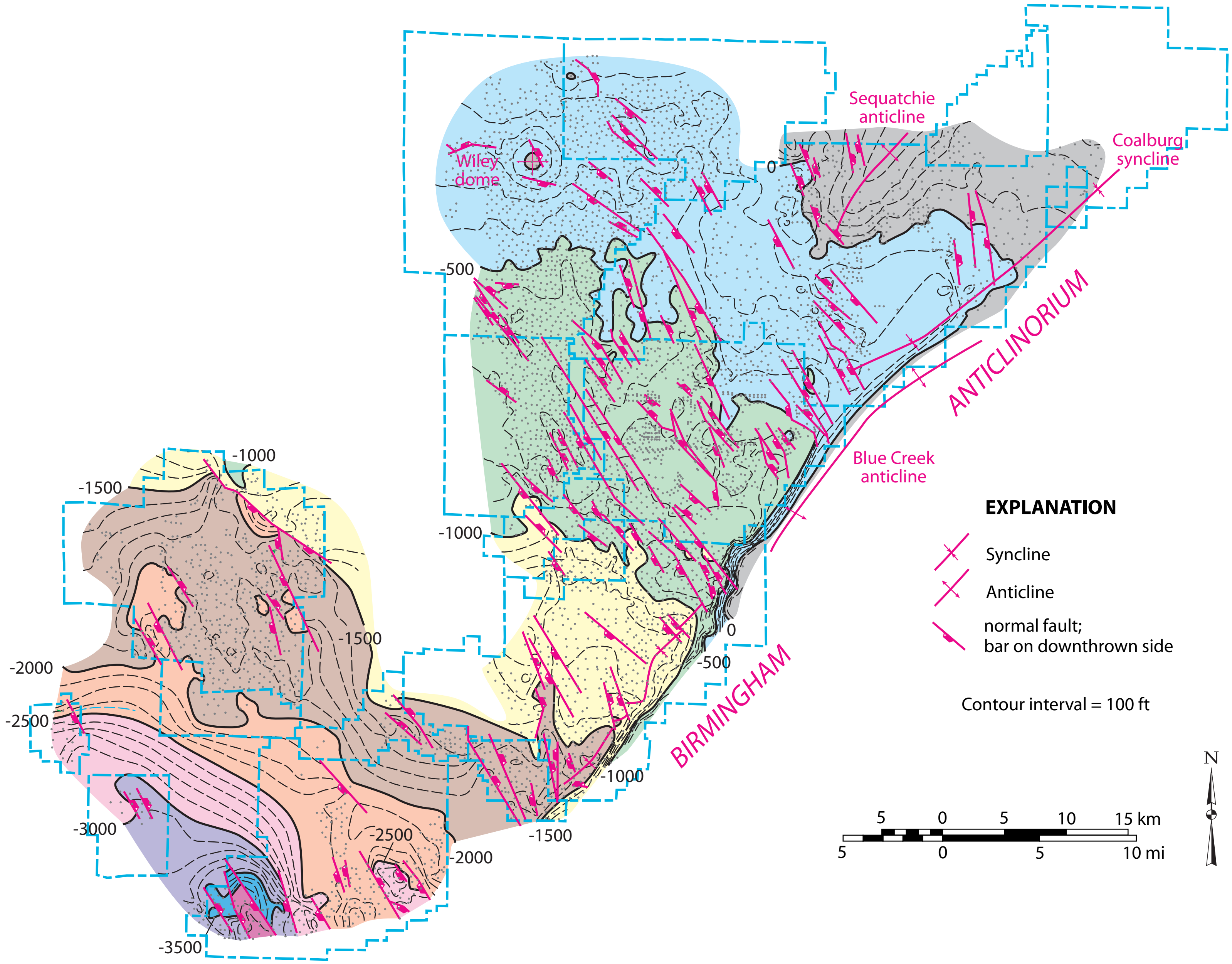



Figure 21.--Generalized structural contour map of the top of the Pratt coal zone in the Black Warrior coalbed methane fairway.

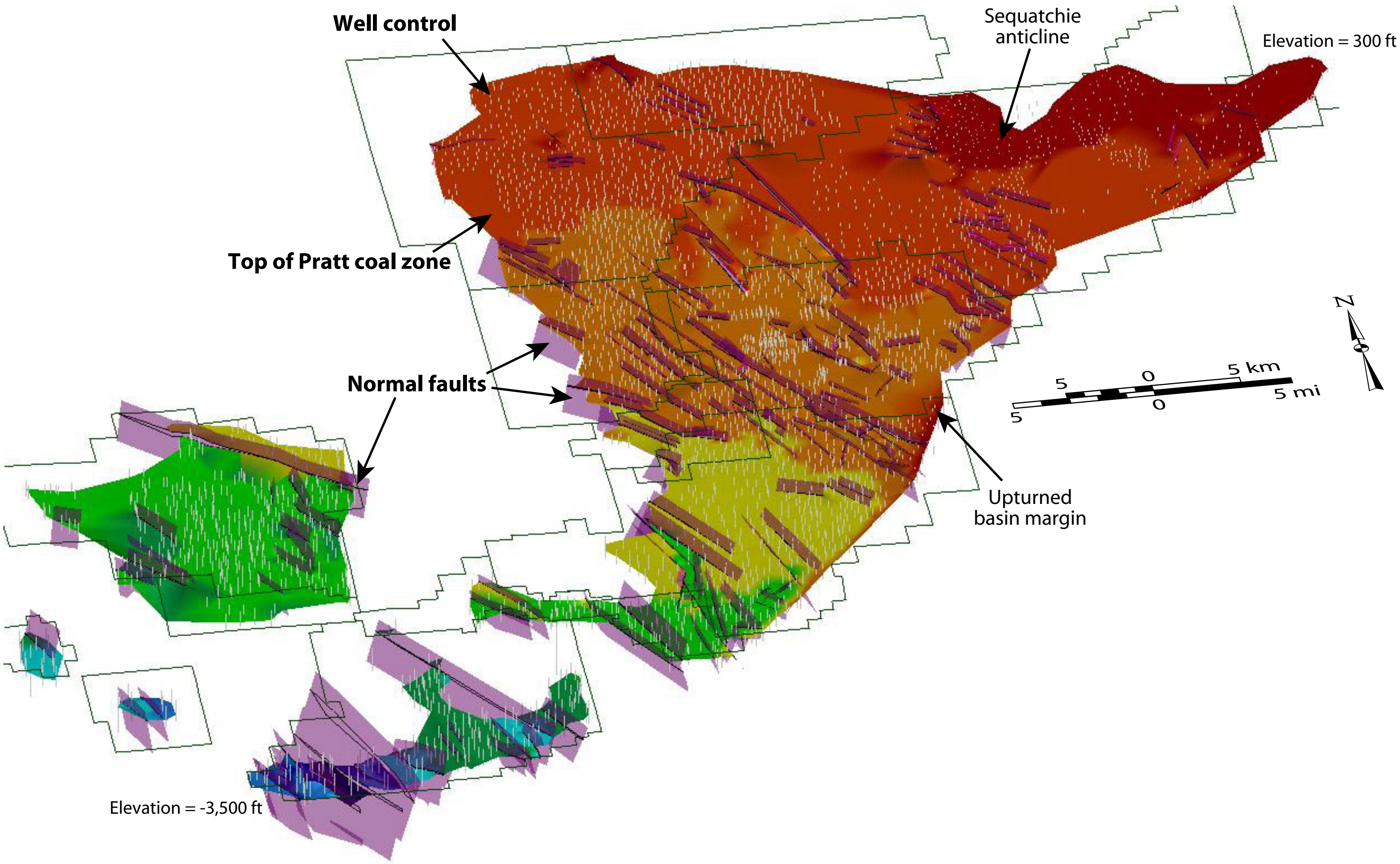



Figure 22.--Three-dimensional perspective view of the structure of the top of the Pratt coal zone in the Black Warrior coalbed methane fairway.

with the Sequatchie anticline (Semmes, 1929) and has an axial trace that follows the southeast margin of the coalbed methane fairway (fig. 21). 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. 21). The forelimb of the structure locally dips steeper than 50° 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. 23). 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° 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

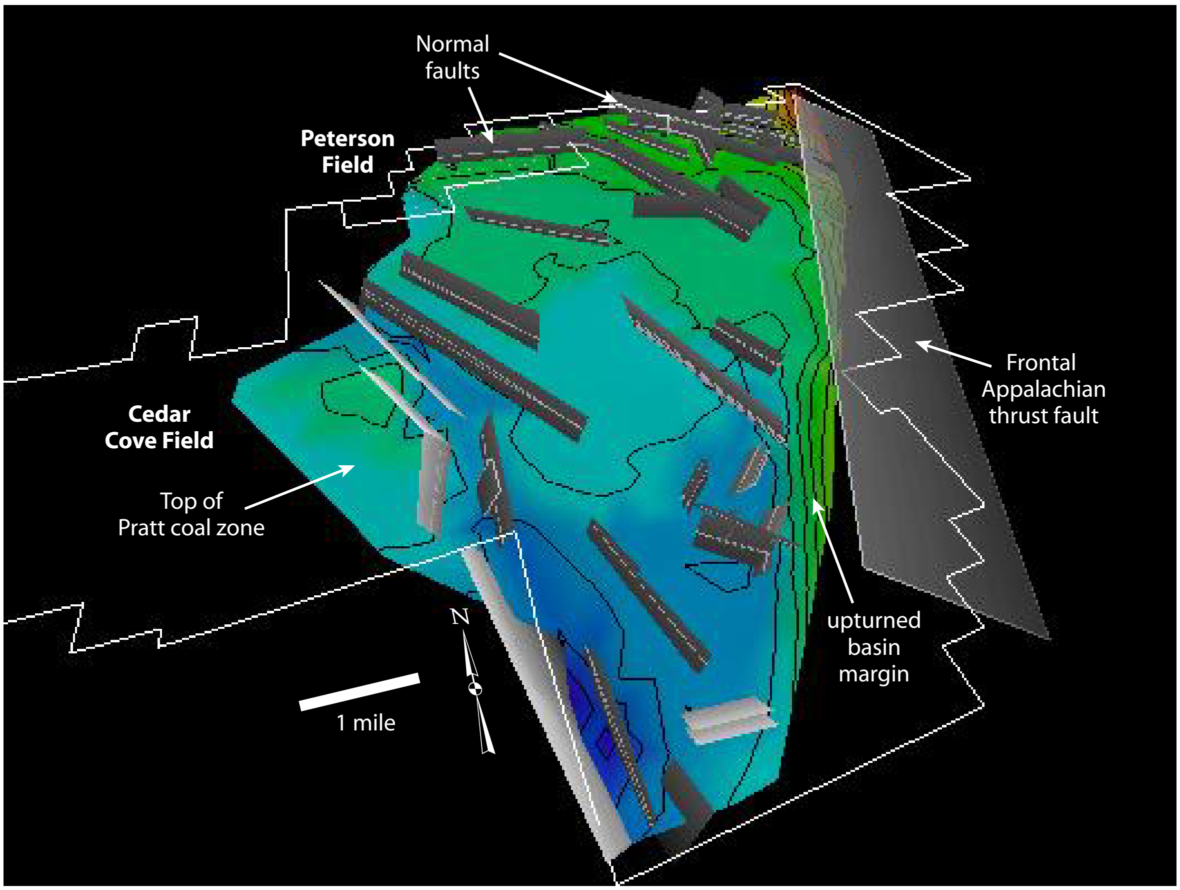



Figure 23.--Structural model of the top of the Pratt coal zone in Cedar Cove and Peterson fields.

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. 21-23). Trace length of the subsurface-mappable faults ranges from about 1 to 8 miles. Fault strike averages about N. 30° W. and ranges from N. 7° W. in eastern Oak Grove Field to N. 54° W. in 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. 21-23). 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. 21, 22) 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. 24).

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. 21, 22). The Sequatchie anticline terminates at a north-south trending swarm of en echelon normal faults in central Oak Grove Field, which Pashin (1994c) interpreted as a transtensional tear fault system marking the edge of the Sequatchie detachment block. Thus, the northeastward trend toward en 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.

## Cretaceous Structure

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

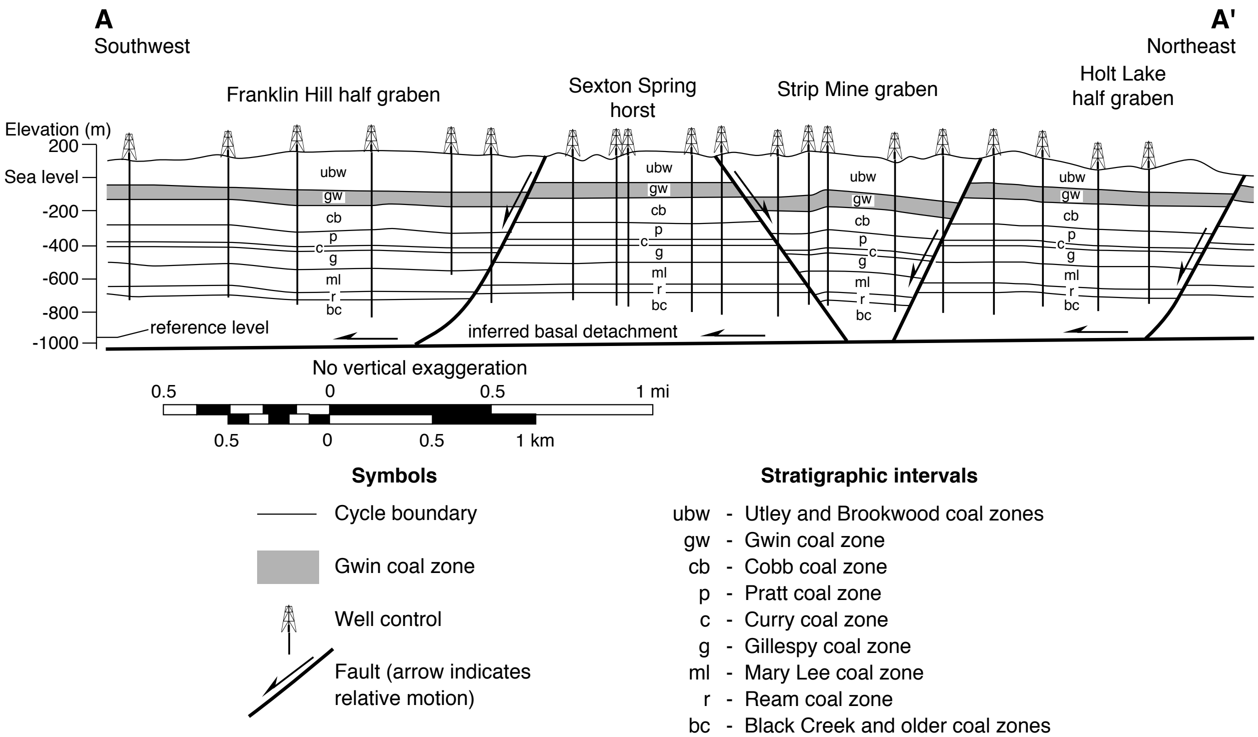



Figure 24.--Balanced structural cross section of the Pottsville Formation in Deerlick Creek Field (modified from Wang and others, 1993).

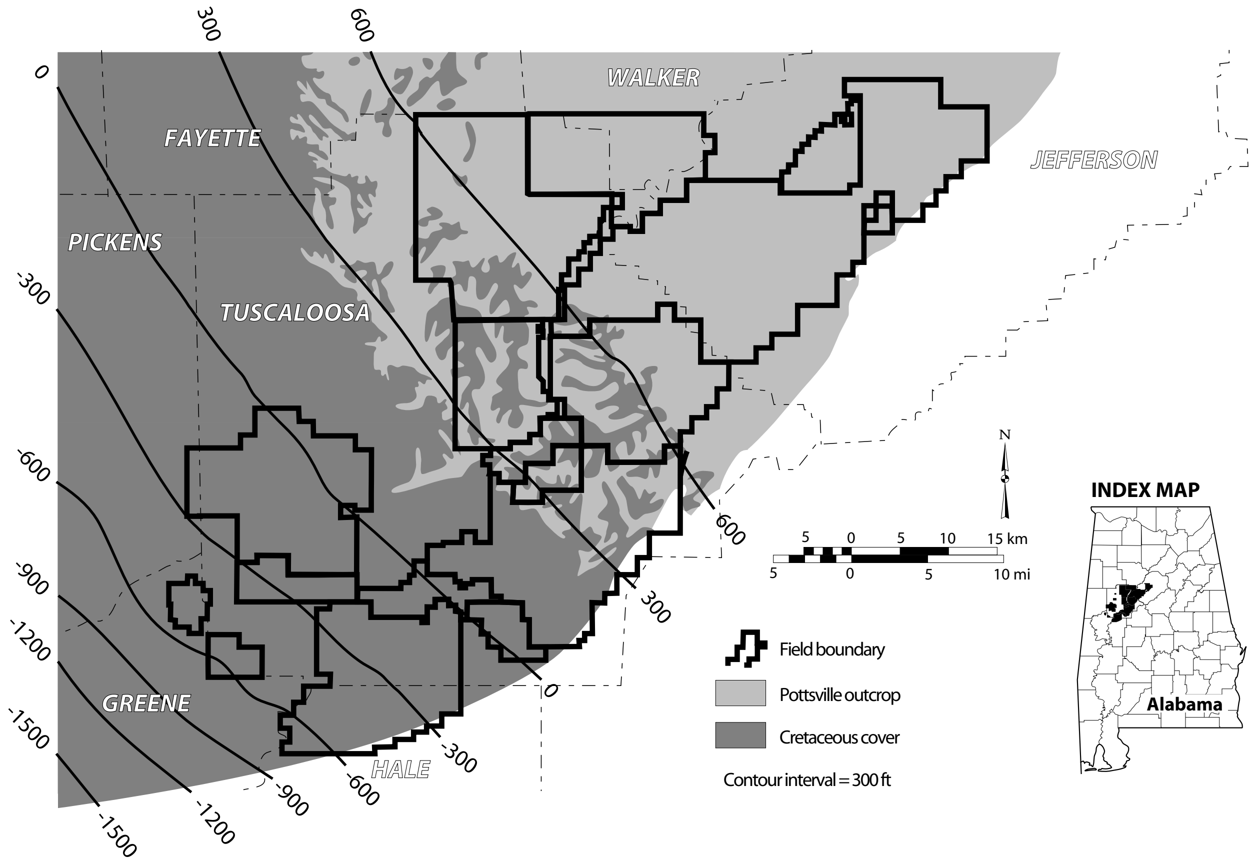



Figure 25.--Structural contour map of the unconformity surface separating the Pottsville Formation and Tuscaloosa Group (modified from Kidd, 1976).

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

## Pottsville Fracture Systems

Strata in Pottsville Coal Interval have effectively no matrix permeability to water, thus flow is concentrated along natural fractures. Fracture systems in the Pottsville Formation are diverse and include joints, cleats, and fault-related shear fractures (figs. 26-28). Joints are simple opening-mode fractures and are ubiquitous features of the earth's crust (Pollard and Aydin, 1988). Vertical joints are widespread in shale and sandstone and are typically spaced between 0.5 and 10 m. Closely spaced joints in coal (about 0.5 to 2.5 cm) are called cleats and are a primary control on aquifer and reservoir quality in the Pottsville Coal Interval. Joint systems in the Pottsville Formation tend to be strata-bound (Pashin and others, 2003; Jin and others, 2003; Pashin and others, in press); that is, the upper and lower tips of the fractures tend to be at or near the upper and lower contacts of the host shale, sandstone, or coal bed (figs. 26, 28). Pashin and others (2003, in press) found that fracture spacing in shale and sandstone increases

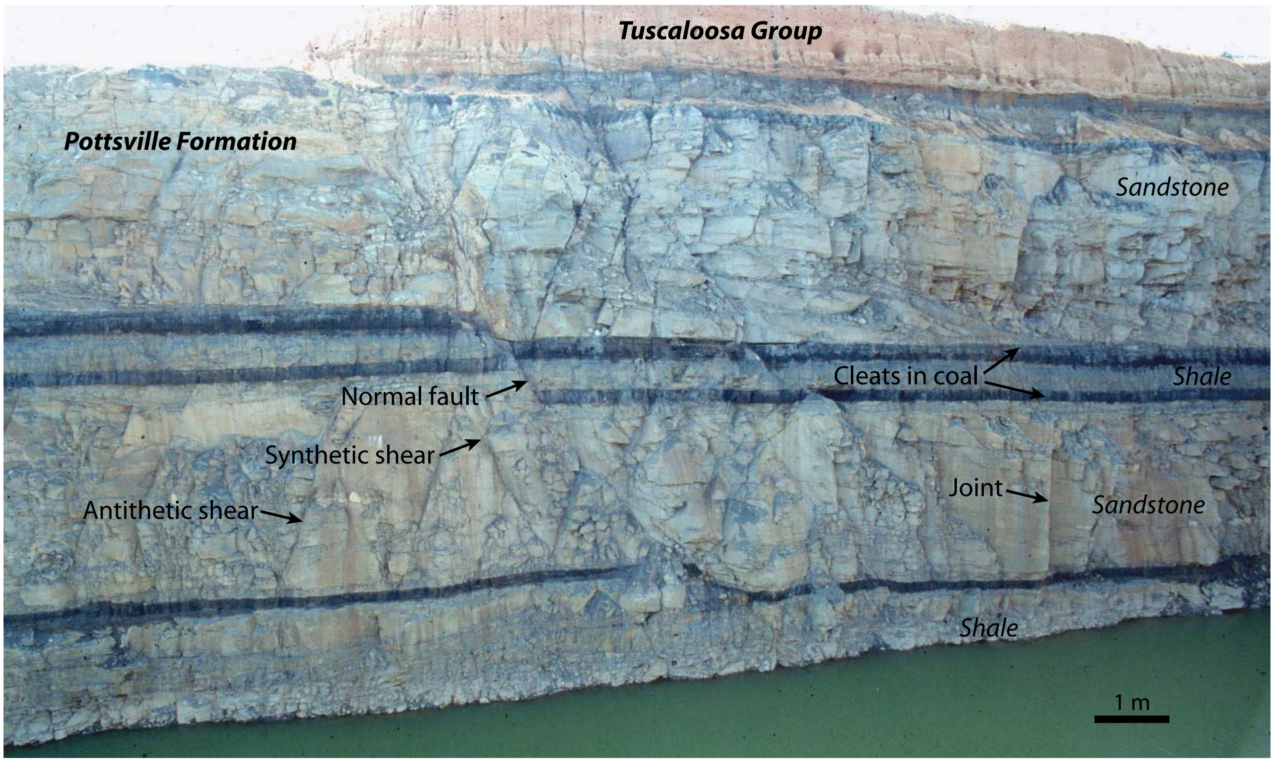
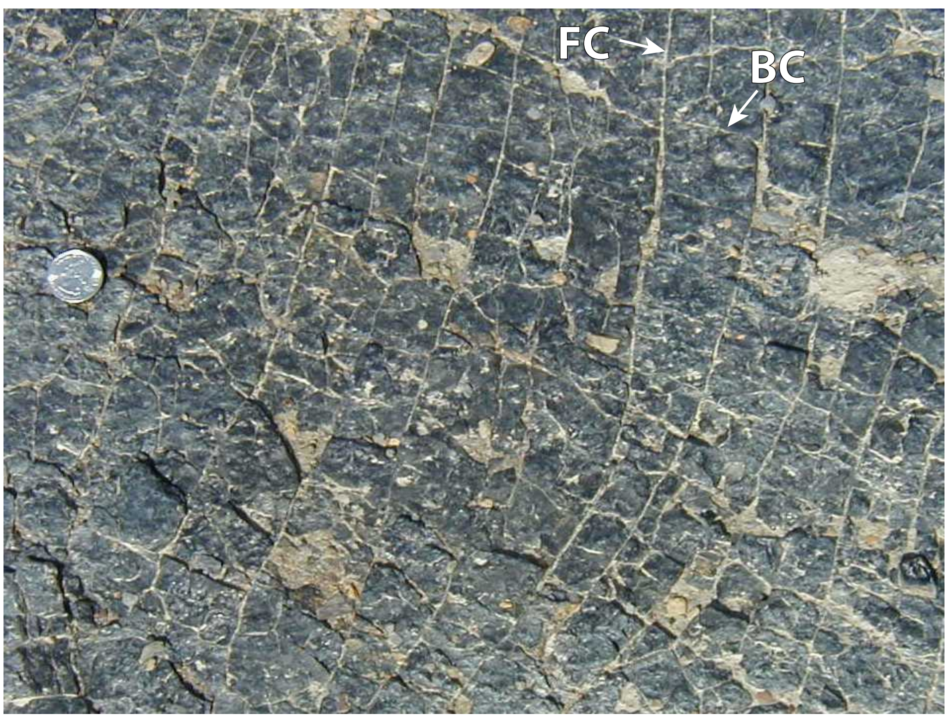



Figure 26.--Photograph of a small normal fault and associated fracturing in an abandoned mine highwall, Brookwood coal zone, Brookwood Field.


Figure 27.--Photograph of jointed shale above the Gwin coal zone in Oak Grove Field (modified from Pashin and others, 1991).

**Vertical exposure**


**Bedding-plane exposure**




FC = Face cleat (systematic joint)
BC = Butt cleat (cross joint)

Figure 28.--Photographs showing cleat systems in Alabama coal.

logarithmically with bed thickness, and McFall and others (1986) and Pashin and others (1999) observed that cleat spacing decreases markedly as coal rank increases. Therefore, fracture height in the Pottsville Formation generally equals bed thickness, and fracturing of adjacent beds took place with a high degree of mechanical and thermal independence.

Joint systems in the Pottsville Formation constitute orthogonal sets of vertical fractures composed of systematic joints and cross joints (Ward and others, 1984; Pashin and others, 1999) (figs. 27, 28). Systematic joints are planar fractures that can have surface traces on the order of 100 m. Cross joints are shorter than systematic joints, tend to strike perpendicular to systematic joints, and commonly terminate at intersections with systematic joints. In coal, systematic joints are referred to as face cleat, and cross joints are called butt cleat (fig. 28).

Systematic joints and cleats have distinctive orientations in the eastern Black Warrior basin (Ward and others, 1984) (fig. 29). Joints in sandstone and shale can be subdivided into a regional joint system and a localized joint system that is restricted to the area containing Appalachian folds (fig. 29A). Systematic joints of the regional joint system strike with a vector mean azimuth of N. 47° E., whereas systematic joints of the fold-related system strike with a vector mean azimuth of N. 64° W. Similarly, cleat systems can be subdivided into a regional cleat system and a localized system that is restricted to the southeast margin of the Black Warrior basin (fig. 29B). Face cleats of the regional cleat system strike with a vector mean azimuth of N. 62° E., which is 15° east of the regional systematic joints. Face cleats in the localized fracture system along the southeast margin of the basin strike with a vector mean azimuth of N. 36° W.

Joints and cleats in the Pottsville Formation are commonly mineralized (Pashin and others, 1999; Pitman and others, 2003). Calcite is the dominant fracture-filling mineral in shale and sandstone, whereas pyrite and calcite are common in coal. Fracture-filling minerals generally

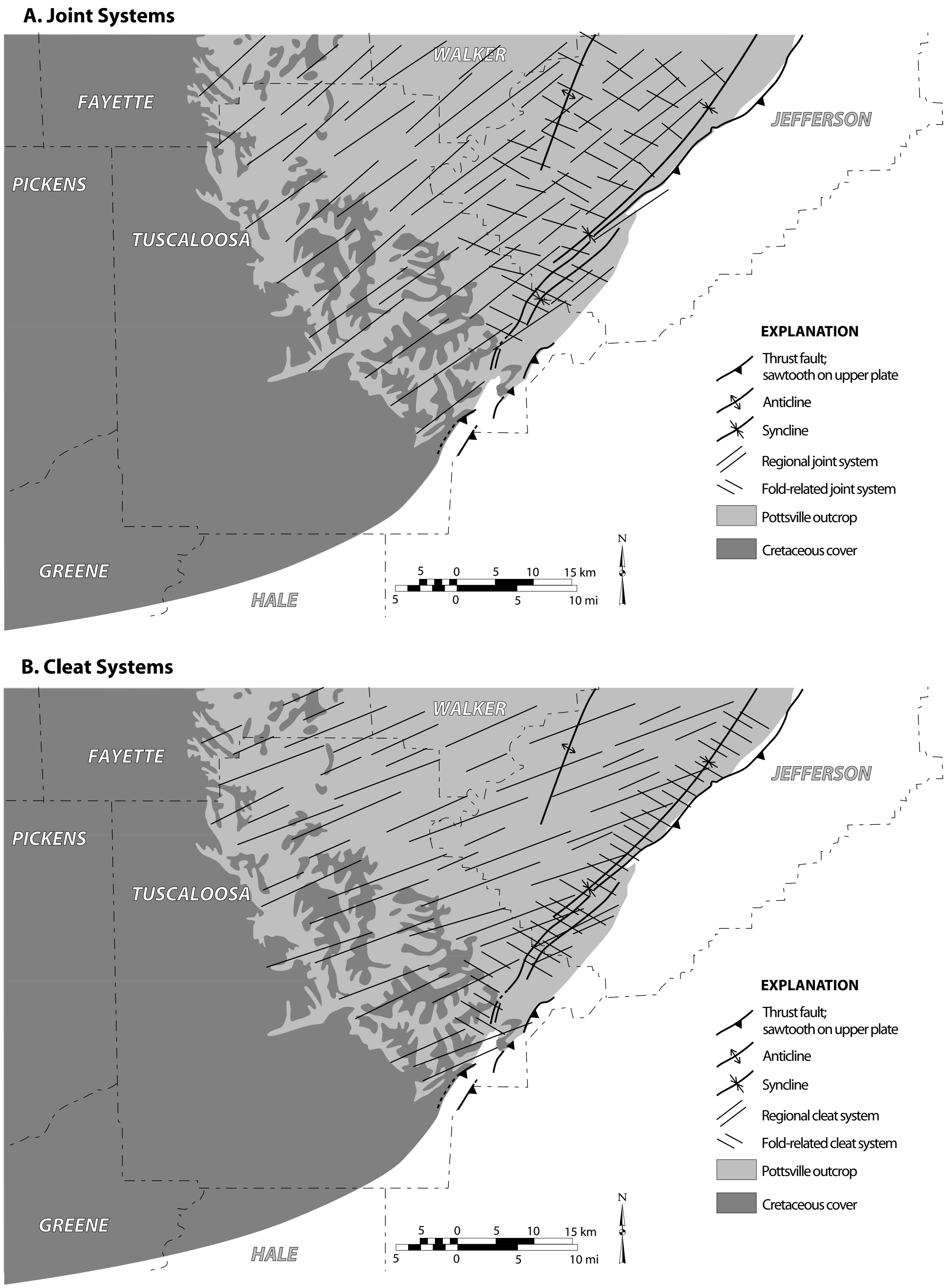



Figure 29.--Generalized maps showing joint and cleat systems in the eastern Black Warrior basin of Alabama (modified from Pashin and others, 1991).

have a patchy distribution and seldom completely fill fractures. Accordingly, the mineral fills are generally not considered major obstacles to fluid flow, and in places may help prop fractures open that would otherwise be closed.

Dipping and slickensided fractures are abundant within 10 m of normal faults and have been interpreted as shear fractures (Pashin and others, 1991) (fig. 26). These fractures form crisscrossing networks and can be subdivided into synthetic and antithetic shears. Synthetic shears dip parallel to the associated fault, whereas antithetic shears dip opposite to the associated fault. Faults and the associated shear-fracture systems cut across bedding and thus are possible avenues for hydrologic communication between reservoir coal beds and the surface. In a study of gas seeps in the Black Warrior basin, Clayton and others (1994) investigated a number of exposed normal faults and found a significant gas seep along one fault in Oak Grove Field. However, Pitman and others (2003) observed pervasive cementation of coal cleats within 10 m of normal faults in the Black Warrior basin, which appears to preclude flow in coal along large parts of many faults (fig. 30).

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 (Pashin and others, 2003) (fig. 31). 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. However, the exponential distribution of fracture apertures indicates that most flow in all fracture systems is concentrated in relatively few fractures.

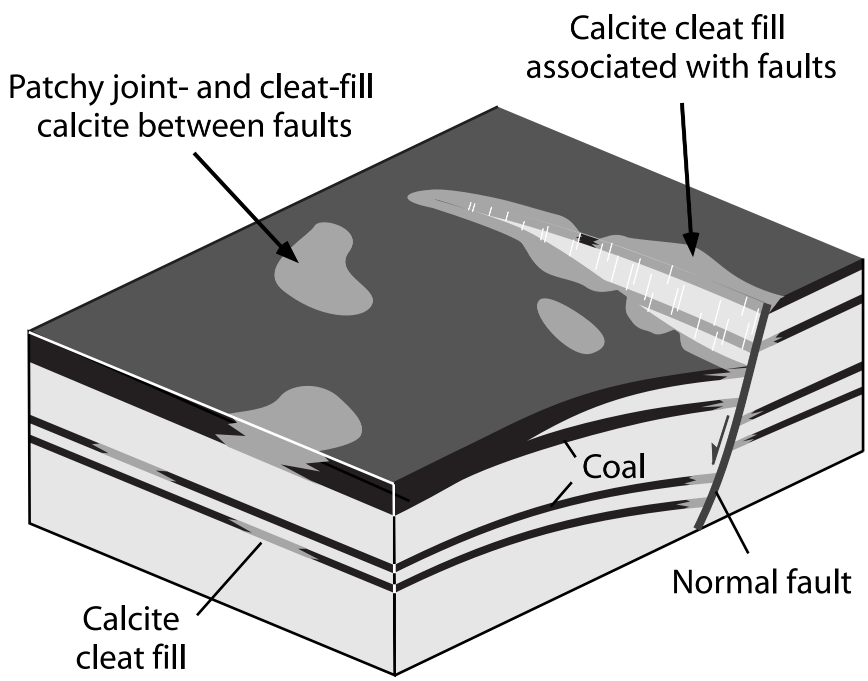



Figure 30.--Generalized model of calcite mineralization in coal of the eastern Black Warrior basin (modified from Pitman and others, 2003).

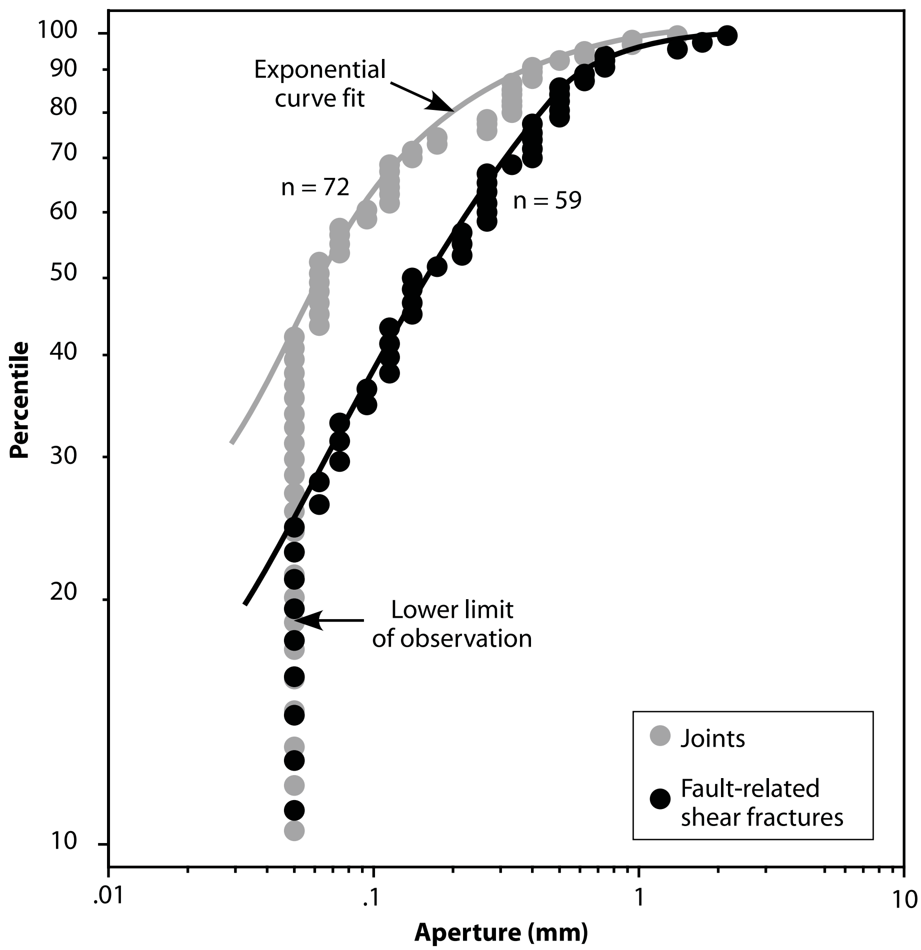



Figure 31.--Percentile plot showing the frequency of kinematic-aperture size classes for joints and fault-related shear fractures in five cores from Brookwood Field (after Pashin and others, 2003).

Discrete fracture network (DFN) computer modeling (Pashin and others, 2003; Jin and others, 2003) indicates that a combination of strata-bound fracturing and exponentially distributed fracture apertures facilitates the development of first-order reservoir compartments around closely spaced coal beds and favors bed-parallel flow in coal over cross-formational flow (figs. 32, 33). Similarly, fault-related shear fractures tend to form elongate reservoir compartments that parallel the strike of faults (Pashin and others, 2003; Jin and others, 2003). Regardless, the gas seep documented by Clayton and others (1994) indicates that tangible leakage risk exists along normal faults. Acidification of formation water adjacent to faults during $CO_2$ flooding, moreover, may dissolve calcite in coal, thereby increasing this risk. Large structural panels lacking significant faults exist in most coalbed methane fields (fig. 21), and to minimize leakage risk, these panels should be given priority for the demonstration of $CO_2$ sequestration and enhanced coalbed methane recovery technology.

## GEOTHERMICS

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 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 (Pashin and McIntyre, 2003a, b) (fig. 34). 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.

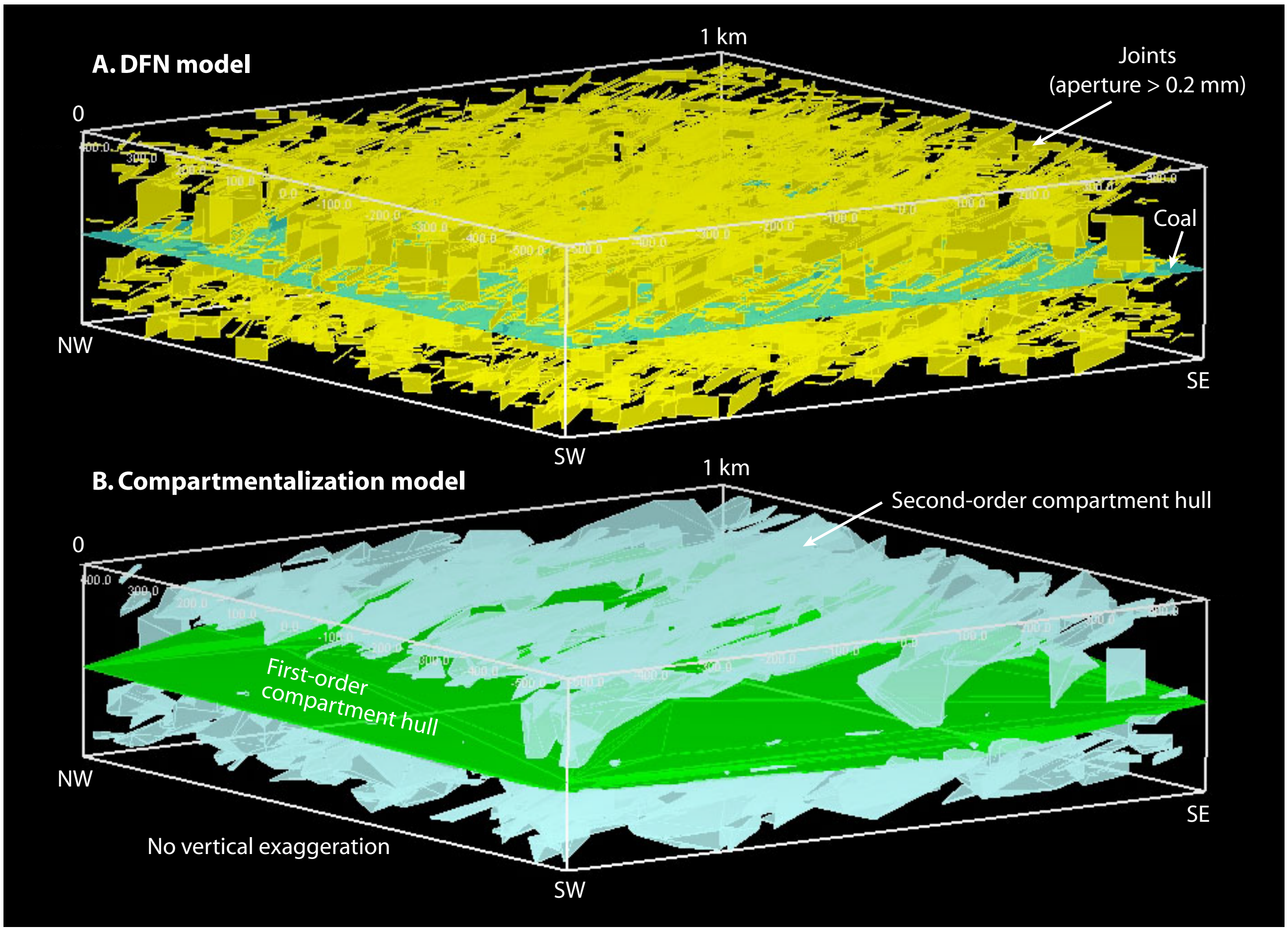



Figure 32.--DFN and compartmentalization models showing relationship of a single coal bed to strata-bound joint networks. (A) DFN model of coal and strata-bound joints. (B) Compartmentalization model showing development of first-order compartment around interconnected coal and joints and second-order compartments developed around interconnected joints isolated from coal (after Pashin and others, 2003).

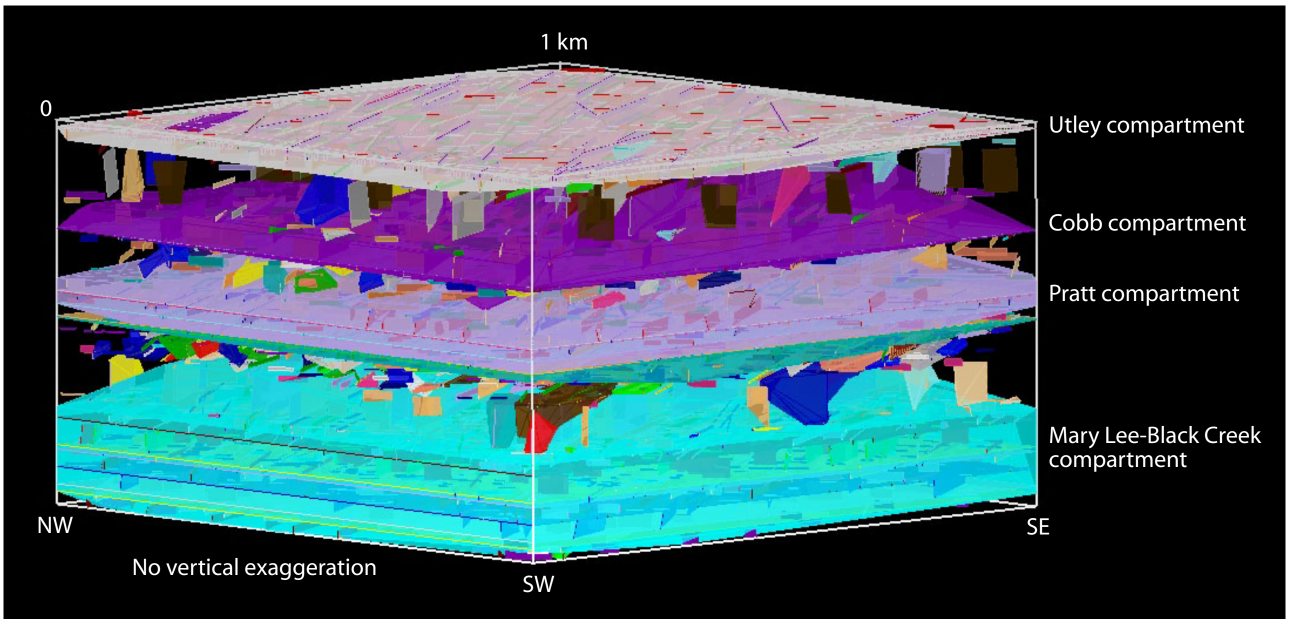



Figure 33.--Compartmentalization model of complete jointed DFN model showing development of first-order reservoir compartments around major coal zones and numerous second-order compartments in thick, shale-dominated intervals between coal zones (after Pashin and others, 2003).

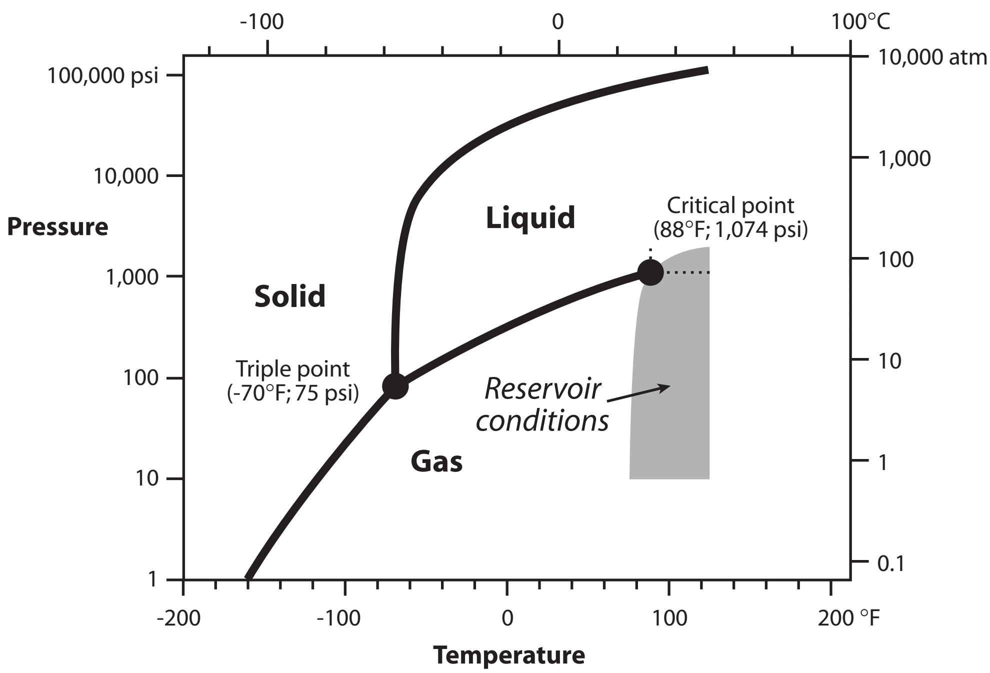



Figure 34.--Phase diagram for $CO_2$ showing relationship of the critical point to reservoir conditions in the Black Warrior coalbed methane fairway (after Pashin and McIntyre, 2003a).

Few empirical studies of the effect of temperature on the adsorption capacity of coal have been performed. However, a study of methane adsorption in the Pittsburgh coal of the Appalachian basin indicates that the sorption capacity of bituminous coal decreases significantly with temperature (Yang and Saunders, 1985) (fig. 35A). According to this study, bituminous coal can adsorb only half as much gas at 200°F as it can at room temperature. As temperature approaches 600°F, moreover, the sorption capacity of coal becomes extremely limited. Extracting data from the isotherms of Yang and Saunders (1985) at 50, 100, and 350 psi indicates that sorption capacity decreases exponentially as temperature increases (fig. 35B). Additionally, common reservoir temperatures in coalbed methane reservoirs of the Black Warrior basin lie in the most temperature-sensitive part of the exponential curves.

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. 36). 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. 37). This distribution 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. 38). 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

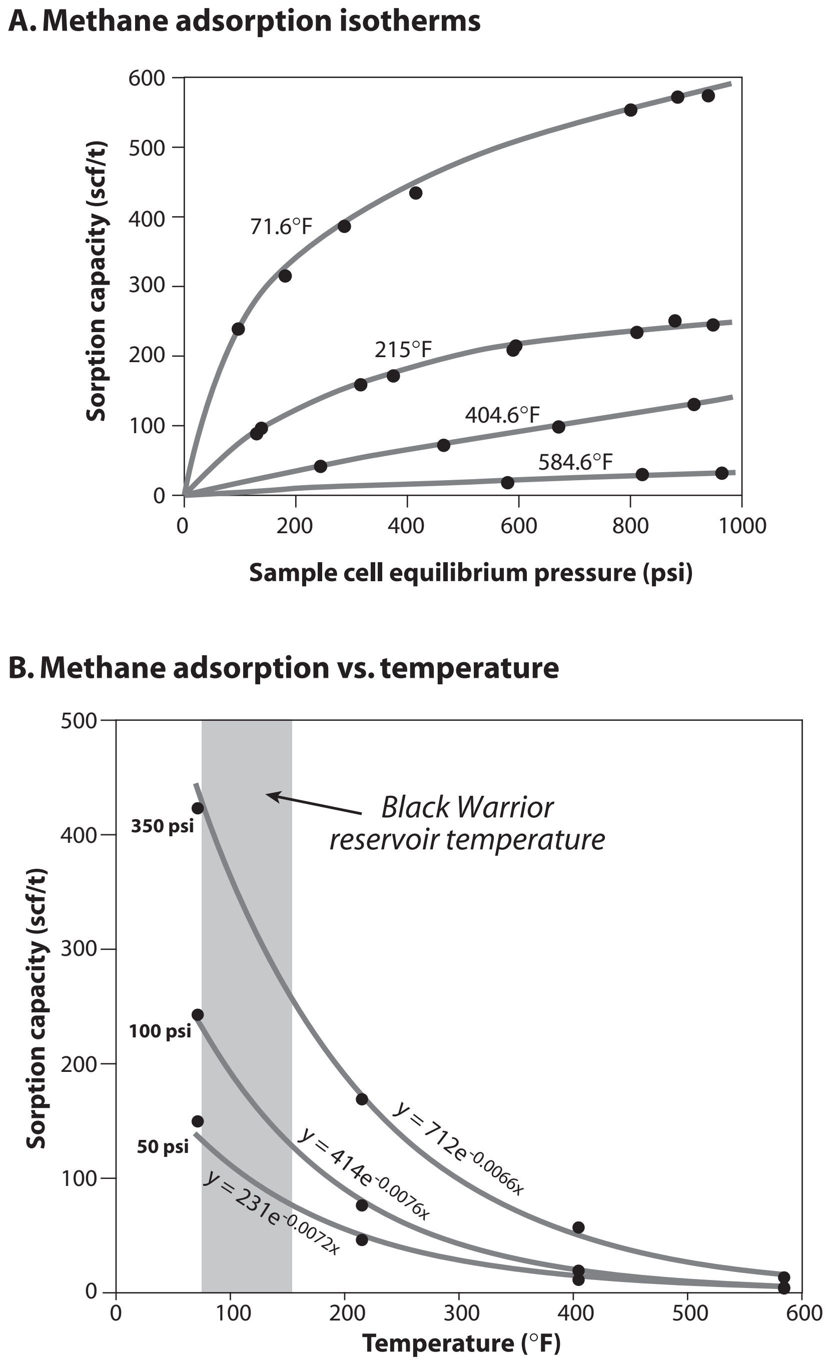



Figure 35.--Relationship of methane sorption to temperature in bituminous coal of the Appalachian basin (after Yang and Saunders, 1985).

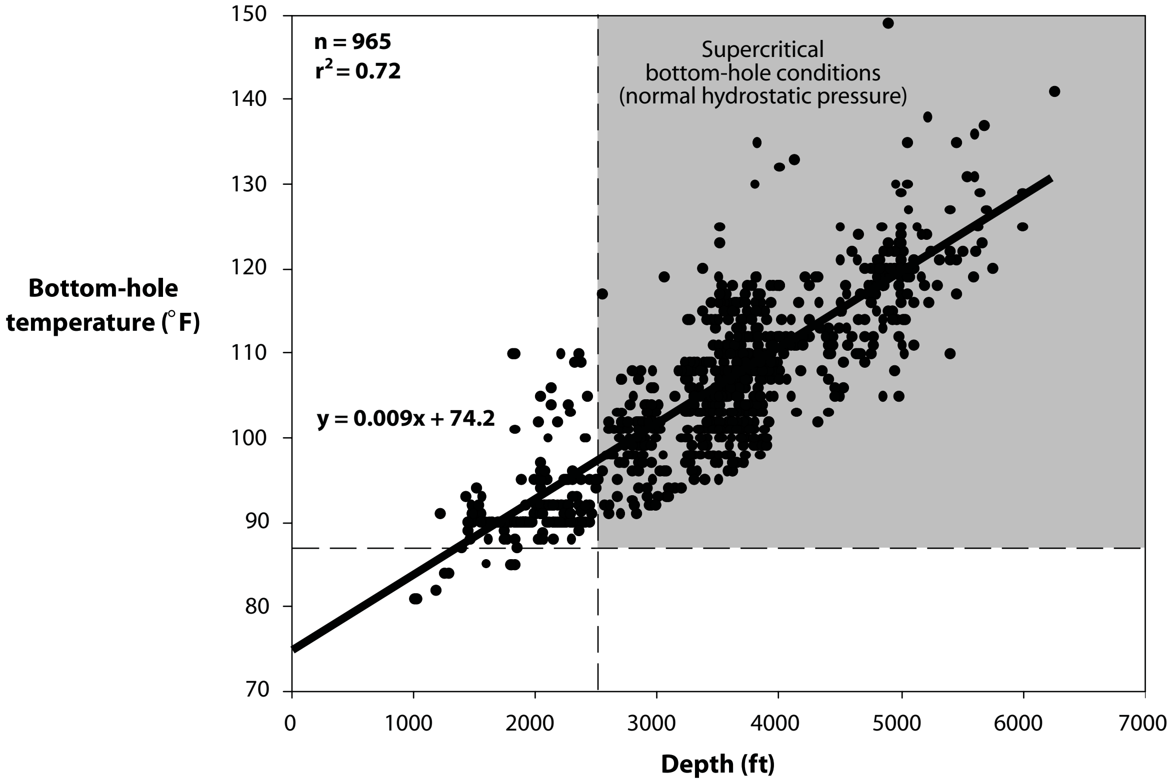



Figure 36.--Temperature-depth plot for coalbed methane wells in the Black Warrior basin.

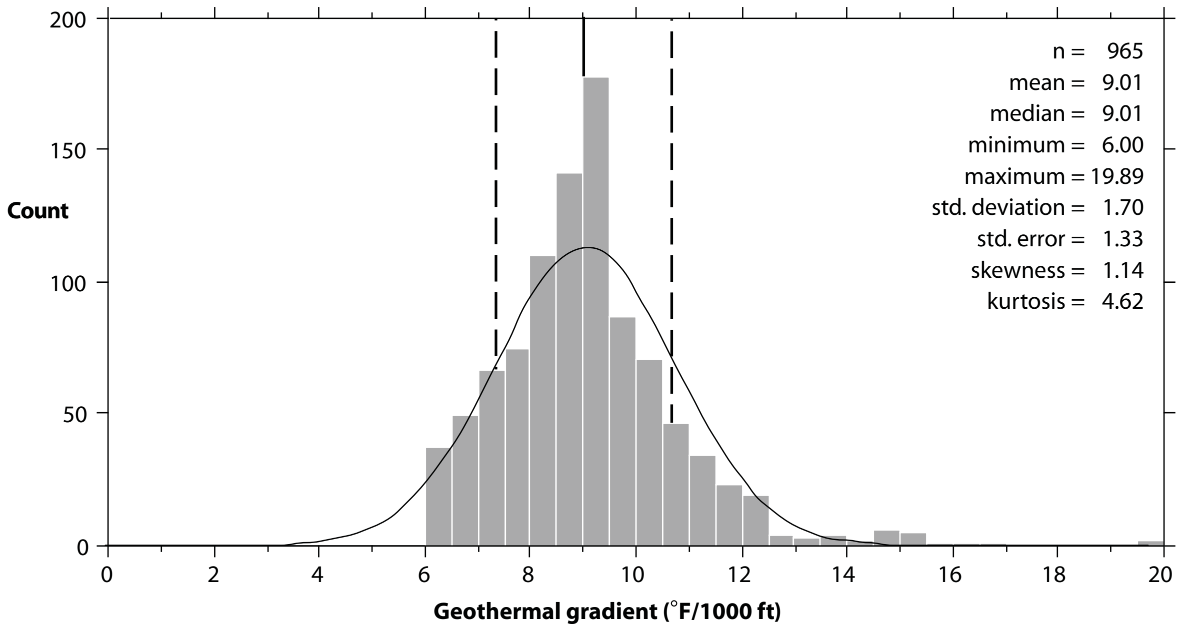



Figure 37.--Histogram showing population distribution of geothermal gradients in the Black Warrior coalbed methane fairway.

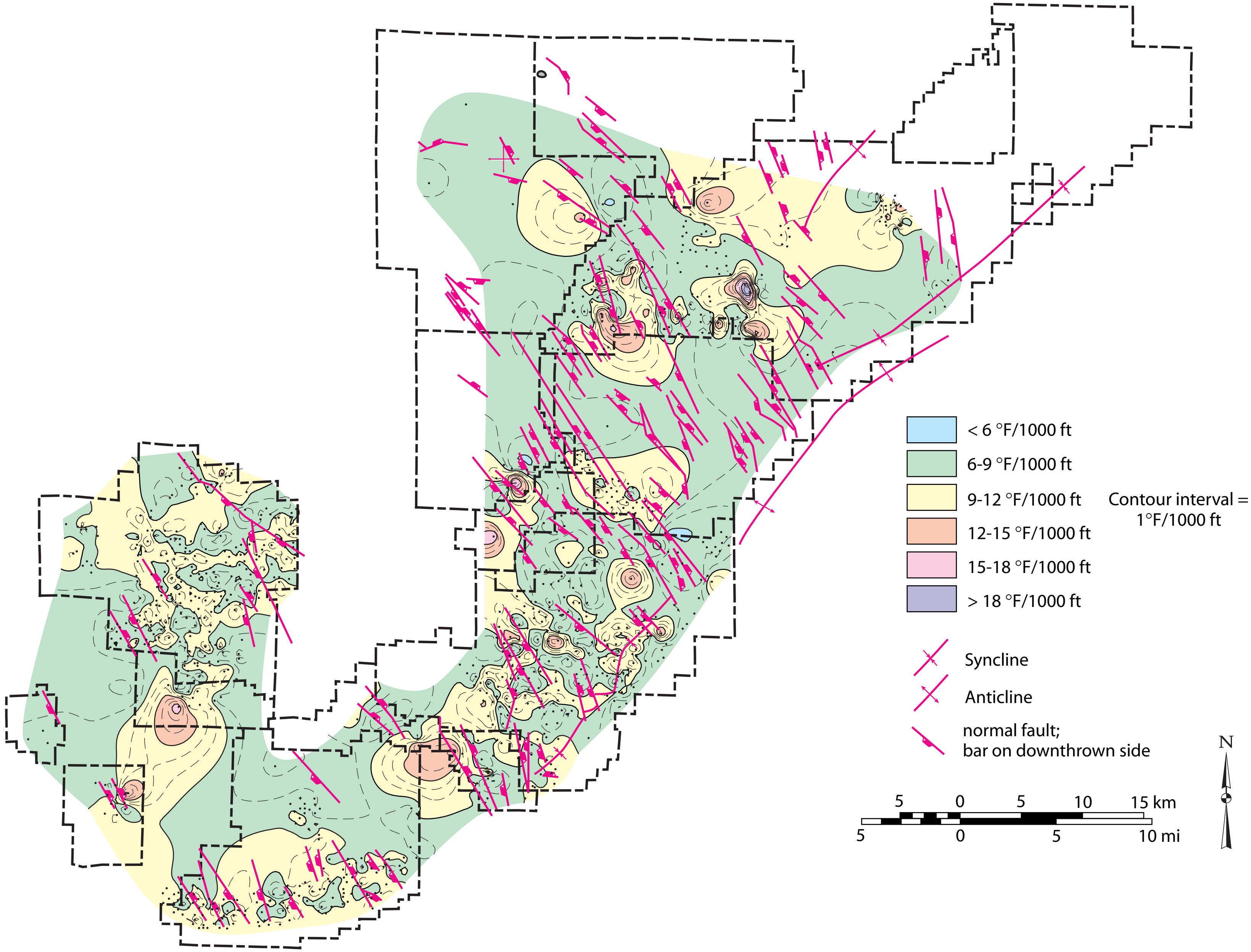



Figure 38.--Map of geothermal gradient in the Black Warrior coalbed methane fairway.

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. 39). 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. 37-39). The Pratt coal zone reaches the critical reservoir temperature of 88°F in Cedar Cove, Holt, and Robinson's Bend fields (fig. 39). However, reservoir pressure must be determined and mapped to predict where supercritical fluid conditions may affect carbon sequestration and enhanced coalbed methane recovery operations.

## HYDROGEOLOGY

Three aspects of hydrogeology that are critical screening criteria for carbon sequestration and enhanced coalbed methane recovery are permeability, 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 sources of drinking water (USDW). Reservoir pressure is a basic limiting factor on gas content,

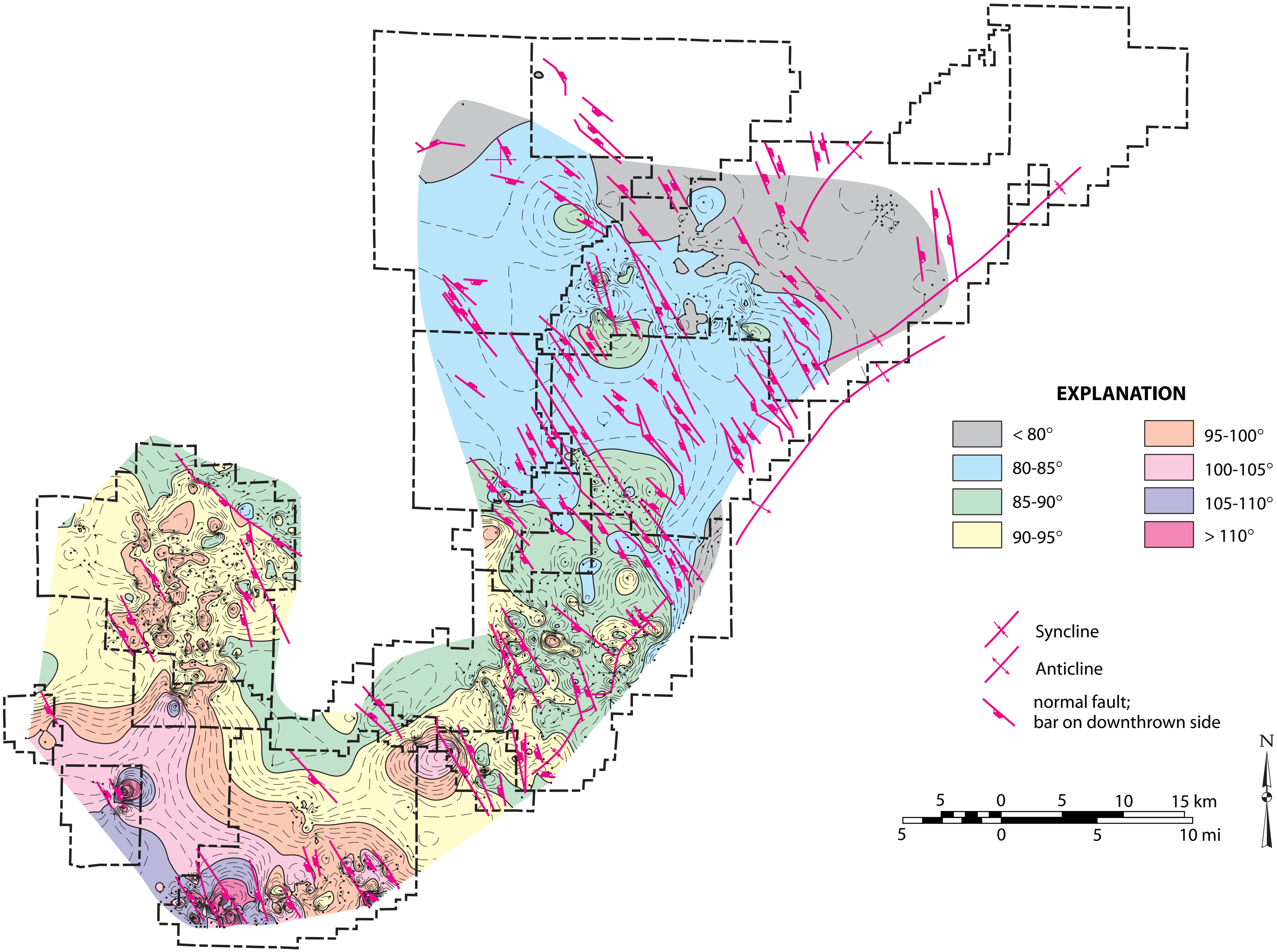



Figure 39.--Map of temperature at the top of the Pratt coal zone in the Black Warrior coalbed methane fairway.

