0316

# 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

Jack C. Pashin, Geological Survey of Alabama, P.O. Box 869999, Tuscaloosa, AL 35486-6999; Marcella R. McIntyre, Department of Geological Sciences, University of Alabama, Tuscaloosa, AL 35487

**Abstract**

Sorption of gas onto coal is sensitive to pressure and temperature, and $CO_2$ can be a supercritical fluid in coalbed methane reservoirs. More than 5,000 coalbed methane wells have been drilled in the Black Warrior basin in west-central Alabama, and the hydrologic and geothermic information from these wells provides a robust database that can be used to assess the potential for $CO_2$ sequestration in coal-bearing strata.

Reservoir temperature within the coalbed methane target zone generally ranges from 80 to 125°F, and geothermal gradient ranges from 6.0 to 19.9°F/1,000 ft. Hydrostatic pressure gradients range from normal (0.43 psi/ft) to extremely underpressured (< 0.05 psi/ft) and have a bimodal distribution. Reservoirs have potential for supercritical fluid conditions beyond a depth of 2,480 ft under a normal pressure gradient. All target coal beds are subcritically pressured in the northeastern half of the coalbed methane exploration fairway, whereas those same beds were in the supercritical phase window prior to gas production in the southwestern half of the fairway.

Although mature reservoirs are in the $CO_2$ gas window, supercritical conditions may develop as reservoirs equilibrate toward normal pressure after abandonment. Coal can hold large quantities of $CO_2$ under supercritical conditions, but the mobility and reactivity of supercritical fluid in coal has not been determined in the field. $CO_2$ sequestration and enhanced coalbed methane recovery show great promise in subcritical reservoirs, and additional research is required to assess the behavior of $CO_2$ in coal under supercritical conditions, where additional sequestration capacity may exist.

## Introduction

Coalbed methane has been produced commercially from the Black Warrior basin of Alabama since 1980, and more than 3,400 wells are currently producing. Many of these wells are reaching maturity, and ECBM (enhanced coalbed methane recovery) through injection of $CO_2$ has potential to reduce greenhouse gas emissions from coal-fired power plants while increasing reserves significantly (Pashin et al., 2001, 2003) (Fig. 1).

The volume of gas that coal can adsorb is sensitive to temperature and pressure (Jüntgen and Karweil, 1966; Kim, 1977; Yang and Saunders, 1985), and these variables can vary greatly in coalbed methane reservoirs (Pashin et al., 1991; Scott et al., 1994; Ayers and Kaiser, 1994). Importantly, the critical point for $CO_2$ is within the range of known reservoir conditions (Fig. 2). Coal can hold a large volume of $CO_2$ under supercritical conditions (Kroos et al., 2001), but little is known about the long-term stability of supercritical $CO_2$ in coal. Supercritical $CO_2$ is commonly used as an organic solvent, so identifying areas where supercritical reservoir conditions may exist or develop is important when screening areas for $CO_2$ sequestration and ECBM.

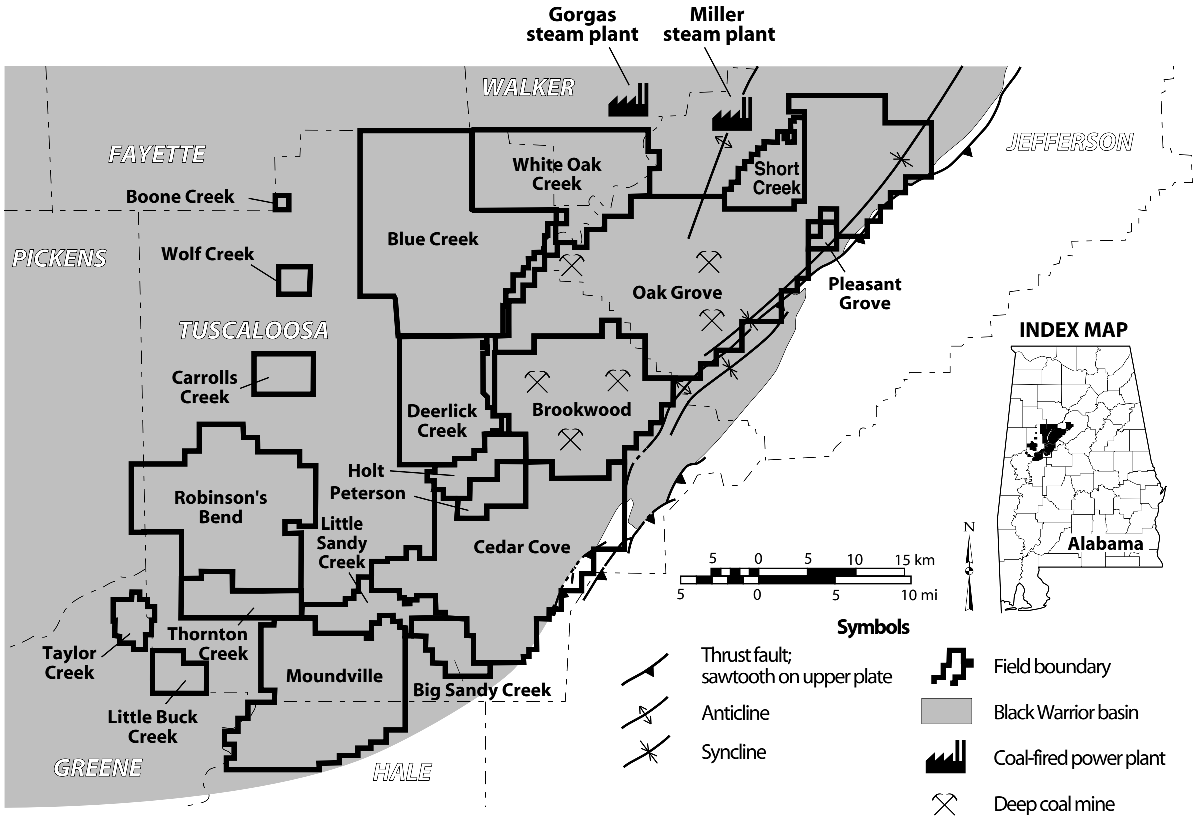


Fig. 1. Index map of the eastern Black Warrior basin in Alabama showing locations of coalbed methane fields, underground coal mines, coal-fired power plants, and Appalachian folds and thrust faults (after Pashin et al., 2001).

