

# **Enhanced Coalbed Methane Recovery Through Sequestration of Carbon Dioxide: Potential for a Market-Based Environmental Solution in the Black Warrior Basin of Alabama**

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## **Abstract**

Sequestration of CO<sub>2</sub> in coal is a market-based environmental solution with potential to reduce greenhouse gas emissions while increasing coalbed methane recovery. Producing coalbed methane through injection of CO<sub>2</sub> is also more efficient than current techniques requiring production and disposal of large quantities of formation water. However, the sequestration capacity of coal basins has yet to be quantified, and screening criteria need to be established to select sites for demonstration of sequestration technology. Our research focuses on the sequestration potential of the Black Warrior coalbed methane fairway of the southeastern United States, where two large coal-fired power plants emitting 31 megatons of CO<sub>2</sub> annually operate adjacent to a thriving coalbed gas industry. The principal objectives of this research are to develop a screening model for site selection that is transferable to highly industrialized coal basins in North America, Europe, and Asia.

Experience from 20 years of coalbed methane development provides a wealth of knowledge that can be used to quantify sequestration potential and develop a screening model that is broadly applicable. Indeed, the geologic variables controlling the distribution and producibility of coalbed methane resources are essentially the same as those determining carbon sequestration potential. These variables include stratigraphic architecture, structural geometry, permeability, hydrogeology, coal quality, gas content, and sorption capacity. Emerging technologies to be considered include CO<sub>2</sub> separators for flue gas and enhanced gas recovery technology. Proximity to power plants, pipeline systems, coalbed methane field design, and the locations of underground coal mines and their reserve areas are all elements of infrastructure that must also be known to screen areas for demonstration and commercialization of carbon sequestration technology.

## **Introduction**

The amount of carbon dioxide (CO<sub>2</sub>) in the earth's atmosphere has risen from pre-industrial levels of 280 ppm to more than 365 ppm, and most of this increase has been within the last 60 years (Keeling and Whorf, 1998). This increase is attributed widely to the burning of fossil fuels, and if current trends in resource utilization continue, anthropogenic CO<sub>2</sub> emissions will triple during the 21<sup>st</sup> Century (IPCC, 1996). Among the principal ways CO<sub>2</sub> emissions may be reduced is by sequestration in geologic formations, including coal. Coal is an especially attractive target for sequestration not only because it can store large quantities of gas, but because CO<sub>2</sub> can be

used to enhance recovery of coalbed methane, thereby providing the basis for a market-based environmental solution (Byrer and Guthrie, 1999; Stevens et al., 1999).

In a discussion of the state of carbon sequestration science, Reichle et al. (1999) expressed the need for studies assessing the sequestration capacity of geologic formations and developing screening criteria for the demonstration and commercialization of CO<sub>2</sub> sequestration technology. In response to this and other needs articulated by Reichle et al. (1999), our research has three major goals: (1) to develop a geologic screening model that is broadly applicable, (2) to quantify the CO<sub>2</sub> sequestration potential of the coalbed methane fairway in the Black Warrior basin of Alabama, and (3) to apply the screening model to identify sites favorable for demonstration of enhanced coalbed methane recovery and mass sequestration of CO<sub>2</sub> emitted from coal-fired power plants. This research is funded primarily by the U.S. Department of Energy and is being conducted in partnership with Jim Walter Resources, Incorporated and Alabama Power Company. The project began in October, 2000 and is scheduled to be completed in September, 2001.

The coalbed methane fairway of the Black Warrior basin (fig. 1) is a logical location to develop screening criteria and procedures from numerous standpoints. According to the U.S. Environmental Protection Agency, Alabama ranks 9<sup>th</sup> nationally in CO<sub>2</sub> emissions from power plants, and two coal-fired power plants are within the coalbed methane fairway. More than 28 billion cubic meters (Bcm) of coalbed methane have been produced from the Black Warrior basin, which ranks second globally in coalbed methane production. Production is now leveling off, and enhanced coalbed methane recovery has the potential to offset impending decline and extend the life and geographic extent of the fairway far beyond current projections.