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

As mentioned previously, strata of the Pottsville Coal Interval in the Black Warrior coalbed methane fairway have effectively no matrix permeability to water. 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 Coal Interval. 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 (1988) 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 (fig. 40).

DFN modeling and well testing indicate that the vertical decrease in the permeability of coal has significant consequences for coalbed methane production and $CO_2$ sequestration. Transmissivity is a function of permeability and bed thickness, and the discrete network models of Pashin and others (2003, in press) and Jin and others (2003) show that shallow coal beds in the Pratt, Cobb, and Utley coal zones are significantly more transmissive that joints in adjacent

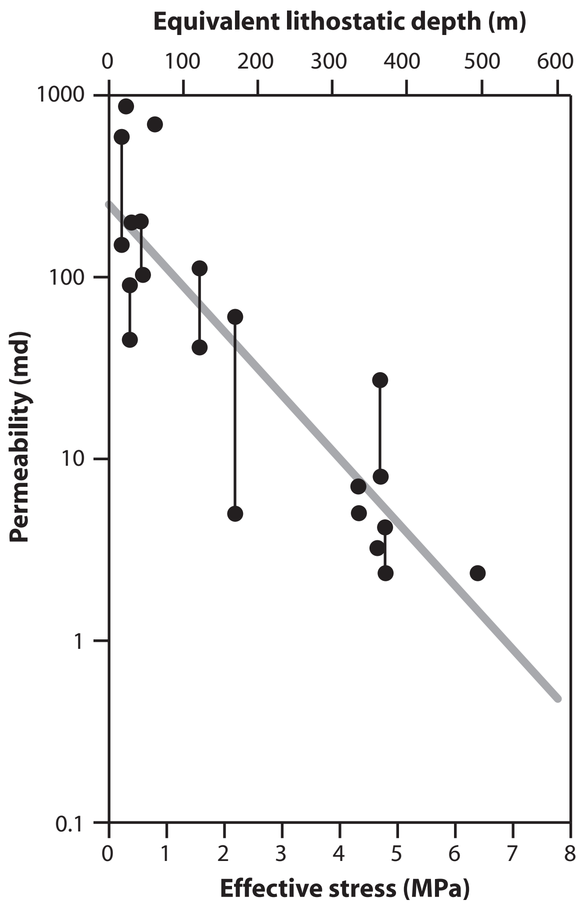



Figure 40.--Plot of permeability versus depth for coal in the eastern Black Warrior basin (modified from McKee and others, 1988).

strata (fig. 41). Thick coal beds in the Mary Lee zone, which is at a depth of about 1,600 feet in the model, have transmissivity comparable to many joints in adjacent strata. By comparison, beds in the Black Creek zone, which is about 2,000 feet deep, have lower transmissivity than fractures in adjacent shale and sandstone beds.

The results of pressure buildup tests in Oak Grove Field (Koenig, 1989) are consistent with the DFN models. Pressure buildup results in the Pratt coal zone provide evidence for permeability anisotropy that is strongly elongate in the face cleat direction (fig. 42). This reflects the high transmissivity of coal relative to adjacent strata and indicates that flow is primarily in coal. In contrast, test results from the Black Creek coal zone indicate reduced permeability anisotropy in the systematic joint direction. This result reflects the limited transmissivity of coal deeper than 2,000 feet and suggests that hydraulic communication took place with fractures in adjacent strata. Hence, in deep reservoirs, injected $CO_2$ may be more difficult to keep in coal than in shallow strata, and leakage of $CO_2$ into adjacent strata may reduce sweep efficiency during enhanced coalbed methane recovery operations.

## Water Chemistry

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) (figs. 43, 44). 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

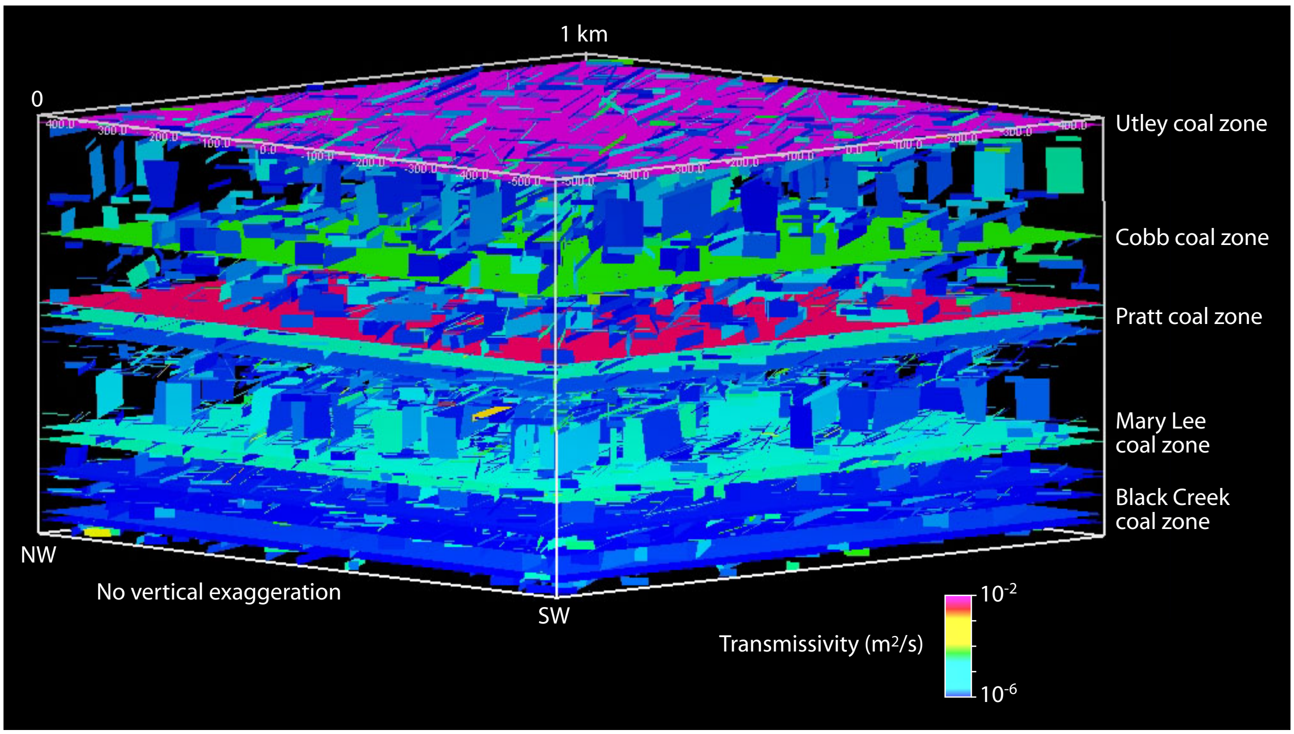



Figure 41.—Color-contoured DFN model showing transmissivity of coal and joints (after Pashin and others, 2003).

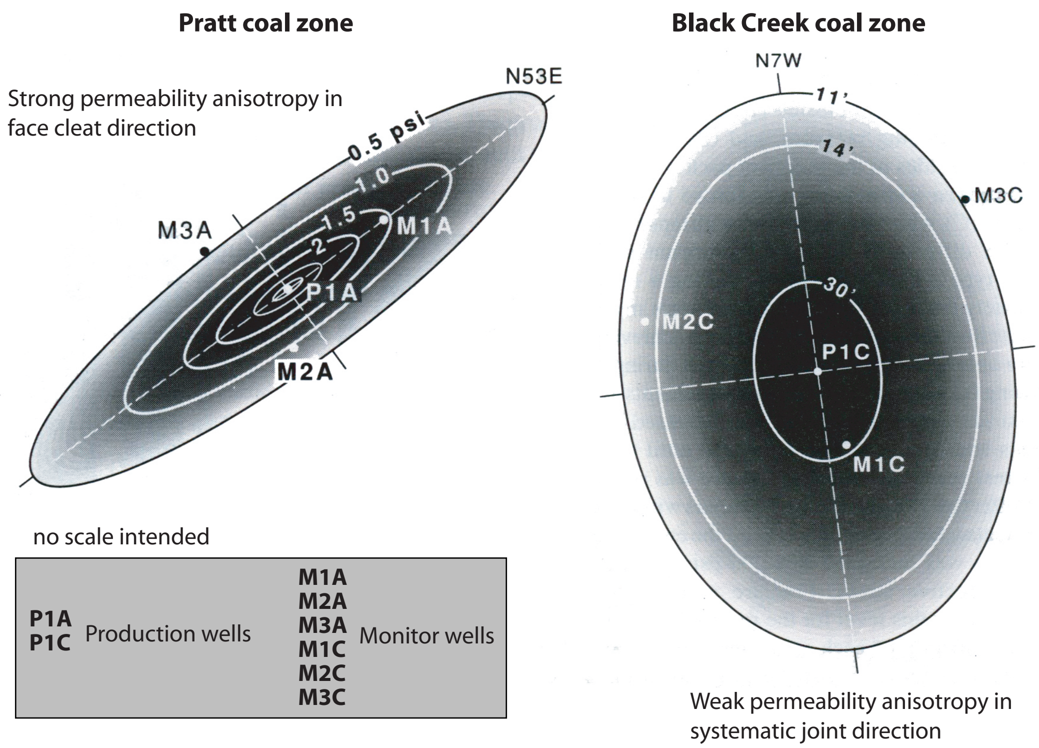



Figure 42.--Pressure buildup test results showing permeability anisotropy in coalbed methane reservoirs of the Black Warrior basin (modified from Koening, 1989).

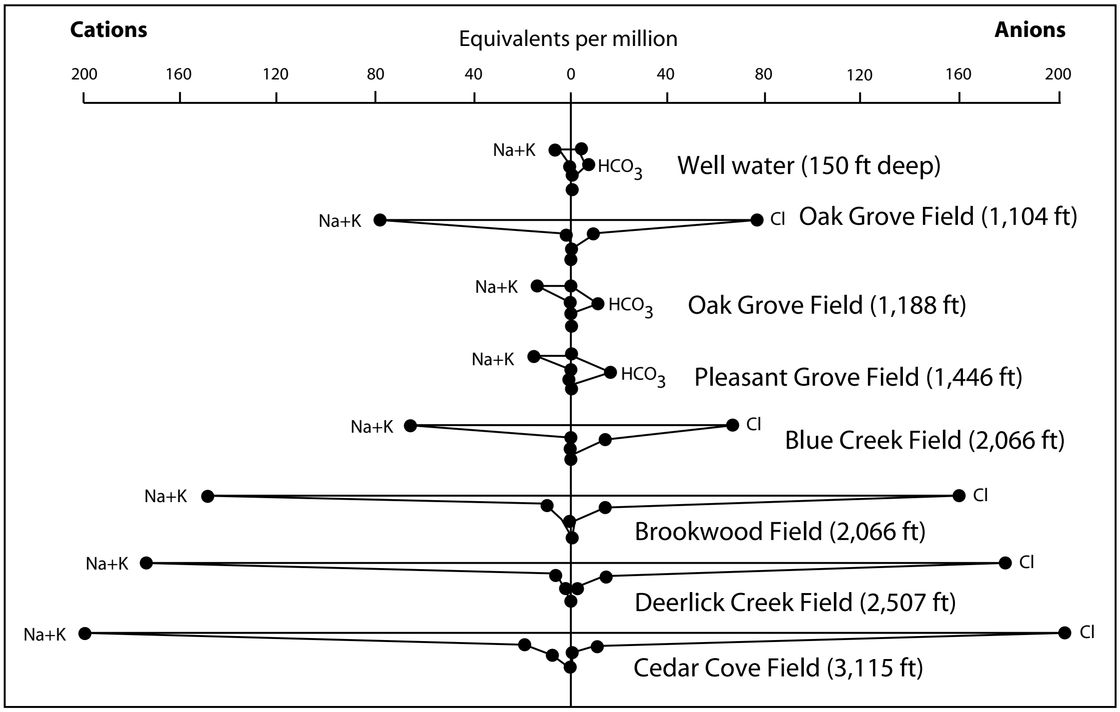



Figure 43.–Stiff diagrams showing the composition of formation water in the Pottsville Formation (modified from Pashin and others, 1991).

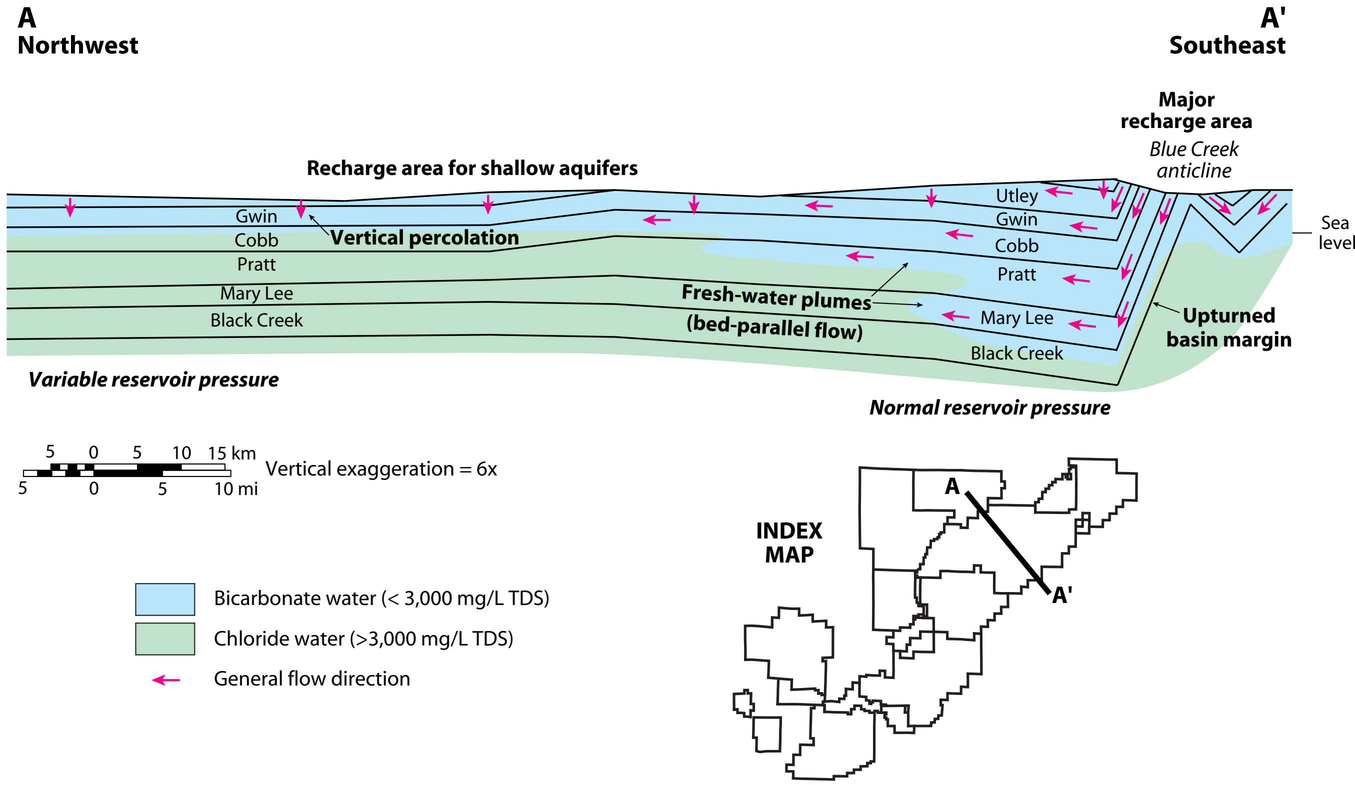



Figure 44.--Generalized structural cross section showing meteoric recharge areas and subsurface flow patterns in the upper Pottsville Formation (after Pashin and others, 2003).

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 (fig. 44). 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 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) (figs. 44, 45). 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.

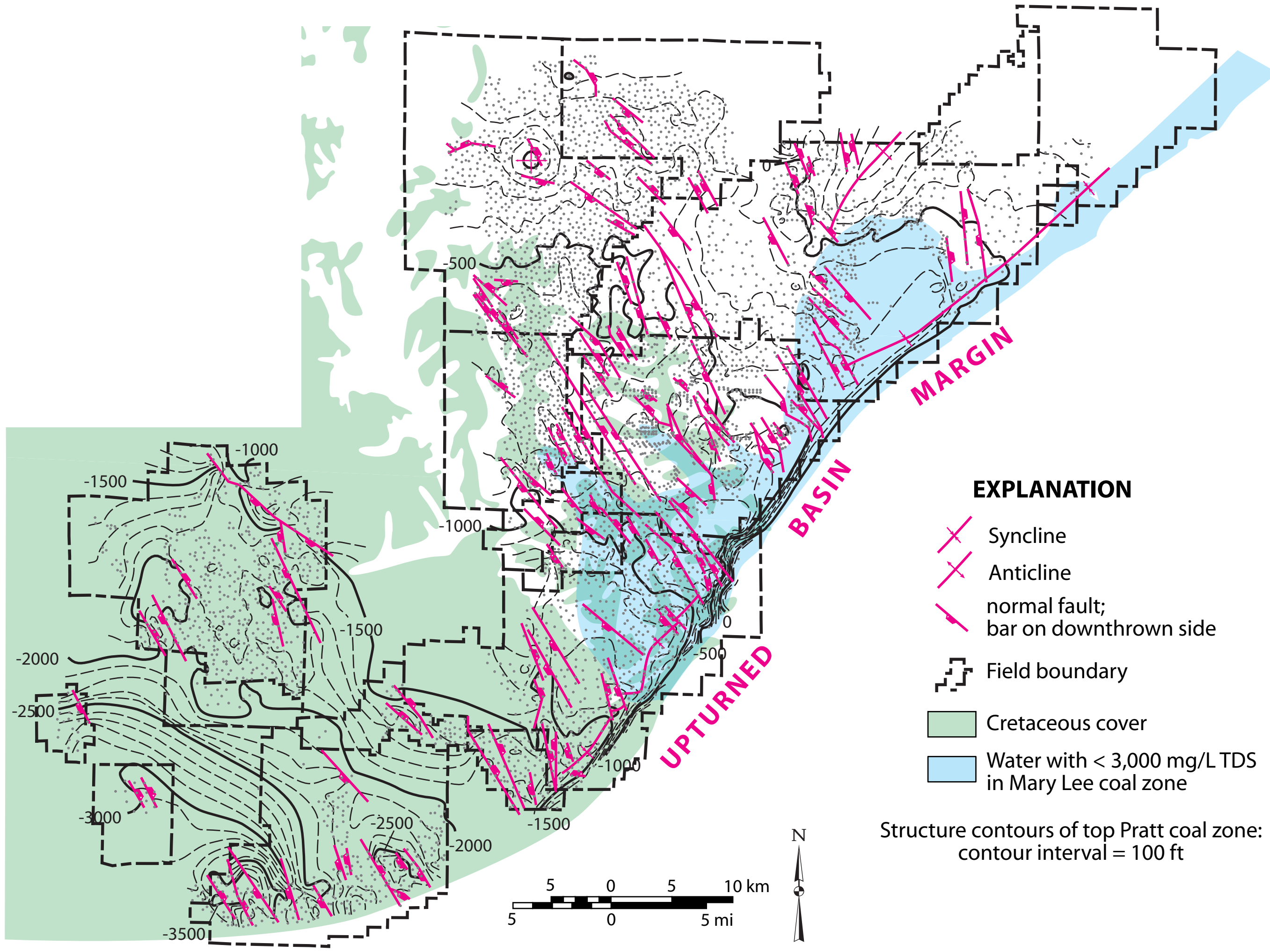



Figure 45.--Relationship of fresh-water plumes in the Mary Lee coal zone along the southeast margin of the Black Warrior basin to geologic structure and Cretaceous cover (modified from Pashin and McIntyre, 2003a).

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 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.

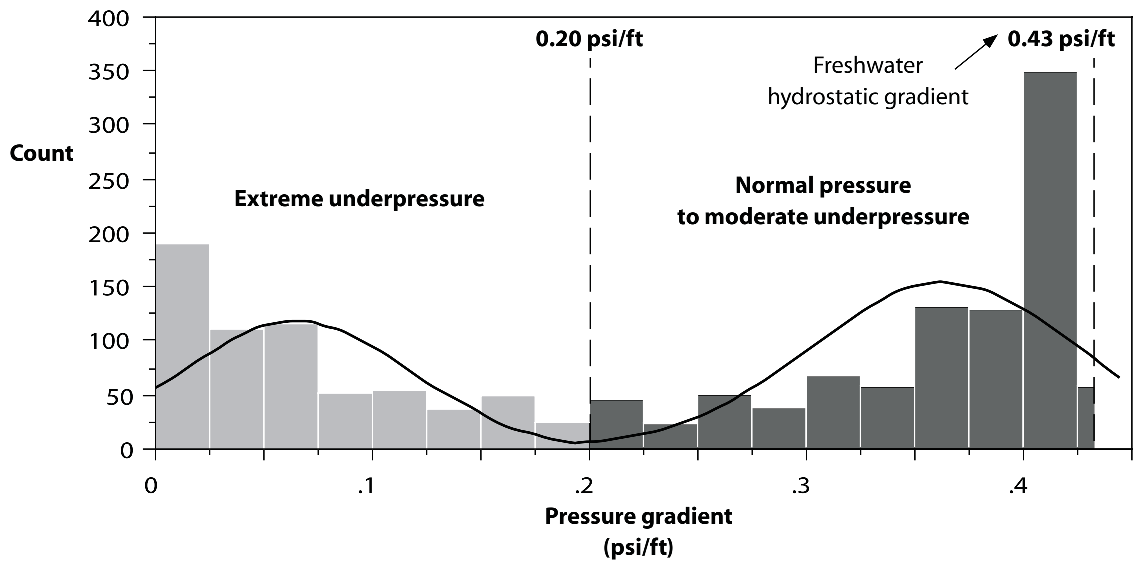
Water chemistry also has direct operational implications for carbon sequestration and enhanced coalbed methane recovery operations. Formation water in the Pottsville Formation is saturated with calcium carbonate, which can lead to precipitation of calcite scale on perforations during gas production. Ellard and others (1997) indicated that scaling is enhanced in wells where the salinity of produced formation fluids decreases over time. Injection of $CO_2$ 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 (Pashin and McIntyre, 2003a, b). 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 minimum 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. 46, 47). 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. 47).

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




| 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 46.--Histogram showing bipolar distribution of hydrostatic pressure gradients in the Black Warrior coalbed methane fairway.

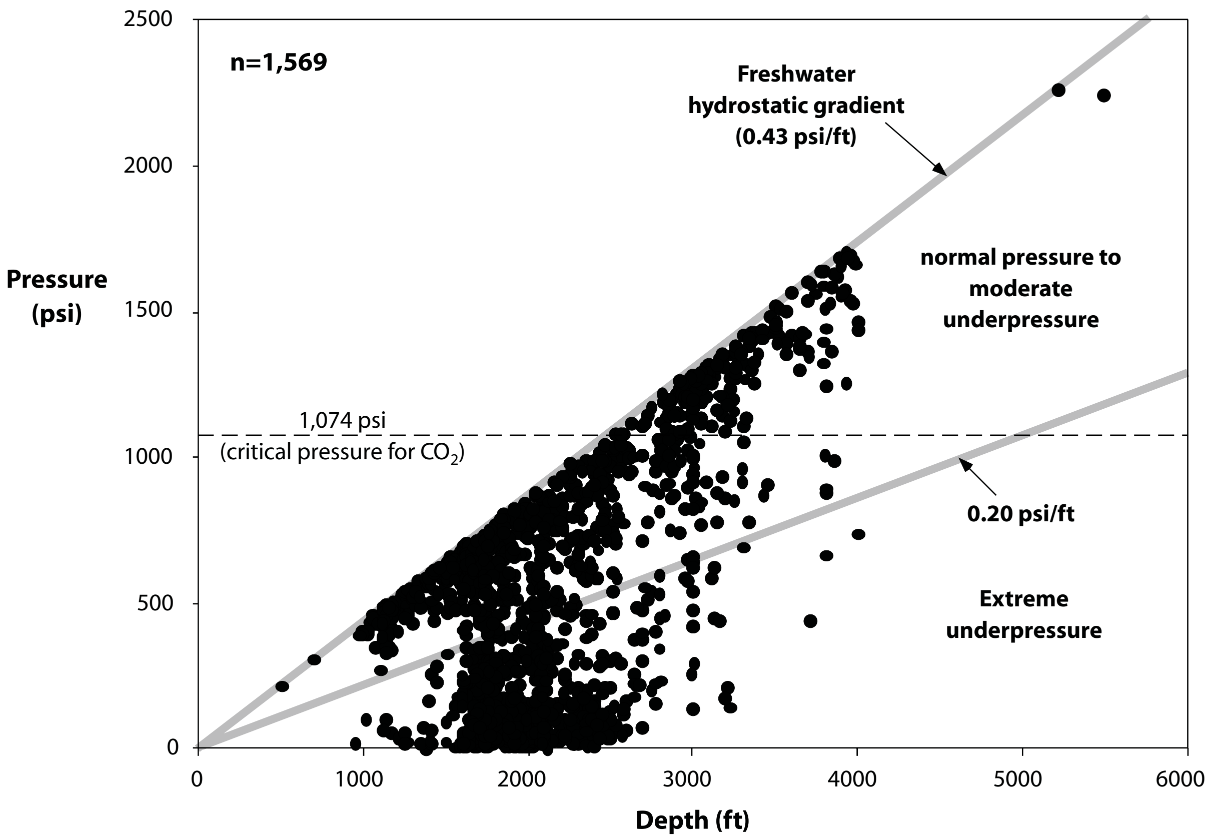



Figure 47.--Pressure-depth plot based on water levels in the Black Warrior coalbed methane fairway.

the northeastern part of the coalbed methane fairway (figs. 48, 49). 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. 47). 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; 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

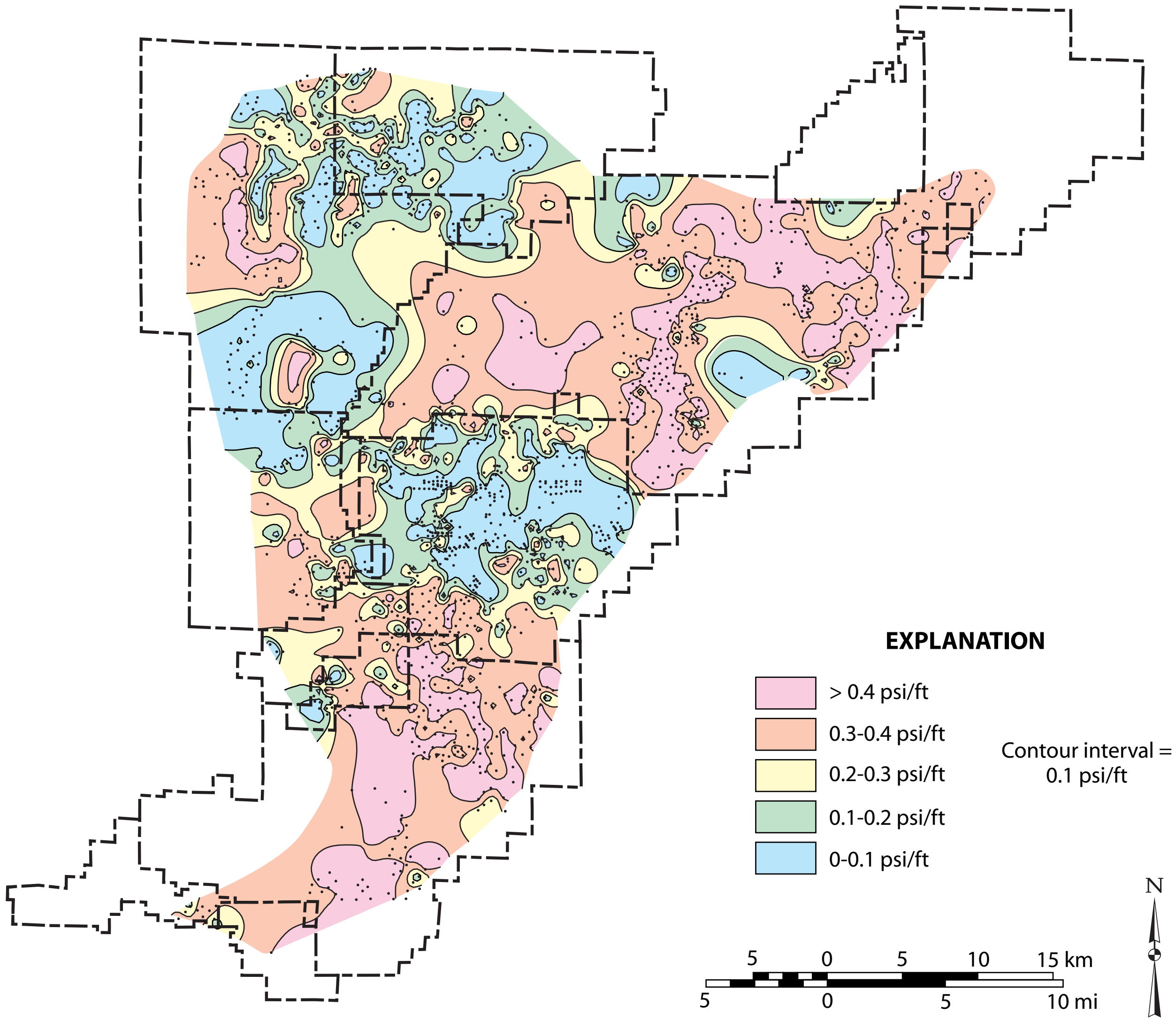



Figure 48.--Map of hydrostatic pressure gradient determined from water levels in the Black Warrior coalbed methane fairway.

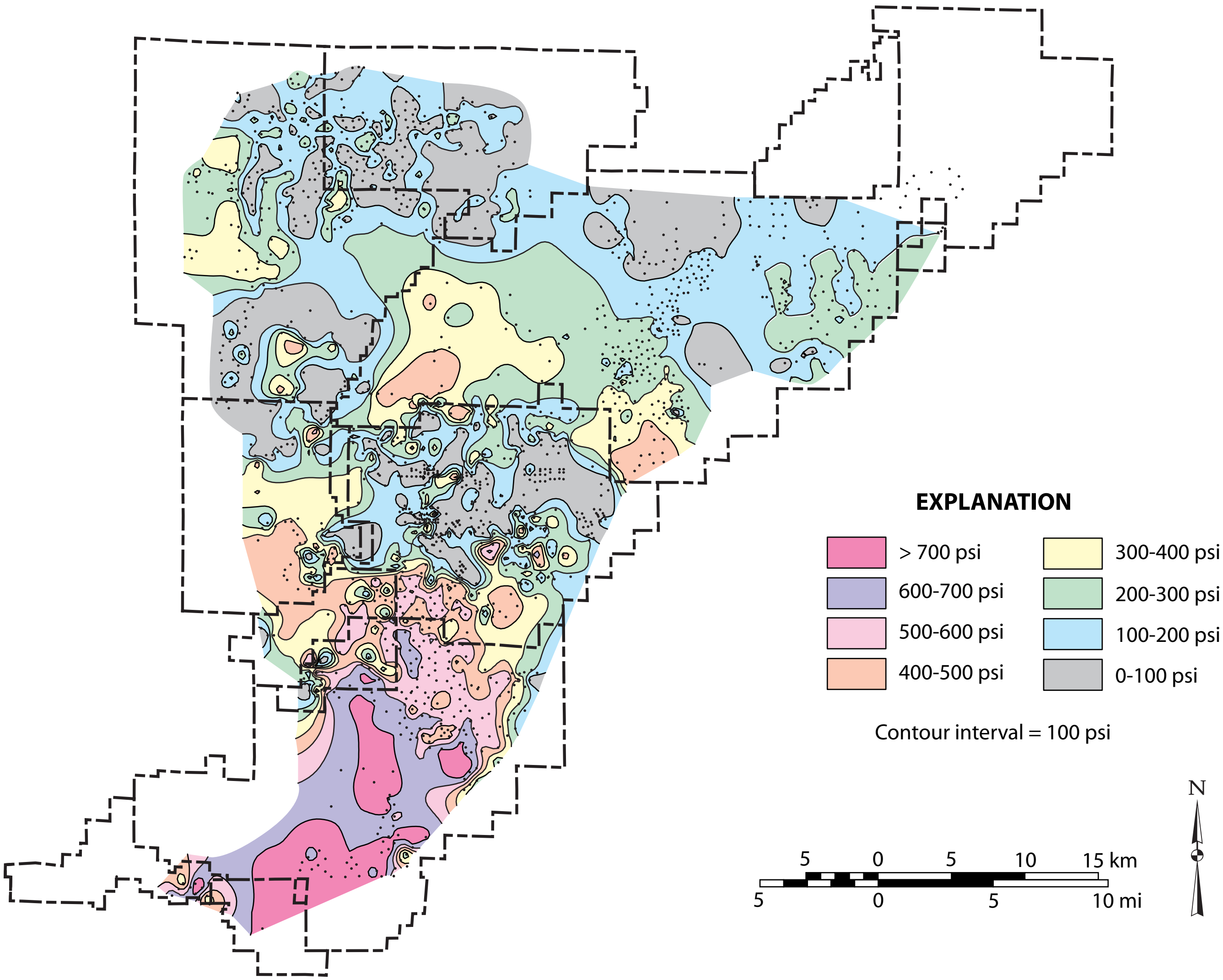



Figure 49.--Map of hydrostatic pressure at the top of the Pratt coal zone in the Black Warrior coalbed methane fairway.

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. 48) 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. 48) 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 $CO_2$. This effect may be mitigated by shrinkage of the coal matrix as gas is desorbed or may be exacerbated by swelling as $CO_2$ 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. 34). 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. 50). 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

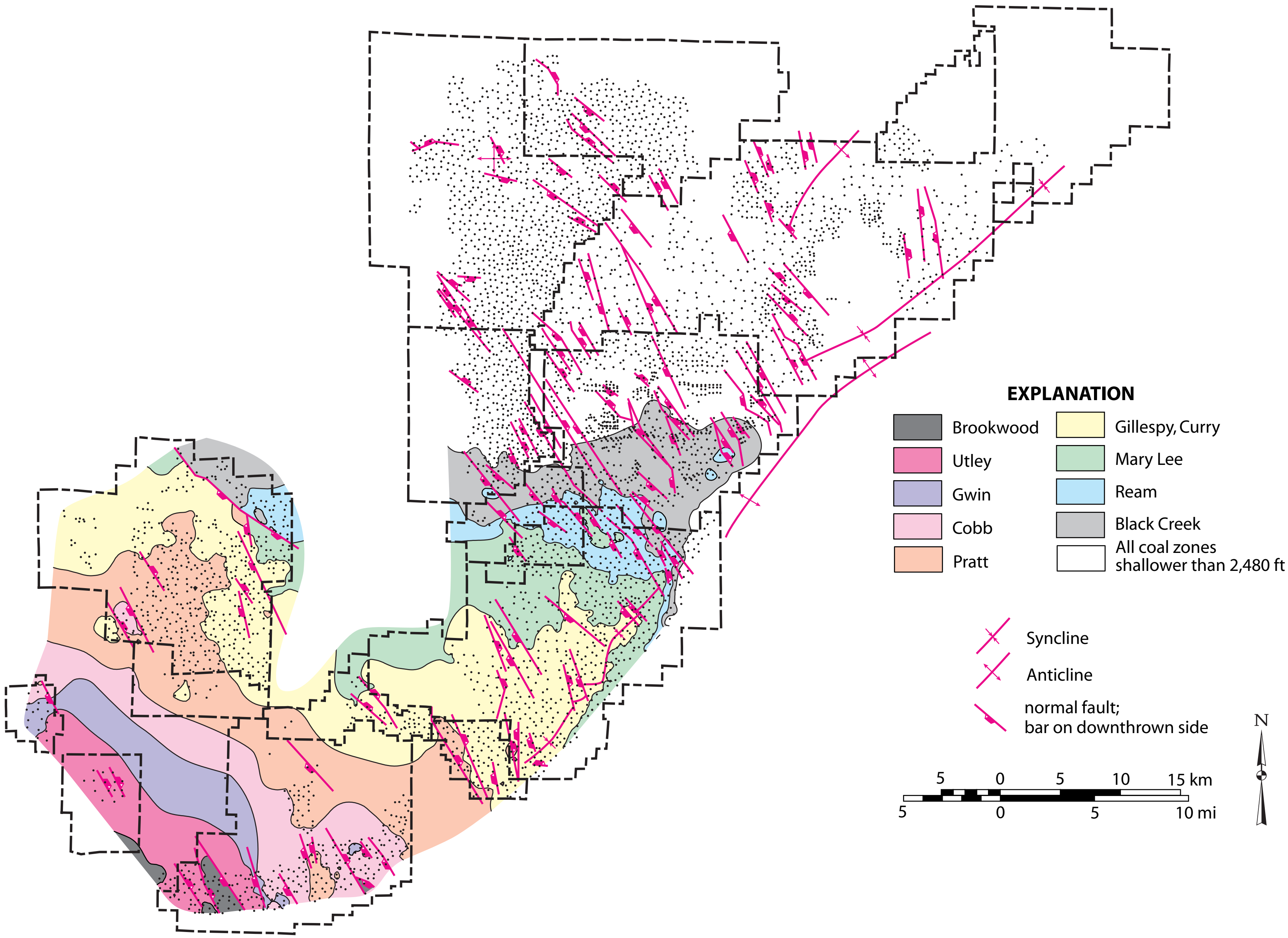



Figure 50.--Map showing shallowest unit where supercritical fluid conditions may develop for $CO_2$ in the Black Warrior coalbed methane fairway.

equilibrates to the natural system after abandonment. Furthermore, if supercritical conditions are eventually met, coal will be significantly undersaturated with $CO_2$.

Subcritical conditions prevail throughout the Pottsville Coal Interval northeast of a line running through Brookwood and Deerlick Creek fields (fig. 50). 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 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 $CO_2$ 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 $CO_2$ in coal, the reactivity of $CO_2$ with formation fluids, and the sweep efficiency of enhanced coalbed methane operations under supercritical conditions need to be researched. Additionally, the $CO_2$-$N_2$-$CH_4$ 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. 51), 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

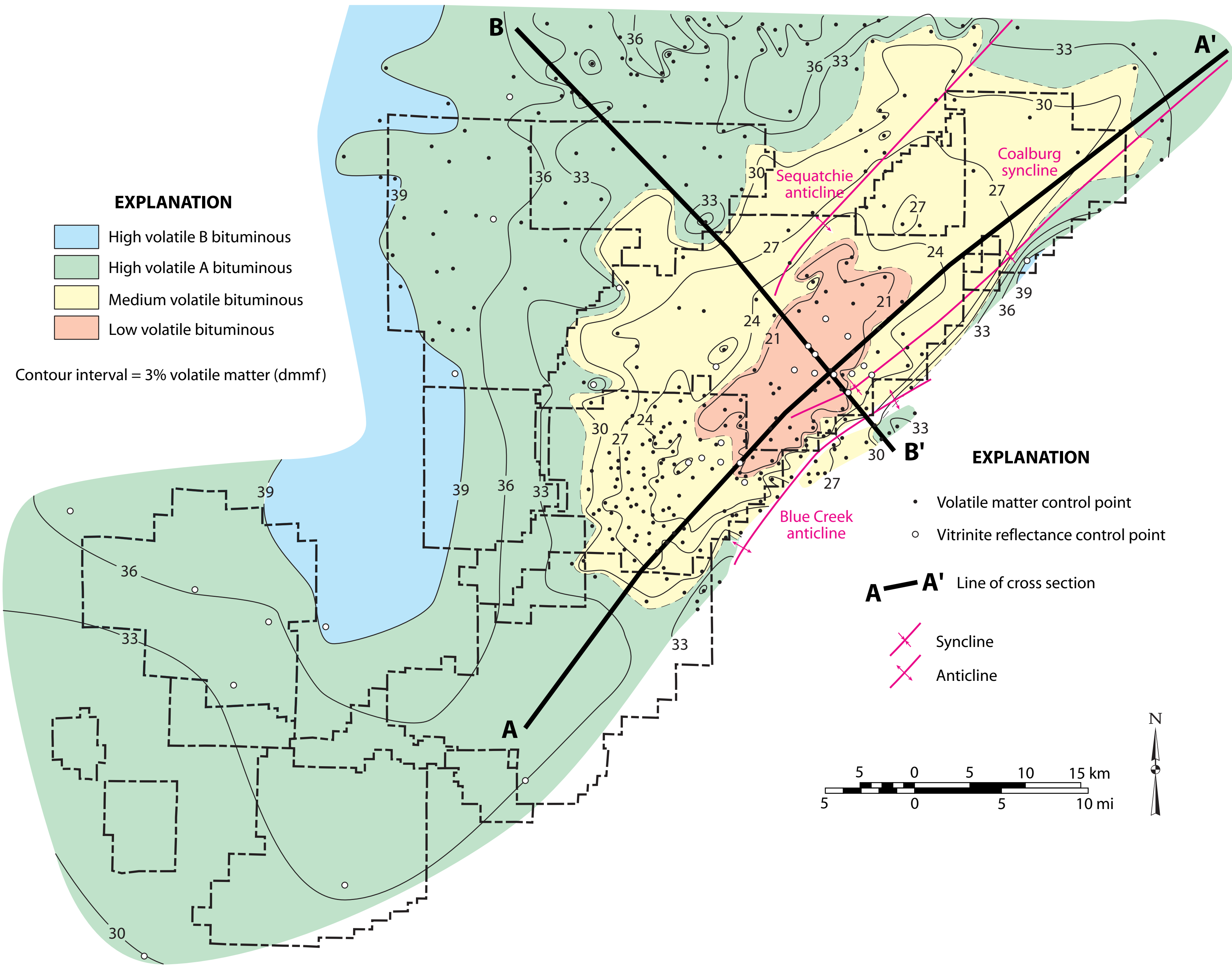



Figure 51.--Coal rank in the Black Warrior coalbed methane fairway based on volatile matter and vitrinite reflectance data from the Mary Lee coal zone.

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 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. 52). 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, 51). Similarly, isovols in most areas are oblique or even perpendicular to strike of the southwest-dipping homocline of the Black Warrior basin (figs. 21, 51). 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 500 and 1,000 feet, provide the best opportunity to determine if a relationship exists and should be the object of future research.

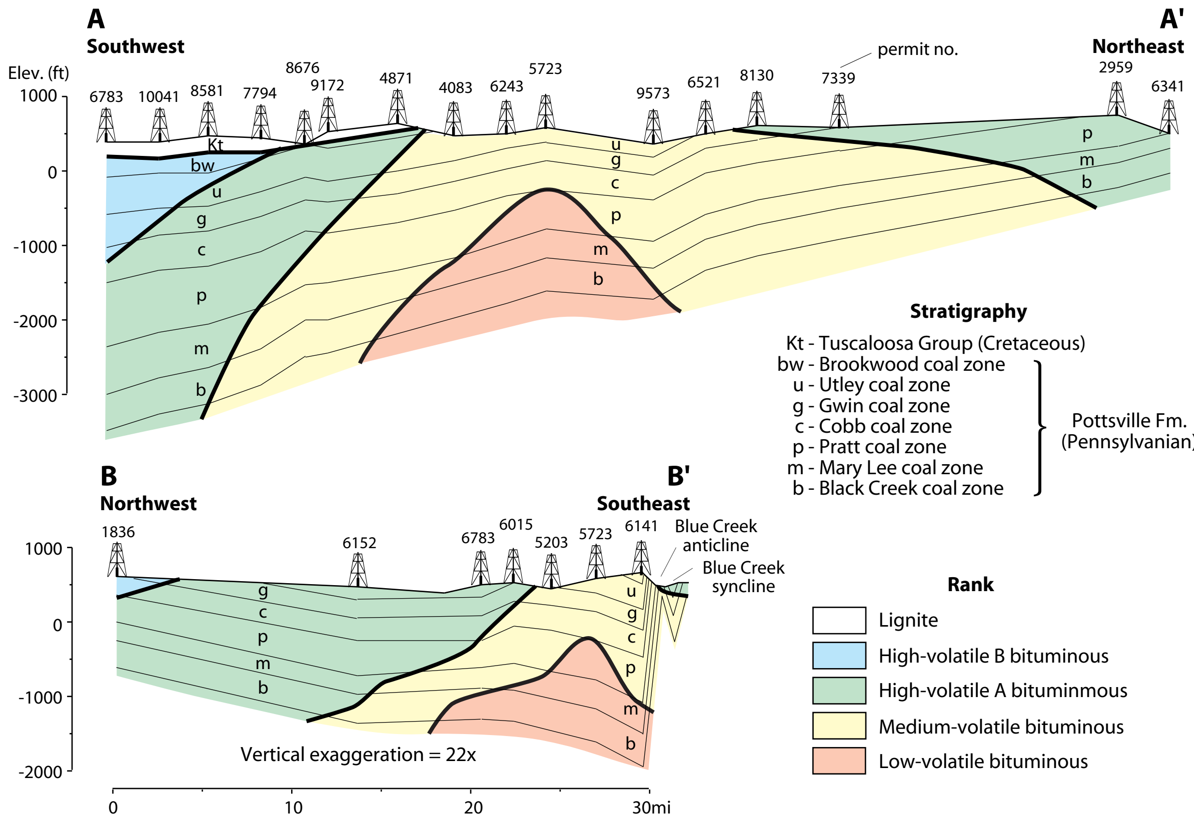



Figure 52.--Cross sections showing the relationship of rank to structure in the Black Warrior coalbed methane fairway (modified from Pashin and others, 1999).

An obvious relationship between rank pattern and thrust belt structure is the strong parallelism of isovols to the forelimb of the Birmingham anticlinorium (fig. 51). 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. 53). 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).

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, 21, 54) 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

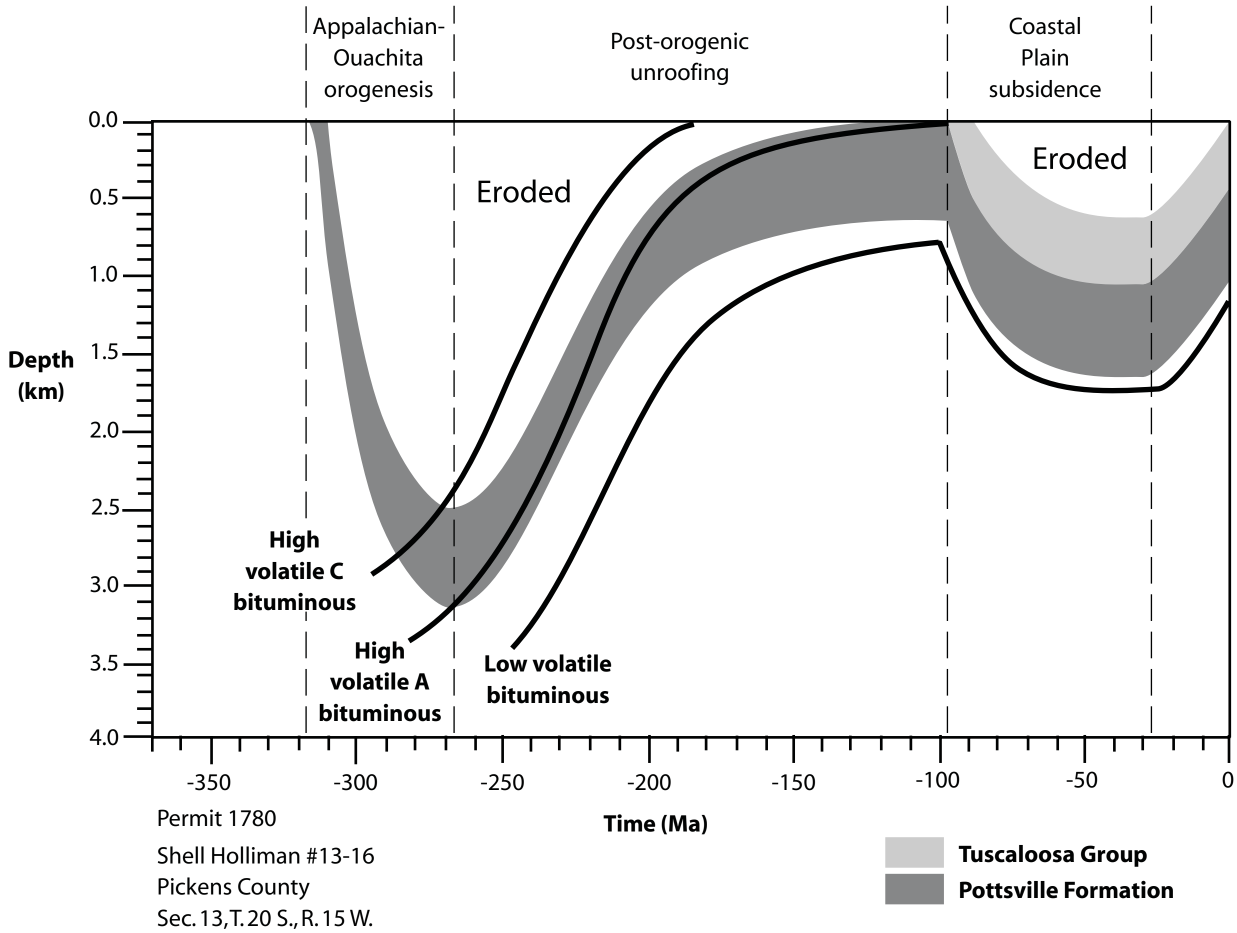



Figure 53.--Generalized relationship between burial history and thermal maturation in the Black Warrior basin (after Carroll and others, 1995).

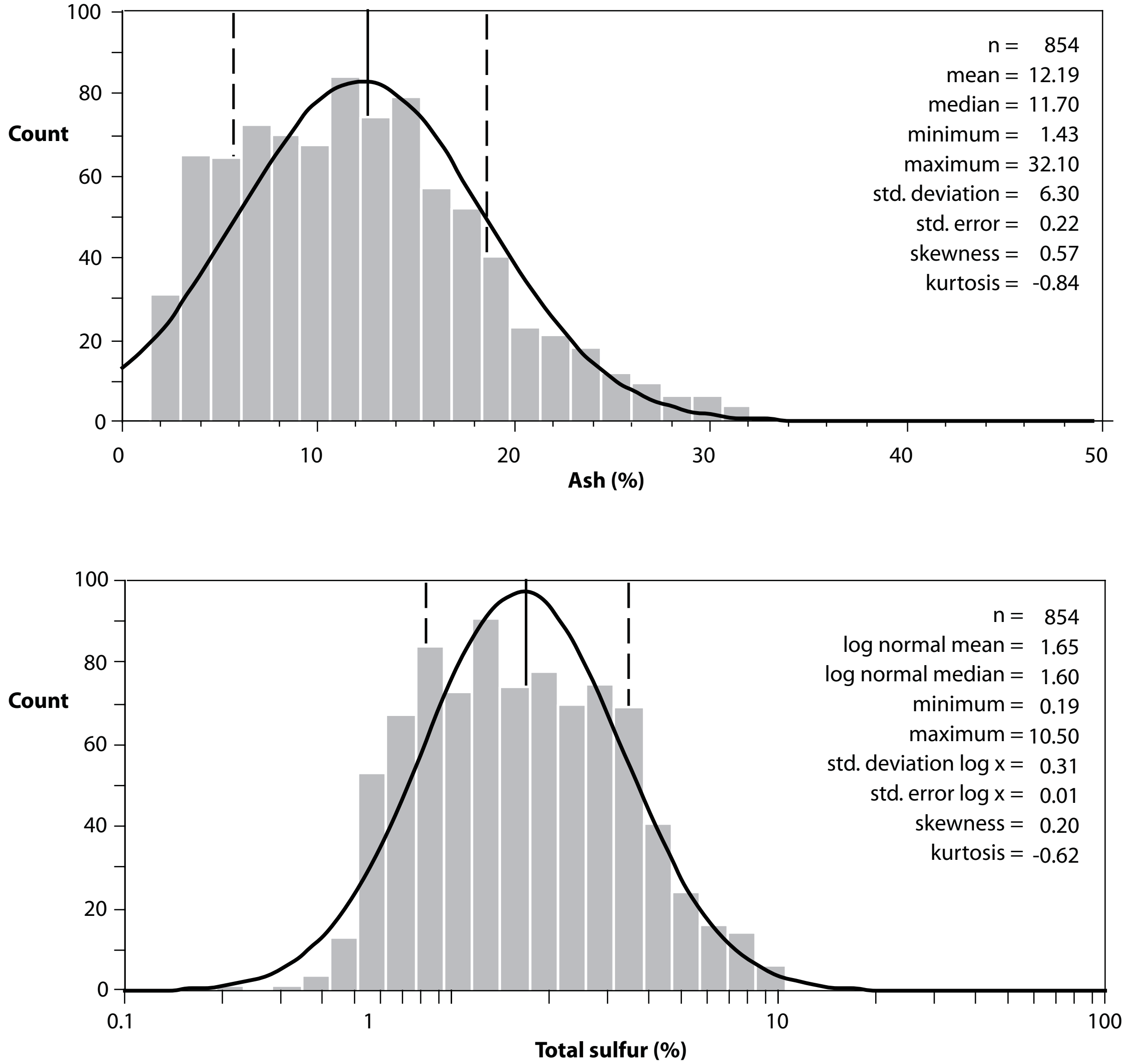



Figure 54.--Histograms showing ash and total sulfur content in coal of the Black Warrior basin.

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. 52). 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. 54). Mean ash content is 12 percent, and values between 6 and 18 percent fall within one standard deviation of the mean.

Some stratigraphic trends of ash content are apparent in the Pottsville Formation (fig. 55). 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. 56). 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

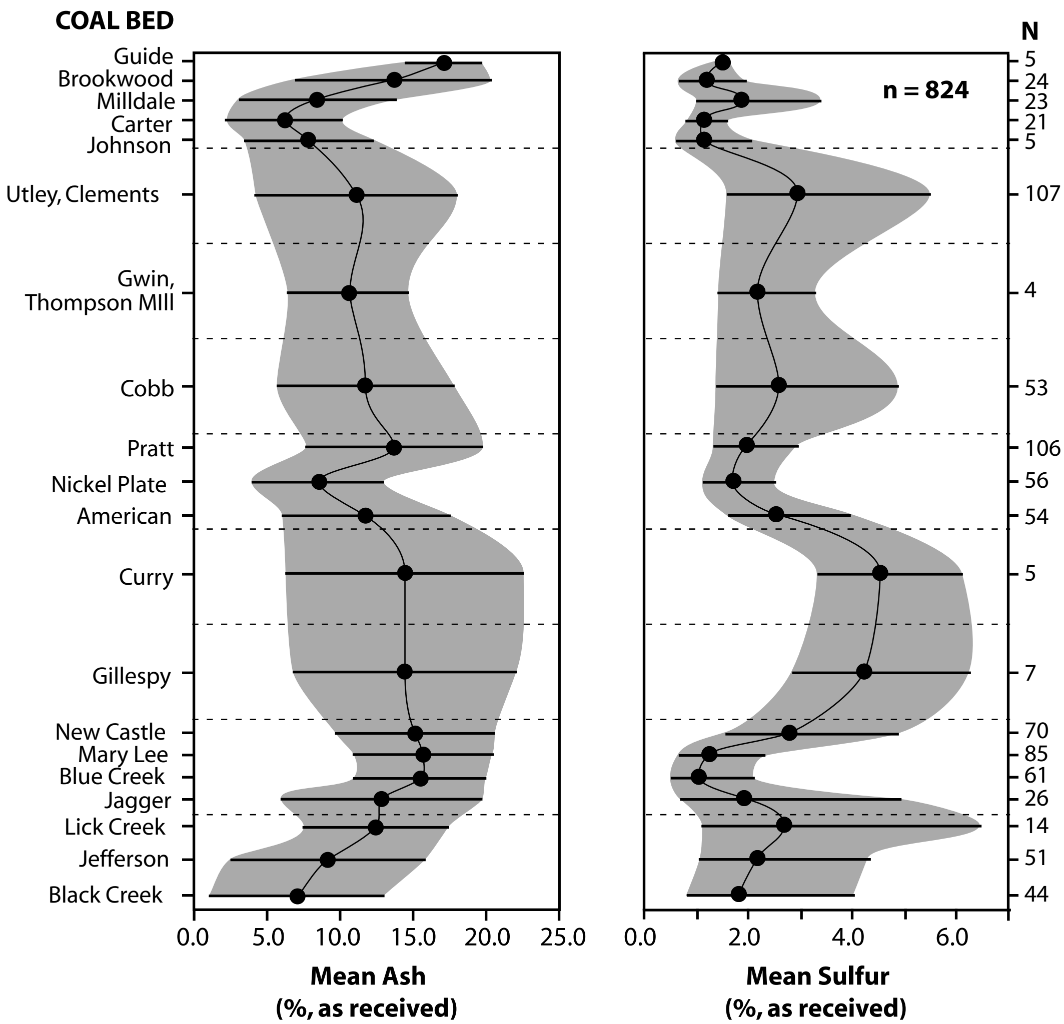



Figure 55.--Relationship of ash and sulfur content to stratigraphy in the Black Warrior basin. Dots mark mean, and shaded area marks values within one standard deviation from the mean.

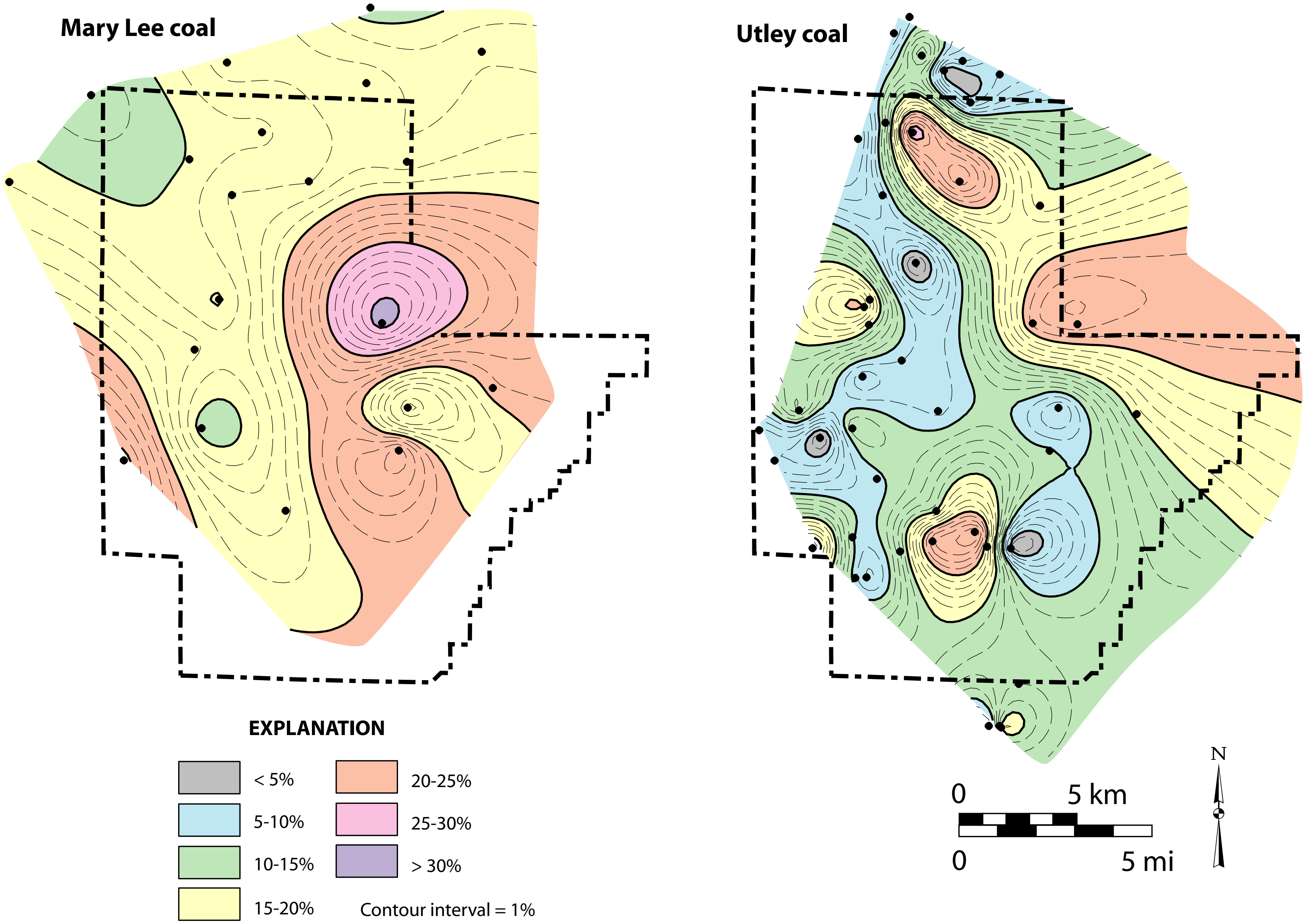



Figure 56.--Maps showing variability of ash content in the Mary Lee and Utley coal beds in Blue Creek Field.

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 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. 54). 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. 55). 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. 57). Regression analysis indicates that organic sulfur content is nearly invariant with respect to total sulfur (fig. 58). Pyritic sulfur, by contrast, has a much wider range of values than organic sulfur (fig. 57). Pyritic sulfur content has a log normal mean of 0.7 percent

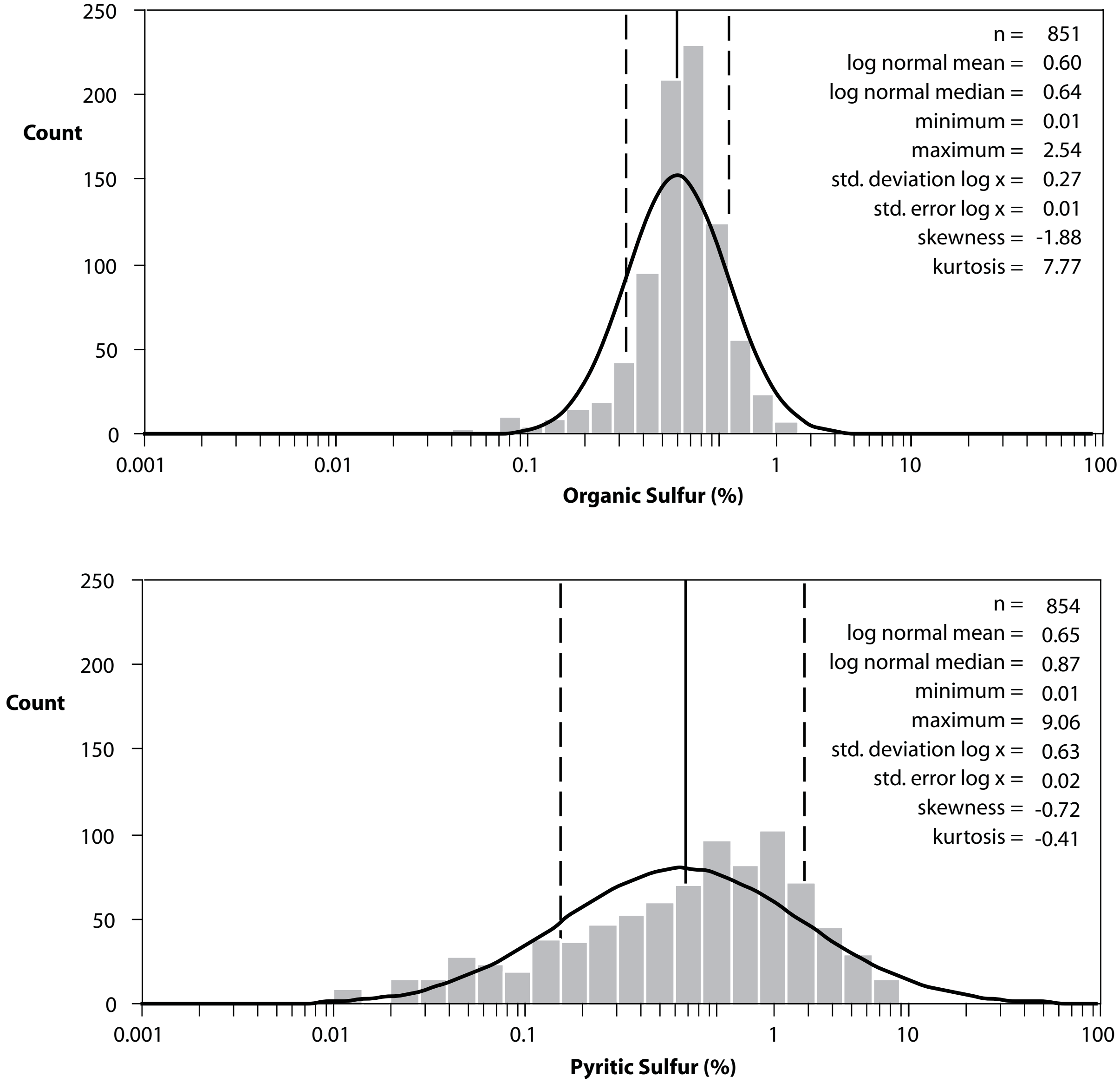



Figure 57.--Histograms showing organic and pyritic sulfur content in coal of the Black Warrior basin.