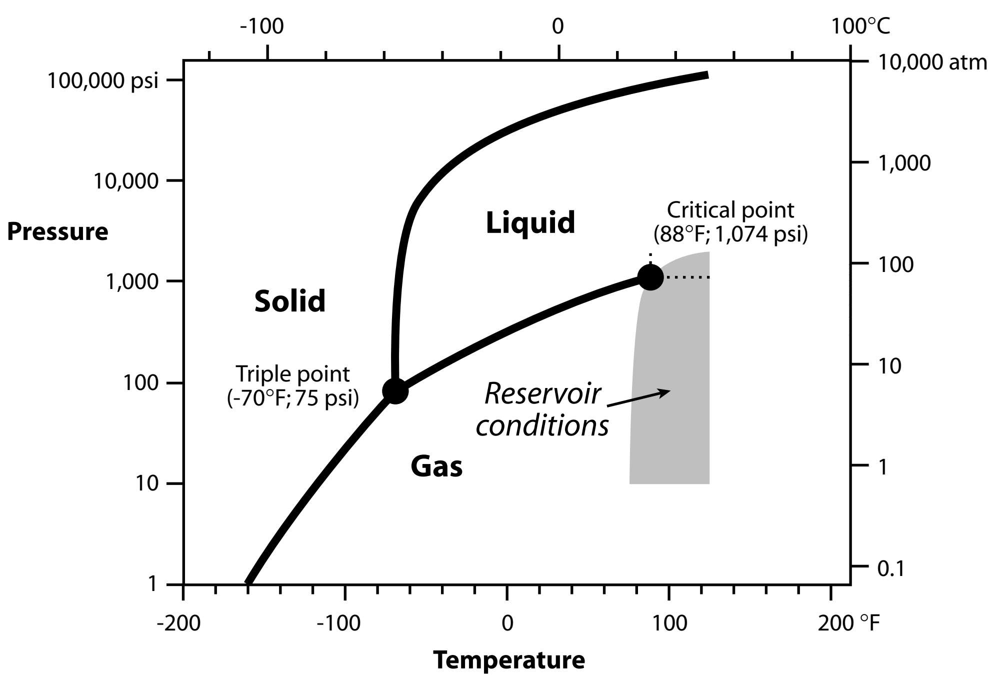


Fig. 2. Phase diagram for $CO_2$ showing relationship of the critical point to temperature-pressure conditions in coalbed methane reservoirs of the Black Warrior basin.

The objective of this paper is to identify, characterize, and interpret areas where supercritical reservoir conditions exist or may develop. This research is part of a larger study sponsored by the U.S. Department of Energy, Jim Walter Resources, Incorporated, and Alabama Power Company that is designed to develop a geologic screening model for $CO_2$ sequestration in coal-bearing strata and to quantify the sequestration potential of coalbed methane reservoirs in the Black Warrior basin.

**Methods**

Hydrologic and geothermal information were obtained from geophysical well logs and compiled in a spreadsheet along with stratigraphic structural data. Geothermal data were derived from bottom-hole temperatures and temperature logs of 965 coalbed methane wells. The geothermal gradient for each well was determined by dividing the difference between bottom-hole temperature and near-surface ground temperature (74°F) by total well depth. 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 (< 6.0°F/1,000 ft). The geothermal data were then analyzed statistically and mapped using the Isomap module of the Geographix Exploration System.

Reservoir pressure was determined from well depth and water-level information in the headers of well logs or was interpreted from resistivity profiles. Because the data recorded vary among logging companies, wells with a recorded bottom-hole temperature rarely include water level information. As a rule, logs recorded by Schlumberger and Halliburton have bottom-hole temperatures, and those recorded by other companies have water levels. Many logs lack information about how long the water level was allowed to equilibrate after drilling, so the water level readings and reservoir pressure calculations should be considered minimum values.

Fresh water (< 10,000 mg/L TDS) exists at depth throughout much of the Black Warrior coalbed methane fairway (Pashin et al., 1991; Ellard et al., 1992), so reservoir pressure was estimated using a hydrostatic gradient of 0.433 psi/ft. Once data were compiled, the hydrostatic pressure gradient for each well was computed. As with geothermal data, water level data were analyzed statistically and mapped with Isomap.

**Regional setting**

More than 110 Bcf of coalbed methane is produced annually from 19 gas fields in the eastern part of the Black Warrior foreland basin (Fig. 1). Cumulative gas production now exceeds 1.3 Tcf, and resources are estimated to be between 10 and 20 Tcf (0.3 to 0.6 Tcm) (Hewitt, 1984; McFall et al., 1986). Coalbed methane reserves are estimated conservatively to be 2.5 Tcf (Rice, 1985), and ECBM may expand the reserve base considerably (Pashin et al., 2001).

Economic coal and coalbed methane resources are in the upper part of the Pottsville Formation, which is of Early Pennsylvanian age. The productive Pottsville section ranges in thickness from about 2,000 ft in the northern coalbed methane fields to more than 4,500 ft in the southern fields. The Pottsville is a siliciclastic succession containing numerous marine-nonmarine depositional cycles, and productive coal beds are distributed throughout the upper Pottsville section (Pashin et al., 1991; Pashin, 1998). Coal rank ranges mainly from high volatile A bituminous through low volatile bituminous (Semmes, 1929; Winston, 1990). Gas at the wellhead is composed mainly of methane (95%) and nitrogen (5%) (Scott, 1993) and is typically produced from coal beds ranging in thickness from 1 to 9 ft. Three to 20 coal beds are completed in most wells.

All coalbed methane fields are in the eastern part of the basin along or northwest of the frontal structures of the Appalachian thrust belt (Figs. 1, 3). Pottsville strata form a southwest-dipping homocline that is broken by numerous normal faults that strike northwest (Semmes, 1929; Pashin and Groshong, 1998). Thin-skinned folds and thrust faults of the Appalachian orogen have deformed the southeast margin of the homocline, and an upturned fold limb follows the southeast basin margin for more than 25 mi (40 km). Pottsville strata are exposed in the eastern part of the study area and are overlain with angular unconformity by poorly consolidated Cretaceous strata of the Gulf Coastal Plain and the