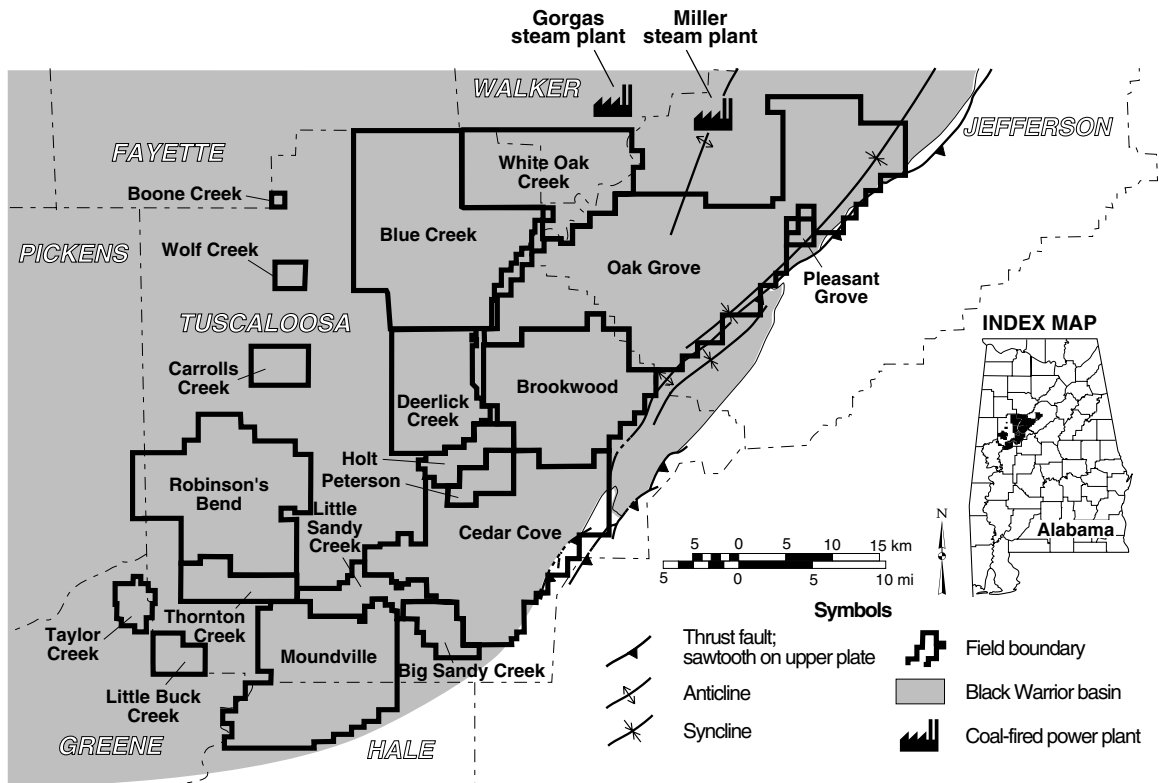


Figure 1.--Index map of the Black Warrior coalbed methane production fairway showing gas fields and coal-fired power plants (after Pashin et al., 1999).

## Geologic Factors

Experience from more than 20 years of commercial coalbed methane development in Alabama facilitates identification of screening criteria for sequestration of CO<sub>2</sub> in coal, because the geologic variables that determine the distribution and producibility of coalbed methane also influence sequestration capacity (fig. 2). Accordingly, our characterization of the Black Warrior basin draws heavily on the time-tested techniques used to evaluate coalbed methane reservoirs (e.g., Elder and Deul, 1974; Pashin et al., 1991; Kaiser et al., 1994). The main geologic factors that should be considered first when screening areas for sequestration of CO<sub>2</sub> in coal are stratigraphy, structural geology, and hydrogeology.

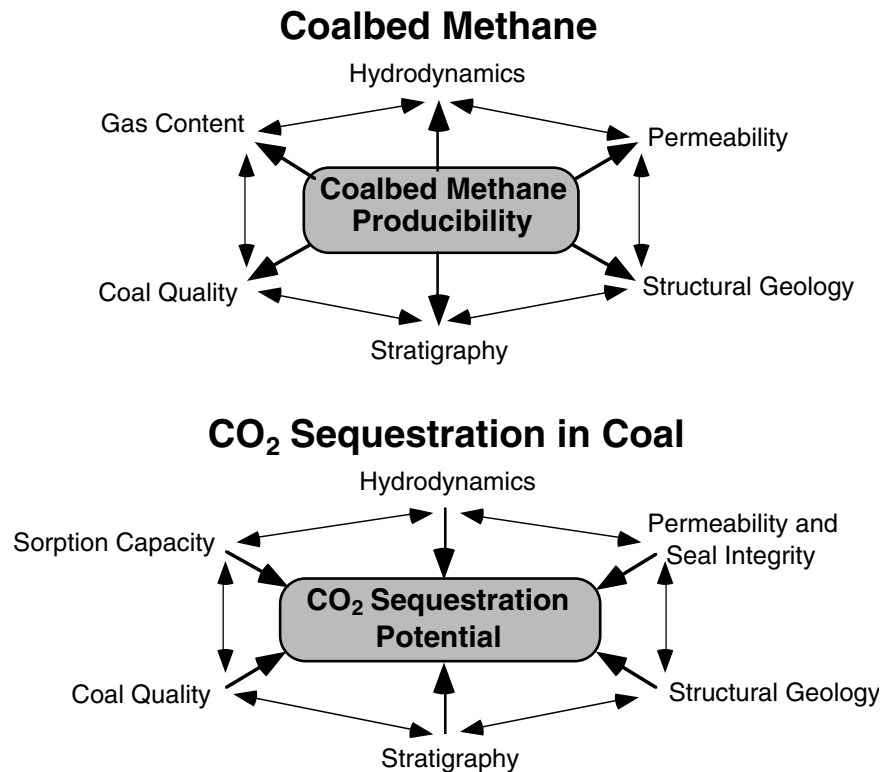


Figure 2.--Diagrams showing the similarity of geologic concepts used to assess coalbed methane producibility and CO<sub>2</sub> sequestration potential.

### Stratigraphy

Economic coal resources in the Black Warrior basin are in the upper part of the Pottsville Formation (fig. 3), which is of Pennsylvanian age (Butts, 1926; Culbertson, 1964; Thomas, 1988). Early workers recognized that Pottsville coal beds occur in a series of stratigraphic clusters (McCalley, 1900; Butts, 1926), and the upper Pottsville has been subdivided into a series of flooding-surface-bounded depositional cycles, each with a widespread coal bed or coal zone in the upper part (Pashin 1994a, b, 1998). Coalbed methane is produced from the Black Creek through Utley cycles.