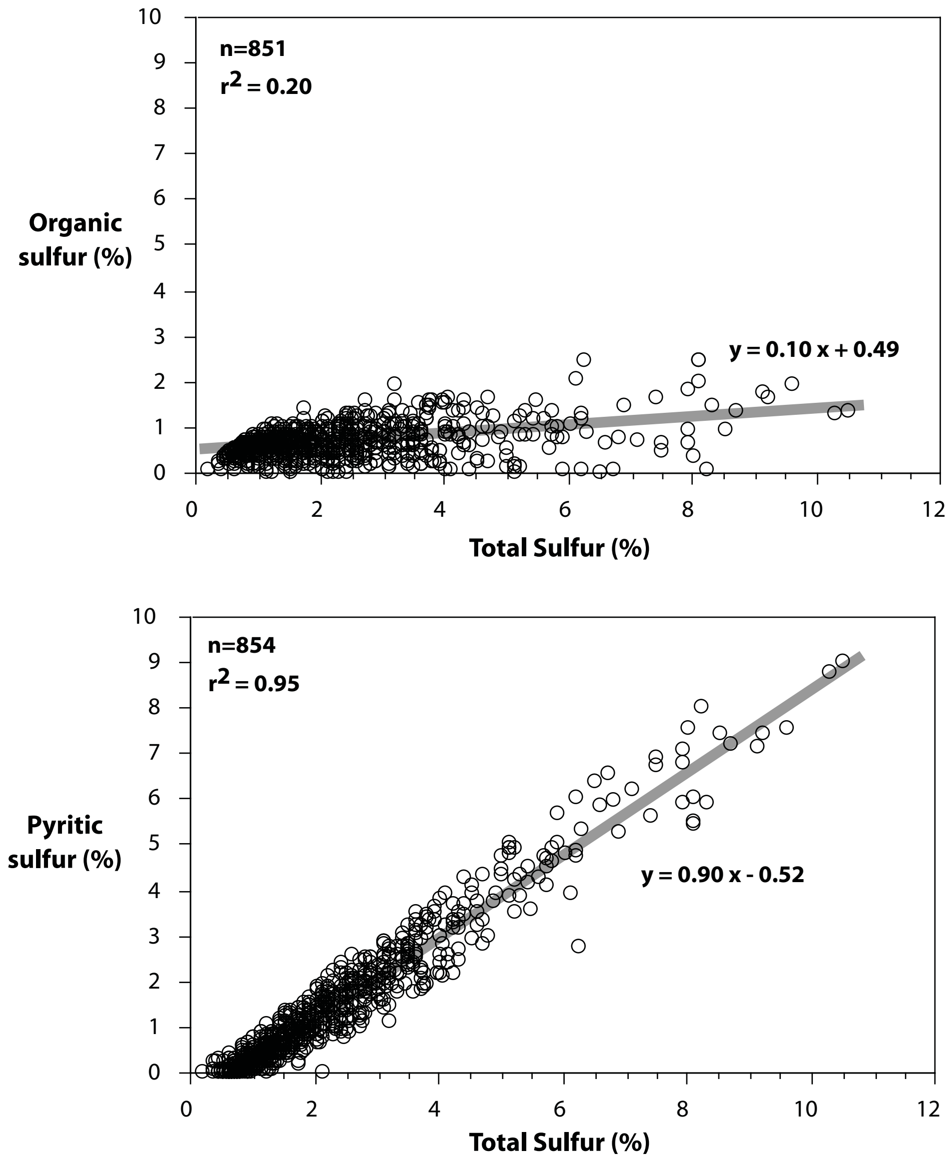



Figure 58.--Regression plots of sulfur forms versus total sulfur in coal of the Black Warrior basin.

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 Black Warrior basin coal at concentrations above 0.6 percent (fig. 58). 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. 59), 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. 59) 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.

## 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

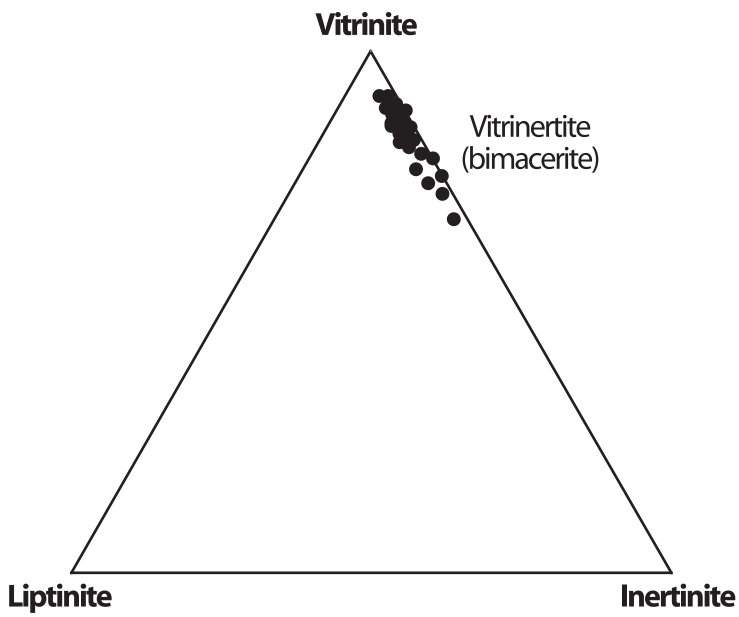



Figure 59.--Ternary plot showing maceral composition of coal samples used for sorption-isotherm, proximate, and ultimate analysis in this study.

may result in complete isothermal saturation of coal with $CO_2$, 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 $CO_2$, which is the greenhouse gas to be sequestered, $CH_4$, which is the objective of enhanced coalbed methane recovery, and $N_2$, which is the dominant constituent of the gas emission stream from coal-fired power plants. Importantly, both $CO_2$ and $N_2$ 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. 60; table 2). Isotherms for $CO_2$ 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 $CO_2$ than $CH_4$ or $N_2$ (Arri and others, 1992; Harpalani and Pariti, 1993; Hall and others, 1994). Interestingly, the three gases show limited overlap in overall sorption performance.

Isotherms from individual coal samples indicate that above 500 psi, coal holds about twice as much $CO_2$ as $CH_4$ and about twice as much $CH_4$ as $N_2$ (fig. 61). These isotherms also show the impact of calculating sorption capacity on different bases. The low moisture percentages in 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.

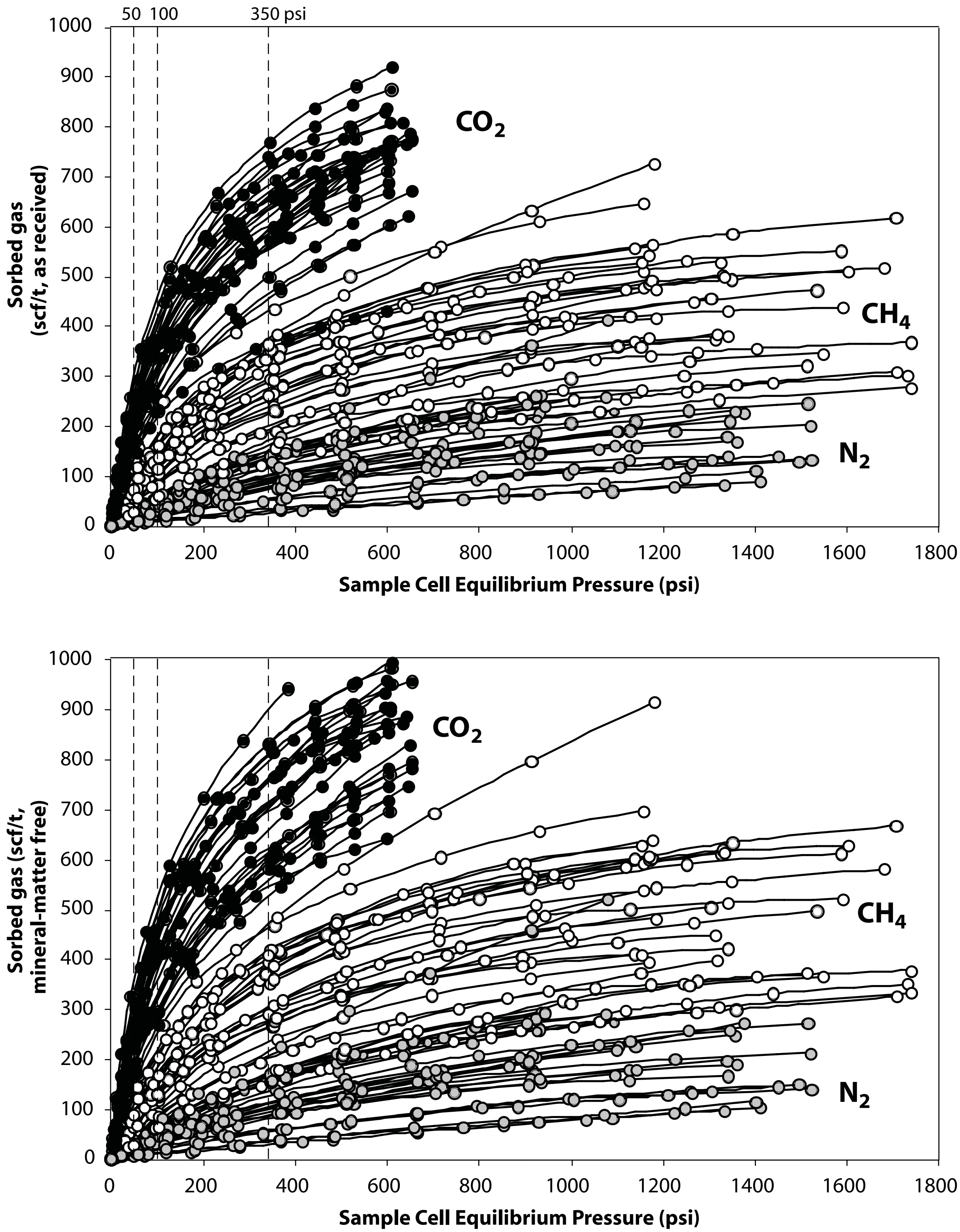



Figure 60.--Isotherm plots showing the capacity of coal in the Black Warrior basin to sorb carbon dioxide, methane, and nitrogen.

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

| Sample Number | Gas | Adsorption @ 50 psi AR (scf/t) | Adsorption @ 50 psi MAF (scf/t) | Adsorption @ 50 psi DMMF (scf/t) | Adsorption @ 100 psi AR (scf/t) | Adsorption @ 100 psi MAF (scf/t) | Adsorption @ 100 psi DMMF (scf/t) | Adsorption @ 350 psi AR (scf/t) | Adsorption @ 350 psi MAF (scf/t) | Adsorption @ 350 psi DMMF (scf/t) |
|---|---|---|---|---|---|---|---|---|---|---|
| AL-CU-TP1-2.0 | $CH_4$ | 38.9 | 39.7 | 41.0 | 75.3 | 76.9 | 79.5 | 198.7 | 202.9 | 209.8 |
| | $CO_2$ | 184.5 | 188.4 | 194.8 | 300.2 | 306.6 | 317.1 | 595.4 | 608.2 | 628.9 |
| | $N_2$ | 8.5 | 8.7 | 8.9 | 16.3 | 16.6 | 17.2 | 51.9 | 53.1 | 54.8 |
| AL-JE-BCCFT-1.0 | $CH_4$ | 49.3 | 51.2 | 52.3 | 86.3 | 89.5 | 91.4 | 225.8 | 234.1 | 239.2 |
| | $CO_2$ | 199.9 | 207.2 | 211.7 | 305.4 | 316.6 | 323.5 | 555.6 | 576.1 | 588.7 |
| | $N_2$ | 11.7 | 12.1 | 12.4 | 26.3 | 27.3 | 27.9 | 77.5 | 80.4 | 82.0 |
| AL-JE-MRM-1.0 | $CH_4$ | 39.2 | 40.8 | 41.8 | 92.2 | 96.0 | 98.5 | 253.3 | 263.8 | 270.5 |
| | $CO_2$ | 176.0 | 183.3 | 188.0 | 299.0 | 311.4 | 319.4 | 586.8 | 611.0 | 626.7 |
| | $N_2$ | 15.3 | 15.9 | 16.4 | 32.0 | 33.3 | 34.2 | 96.1 | 100.0 | 102.6 |
| AL-JE-TPLM-1.0 | $CH_4$ | 63.1 | 71.9 | 74.1 | 112.4 | 128.2 | 132.2 | 263.1 | 299.9 | 309.3 |
| | $CO_2$ | 212.9 | 242.7 | 250.4 | 329.7 | 375.9 | 387.7 | 602.7 | 687.1 | 708.6 |
| | $N_2$ | 19.9 | 22.7 | 23.4 | 29.9 | 34.1 | 35.1 | 87.5 | 99.8 | 102.9 |
| AL-MA-LM1-1.0 | $CH_4$ | 29.7 | 33.9 | 35.7 | 56.2 | 64.2 | 67.5 | 142.1 | 162.3 | 170.9 |
| | $CO_2$ | 153.1 | 174.8 | 184.0 | 250.1 | 285.6 | 300.7 | 502.5 | 573.9 | 604.1 |
| | $N_2$ | 3.5 | 4.1 | 4.3 | 7.0 | 8.0 | 8.4 | 24.3 | 27.8 | 29.3 |
| AL-MA-LM2-1.0 | $CH_4$ | 23.1 | 27.1 | 28.7 | 46.4 | 54.3 | 57.5 | 126.8 | 148.7 | 157.2 |
| | $CO_2$ | 147.5 | 172.9 | 182.9 | 235.3 | 275.8 | 291.7 | 467.5 | 547.9 | 579.7 |
| | $N_2$ | 4.5 | 5.2 | 5.6 | 8.9 | 10.4 | 11.1 | 28.4 | 33.4 | 35.3 |
| AL-MA-MB2-1.0 | $CH_4$ | 28.5 | 29.8 | 31.6 | 53.3 | 55.6 | 59.0 | 143.4 | 149.7 | 158.7 |
| | $CO_2$ | 172.8 | 180.3 | 191.2 | 270.4 | 282.2 | 299.3 | 571.6 | 596.5 | 632.7 |
| | $N_2$ | 5.6 | 5.9 | 6.2 | 10.6 | 11.0 | 11.7 | 33.3 | 34.8 | 36.9 |
| AL-TU-EPBC-1131.2 | $CH_4$ | 47.8 | 52.3 | 54.3 | 102.0 | 111.5 | 115.8 | 238.0 | 260.1 | 270.1 |
| | $CO_2$ | 191.1 | 208.9 | 216.8 | 311.0 | 340.0 | 353.0 | 597.4 | 653.0 | 678.1 |
| | $N_2$ | 16.9 | 18.4 | 19.1 | 28.8 | 31.5 | 32.7 | 77.8 | 85.1 | 88.3 |
| AL-TU-EPBC-1690.2 | $CH_4$ | 58.5 | 69.0 | 71.7 | 101.4 | 119.7 | 124.3 | 228.6 | 269.8 | 280.4 |
| | $CO_2$ | 198.3 | 234.1 | 243.3 | 313.6 | 370.2 | 384.7 | 586.8 | 692.6 | 719.8 |
| | $N_2$ | 11.2 | 13.2 | 13.8 | 21.7 | 25.6 | 26.6 | 73.9 | 87.2 | 90.6 |
| AL-TU-EPBC-2051.2 | $CH_4$ | 39.2 | 40.3 | 41.3 | 79.7 | 81.9 | 83.8 | 195.4 | 200.8 | 205.6 |
| AL-TU-JWR41-1.0 | $CH_4$ | 74.8 | 82.9 | 85.1 | 136.7 | 151.6 | 155.6 | 314.9 | 349.2 | 358.4 |
| | $CO_2$ | 269.6 | 299.0 | 306.9 | 422.9 | 469.1 | 481.4 | 743.9 | 825.0 | 846.6 |
| | $N_2$ | 16.6 | 18.4 | 18.9 | 30.0 | 33.3 | 34.2 | 84.1 | 93.4 | 95.8 |
| AL-TU-JWR41-2.0 | $CH_4$ | 79.2 | 85.0 | 86.8 | 148.3 | 159.1 | 162.6 | 342.9 | 367.7 | 375.9 |
| | $CO_2$ | 292.2 | 313.4 | 320.4 | 443.0 | 475.1 | 485.7 | 771.4 | 827.3 | 845.9 |
| | $N_2$ | 19.6 | 21.1 | 21.5 | 36.5 | 39.2 | 40.0 | 100.6 | 107.9 | 110.3 |
| AL-TU-JWR626-1400.0 | $CH_4$ | 97.9 | 111.6 | 114.9 | 175.3 | 199.7 | 205.7 | 347.5 | 396.0 | 407.9 |
| | $CO_2$ | 232.4 | 264.9 | 272.8 | 374.5 | 426.8 | 439.6 | 656.3 | 747.9 | 770.3 |
| | $N_2$ | 18.4 | 21.0 | 21.6 | 38.6 | 44.0 | 45.3 | 118.0 | 134.5 | 138.6 |
| AL-TU-JWR626-1947.5 | $CH_4$ | 65.5 | 73.0 | 75.0 | 130.6 | 145.5 | 149.6 | 351.2 | 391.4 | 402.4 |
| | $CO_2$ | 217.9 | 242.9 | 249.8 | 349.6 | 389.6 | 400.5 | 631.9 | 704.2 | 724.0 |
| | $N_2$ | 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).

| | | Adsorption @ 50 psi | | | Adsorption @ 100 psi | | | Adsorption @ 350 psi | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sample Number | Gas | 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 | $CH_4$ | 51.3 | 57.7 | 59.8 | 110.9 | 124.7 | 129.2 | 266.5 | 299.8 | 310.6 |
| | $CO_2$ | 223.5 | 251.3 | 260.4 | 354.4 | 398.5 | 413.0 | 663.1 | 745.7 | 772.7 |
| | $N_2$ | 15.9 | 17.9 | 18.6 | 31.2 | 35.0 | 36.4 | 90.0 | 101.3 | 104.9 |
| AL-WA-HV2-1.0 | $CH_4$ | 27.6 | 31.4 | 32.7 | 54.7 | 62.1 | 64.7 | 151.2 | 172.0 | 179.0 |
| | $CO_2$ | 133.9 | 152.2 | 158.5 | 226.9 | 257.9 | 268.6 | 458.0 | 520.8 | 542.4 |
| | $N_2$ | 12.8 | 14.5 | 15.2 | 20.5 | 23.3 | 24.2 | 49.7 | 56.5 | 58.8 |
| AL-WA-NV-1.0 | $CH_4$ | 26.1 | 27.2 | 28.5 | 56.7 | 59.0 | 62.1 | 162.3 | 168.9 | 177.7 |
| | $CO_2$ | 165.2 | 172.0 | 180.9 | 273.0 | 284.3 | 298.9 | 564.7 | 588.0 | 618.3 |
| | $N_2$ | 7.9 | 8.2 | 8.6 | 16.1 | 16.8 | 17.6 | 52.2 | 54.3 | 57.1 |

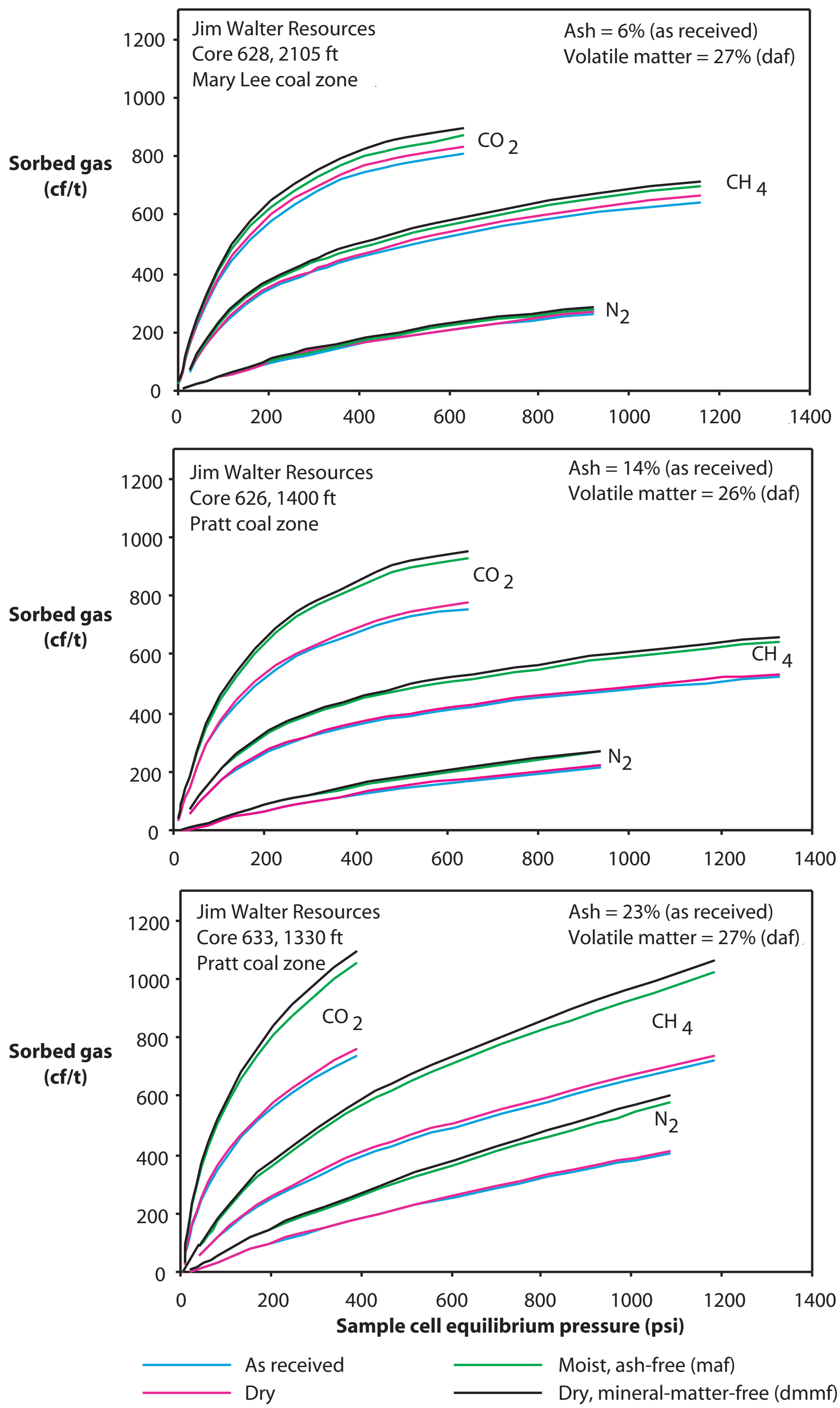



Figure 61.--Comparison of isotherms calculated on different bases in coal of variable ash content and constant rank.

Sorption capacity correlates significantly with volatile matter and ash content (figs. 62-65; 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. 62, 63). Interestingly, $CO_2$ (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 $CH_4$ and 0.78 to 0.89 for $N_2$).

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. 64, 65). On an as-received basis, $CO_2$ capacity is most poorly correlated with ash content (r = 0.00 to 0.14), and $N_2$ 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. 65). Examination of the scatterplots indicates that data points tend to be widely scattered and that the 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. 66).

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

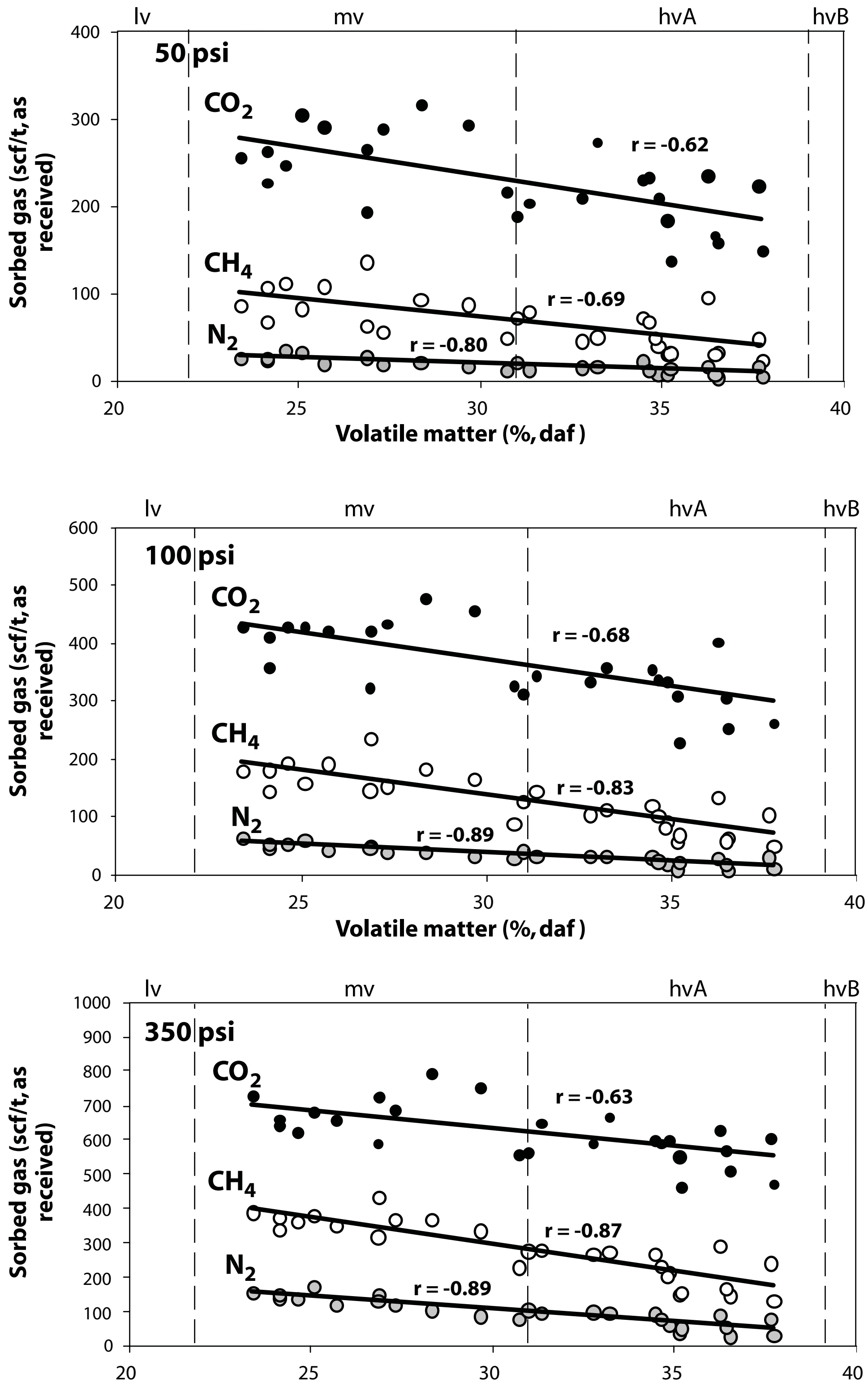



Figure 62.--Scatterplots showing correlation between sorption capacity (as-received) and volatile matter (daf)

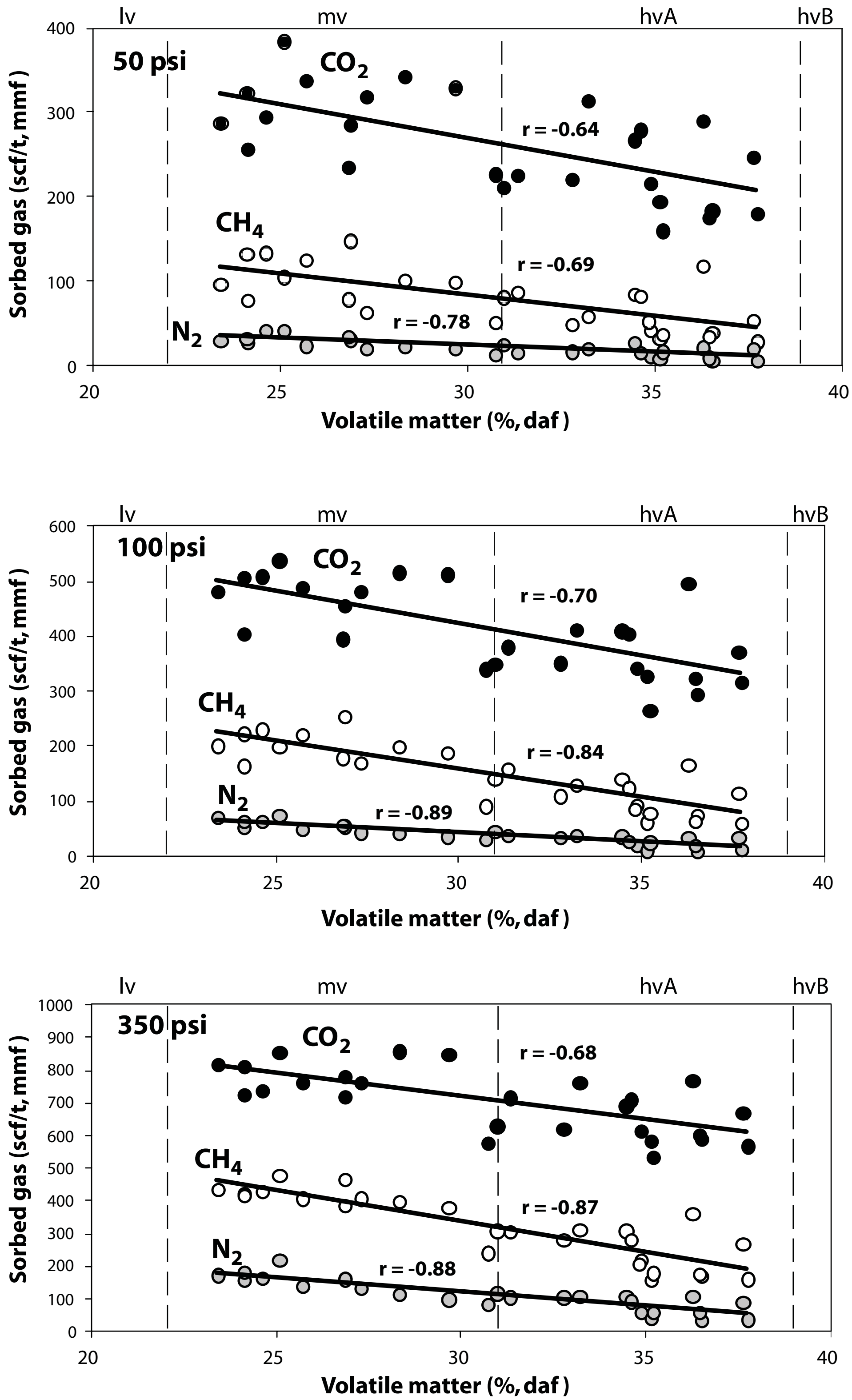



Figure 63.--Scatterplots showing correlation between sorption capacity (mmf) and volatile matter (daf)

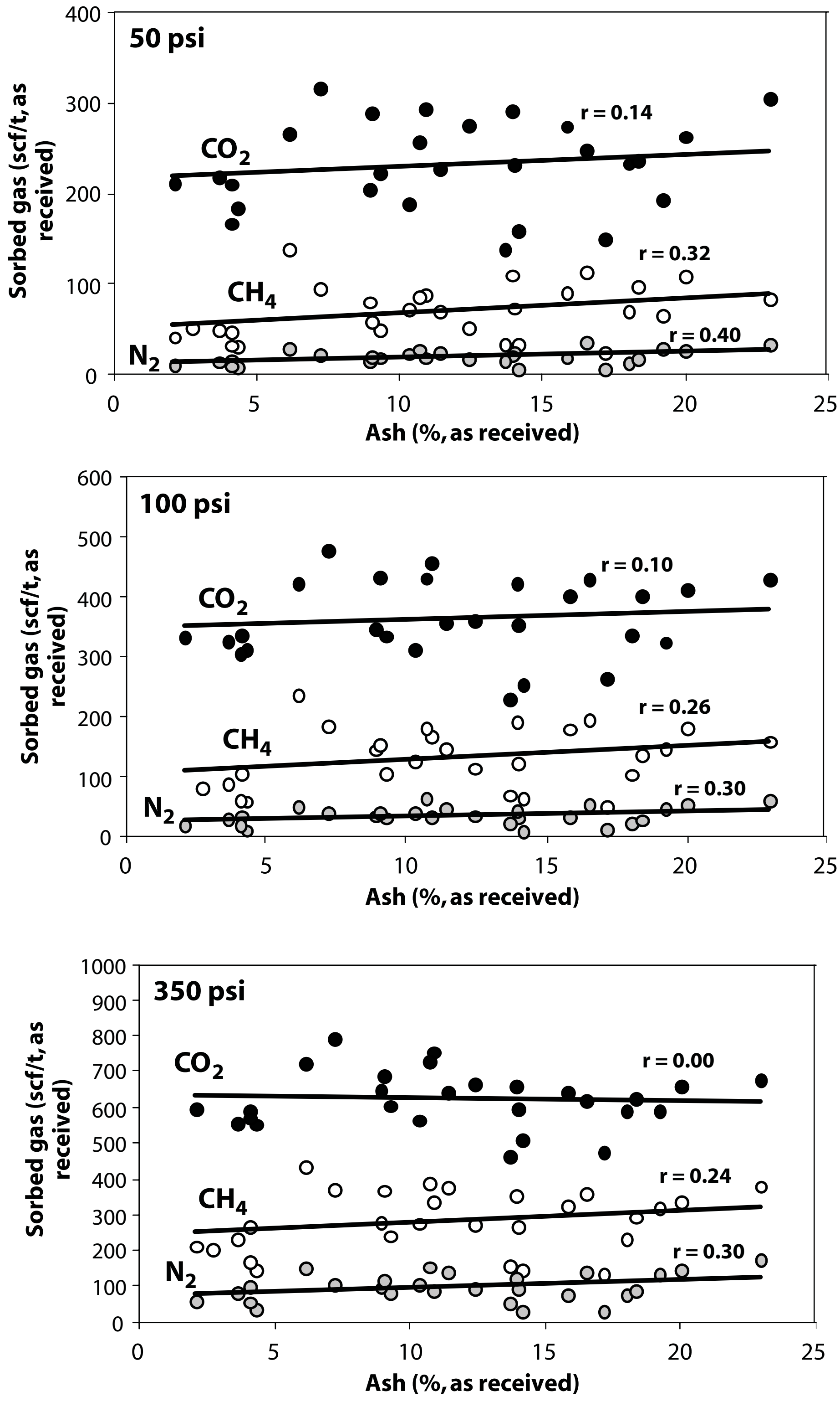
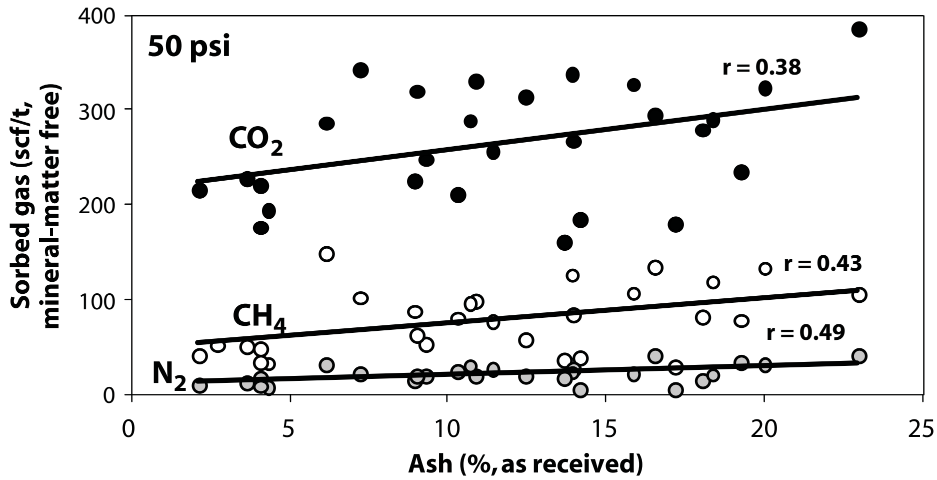
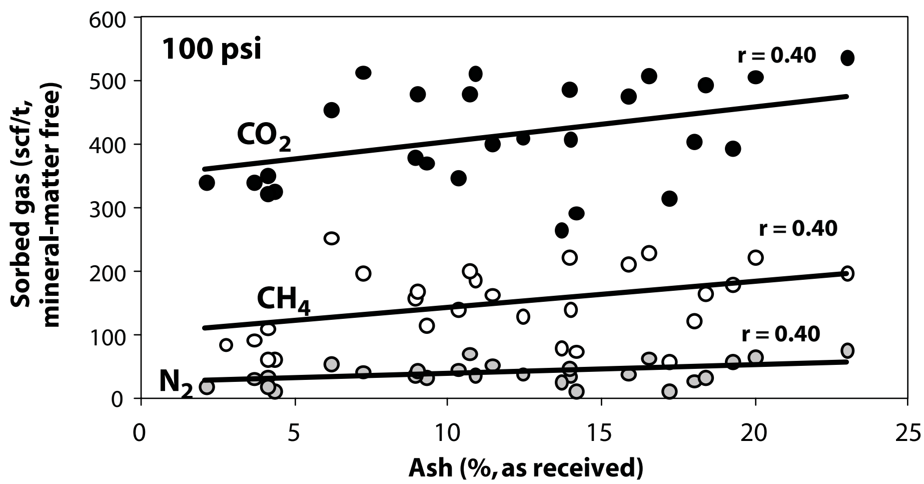



Figure 64.--Scatterplots showing correlation between sorption capacity (as-received) and ash content (as-received).



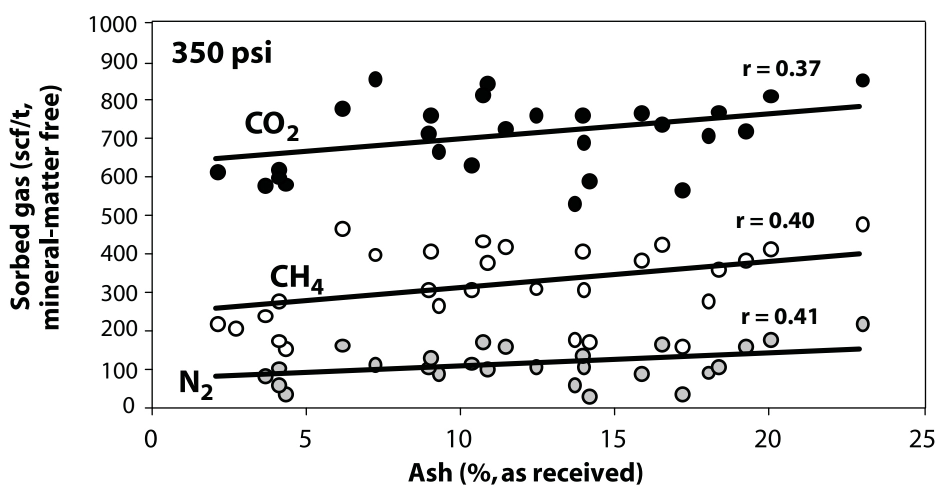




Figure 65.--Scatterplots showing correlation between sorption capacity (mmf) and ash content (as-received).

Table 3. Results of proximate analysis.

| Sample Number | As Received<br>Moisture<br>% | Ash<br>% | Fixed Carbon<br>% | Volatile matter<br>% | Calorific value<br>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).

| | As Received | | | | |
|---|---|---|---|---|---|
| | Moisture | Ash | Fixed Carbon | Volatile matter | Calorific value |
| Sample Number | % | % | % | % | 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.

| | Dry Basis | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | C | H | N | O | Mineral Matter | Total S | Sulfatic S | Organic S | Pyritic S |
| Sample Number | % | % | % | % | % | % | % | % | % |
| 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).

| | Dry Basis | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | C | H | N | O | Mineral Matter | Total S | Sulfatic S | Organic S | Pyritic S |
| Sample Number | % | % | % | % | % | % | % | % | % |
| 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 |

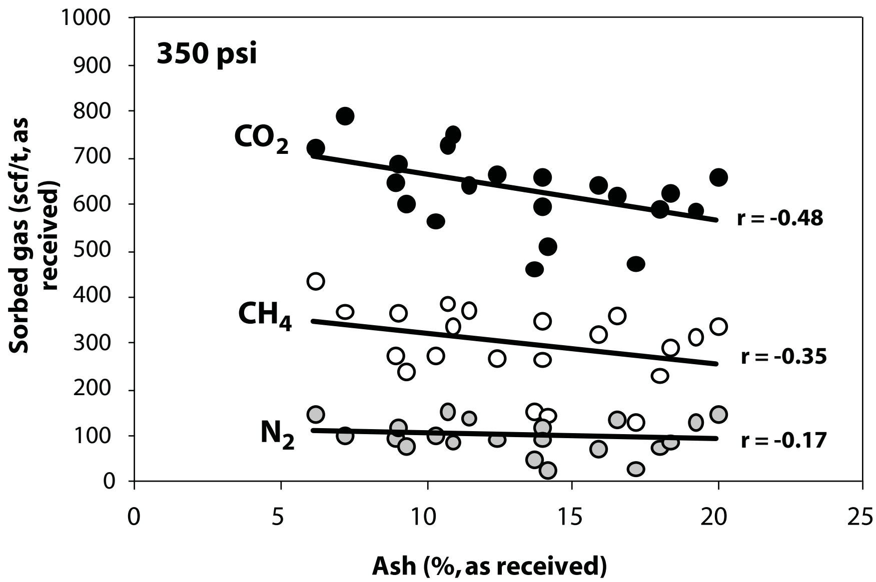



Figure 66.--Scatterplots showing negative correlation between sorption capacity (as-received) and ash content (as-received) for samples with ash content between 5 and 21 percent.

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. 62, 63), the positive correlation between ash content and sorption capacity is counterintuitive (figs. 64, 65). Although isolating data between 5 and 21 percent ash yields the expected negative correlation (fig. 66), coal with extremely low ash content (< 5 percent) nevertheless has retarded sorption potential (figs. 64, 65). The reasons for the poor performance of low-ash coal are unclear and should be the focus of further research. 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 $CH_4$ at 50 psi and 128 scf/t at 100 psi, so a large gas resource appears to remain untapped (fig. 60). At these same pressures, coal holds an average of 230 to 361 scf/t of $CO_2$, so large volumes of $CO_2$ 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 $N_2$ at these pressures, so relatively little $N_2$ 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 $N_2$ breaks through early (Stevens and others, 1999a, b), whereas early breakthrough of $CO_2$ has not been observed. This research further indicates that coal does not need to be fully saturated with $CO_2$ to drive enhanced coalbed methane recovery. Perhaps an optimal mix of $CO_2$ and $N_2$ is attainable that provides for efficient enhanced coalbed methane recovery while minimizing the cost of refining $CO_2$ 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 $CO_2$.

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. 67). 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

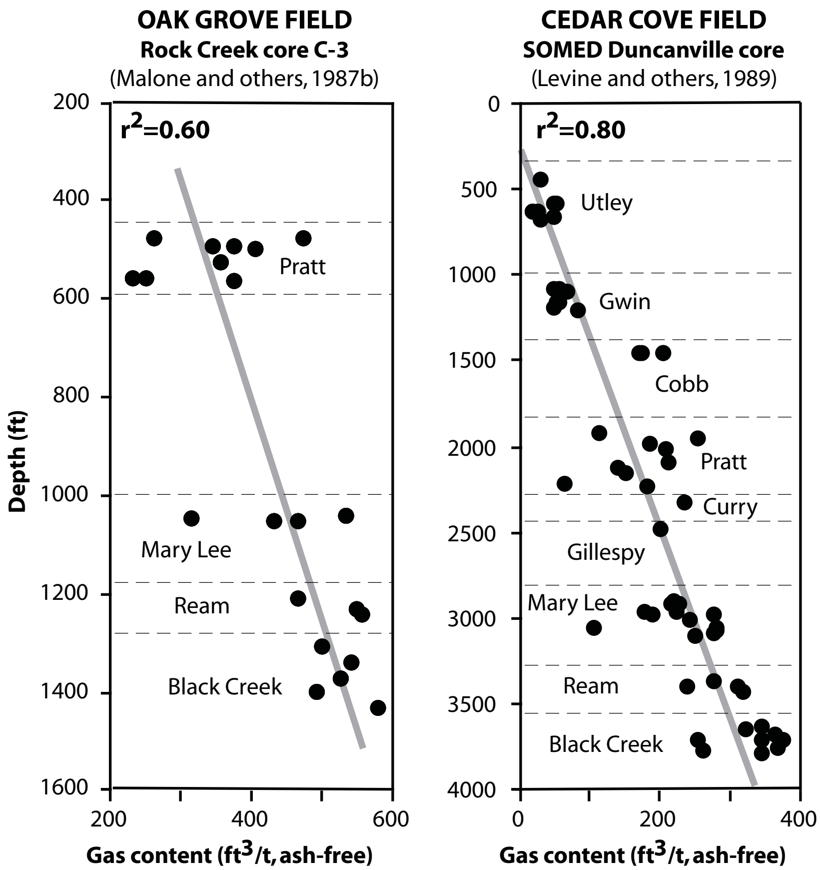



Figure 67.--Plots of gas content versus depth for two cores in the Black Warrior coalbed methane fairway.

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).

Explaining why gas content is so variable is difficult because numerous factors affect the ability of coal to generate and retain gas, as well as the accuracy of gas content measurements. Those factors include coal quality, reservoir pressure, basin hydrodynamics, and analytical error. 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. 44). Burial history analysis suggests that plume development may have begun during the late stages of Mesozoic unroofing (fig. 53).

Subsequent reburial below coastal plain strata (fig. 53) 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 $CO_2$ 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. 68). 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. 69). 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 fields are where mining has passed through vertical wells and areas of recent development peripheral to the mines.

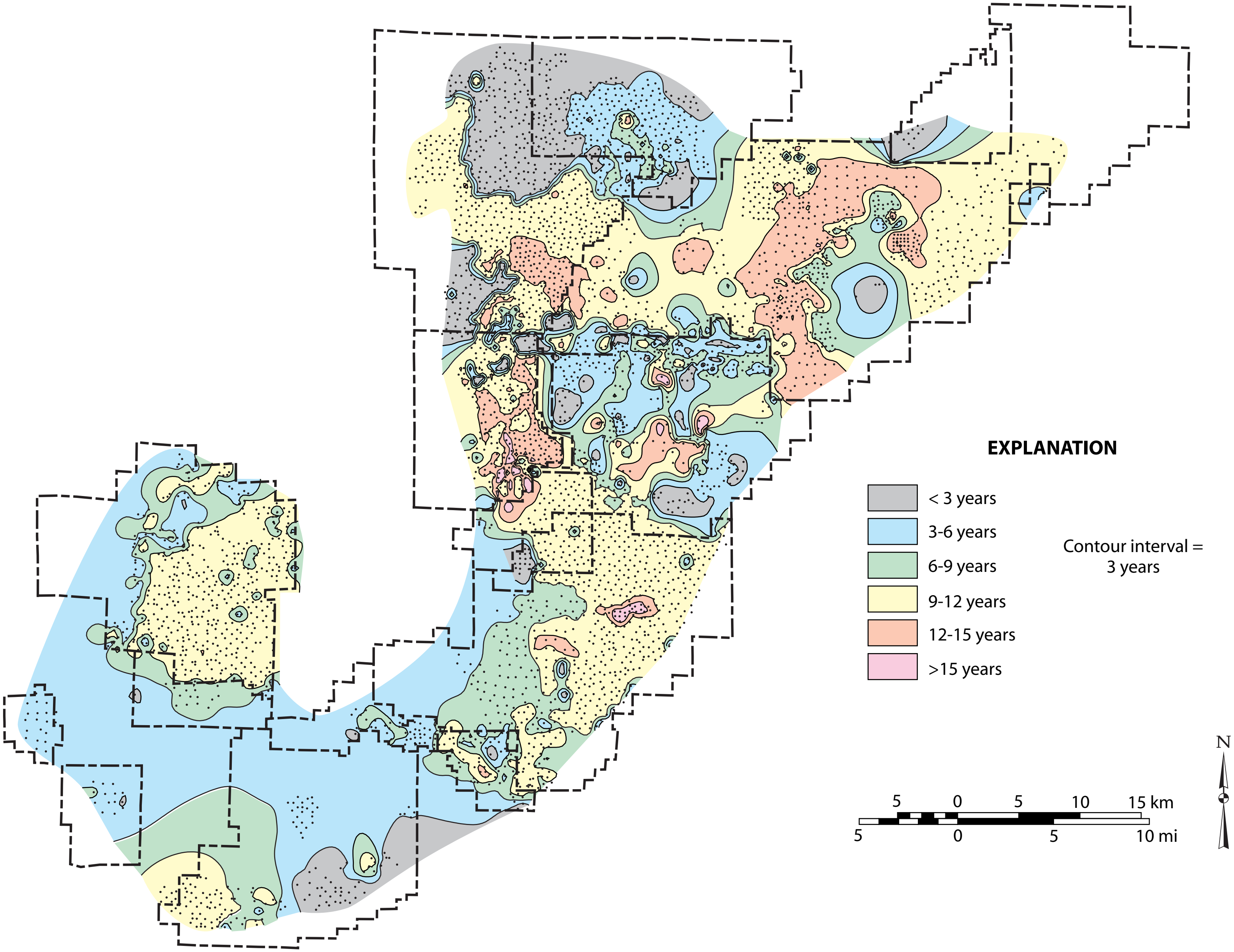



Figure 68.--Map showing years of reported production from vertical wells in the Black Warrior coalbed methane fairway.

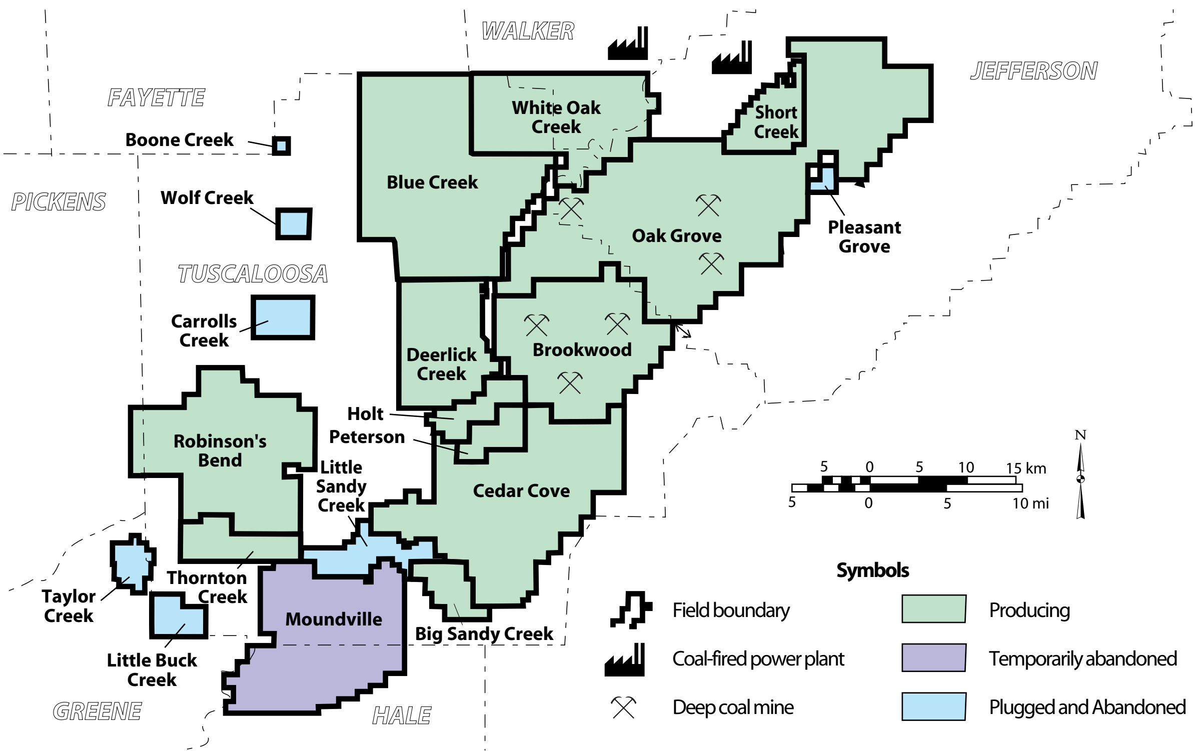



Figure 69.--Map showing generalized status of coalbed methane fields in the Black Warrior basin.

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. 70). 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. 71-73). Cumulative gas production from vertical wells has a log-normal mean of 136 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. 73). Peak gas production for wells that have produced longer than 48

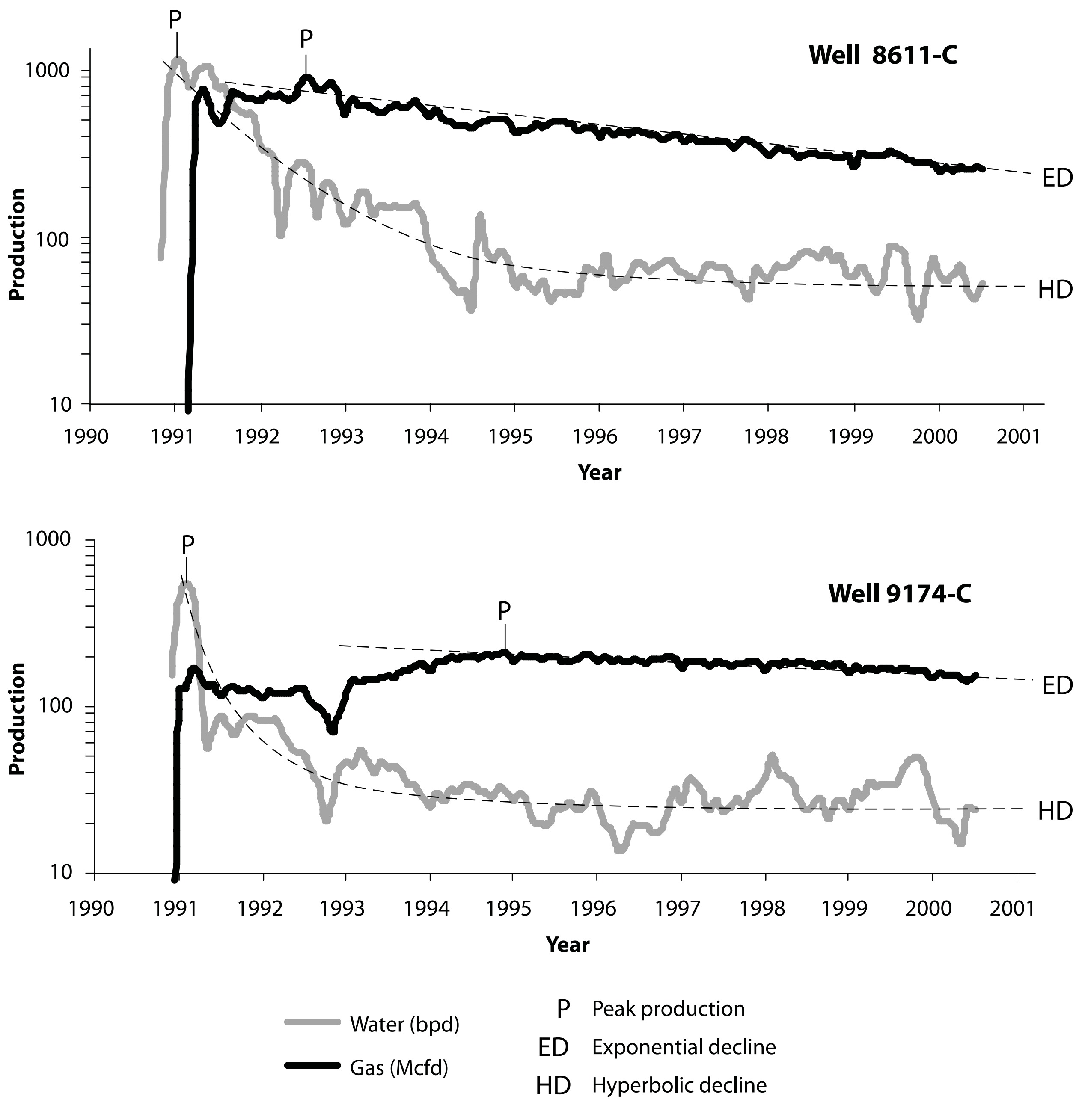
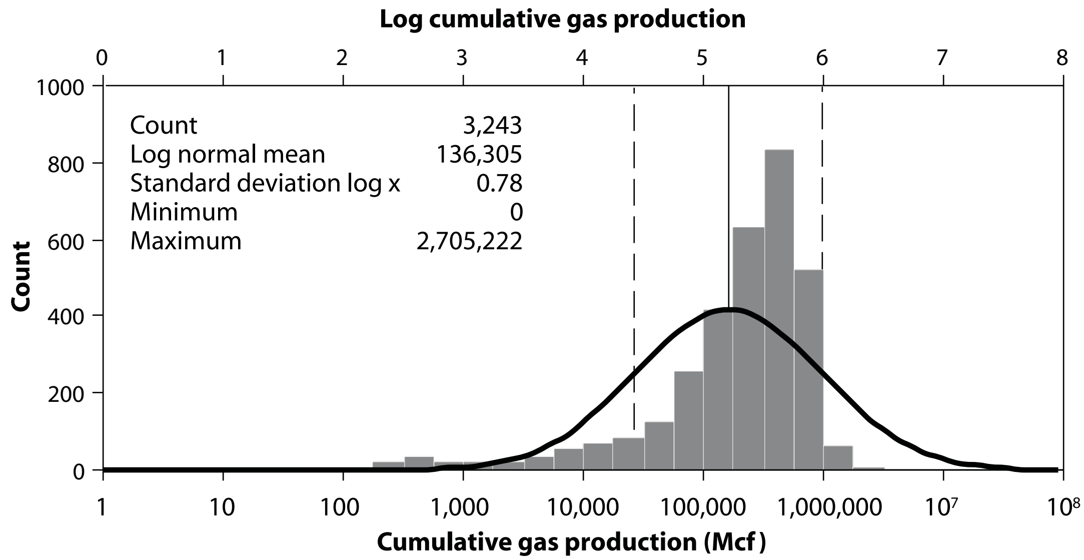



Figure 70.--Decline curves for gas and water production from two wells in Deerlick Creek Field (modified from Cox, 2002).



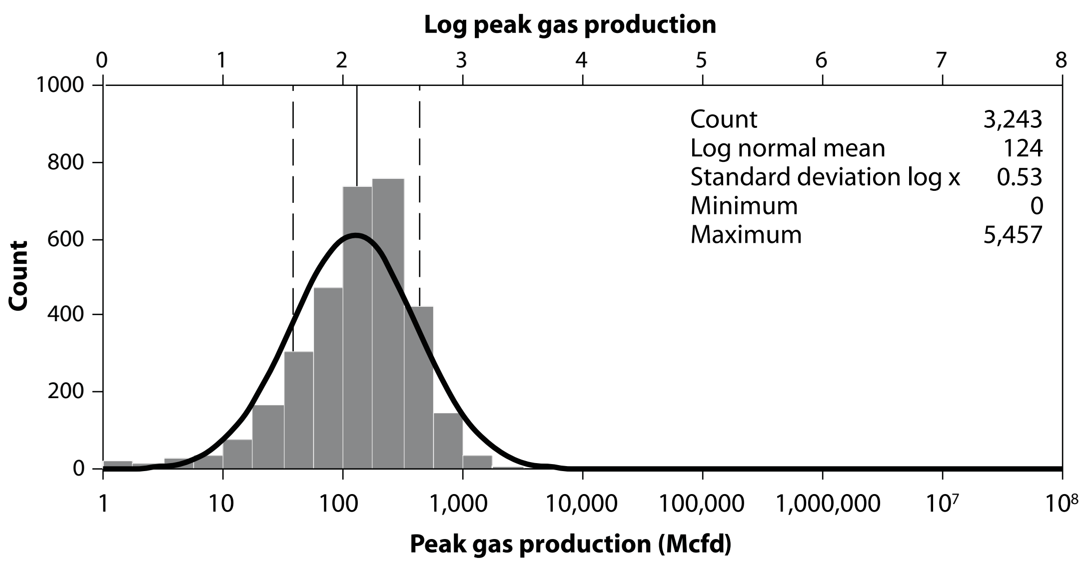




Figure 71.--Histograms of cumulative and peak gas production from coalbed methane wells in the Black Warrior basin.

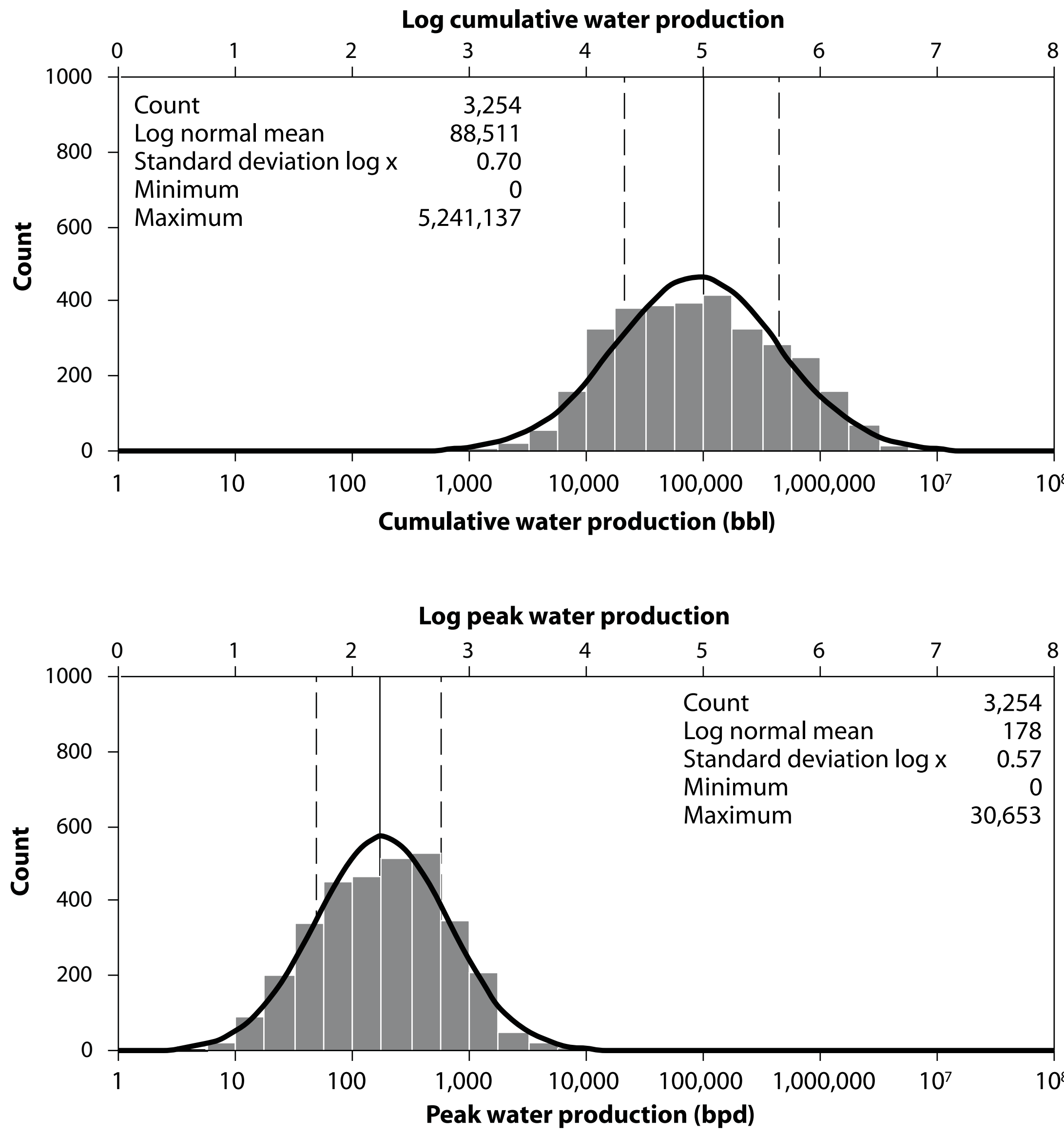



Figure 72.--Histograms of cumulative and peak water production from coalbed methane wells in the Black Warrior basin.