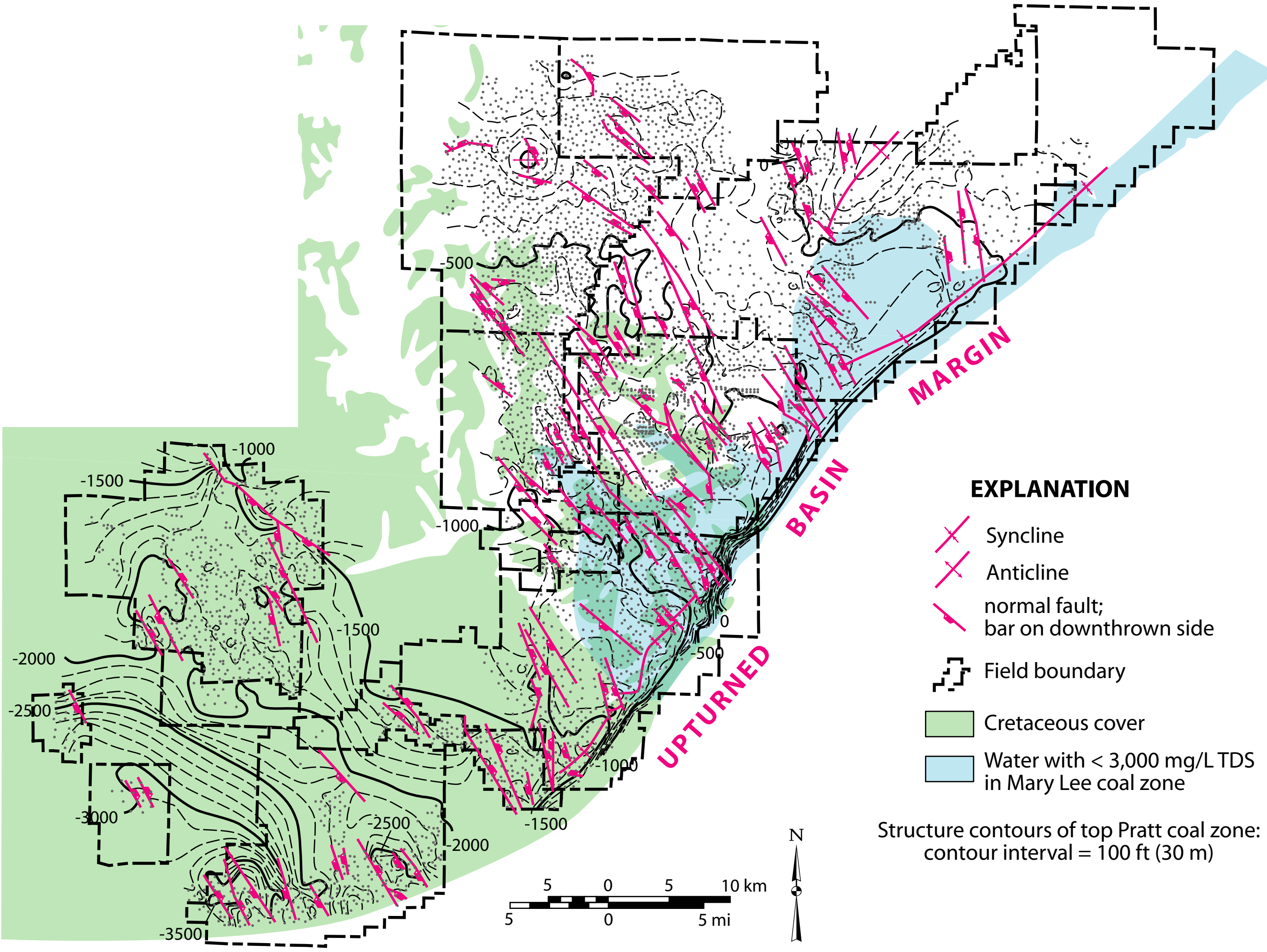


Fig. 3. Generalized structural contour map of the top of the Pratt coal zone in the Black Warrior coalbed methane fields showing location of Cretaceous cover and fresh-water plumes in the Mary Lee coal zone.

Mississippi Embayment in the western part of the study area (Mellen, 1947; Kidd, 1976) (Fig. 3). Cretaceous strata reach a thickness greater than 800 ft in the southwestern coalbed methane fields.

Strata in the upper Pottsville effectively have no matrix permeability to water, so virtually all flow of water is 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 coalbed methane fields. On the basis of slug tests, the Pottsville can be considered poorly transmissive and has permeability between 10 and 100 md at reservoir depth (McKee et al., 1988).

Water chemistry varies significantly in the coalbed methane fields, with sodium bicarbonate water predominating shallower than 1,000 ft and sodium chloride water predominating deeper (Pashin et al., 1991). TDS content of water produced from the Pottsville Formation is commonly lower than 10,000 mg/L east of Cretaceous cover, and TDS content is lower than 3,000 mg/l deeper than 1,000 ft (300 m) near the southeast basin margin (Fig. 3). Water with TDS content lower than 3,000 mg/L defines a series of fresh-water plumes that are apparently fed by meteoric recharge of reservoir coal beds that come to the surface along the upturned southeastern basin margin (Pashin et al., 1991). Cretaceous strata contain poorly consolidated sand and gravel units that form major aquifers that intercept meteoric recharge, and below thick Cretaceous cover the salinity of upper Pottsville Formation water can exceed that of sea water (30,000 mg/l) (Ellard et al., 1992; Ortiz et al., 1993).

**Reservoir Temperature**

Reservoir temperature is an important concern in coalbed methane production and enhanced gas recovery because the sorption capacity of coal decreases significantly with increasing temperature (Yang and Saunders, 1985; Scott et al., 1994; Kroos et al., 2001). 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 ft (Fig. 4). Importantly, 99% of the bottom-hole temperatures recorded in coalbed methane wells of the Black Warrior basin are greater than 88°F. Temperature and depth correlate with a determination coefficient ($r^2$) 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°F above the current mean annual surface temperature. Geothermal gradient data have a normal distribution with a strong central tendency about a mean of 9.0°F/1,000 ft and range from about 6 to 20°F/1,000 ft. These generally low geothermal gradients are typical of shaly foreland-basin successions and variability of the geothermal gradient may reflect a combination of basin hydrodynamics and heterogeneous basement heat flow (Majorowicz and Jessop, 1981; Hitchon, 1984).

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. 5). The overall temperature pattern reflects the geologic structure of the coalbed methane fairway, and contours parallel some major normal faults in northeastern Robinson's Bend, northeastern Cedar Cove, and Moundville fields, as well as the upturned southeast basin margin in northeastern Cedar Cove Field. Areas with elevated geothermal gradient form bull's-eye contour patterns that are superimposed on the structure-dominated pattern. The Pratt coal zone reaches the critical reservoir temperature of 88°F in Cedar Cove, Holt, and Robinson's Bend fields. However, reservoir pressure must be determined and mapped to predict where supercritical fluid conditions may affect $CO_2$ sequestration and ECBM operations.