The diverse depositional styles of the Pottsville Formation the Black Warrior basin have been central in the development of geologic models for Carboniferous coal-bearing strata in the eastern United States (e.g., Ferm and Weisenfluh, 1989; Gastaldo et al., 1993; Pashin, 1998). The geometry of coal bodies in the Pottsville Formation is variable and is a primary control on the

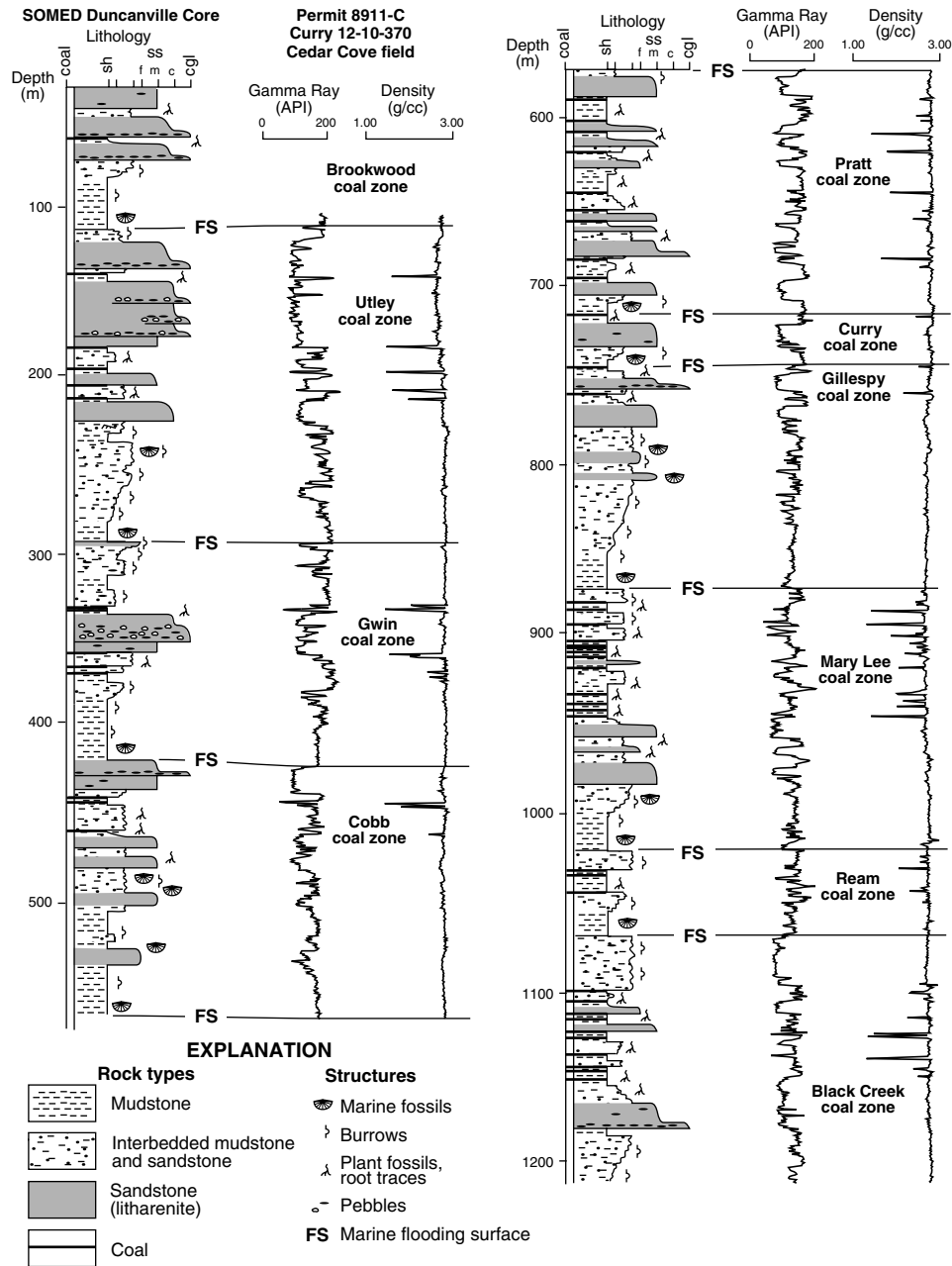


Figure 3.--Measured section of the Pottsville Formation showing flooding-surface-bounded depositional cycles and economic coal zones (after Pashin and Hinkle, 1997).

distribution of coal and coalbed methane resources. Typical examples of coal-body geometry include progressive and zig-zag bed splits in the Black Creek coal zone and valley-fill coal bodies in the Mary Lee coal zone (Pashin et al., 1991; Pashin, 1994a) (fig. 4). Although coal thickness controls well performance in few parts of the Black Warrior basin, thickness and coal utilization are primary determinants of the completion techniques that are chosen (Pashin, 1994a). Near underground coal mines, for example, single-zone completions are prevalent in the thick coal beds of the Mary Lee coal zone, whereas multiple-zone completions taking advantage of the Black Creek through Utley coal zones are common in many parts of the basin. Perforated