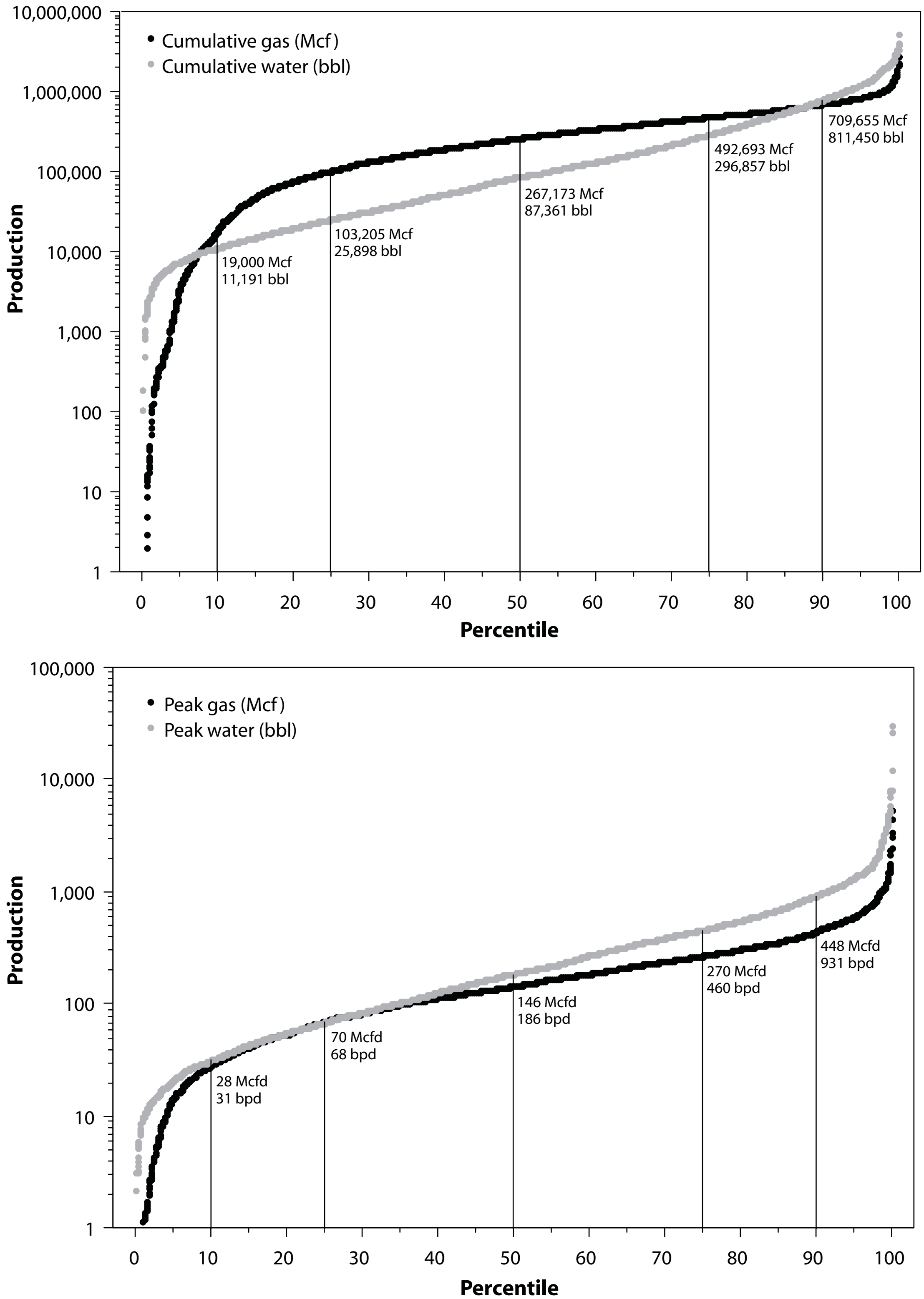



Figure 73.--Percentile plots of cumulative and peak water production from coalbed methane wells in the Black Warrior basin.

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. 74). 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. 75). 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. 76).

## Production Maps

Mapping cumulative and peak gas and water production demonstrates the variable performance of vertical coalbed methane wells (figs. 77-80). 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. 77). 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,

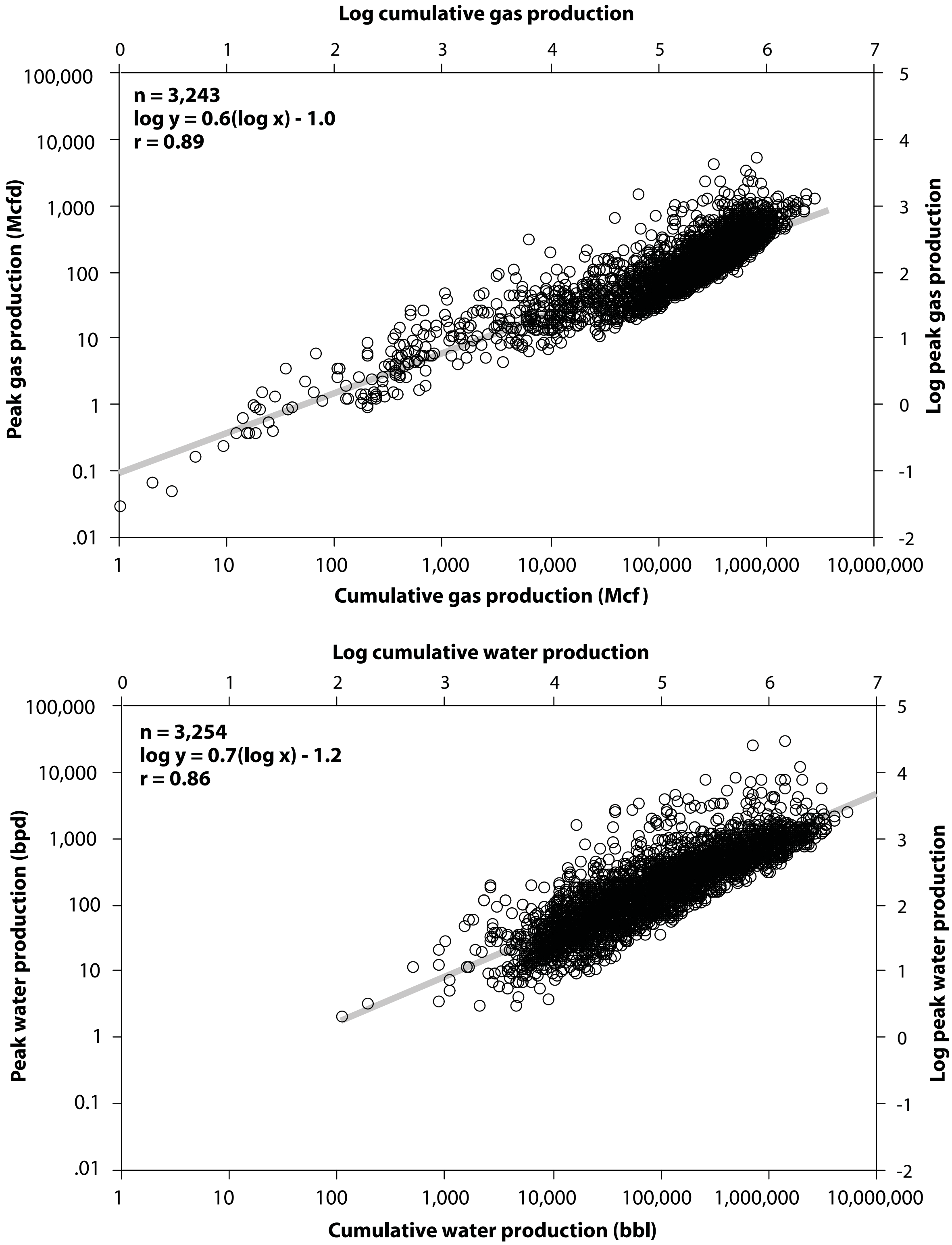



Figure 74.--Scatterplots showing correlation between peak and cumulative production values from coalbed methane wells in the Black Warrior basin.

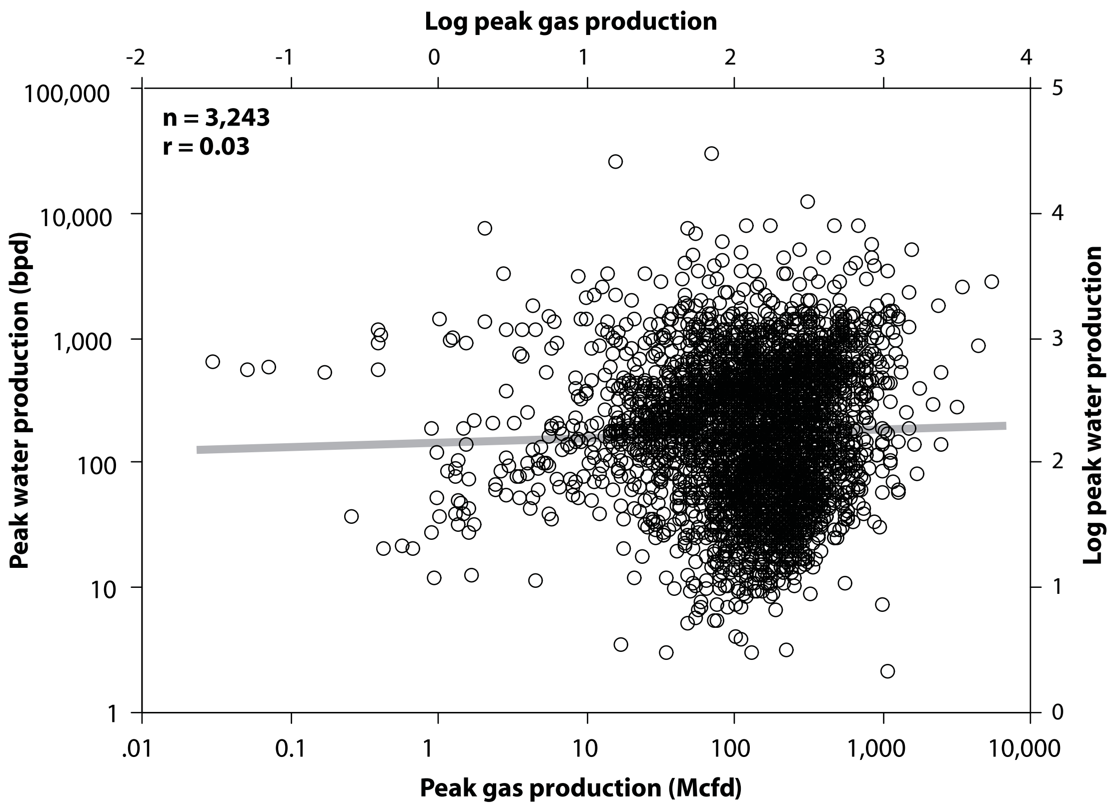



Figure 75.--Scatterplot showing lack of correlation between peak water and gas production in the Black Warrior coalbed methane fairway.

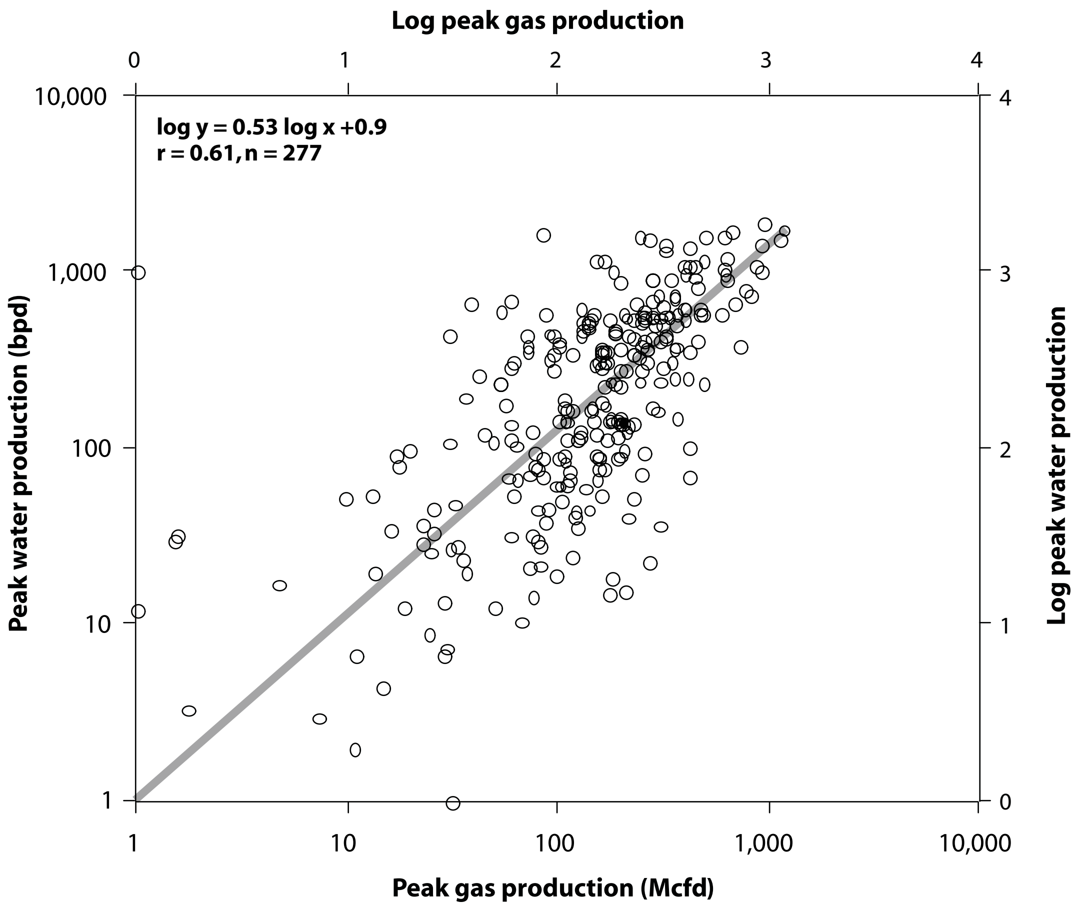



Figure 76.--Scatterplot showing modest correlation between water and gas production in Deerlick Creek Field (modified from Cox, 2002).

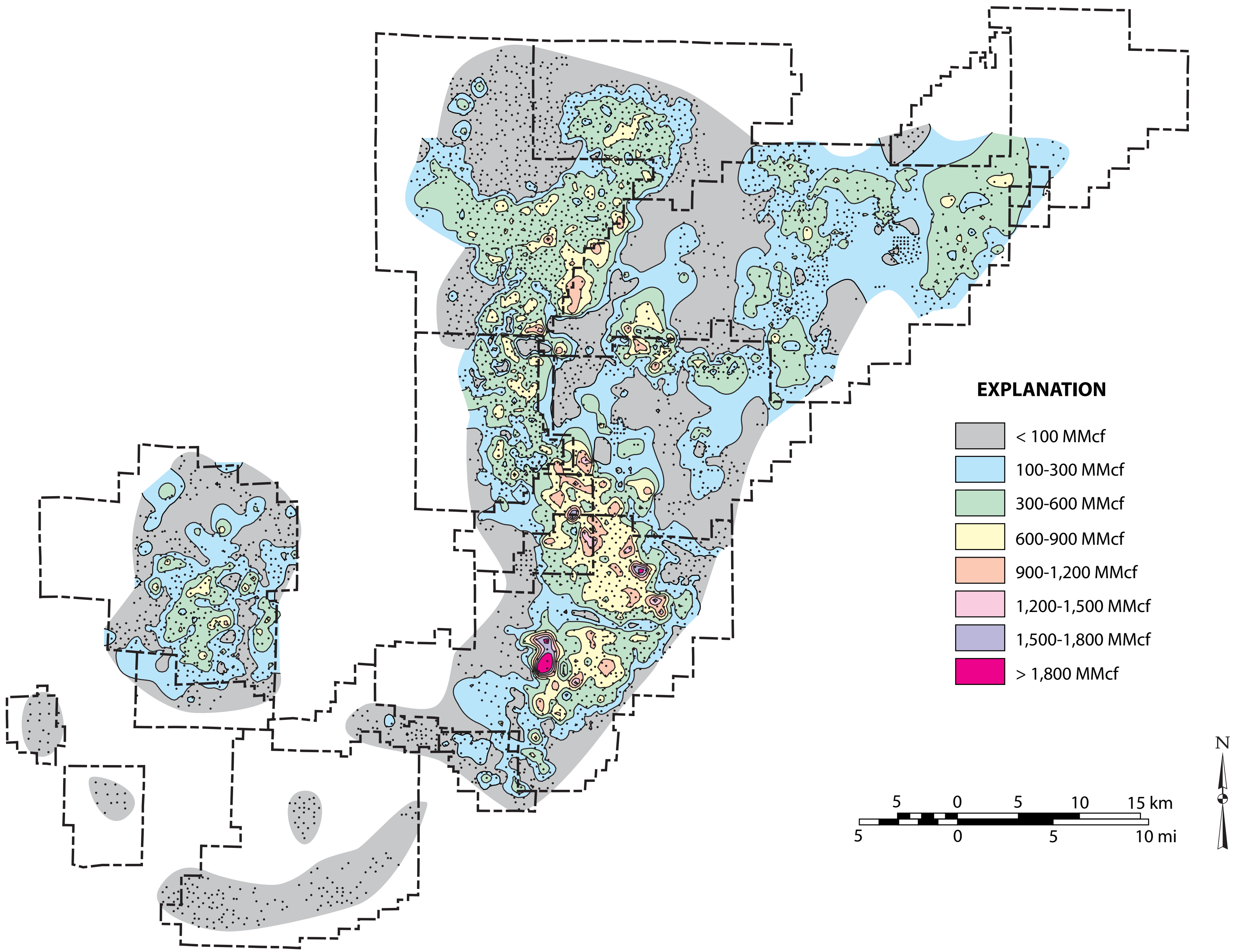



Figure 77.--Map of cumulative gas production from vertical wells in the Black Warrior coalbed methane fairway.

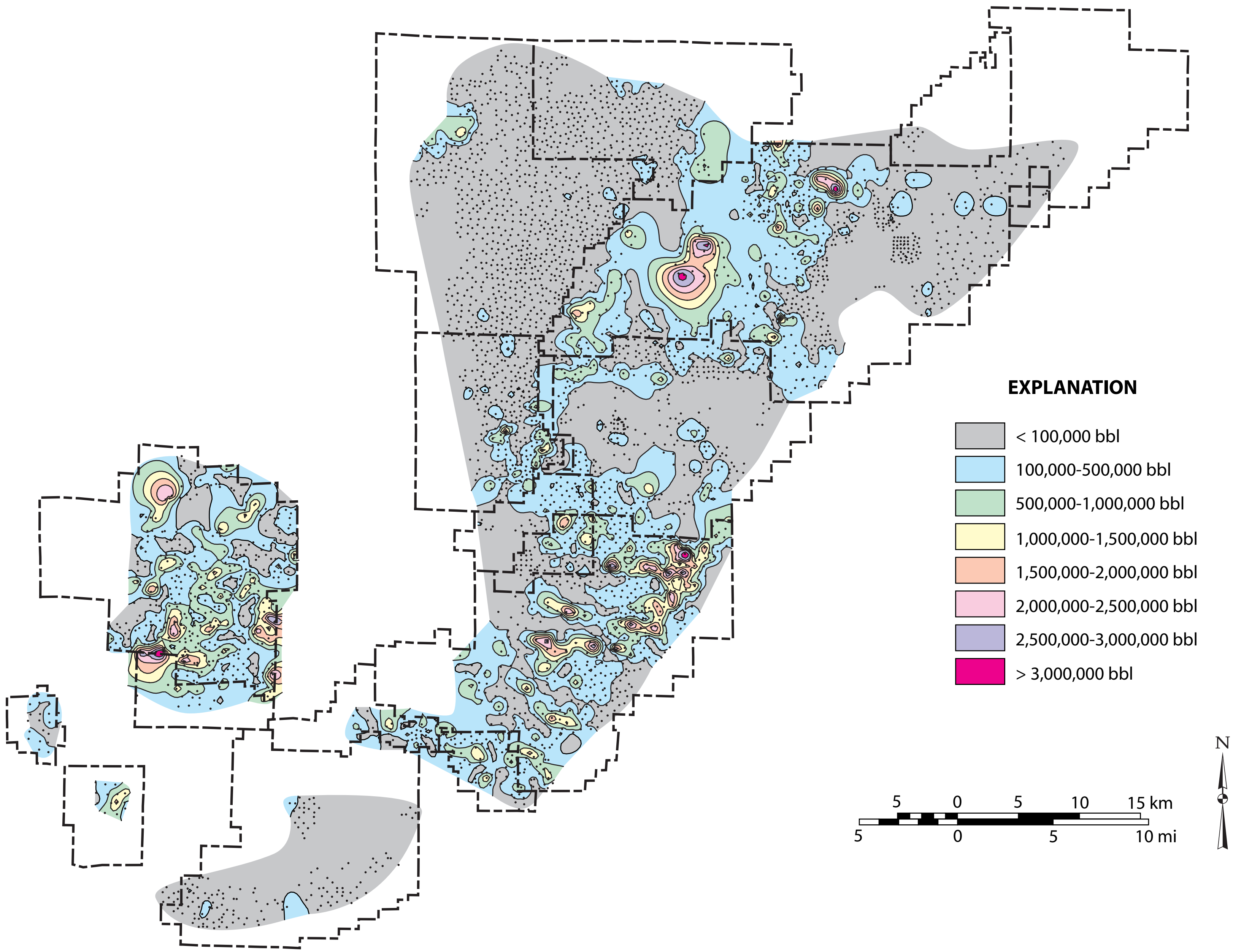



Figure 78.--Map of cumulative water production from vertical wells in the Black Warrior coalbed methane fairway.

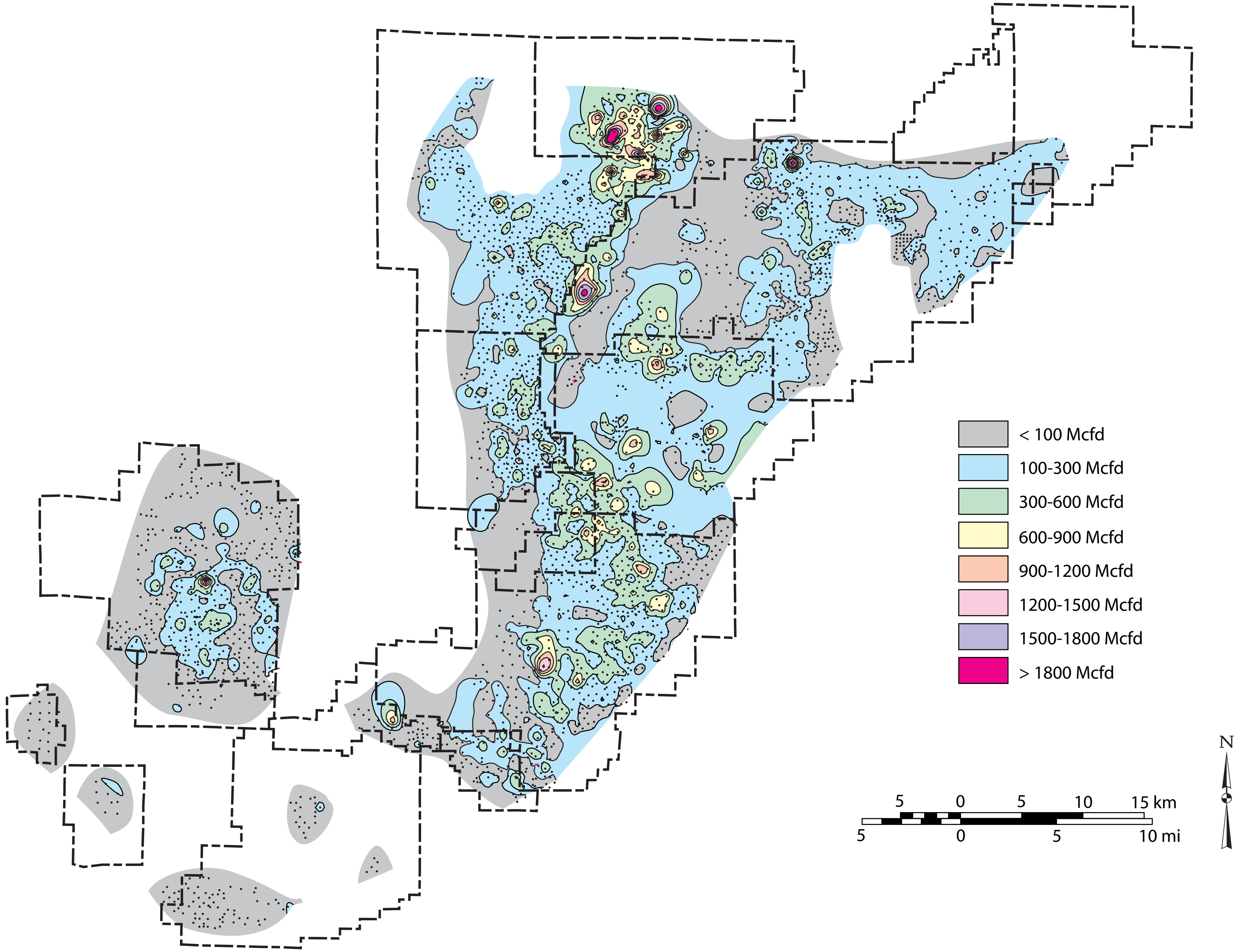



Figure 79.--Map of peak gas production in the Black Warrior coalbed methane fairway for wells reporting data for 48 months or more.

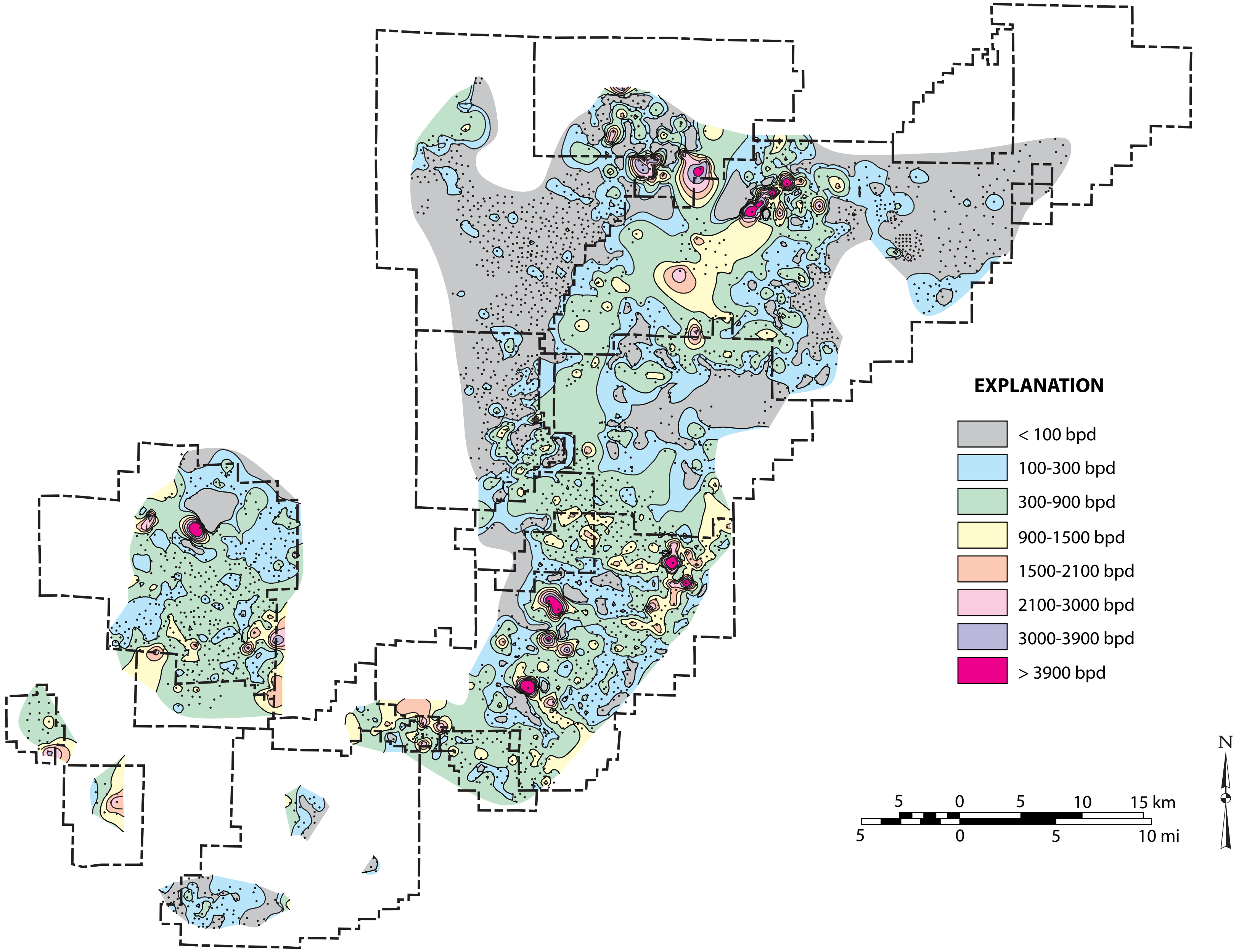



Figure 80.--Map of peak water production in the Black Warrior coalbed methane fairway for wells reporting data for 48 months or more.

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. 78). 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. 77, 78). 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 even view of the productivity of coalbed methane wells in the Black Warrior basin (figs. 79, 80). 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. 77, 79). 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. 79).

Peak water production trends also tend to follow those of cumulative water production (figs. 78, 80), as would be expected because of the high level of correlation between peak and cumulative production variables (fig. 74). 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. 79, 80). 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. 81, 82), but in many places, a more localized approach to geological characterization is required to diagnose the controls on well performance (figs. 83, 84). 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

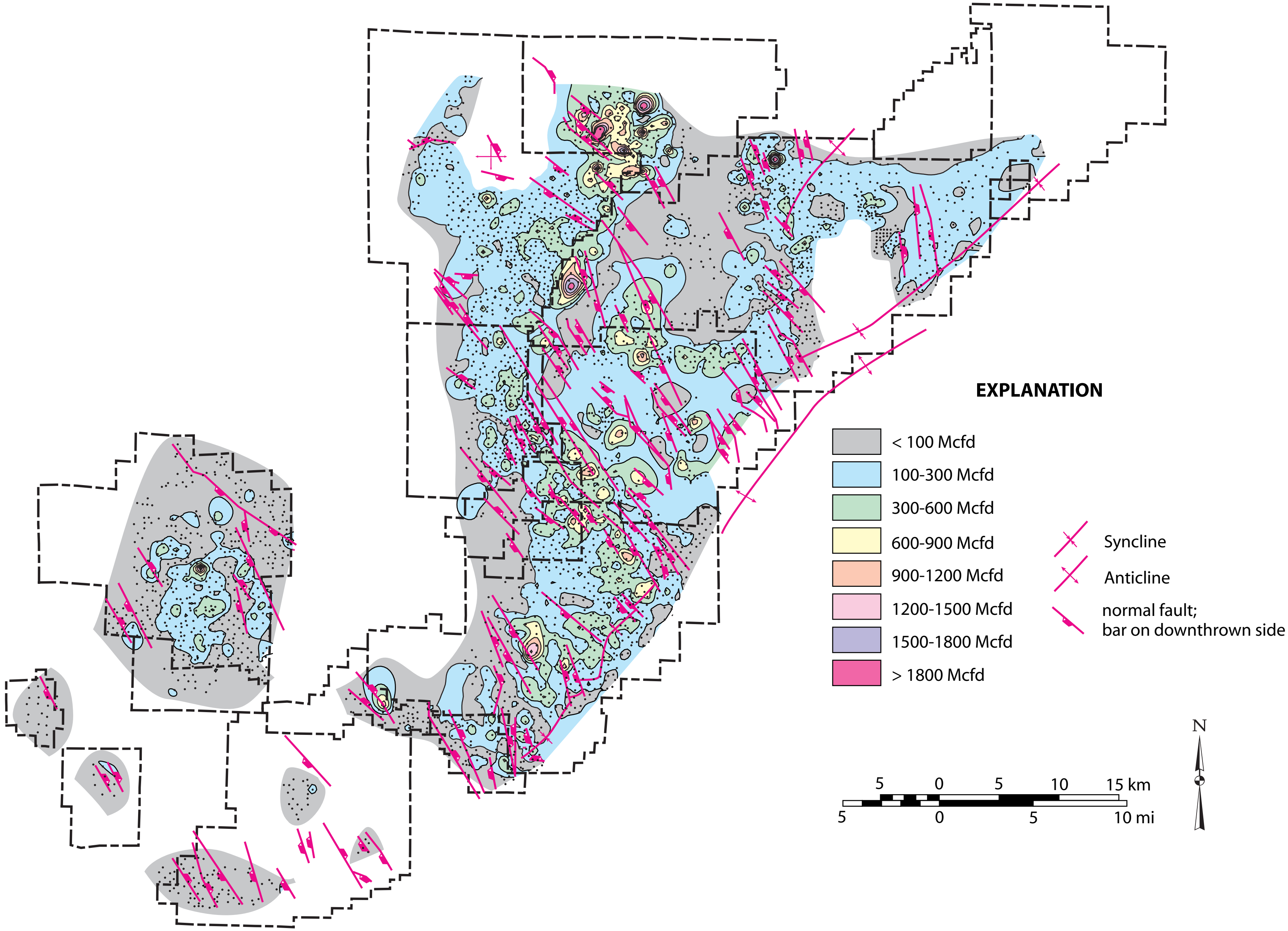



Figure 81.–Map showing relationship of peak gas production to structural traces in the Black Warrior coalbed methane fairway.

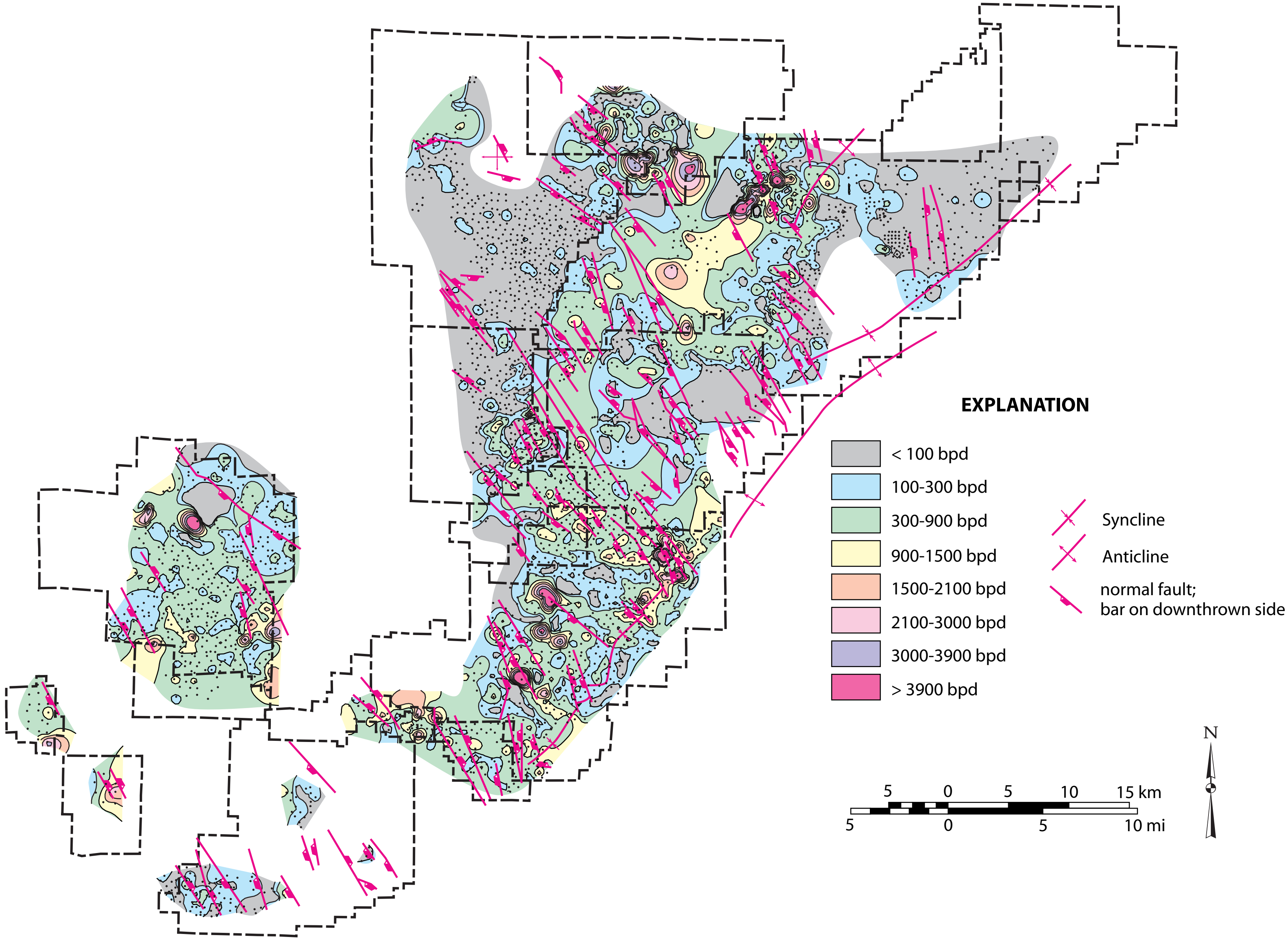



Figure 82.--Map showing the relationship between peak water production and structural traces in the Black Warrior coalbed methane fairway.

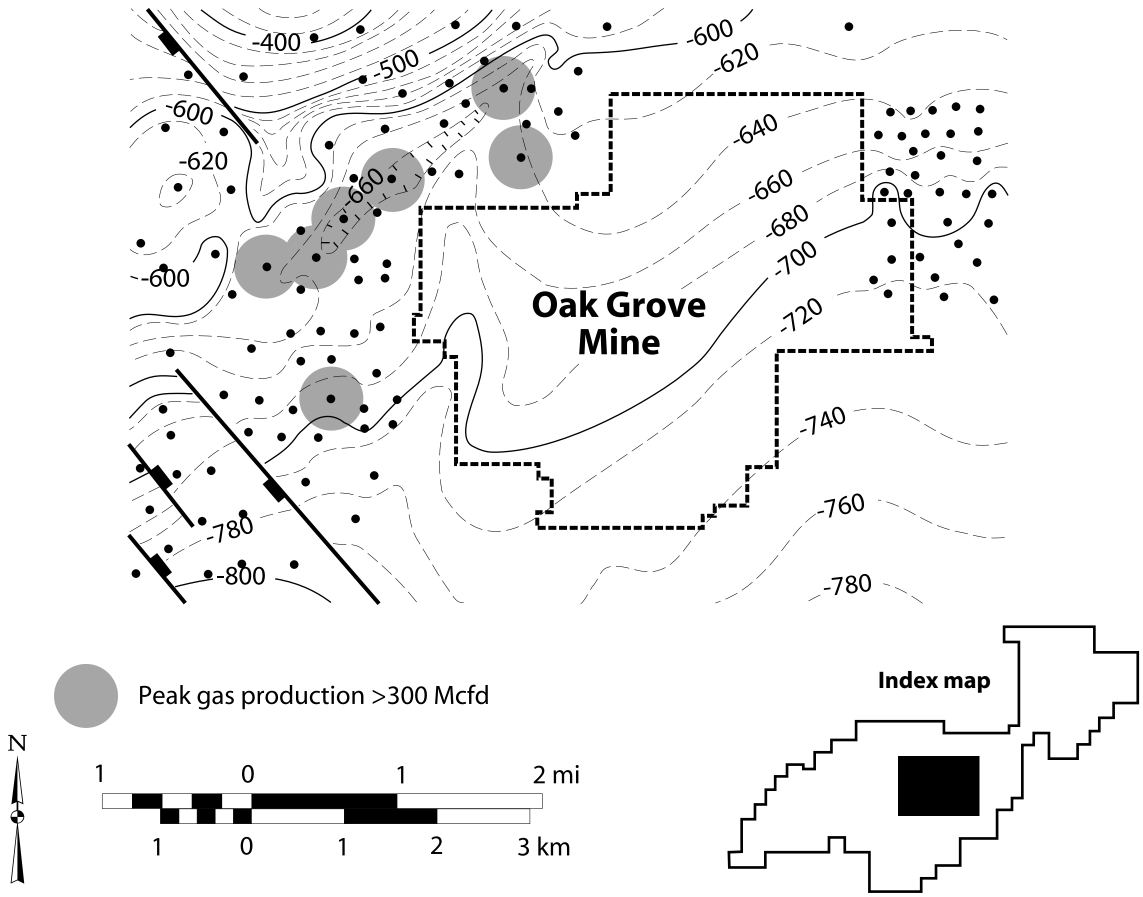



Figure 83.--Map showing alignment of exceptionally productive gas wells along a synclinal fold hinge in Oak Grove Field (modified from Pashin and others, 1991).

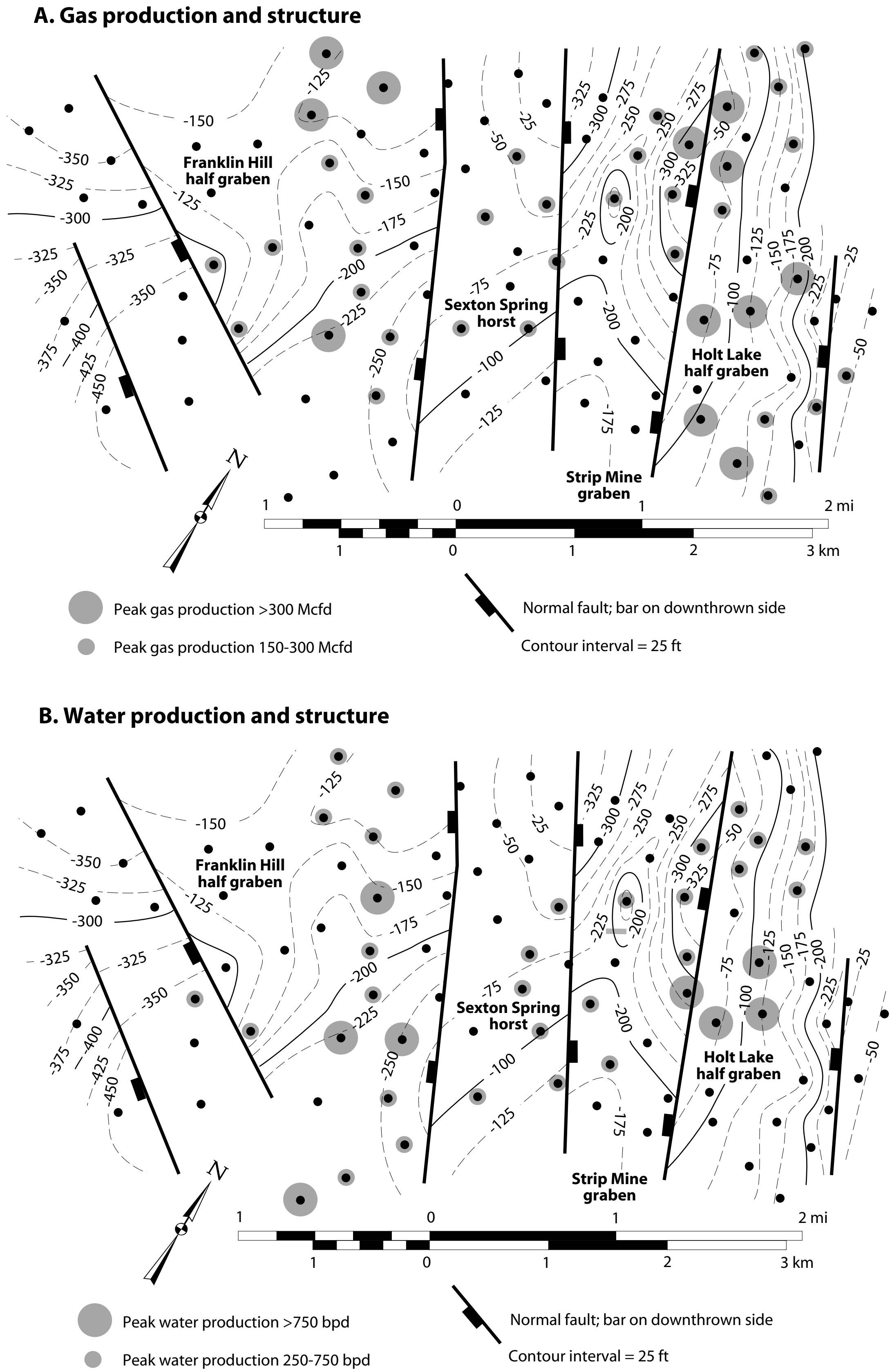



Figure 84.--Map showing relationship of gas and water production to extensional structure in Deerlick Creek Field (modified from Pashin and others, 1995).

from the more gently dipping northwest limb of the Coalburg syncline (Pashin and others, 1991) (fig. 83). 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. 82).

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. 84). 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 (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.

Bed-parallel views of 3-D structural models confirm the degree to which normal faults segment coalbed methane reservoirs in Deerlick Creek Field (Groshong and others, 2003) (fig. 85). These models show that exceptionally productive wells are concentrated on one side of each fault. Well performance is poorest in wells that penetrate the faults in the Black Creek-Pratt completion zone in these models. Therefore, although the faults segment the reservoir, the faults do not contribute significantly to fluid production. Reduced fluid production in wells penetrating

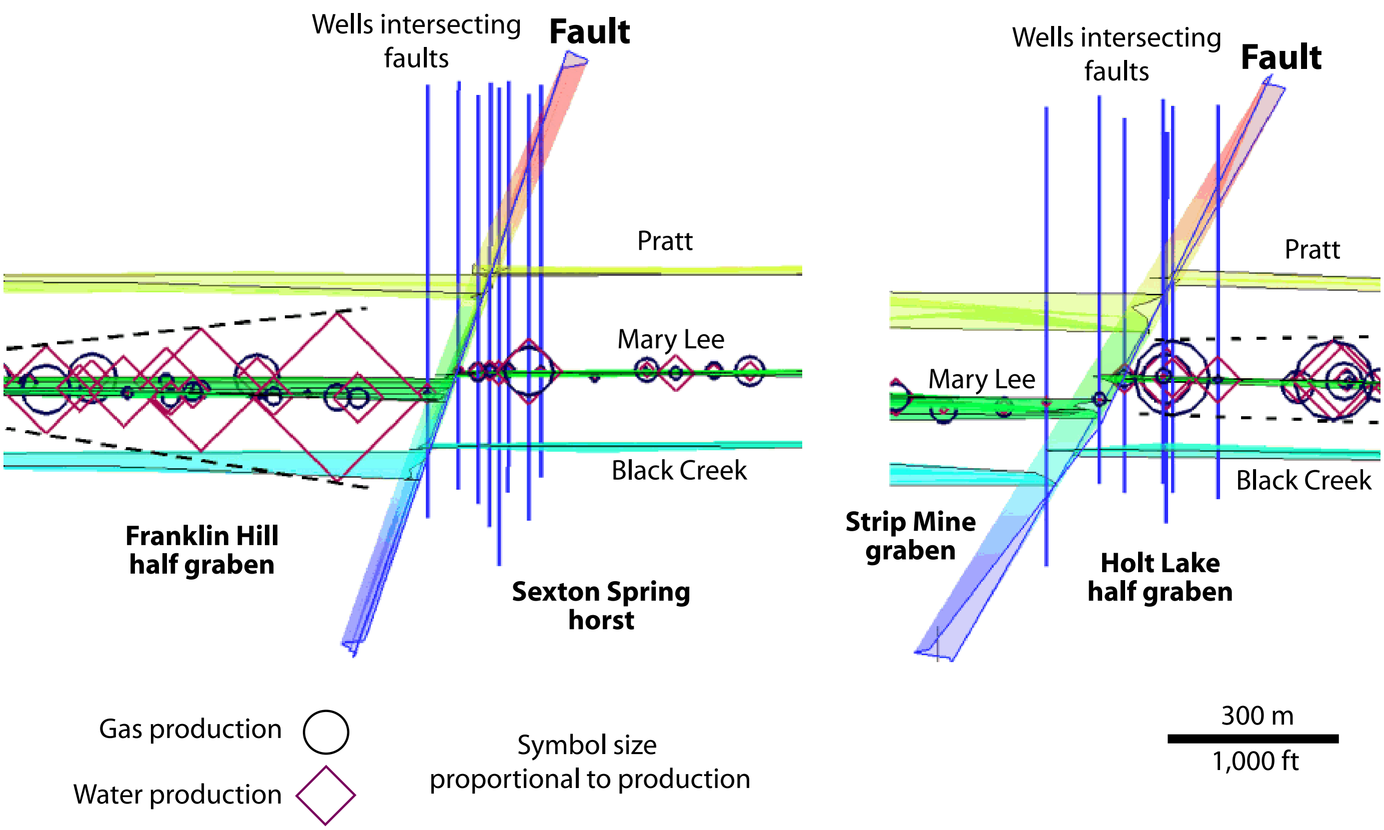



Figure 85.--3D computer model showing structural segmentation of coalbed methane reservoirs in Deerlick Creek Field and exceptionally poor production performance of wells penetrating normal faults and completed in the Mary Lee coal zone (modified from Groshong and others, 2003).

faults in the Black Creek-Pratt interval apparently reflects a combination of isolation from meteoric recharge and cementation of coal with calcite along faults (fig. 30). In Cedar Cove Field, by contrast, many wells penetrating normal faults have produced exceptional amounts of water (McIntyre and others, 2003). Pashin and others (2003) suggested that exceptional water production in wells penetrating these faults reflects proximity to the recharge zone along the southeast margin of the Black Warrior basin (figs. 44, 82).

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. 21, 81). 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. 81, 82). 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. 77). 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. 48, 78, 80). 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 though 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. 79, 83), 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 $CO_2$ into coal changes the balance of relative permeability between gas and water, and the high viscosity of $CO_2$ relative to $CH_4$ 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 therefore present hazards for cross-formational leakage of injected $CO_2$. Fault zones may in places 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.

## POTTSVILLE GAS CAPACITY

Analysis of sorption isotherms indicates that rank and ash content are the principal controls on the sorption capacity of coal in the Black Warrior coalbed methane fairway (figs. 62-66). Ash content varies considerably between data points and among coal beds (fig. 56) and is thus a difficult variable to use to estimate gas capacity in regional assessments. Rank, by comparison, varies systematically within and among coal beds and can be interpolated between data points with a high degree of confidence (figs. 51, 52). Rank also correlates more strongly with sorption capacity than any other variable and is thus a superior parameter for regional assessment of gas capacity (figs. 62, 63). As an example, the $CO_2$ sorption capacity of the Mary Lee coal zone at 100 psi can be mapped on the basis of the rank-sorption capacity regression line (fig. 86).

Temperature has a significant impact on sorption capacity (fig. 35), and analysis of the geothermal regime of the Pottsville Formation indicates that reservoir temperature and geothermal gradient vary significantly in the coalbed methane fairway (figs. 36-39). Using the data of Yang and Saunders (1985), a temperature correction factor was derived that divides the volume of gas adsorbed at a given temperature by that adsorbed at 80°F (fig. 87), which is the temperature at which all isotherms in this study were derived. Mapping the temperature correction factor for the Mary Lee coal zone at 100 psi indicates that sorption capacity is locally reduced by more than 25 percent in parts of the southwestern coalbed methane fields (fig. 88). Rank-estimated sorption capacity can be corrected for reservoir temperature simply by multiplying the grid of sorption capacity by the corresponding grid of temperature correction factor. To estimate the amount of gas that coal can hold per unit area, grids of gas capacity can be multiplied by coal thickness and the appropriate tonnage factor, which is 1,800 tons per foot of coal per acre in the Pottsville Formation (Ward, 1984).

In the following sections, maps of temperature-corrected sorption capacity are presented and discussed for each gas considered in this study at pressures of 50, 100, and 350 psi. Maps of the Mary coal zone are presented in scf/t to quantify the sorption capacity per unit weight of coal, and maps of the complete Black Creek-Brookwood interval are presented in MMcf/ac (millions

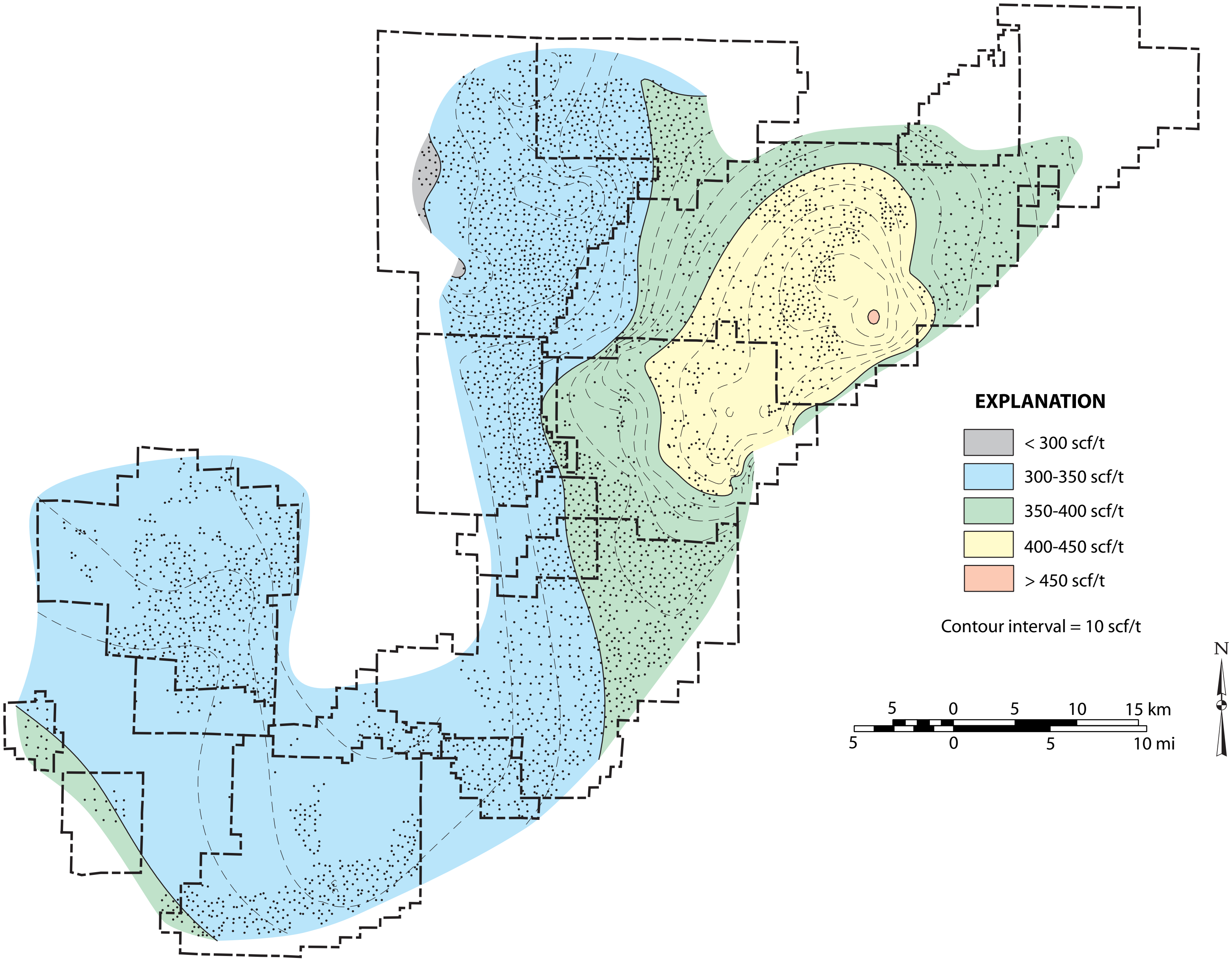



Figure 86.--Rank-estimated $CO_2$ capacity (scf/t, as received) of the Mary Lee coal zone at 100 psi.

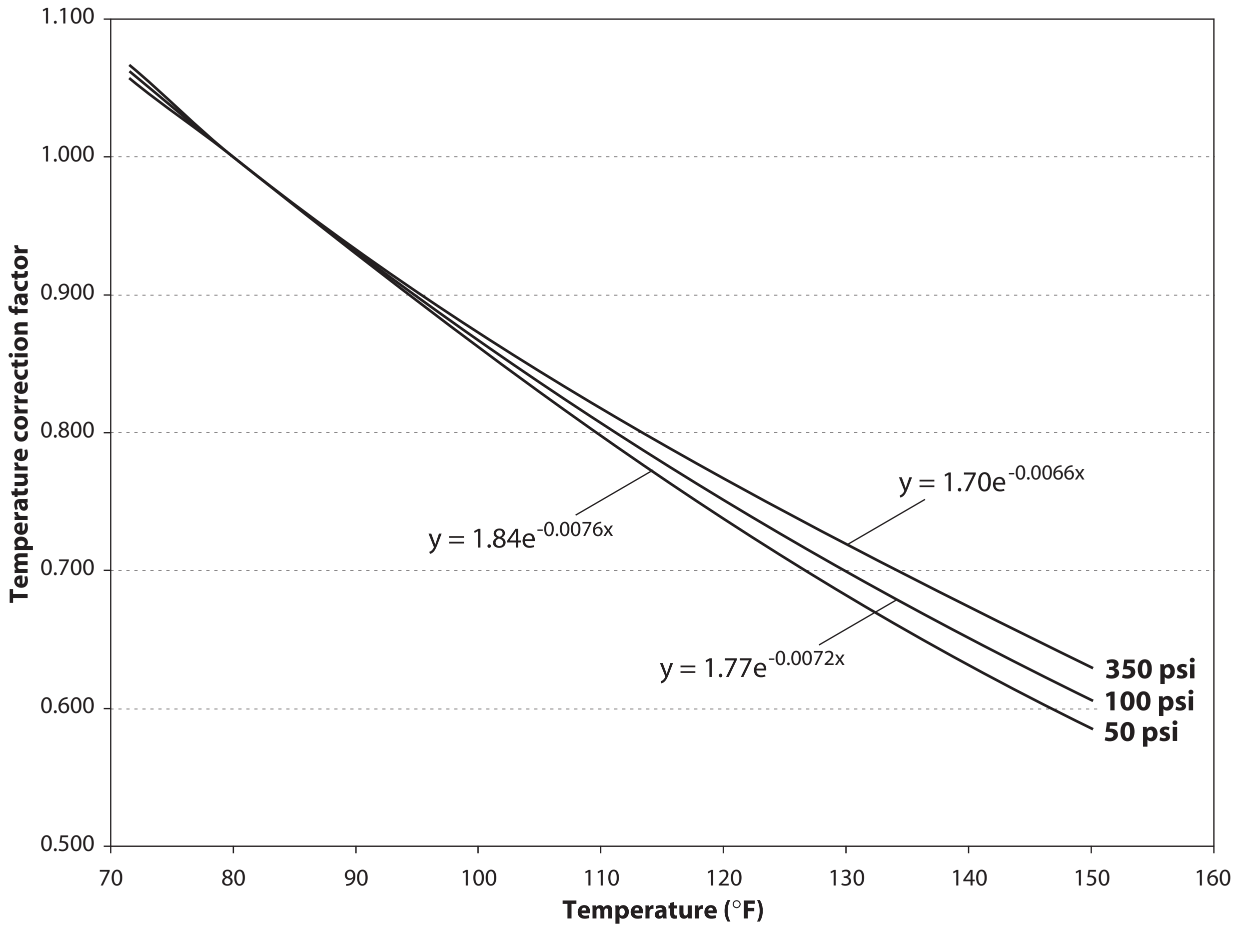



Figure 87.--Plot of temperature correction factor versus temperature (based on data from Yang and Saunders, 1985). Correction factor is calculated relative to the temperature at which isotherms were determined (80°F).

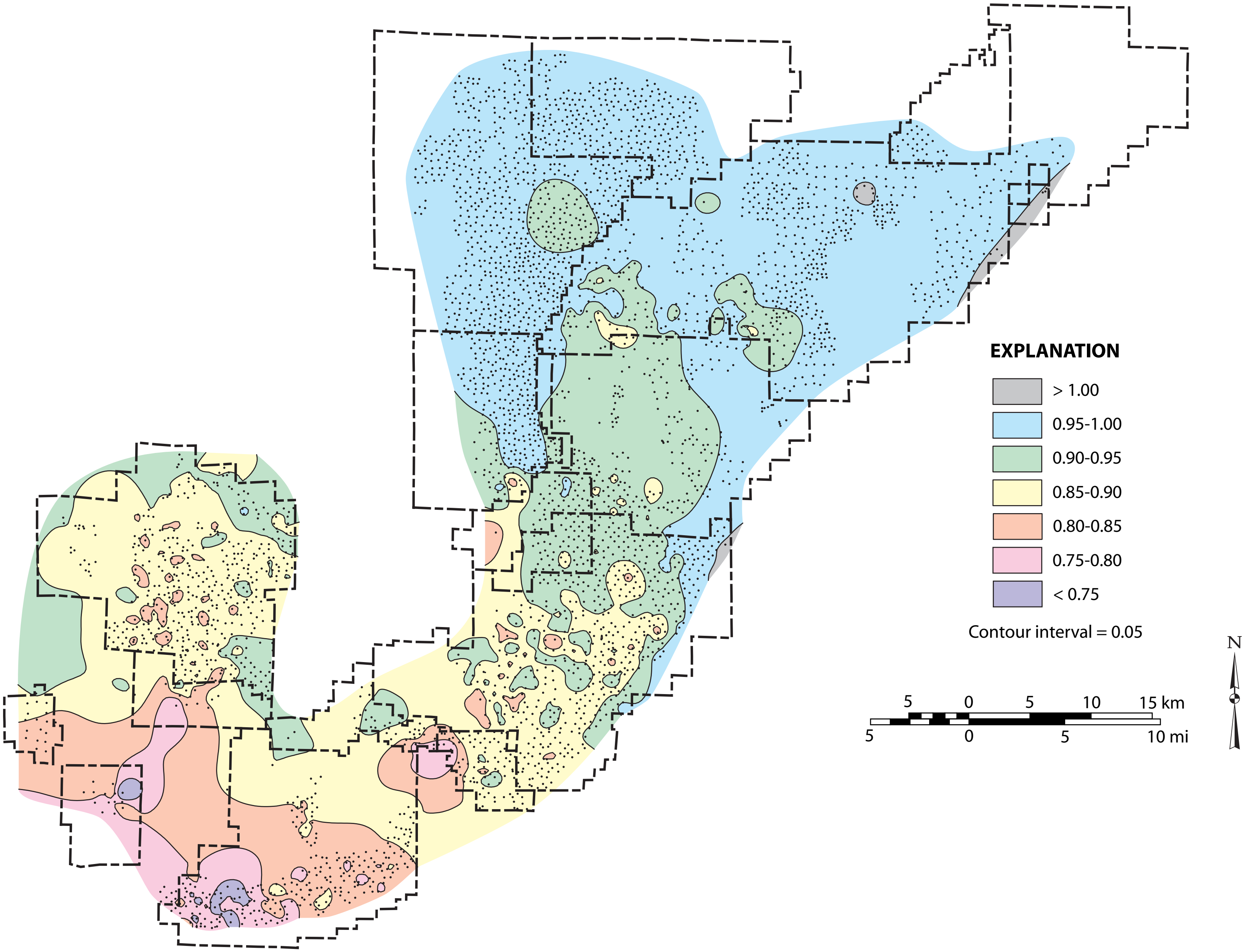



Figure 88.--Map of temperature correction factor used to estimate gas capacity in the Mary Lee coal zone at 100 psi.

of standard cubic feet per acre) to quantify the volume of gas per unit area that upper Pottsville coal can hold.

### Unswept Methane

Mapping the temperature-corrected $CH_4$ sorption capacity of the Mary Lee coal zone indicates that the regional rank pattern is a fundamental control on the distribution of unswept methane and that the highest volumes of unswept gas per unit weight of coal may be in Oak Grove and Brookwood fields (figs. 51, 89-91). At a pressure of 50 psi, $CH_4$ capacity is estimated to be between 40 and 100 scf/t (fig. 89), whereas at a pressure of 100 psi, $CH_4$ capacity ranges from about 80 to 200 scf/t (fig. 90). At 350 psi, by contrast, $CH_4$ capacity ranges from about 170 to 420 scf/t (fig. 91).

Although the rank pattern is the principal determinant of the gas capacity per unit weight of coal, coal thickness exerts a major control on the gas capacity per unit area in the Black Creek-Brookwood interval (figs. 9, 92-94). Accordingly, $CH_4$ capacity increases toward the southeast and tends to be greatest in Cedar Cove and Moundville fields. At 50 psi, $CH_4$ capacity ranges from less than 1 MMcf/ac in the northwest parts of the coalbed methane fairway and is greater than 4 MMcf/ac along the southeast margin of the fairway; $CH_4$ capacity locally exceeds 7 MMcf/ac in Moundville Field (fig. 92). At 100 psi, $CH_4$ capacity ranges from less than 2 to about 14 MMcf/ac (fig. 93), and at 350 psi, $CH_4$ capacity ranges from about 5 to 35 MMcf/ac (fig. 94).