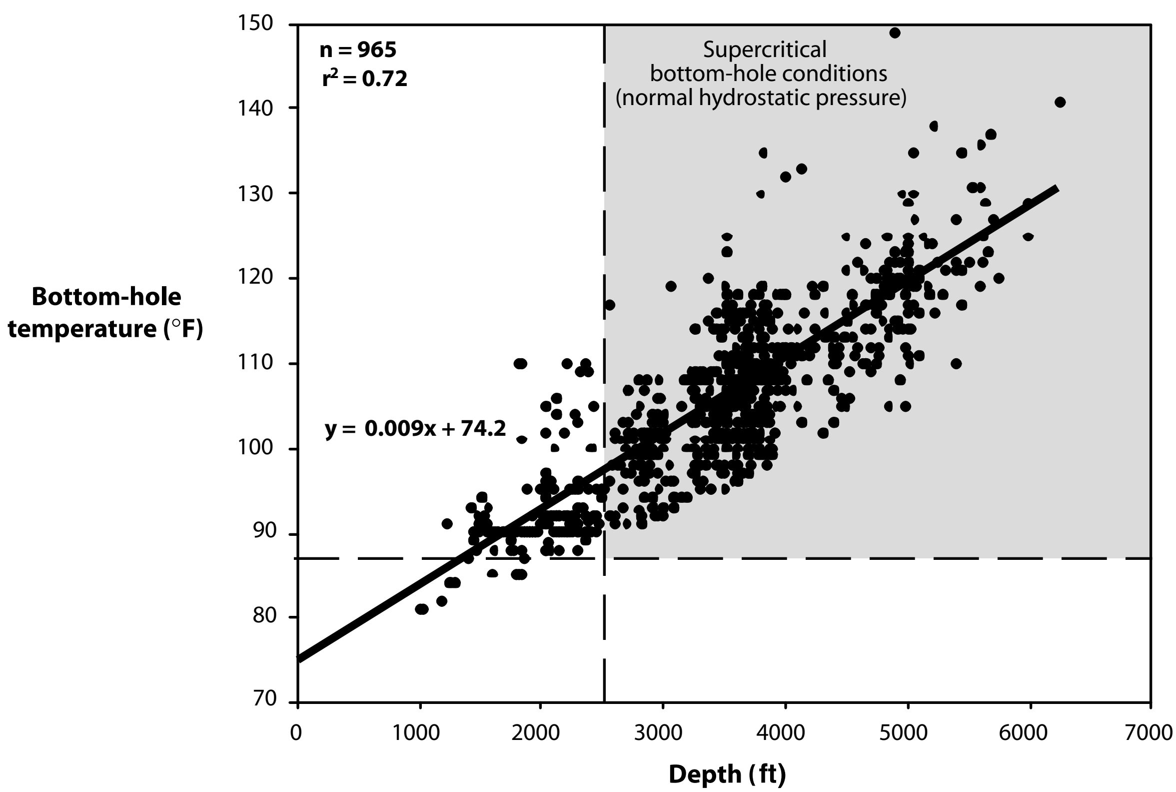


Fig. 4. Temperature-depth plot for coalbed methane wells in the Black Warrior basin.

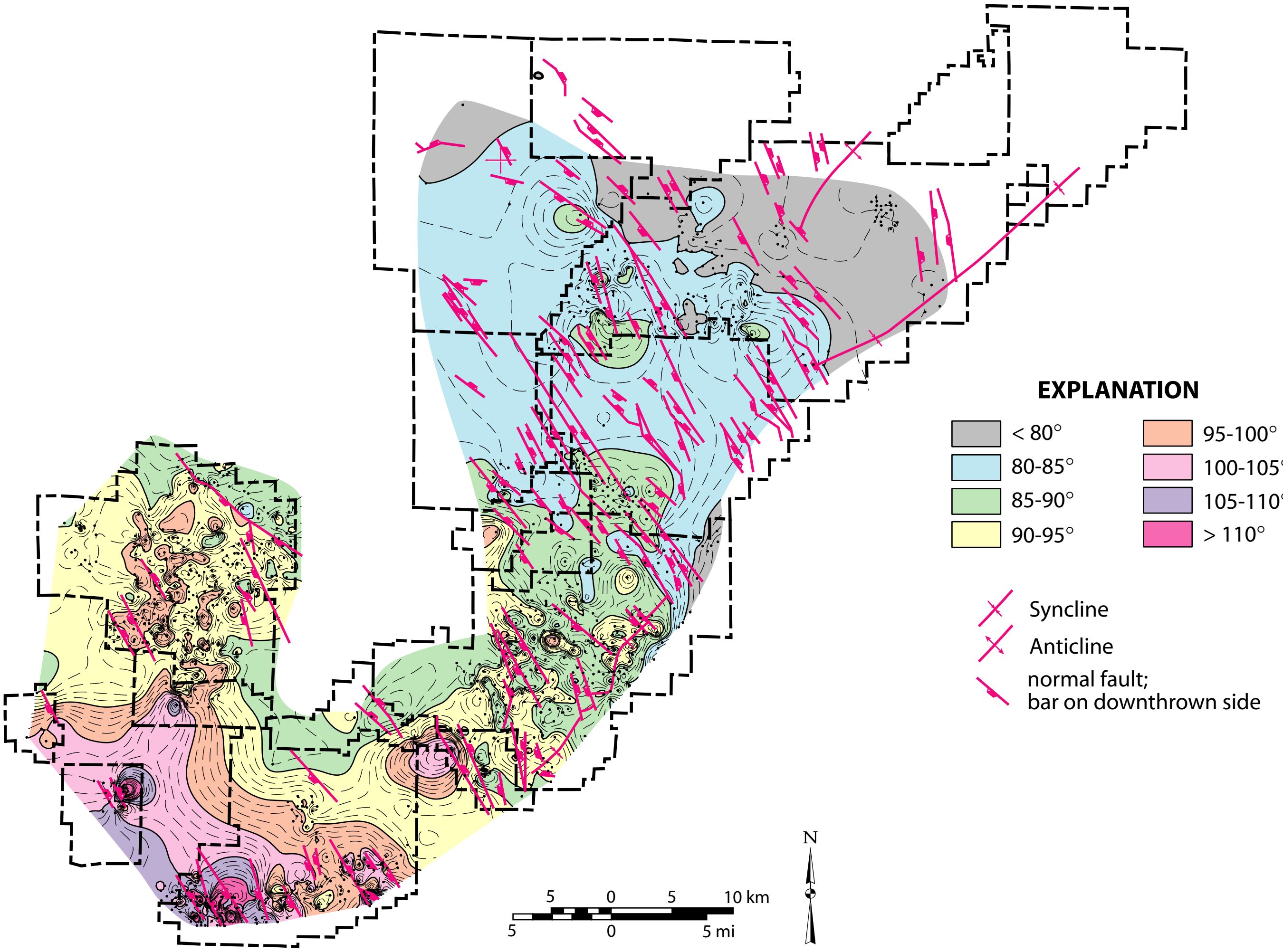


Fig. 5. Map of temperature at the top of the Pratt coal zone in the Black Warrior coalbed methane fields.

**Reservoir Pressure**

Reservoir pressure includes lithostatic and hydrostatic components, and each of these components is of critical concern in coalbed methane production and $CO_2$ sequestration. Lithostatic and hydrostatic stress combine to influence the transmissivity of coal, which is much more stress-sensitive than other rock types (McKee et al., 1988; Bustin, 1997). Lowered hydrostatic pressure is a major determinant of how much gas coal can sorb, and lowered hydrostatic pressure is the principal mechanism by which gas is produced.