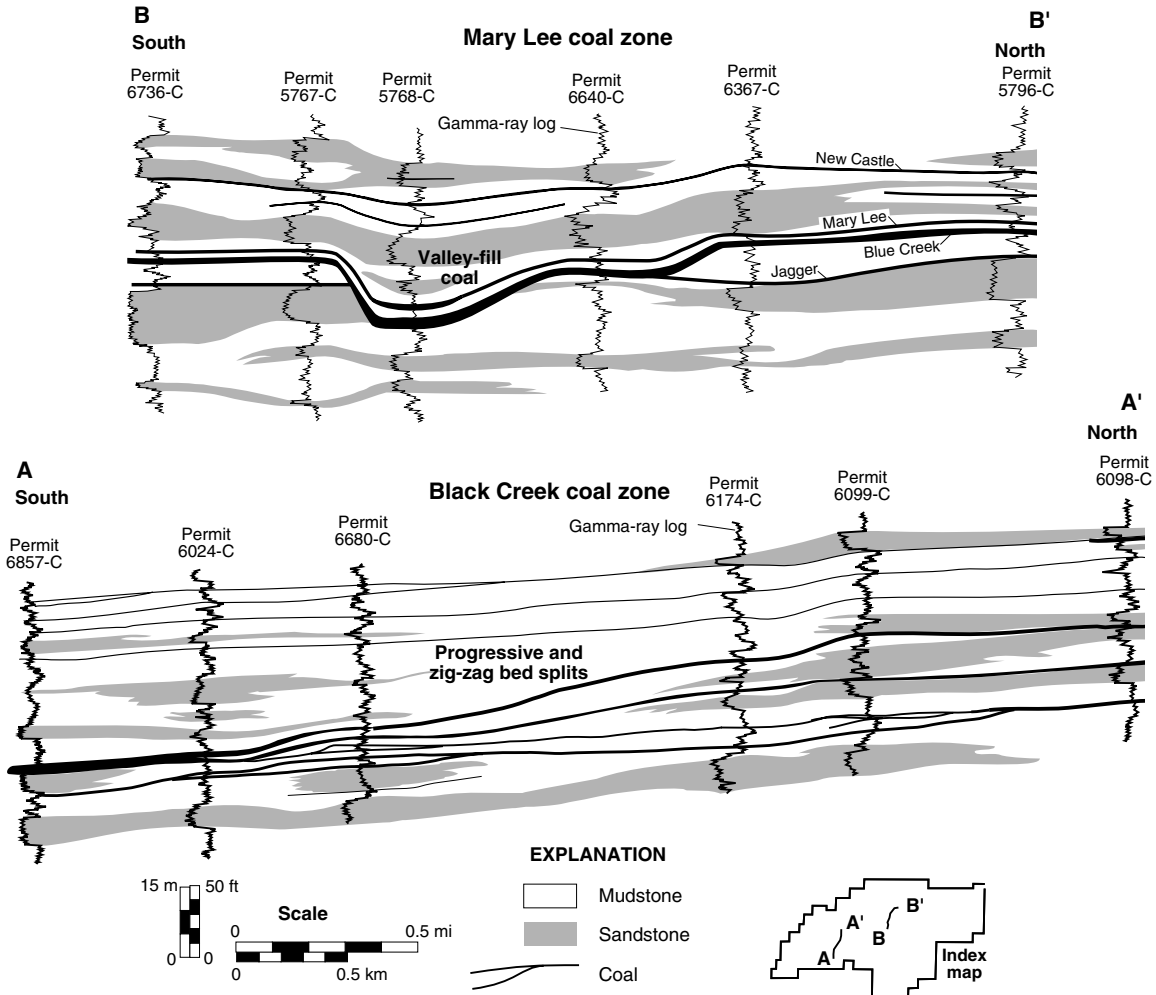


Figure 4.--Stratigraphic cross sections showing variation of coal-body geometry in Oak Grove Field (after Pashin et al., 1991).

coal beds in the coalbed methane fairway are typically thicker than 0.3 m, and thinner beds are thus considered unlikely targets for enhanced coalbed methane recovery and CO<sub>2</sub> sequestration.

### Structural Geology

Structural variables to be analyzed when screening areas for CO<sub>2</sub> sequestration potential include fold geometry, fault geometry, and fracture architecture. The Black Warrior basin is a late Paleozoic foreland basin that formed adjacent to the Ouachita and Appalachian orogenic belt (Thomas, 1988), and the coalbed methane fairway is developed along the northwest margin of the Appalachian orogen (fig. 1). Thin-skinned faults and folds of extensional and compressional origin are widespread in the coalbed methane fairway (Rodgers, 1950; Wang et al., 1993; Cates and Groshong, 1999) (fig. 5), and these structures influence gas and water production (Pashin et al., 1995; Pashin and Groshong, 1998). Faults constitute fundamental discontinuities in coalbed methane reservoirs, and the abundance and openness of natural fractures (e.g., cleats, joints, and shear fractures) between faults appear to be functions of structural geometry. Indeed, understanding the relationships among structural geometry, fracturing, and permeability is integral to characterizing Pottsville coal as a carbon sequestration medium, because matrix permeability is minimal.

Fracturing is a source of interwell heterogeneity in the Pottsville formation that makes the performance of individual wells difficult to predict (Pashin and Groshong, 1998). However,