On the basis of these results, the $CH_4$ capacity of the Black Warrior coalbed methane fairway is estimated to be 1.49 Tcf at 50 psi, 2.82 Tcf at 100 psi, and 5.94 Tcf at 350 psi (table 5). Hydrostatic pressure has been depleted in the coalbed methane fairway by prolonged dewatering, and the reservoir must be cored or the stabilized reservoir pressure must be determined in

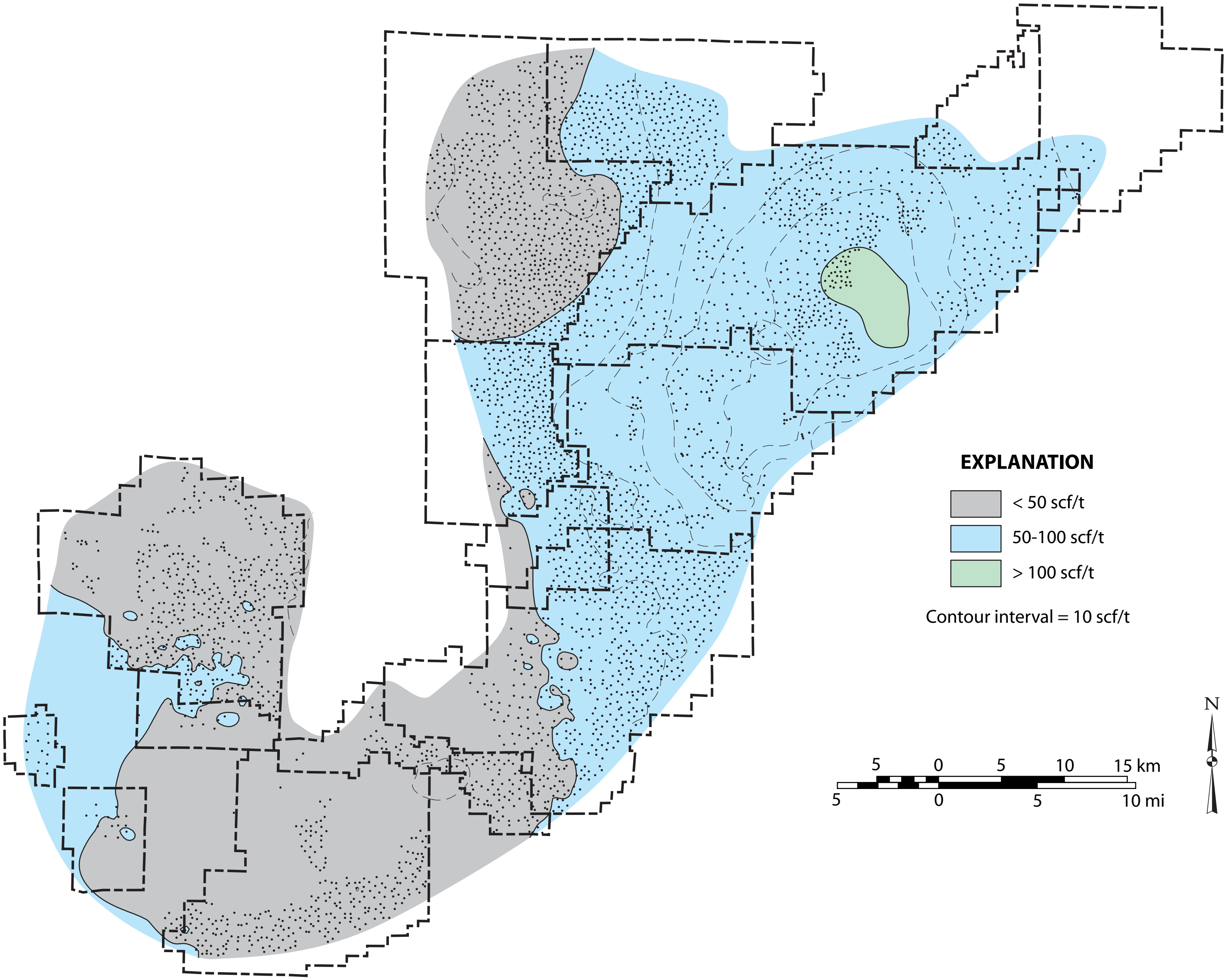



Figure 89.–Map of estimated unswept methane content (scf/t, as received) in the Mary Lee coal zone at 50 psi.

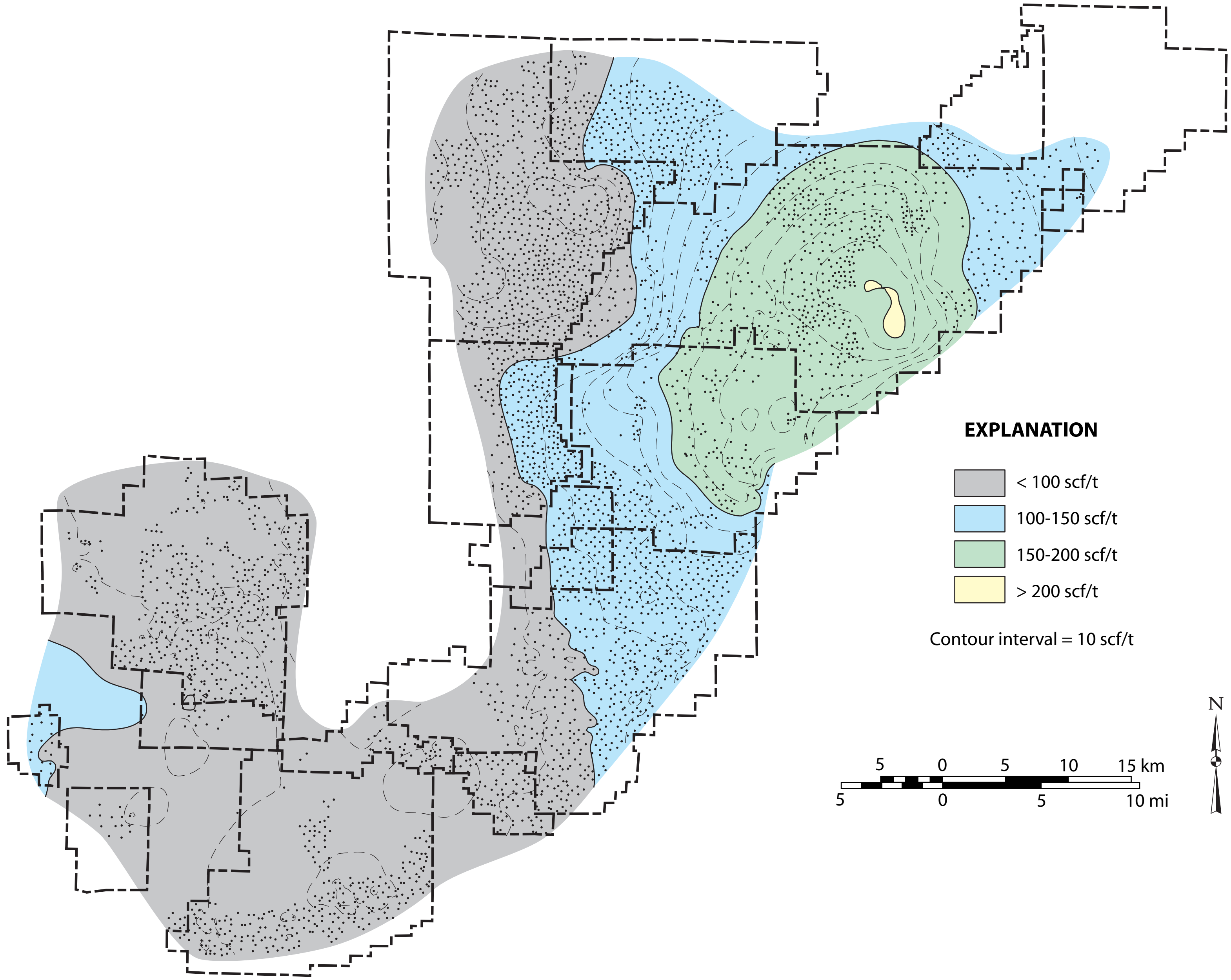



Figure 90.--Map of estimated unswept methane content (scf/t, as received) in the Mary Lee coal zone at 100 psi.

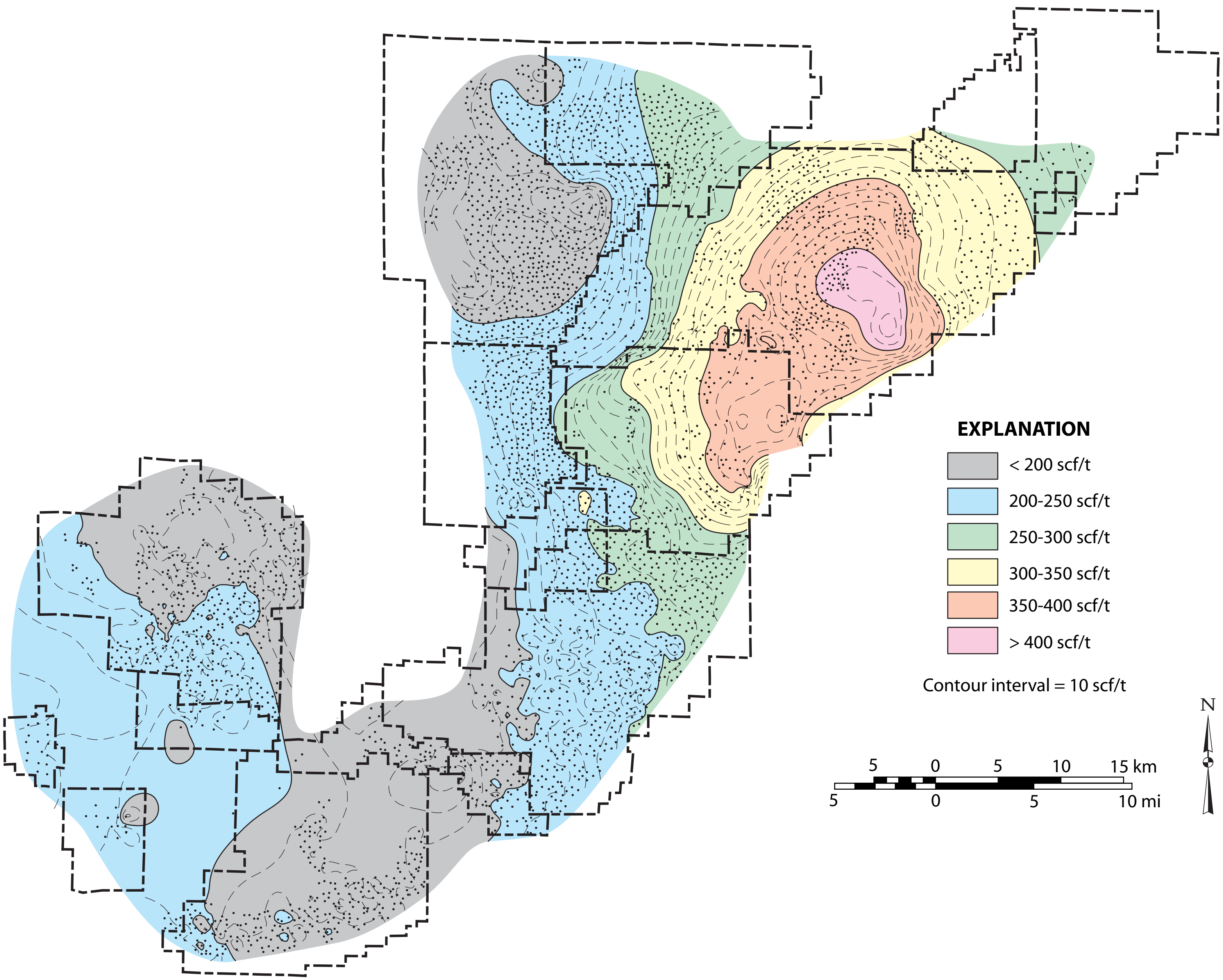



Figure 91.--Map of estimated unswept methane content (scf/t, as received) in the Mary Lee coal zone at 350 psi.

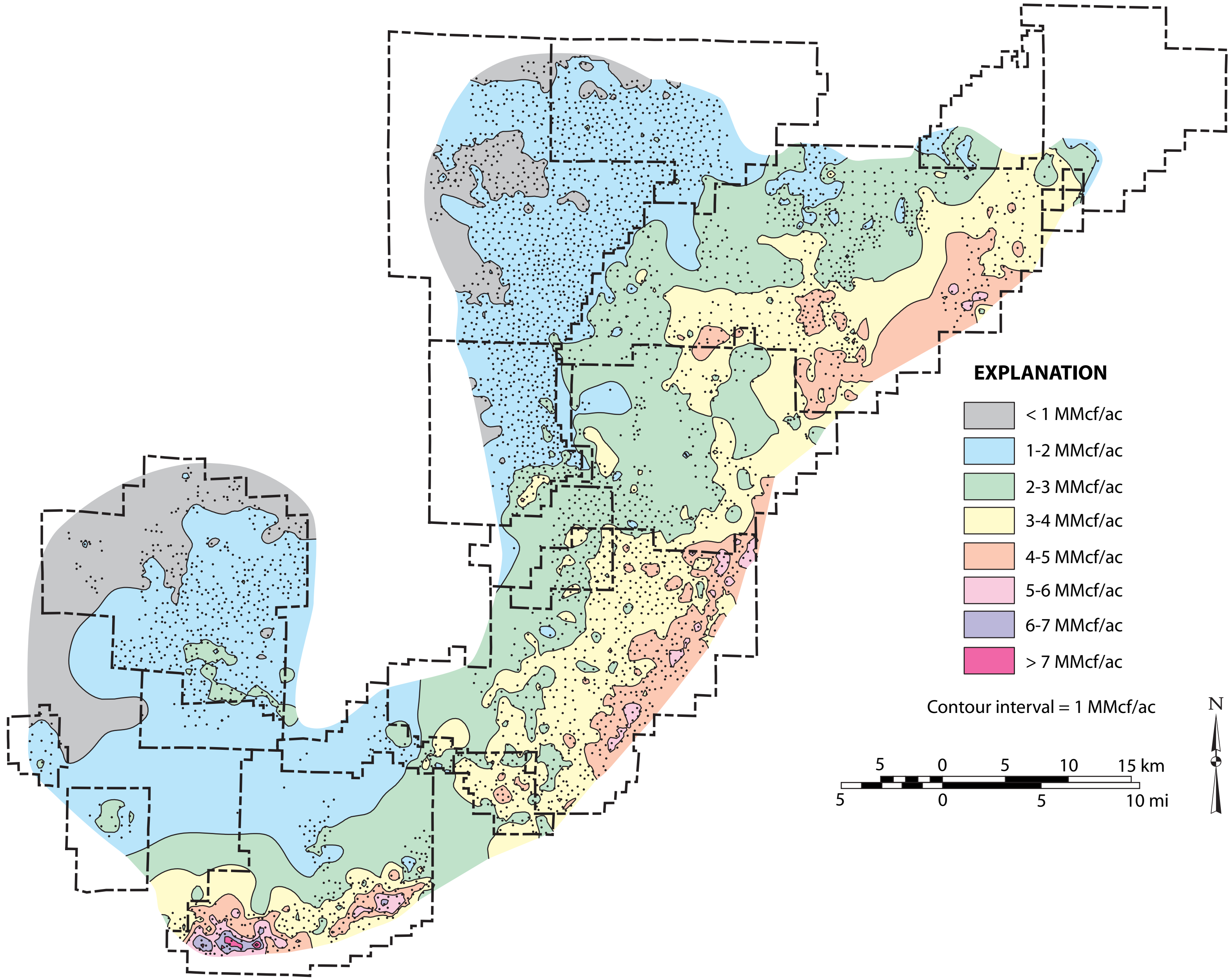



Figure 92.--Map of estimated unswept methane content (MMcf/ac, as-received) in the upper Pottsville Formation at 50 psi.

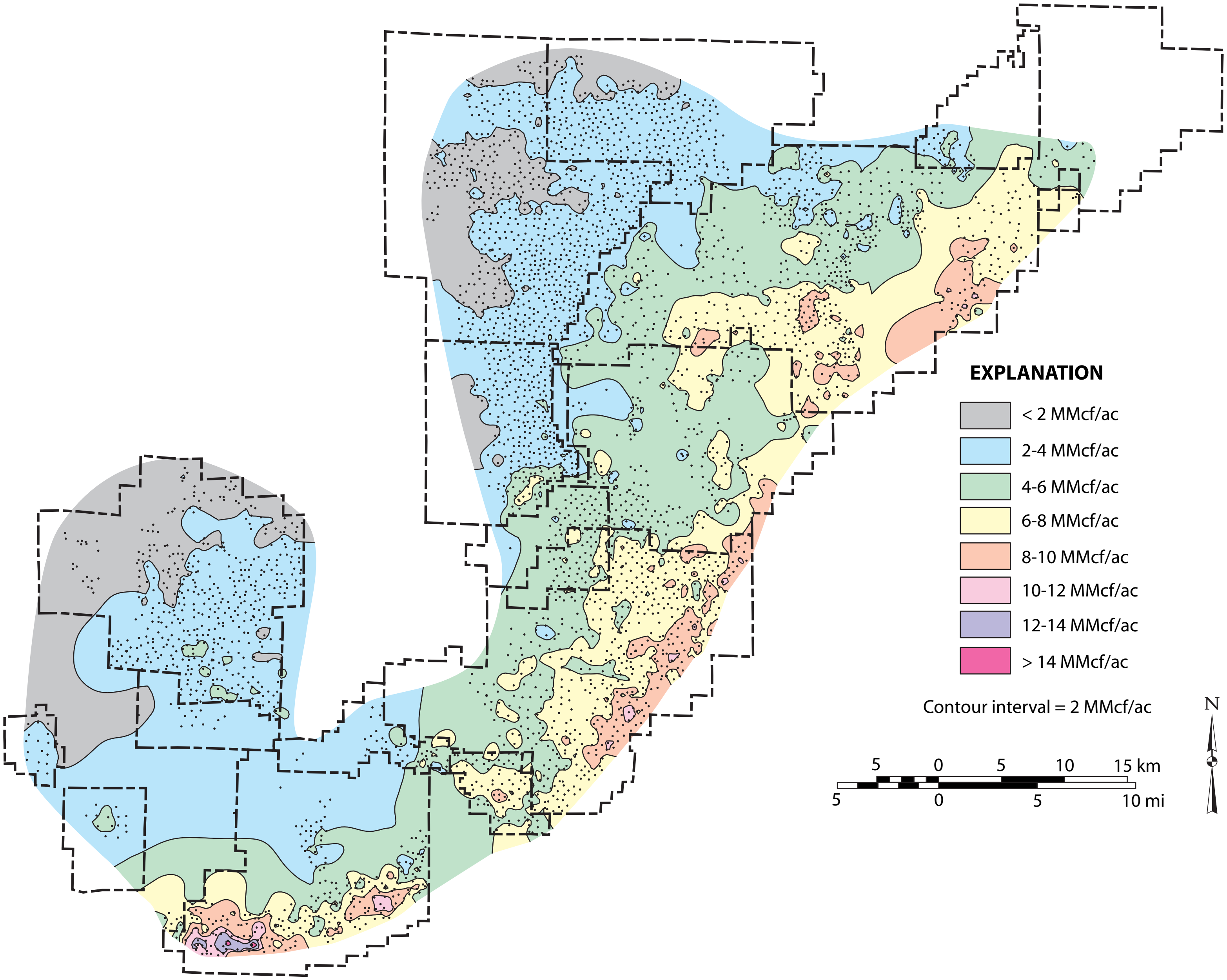



Figure 93.--Map of estimated unswept methane content (MMcf/ac, as-received) in the upper Pottsville Formation at 100 psi.

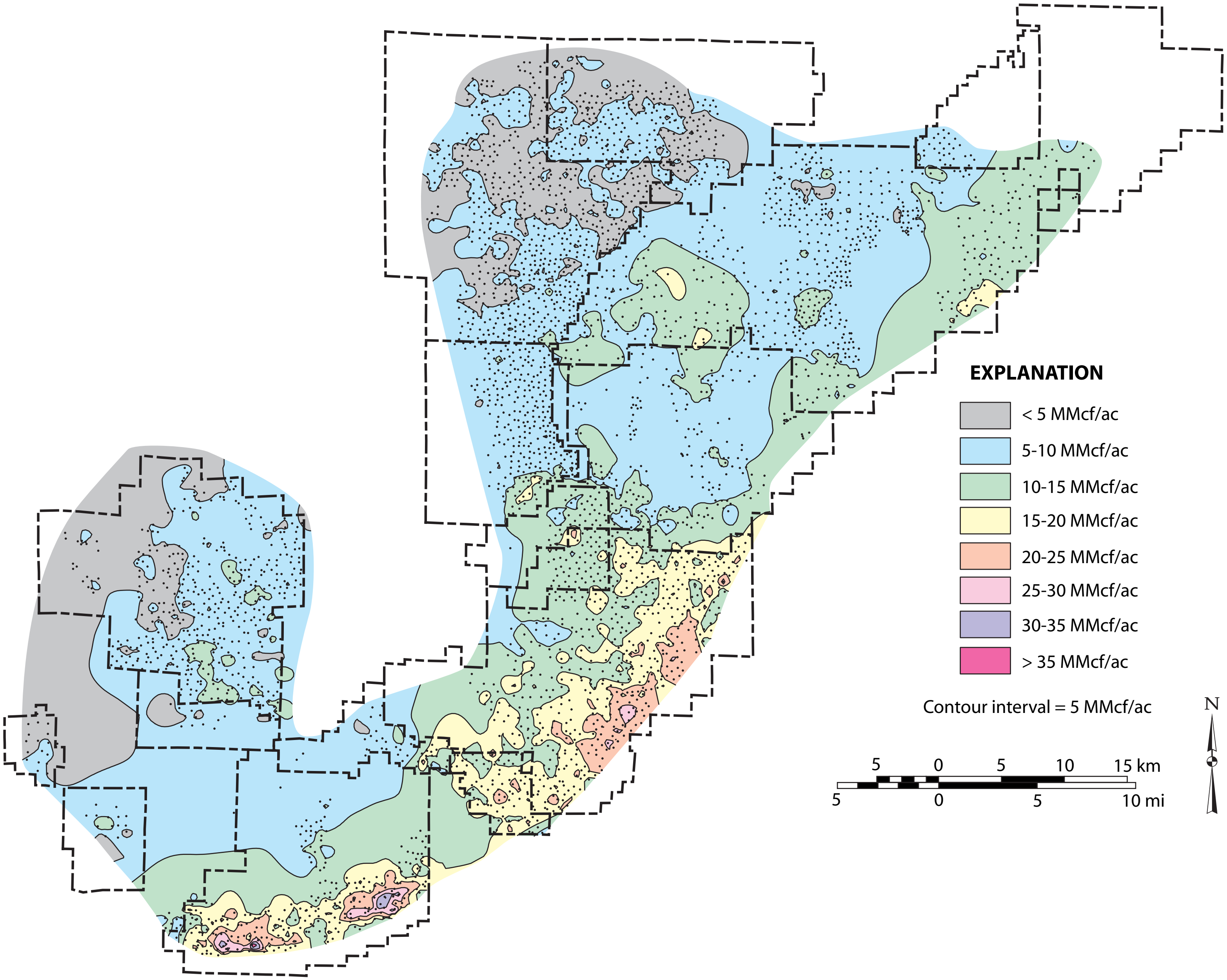



Figure 94.--Map of estimated unswept methane content (MMcf/ac, as-received) in the upper Pottsville Formation at 350 psi.

Table 5. Estimated gas capacity of the Black Warrior coalbed methane fairway.

| | Acres | $CH_4$ (Bcf) | | | $N_2$ (Bcf) | | | $CO_2$ (Bcf) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 50 psi | 100 psi | 350 psi | 50 psi | 100 psi | 350 psi | 50 psi | 100 psi | 350 psi |
| **COALBED METHANE FAIRWAY** | | | | | | | | | | |
| Total capacity | **666,593** | **1,493.7** | **2,822.5** | **5,942.1** | **381.1** | **673.7** | **1,982.2** | **5,434.5** | **8,578.1** | **14,925.5** |
| Fresh-water limitation | 119,587 | 402.1 | 765.3 | 1,404.0 | 109.5 | 201.4 | 581.9 | 1,291.5 | 2,028.7 | 3,423.2 |
| Coal reserve areas without fresh-water limitation (TDS < 3,000 mg/L) | 39,051 | 94.0 | 178.4 | 302.7 | 25.2 | 46.0 | 133.2 | 311.1 | 488.8 | 830.3 |
| Faulted areas without fresh-water limitation (TDS < 3,000 mg/L) | 276,469 | 558.6 | 1,053.4 | 2,353.2 | 138.2 | 231.0 | 712.5 | 2,141.1 | 3,389.7 | 5,967.8 |
| **INDIVIDUAL FIELDS** | | | | | | | | | | |
| Big Sandy Creek | 3,164 | 11.1 | 20.7 | 53.8 | 2.6 | 4.2 | 12.8 | 46.8 | 74.1 | 132.5 |
| Blue Creek | 55,973 | 63.8 | 117.9 | 292.8 | 14.0 | 21.9 | 67.6 | 289.1 | 457.5 | 829.5 |
| Brookwood | 8,758 | 25.8 | 49.2 | 80.8 | 7.2 | 13.4 | 38.5 | 78.8 | 123.6 | 206.8 |
| Cedar Cove | 16,159 | 52.5 | 98.7 | 247.2 | 12.8 | 21.9 | 65.5 | 205.6 | 325.5 | 571.4 |
| Deerlick Creek | 12,752 | 20.8 | 38.9 | 101.1 | 5.0 | 8.5 | 25.4 | 82.6 | 130.4 | 230.1 |
| Holt | 1,042 | 2.6 | 4.8 | 12.4 | 0.6 | 1.1 | 3.3 | 9.6 | 15.1 | 26.4 |
| Little Sandy Creek | 2,017 | 5.3 | 9.9 | 26.0 | 1.2 | 2.0 | 6.2 | 22.0 | 35.0 | 62.8 |
| Moundville | 12,450 | 35.9 | 67.4 | 181.4 | 8.5 | 15.0 | 43.3 | 146.5 | 232.5 | 418.2 |
| Oak Grove | 42,359 | 118.3 | 225.0 | 398.3 | 32.2 | 59.1 | 170.6 | 381.2 | 598.2 | 1,010.1 |
| Peterson | 2,041 | 5.6 | 10.5 | 24.6 | 1.4 | 2.4 | 7.2 | 20.8 | 32.9 | 57.1 |
| Robinson's Bend | 50,237 | 62.9 | 117.5 | 329.9 | 14.4 | 30.3 | 71.6 | 270.8 | 429.9 | 776.2 |
| Short Creek | 2,021 | 4.1 | 7.7 | 15.7 | 1.1 | 2.0 | 5.7 | 13.6 | 21.4 | 36.1 |
| Taylor Creek | 2,115 | 2.6 | 4.9 | 9.2 | 0.7 | 1.4 | 3.4 | 9.6 | 15.2 | 26.8 |
| Thornton Creek | 3,858 | 5.9 | 11.1 | 25.3 | 1.4 | 3.2 | 7.2 | 23.9 | 37.9 | 67.9 |
| White Oak Creek | 16,540 | 22.1 | 41.2 | 83.8 | 5.2 | 8.8 | 26.3 | 89.8 | 141.7 | 252.2 |
| **Total** | **231,486** | **439.0** | **825.4** | **1,882.2** | **108.3** | **195.3** | **554.6** | **1,690.8** | **2,670.9** | **4,704.1** |
| **PARTS OF FIELDS WITH FRESH-WATER LIMITATION (TDS < 3,000 mg/L)** | | | | | | | | | | |
| Cedar Cove | 23,491 | 90.7 | 171.9 | 388.1 | 23.6 | 42.4 | 124.2 | 317.3 | 500.7 | 861.5 |
| Holt | 1,199 | 3.1 | 5.8 | 13.0 | 0.8 | 1.4 | 4.1 | 11.3 | 17.9 | 30.8 |
| Oak Grove | 6,299 | 26.9 | 51.3 | 78.4 | 7.6 | 14.2 | 40.5 | 80.4 | 125.9 | 207.3 |
| Peterson | 2,470 | 7.5 | 14.2 | 32.1 | 1.9 | 3.4 | 10.0 | 27.0 | 42.7 | 73.7 |
| **Total** | **33,459** | **128.1** | **243.3** | **511.6** | **33.9** | **61.4** | **178.8** | **436.0** | **687.1** | **1,173.4** |
| **TOTAL FOR FIELDS** | **264,945** | **567.1** | **1,068.7** | **2,393.8** | **142.2** | **256.7** | **733.5** | **2,126.8** | **3,358.0** | **5,877.5** |

advance of enhanced recovery operations to accurately estimate the amount of unswept gas that remains to be recovered. The estimate at 350 psi approaches the original gas resource in the coal and is thus an unrealistic value for assessment of unswept methane in the fairway. The values estimated at 50 psi are consistent with the 80 percent recovery factor that is commonly used in reserve assessments and thus appear to be the most useful values for predicting unswept methane in the upper Pottsville Formation. Estimates made at 100 psi may be most applicable to deep reservoirs in the southwestern part of the coalbed methane fairway where initial hydrostatic pressure was high.

## Nitrogen Capacity

As with $CH_4$ capacity, the maps of $N_2$ capacity per unit weight of coal closely resemble the regional rank pattern (figs. 51, 95-97). However, the temperature-corrected sorption capacity for $N_2$ is significantly lower than that for $CH_4$ (figs. 89-91, 95-97). At 50 psi, for example, $N_2$ capacity ranges from less than 10 to only 30 scf/t (fig. 95). At 100 psi, $N_2$ capacity ranges from about 20 scf/t to 100 scf/t (fig. 96); and at 350 psi, $N_2$ capacity ranges from about 40 to 170 scf/t (fig. 97).

$N_2$ sorption capacity per unit area in the upper Pottsville Formation increases southeastward, and maximum values are in southwestern Moundville Field (figs. 98-100). At 50 psi, sorption capacity ranges from less than 0.5 MMcf/ac to about 2.0 MMcf/ac (fig. 98). At 100 psi, $N_2$ sorption capacity ranges from less than 0.5 MMcf/ac to 3.5 MMcf/ac (fig. 99); and at 350 psi, sorption capacity increase southeastward from less than 1.0 MMcf/ac to a maximum of 10 MMcf/ac (fig. 100).

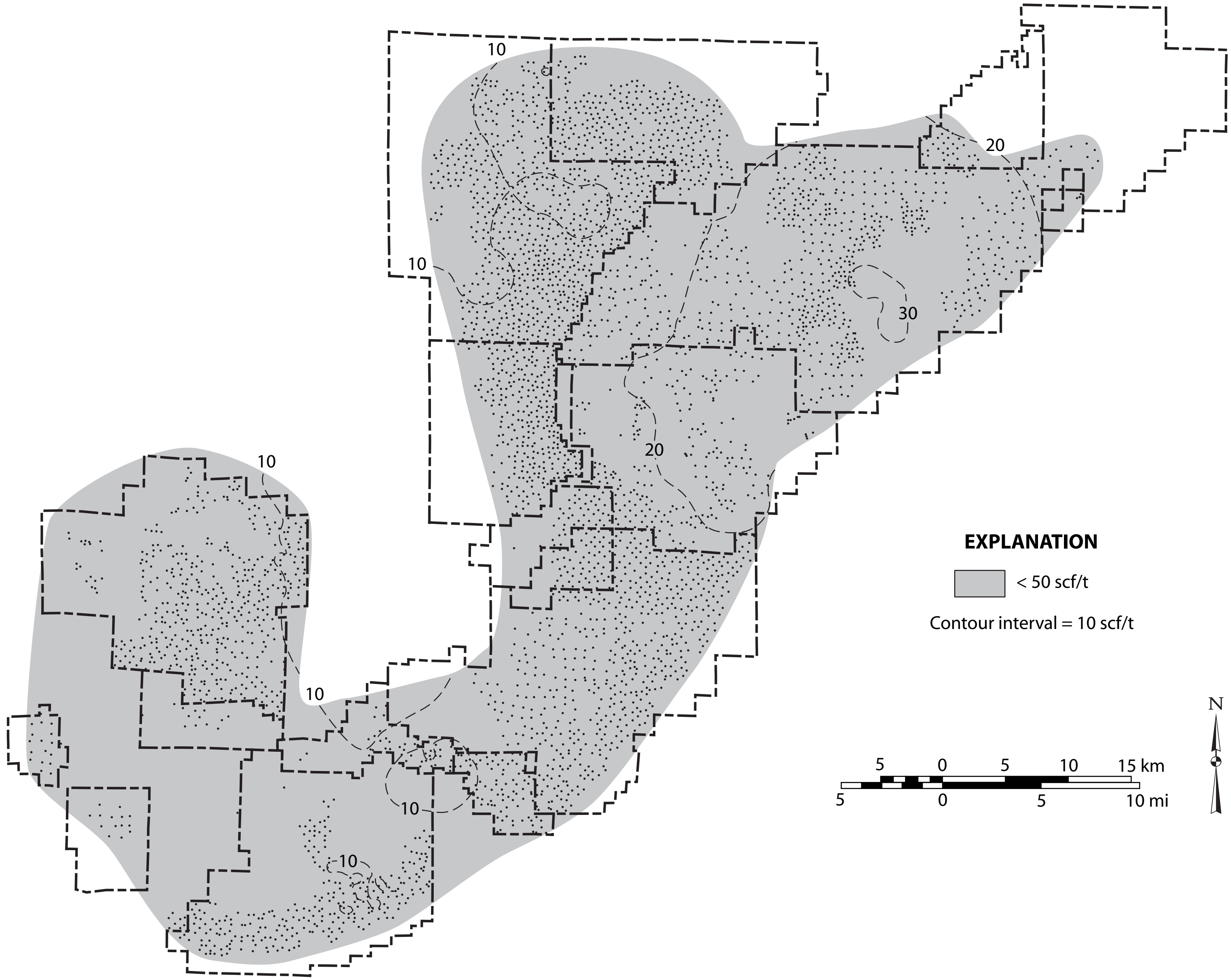



Figure 95.--Map of estimated nitrogen capacity (scf/t, as-received) in the Mary Lee coal zone at 50 psi.

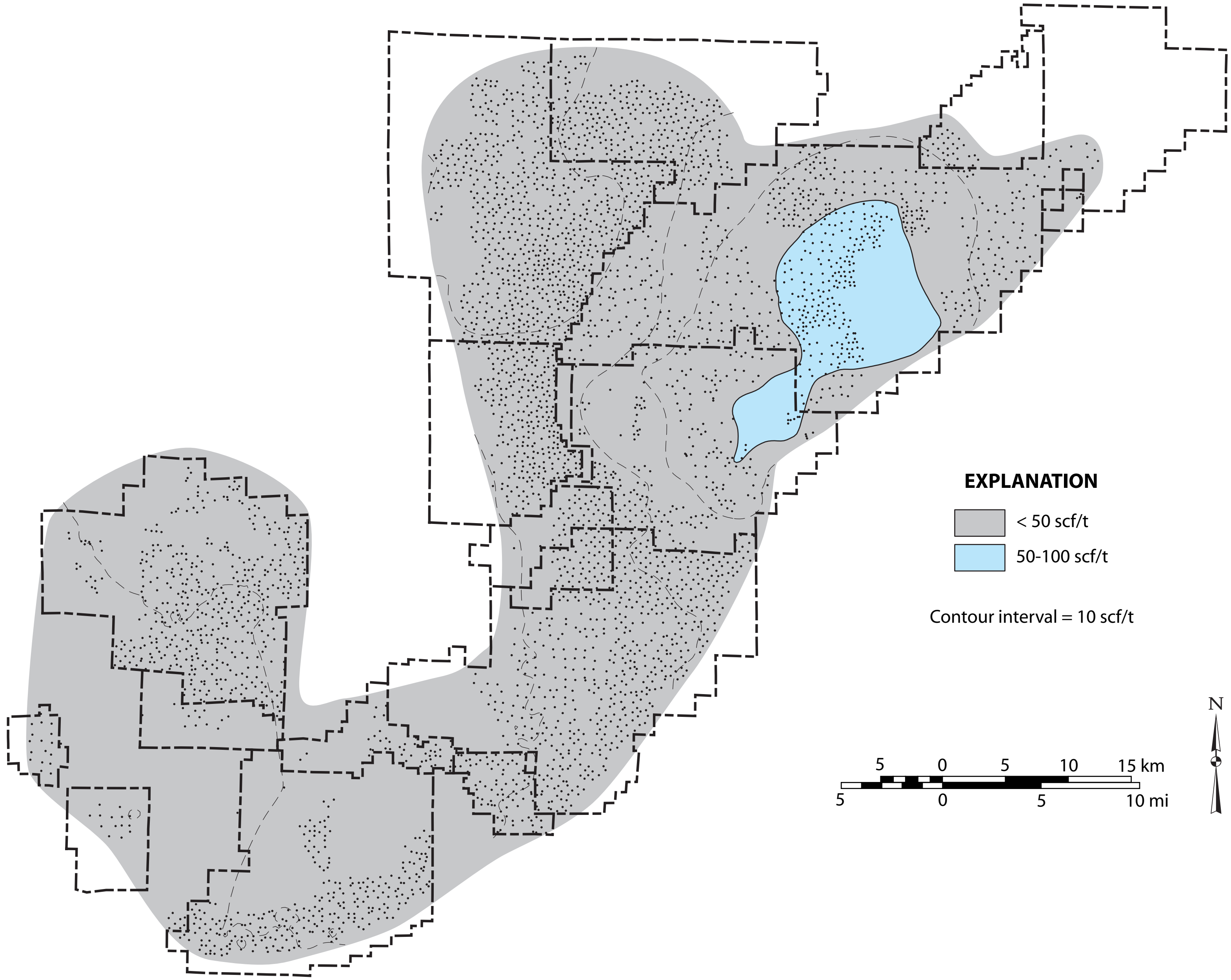



Figure 96.--Map of estimated nitrogen capacity (scf/t, as-received) in the Mary Lee coal zone at 100 psi.

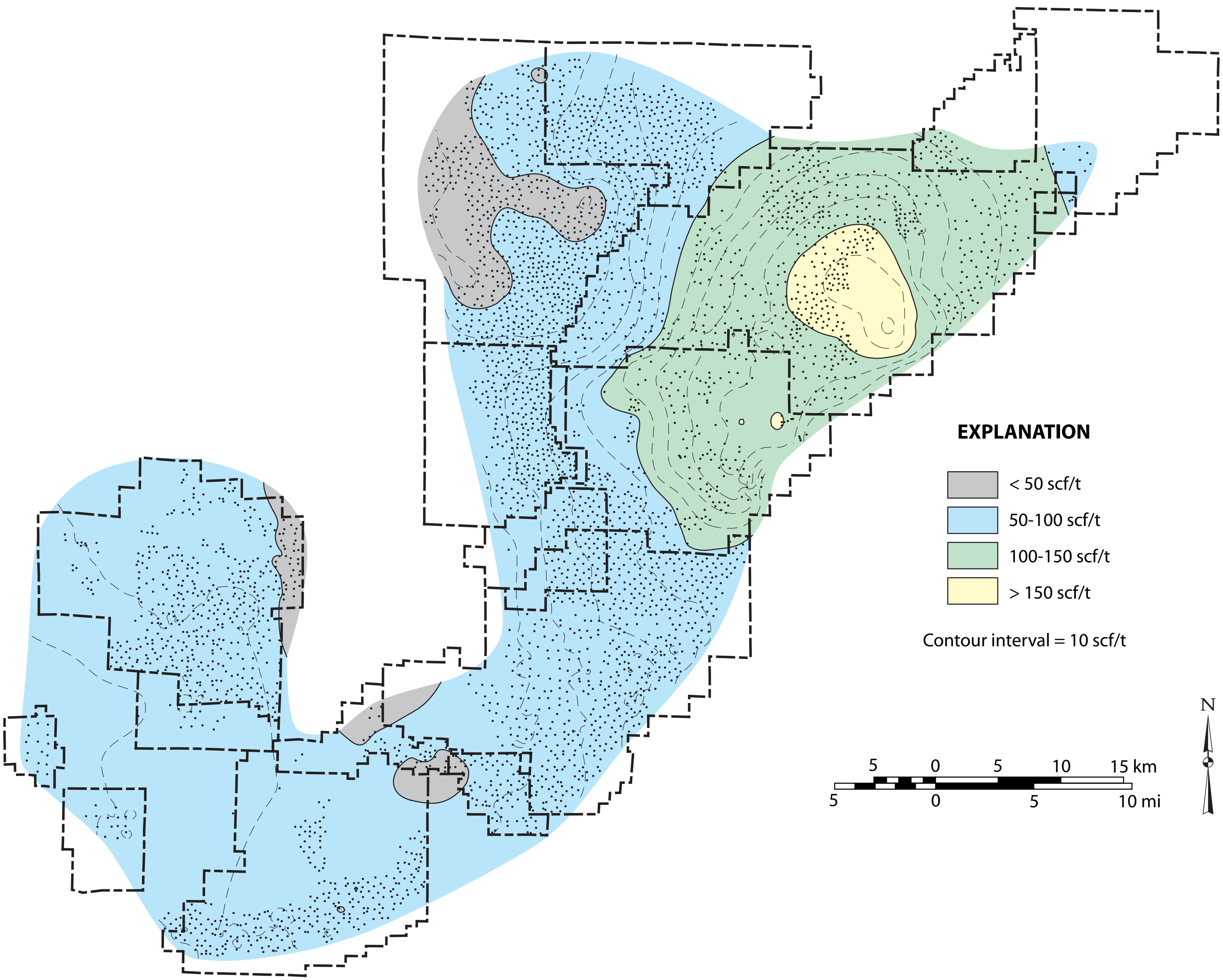



Figure 97.--Map of estimated nitrogen capacity (scf/t, as-received) in the Mary Lee coal zone at 350 psi.

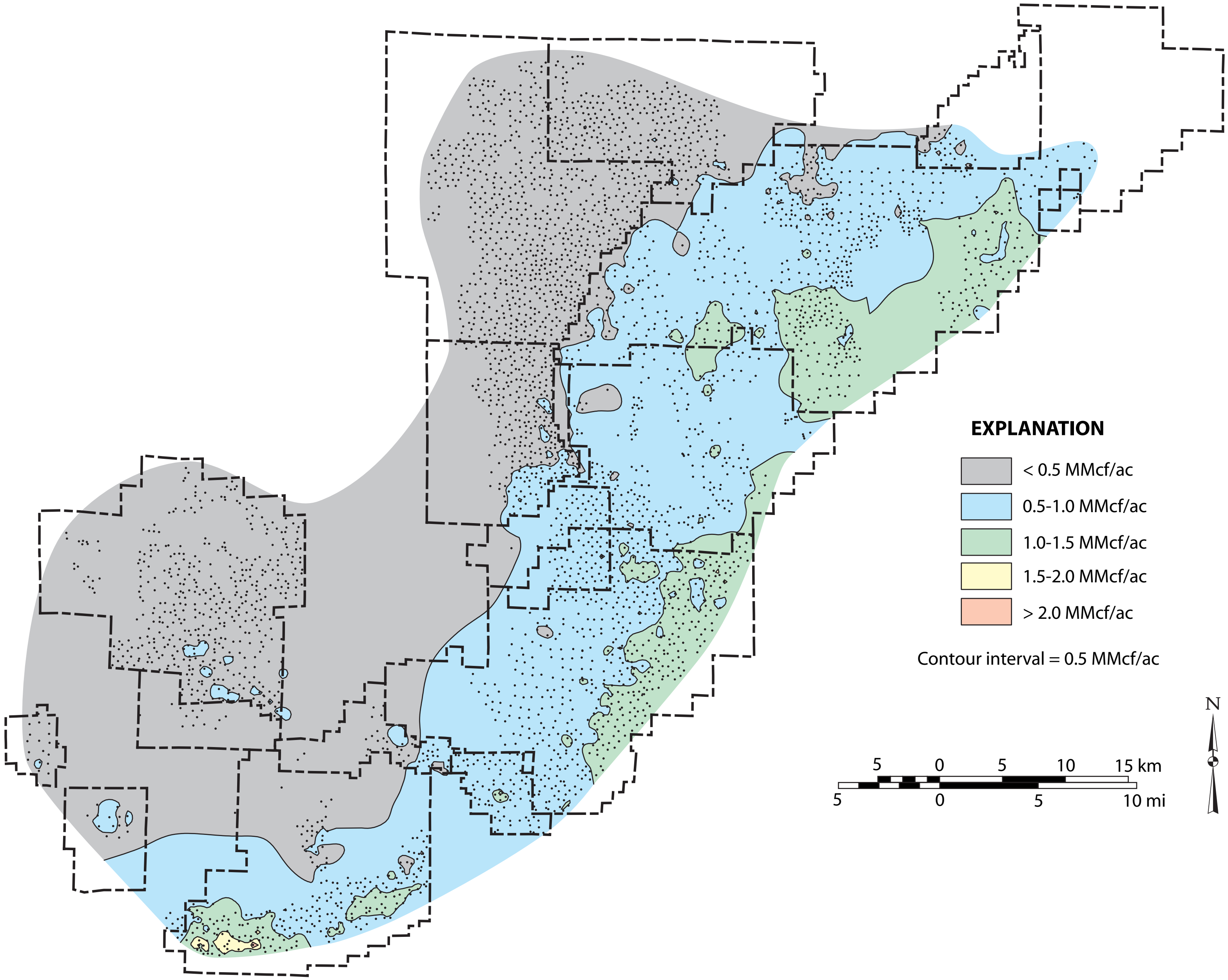



Figure 98.--Map of estimated nitrogen capacity (MMcf/ac, as-received) in the upper Pottsville Formation at 50 psi.

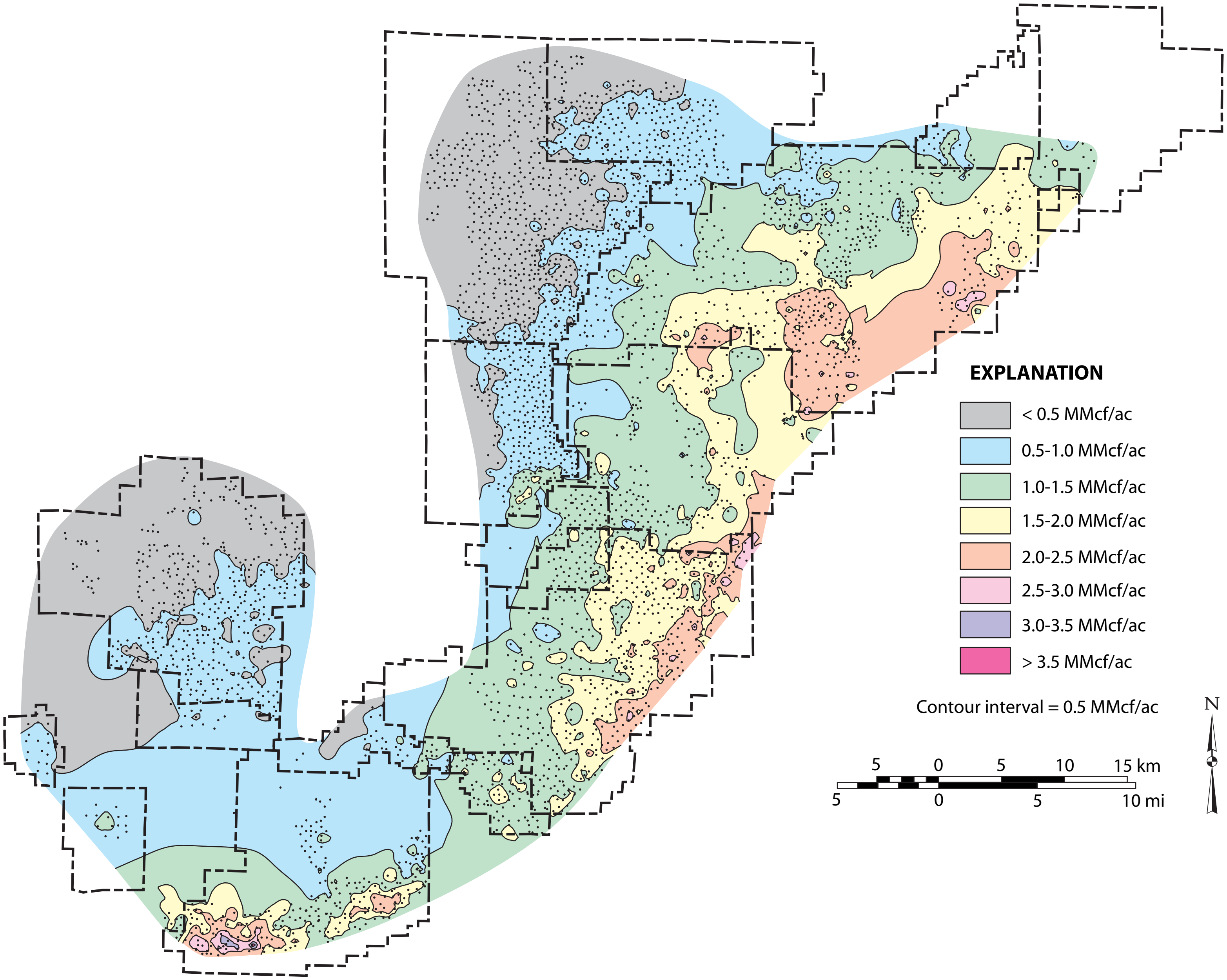



Figure 99.--Map of estimated nitrogen capacity (MMcf/ac, as-received) in the upper Pottsville Formation at 100 psi.

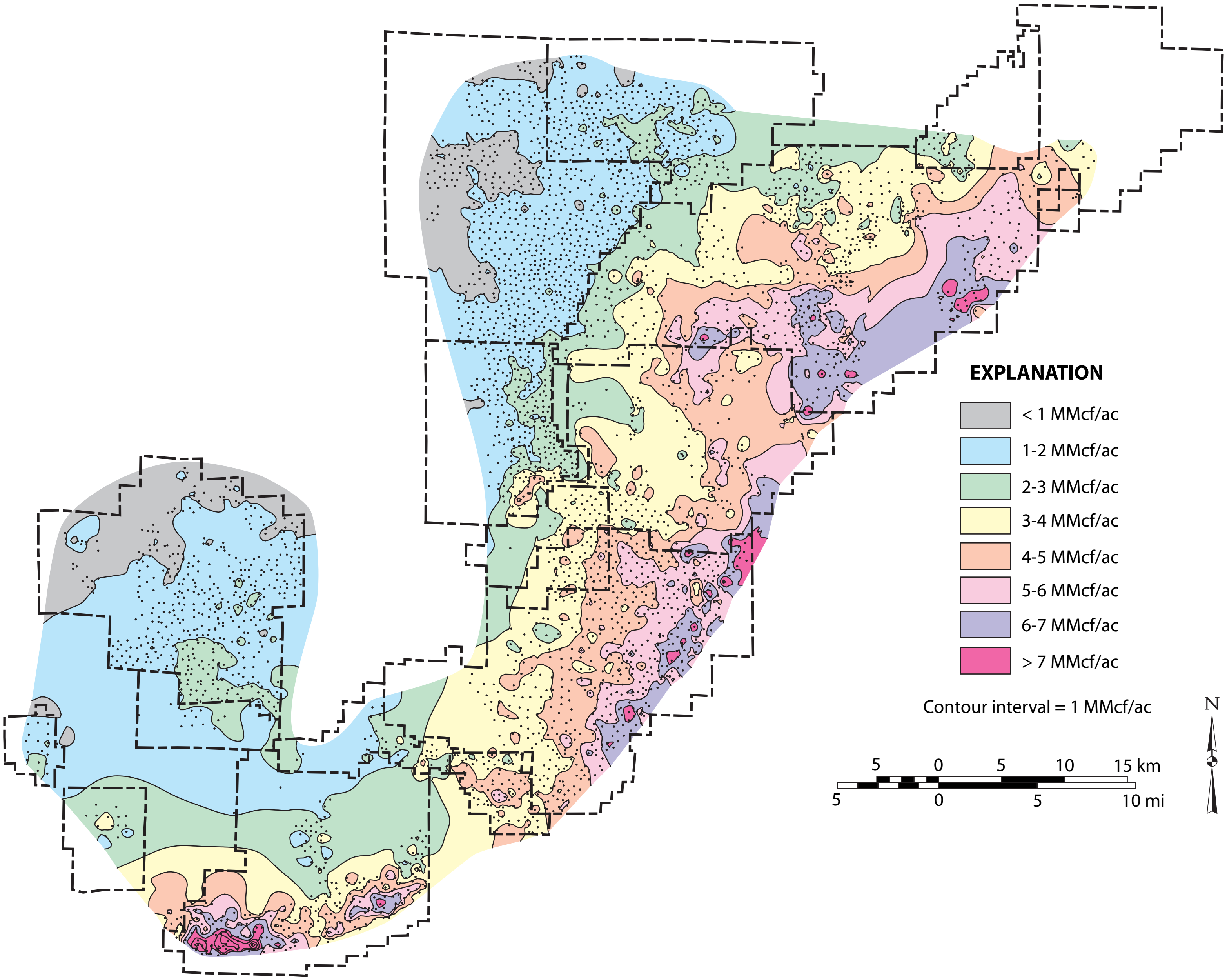



Figure 100.--Map of estimated nitrogen capacity (MMcf/ac, as-received) in the upper Pottsville Formation at 350 psi.

The total nitrogen capacity of the coalbed methane fairway is calculated to be only 0.38 Tcf at 50 psi, 0.67 Tcf at 100 psi, and 1.98 Tcf at 350 psi (table 5). These results indicate that limited amounts of $N_2$ can potentially be used to drive enhanced coalbed methane recovery in the Black Warrior basin. An optimal mix of $N_2$ and $CO_2$ may further help contain the cost of enhanced coalbed methane recovery. However a key concern with $N_2$ flooding in coal is early breakthrough of injected $N_2$ relative to $CO_2$, which is more readily adsorbed by bituminous coal (Stevens and others, 1999a, b).

## Carbon Dioxide Capacity

Maps of $CO_2$ capacity per unit weight of coal also reflect the regional rank pattern and indicate that the carbon sequestration capacity of the coalbed methane fairway is significant (figs. 51, 101-103). At 50 psi, $CO_2$ sorption capacity is estimated to range from 150 to 280 scf/t (fig. 101), and at 100 psi, sorption capacity ranges from 250 to 440 scf/t (fig. 102). At a pressure of 350 psi, $CO_2$ sorption capacity ranges from about 500 to 700 scf/t (fig. 103).

As is the case for $CH_4$ and $N_2$, $CO_2$ capacity per unit area in the upper Pottsville Formation increases toward the southeast and reflects regional trends of coal thickness (figs. 9, 104-106). At 50 psi, $CO_2$ capacity ranges from about 5 to 30 MMcf/ac (fig. 104), whereas at 100 psi, $CO_2$ capacity ranges from 5 to 45 MMcf/ac (fig. 105). At 350 psi, by comparison, $CO_2$ capacity ranges from about 10 to 75 MMcf/ac (fig. 106).

Based on these maps, the total $CO_2$ capacity of the upper Pottsville Formation in the Black Warrior coalbed methane fairway is estimated to be 5.43 Tcf at 50 psi, 8.58 Tcf at 100 psi, and 14.93 Tcf at 350 psi (table 5). These results indicate that large volumes of $CO_2$ can be sequestered at modest pressure. However, sequestration and enhanced recovery experiments will

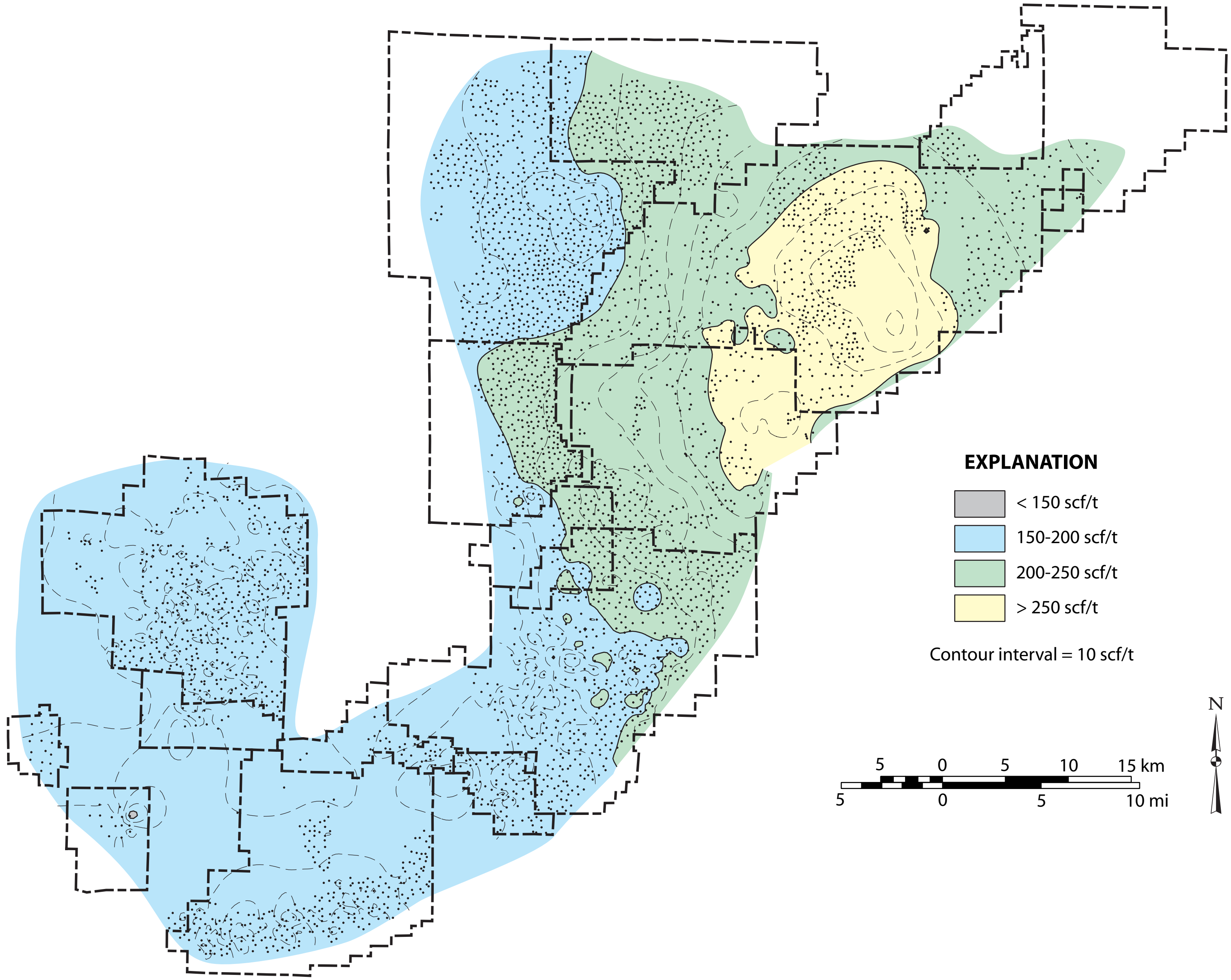



Figure 101.--Map of estimated carbon dioxide capacity (scf/t, as-received) in the Mary Lee coal zone at 50 psi.

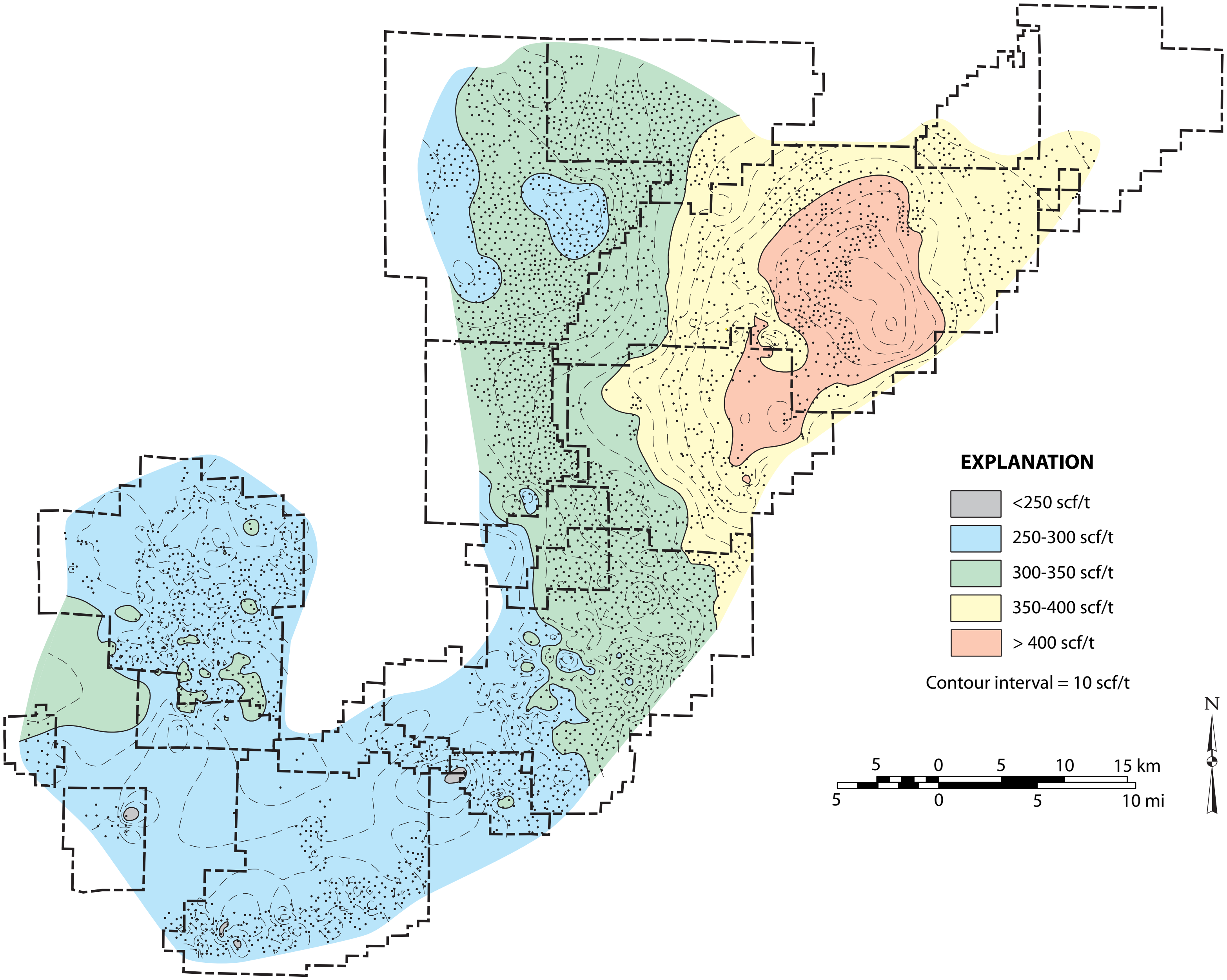



Figure 102.--Map of estimated carbon dioxide capacity (scf/t, as-received) in the Mary Lee coal zone at 100 psi.

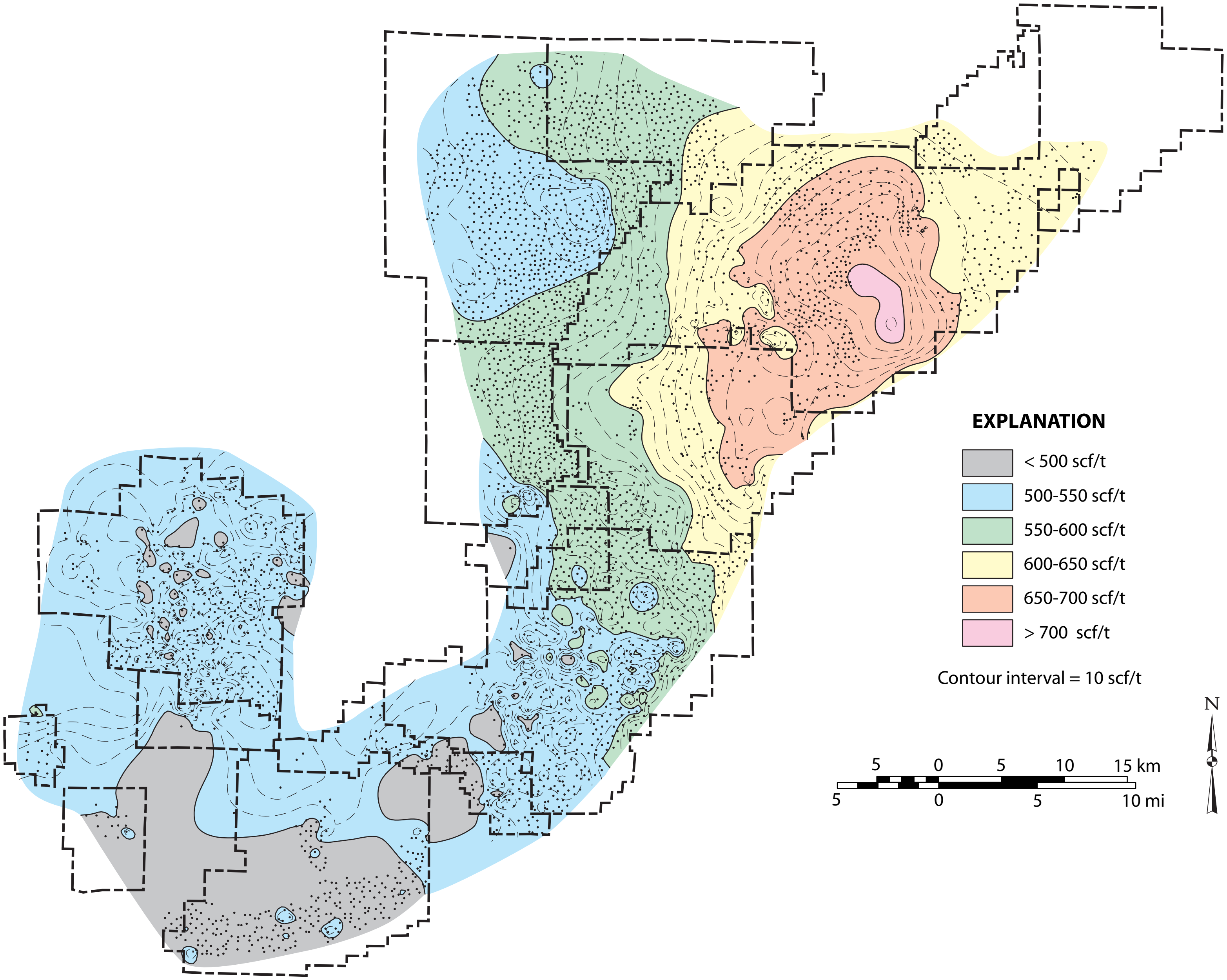



Figure 103.--Map of estimated carbon dioxide capacity (scf/t, as-received) in the Mary Lee coal zone at 350 psi.