Water-level data indicate that the hydrostatic pressure gradient in the Black Warrior coalbed methane fairway ranges from normal (0.43 psi/ft) to abnormally low (<0.05 psi/ft) (Fig. 6). A pressure-depth plot indicates that pressure gradient has a bimodal 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. Wells with normal pressure to moderate underpressure exist at all bottom-hole depths, whereas extremely underpressured wells are clustered between 1,500 and 2,000 ft.

Water-level data are available to map minimum hydrostatic pressure gradient prior to degasification in the northern part of the coalbed methane fairway (Fig. 7). Wells with near-normal hydrostatic pressure gradients span large areas of Cedar Cove, Deerlick Creek, Blue Creek, and Oak Grove Fields. A large area of extreme underpressure is in Brookwood Field. In this area, hydrostatic pressure at the top of the Pratt coal zone is projected to be less than 100 psi. Other significant pockets of extreme underpressure

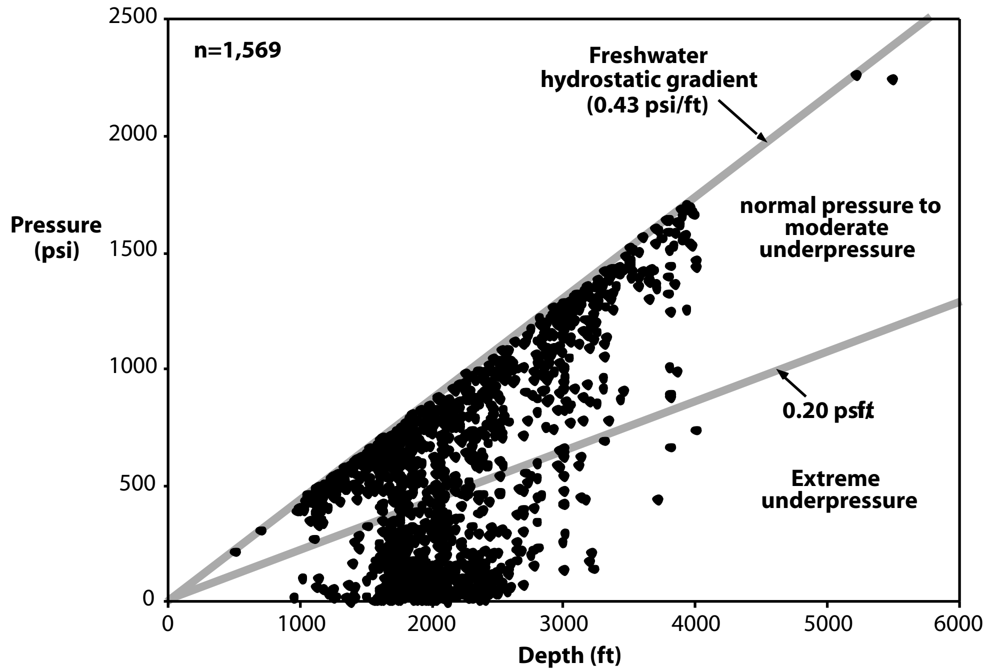


Fig. 6. Pressure-depth plot for coalbed methane wells in the Black Warrior basin.

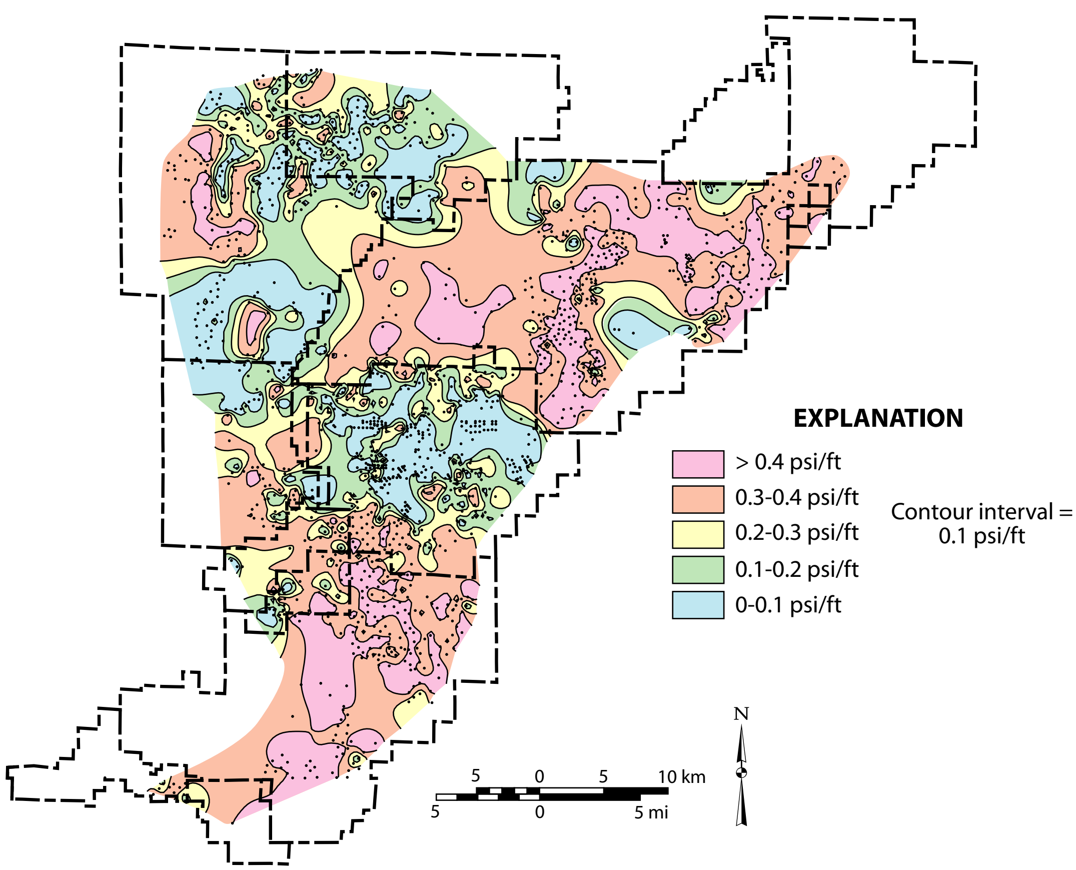


Fig. 7. Map of hydrostatic pressure gradient in the Black Warrior coalbed methane fields.

exist in parts of Deerlick Creek, Blue Creek, and White Oak Creek fields. In some areas, the hydrostatic 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 (Fig. 6) reflects a combination of anthropogenic and natural factors. Dewatering associated with longwall mining that predates the coalbed methane industry appears to be a major cause of underpressure in Brookwood and eastern Oak Grove fields. In Brookwood Field, the Blue Creek coal of the Mary Lee zone is mined at a depth of about 2,000 ft, which partly explains the clustering of extremely underpressured wells at this level. 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 et al., 1991; Pashin and Hinkle, 1997). Pockets of extreme underpressure in Deerlick Creek, Blue Creek, and White Oak Creek fields are isolated 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 (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. 7) may reflect connection to the fresh-water recharge area along the southeast basin margin (Fig. 3). 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 within target coal zones quite rapidly as gas evolves into open fractures and flow is disconnected from the regional recharge system.