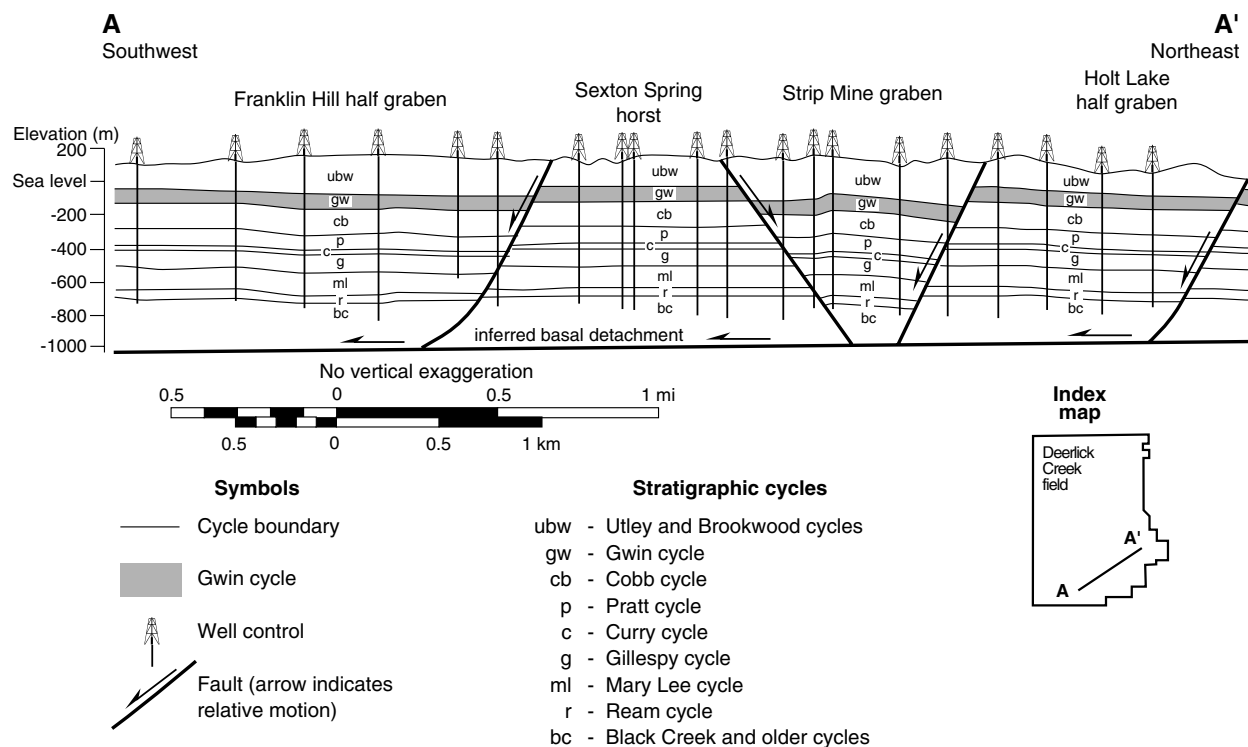


Figure 5.—Structural cross section of horst and graben system in Deerlick Creek Field (after Pashin and Groshong, 1998).

quantitative balanced models of structural geometry have proven useful for identifying areas with enhanced fracture permeability and improved well performance. Predicting the distribution fracture-related permeability in the Pottsville Formation is important in both coalbed methane production and carbon sequestration. As currently practiced in coalbed methane production, the goal is to dewater coal and adjacent strata to reduce formation pressure, thereby causing gas to desorb, and virtually all mobile water is in natural fractures. Open fracture networks are also important for sequestration of CO<sub>2</sub> because they provide access to a large quantity of coal and provide the surface area required for gas to sorb rapidly into the coal microstructure. However, the structural integrity of the strata bounding the coal is of greater concern in CO<sub>2</sub> sequestration than in coalbed methane production because maximum gas injection rates must be maintained with minimal leakage of CO<sub>2</sub> from the coal to the surrounding country rock or the surface.

### Hydrogeology

Hydrogeologic factors affecting coalbed methane reservoirs include reservoir pressure and water chemistry. Dewatering related to active mining and coalbed methane industries makes the hydrologic system in the Pottsville Formation highly dynamic (Pashin et al., 1991; Pashin and Hinkle, 1997). For example, subsurface flow related to recharge along the margins of the basin has had a strong effect on water chemistry, and mining and degasification operations have decreased reservoir pressure. Water chemistry is a critical concern for the coalbed methane industry because produced water must be disposed safely and economically, but these concerns have minimal impact on the potential for sequestration of CO<sub>2</sub> and enhanced coalbed methane recovery.

Reservoir pressure, by comparison, is a critical variable determining CO<sub>2</sub> sequestration potential because it is a primary determinant of gas sorption capacity in coal (Kim, 1977). Vertical hydrostatic pressure gradients in the Pottsville Formation range from fresh-water hydrostatic (0.43 psi/ft) to underpressured (<0.43 psi/ft), which is typical for geologically old

basins like the Carboniferous-Permian coal basins of eastern North America, Europe, Asia, and Australia (Kaiser, 1993). Mapping pressure gradients indicates significant heterogeneity in the Black Warrior coalbed methane fairway. Natural areas of underpressure exist in most coalbed methane fields, and large areas of underpressure exist around active underground coal mines (Pashin et al., 1991).

#### Sorption Capacity and Gas Content

The sorption behavior of coal as a methane reservoir has been a subject of intense research (e.g., Kim, 1977; Clarkson et al., 1997; Bustin and Clarkson, 1998), and sorption capacity is sensitive to pressure and temperature. Comparatively few investigators have examined sorption of CO<sub>2</sub> in carboniferous coal, and only Wolf et al. (1999) have published experiments on CO<sub>2</sub> sorption in Carboniferous coal. These studies show that coal can hold approximately twice as much CO<sub>2</sub> as methane, and precise determination of sorption capacity of coal in the Black Warrior basin is required so that the sequestration capacity of the coalbed methane fairway can be quantified. Nitrogen is another gas that has potential for enhanced coalbed methane recovery (Puri and Yee, 1990), and separation of CO<sub>2</sub>-nitrogen mixtures from flue gas may prove to be more economical than separation of pure CO<sub>2</sub>.

In addition to temperature and pressure, the rank, grade, and maceral composition of coal has a significant influence on sorption capacity (Lamberson and Bustin, 1993; Bustin and Clarkson, 1998). Coal in the Black Warrior coalbed methane fairway generally ranges in rank from low-volatile bituminous to high-volatile A bituminous (fig. 6), and ash and sulfur content are variable (Winston, 1990a, b; Carroll et al., 1995). Coal in the Black Warrior basin is generally trimacerite with vitrinite content ranging from 70 to 95 percent, liptinite content ranging from 1 to 10 percent, and inertinite content ranging from 3 to 25 percent (Levine et al., 1989). The combination of abundant gas-prone vitrinite and low concentrations of oil-prone liptinite contribute to source-rock potential and preservation of a gas-permeable micropore system (Levine, 1993).