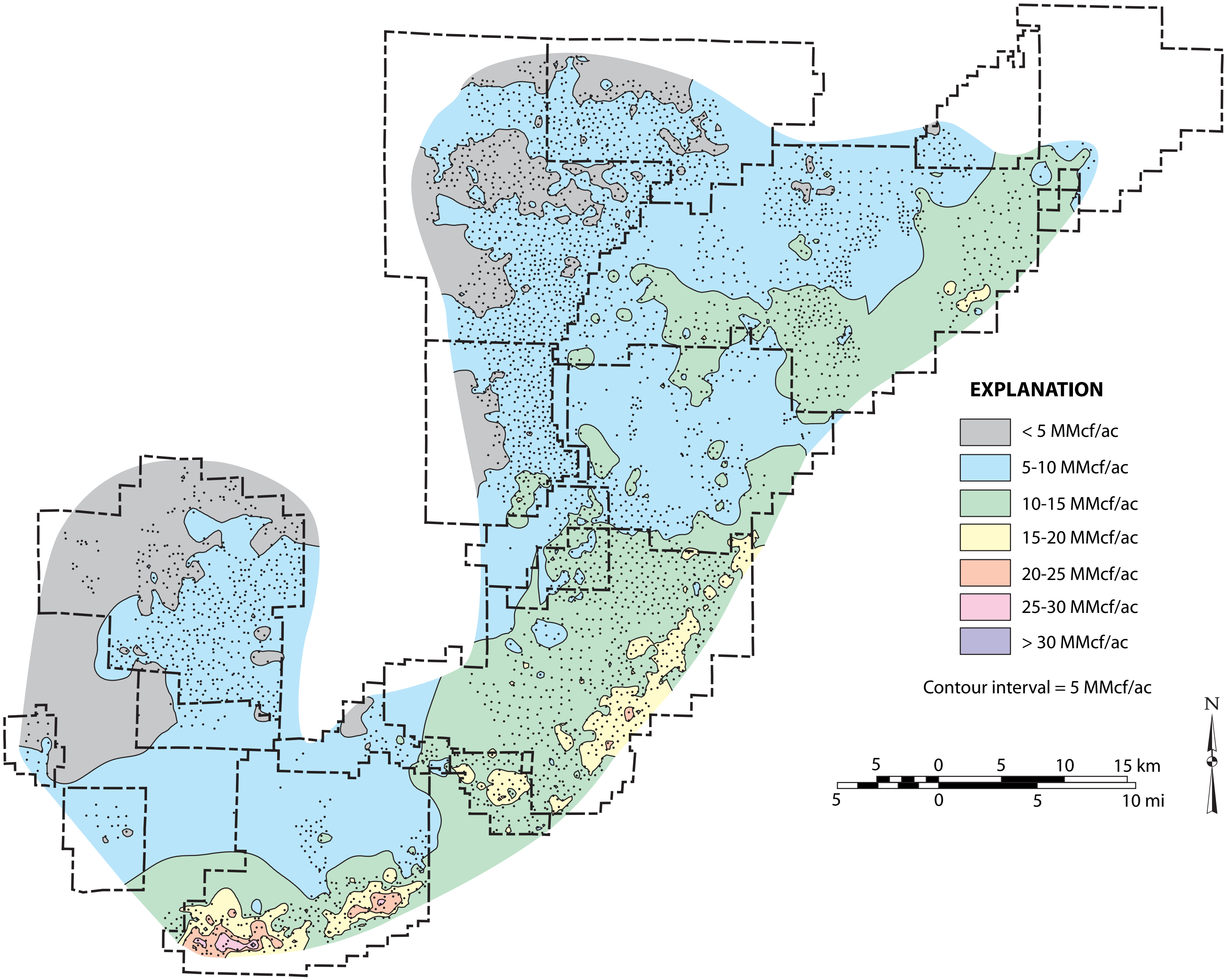



Figure 104.--Map of estimated carbon dioxide capacity (MMcf/ac, as-received) in the upper Pottsville Formation at 50 psi.

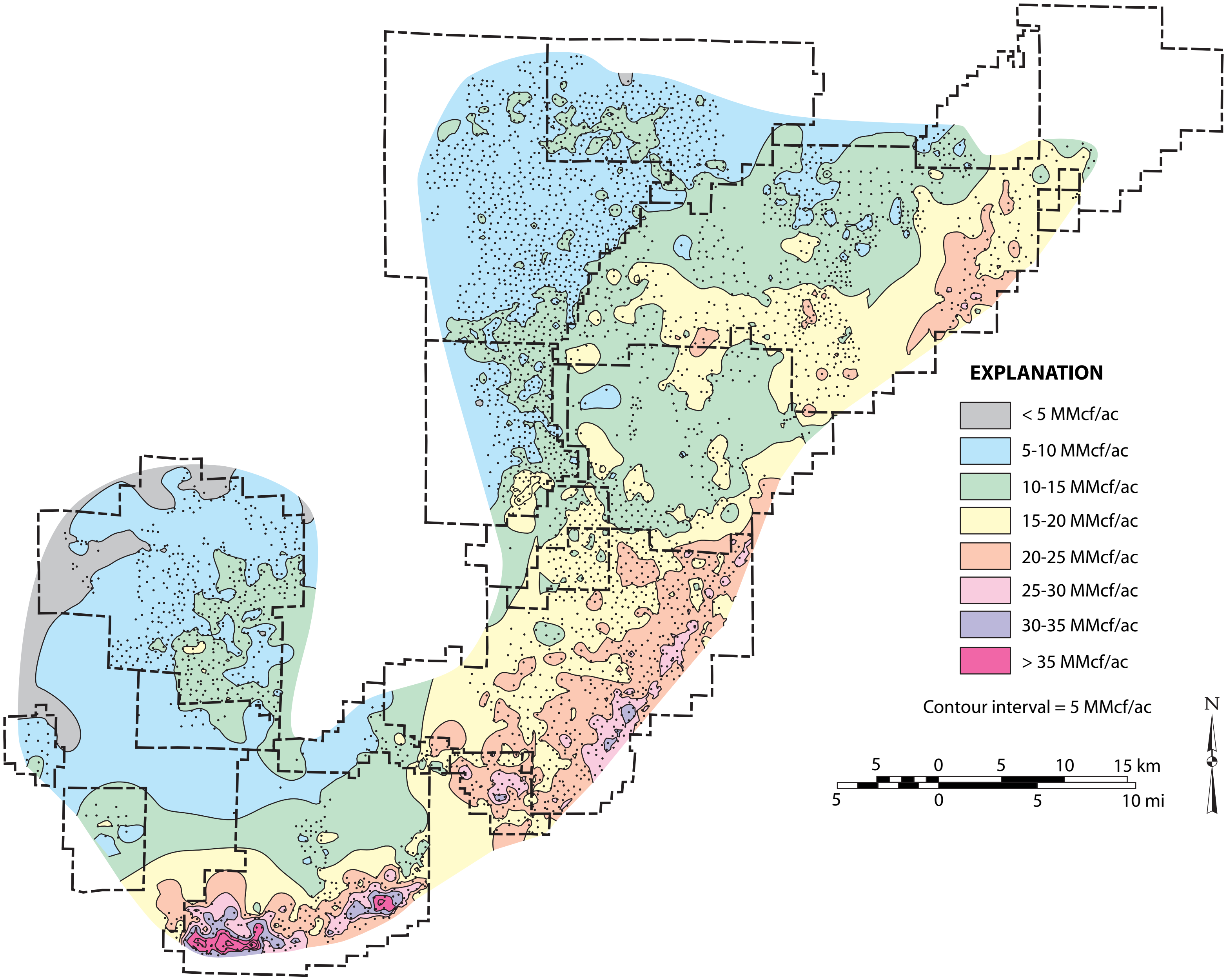



Figure 105.--Map of estimated carbon dioxide capacity (MMcf/ac, as-received) in the upper Pottsville Formation at 100 psi.

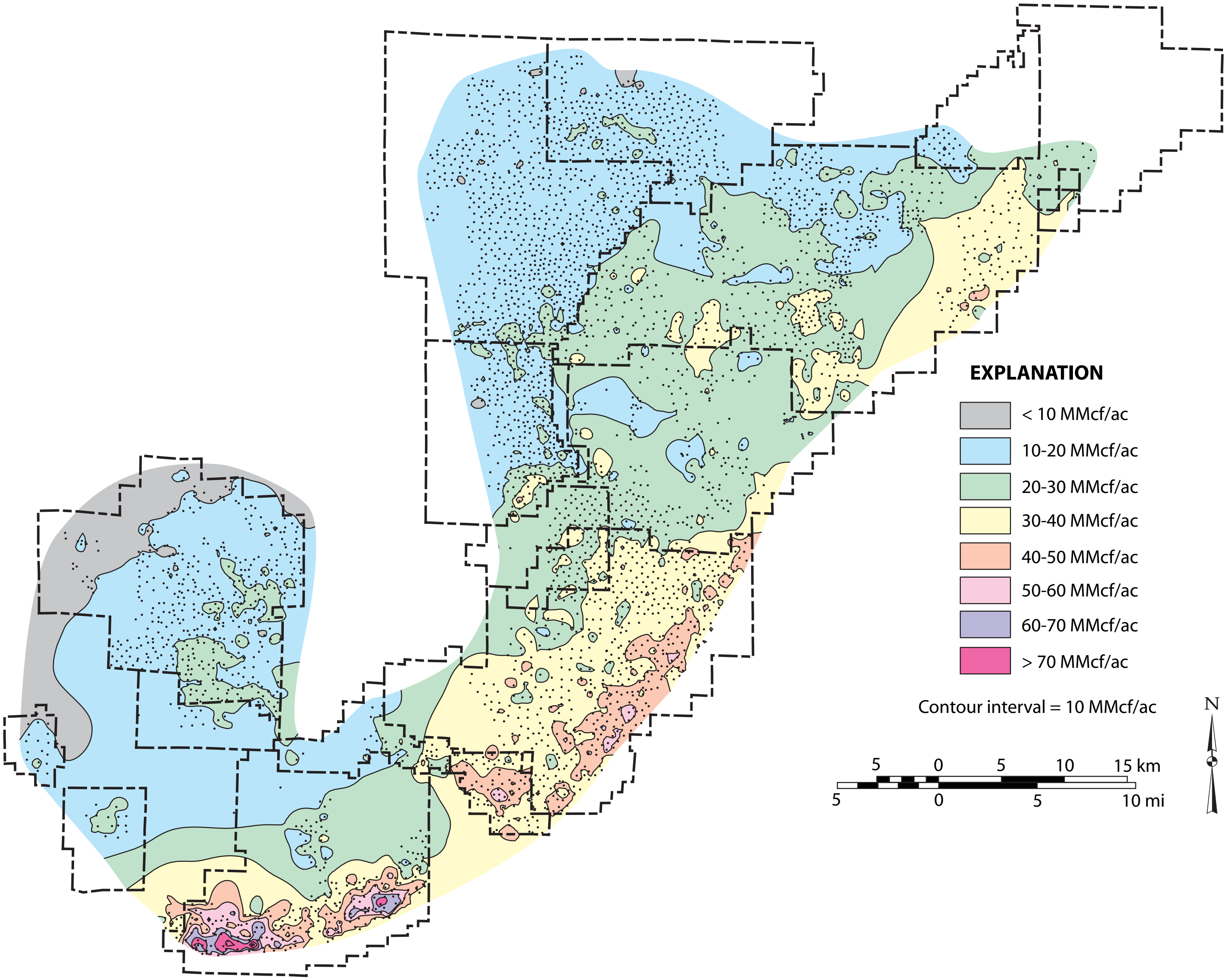



Figure 106.--Map of estimated carbon dioxide capacity (MMcf/ac, as-received) in the upper Pottsville Formation at 350 psi.

need to be conducted in the Black Warrior basin to determine the appropriate injection strategies and procedures. For instance, if the ambient reservoir pressure in a mature production area is 50 psi, then $CO_2$ will need to be injected at a higher pressure to ensure that the gas will enter the coal and that the remaining coalbed methane can be swept. To minimize the cost of the $CO_2$ required for enhanced recovery operations, $CO_2$ should be injected at the lowest pressure possible to gain efficient sweep. If $CO_2$ is injected to the point that the mean reservoir pressure in the interest area is raised to 100 psi, then nearly 6 scf (standard cubic feet) of $CO_2$ will need to be injected for each scf of coalbed methane that can be recovered. If the primary goal is to sequester as much $CO_2$ as possible, then experiments will need to be conducted to determine the highest pressure that $CO_2$ can be sequestered safely in the Pottsville Formation. Under this type of scenario, the values calculated for 350 psi may provide reasonable estimates of sequestration capacity.

The estimates given above assume that the entire Black Warrior coalbed methane fairway is available for sequestration and that the efficiency of sequestration and enhanced recovery efforts are 100 percent. However, numerous factors affect where sequestration and enhanced recovery technology can be applied safely and efficiently, and it is doubtful that the complete coalbed methane fairway is viable for $CO_2$ injection. Additionally, the efficiency of sequestration and enhanced recovery operations remains to be determined. Therefore, screening procedures were developed and applied to the Black Warrior coalbed methane fairway so that more meaningful estimates of sequestration capacity and unswept coalbed methane resources could be made.

## GEOLOGIC SCREENING MODEL

Geology, technology, and infrastructure are critical factors that need to be understood in order to screen and prioritize areas for the demonstration and application of carbon sequestration technology (fig. 107; plate 11). Key geologic screening factors are those that have been emphasized in this report, specifically stratigraphy, geologic structure, geothermics, hydrogeology, coal quality, and sorption capacity. Technological factors that must be considered include the type of sequestration technology to be applied, specifically whether sequestration will be primarily for enhanced coalbed methane recovery or for mass sequestration of $CO_2$ derived from power-plant flue gas. Also important are the types and locations of $CO_2$ sources, coalbed methane field design and maturity, gas transmission infrastructure, the locations of underground coal mines and reserves, and the locations of communities.

Plate 11 presents a comprehensive screening model in flow-chart form that should be applicable to all coal basins. On the left side of the chart are the general geologic factors that need to be considered, as well as the category of technology and infrastructure. To the right of each factor, a series of specific screening criteria are defined. The flow chart continues with specific observations related to each screening criterion; each observation leads to a decision point and action related to the application of sequestration technology in coal-bearing strata.

Decision points are represented as three types of road signs. The green highway sign signifies a “go” decision in which assessment of a given area or stratigraphic interval continues or a specific sequestration technology can be demonstrated or applied. Yellow caution signs indicate that care must be taken when considering an area or stratigraphic interval for sequestration; these symbols denote observations where additional information is needed to reach a final decision point. In some cases, other observations facilitate a final decision, whereas in other cases,

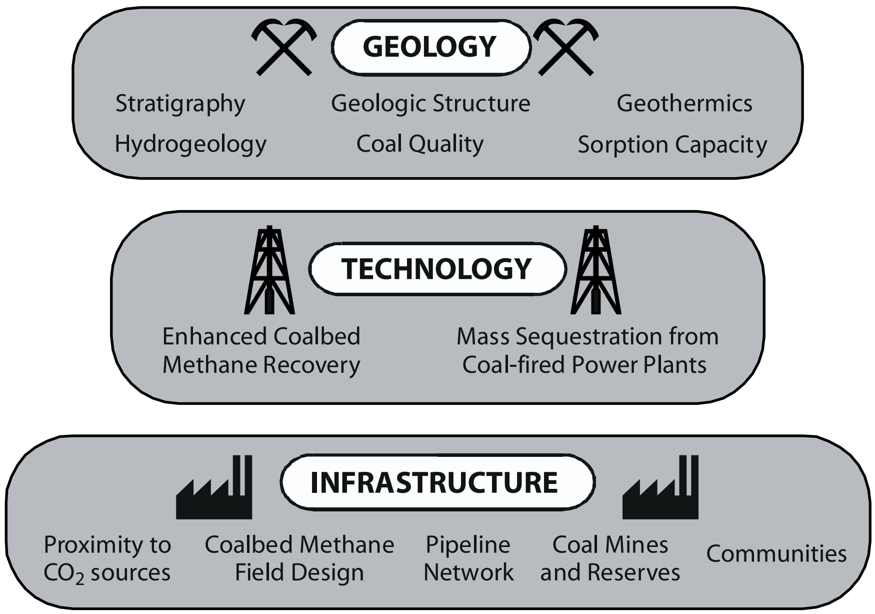



Figure 107.--Geologic, technologic, and infrastructural factors that are useful for screening areas for the application of $CO_2$ sequestration and enhanced coalbed methane recovery technology in coal-bearing strata (modified from Pashin and others, 2001a).

research is required to reach a decision point. Red stop signs signify a “no-go” decision and mark observations that exclude areas from consideration for $CO_2$ sequestration in coal. The “no-go” decision may be for technical reasons that preclude the application of sequestration technology or may be for legal or administrative reasons.

Each action leads to three ultimate outcomes, which are enhanced coalbed methane recovery, pure sequestration (i.e., without enhanced recovery), or sequestration infeasible. Adjacent to cautionary items, black lines lead to other possible observation-action pairs. To the right of each action, blue lines lead to enhanced coalbed methane recovery, green lines lead to pure sequestration, and pink lines lead to sequestration infeasible. Note that numerous actions lead to both enhanced coalbed methane recovery and pure sequestration. In the following sections, we review the screening factors, criteria, and observations to help explain how and why decision points can be reached and how the best areas can be identified for the application of $CO_2$ sequestration technology.

## Stratigraphy

Critical stratigraphic screening criteria include continuity, depth, thickness, and stratigraphic architecture (plate 11). Continuity is important because target coal beds should be widespread enough to host multiple five-spot patterns for enhanced recovery or should be widespread enough to facilitate pure sequestration over large areas. Accordingly, widespread coal beds should be assessed for sequestration potential, whereas highly localized beds should be excluded. Coalbed methane production is common between depths of 500 and 4,500 feet. However, extremely shallow coal may be excluded because of legal and administrative guidelines. For example, surface casing must be placed to a minimum depth, and hydraulic fracturing may not be permitted above a certain depth to protect shallow domestic water supplies. Additionally, extremely shallow coal may facilitate leakage of injected $CO_2$ to the surface, so as a general guideline, sequestration in coal shallower than 500 feet should be avoided.

Coal thickness is another critical variable that can be used to screen areas for $CO_2$ sequestration. In general, all beds that have sufficient thickness to be completed for coalbed methane production should be considered as having potential for $CO_2$ sequestration, whereas coal beds that are too thin to complete should be excluded. Completable bed thickness varies from basin to basin. At one extreme, for example, is the Black Warrior basin, where coal beds as thin as 1 foot are completed for gas production (Pashin and Hinkle, 1997), whereas at the other extreme is the Powder River basin, where coal beds mainly thicker than 50 feet have been completed (Ayers, 2002).

Stratigraphic architecture is also a key component of geologic screening, especially for determining what type of technology to apply (plate 11). In Tertiary strata of the Powder River basin, the dominant coal resources are concentrated in extremely thick beds, and thus single-zone completion technology is most appropriate (Flores, 1993; Ayers, 2002). By comparison, coalbed methane operations in Upper Cretaceous strata of the San Juan basin tend to be concentrated in a single coal zone, thus multiple-zone technology is applied within a narrow stratigraphic interval. At the other extreme are Carboniferous coal-bearing strata, in which coal resources tend to be dispersed throughout the section, and multiple-zone technology must be applied over intervals spanning thousands of feet (fig. 5).

## Geologic Structure

Geologic structure comprises three major geologic screening criteria, which are structural continuity, seal integrity, and fracture architecture. Ideally, areas with minimal structural heterogeneity favor $CO_2$ sequestration because potential sinks can be continuous over large areas, and structure-related permeability contrast is minimized. Strata with closely spaced faults and tight folds should be excluded because they limit reservoir continuity, affect production performance, and may pose leakage risks for injected $CO_2$ (Clayton and others, 1994; Pashin and Groshong, 1998; Shipton and others, 2001).

Seal integrity is one of the most important factors that determines where $CO_2$ can be sequestered in coal (plate 11). If both the roof and floor strata of a target coal bed are sealing, then $CO_2$ can be sequestered safely. If permeable roof or floor strata exist, as is common in many coal-bearing sections (e.g., Ayers and Kaiser, 1994), injected gas may leak into the adjacent strata, so other seals must be sought to correctly assess the viability of sequestration operations. If regional seals exist within or above the coal-bearing section, as is the case in parts of northern Europe (Hamelinck and others, 2001; van Bergen and others, 2003), then the sequestration potential of coal below the shallowest seal can be assessed. In this case, however, the capacity of other porous strata below the regional seal should be considered. If no sealing strata are present in the section, then a high risk of leakage exists, and the area should be excluded from consideration.

Fracture architecture is a significant consideration when screening areas for sequestration potential. Virtually all sedimentary rock is fractured, but the geometry and distribution of fracture systems can vary greatly (National Research Council, 1996). Discrete network models indicate that strata-bound fracture systems, such as cleat systems and joint systems in the

Pottsville Formation, give rise to tortuous flow paths and tend to favor bed-parallel flow (Pashin and others, in press). Trans-stratal fractures, such as are common in fault zones, however, pose the most significant avenues for cross-formational flow and should therefore be approached cautiously if not avoided altogether.

## Geothermics

Whereas stratigraphy and structure are critical factors that determine the viability of an area for sequestration, geothermal factors are important mainly for prioritizing areas (plate 11). Reservoir temperature can be used to help prioritize areas for sequestration because of reduced sorption capacity in areas with elevated reservoir temperature or geothermal gradient (figs. 35, 87). Most importantly, reservoir temperature must be known to accurately determine the sequestration capacity at a given site. The critical point for $CO_2$ is at a temperature of only 88°F, so geothermic and hydrostatic pressure data are key for predicting the phase and behavior of injected $CO_2$.

## Hydrogeology

Hydrogeology has diverse effects on the applicability of $CO_2$ sequestration technology to coal, and the key hydrogeologic screening criteria are permeability, water chemistry, and reservoir pressure (plate 11). Significant permeability is required so that coal can transmit large volumes of $CO_2$ and $CH_4$. Coal matrix can swell significantly as it imbibes $CO_2$, thereby decreasing permeability (Palmer and Mansoori, 1998; Pekot and Reeves, 2003; White and others, 2003). Therefore, if coal is not permeable enough to produce methane, it is a poor prospect for $CO_2$ sequestration. In the Black Warrior basin, permeability varies by more than an order of magnitude at a given depth, permeability decreases exponentially with depth, and reservoir quality deteriorates significantly below a depth of 2,000 feet (McKee and others, 1988; Koenig, 1989) (fig. 40). In the San Juan basin, however, major production is from coal at a depth of about 3,500 feet (Ayers and Kaiser, 1994). Thus, the vertical and lateral distribution of permeability can vary significantly within and among basins.

As mentioned previously, water chemistry imposes no technical limitation on sequestration potential, but is critical from an administrative standpoint because of UIC regulations in the United States and similar regulations in European petroleum provinces. Furthermore, water chemistry is one of the few screening criteria that differentiates where pure sequestration and enhanced coalbed methane recovery can be performed (plate 11). In the United States, $CO_2$ injection without enhanced hydrocarbon recovery (Class I UIC) is restricted to formations with water containing more than 10,000 mg/L TDS, whereas an aquifer exemption can be obtained for enhanced recovery operations in formations where TDS content is between 3,000 and 10,000 mg/L (Class II UIC). Below 3,000 mg/L, all underground injection is prohibited, and $CO_2$ sequestration is not possible. Importantly, many coalbed methane reservoirs contain formation waters with less than 10,000 mg/L TDS (Pashin and others, 1991; Ayers and Kaiser, 1994; van Voast, 2003), so most sequestration activities in coal will need to be conducted as part of an enhanced recovery program. Moreover, UIC guidelines may need to be revised to take advantage of the large volume of deep coal resources within existing coalbed methane plays where TDS content is less than 3,000 mg/L.

Reservoir pressure is a basic control on how much $CO_2$ can be sequestered in coal and how much coalbed methane remains unswept (figs. 60, 61). The critical point for $CO_2$ lies at 88°F and 1,074 psi, which is at a depth of 2,480 feet under normal hydrostatic conditions. Major and potentially violent volumetric changes take place in $CO_2$ near the critical point, ideal gas law does not apply to supercritical fluids because they are incompressible, and supercritical $CO_2$ can weaken and react with coal (White and others, 2003). Rapid volumetric changes near the critical point may pose problems for wellbore stability and reservoir integrity, so it may be best to focus sequestration activities in reservoirs that are either subcritically pressured or are pressured significantly beyond the critical point. Coal can hold large quantities of supercritical $CO_2$ (Kroos and others, 2002), but more work needs to be done to understand the mobility and reactivity of supercritical fluid in coal, especially at high gas saturation. Coal in the San Juan basin has stored modest concentrations of supercritical $CO_2$ over geologic time (Scott, 1993; Kaiser, 1993), so safe, long-term sequestration is possible. Regardless, supercritical $CO_2$ raises issues with the quantification of sequestration potential, and it is unclear whether sorption provides any advantage over free storage once the fluid becomes incompressible.

## Coal Quality

The most important coal quality parameters for geologic screening are coal rank and ash content (plate 11). Of these parameters, rank is extremely important for regional assessment because it correlates well with sorption capacity (figs. 62, 63) and can be predicted with at least some confidence between widely spaced control points. Coal rank also appears to have implications for the type of sequestration technology that can be applied. Low-rank coal (lignite to subbituminous) can adsorb 6 to 18 times as much $CO_2$ as methane at a given pressure (Gluskoter and others, 2002). Accordingly, low-rank coal appears an excellent sink for greenhouse gas. However, the limited $CH_4$ capacity coupled with the large volumes of $CO_2$ required to sweep remaining coalbed methane may make low-rank coal an unattractive target for enhanced coalbed methane recovery. Moreover, recent research suggests that at low pressure, coal may preferentially adsorb $CH_4$ over $CO_2$ (Busch and others, 2003). Coal of high volatile A bituminous through low volatile bituminous rank appears well suited for both pure sequestration and enhanced recovery. However, low matrix diffusivity in anthracite coal makes the potential for gas recovery and sequestration in extremely high-rank coal questionable.

Ash content generally correlates negatively with sorption capacity (fig. 66) and can therefore be used to prioritize areas for $CO_2$ sequestration and enhanced coalbed methane recovery. A key difficulty, however, is that ash content can vary extremely both geographically and stratigraphically. Moreover, ash data are commonly too sparse in areas of coalbed methane production to be useful for regional assessment of coalbed methane potential. Regardless, in areas where a significant body of ash data are available, low-ash coal can be given priority over high-ash coal for sequestration and enhanced recovery.

## Sorption Capacity

The capacity of coal to hold $CO_2$, $CH_4$, and $N_2$ has significant implications for how sequestration technology can be applied (plate 11). As discussed previously, relatively low $CO_2$:$CH_4$ sorption ratios in high-rank coal can help contain the costs of enhanced recovery, whereas high $CO_2$:$CH_4$ sorption ratios in low-rank coal appear to favor pure sequestration over enhanced recovery. Even so, current UIC regulations make the implementation and administration of enhanced recovery operations (Class II UIC) easier and more widely applicable than pure sequestration operations (Class I UIC), so there is incentive to apply sequestration technology under enhanced recovery guidelines in spite of the economics.

If economic quantities of coalbed methane remain unswept, then the advantages of sequestration coupled with enhanced coalbed methane recovery are obvious. If the unswept methane is subeconomic, then pure sequestration is favored over enhanced recovery. Again, however, UIC guidelines favor enhanced recovery regardless of the economics of unswept gas. In areas where $CO_2$:$CH_4$ sorption ratios are low, a pure $CO_2$ flood may suffice for enhanced coalbed methane recovery. One possibility to improve the economics of enhanced coalbed methane recovery in areas of high $CO_2$:$CH_4$ sorption ratios is to dilute the $CO_2$ with $N_2$, which can facilitate saturation of coal with injected gas, and perhaps facilitate efficient gas sweep, at relatively low pressure. Of course, potential for early breakthrough of $N_2$ is a key concern during enhanced recovery operations (Stevens and others, 1999a, b). Other gases, such and $SO_X$ and $NO_X$ emissions from coal-fired power plants and $H_2S$ from sour gas operations can contribute significantly to sequestration, enhanced recovery, and emissions reduction programs (Chikatamarla and Bustin, 2003).

## Technology and Infrastructure

Technological and infrastructural screening criteria include the location and types of $CO_2$ sources, gas field infrastructure, gas transmission systems, potentially mineable coal resources, coal mines, core holes, and communities (plate 11). Proximity to sources of $CO_2$ is important for prioritizing areas for carbon sequestration. Prioritizing areas near coal-fired power plants can help reduce the costs associated with the transportation of $CO_2$ to the injection site. Other sources of $CO_2$, such as the relatively pure streams produced by coal gasification, as well as $CO_2$ separated from natural gas in amine plants, may be important sources for a sequestration program. Proximity to commercial sources of $CO_2$, including existing $CO_2$ transmission systems, should be considered when screening areas for demonstration projects to help control costs. For example, a commercial $CO_2$ pipeline that transports gas for enhanced oil recovery projects is used as a source for a sequestration demonstration project in coalbed methane reservoirs of the San Juan basin (Stevens and others, 1999a, b).

In basins with coalbed methane fields, field design is a critical screening criterion. In mature fields, a determination must be made whether to convert existing production wells into injector wells or whether economics support downspacing of well patterns by drilling new injection or production wells. Areas of active exploration and development should be approached cautiously because it is unclear whether $CO_2$ flooding can be used as an early production technique. One concern is that the high viscosity of $CO_2$ relative to methane will change the relative permeability balance, thereby contributing to water disposal concerns in young coalbed methane projects. Abandoned coalbed methane wells should also be approached with caution, and the integrity of abandoned wells should be evaluated before initiating a sequestration or enhanced recovery program.

A critical issue is developing and managing the infrastructure to transport $CO_2$ from the source and distribute the gas to injection wells. Existing pipeline infrastructure in coalbed methane fields may provide right of way that can facilitate the transportation and distribution of $CO_2$. If no pipeline infrastructure exists in a basin, then options for transportation and distribution, which may include vehicular transportation and tank storage, need to be considered.

Injecting $CO_2$ into coal can create blackdamp conditions in coal mines, which pose a major suffocation hazard to coal miners. Therefore, existing mines and potentially mineable coal reserves should be protected from sequestration operations for reasons of safety, economics, and energy security (Reichle and others, 1999). This is the ultimate reason that sequestration initiatives are focusing on deep, unmineable coal beds.

Core holes have been drilled in the coal basins of North America and Europe since the 19th century, and the locations of many of these core holes may be indefinite. An important safety concern in sequestration operations is determining if any unplugged core holes exist that extend downward to reservoir depth. If deep, unplugged cores exist, they should be plugged before $CO_2$ is injected. If deep core holes are suspected to exist in an area but are undocumented, the core holes should be found and plugged, which may prove difficult, or the area should be excluded from consideration. Some states require surveys of core holes prior to drilling and hydraulic fracturing, and many geological surveys, regulatory authorities, and companies maintain databases that can help screen areas for the existence of unplugged core holes that may pose a leakage risk.

A fundamental safety concern is making sure that communities are protected from any potential leakage risk associated with sequestration activities. Therefore, all cities and villages should be eliminated from consideration. Similarly isolated dwellings and businesses should also be protected until sequestration technology is demonstrated and leakage risks are understood through practical experience. To facilitate public safety, demonstration programs should ideally include a soil-gas sampling program to measure possible $CO_2$ flux from the reservoir to the surface.

## APPLICATION OF SCREENING MODEL TO THE BLACK WARRIOR COALBED METHANE FAIRWAY

The screening model (plate 11) can be applied directly to the Black Warrior coalbed methane fairway to identify areas where sequestration and enhanced coalbed methane programs can be implemented. Each screening criterion is considered in the following sections, and geologic, technologic, and infrastructural limitations are identified. The result of the screening process is a more realistic quantification of sequestration potential that accounts for real-world limitations (table 5).

### Stratigraphy

The vast majority of coal beds in the Black Warrior coalbed methane fairway are widespread enough to host five-spot well patterns (plates 1-10). Therefore, coal beds throughout the fairway are well suited for carbon sequestration and enhanced coalbed methane recovery. Beds thicker than 1 foot are dispersed throughout the upper Pottsville section and have strong potential for sequestration and enhanced recovery. The Black Creek through Pratt zones are prospective throughout the fairway, whereas coal resources in the Cobb though Brookwood zones are concentrated in the Moundville-Cedar Cove depocenter, where more than 70 feet of coal is available locally (figs. 8-19).

Dispersal of numerous coal beds through 1,500 to 4,000 feet of section (figs. 5, 8, 9) dictates that multiple zone completion techniques must be used to access both the resource and sequestration potential. Coalbed methane production began with single zone completions in the Mary Lee coal zone and progressed toward multiple zone technology (Elder and Deul, 1974; Graves, 1983). Similarly, demonstration programs for sequestration and enhanced recovery in the Black Warrior coalbed methane fields should focus initially on single coal beds or zones to simplify experiments and facilitate monitoring and verification. Following initial demonstration, however, efforts should focus on multiple zone technology to access the full sequestration potential of the Pottsville Formation.

## Geologic Structure

Structural continuity is a critical screening criterion in the Pottsville Formation because normal faults are abundant in the Black Warrior basin (fig. 108). Normal faults pose problems for enhanced recovery and carbon sequestration because they are fundamental discontinuities in coal and thus segment the reservoir and limit hydraulic continuity (Pashin and Groshong, 1998; Groshong and others, 2003) (figs. 21, 24, 26). Some faults may pose leakage risks, but pervasive carbonate cement appears to limit fluid production along many faults (figs. 30, 84). Acidification of formation water during injection of $CO_2$, however, can dissolve calcite, thus increasing the risk of leakage along faults. Therefore, faults should be approached with caution because they limit reservoir continuity and pose potential leakage risks. The faults tend to be concentrated in swarms, and between these swarms are large structural panels that apparently can house multiple five-spot patterns safely for sequestration and enhanced recovery (fig. 109). The largest structurally coherent panels are in Oak Grove, White Oak Creek, Blue Creek, Deerlick Creek, Cedar Peterson, Cedar Cove, and Robinson’s Bend fields.

Seal integrity is a screening criterion of limited concern in the Black Warrior coalbed methane fairway because shale and sandstone have effectively no matrix permeability. Fracture architecture, however, is of great concern because natural fractures are the most viable conduits for cross-formational flow in the Pottsville Formation. Pashin and others (in press) found

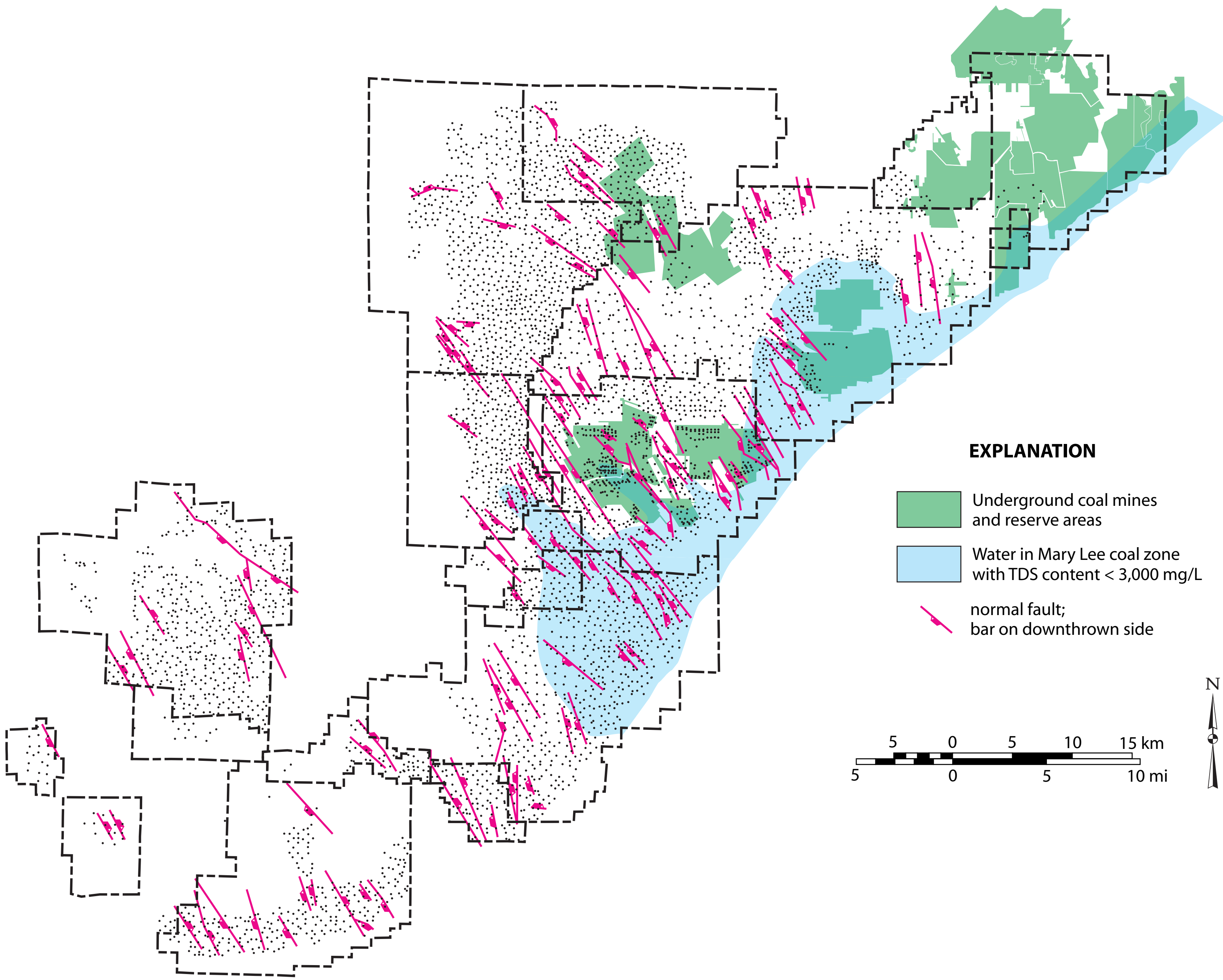



Figure 108.--Areas where sequestration potential is limited by faulting, coal reserves, and fresh formation water.

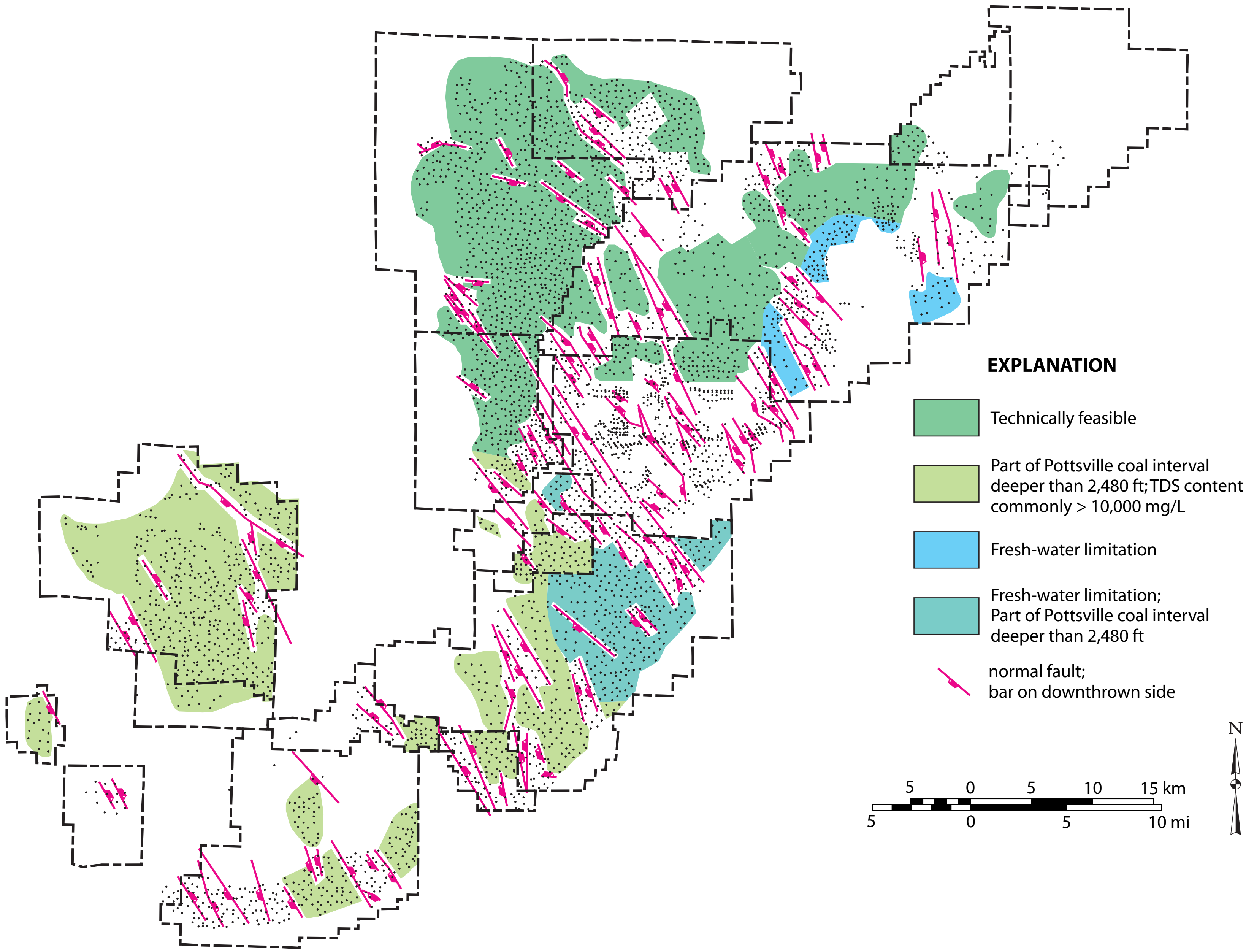



Figure 109.--Parts of the Black Warrior coalbed methane fairway where $CO_2$ sequestration is technically feasible.

that the Pottsville is dominated by strata-bound fractures that favor bed-parallel flow and the development of first-order reservoir compartments around individual coal zones (figs. 32, 33). Faults and the related shear fractures constitute major cross-stratal fracture systems in the Pottsville Formation, and sequestration activities should be avoided within fault swarms for the reasons stated in the previous paragraph.

## Geothermics

Geothermal gradient and reservoir temperature are highly variable in the coalbed methane fairway (figs. 36-39). Even so, these variables are minor screening criteria for carbon sequestration and enhanced coalbed methane recovery in the Black Warrior basin. Variation of geothermal gradient and reservoir temperature are important components required to estimate sorption capacity (figs. 87-106) but do not emerge as criteria that can be used to include or exclude a specific location from a sequestration strategy.

Many coal beds in the fairway are warmer than the critical temperature of 88°F (figs. 36, 39), but pressure data must also be considered to determine where phase relationships are a consideration (plate 11). This is because critical temperature is reached much shallower than critical pressure under normal hydrostatic conditions, let alone the pressure-depleted conditions that typify mature coalbed methane reservoirs (figs. 34, 36, 47).

## Hydrogeology

Hydrogeologic variables (plate 11) are extremely important screening criteria for the application of carbon sequestration technology to the Black Warrior basin. Permeability-depth relationships (fig. 40) indicate that many reservoirs deeper than 2,000 feet may prove problematic for enhanced recovery, especially because swelling of coal during $CO_2$ injection may reduce permeability further. Additionally, pressure-buildup test results and the high transmissivity of some joints relative to coal indicate that it may be difficult to maintain injection of $CO_2$ into coal without significant leakage into open fractures in the bounding strata (figs. 41, 42). However, it is difficult to exclude deep strata until real-world tests are performed.

Water chemistry has strong implications for how sequestration technology can be applied to the Black Warrior coalbed methane fairway. The fresh-water plumes along the southeast margin of the coalbed methane fairway, as well as other areas where TDS content may be less than 3,000 mg/L, must be excluded from any underground injection activities because of existing UIC regulations (figs. 44, 45, 108). If regulations are rewritten to remove the fresh-water limitation for sequestration in these strata, then an unswept coalbed methane resource of more than 0.4 Tcf (estimated at 50 psi) may be accessed within the fresh-water plumes, and a sequestration capacity of 3.5 Tcf (estimated at 350 psi) can be realized (table 5). Most of the coalbed methane fairway contains formation water with TDS content higher than 3,000 mg/L, and in these areas, enhanced coalbed methane recovery operations can proceed in accordance with Class II UIC guidelines. Water with TDS content higher than 10,000 mg/L TDS is most common below thick Cretaceous cover (Ellard and others, 1992). Therefore, pure sequestration operations can comply with Class I UIC guidelines on a widespread basis only in the southwestern coalbed methane fields, including Cedar Cove, Moundville, and Robinson's Bend fields (figs. 45, 62).

The role of reservoir pressure for screening the Black Warrior coalbed methane fairway is indefinite because pressure has been depleted significantly by years of dewatering for primary gas production. Large parts of the fairway were normally pressured prior to dewatering and gas production (figs. 47, 48). Considering the compartmentalized nature of Pottsville coalbed methane reservoirs, it is unclear whether pressure will return to normal or how fast reservoir pressure will increase by hydrologic recharge following abandonment. Regardless, potential exists for pressure to equilibrate to normal hydrostatic conditions, facilitating the development of supercritical reservoir conditions deeper than 2,480 feet in the southern half of the coalbed methane fairway (Pashin and McIntyre, 2003a, b) (fig. 50). Extreme volumetric changes near the critical point may affect reservoir integrity, especially near wellbores, but isotherms dictate that the reservoirs should be undersaturated with $CO_2$ if critical pressure is achieved, thereby limiting long-term storage concerns. Based on the well-testing results of McKee and others, (1988) and Koenig (1989), moreover, low permeability below 2,480 feet poses more of an obstacle to sequestration operations than supercritical reservoir conditions.

## Coal Quality

Coal rank has a strong impact on the amount of gas that can be sequestered in coal, and the highest gas concentrations on a volumetric or per weight basis are in the elliptical area containing medium- and low-volatile bituminous coal in Oak Grove and Brookwood fields (figs. 51, 52, 89-103). Mapping gas capacity per unit area, however, indicates that coal thickness is as important as rank for quantifying untapped methane and sequestration potential (figs. 9, 92-106). Although coal rank does not necessarily exclude any part of the coalbed methane fairway from a sequestration program, high-rank coal resources should be given priority because unswept methane and sequestration capacity are less dilute than in lower rank coal resources.

Although ash content affects sorption capacity (fig. 66), ash data are sparse in most of the coalbed methane fairway. Where data are available, only the beds with significant mining potential have been sampled, and the data have little or no value for prediction of ash content between control points (fig. 56). Ash content averages only 12 percent in the Black Warrior basin (fig. 54) and thus is not as critical a parameter as rank when screening areas (plate 11). However, the apparently reduced sorption capacity of coal containing less than 5 percent ash (figs. 64-66) should be the subject of further investigation.

## Sorption Capacity

Coal in the Black Warrior basin apparently contains significant concentrations of unswept coalbed methane and can hold large volumes of unswept gas (figs. 89-106; table 5). Between 50 and 350 psi, the $CO_2$:$CH_4$ sorption ratio is generally between 2:1 and 3:1, which is typical of bituminous coal and appears suited for enhanced coalbed methane recovery. However, if the $CO_2$ is sequestered at pressure higher than the depleted reservoir pressure, the $CO_2$:$CH_4$ ratio increases significantly, and the economics of enhanced recovery become less attractive (table 5). Additionally, research needs to be performed to understand the maximum pressure at which $CO_2$ can be sequestered in the upper Pottsville Formation without significant risk of leakage. If pressures above 350 psi can be realized safely, then the sequestration capacity is significantly higher than the estimates given in table 5.

The economics of unswept methane are unclear in the Pottsville Formation, but at a depleted reservoir pressure of only 50 psi, as much as 7 MMcf/ac may be available, and the volume of unswept gas increases significantly toward the southeast (fig. 92). Concentrations of 1 to 7 MMcf/ac translate to 40 to 280 MMcf of unswept gas in a 40-acre drilling unit. Currently high gas prices exceeding $5.00/Mcf translate to a total value of more than 0.2 to 1.4 million dollars per 40-acre drilling unit. Much of the economic uncertainty, however, revolves around unknown recovery efficiency, the cost of $CO_2$ refined from coal-fired power plants, and the cost of transporting $CO_2$ to the coalbed methane fields.

The economics of enhanced recovery in the Black Warrior basin may be improved by co-injection of $N_2$, but experiments are required to determine the feasibility of co-injection and the rates and proportions at which $N_2$ should be injected. Co-injection of $SO_X$ and $NO_X$ may also provide a worthwhile component of a sequestration program and increase the attractiveness of sequestration and enhanced recovery projects to electric power utilities.

## Technology and Infrastructure

Technological and infrastructural variables are extremely important screening criteria for the application of carbon sequestration technology in the Black Warrior basin. The major $CO_2$ sources near the Black Warrior coalbed methane fairway are two power plants located immediately north of the coalbed methane fields (fig. 110). A permit application for a new coal-fired power plant in Brookwood Field has been submitted by Jim Walter Resources, Incorporated. The two active plants favor demonstration and initial application of sequestration technology in the northern coalbed methane fields. If the proposed power plant is approved and constructed, then a $CO_2$ source that is central to the coalbed methane fields will be available. A commercial pipeline source of $CO_2$ is available to the west of the Black Warrior basin in Jackson, Mississippi, and some of this gas could be used for demonstration projects. Also, several chemical companies serving the Black Warrior basin area can supply large quantities of $CO_2$ to demonstration projects at reasonable cost.

The infrastructure and maturity of the coalbed methane fields has a significant impact on where sequestration technology can be applied (figs. 68, 69). Most fields have been developed

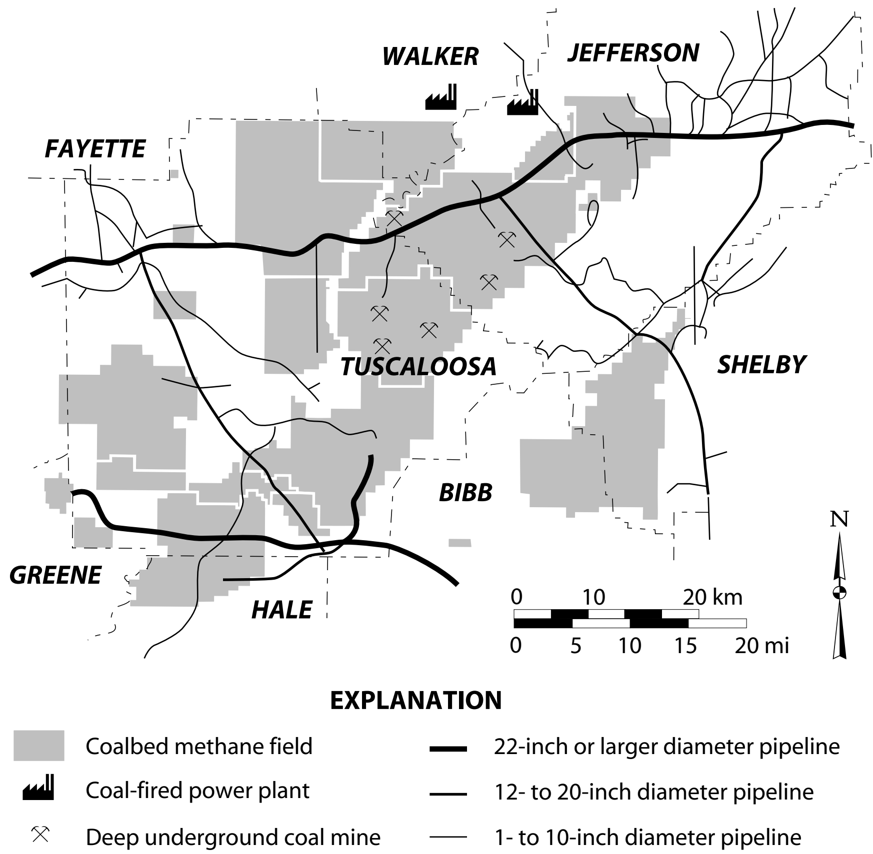



Figure 110.--Locations of gas-transmission pipelines and coal-fired power plants near the Black Warrior coalbed methane fairway (modified from Pashin and others, 2001a).

using 40- to 80-acre well spacing and, in these areas, enhanced recovery operations may be feasible by converting production wells to injectors. The economics of drilling new wells for injection are questionable, although injection wells should perhaps be drilled during demonstration projects to minimize well spacing and thus decrease the amount of $CO_2$ injected and the time required to obtain results. Wells are spaced effectively at 160 acres in western Oak Grove Field, and an infill drilling program is currently under way to recover untapped gas in this area. Therefore, enhanced recovery operations in this area should probably wait until the infill wells approach maturity. Some of the southwestern coalbed methane fields are abandoned or temporarily abandoned so it is unclear whether enhanced recovery operations are feasible in these areas. Recompletion efforts are underway in Moundville Field, and if these efforts are successful, the field may be a candidate for enhanced recovery in the future. The remaining fields are approaching maturity and are thus strong candidates for enhanced recovery experiments. Most active development is along the northern edge of the coalbed methane fairway, and when these areas reach maturity, they will have the advantage of being very close to coal-fired power plants.

An active transmission pipeline system is developed in the coalbed methane fairway (fig. 110). Two large-diameter, regional transmission pipelines extend through the coalbed methane fields, and large gathering systems connect the producing wells to the transmission pipeline network. Therefore, these pipeline networks may provide right of way and supporting infrastructure for a $CO_2$ distribution system that may be required to implement sequestration and enhanced recovery programs throughout the fairway.

Protection of underground coal mines and coal reserves in the Black Warrior basin is extremely important for determining where sequestration technology can be applied.

Underground coal mines and associated reserve areas are concentrated in the Mary Lee and Pratt coal zones in Brookwood, Oak Grove, and White Oak Creek fields (fig. 108). Coal beds in the Cobb and Gwin are commonly thicker than 4 feet in Cedar Cove field, but it is questionable whether this coal maintains thickness over a large enough area to be prospective for underground mining. The gas capacity of coal in reserve areas outside the fresh-water plumes is given in table 5.

Numerous deep coreholes have been drilled in association with coal and coalbed methane exploration in the Black Warrior basin. The vast majority of the core holes reaching reservoir depth have been plugged, and the locations of these core holes are well documented. Additionally, the State Oil and Gas Board of Alabama requires a survey of core holes to be performed before coalbed methane wells are stimulated, and similar surveys should be performed before enhanced recovery experiments are attempted. Accordingly, few problems associated with unknown or unplugged core holes are anticipated in the Black Warrior coalbed methane fairway.

Although the coalbed methane fairway is developed in the Birmingham-Tuscaloosa economic corridor, nearly all development has been in rural areas. Although large tracts appear suitable for development, small communities and isolated dwellings and businesses are common in some areas. Identifying dwellings and businesses is beyond the scope of this study, but careful screening should be performed as demonstration projects are proposed and enhanced recovery operations are planned.

## DISCUSSION: SCREENING RESULTS

According to the U.S. Environmental Protection Agency, $CO_2$ emissions from electric utilities serving the Black Warrior basin of Alabama emitted approximately 31 MMst (million short tons) (2.4 Tcf) of $CO_2$ in 1997. The total capacity of the Black Warrior coalbed methane fairway is estimated to be 189 MMst (14.9 Tcf) at 350 psi, which is equivalent to 6.1 years of emissions (table 6). Applying the geologic screening model to the coalbed methane fairway indicates that parts of the fairway are not available for sequestration because of geologic, safety, and legal reasons. The principal limitations on where $CO_2$ can be sequestered in the coalbed methane fairway are water with TDS less than 3,000 mg/L, coal mines and reserves, and fault zones (figs. 108, 109). More than 43 MMst (3.4 Tcf) of $CO_2$ capacity, or 1.4 years of emissions, must be excluded because of the fresh-water limitation (table 6). An additional 11 MMst (0.8 Tcf), or 0.4 years of emissions must be subtracted to protect underground mines and coal reserves outside the areas with fresh-water limitation. An additional 76 MMst (6.0 Tcf) of $CO_2$ or 2.5 years of emissions, cannot be sequestered in faulted areas outside the area of fresh-water limitation. Therefore, the capacity of the coalbed methane fairway that can be accessed without technical limitation is about 60 MMst (4.7 Tcf) of $CO_2$, which is equivalent to 1.9 years of emissions.

Analysis of individual coalbed methane fields indicates that sequestration potential varies considerably (tables 5, 6). Oak Grove, Blue Creek, Robinson's Bend, Cedar Cove, and Moundville have a realistic sequestration potential of 46 MMst (3.6 Tcf) of $CO_2$ at 350 psi, which is more than 75 percent of the total capacity of the coalbed methane fairway. If the fresh-water restriction on underground injection were removed to facilitate sequestration efforts, nearly 15 MMst (1.2 Tcf) of additional capacity would be realized for a total capacity of 75 MMst (5.9

Table 6. Estimated tonnages of carbon dioxide and carbon that can be sequestered in the Black Warrior coalbed methane fairway.

| | Acres | Carbon dioxide (thousand short tons) | | | Carbon (thousand short tons) | | |
|---|---|---|---|---|---|---|---|
| | | 50 psi | 100 psi | 350 psi | 50 psi | 100 psi | 350 psi |
| **COALBED METHANE FAIRWAY** | | | | | | | |
| Total capacity | **666,593** | **68,996.0** | **108,907.7** | **189,493.8** | **18,830.4** | **29,723.1** | **51,716.8** |
| Fresh-water limitation | 119,587 | 16,396.8 | 25,755.9 | 43,461.3 | 4,475.0 | 7,029.3 | 11,861.5 |
| Coal reserve areas without fresh-water limitation (TDS < 3,000 mg/L) | 39,051 | 3,950.0 | 6,205.8 | 10,541.8 | 1,078.0 | 1,693.7 | 2,877.1 |
| Faulted areas without fresh-water limitation (TDS < 3,000 mg/L) | 276,469 | 27,183.2 | 43,036.0 | 75,767.5 | 7,418.9 | 11,745.4 | 20,678.5 |
| **INDIVIDUAL FIELDS** | | | | | | | |
| Big Sandy Creek | 3,164 | 593.9 | 941.4 | 1,681.8 | 162.1 | 256.9 | 459.0 |
| Blue Creek | 55,973 | 3,670.4 | 5,808.7 | 10,531.4 | 1,001.7 | 1,585.3 | 2,874.2 |
| Brookwood | 8,758 | 999.9 | 1,568.8 | 2,625.8 | 272.9 | 428.2 | 716.6 |
| Cedar Cove | 16,159 | 2,610.7 | 4,131.9 | 7,254.5 | 712.5 | 1,127.7 | 1,979.9 |
| Deerlick Creek | 12,752 | 1,049.1 | 1,656.1 | 2,921.4 | 286.3 | 452.0 | 797.3 |
| Holt | 1,042 | 121.7 | 192.2 | 334.8 | 33.2 | 52.5 | 91.4 |
| Little Sandy Creek | 2,017 | 279.7 | 444.3 | 797.9 | 76.3 | 121.3 | 217.8 |
| Moundville | 12,450 | 1,860.1 | 2,951.8 | 5,309.3 | 507.6 | 805.6 | 1,449.0 |
| Oak Grove | 42,359 | 4,840.0 | 7,594.3 | 12,824.4 | 1,320.9 | 2,072.6 | 3,500.0 |
| Peterson | 2,041 | 264.0 | 417.3 | 725.4 | 72.1 | 113.9 | 198.0 |
| Robinson's Bend | 50,237 | 3,438.1 | 5,457.8 | 9,854.4 | 938.3 | 1,489.6 | 2,689.5 |
| Short Creek | 2,021 | 173.2 | 271.9 | 458.3 | 47.3 | 74.2 | 125.1 |
| Taylor Creek | 2,115 | 121.7 | 193.2 | 339.7 | 33.2 | 52.7 | 92.7 |
| Thornton Creek | 3,858 | 303.4 | 481.2 | 861.7 | 82.8 | 131.3 | 235.2 |
| White Oak Creek | 16,540 | 1,140.1 | 1,799.0 | 3,202.5 | 311.1 | 491.0 | 874.0 |
| **Total** | **231,486** | **21,466.0** | **33,909.9** | **59,723.1** | **5,858.5** | **9,254.7** | **16,299.7** |
| **PARTS OF FIELDS WITH FRESH-WATER LIMITATION (TDS < 3,000 mg/L)** | | | | | | | |
| Cedar Cove | 23,491 | 4,028.5 | 6,356.9 | 10,938.0 | 1,099.5 | 1,734.9 | 2,985.2 |
| Holt | 1,199 | 143.8 | 226.7 | 391.6 | 39.2 | 61.9 | 106.9 |
| Oak Grove | 6,299 | 1,020.7 | 1,597.9 | 2,632.4 | 278.6 | 436.1 | 718.4 |
| Peterson | 2,470 | 343.0 | 541.5 | 935.9 | 93.6 | 147.8 | 255.4 |
| **Total** | **33,459** | **5,536.1** | **8,723.0** | **14,897.9** | **1,510.9** | **2,380.7** | **4,065.9** |
| **TOTAL FOR FIELDS** | **264,945** | **27,002.0** | **42,633.0** | **74,621.0** | **7,369.4** | **11,635.4** | **20,365.6** |

Tcf). Lifting the fresh-water restriction would have the strongest effect in Cedar Cove Field, where an additional 10 MMst (0.9 Tcf) of $CO_2$ could be sequestered in areas lacking mapped normal faults and mineable coal reserves (fig. 109).

If reservoir pressure in the coalbed methane fairway were assumed to be depleted to 50 psi, then nearly 1.49 Tcf of gas remains unswept (table 5). Considering the same limitations that affect $CO_2$ capacity, more than 0.44 Tcf of $CH_4$ may be accessible in areas without fresh water, coal mines and reserves, and fault zones. Removing the fresh-water restriction would add 0.13 Tcf, leaving a technically accessible gas resource of 0.57 Tcf. Were 80 percent of this gas to be recovered, then enhanced recovery efforts would result in a reserve expansion of more than 18 percent. Even though a significant part of Oak Grove field is unavailable because of coal reserves and faulting, the high rank of the coal in this area supports an unswept gas resource of more than 118 Bcf. Blue Creek and Robinson's Bend field contain more than 50 Bcf of unswept gas that appears accessible, although this resource is more dilute than that in the southeastern coalbed methane fields (table 5; figs. 89, 92).

Comparison of gas capacity numbers indicates that coal in the Black Warrior basin can sorb up to 15 times more $CO_2$ than $N_2$ at 50 psi and 8 times more $CO_2$ than $N_2$ at 350 psi (table 5; fig. 62). Accordingly, a small percentage of $N_2$ in the injectate may reduce the costs of enhanced recovery operations substantially. However, it is not clear what the effect of a $CO_2$-$N_2$ mixture will be on sweep efficiency or whether small concentrations of $N_2$ will break through rapidly. Moreover, if greenhouse gas reduction is a major goal of enhanced recovery operations, then the introduction of $N_2$ into the reservoir will reduce sequestration capacity significantly.

## RECOMMENDATIONS

Tables 5 and 6 indicate that the potential for $CO_2$ sequestration and enhanced coalbed methane recovery in the Black Warrior basin is substantial and can result in significant reduction of greenhouse gas emissions while increasing natural gas reserves. Application of the geologic screening model (plate 11) to the Black Warrior coalbed methane fairway indicates that sequestration and enhanced recovery operations are possible in nearly all coalbed methane fields, and the only areas that appear to be technically infeasible within those fields are areas with coal reserves and fault systems (figs. 108, 109).

The gas capacity values given in this study serve as conservative guidelines that are intended to facilitate the demonstration and implementation of sequestration technology in the Black Warrior basin. The next logical step for this basin is the initiation of a demonstration project for $CO_2$ sequestration and enhanced coalbed methane recovery technology. Based on the screening criteria discussed in previous sections, demonstration projects can be conducted effectively in many fields, and the large structural panels lacking coal reserves and fault systems in Blue Creek, Deerlick Creek, Cedar Cove, and Oak Grove fields are perhaps the most desirable places to begin.

A broad range of analytical, monitoring, and verification techniques are recommended to implement an effective demonstration program in the Black Warrior basin. We recommend that a new injection well be drilled within an existing 40-acre well pattern to minimize spacing, thereby ensuring timely project results. The new well should be cored to determine the amount of unswept coalbed methane, and pressure should be gauged to verify the degree to which reservoir pressure has been depleted between mature coalbed methane wells. Also desirable would be a pattern of three monitoring wells between the injection and production wells to monitor pressure changes and gas composition. These wells should also be cored to determine unswept gas content. The monitor design could be similar to that employed at the Rock Creek test site, which was used to demonstrate and develop completion technology for coalbed methane reservoirs (Schraufnagel and others, 1991; Young and others, 1993). Initial experiments should focus on a single coal bed to minimize the variables affecting $CO_2$ sequestration and enhanced coalbed methane recovery. Later experiments should focus on the implementation of multiple zone technology, because the main potential of the Pottsville Formation for sequestration and enhanced recovery lies in numerous coal seams dispersed through more than 1,500 feet of section (figs. 5, 8, 9).