Natural underpressure in parts of Deerlick Creek, Blue Creek and White Oak Creek fields (Fig. 7) 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 unlikely because gas production has been highly successful in these fields (Levine et al., 1997; Pashin et al., 2003). Isolation from recharge is feasible at least locally, because major changes in hydrostatic pressure gradient across drilling units provides evidence for compartmentalization, and water production from underpressured wells is limited (Pashin et al., 2003). Another factor to be considered is that significant gas pressure may exist that must be detected by gauges rather than by analysis of water levels. Economically viable gas content in coal in the areas of natural underpressure further suggests that reservoir pressure is higher than can be predicted by water-level data.

**Supercritical fluid potential**

As already mentioned, $CO_2$ has potential to become a supercritical fluid where reservoir temperature exceeds 88°F and pressure exceeds 1,074 psi (Fig. 2). In a normally pressured freshwater system, critical pressure is reached at a depth of 2,480 ft. Critical bottom-hole temperature is exceeded well above this depth in nearly all coalbed methane wells, so supercritical fluid conditions potentially are widespread in the Pottsville Formation (Fig. 4). However, active coalbed methane reservoirs are in a depressurized state, so supercritical conditions can only be reached as the reservoir equilibrates to natural pressure levels after abandonment. As natural pressure levels are restored, coal will become increasingly undersaturated with $CO_2$ and other gases.

Mapping to delineate where each Pottsville coal zone reaches a depth of 2,480 ft indicates that subcritical conditions will persist after abandonment throughout the Pottsville reservoir interval from Brookwood and Deerlick Creek fields northward (Fig. 8). The Black Creek coal zone exceeds critical depth within these fields, and supercritical conditions may develop at higher stratigraphic intervals toward the structurally deepest parts of the coalbed methane fairway. In the footwall block of a major half graben in Robinson's Bend Field, supercritical potential is restricted mainly to the Black Creek coal zone, whereas in the hanging-wall block, supercritical conditions may develop as high as the Pratt coal zone. In southwestern Moundville Field, the complete Pottsville reservoir interval exceeds critical depth.

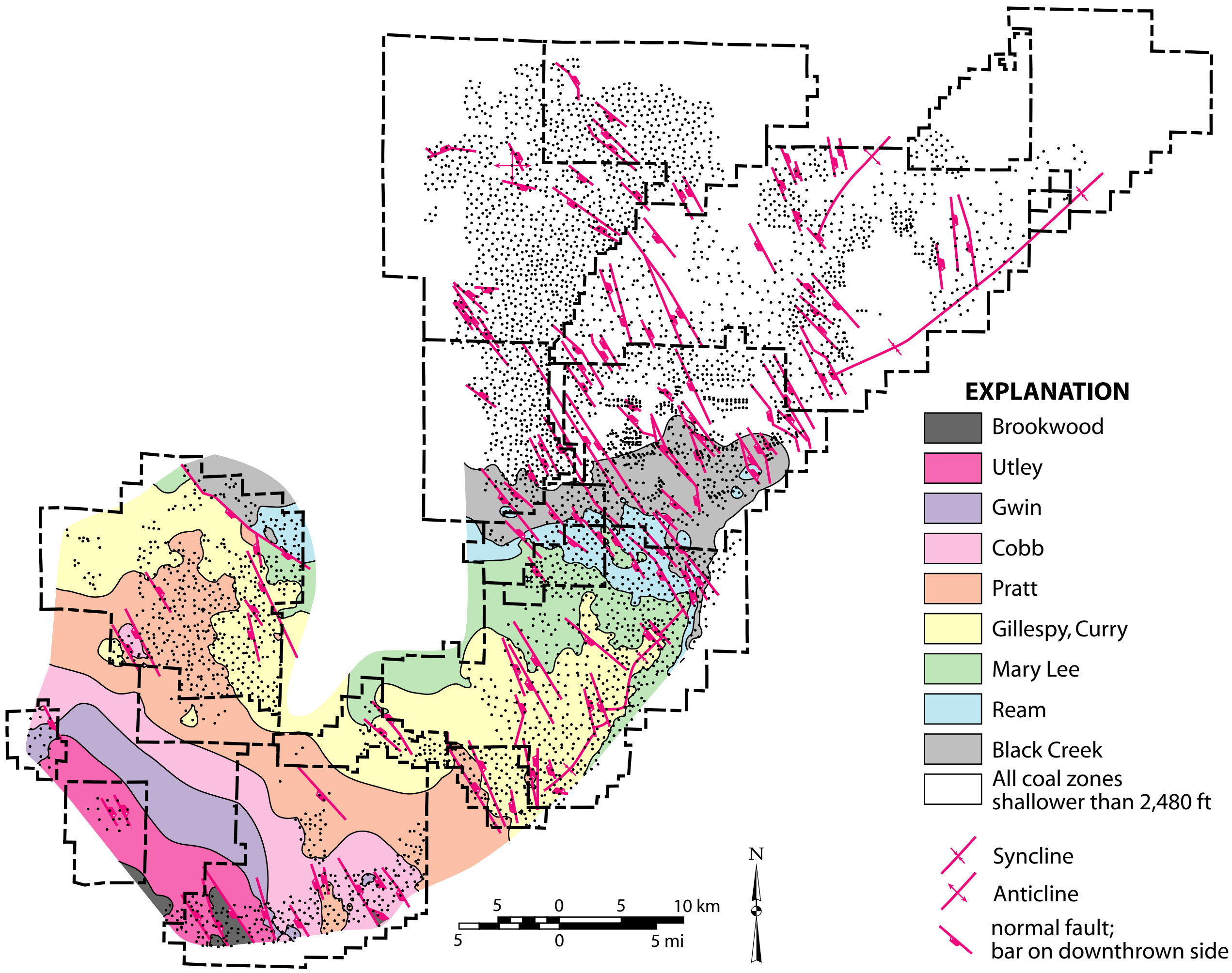


Fig. 8. Map showing shallowest coal zone where supercritical fluid conditions for $CO_2$ can potentially develop in the Black Warrior coalbed methane fields.

The precise significance of critical depth in the Black Warrior coalbed methane fairway is unclear. Abnormally low reservoir pressure may ensure persistence of 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 Langmiur monolayer adsorption theory (Kroos et al., 2001), so potential exists for enhanced sequestration capacity below a depth of 2,480 ft. However, the $CO_2$-$CH_4$-$N_2$ chemical system is poorly understood, and it is possible that mixed gases in this system reach a state of nonideality under different temperature-pressure conditions than is predicted for single gases (Horita et al., 2001). Furthermore, Kroos et al. (2001) suggested that swelling of coal matrix at high gas saturation may ultimately retard sequestration capacity under supercritical reservoir conditions.