Natural gas in the Black Warrior coalbed methane fairway contains approximately 95 percent methane and 5 percent nitrogen (Rice, 1993; Scott, 1993), and total gas content is locally higher than 22 scm/t (standard cubic meters per metric ton) (Malone et al., 1987a; Levine et al., 1989). However, gas content ranges considerably as does reservoir pressure, and parts of the Black Warrior basin are naturally depleted of gas (Malone et al., 1987b). Isotopic evidence indicates that the gas is a mixture of thermogenic methane formed during coalification and late-stage biogenic gas that formed during regional unroofing as fresh-water began infiltrating the Pottsville Formation (Rice, 1993). Understanding the distribution of gas in the Pottsville has important implications for enhanced coalbed methane recovery and CO<sub>2</sub> sequestration in the absence of coalbed methane production. In the former case, the gas already in place represents a resource that can be recovered with unprecedented efficiency, whereas in the latter, what gas is present already occupies sorption sites and thus reduces sequestration capacity. In developed regions like the Black Warrior basin, determining the extent of depletion of the coalbed methane resource will determine the feasibility of enhanced coalbed methane recovery operations.

#### Technology and Infrastructure

Screening areas for the demonstration and commercialization of carbon sequestration technology requires not only analysis of geologic variables, but also requires careful analysis of available technology, emerging technology, and regional infrastructure (fig. 7). Development of path-breaking technologies for separation of CO<sub>2</sub> from flue gas is required for commercialization of carbon sequestration technology, and candidate separation technologies include membrane separators, pressure-swing adsorption, and cryogenics. In Ohio, researchers at Northwest Fuel Development, Incorporated, are using an abandoned underground coal mine as a filter to separate CO<sub>2</sub> from flue gas. The primary goal in the development and deployment of separation technology is that the delivered cost of CO<sub>2</sub> must be low enough for coalbed methane to remain competitive on the open gas market.

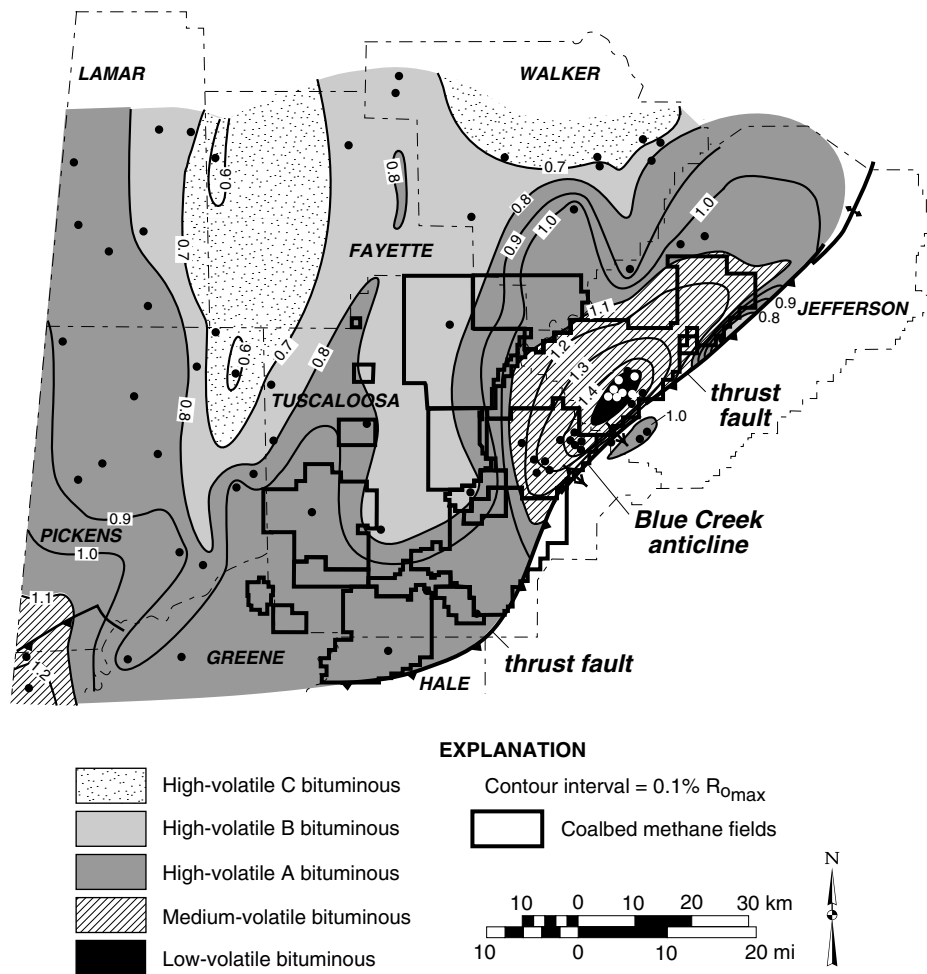


Figure 6.--Rank map of the Mary Lee coal zone in the Black Warrior basin of Alabama (after Winston, 1990a; Carroll et. al., 1995).

Enhanced coalbed methane recovery will employ a distinct set of technologies, and other technologies may be required for mass sequestration of CO<sub>2</sub> from coal-fired power plants. For example, enhanced coalbed methane recovery operations will undoubtedly make use of existing facilities by converting production wells for injection and will use time-tested technological approaches, such as organization of injection wells and production wells in five-spot patterns. Enhanced coalbed methane recovery is potentially the most efficient mode of sequestration because it can make use of the entry points to coal that are currently provided by more than 2,800 wells and because it involves the displacement and use of other gases that now occupy sorption sites. However, implementation of enhanced coalbed methane recovery throughout the fairway will take many years, and the volume of CO<sub>2</sub> demanded by enhanced coalbed methane recovery operations may be a small fraction of the 31 million tons of CO<sub>2</sub> emitted annually from coal-fired power plants in the Black Warrior basin. Therefore, independent approaches involving mass disposal of CO<sub>2</sub> into coal may be required to attain meaningful reductions in greenhouse gas emissions.