Public safety is a paramount concern in the demonstration and implication of sequestration technology, and so demonstration test sites should be in areas isolated from dwellings and businesses. Soil gas should be monitored before, during and after injection to determine if leakage of injected $CO_2$ and swept $CH_4$ is an issue. Demonstration programs also should focus on determining the appropriate injection pressure for $CO_2$, determining whether $CO_2$-$N_2$ mixtures are viable, and determining the maximum safe sequestration pressure for Pottsville coalbed methane reservoirs. Determining optimal gas injection rates, sweep efficiencies, and sequestration efficiencies are required to confidently calculate the proportion of power-plant $CO_2$ emissions that can be sequestered and how much coalbed methane can be recovered by $CO_2$ flooding.

## TECHNOLOGY TRANSFER

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

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, 2003) is available for download through the web page. This report will also be made available through the web page. Also available for download are PDF files of project members' contributions to the 2003 International Coalbed Methane Symposium Proceedings.

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
John Mark Goodman, Southern Company
Gary Hart, Southern Company
John Hollingshead, Geomet Operating Company
Paul Mock, Chevron-Texaco
Phil Malone, Geomet Operating Company
Jerry Saulsberry, Energen Resources Corporation
Rhonda Tinsley, Southern Company
Charles Willis, Black Warrior Methane Corporation

A meeting of the advisory committee was held in May 2003 at the Geological Survey of Alabama in conjunction with the 2003 International Coalbed Methane Symposium at the University of Alabama. 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 project period, numerous presentations on the $CO_2$ sequestration potential of the Black Warrior basin were made. The results of this study were presented to the Warrior Basin Section of the Society of Petroleum Engineers, annual meetings of the American Association of Petroleum Geologists, the Coal-Seq I and II Fora, the 2001 and 2003 International Coalbed Methane Symposia, the annual meeting of The Society for Organic Petrology, the Southeastern Section of the Geological Society of America, the Alabama Mining Institute, in a short course at the Gulf Coast Association of Geological Societies annual meeting, and at the Annual Conference and Exhibition of the Air & Waste Management Association.

Recently, Dr. Pashin was honored to give an invited keynote lecture at the XV International Congress on Carboniferous and Permian Stratigraphy and Geology in Utrecht, The Netherlands, on heterogeneity in coalbed methane reservoirs and the applicability of $CO_2$ sequestration technology (Pashin, 2003). Project presentations have also received awards. A poster session at the 2002 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. An oral presentation at the 2003 American Association of Petroleum Geologists Annual Meeting received the Frank K. Kottlowski Memorial Presentation Award (Best Paper) (Pashin and Carroll, 2003). Furthermore, Jack Pashin was just named a Distinguished Lecturer by the American Association of Petroleum Geologists and will conduct two lecture tours to present his work on $CO_2$ sequestration and coalbed methane. Additional presentations are planned for 2004, and final results of this project will be published as an Alabama Geological Survey Bulletin.

# CONCLUSION

Sequestration of $CO_2$ 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.

Coalbed methane reservoirs in the upper Pottsville Formation of the Black Warrior basin are extremely heterogeneous, and this heterogeneity must be considered to screen areas for the application of $CO_2$ sequestration and enhanced coalbed methane recovery technology. Major screening factors include stratigraphy, geologic structure, geothermics, hydrogeology, coal quality, sorption capacity, technology, and infrastructure. Applying the screening model to the Black Warrior basin indicates that geologic structure, water chemistry, and the distribution of coal mines and reserves are the principal determinants of where $CO_2$ can be sequestered. By comparison, coal thickness, temperature-pressure conditions, and coal quality are the key determinants of sequestration capacity and the quantity of coalbed methane that can be accessed through enhanced recovery operations.

Upper Pottsville coal beds are preserved in a series of flooding-surface-bounded depositional cycles of fluvial-deltaic origin that span 1,500 to more than 4,000 feet of section. More than 20 coal beds have been completed in some wells. Coal beds as thin as 1 foot are commonly completed, and net completable coal thickness ranges from about 10 to more than 70 feet. Because coal and coalbed methane resources are dispersed widely through a thick section, multiple zone technology will need to be developed and applied to realize the potential of upper Pottsville strata for $CO_2$ sequestration and enhanced coalbed methane recovery.

Compressional folds and extensional faults are abundant in the Black Warrior basin, and these structures have a significant effect on the production performance of coalbed methane wells. Normal faults are major reservoir discontinuities, and trans-stratal fracture systems associated with these faults pose potential leakage risks. Therefore, $CO_2$ sequestration and enhanced recovery operations should avoid fault zones. Strata-bound joint and cleat systems are developed between the fault zones, and these fracture systems tend to favor the development of reservoir compartments around individual coal zones that favor bed-parallel flow over cross-formational flow.

Permeability, water chemistry, and temperature-pressure conditions are the key hydrologic and geothermal variables to be considered when screening coalbed methane reservoirs. Permeability-depth relationships in the Pottsville Formation favor sequestration and enhanced recovery efforts in coal shallower than 2,000 feet. Water chemistry is a fundamental control on where sequestration technology can be applied because of UIC regulations. Fresh-water plumes along the southeast margin of the Black Warrior basin contain water with TDS content less than 3,000 mg/L, and current UIC regulations prohibit underground injection into water that fresh. Most of the coalbed methane fields contain water with 3,000 to 10,000 mg/L TDS, and an aquifer exception can be obtained to facilitate enhanced hydrocarbon recovery programs (Class II UIC). Water with TDS content higher than 10,000 mg/L is common in some of the southwestern coalbed methane fields, and in these areas, $CO_2$ can be injected into coal without enhanced hydrocarbon recovery (Class I UIC).

Coalbed methane reservoirs in the Black Warrior basin are normally pressured to underpressured, and geothermal gradients are generally between 8 and 15°F per 1,000 feet. Temperature correlates negatively and significantly with the sorption capacity of coal and must therefore be considered in regional estimates of sequestration capacity. Reservoir pressure has been depleted by prolonged dewatering associated with coalbed methane production. Beyond a depth of 2,480 feet, $CO_2$ will become a supercritical fluid if the reservoir returns to a normal hydrostatic pressure gradient. Supercritical $CO_2$ can weaken and react with coal, and rapid volumetric changes at the critical point raise some concerns about reservoir integrity and wellbore integrity. However, coal has stored supercritical $CO_2$ under natural conditions over geologic time.

The most important coal quality parameters determining how much gas can be stored in coal are ash content and rank. Ash content correlates negatively with sorption capacity, but the utility of ash content for regional assessment of sequestration and enhanced recovery potential is limited because ash data are too variable to predict between data points. Coal rank correlates highly with gas sorption capacity and is a regionalized variable that can be projected between data points with confidence. For these reasons, rank and reservoir temperature are key variables required to quantify the sequestration potential of coalbed methane reservoirs in the Black Warrior basin.

The sorption capacity per unit weight of coal in the Black Warrior coalbed methane fairway is influenced strongly by rank and reservoir temperature, whereas the sorption capacity per unit area of coal in the upper Pottsville Formation is influenced strongly by coal thickness. At 100 to

350 psi, upper Pottsville coal can adsorb between 250 and 700 scf/t and between 5 to 80 MMcf/ac of $CO_2$ on an as-received basis. Estimated at a modest pressure of 50 psi, unswept coalbed methane resources range from 40 to 100 scf/t and 1 to 7 MMcf/ac.

Numerous technological and infrastructural variables must be examined to screen areas for $CO_2$ sequestration and enhanced coalbed methane recovery. Critical variables for the Black Warrior coalbed methane fairway include proximity to coal-fired power plants, the design and maturity of coalbed methane fields, and pipeline infrastructure. Identifying the locations of underground coal mines, coal reserves, unplugged core holes, and communities are also important components of a screening strategy. Two coal-fired power plants are at the northern margin of the coalbed methane fairway, and a new plant is planned for the central part of the fairway. Most of the fairway is reaching maturity, although infill drilling and recompletion programs in some fields limit where demonstration and enhanced recovery programs should be sited. Coal mines and coal reserves are scattered through the northern part of the coalbed methane fairway and should be protected from sequestration activities.

Coal-fired power plants serving the Black Warrior basin in Alabama emit approximately 31 MMst (2.4 Tcf) of $CO_2$ annually. The total sequestration capacity of the Black Warrior coalbed methane fairway at 350 psi is about 189 MMst (14.9 Tcf), which is equivalent to 6.1 years of greenhouse gas emissions from the coal-fired power plants. Applying the geologic screening model indicates that significant parts of the coalbed methane fairway are not accessible because of fault zones, coal mines, coal reserves, and formation water with TDS content less than 3,000 mg/L. Excluding these areas leaves a sequestration potential of 60 MMst (4.7 Tcf), which is equivalent to 1.9 years of emissions. Therefore, if about10 percent of the flue gas stream from nearby power plants is dedicated to enhanced coalbed methane recovery, a meaningful reduction of $CO_2$ emissions can be realized for nearly two decades. If the fresh-water restriction were removed for the purposes of $CO_2$ sequestration, an additional 10 MMst (0.9 Tcf) of $CO_2$ could feasibly be sequestered. The amount of unswept coalbed methane in the fairway is estimated to be 1.49 Tcf at a pressure of 50 psi. Applying the screening model results in an accessible unswept gas resource of 0.44 Tcf. Removal of the fresh-water restriction would elevate this number to 0.57 Tcf. If a recovery factor of 80 percent can be realized, then enhanced recovery activities can result in an 18 percent expansion of coalbed methane reserves in the Black Warrior basin.

Results of this investigation indicate that the potential for $CO_2$ sequestration and enhanced coalbed methane recovery in the Black Warrior basin is substantial and can result in significant reduction of greenhouse gas emissions while increasing natural gas reserves. Application of the geologic screening model to the Black Warrior coalbed methane fairway indicates that sequestration and enhanced recovery operations are possible in nearly all coalbed methane fields, and the only areas that appear to be technically infeasible within those fields are areas with coal reserves and fault systems. Future work should focus on the development and implementation of demonstration programs that focus on determination of optimal $CO_2$ injection rates, quantification of sequestration and enhanced gas recovery efficiency, and monitoring and verification of sequestration activities.

# REFERENCES

Aitken, J. F., and Flint, S. S., 1994, High-frequency sequences and the nature of incised-valley fills of the Breathitt Group (Pennsylvanian), Appalachian foreland basin, eastern Kentucky: Society of Economic Paleontologists and Mineralogists Special Publication 51, p. 353-368.

Aitken, J. F., and Flint, S. S., 1995. The application of high-resolution sequence stratigraphy to fluvial systems: a case study from the Upper Carboniferous Breathitt Group, eastern Kentucky, USA: Sedimentology, v. 42, p. 3-30

Arri, L. E., Yee, D., Morgan, W. D., and Jeansonne, M. W., 1992, Modelling coalbed methane production with binary gas sorption: Casper, Wyoming, Society of Petroleum Engineers Rocky Mountain Regional Meeting, paper SPE 24363, p. 459-472.

Ayers, W. B., Jr., 2002, Coalbed gas systems, resources, and production and a review of contrasting cases from the San Juan and Powder River Basins: American Association of Petroleum Geologists Bulletin, v. 86, p. 1853-1890.

Ayers, W. B., Jr., and Kaiser, W. A. (eds.), 1994, Coalbed methane in the Upper Cretaceous Fruitland Formation, San Juan Basin, Colorado and New Mexico: Texas Bureau of Economic Geology Report of Investigations 218, 216 p.

Bibler, C. J., Marshall, J. S., and Pilcher, R. C., 1998, Status of worldwide coal mine methane emissions and use: International Journal of Coal Geology, v. 35, p. 283-310.

Bradley, J. S., 1975, Abnormal formation pressure: American Association of Petroleum Geologists Bulletin, v. 59, p. 957-973.

Bradley, J. S., and Powley, D. E., 1994, Pressure compartments in sedimentary basins: a review: American Association of Petroleum Geologists Memoir 61, p. 3-26.

Bragg, L. J., Oman, J. K., Tewalt, S. J., Oman, C. L., Rega, N. H., Washington, P. M., and Finkelman, R. B., 1998, U.S. Geological Survey coal quality database (COALQUAL), version 2.0: U.S. Geological Survey Open-File Report 97-134, unpaginated CD-ROM.

Busch, A., Gensterblum, Y., Siemons, N., Kroos, B. M., van Bergen, F., Pagnier, H. J. M., and David, P., 2003, Investigation of preferential sorption behaviour of CO2 and CH4 on coals by high pressure adsorption/desorption experiments with gas mixtures: Tuscaloosa, Alabama, University of Alabama College of Continuing Studies, 2003 International Coalbed Methane Symposium Proceedings, Paper 0350, 14 p.

Bustin, R. M., 1997, Importance of fabric and composition on the stress sensitivity of permeability in some coals, northern Sydney basin, Australia: relevance to coalbed methane exploitation: American Association of Petroleum Geologists Bulletin, v. 81, p. 1894-1908.

Bustin, R. M., and Clarkson, C. R., 1998, Geological controls on coalbed methane reservoir capacity and gas content: International Journal of Coal Geology, v. 38, p. 3-26.

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

___1926, The Paleozoic rocks, *in* Adams, G. I., Butts, Charles, Stephenson, L. W., and Cooke, C. W., Geology of Alabama: Alabama Geological Survey Special Report 14, p. 41-230.

___1927, Bessemer-Vandiver folio: U.S. Geological Survey Geologic Atlas, Folio 221, 22 p.

Byrer, C. W., and Guthrie, H. D., 1999, Appalachian coals: Potential reservoirs for sequestering carbon dioxide emissions from power plants while enhancing CBM production: Tuscaloosa, Alabama, 1999 International Coalbed Methane Symposium Proceedings, p. 319-327.

Carroll, R. E., and Pashin, J. C., 1999, Coal resources of the Cahaba coalfield, *in* Pashin, J. C., and Carroll, R. E., eds., Geology of the Cahaba Coalfield: Alabama Geological Society 36th Annual Field Trip Guidebook, p. 59-69.

Carroll, R. E., Pashin, J. C., and Kugler, R. L., 1995, Burial history and source-rock characteristics of Upper Devonian through Pennsylvanian strata, Black Warrior basin, Alabama: Alabama Geological Survey Circular 187, 29 p.

Casagrande, D. J., 1987, Sulphur in peat and coal, in Scott, A. C., ed., Coal and coal-bearing strata: recent advances: London Geological Society Special Publication 32, p. 87-105.

Casagrande, D. J., and Siefert, K., 1977, Origins of sulfur in coal: importance of ester-sulfate content: Science, v. 195, p. 675-676.

Cates, L. M., and Groshong, R. H., Jr., 1999, Confirmation of regional thin-skinned extension in the eastern Black Warrior basin, Alabama, *in* Pashin J. C., and Carroll, R. E., eds., 1999, Geology of the Cahaba coalfield: Alabama Geological Society 36th Annual Field Trip Guidebook, p. 49-57.

Chesnut, D. R., 1994, Eustatic and tectonic control of deposition of the Lower and Middle Pennsylvanian strata of the central Appalachian basin. Society of Economic Paleontologists and Mineralogists Concepts in Sedimentology and Paleontology 4, p. 51-64.

Clarkson, C. R., and Bustin, R. M., 1996, Variation in micropore capacity and size distribution in coals of the western Canadian sedimentary basin: Fuel, v. 73, p. 272-277.

___1997, Variation in permeability with lithotype, and maceral composition of Cretaceous coals of the Canadian Cordillera: International Journal of Coal Geology, v. 33, p. 135-152.

Clayton, J. L., Leventhal, J. S., Rice, D. D., Pashin, J. C., Mosher, Byard, and Czepiel, Peter, 1994, Atmospheric methane flux from coals—preliminary investigation of coal mines and geologic structures in the Black Warrior basin, Alabama, *in* Howell, D. G., ed., The Future of Energy Gases: U.S. Geological Survey Professional Paper 1570, p. 471-492.

Cox, M. H., 2002, Relationship between fracture transmissivity and structure in coalbed methane fields of the eastern Black Warrior basin, Alabama: Tuscaloosa, University of Alabama, unpublished Master's thesis, 95 p.

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

Demko T. M., and Gastaldo R. A., 1996, Eustatic and autocyclic influences on deposition of the lower Pennsylvanian Mary Lee coal zone, Warrior Basin, Alabama: International Journal of Coal Geology, v. 31, p. 3-19.

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

Diamond, W. P., and Schatzel, S. J., 1998, Measuring the gas content of coal: a review: International Journal of Coal Geology, v. 35, p. 311-331.

Diessel, C. F. K., 1992, Coal-bearing depositional systems: New York, Springer-Verlag, 400 p.

___1998, Sequence stratigraphy applied to two coal seams: two case histories: Society of Economic Paleontologists and Mineralogists Special Publication 59, p. 151-173.

Eble, C. F., 1990, A palynological transect, swamp interior to swamp margin, in the Mary Lee coal bed, Warrior basin, Alabama, *in* Gastaldo, R. A., Demko, T. M., and Liu, Y. eds., Carboniferous coastal environments of the Mary Lee coal zone, Marion and Walker Counties, Alabama: Geological Society of America Southeastern Section Guidebook, Field Trip 5, Alabama Geological Survey Guidebook Series 3-VI, p. 65-81.

Elder, C. H., and Deul, Maurice, 1974, Degasification of the Mary Lee coalbed near Oak Grove, Jefferson County, Alabama, by vertical borehole in advance of mining: U.S. Bureau of Mines Report of Investigations 7968, 21 p.

___1975, Hydraulic stimulation increases degasification rate of coal beds: U.S. Bureau of Mines Report of Investigations 8047, 17 p.

Ellard, J. S., T. B. Moffett, and Litzinger, L. A., 1997, Production-related causes of scaling in wells in the Cedar Cove and Oak Grove coalbed methane fields of central Alabama: Tuscaloosa, Alabama, University of Alabama, College of Continuing Studies, 1997 International Coalbed Methane Symposium Proceedings, p. 235-247.

Ellard, J. S., Roark, R. P., and Ayers, W. B., Jr., 1992, Geologic controls on coalbed methane production: an example from the Pottsville Formation (Pennsylvanian Age), Black Warrior basin, Alabama, U.S.A., *in* Beamish, B. B., and Gamson, P. D., eds., Symposium on coalbed methane research and development in Australia: Townsville, Australia, James Cook University of North Queensland, p. 45-61.

Ferm, J. C., 1970, Allegheny deltaic deposits: Society of Economic Paleontologists and Mineralogists Special Publication 15, p. 246-255.

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

Ferm, J.C., and Weisenfluh, G. A., 1989, Evolution of some depositional models in Late Carboniferous rocks of the Appalachian coal fields: International Journal of Coal Geology, v. 12, p. 259-292.

Flores, R. M., 1993, Coal-bed and related depositional environments in methane gas-producing sequences: American Association of Petroleum Geologists Studies in Geology 38, p. 13-37.

Galloway, W.E., 1989, Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units: American Association of Petroleum Geologists Bulletin, v. 73, p. 125-142.

Gamson, P. D., Beamish, B. B., and Johnson, D. P., 1993, Coal microstructure and micropermeability and their effects on natural gas recovery: Fuel, v. 72, p. 87-99.

Gan, H., Nandi, S. P., and Walker, P. L., Jr., 1972, Nature of porosity in American coals: Fuel, v. 51, p. 272-277.

Gastaldo, R. A., Demko, T. M., and Liu, Y., 1993, Application of sequence and genetic stratigraphic concepts to Carboniferous coal-bearing strata: An example from the Black Warrior Basin, USA: Geologische Rundschau, v. 82, p. 212-226.

Gentzis, Thomas, 2000, Subsurface sequestration of carbon dioxide—an overview from an Alberta (Canada) perspective: International Journal of Coal Geology, v. 43, p. 287-305.

Gluskoter, H. J., Stanton, R. W., Flores, R. M., and Warwick, P. D., 2002, Adsorption of carbon dioxide and methane in low-rank coals and the potential for sequestration of carbon dioxide (abstract): American Association of Petroleum Geologists Annual Meeting Program, p. A64.

Gluskoter, H. J., and Simon, J. A., 1968, Sulfur in Illinois coals: Illinois State Geological Survey Circular 432, 28 p.

Graves, S. L., Patton, A. F., and Beavers, W. M., 1983, Multiple zone coal degasification potential in the Warrior coal field of Alabama: Gulf Coast Association of Geological Societies Transactions, v. 33, p. 275-280.

Groshong, R. H., Jr., Cox, M. H., Pashin, J. C., and McIntyre, M. R., 2003, Relationship between gas and water production and structure in southeastern Deerlick Creek coalbed methane field, Black Warrior basin, Alabama: Tuscaloosa, Alabama, University of Alabama College of Continuing Studies, 2003 International Coalbed Methane Symposium Proceedings, Paper 0306, 12 p.

Guohai Jin, Pashin, J. C., and Payton, J. W., 2003, Application of discrete fracture network models to coalbed methane reservoirs of the Black Warrior basin: Tuscaloosa, Alabama, University of Alabama College of Continuing Studies, 2003 International Coalbed Methane Symposium Proceedings, Paper 0321, 13 p.

Hall, F. E., Zhou, C., Gasem, K. A. M., Robinson, R. L., and Yee, D., 1994, Adsorption of pure methane, nitrogen, and carbon dioxide and their binary mixtures on wet Fruitland coal: Society of Petroleum Engineers, paper 29194.

Hamelinck, C. N., Faaij, A. P. C., Ruijg, G. J., Janseen, D., Pagnier, H., van Bergen, F., Wolf, K. –H., Barzandji, O., Bruining, H., and Schreurs, H., 2001, Potential for $CO_2$ sequestration and enhanced coalbed methane production in the Netherlands: Utrecht, Netherlands Agency for Energy and the Environment, 105 p.

Harpalani, S., and Ouyang, S., 1999, A new laboratory technique to estimate gas diffusion characteristics of coal: Tuscaloosa, Alabama, University of Alabama, College of Continuing Studies, 1999 International Coalbed Methane Symposium Proceedings, p. 141-152.

Harpalani, S. and Pariti, U. M., 1993, Study of coal sorption isotherms using a multicomponent gas mixture: Tuscaloosa, Alabama, University of Alabama, College of Continuing Studies, 1993 International Coalbed Methane Symposium Proceedings, p. 151-160.

Harpalani, S., and Schraufnagel, R. A., 1990, Shrinkage of coal matrix with release of gas and its impact on permeability of coal: Fuel, v. 69, p. 551-556.

Hawkins, W. B., Groshong, R. H., Jr., and Pashin, J. C., 1999, Normal faults along the southwestern margin of the Alabama promontory: Multiple episodes of Paleozoic activity: Geological Society of America Abstracts with Programs, v. 31, p. A-111.

Heckel, P. H., Gibling, M. R, and King, N. R., 1998, Stratigraphic model for glacial-eustatic Pennsylvanian cyclothems in highstand nearshore detrital regimes: Journal of Geology, v. 106, p. 373-383.

Hewitt, J. L., 1984, Geologic overview, coal, and coalbed methane resources of the Warrior basin—Alabama and Mississippi, *in* Rightmire, C. T., Eddy, G. E., and Kirr, J. N., eds., Coalbed methane resources of the United States: American Association of Petroleum Geologists Studies in Geology 17, p. 73-104.

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

Hinkle, Frank, and Sexton, T. A., 1984, Alabama's coalbed gas industry: Alabama State Oil and Gas Board Report 8, 18 p.

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

Holditch, S. A., Ely, J. W., and Carter, R. H., 1989, Development of a coal seam fracture design manual: Tuscaloosa, Alabama, University of Alabama, 1989 Coalbed Methane Symposium Proceedings, p. 299-320.

Horita, J., Blencoe, J. G., and Cole, D. R., 2001, Fundamental geochemical research on long-term carbon sequestration in subsurface environments (abstract): 2001 American Association of Petroleum Geologists Annual Convention Proceedings, p. A93.

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

IPCC, 1996, Climate change 1995: The science of climate change: Cambridge, U.K., Cambridge University Press, 584 p.

Joubert, J. L., Grein, C. T., and Bienstock, Daniel, 1973, Sorption of methane in moist coals: Fuel, v. 52, p. 181-185.

___1974, Effects of moisture on the methane capacity of American coals: Fuel, v. 53, p. 186-191.

Jüntgen, H., and Karweil, J., 1966, Gasbildung und Gasspeicherung in Steinkohlenflözen, Teilen 1 und 2: Erdol und Kohle-Erdgas-Petrochemie, v. 19, p. 339-344.

Kaiser, W. R., 1993, Abnormal pressure in coal basins of the western United States: Tuscaloosa, Alabama, University of Alabama, 1993 International Coalbed Methane Symposium Proceedings, v. 1, p. 173-186.

Kaiser, W. R., Hamilton, D. S., Scott, A. R., and Tyler, R., 1994, Geological and hydrological controls on the producibility of coalbed methane: Journal of the Geological Society of London, v. 151, p. 417-420.

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

Keeling, C. D., and Whorf, T. P., 1998, Atmospheric $CO_2$ records from sites in the SIO air sampling network, *in* Trends: A compendium of data on global change: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory.

Kim, A. G., 1977, Estimating methane content of bituminous coals from adsorption data: U.S. Bureau of Mines Report of Investigations 2845, 22 p.

Kreitler, C. W., 1989, Hydrogeology of sedimentary basins: Journal of Hydrology, v. 106, p. 29-53.

Kroos, B. M., van Bergen, F., Gensterblum, Y., Siemons, N, Pagnier, H. J. M., and David, P., 2001, High-pressure methane and carbon dioxide sorption on dry and moisture-equilibrated Pennsylvanian coals: International Journal of Coal Geology, v. 51, p. 69-92.

Lamarre, R. A., Pratt, T., and Burns, T. D., 2001, Reservoir characterization study significantly increases coalbed methane reserves at Drunkard's Wash Unit, Carbon County, Utah: (abstract): American Association of Petroleum Geologists Annual Convention Proceedings, p. A111.

Lamberson, M. N., and Bustin, R. M., 1993, Coalbed methane characteristics of the Gates Formation coals, northeastern British Columbia: American Association of Petroleum Geologists Bulletin, v. 77, p. 2062-2076.

Lambert, S. W., Trevits, M. A., and Steidl, P. F., 1980, Vertical borehole design and completion practices to remove methane gas from mineable coal beds: U.S. Department of Energy Report DOE/CMTC/TR-80/2, 163 p.

Landis, E. R., and Weaver, J. N., 1993, Global coal occurrence: American Association of Petroleum Geologists Studies in Geology 38, p. 1-12.

Chikatamarla, L., and Bustin, R. M., 2003, Sequestration potential of acid gases in western Canadian coals: Tuscaloosa, Alabama, University of Alabama, College of Continuing Studies, 2003 International Coalbed Methane Symposium Proceedings, paper 360, 16 p..

Levine, J. R., 1993, Coalification: the evolution of coal as a source rock and reservoir rock for oil and gas: American Association of Petroleum Geologists Studies in Geology 38, p. 39-77.

___1996, Model study of the influence of matrix shrinkage on the absolute permeability of coal bed reservoirs: Geological Society of London Special Publication 109, p. 197-212.

Levine J. R., Camp, B. S., Lewis, C. R., and Minor, D., 1997, Maximizing production and profitability of coal seam gas without tax credit incentives, White Oak Creek Field, Black Warrior basin, Alabama: Tuscaloosa, Alabama, University of Alabama, College of Continuing Studies, 1997 International Coalbed Methane Symposium Proceedings, p. 331-339.

Levine, J. R., and Telle, W. R., 1989, A coalbed methane resource evaluation in southern Tuscaloosa County, Alabama: Tuscaloosa, Alabama, University of Alabama, School of Mines and Energy Development Research Report 89-1, 90 p.

___1991, Coal rank patterns in the Cahaba coal field and surrounding areas, and their significance, *in* Thomas, W. A., and Osborne, W. E., eds., Mississippian-Pennsylvanian tectonic history of the Cahaba synclinorium: Alabama Geological Society 28th Annual Field Trip Guidebook, p. 99-117.

Liu, Y., and Gastaldo, R. A., 1992, Characteristics of a Pennsylvanian ravinement surface: Sedimentary Geology, v. 77, p. 197-213.

Lyons, P. C., 1992, An Appalachian isochron: a kaolinized Carboniferous air-fall volcanic-ash deposit (tonstein): Geological Society of America Bulletin, v. 104, p. 1515-1527.

___1997, Central-northern Appalachian coalbed methane flow grows: Oil & Gas Journal, July 7, 1997, p. 76-79.

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

Malone, P. G., Briscoe, F. H., Camp, B. S., and Boyer, C. M., II, 1987a, Discovery and explanation of low gas contents encountered in coalbeds at the GRI/USSC Big Indian Creek Site, Warrior basin, Alabama: Tuscaloosa, Alabama, University of Alabama, 1987 Coalbed Methane Symposium Proceedings, p. 63-72.

___1987b, Methods of calculating coalbed methane reserves with insight into the advantages and disadvantages of each method: Tuscaloosa, Alabama, University of Alabama, 1987 Coalbed Methane Symposium Proceedings, p. 73-80.

Mavor, M. J., and Nelson, C. R., 1997, Coalbed reservoir gas-in-place analysis: Chicago, Gas Research Institute Report GRI-97/0263, 144 p.

Mavor, M. J., Owen, L. B., and Pratt, T. J., 1990, Measurement and evaluation of coal sorption isotherm data: New Orleans, 65th Annual Technical Conference of the Society of Petroleum Engineers, Paper SPE 20728, p. 157-170.

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

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

McFall, K. S., Wicks, D. E., and Kuuskraa, V. A., 1986, A geological assessment of natural gas from coal seams in the Warrior basin, Alabama - topical report (September 1985-September 1986): Washington, D. C., Lewin and Associates, Inc., Gas Research Institute contract no. 5084-214-1066, 80 p.

McIntyre, M. R., Groshong, R. H., Jr., and Pashin, J. C., 2003, Structure of Cedar Cove and Peterson coalbed methane fields and correlation to gas and water production: Tuscaloosa, Alabama, University of Alabama College of Continuing Studies, 2003 International Coalbed Methane Symposium Proceedings, Paper 0312, 14 p.

McKee, C. R., Bumb, A. C., and Koenig, R. A., 1988, Stress-dependent permeability and porosity of coal and other geologic formations: Society of Petroleum Engineers Formation Evaluation, March, 1988, p. 81-91.

Mellen, F. F., 1947, Black Warrior basin, Alabama and Mississippi: American Association of Petroleum Geologists Bulletin, v. 31, p. 1801-1816.

Metzger, W. J, 1964, Clay mineral analysis of some Warrior basin underclays: Alabama Geological Survey Circular 28, 8 p.

___1965, Pennsylvanian stratigraphy of the Warrior basin, Alabama: Alabama Geological Survey Circular 30, 80 p.

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

National Research Council, 1996, Rock fractures and fluid flow—contemporary understanding and applications: Washington, D.C., National Academy Press, 551 p.

Ortiz, I., Weller, T. F., Anthony, R. V., Frank, J., Linz, D., and Nakles, D., 1993, Disposal of produced waters: underground injection option in the Black Warrior basin: Tuscaloosa, Alabama, University of Alabama, 1993 International Coalbed Methane Symposium Proceedings, p. 339-364.

Osborne, W. E., Szabo, M. W., Copeland, C. W., Jr., and Neathery, T. L., 1989, Geologic map of Alabama: Alabama Geological Survey Special Map 221, scale 1:500,000.

Palmer, I. And Mansoori, J., 1998, How permeability depends on stress and pore pressure in coalbeds: a new model: Society of Petroleum Engineers Reservoir Evaluation and Engineering, paper SPE 52607, p. 539-544.

Papp, A. R., Hower, J. C., and Peters, D. C., 1998, Atlas of coal geology: American Association of Petroleum Geologists Studies in Geology 45, CD-ROM.

Pashin, J. C., 1994a, Flexurally influenced eustatic cycles in the Pottsville Formation (Lower Pennsylvanian), Black Warrior basin, Alabama, *in* Dennison, J. M., and Ettensohn, F. R. eds., Tectonic and Eustatic Controls on Sedimentary Cycles: Society of Economic Paleontologists and Mineralogists Concepts in Sedimentology and Paleontology, v. 4, p. 89-105.

___1994b, Cycles and stacking patterns in Carboniferous rocks of the Black Warrior foreland basin: Gulf Coast Association of Geological Societies Transactions, v. 44, p. 555-563.

___1994c, Coal-body geometry and synsedimentary detachment folding in Oak Grove coalbed-methane field, Black Warrior basin, Alabama: American Association of Petroleum Geologists Bulletin, v. 78, p. 960-980.

___1998, Stratigraphy and structure of coalbed methane reservoirs in the United States: an overview: International Journal of Coal Geology, v. 35, p. 207-238.

___2003, Geologic heterogeneity in Carboniferous coalbed methane reservoirs: implications for natural gas production and carbon sequestration: Utrecht, The Netherlands, Universiteit

Utrecht, XV International Congress on Carboniferous and Permian Stratigraphy Abstracts, p. 393-394.

Pashin, J. C., and Carroll, R. E., 2002, Influence of coal quality on the carbon sequestration potential of coalbed methane reservoirs in the Black Warrior basin (abstract): American Association of Petroleum Geologists 2002 Annual Meeting Program, p. A137.

___2003, Defining the supercritical carbon dioxide window for coalbed methane reservoirs in the Black Warrior basin: implications for carbon sequestration and enhanced coalbed methane recovery: American Association of Petroleum Geologists Annual Convention Program, p. A133.

Pashin, J. C., Carroll, R. E., Barnett, R. L., and Beg, M. A., 1995, Geology and coal resources of the Cahaba coal field: Alabama Geological Survey Bulletin 163, 49 p.

Pashin, J. C., Carroll, R. E., Groshong, R. H., Jr., Raymond, D. E., McIntyre, Marcella, and Payton, W. J., 2003, Geologic screening criteria for sequestration of $CO_2$ in coal: quantifying potential of the Black Warrior coalbed methane fairway, Alabama: Annual Technical Progress Report, U.S. Department of Energy, National Technology Laboratory, contract DE-FC-00NT40927, 190 p.

Pashin, J. C., Carroll, R. E., Hatch, J. R., and Goldhaber, M. B., 1999, Mechanical and thermal control of cleating and shearing in coal: examples from the Alabama coalbed methane fields, USA, in Mastalerz, M., Glikson, M., and Golding, S., eds., Coalbed Methane: Scientific, Environmental and Economic Evaluation: Dordrecht, Netherlands, Kluwer Academic Publishers, p. 305-327.

Pashin, J. C., and Groshong, R. H., Jr., 1998, Structural control of coalbed methane production in Alabama: International Journal of Coal Geology, v. 38, p. 89-113.

Pashin, J. C., Groshong, R. H., Jr., and Carroll, R. E., 2001a, Enhanced coalbed methane recovery through sequestration of carbon dioxide: potential for a market-based environmental solution in the Black Warrior basin of Alabama: Washington, D.C., U.S. Department of Energy, National Energy Technology Laboratory, First National Conference on Carbon Sequestration Proceedings, unpaginated CD-ROM.

___2001b, Carbon sequestration potential of coalbed methane reservoirs in the Black Warrior basin: a preliminary look: Tuscaloosa, Alabama, University of Alabama, College of Continuing Studies, 2001 International Coalbed Methane Symposium Proceedings, p. 51-62.

Pashin, J. C., Groshong, R. H., Jr., and Wang, Saiwei, 1995, Thin-skinned structures influence gas production in Alabama coalbed methane fields: Tuscaloosa, Alabama, University of Alabama, InterGas '95 Proceedings, p. 39-52.

Pashin, J. C., Guohai Jin, and Payton, J. W., 2003, Three-dimensional characterization of natural and induced fractures in coalbed methane reservoirs of the Black Warrior basin in Alabama: U.S. Environmental Protection Agency Final Report, Contract X-97405600-0, 119 p.

___, in press, Three-dimensional computer models of natural and induced fractures in coalbed methane reservoirs of the Black Warrior basin: Alabama Geological Survey Bulletin 174.

Pashin, J. C., and Hinkle, Frank, 1997, Coalbed methane in Alabama: Alabama Geological Survey Circular 192, 71 p.

Pashin, J. C., and McIntyre, M. R., 2003a, Temperature-pressure conditions in coalbed methane reservoirs of the Black Warrior basin, Alabama, U.S.A: implications for carbon sequestration and enhanced coalbed methane recovery: International Journal of Coal Geology, v. 54, p. 167-183.

___2003b, Defining the supercritical phase window for $CO_2$ in coalbed methane reservoirs of the Black Warrior basin: implications for $CO_2$ sequestration and enhanced coalbed methane recovery: Tuscaloosa, Alabama, University of Alabama College of Continuing Studies, 2003 International Coalbed Methane Symposium Proceedings, Paper 0316, 12 p.

Pashin, J. C., and Sarnecki, J. C., 1990, Coal-bearing strata near Oak Grove and Brookwood coalbed-methane fields, Black Warrior basin, Alabama: Geological Society of America Southeastern Section Guidebook, Field Trip 5, Alabama Geological Survey Guidebook Series 3-V, 37 p.

Pashin, J. C., Ward, W. E., II, Winston, R. B., Chandler, R. V., Bolin, D. E., Richter, K. E., Osborne, W. E., and Sarnecki, J. C., 1991, Regional analysis of the Black Creek-Cobb coalbed-methane target interval, Black Warrior basin, Alabama: Alabama Geological Survey Bulletin 145, 127 p.

Pekot, L. J., and Reeves, S. R., 2003, Modeling the effects of matrix shrinkage and differential swelling on coalbed methane recovery and carbon sequestration: Tuscaloosa, Alabama, University of Alabama College of Continuing Studies, 2003 International Coalbed Methane Symposium Proceedings, Paper 0328, 16 p.

Pitman, J. K., Pashin, J. C., Hatch, J. R., and Goldhaber, M. B., 2003, Origin of minerals in joint and cleat systems of the Pottsville Formation, Black Warrior basin, Alabama: implications for coalbed methane generation and production: American Association of Petroleum Geologists Bulletin, v. 87, p. 713-731.

Pollard, D. D., and Aydin, A., 1988, Progress in understanding jointing over the last century: Geological Society of America Bulletin, v. 100, p. 1181-1204.

Puri, R., and Yee, D., 1990, Enhanced coalbed methane recovery: New Orleans, $65^{th}$ Annual Technical Conference of the Society of Petroleum Engineers, paper SPE 20732, p. 193-202.

Raymond, R. N., 1991, Regulatory aspects of permitting and operating a class II salt water disposal (SWD) well in the coalbed methane production areas of Alabama: Tuscaloosa, Alabama, University of Alabama, 1991 Coalbed Methane Symposium Proceedings, p. 69-73.

Reichle, D., Houghton, J., Kane, B., and Ekmann, J., 1999, Carbon sequestration: State of the science: U.S. Department of Energy, Offices of Science and Fossil Energy, unpaginated PDF document.

Renton, J. J., and Cecil, C. B., 1979, The origin of mineral matter in coal, *in* Donaldson, A. C., Presley, M. W., and Renton, J. J., eds., Carboniferous Coal Guidebook, v. 1: West Virginia Geologic and Economic Survey Bulletin 37-1, p. 206-233.

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

Rheams, L. J., and Benson, D. J., 1982, Depositional setting of the Pottsville Formation in the Black Warrior basin: Alabama Geological Society 19th Annual Field Trip Guidebook, 94 p.

Rice, D. D., 1993, Composition and origins of coalbed gas: American Association of Petroleum Geologists Studies in Geology 38, p. 159-184.

___1995, Geologic framework and description of coal-bed gas plays: U.S. Geological Survey Digital Data Series DDS-30, 103 p.

Rodgers, John, 1950, Mechanics of Appalachian folding as illustrated by the Sequatchie anticline, Tennessee and Alabama: American Association of Petroleum Geologists Bulletin, v. 34, p. 672-681.

Schraufnagel, R. A., Spafford, S. D., and Saulsberry, J. L., 1991, Multiple seam completion and production experience at Rock Creek: Tuscaloosa Alabama, University of Alabama, College of Continuing Studies, 1991 Coalbed Methane Symposium Proceedings, p. 211-221.

Scott, A. R., 1993, Composition and origin of coalbed gases from selected basins in the United States: Tuscaloosa, Alabama, University of Alabama, 1993 International Coalbed Methane Symposium Proceedings, p. 207-222.

___2002, Hydrogeologic factors affecting gas content distribution in coal beds: International Journal of Coal Geology, v. 50, p. 363-387.

Scott, A. R., Kaiser, W. R., and Ayers, W. B., Jr., 1994, Thermogenic and secondary biogenic gases, San Juan basin, Colorado and New Mexico—Implications for coalbed gas producibility: American Association of Petroleum Geologists Bulletin, v. 78, p. 1186-1209.

Semmes, D. R., 1929, Oil and gas in Alabama: Alabama Geological Survey Special Report 15, 408 p.

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

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

Shipton, Z. K., Evans, J. P., and Kolesar, P. T., 2001, Analysis of $CO_2$-charged fluid migration along faults in naturally occurring gas systems (abstract): American Association of Petroleum Geologists Annual Convention Program, p. A185.

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

___1960, Coal analyses made at the Alabama State Mine Experiment Station, 1944-60 and some other unpublished analyses: Alabama State Mine Experiment Station Bulletin 7, 39 p.

Smith, J. K., 1995, Normal faults in Holt and Peterson coalbed methane fields, Black Warrior basin, Tuscaloosa County, Alabama: Tuscaloosa, University of Alabama, unpublished Master’s thesis, 76 p.

Sparks, D. P., Lambert, S. W., and McLendon, T. H., 1993, Coalbed gas well flow performance controls, Cedar Cove area, Warrior basin, U.S.A.: Tuscaloosa, Alabama, University of Alabama, 1993 International Coalbed Methane Symposium Proceedings, p. 529-548.

Spears, D. A., 1970, A kaolinitic mudstone (tonstein) in the British coal measures: Journal of Sedimentary Petrology, v. 40, p. 386-394.

___1987, Mineral matter in coals, with special reference to the Pennine Coalfields, *in* Scott, A. C., ed., Coal and coal-bearing strata: recent advances: London Geological Society Special Publication 32, p. 171-185.

Stach, E., Mackowsky, M. –Th., Teichmüller, M., Taylor, G. H., Chandra, D., and Teichmüller, R., 1982, Stach's Textbook of Coal Petrology: Berlin, Gebruder Borntraeger, 535 p.

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

Stevens, S. H., Spector, D., and Riemer, P., 1999a, Enhanced coalbed-methane recovery by use of $CO_2$: Society of Petroleum Engineers Formation Evaluation, paper 48881.

Stevens, S. H., Schoeling, L., and Pekot, L., 1999b, $CO_2$ injection for enhanced coalbed methane recovery: Project screening and design: Tuscaloosa, Alabama, University of Alabama, 1999 International Coalbed Methane Symposium Proceedings, p. 309-317.

Telle, W. R., and Thompson, D. A., 1987, Preliminary characterization of the coalbed methane potential of the Cahaba coal field, central Alabama: Tuscaloosa, Alabama, University of Alabama, 1987 Coalbed Methane Symposium Proceedings, p. 141-151.

___1988, The Cahaba coal field: a potential coalbed methane development area in central Alabama: Tuscaloosa, Alabama, University of Alabama, School of Mines and Energy Development Research Report 88-1, 174 p.

Telle, W. R., Thompson, D. A., Lottman, L. K., and Malone, P. G., 1987, Preliminary burial-thermal history investigations of the Black Warrior basin: implications for coalbed methane and conventional hydrocarbon development: Tuscaloosa, Alabama, University of Alabama, 1987 Coalbed Methane Symposium Proceedings, p. 37-50.

Thomas, W. A, 1985a, The Appalachian-Ouachita connection: Paleozoic orogenic belt at the southern margin of North America: Annual Review of Earth and Planetary Sciences, v. 13, p. 175-199.

___1985b, Northern Alabama sections, *in* Woodward, N. B., ed., Valley and Ridge thrust belt: balanced structural sections, Pennsylvania to Alabama: University of Tennessee Department of Geological Sciences Studies in Geology 12, p. 54-60.

___1988, The Black Warrior basin, *in* Sloss, L. L., ed., Sedimentary cover - North American craton: Geological Society of America, The Geology of North America, v. D-2, p. 471-492.

___1995, Diachronous thrust loading and fault partitioning of the Black Warrior foreland basin within the Alabama recess of the Late Paleozoic Appalachian-Ouachita thrust belt: Society of Economic Paleontologists and Mineralogists Special Publication 52, p. 111-126.

___2001, Mushwad: ductile duplex in the Appalachian thrust belt in Alabama: American Association of Petroleum Geologists Bulletin, v. 85, p. 1847-1869.

Thomas, W. A., Viele, G. W., Platt, L. B., and Schmidt C. J., 1989, Contrasts in style of American thrust belts: Washington, D. C., American Geophysical Union, 28th International Geological Congress Guidebook T380, 112 p.

Vail, P. R., 1987, Seismic stratigraphy interpretation procedure: American Association of Petroleum Geologists Studies in Geology 27, v. 1, p. 1-10.

van Bergen, F., Pagnier, H. J. M., van der Meer, L. G. H., van den Belt, F. J. G., Winthaegen, P. L. A., and P., Krzystolik, 2003, Development of a field experiment of ECBM in the Upper Silesian coal basin of Poland (RECOPOL): Tuscaloosa, Alabama, University of Alabama College of Continuing Studies, 2003 International Coalbed Methane Symposium Proceedings, Paper 0320, 8 p.

Van Voast, W. A., 2003, Geochemical signature of formation waters associated with coalbed methane: American Association of Petroleum Geologists Bulletin, v. 87, p. 667-676.

Wang, Saiwei, Groshong, R. H., Jr., and Pashin, J. C., 1993, Thin-skinned normal faults in Deerlick Creek coalbed-methane field, Black Warrior basin, Alabama, *in* Pashin, J. C., ed., New Perspectives on the Mississippian System of Alabama: Alabama Geological Society 30th Annual Field Trip Guidebook, p. 69-78.

Wanless, H. R., 1976, Appalachian region. U.S. Geological Survey Professional Paper, 853-C: 17-62.

Ward, W. E., 1984, Reserve base of bituminous coal and lignite in Alabama: Alabama Geological Survey Circular 118, 102 p.

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

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

White, C. W., Strazisar, B. R., Granite, E. J., Hoffman, J. S., and Pennline, H. W., 2003, 2003 critical review: separation and capture of $CO_2$ from large stationary sources and sequestration in geological formations—coalbeds and deep saline aquifers: Journal of the Air & Waste Management Association, v. 53, p. 645-715.

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

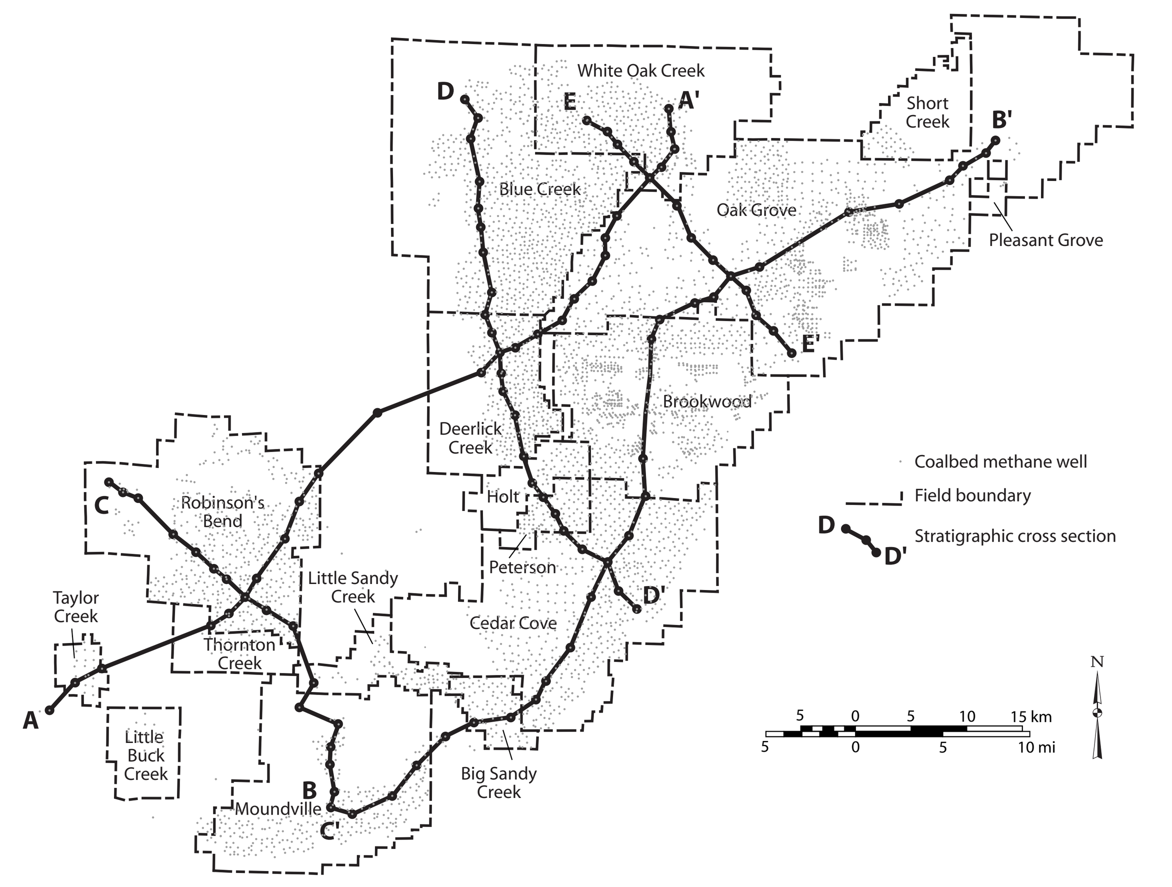
Winston, R. B., 1990a, Vitrinite reflectance of Alabama's bituminous coal: Alabama Geological Survey Circular 139, 54 p.

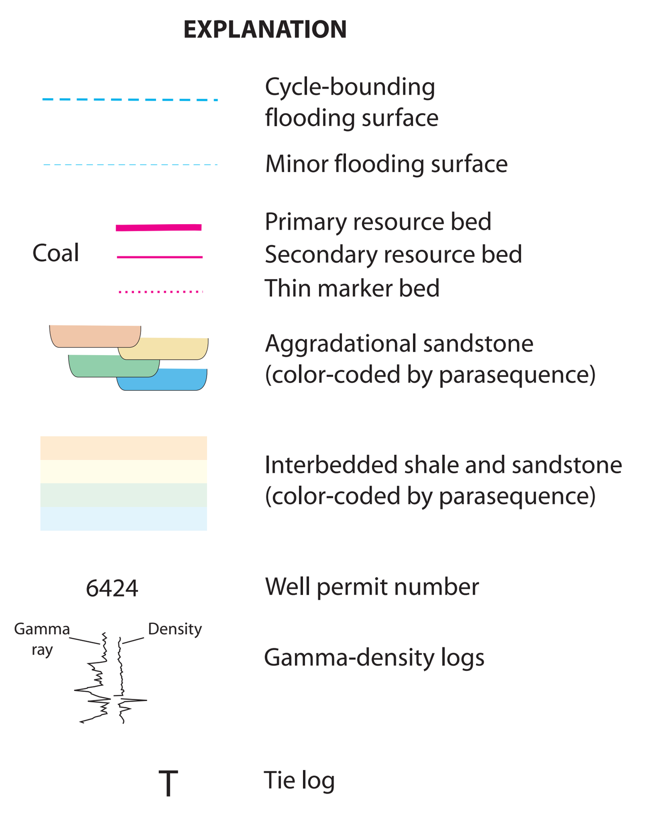
___1990b, Preliminary report on coal quality trends in upper Pottsville Formation coal groups and their relationships to coal resource development, coalbed methane occurrence, and geologic history in the Warrior coal basin, Alabama: Alabama Geological Survey Circular 152, 53 p.

Yang, R. T., and Saunders, J. T., 1985, Adsorption of gases on coals and heat-treated coals at elevated temperature and pressure: Fuel, v. 64, p. 616-620.

Young, G. B. C., Paul, G. W., Saulsberry, J. L., and Schraufnagel, R. A., 1993, Characterization of coalbed reservoirs at the Rock Creek project site, Alabama: Tuscaloosa, Alabama, University of Alabama, College of Continuing Studies, 1993 International Coalbed Methane Symposium Proceedings, p. 705-714.

Zuber, M. D., and Boyer, C. M., II, 2001, Comparative analysis of coalbed methane production trends and variability—impact on exploration and production: Tuscaloosa, Alabama, University of Alabama, 2001 International Coalbed Methane Symposium Proceedings, p. 245-256.

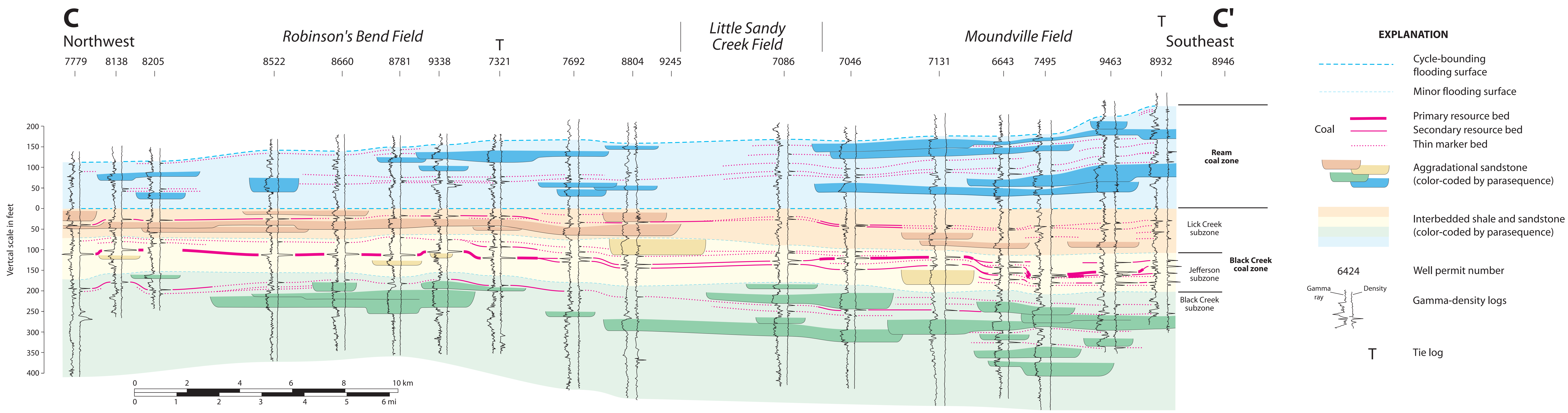



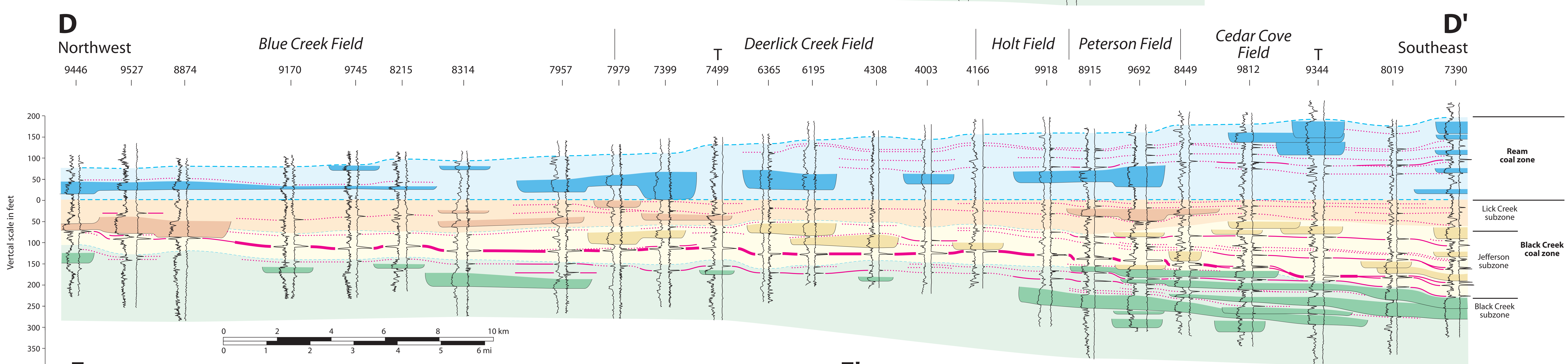


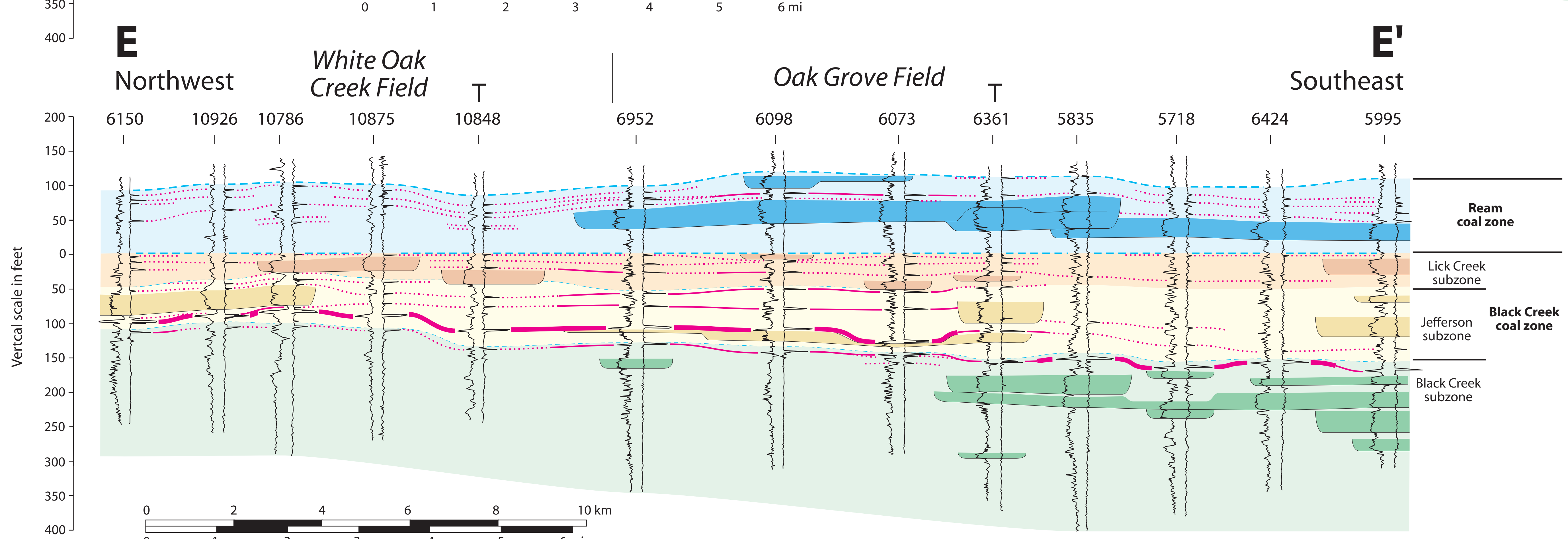
**CROSS SECTIONS A-A' AND B-B' OF THE BLACK CREEK AND REAM COAL ZONES IN THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA**

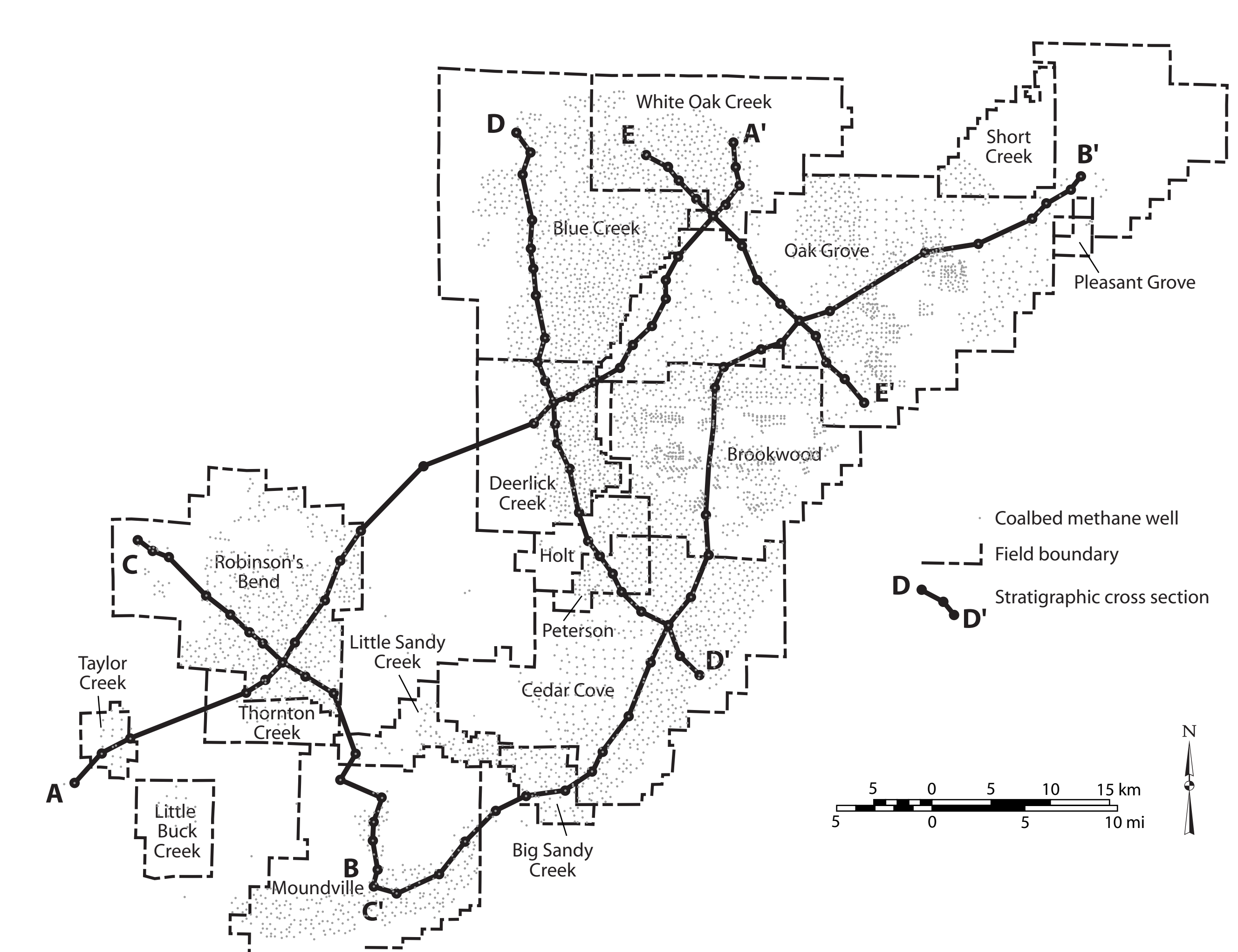
By
Jack C. Pashin and Dorothy E. Raymond
2002