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 further to ensure safe $CO_2$ sequestration and ECBM operations. This is especially important in the Black Warrior basin, where a heterogeneous pressure regime and complex geologic structure pose potential risks for $CO_2$ sequestration. Along faults in Utah, for example, springs charged with $CO_2$ erupt periodically as geysers (Shipton et al., 2001), and Clayton et al. (1994) documented a gas seep along a normal fault in the Black Warrior basin. Care must also be taken to avoid injection of $CO_2$ into potentially mineable

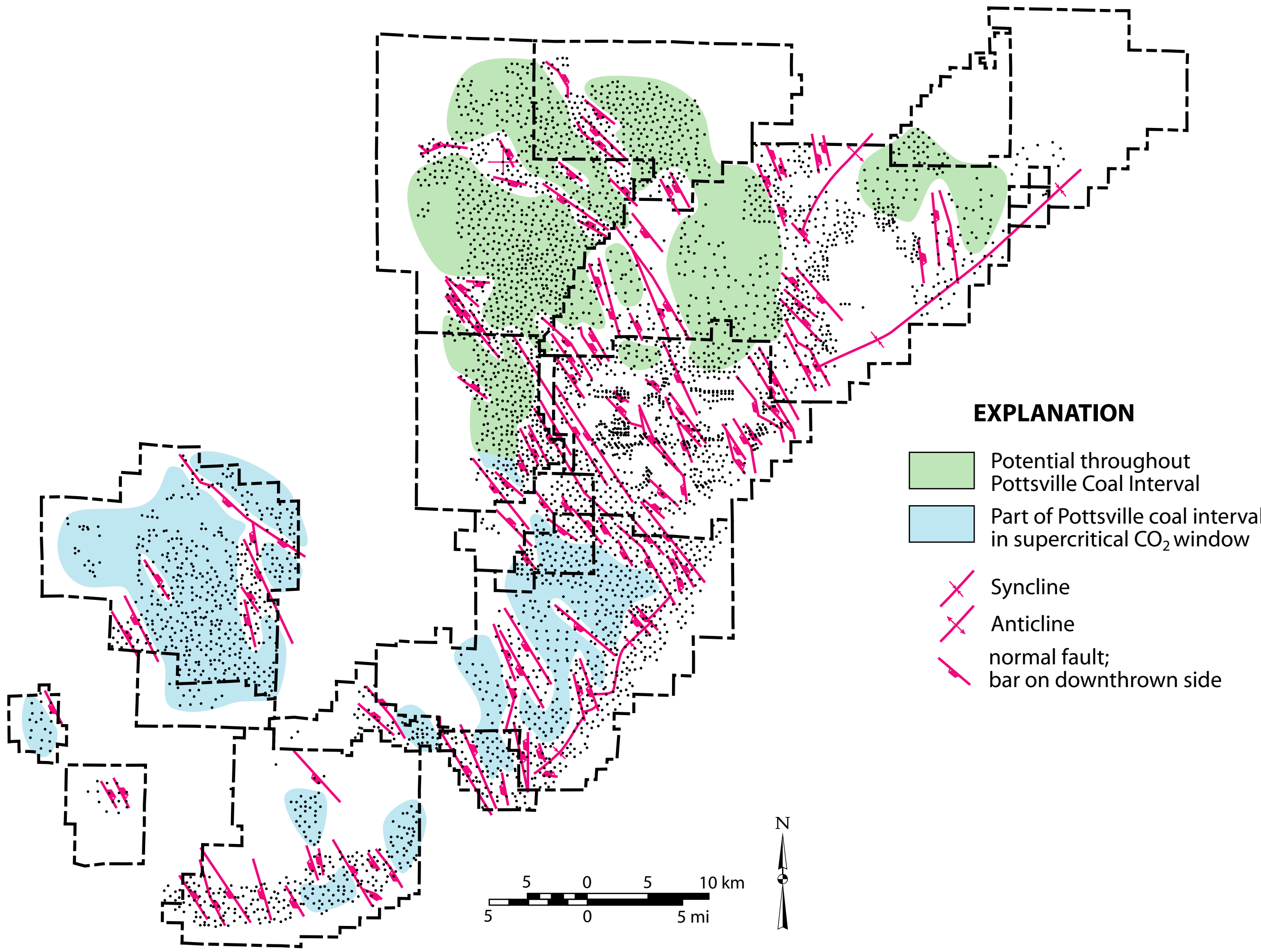


Fig. 9. Areas of the Black Warrior basin where hydrologic conditions and geologic structure reduce risk for demonstration of $CO_2$ sequestration and ECBM technology.

coal beds, which would result in exchange of a manageable firedamp condition for what may be an unmanageable blackdamp condition that would create suffocation hazards and lead to emissions counterproductive to the goal of $CO_2$ sequestration.

Although potential for supercritical reservoir conditions and complex structure pose significant risks for $CO_2$ sequestration and ECBM in the Pottsville Formation, major tracts of land exist where $CO_2$ may be sequestered safely (Fig. 9). Among the most promising areas are large parts of Blue Creek, northern Deerlick Creek, and western Oak Grove Fields that lack normal faults and can host a multitude of injection and production wells arranged in five-spot patterns. Large tracts lacking faults also exist in Cedar Cove and Robinson's Bend fields, and in these areas operations can focus on coal beds above the Pratt coal zone.

## Conclusions

Geothermic and hydrologic conditions are diverse in the Black Warrior coalbed methane fields and reflect a combination of natural and anthropogenic factors. Reservoir temperature within the coalbed methane target zone generally ranges from 80 to 125°F, and 99% of the recorded bottom-hole temperatures exceed the critical temperature of 88°F. Hydrostatic pressure gradients range from normally pressured to extremely underpressured. Pressure-depth plots indicate a compartmentalized system in which wells tend to be normally pressured or nearly pressure-depleted. Normal pressure is typical of areas proximal to a major recharge zone along near the southeast margin of the Black Warrior basin.

Major pockets of extreme underpressure are developed around deep longwall coal mines predating coalbed methane drilling. Other pockets of underpressure are isolated from underground mining and appear to represent free gas in fractures in regions distal to the main recharge area.

Temperature-pressure conditions in the Pottsville Formation dictate that coalbed methane reservoirs never cross the gas-liquid condensation line for $CO_2$. However, $CO_2$ can become a supercritical fluid beyond a depth of 2,480 ft under normally pressured conditions. No potential exists for supercritical conditions to develop in the northern half of the coalbed methane production fairway, and dewatering during coalbed methane production has reduced reservoir pressure significantly in all coalbed methane fields. If reservoir pressure returns to normal following abandonment of the fields, supercritical conditions may develop in the southern half of the production fairway. Where supercritical conditions develop, increasing reservoir pressure will cause major undersaturation of coal with $CO_2$, which may mitigate risks associated with supercritical fluid.