Drilling patterns in the coalbed methane fairway suggest that the effective drainage area of a coalbed methane well is no greater than 65 hectares, and it is doubtful that the injection radius of a single well would incorporate a much greater area with any efficiency. Accordingly, innovative technologies will need to be developed to maximize the rate and efficiency of sequestration. Among the many possibilities for attaining these goals are horizontal drilling in radial patterns



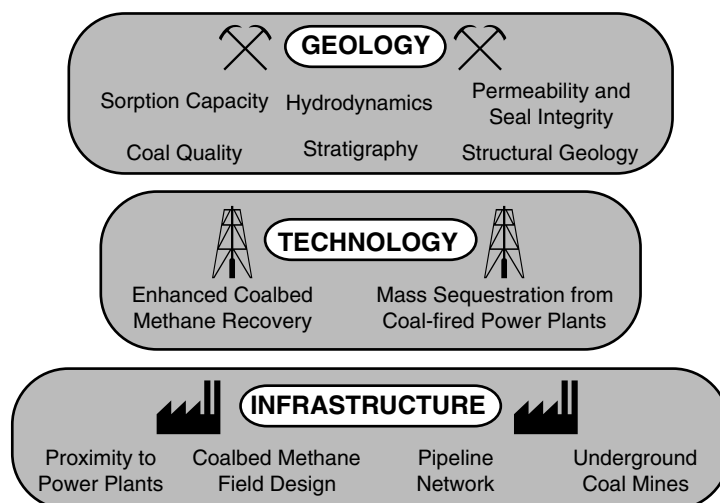


Figure 7.--Geologic, technologic, and infrastructural variables to be considered when developing a screening model for CO<sub>2</sub> sequestration in coal.

and in multiple coal beds. Although this approach is technically feasible, costs currently are prohibitive. Considering the rate of technological advance in drilling and geophysical logging, however, costs should fall substantially during the next 10 to 25 years.

Infrastructure influences how a screening model can be applied because it determines where specific technologies can be used at reasonable cost. Relevant infrastructure in the Black Warrior basin includes roads, power plants, a power grid, coalbed methane fields, pipeline network, and deep underground coal mines (fig. 8). Two power plants are just north of the coalbed methane production fairway, so demonstration of sequestration technology will probably take place in one of the northern coalbed methane fields, such as Oak Grove Field or White Oak Creek Field. Design of the coalbed methane fields is another factor to be considered. For example, wells drilled with an effective spacing of 65 hectares may be too far apart to implement enhanced coalbed methane recovery without drilling infill wells for CO<sub>2</sub> injectors, whereas a spacing of 32 or 16 hectares may be ideal for conversion of selected production wells to injectors. All of the coalbed methane fields have ready access to natural gas pipelines, and perhaps some pipeline segments in abandoned fields can be converted for transmission of CO<sub>2</sub>. Pipeline conversion is obviously not desirable in active fields, but existing pipeline paths may provide right of way where CO<sub>2</sub> pipelines can also be constructed.

Deep underground coal mines are operating in Oak Grove and Brookwood fields, and coalbed methane production was initiated in Alabama to increase mine safety (Elder and Deul, 1974; Lambert et al., 1980). Coal mines account for approximately 6.5 percent of global methane emissions (Boyer et al., 1990), and emissions from a single ventilation shaft in Brookwood Field exceed 71 million cubic meters per year (Clayton et al., 1994). Flooding of coal with CO<sub>2</sub> or CO<sub>2</sub>-nitrogen mixes can reduce methane-related hazards and may further reduce methane emissions from coal mines. This is important because methane is a much stronger greenhouse gas than CO<sub>2</sub>. Although injection of CO<sub>2</sub> in coal may reduce the risk of explosion, CO<sub>2</sub> in coal mines can pose a suffocation hazard, and reserve areas are inherently not prospective for long-term sequestration of greenhouse gases. Even so, the potential utility of abandoned mines as part of a flue gas separation system indicates that deep coal mines may play a central role in the application of carbon sequestration technology.

### **Preliminary Assessment of Sequestration Potential**

The U.S. Environmental Protection Agency estimates that 31 million tons of CO<sub>2</sub> were emitted in 1997 by the two coal-fired power plants adjacent to the Black Warrior coalbed methane fairway. Coalbed methane resources in the Black Warrior basin of Alabama are