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



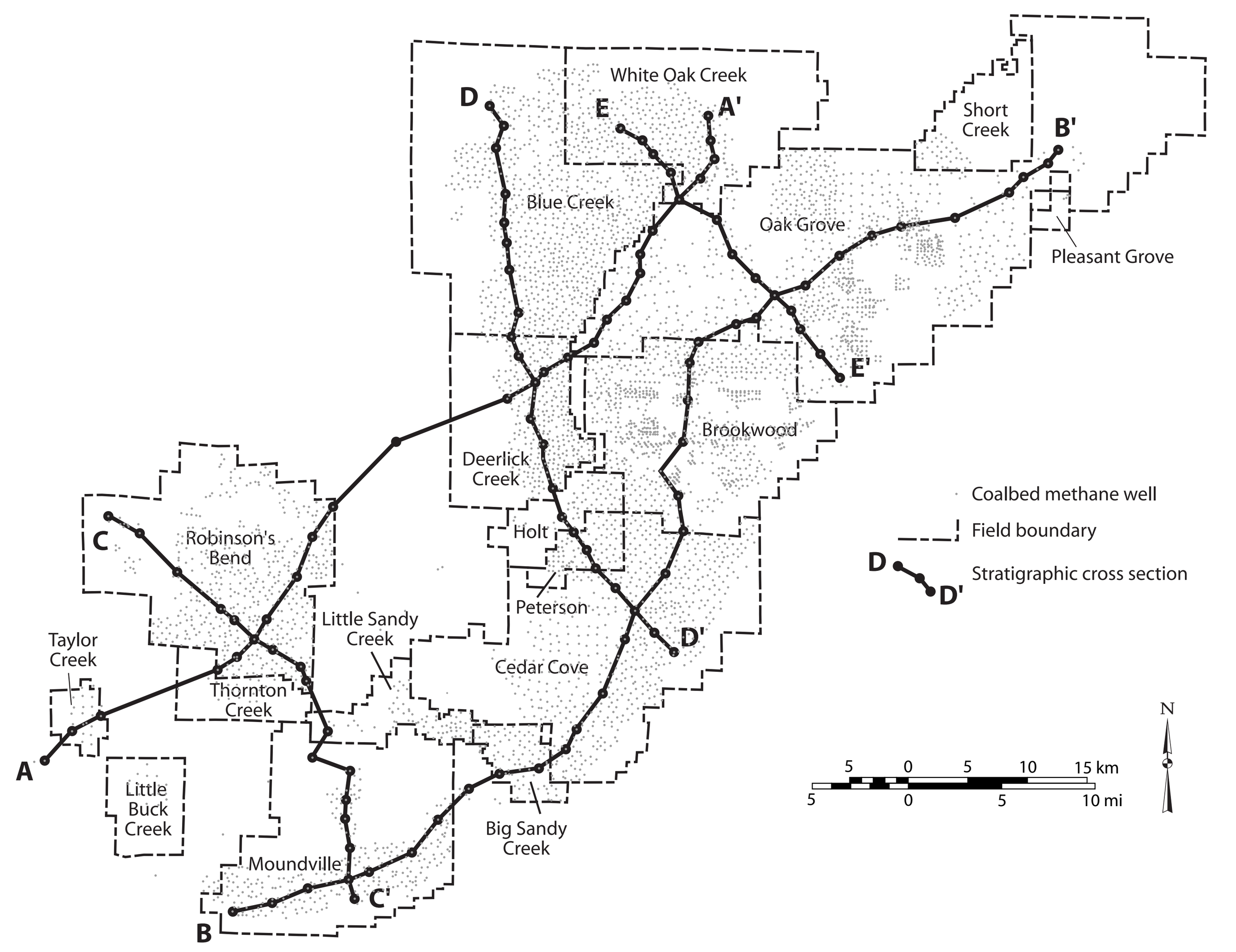



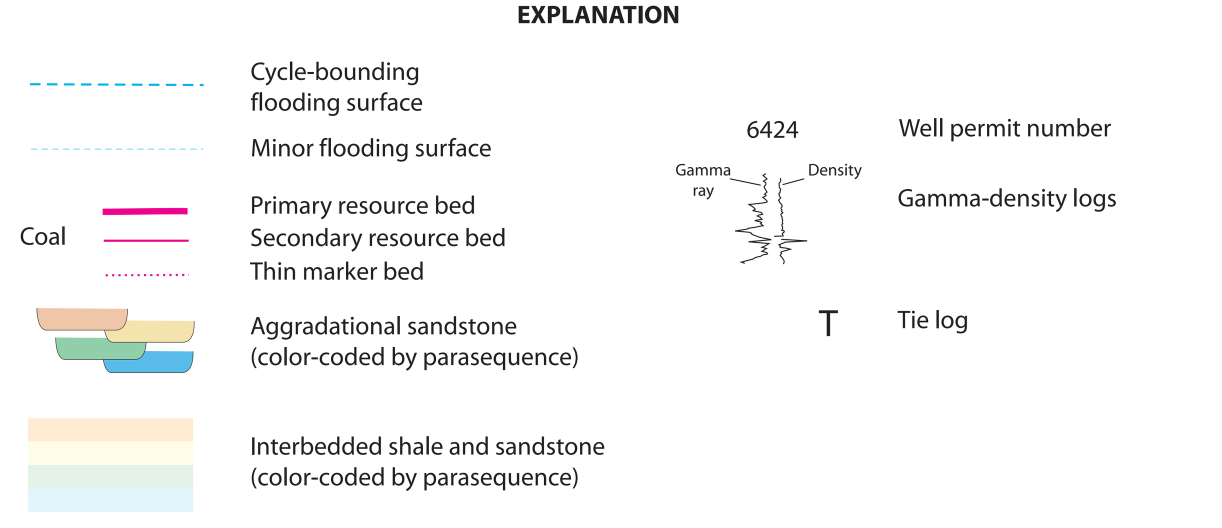

**CROSS SECTIONS C-C', D-D', AND E-E' OF THE BLACK CREEK AND REAM COAL ZONES IN THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA**

By
Jack C. Pashin and Dorothy E. Raymond
2002

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

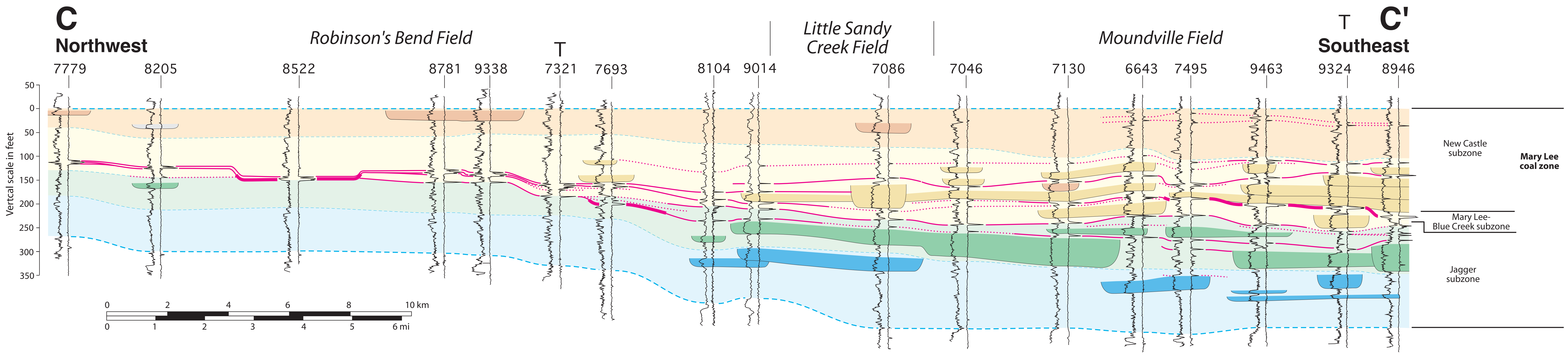


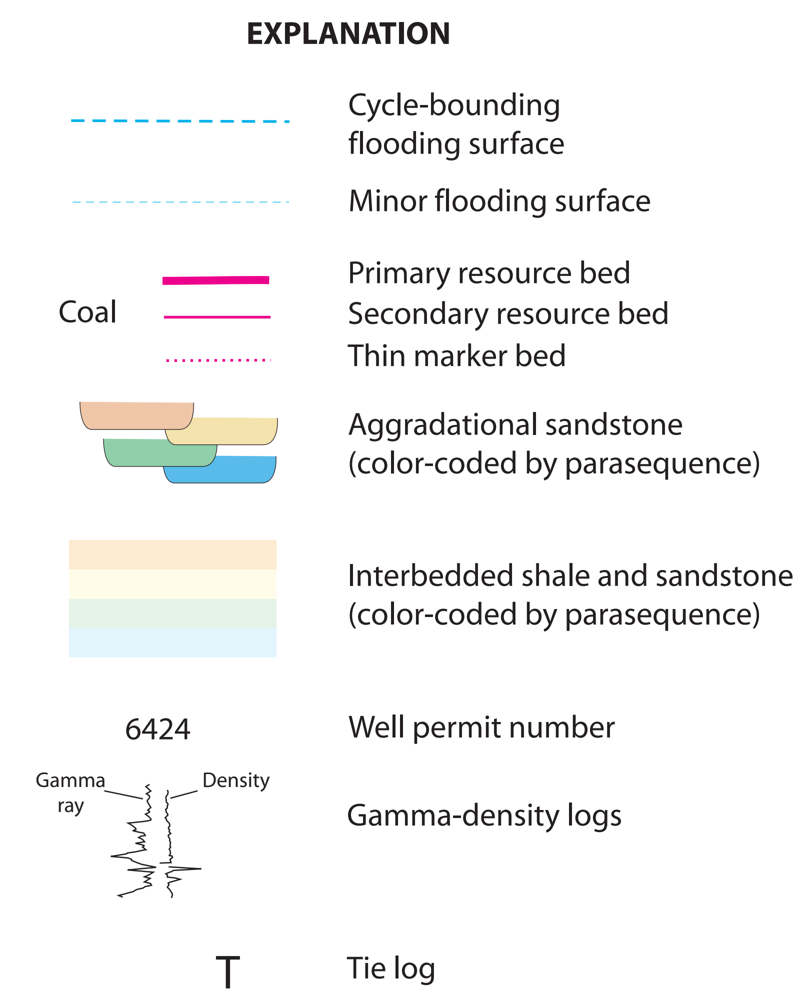


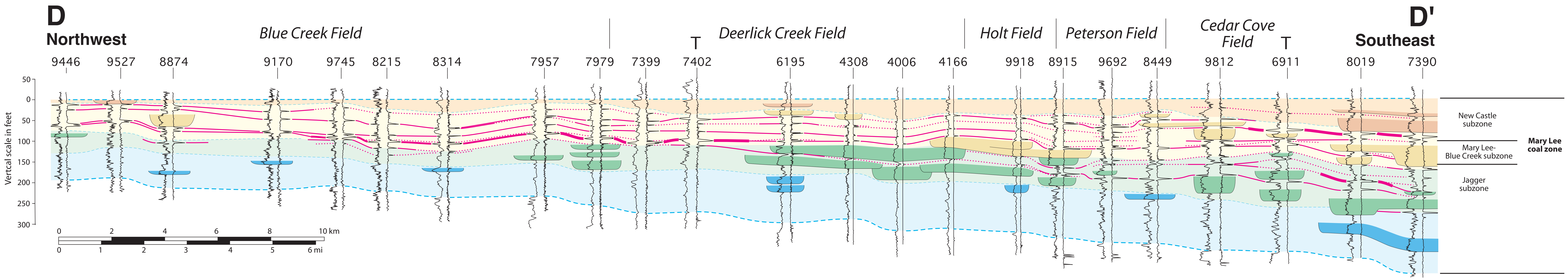

## CROSS SECTIONS A-A' AND B-B' OF THE MARY LEE COAL ZONE IN THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA

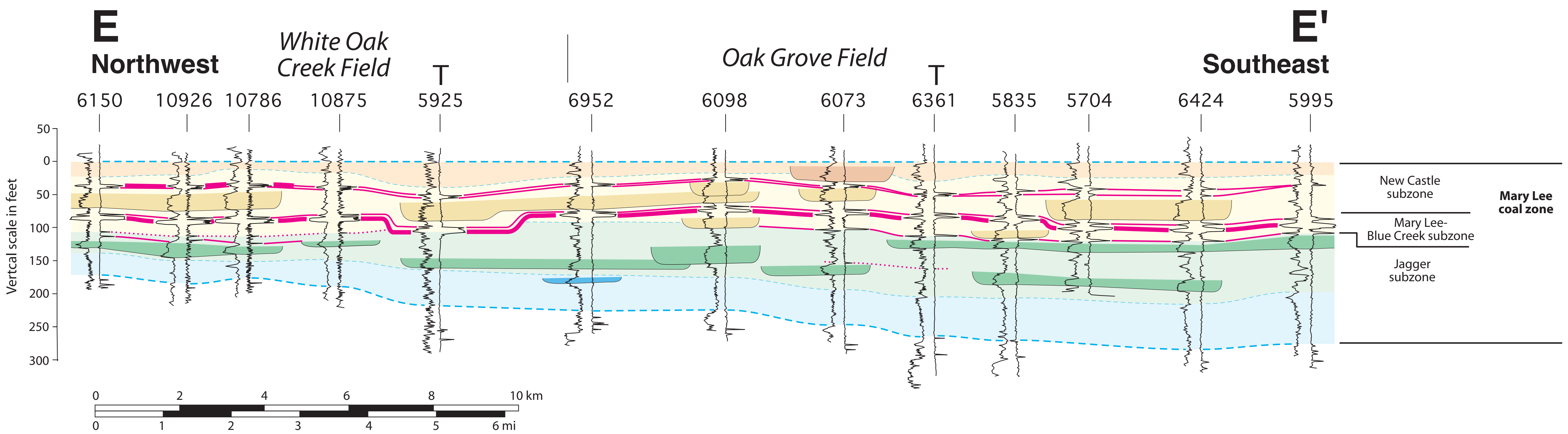
By
Dorothy E. Raymond and Jack C. Pashin
2002

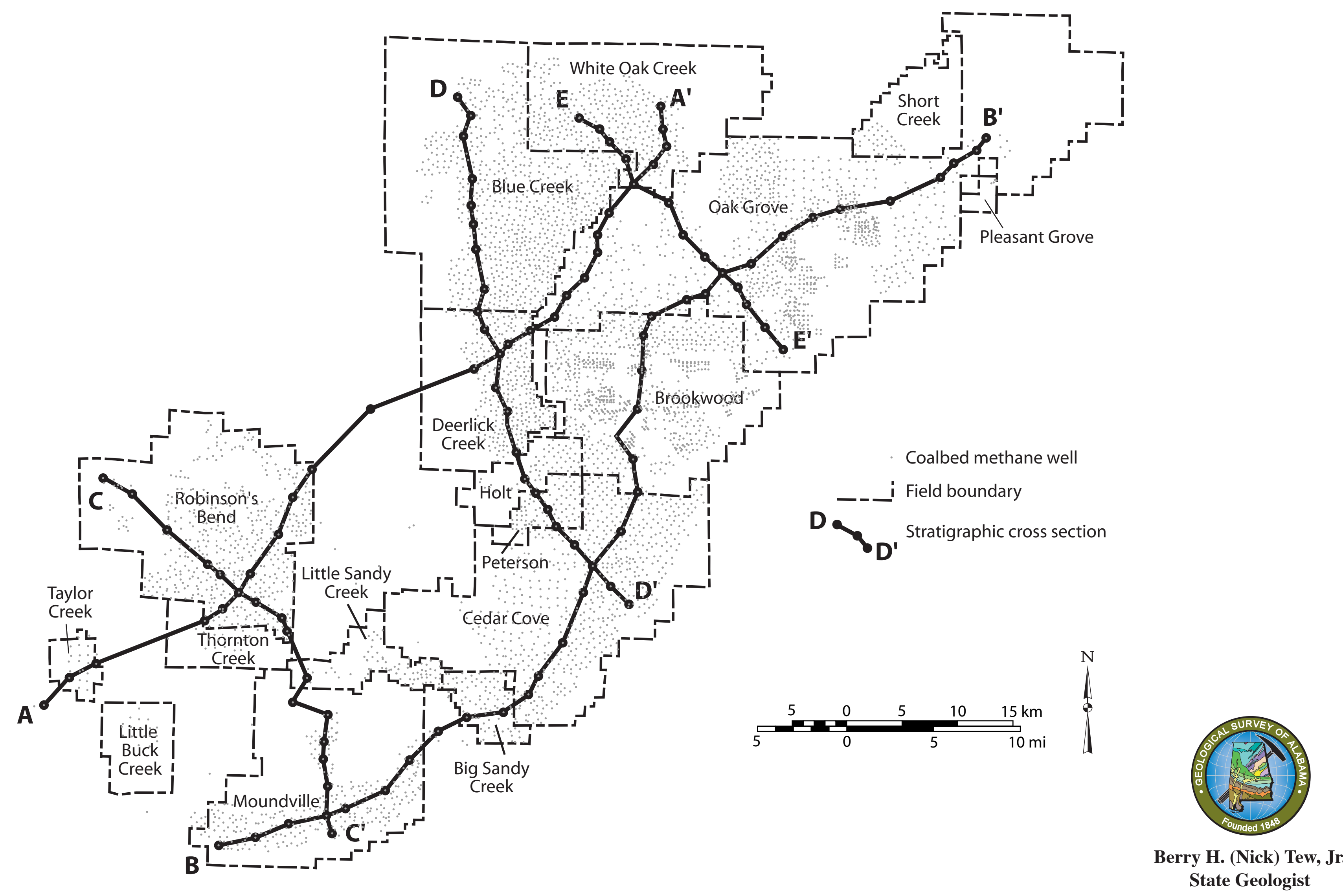
Berry H. (Nick) Tew, Jr.
State Geologist



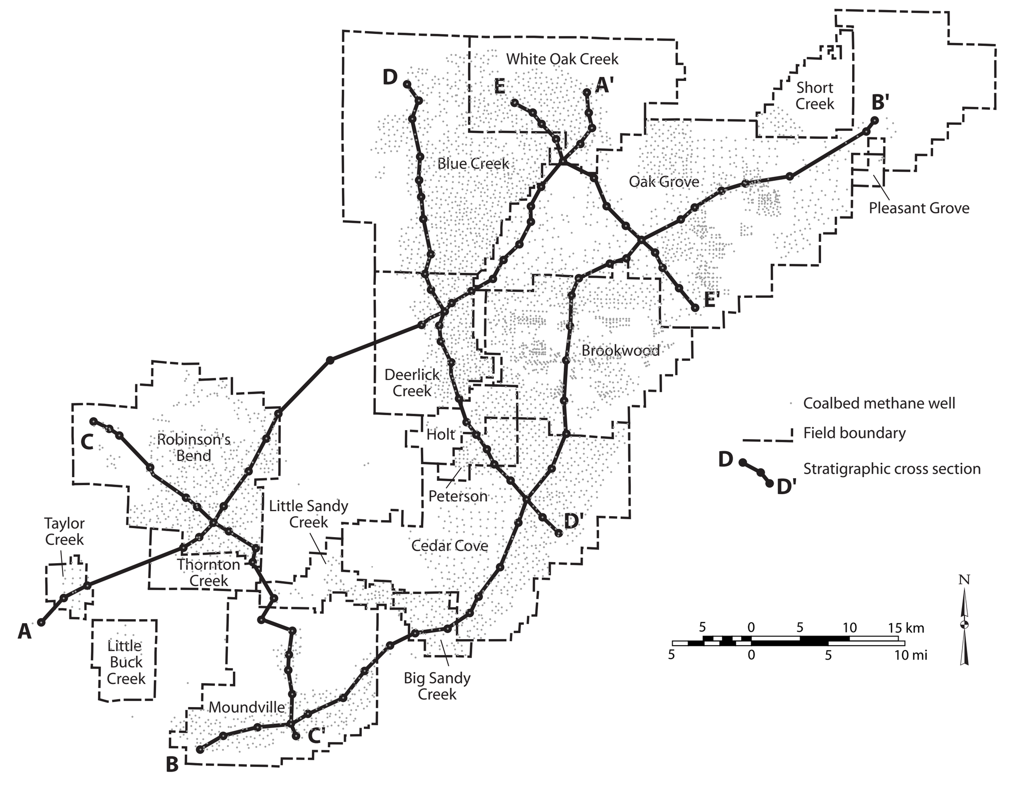



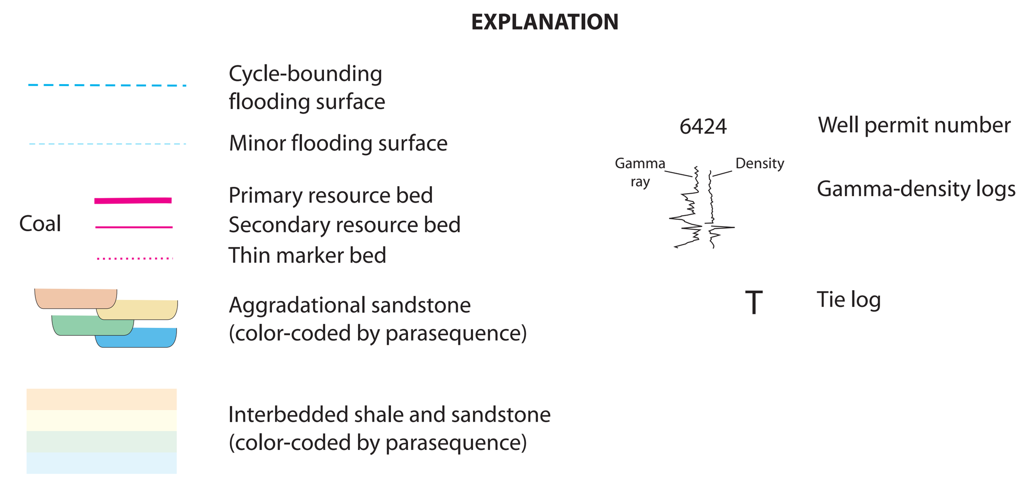

**CROSS SECTIONS C-C', D-D', AND E-E' OF THE MARY LEE COAL ZONE IN THE BLACK WARRIOR COAL BED METHANE FAIRWAY, ALABAMA**

By
Dorothy E. Raymond and Jack C. Pashin
2002

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

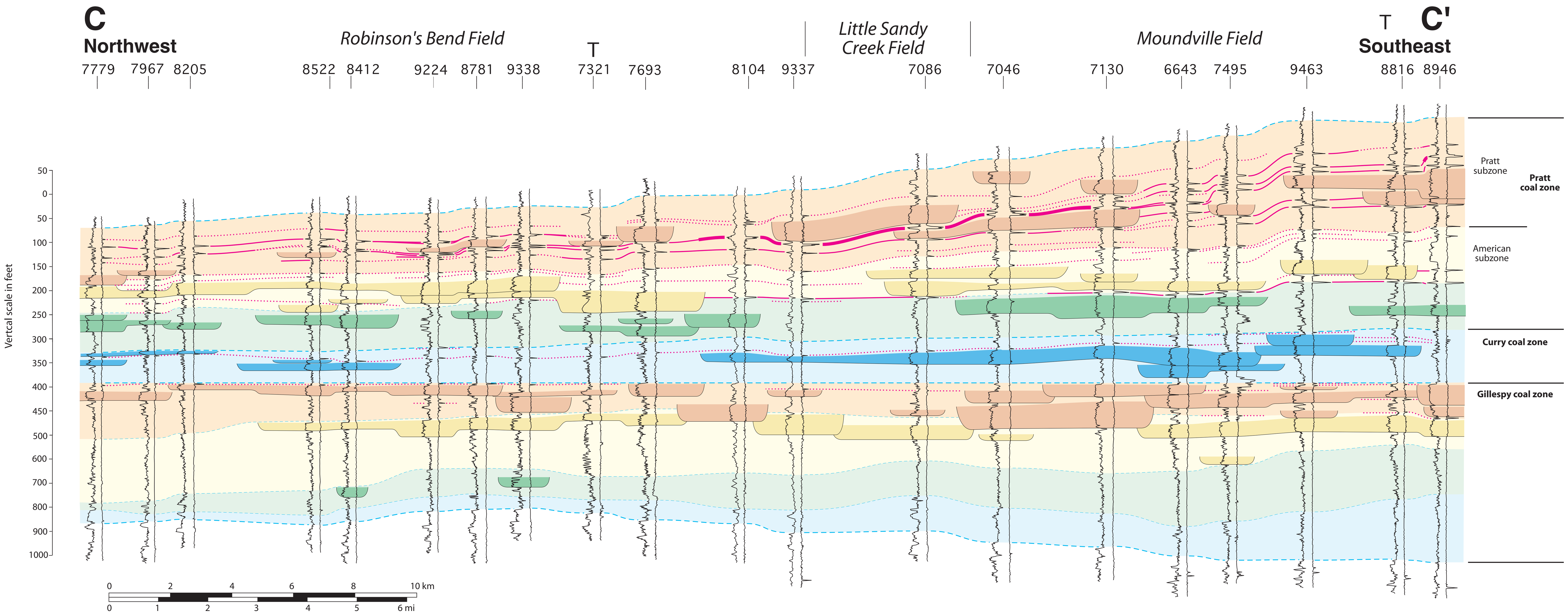


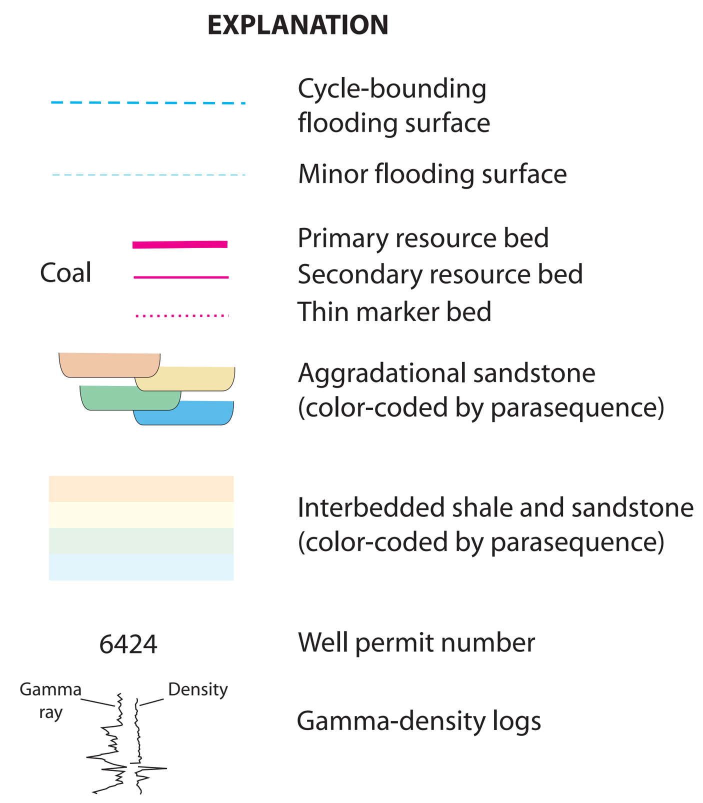


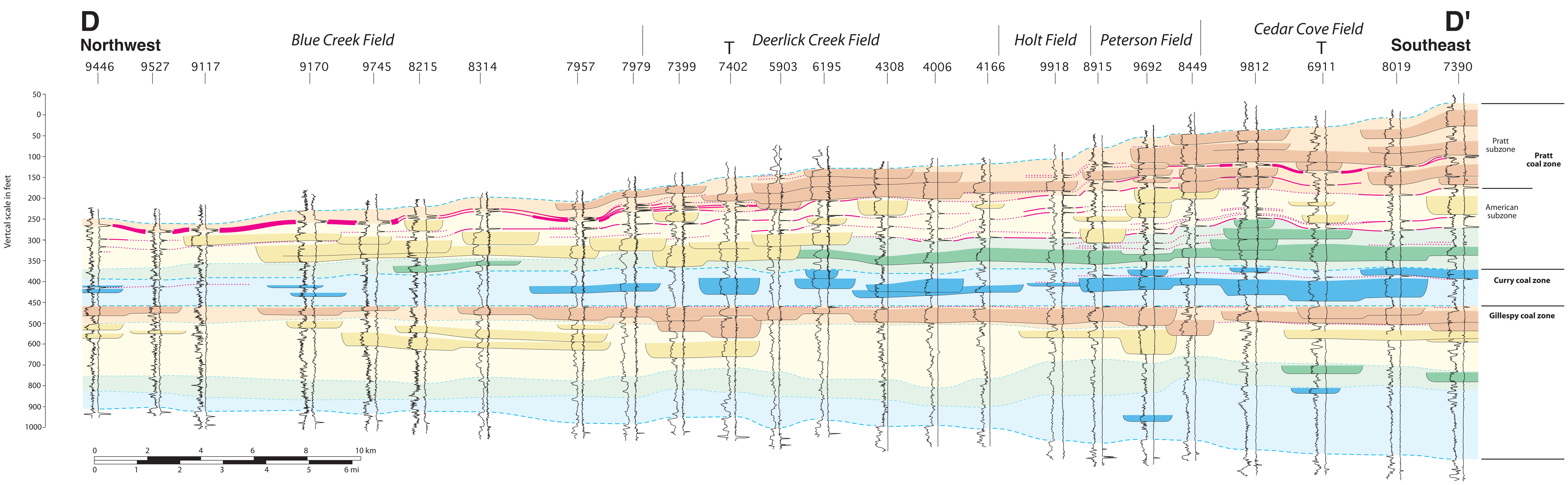

**CROSS SECTIONS A-A' AND B-B' OF THE GILLESPY, CURRY, AND PRATT COAL ZONES IN THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA**

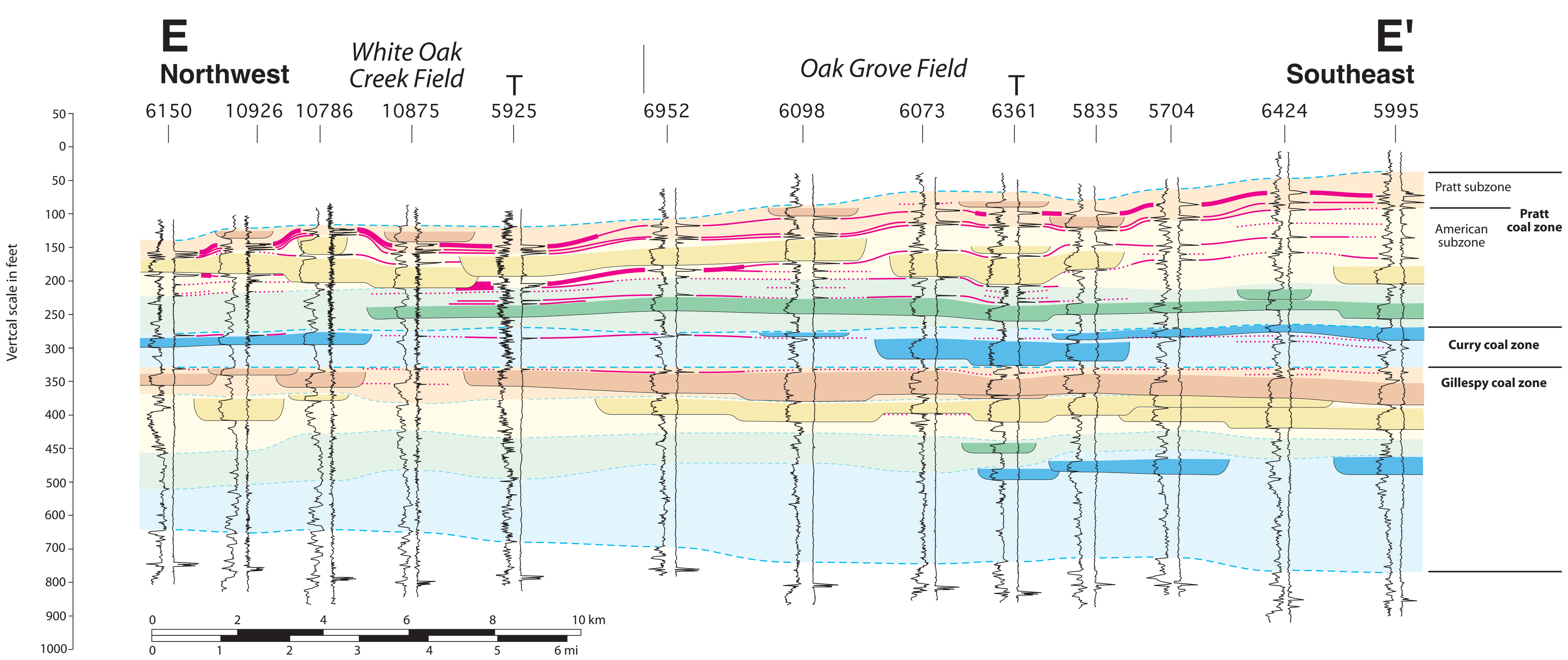
By
Dorothy E. Raymond and Jack C. Pashin
2002

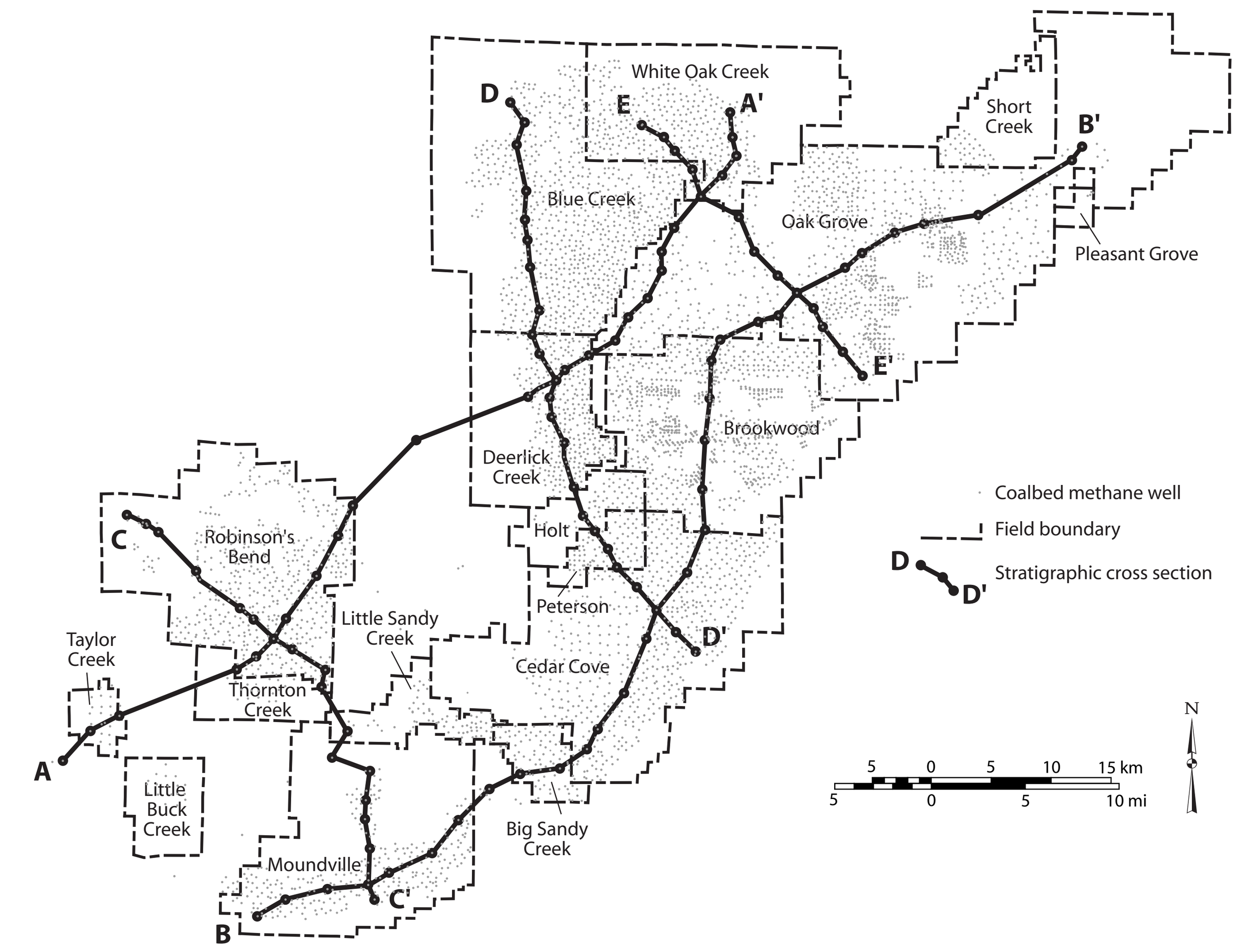
Berry H. (Nick) Tew, Jr.
State Geologist



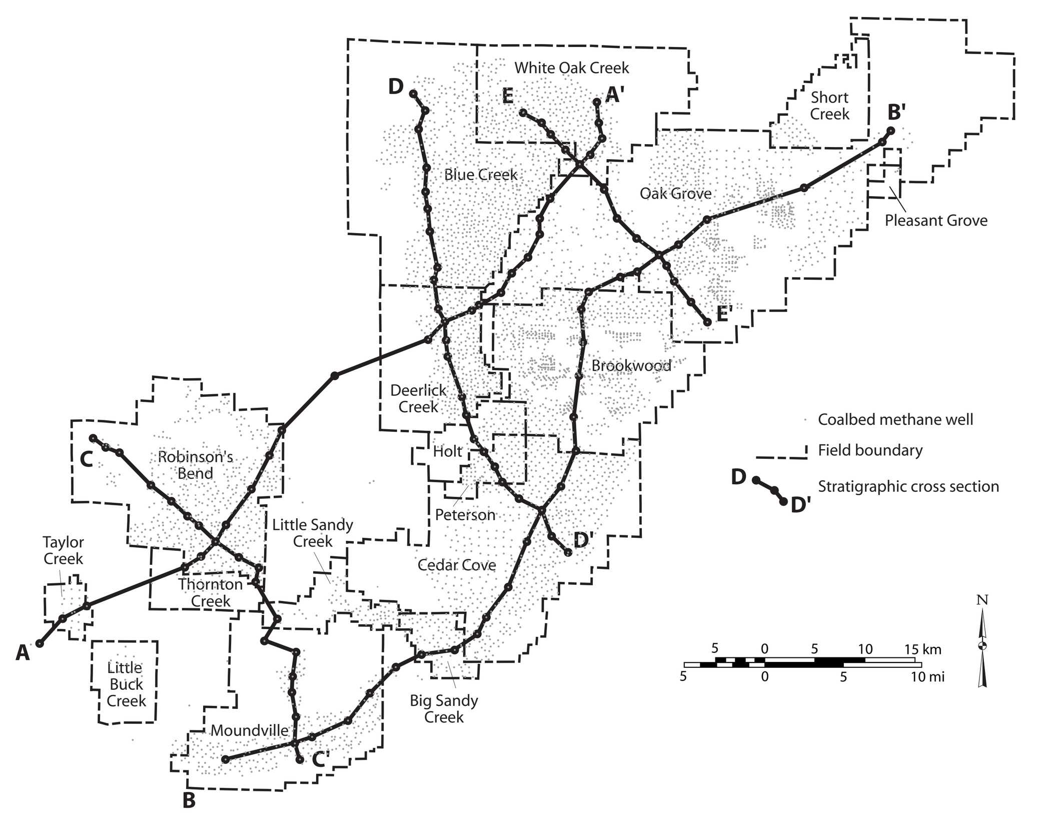




## CROSS SECTIONS C-C', D-D', AND E-E' OF THE GILLESPY, CURRY, AND PRATT COAL ZONES IN THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA

By
Dorothy E. Raymond and Jack C. Pashin
2002

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



**EXPLANATION**

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)

6424 Well permit number

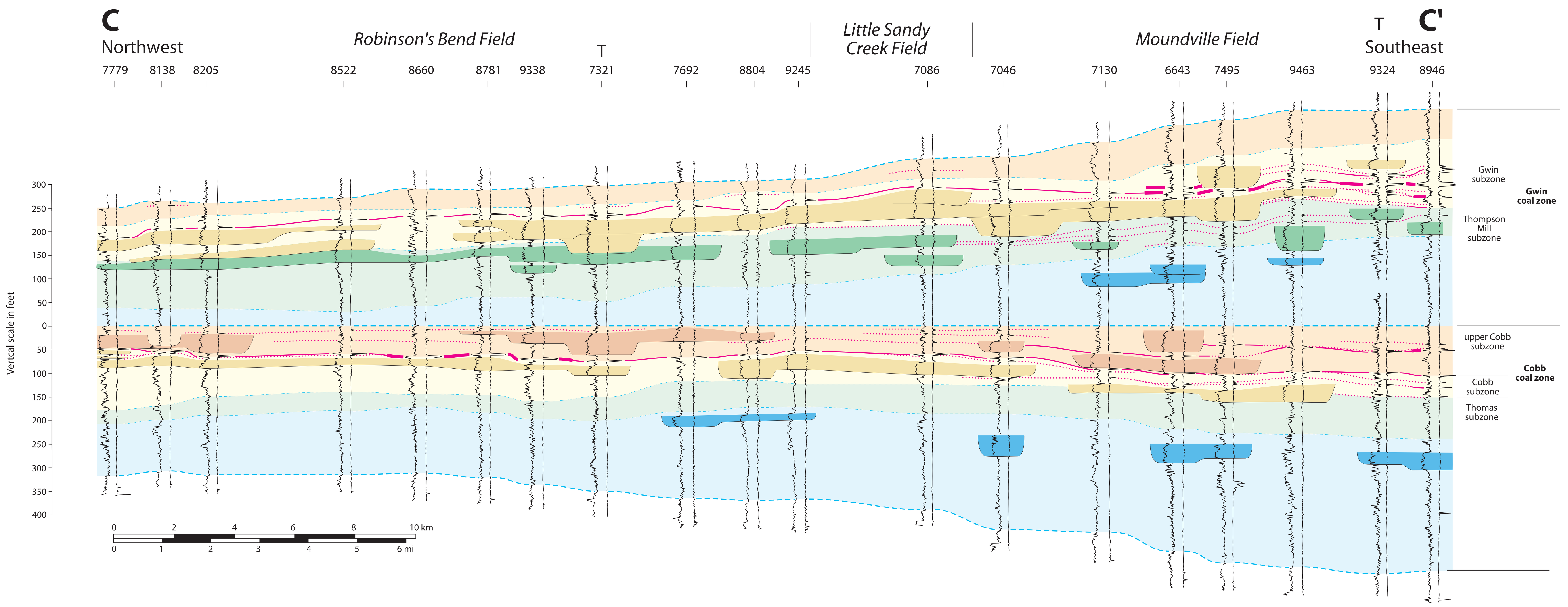
Gamma ray / Density — Gamma-density logs

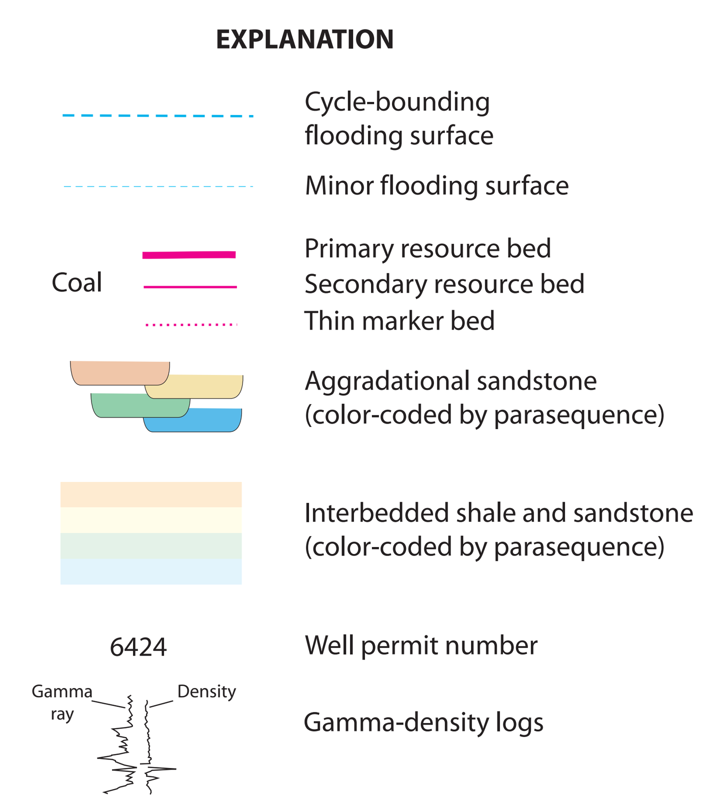
T Tie log

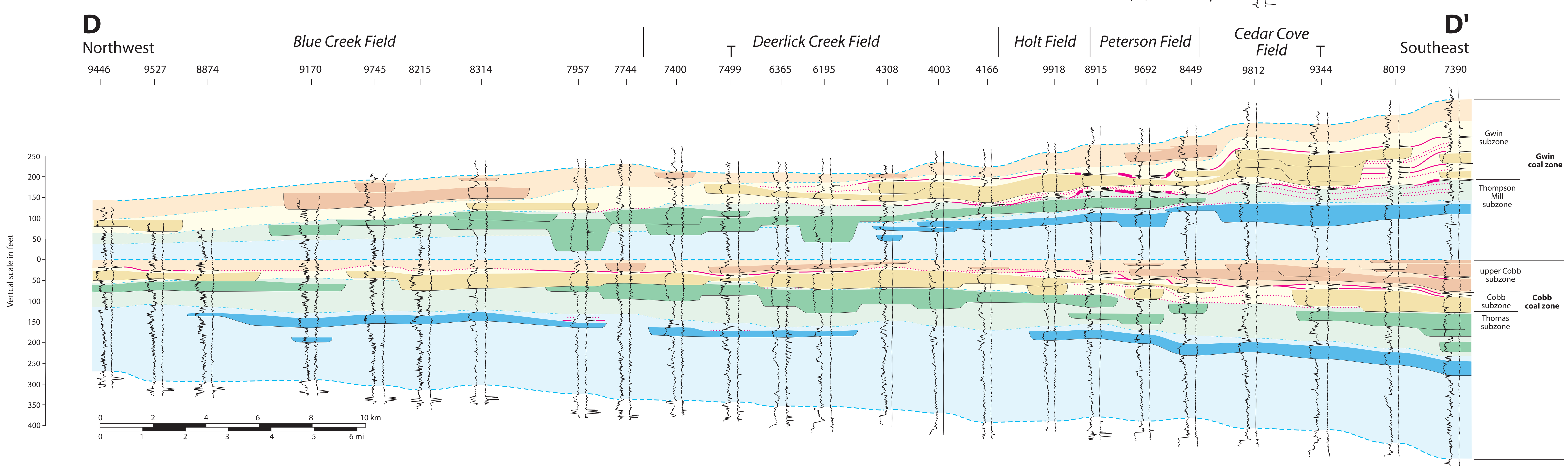
## CROSS SECTIONS A-A', AND B-B' OF THE COBB AND GWIN COAL ZONES IN THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA

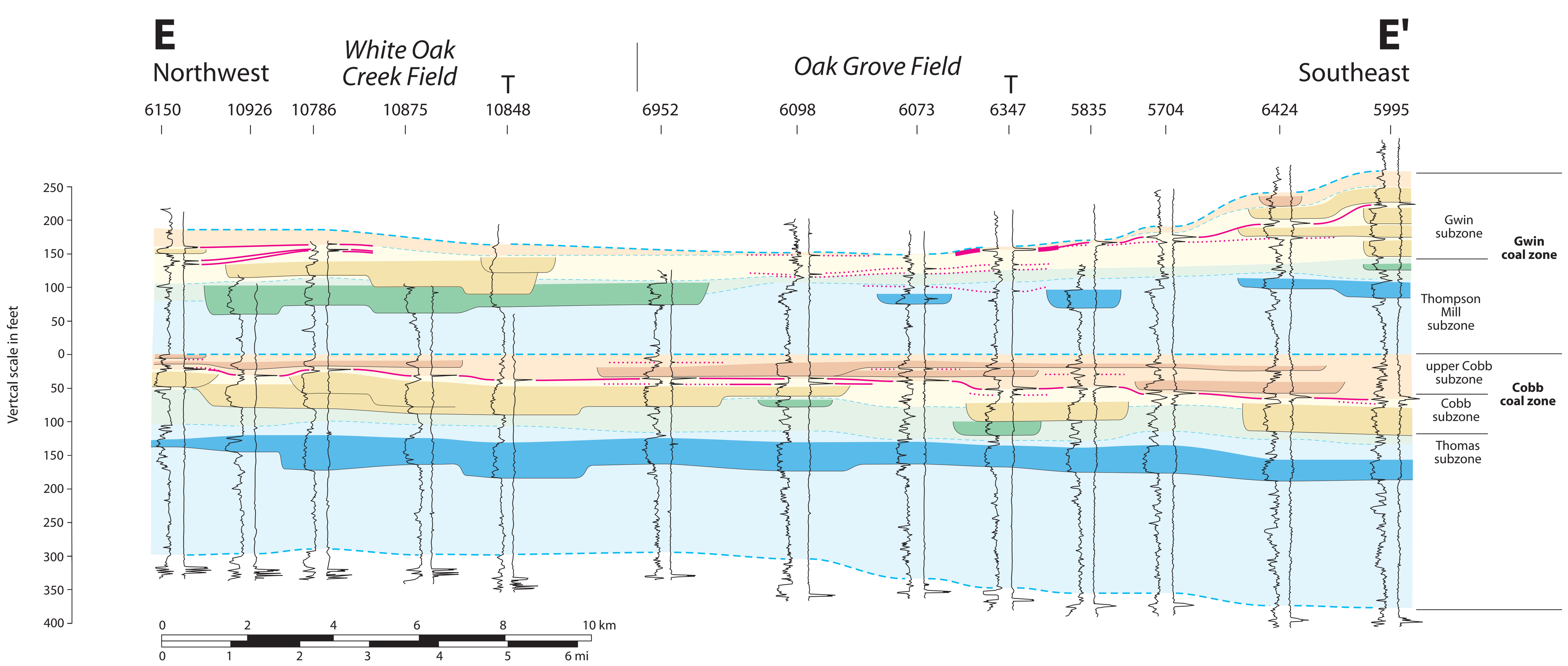
By
Jack C. Pashin and Dorothy E. Raymond
2002

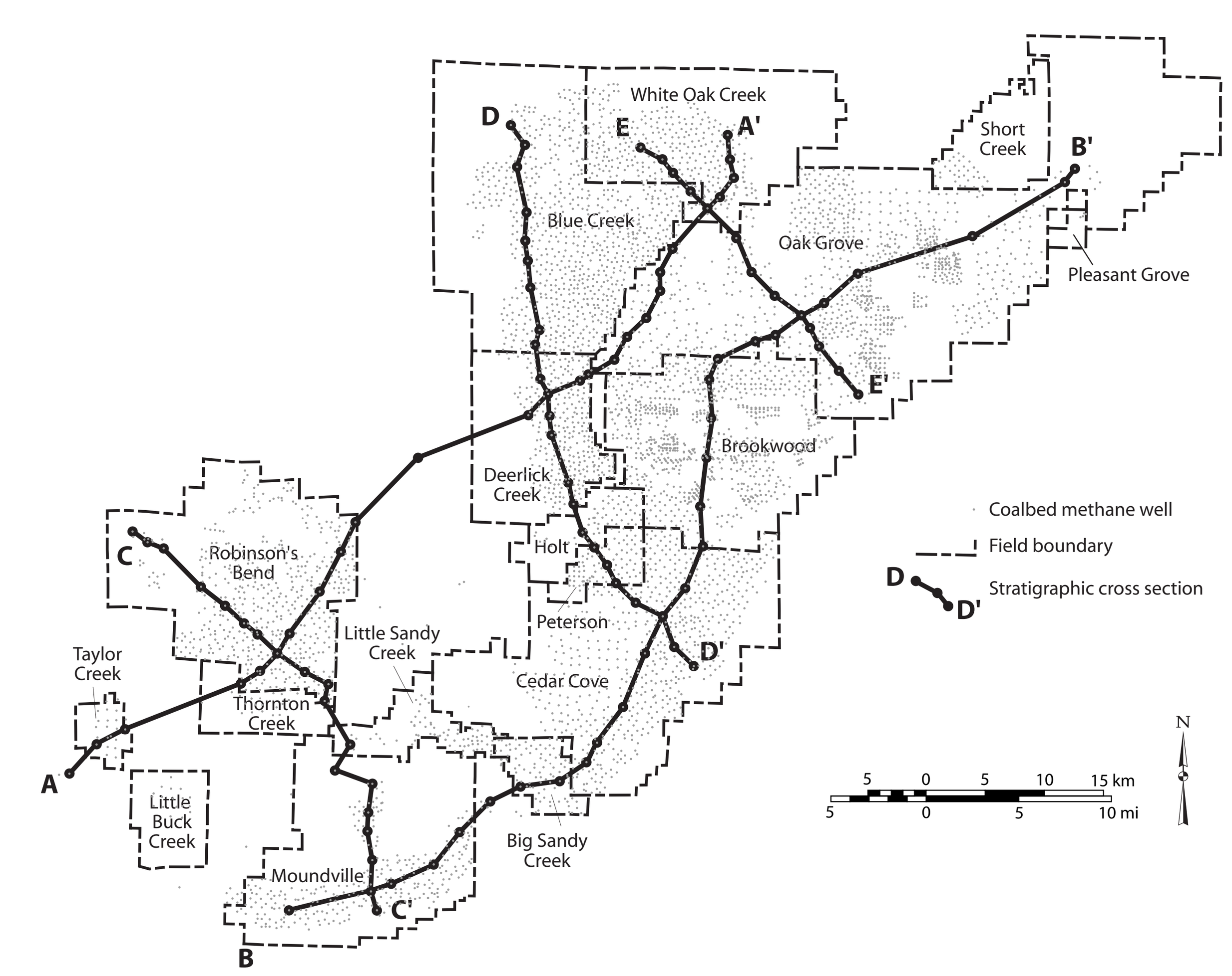
Berry H. (Nick) Tew, Jr.
State Geologist




**CROSS SECTIONS C-C', D-D', AND E-E' OF THE COBB AND GWIN COAL ZONES IN THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA**

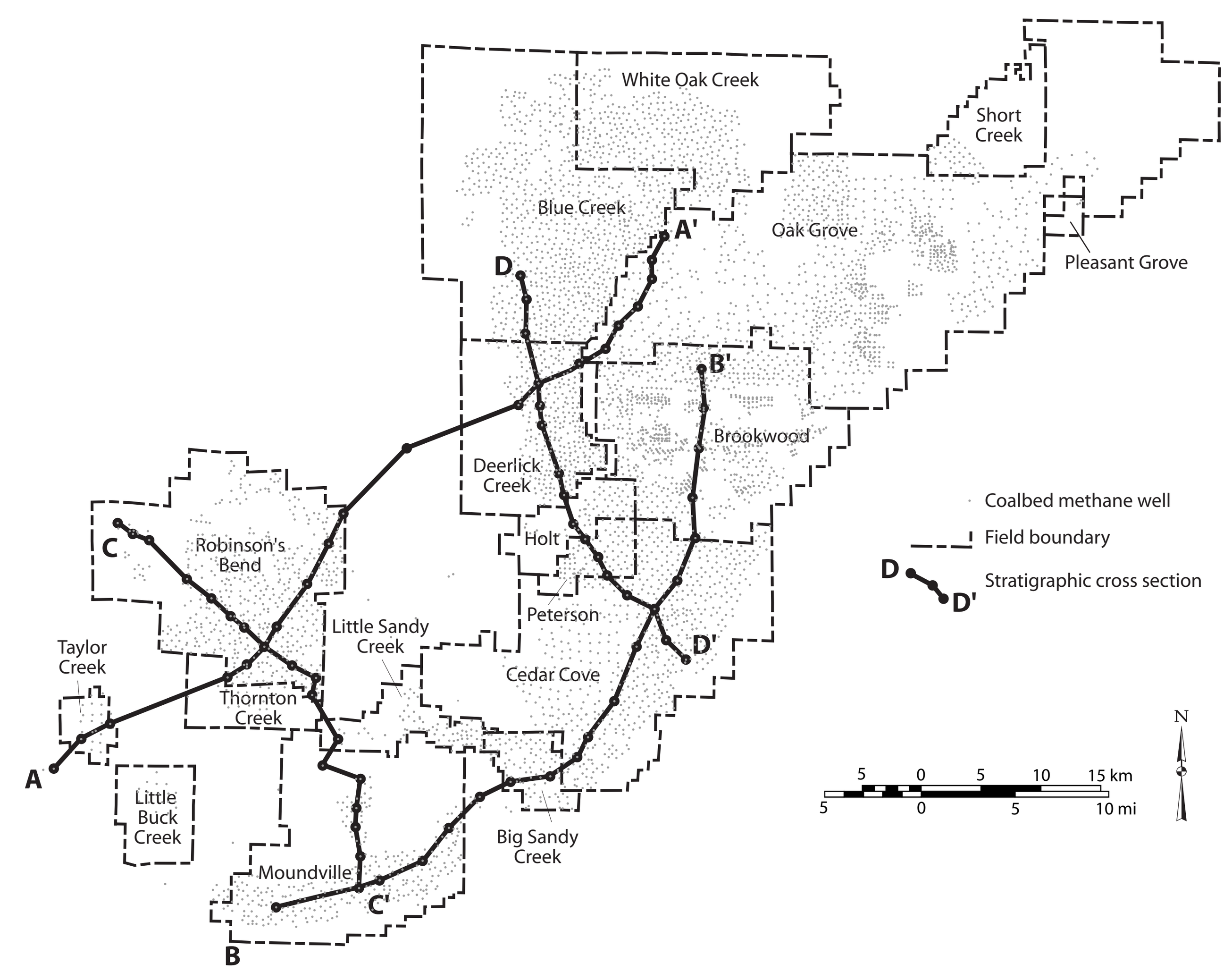
By
Jack C. Pashin and Dorothy E. Raymond
2002

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



**EXPLANATION**

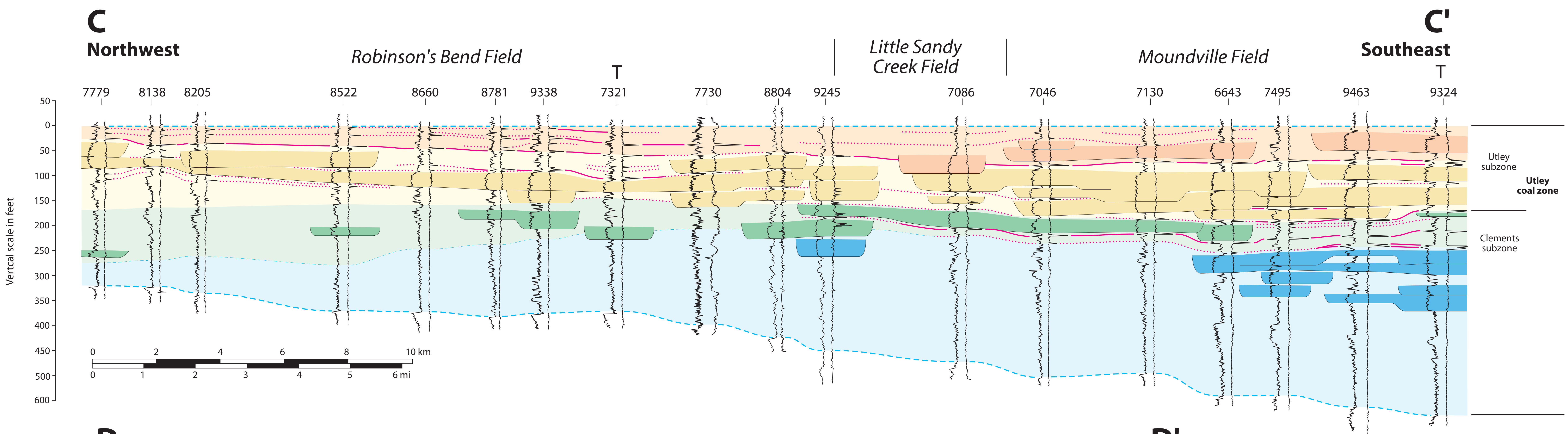
- Cycle-bounding flooding surface
- Minor flooding surface
- Coal: Primary resource bed; Secondary resource bed; Thin marker bed
- Aggradational sandstone (color-coded by parasequence)
- Interbedded shale and sandstone (color-coded by parasequence)
- 6424 — Well permit number
- Gamma ray / Density — Gamma-density logs

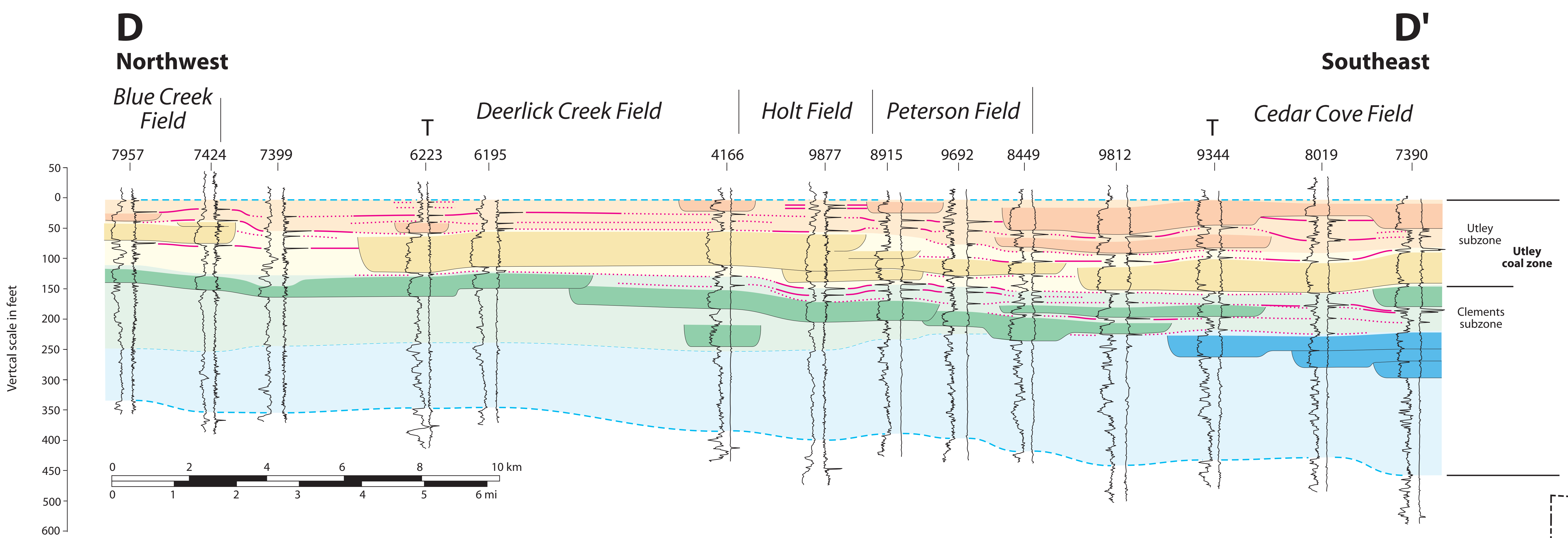



## CROSS SECTIONS A-A' AND B-B' OF THE UTLEY COAL ZONE IN THE BLACK WARRIOR COALBED METHANE FAIRWAY, ALABAMA

By
Jack C. Pashin and Dorothy E. Raymond
2002

Berry H. (Nick) Tew
State Geologist




**EXPLANATION**

Cycle-bounding flooding surface

Minor flooding surface

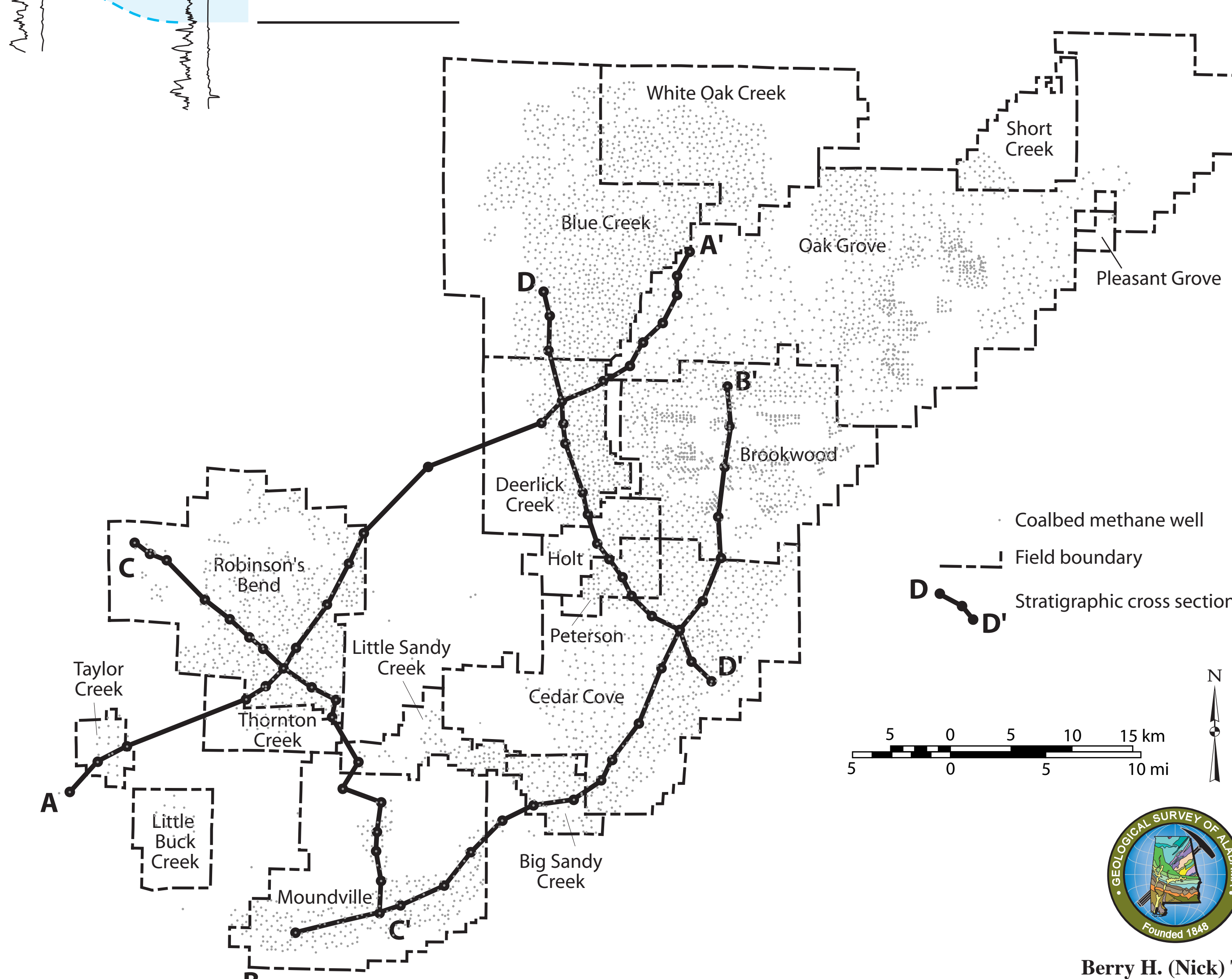
Coal
- Primary resource bed
- Secondary resource bed
- Thin marker bed

Aggradational sandstone (color-coded by parasequence)

Interbedded shale and sandstone (color-coded by parasequence)

6424 — Well permit number

Gamma ray / Density — Gamma-density logs




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

By
Jack C. Pashin and Dorothy E. Raymond
2002

Berry H. (Nick) Tew
State Geologist

# GEOLOGIC SCREENING MODEL FOR $CO_2$ SEQUESTRATION IN COALBED METHANE RESERVOIRS

By
Jack C. Pashin
2003


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