Coal can hold large quantities of supercritical $CO_2$, but the mobility and reactivity of that fluid is unknown and should be researched further. Furthermore, phase relationships for $CO_2$ in mixed gas systems should be explored further to confirm boundary conditions, thereby ensuring safe sequestration of greenhouse gas in deep coal. Faults are abundant in the Black Warrior basin and may pose risks for leakage during enhanced coalbed methane operations, and mineable coal reserves should be protected from sequestration activities, which could give rise to unmanageable blackdamp conditions. Even with these constraints, large tracts of land exist that lack normal faults, deep mineable reserves, and potential for supercritical fluid conditions, and it is in these areas that risk can be minimized when demonstrating $CO_2$ sequestration and ECBM technology.

**Acknowledgments**

This report was prepared with the support of the U.S. Department of Energy under Award no. DE-FC26-00NT40927. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the DOE. The suggestions of J. Drahovzal substantially improved this contribution.

**References**

Ayers, W.B., Jr., and Kaiser, W.A. (Editors), 1994. Coalbed methane in the Upper Cretaceous Fruitland Formation, San Juan Basin, Colorado and New Mexico. TX Bur. Econ. Geol., Rept. Inv. 218, 216 pp.

Bradley, J.S., 1975. Abnormal formation pressure. Am. Ass. of Petrol. Geol. Bull., 59:957-973.

Bradley, J.S., and Powley, D E., 1994. Pressure compartments in sedimentary basins: a review. Am. Assoc. Petrol. Geol. Mem. 61:3-26.

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. Am. Ass. Petrol. Geol. Bull., 81:1894-1908.

Clayton, J.L., Leventhal, J.S., Rice, D.D., Pashin, J.C., Mosher, B., and Czepiel, P., 1994. Atmospheric methane flux from coals—preliminary investigation of coal mines and geologic structures in the Black Warrior Basin. U.S. Geol. Surv. Prof. Pap. 1570, pp. 471-492.

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: B.B. Beamish and P.D. Gamson (Editors), Symposium on coalbed methane research and development in Australia. James Cook University, Townsville Australia, 1:45-61.

Horita, J., Blencoe, J.G., and Cole, D.R., 2001. Fundamental geochemical research on long-term carbon sequestration in subsurface environments (abs.). 2001 AAPG Ann. Conv. Proc., p. A93.

Hitchon, B., 1984. Geothermal gradients, hydrodynamics, and hydrocarbon occurrences, Alberta, Canada. Am. Ass. Petrol. Geol. Bull., 68:713-743.

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., (Editors)., Coalbed methane resources of the United States. Am. Ass. Petrol. Geol. Studies in Geol., 17:73-104.

Jüntgen, H., and Karweil, J., 1966. Gasbildung und Gasspeicherung in Steinkohlenflözen, Teilen 1 und 2. Erdol und Kohle-Erdgas-Petrochem., 19:339-344.
Kaiser, W.R., 1993. Abnormal pressure in coal basins of the western United States. 1993 Int. Coalbed Methane Symp. Proc., Univ. AL, Tuscaloosa, AL, 1: 173-186.
Kidd, J.T., 1976. Configuration of the top of the Pottsville Formation in west-central Alabama. AL State Oil and Gas Board Oil and Gas Map 1.
Kim, A. G., 1977. Estimating methane content of bituminous coals from adsorption data. U.S. Bur. Mines Rept. Inv. 2845, 22 pp.
Kreitler, C. W., 1989. Hydrogeology of sedimentary basins. Jour. Hydrol., 106:29-53.
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. Int. Jour. of Coal Geol., 51:69-92.
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. 1997 Int. Coalbed Methane Symp. Proc., Univ. AL, Tuscaloosa, AL, pp. 331-339.
Majorowicz, J.A., and Jessop, A.M., 1981. Regional heat flow patterns in the Western Canadian Sedimentary Basin. Tectonophysics, 74:209-238.
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. Gas Research Inst., Topical Rept. GRI 86/0272, 80 pp.
McKee, C.R., Bumb, A.C., and Koenig, R.A., 1988. Stress-dependent permeability and porosity of coal and other geologic formations. Soc. Petrol. Eng. Formation Evaluation, March, 1988, pp. 81-91.
Mellen, F. F., 1947. Black Warrior basin, Alabama and Mississippi. Am. Ass. Petrol. Geol. Bull., 31:1801-1816.
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. 1993 Int. Coalbed Methane Symp. Proc., Univ. AL, Tuscaloosa, AL, pp. 339-364.
Pashin, J.C., 1998. Stratigraphy and structure of coalbed methane reservoirs in the United States: an overview. Int. J. Coal Geology, v. 35, p. 207-238.
Pashin, J.C., Carroll, R.E., Groshong, R.H., Jr., Raymond, D.E., McIntyre, M. R., 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. Ann. Tech. Progress Rept., U.S. Dept. Energy, Nat. Energy Tech. Lab., contract DE-FC-00NT40927, 190 pp.
Pashin, J.C., and Groshong, R.H., Jr., 1998. Structural control of coalbed methane production in Alabama: Int. J. Coal Geol., 38:89-113.
Pashin, J.C., Groshong, R.H., Jr., and Carroll, R.E., 2001. Carbon sequestration potential of coalbed methane reservoirs in the Black Warrior basin: a preliminary look. 2001 Int. Coalbed Methane Symp. Proc., Tuscaloosa, AL, pp. 51-62.
Pashin, J.C., and Hinkle, F., 1997. Coalbed methane in Alabama. AL Geol. Surv., Circ. 192, 71 pp.
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. AL Geol. Surv., Bull. 145, 127 pp.
Rice, D.D., 1995. Geologic framework and description of coal-bed gas plays. U.S. Geol. Surv. Digital Data Ser., DDS-30, 103 pp.
Scott, A.R., 1993. Composition and origin of coalbed gases from selected basins in the United States. 1993 Int. Coalbed Methane Symp. Proc., Univ. AL, Tuscaloosa, AL, 2: 207-222.
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. Am. Ass. Petrol. Geol. Bull., 78:1186-1209.
Semmes, D.R., 1929. Oil and gas in Alabama. Alabama Geol. Surv., Spec. Rept. 15, 408 pp.
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. 2001 AAPG Ann. Conv. Prog., p. A185.
Winston, R.B., 1990. 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. AL Geol. Surv., Circ. 152, 53 pp.
Yang, R. T., and Saunders, J. T., 1985. Adsorption of gases on coals and heat-treated coals at elevated temperature and pressure. Fuel, 64:616-620.