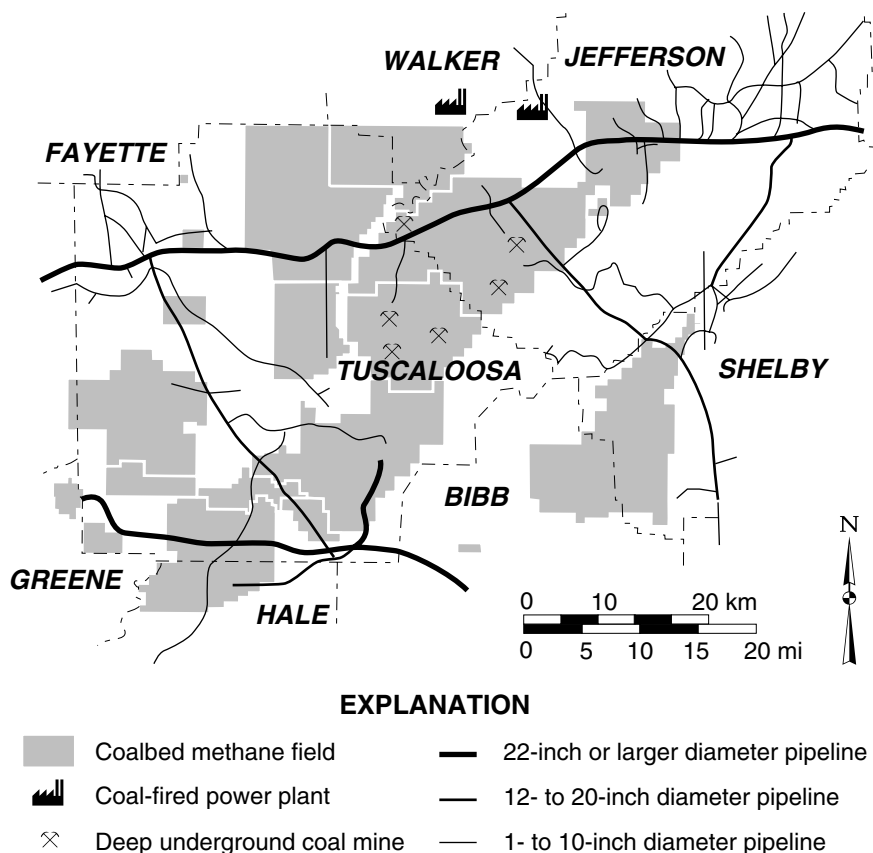


Figure 8.--Locations of coal-fired power plants, gas pipelines, and deep coal mines in the Black Warrior coalbed methane fairway (after Pashin and Hinkle, 1997).

estimated to be between 300 and 600 Bcm (Hewitt, 1984; McFall et al., 1986). Since coal can hold approximately twice as much CO<sub>2</sub> as methane, converting the methane to CO<sub>2</sub> yields a sequestration potential of 600 to 1,200 Bcm, or 1.1 to 2.2 billion metric tons (Bt). Most coal is undersaturated with gas, so the potential for sequestration is probably higher. Using 2.2 Bt as a baseline estimate, capacity exists to sequester all emissions from the basin for 72 years at current rates. Coal-fired power plants within a 100-km radius of the coalbed methane fairway emitted approximately 63 Bt of CO<sub>2</sub> in 1997, and this could be sequestered for 35 years at current emission rates.

Sequestration of CO<sub>2</sub> in the Black Warrior coalbed methane fairway shows exceptional promise for commercial application because (1) the coalbed methane industry represents a substantial market for CO<sub>2</sub> and (2) coal-fired power plants are the only nearby sources that produce CO<sub>2</sub> in enough quantity to facilitate enhanced coalbed methane recovery at a large scale. Costs of commercialization in terms of dollars per ton of carbon equivalent emission avoided are currently unknown, but commercialization is feasible if current pipeline prices are used as a delivery target. Pipeline CO<sub>2</sub> currently costs \$9 to \$12 per thousand cubic meters (Mcm), and coalbed methane prices in the Black Warrior basin are higher than \$100/Mcm. Considering that coal sorbs twice as much CO<sub>2</sub> as methane, these values add \$18 to \$24/Mcm to current lifting costs, which for most operators are \$35/Mcm. Stevens and others (1999) estimated that only 20 to 60 percent of the in-place coalbed methane resource is recovered by conventional methods, so increased efficiency through CO<sub>2</sub> injection may justify considerable investment, especially if CO<sub>2</sub> can be separated from flue gas and delivered to the wellhead at substantially lower cost. Based on experience with an enhanced coalbed methane recovery pilot in the western United

States, these workers further suggest that the target coal need not be fully saturated with CO<sub>2</sub> to mobilize methane.

According to Hobbs et al. (1997), Cedar Cove Field is projected to have a productive life span of approximately 30 years. Extrapolating this result to the other coalbed methane fields, abandonment of the fairway can be expected around 2030 if enhanced coalbed methane recovery is not implemented. Therefore, a brisk schedule of research and development is in progress for the Black Warrior coalbed methane fairway. Enhanced coalbed methane recovery programs may extend the productive life of all coalbed methane fields by as much as 40 percent. Moreover, implementation of a market-based solution like enhanced coalbed methane recovery can lay the groundwork and infrastructure required for more intensive greenhouse-gas sequestration efforts.

### **Summary and Conclusions**

Sequestration of CO<sub>2</sub> in coal is a promising market-based environmental solution that can reduce greenhouse gas emissions while increasing coalbed methane recovery. Experience from more than 20 years of commercial coalbed methane development in the Black Warrior basin provides a wealth of knowledge that can be used to quantify sequestration potential and develop a screening model that is broadly applicable to the coal basins of North America, Europe and Asia. The geologic factors determining the distribution and producibility of coalbed methane resources are essentially the same as those determining carbon sequestration potential and include stratigraphy, structure, hydrogeology, and sorption capacity.

Technology and infrastructure must also be considered when screening areas for the demonstration and implementation of carbon sequestration technology. Emerging technologies to be considered include CO<sub>2</sub> separators for flue gas and enhanced gas recovery technology. A vital goal of sequestration is to deliver CO<sub>2</sub> at low enough cost so that coalbed methane remains economically viable on the open market. Once enhanced coalbed methane recovery is established, the groundwork can be laid for more intensive carbon sequestration efforts independent of the natural gas industry. Carbon sequestration further has potential to improve safety in underground coal mines, and abandoned mines can play a role in the separation of CO<sub>2</sub> from flue gas.

Infrastructure plays a critical role in the ways that carbon sequestration programs can proceed. In a maturely developed basin like the Black Warrior, sequestration efforts will take advantage of the existing power generation, pipeline, and coalbed methane field facilities. Although a lack of infrastructure in many undeveloped basins may limit the applicability of carbon sequestration technology, a high degree of flexibility also exists. For example, flooding coal with CO<sub>2</sub> has potential for use as a primary production procedure that will eliminate concerns associated with water disposal and foster unprecedented recovery of the coalbed methane resource.

### **Acknowledgment**

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