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Coalbed methane potential in the Appalachian states of Pennsylvania,West Virginia, Maryland, Ohio, Virginia, Kentucky, and Tennessee--An overview

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Abstract

This report focuses on the coalbed methane (CBM) potential of the central Appalachian basin (Virginia, eastern Kentucky, southern West Virginia, and Tennessee) and the northern Appalachian basin (Pennsylvania, northern West Virginia, Maryland, and Ohio). As of April 1996, there were about 800 wells producing CBM in the central and northern Appalachian basin. For the Appalchian basin as a whole (including the Cahaba coal field, Alabama, and excluding the Black Warrior Basin, Alabama), the total CBM production for 1992, 1993, 1994, and 1995, is here estimated at 7.77, 21.51, 29.99, and 32 billion cubic feet (Bcf), respectively. These production data compare with 91.38, 104.70, 110.70, and 112.11 Bcf, respectively, for the same years for the Black Warrior Basin, which is the second largest CBM producing basin in the United States. For 1992-1995, 92-95% of central and northern Appalachian CBM production came from southwestern Virginia, which has by far the largest CBM production the Appalachian states, exclusive of Alabama. For 1994, the average daily production of CBM wells in Virginia was 119.6 Mcf/day, which is about two to four times the average daily production rates for many of the CBM wells in the northern Appalachian basin.

For 1992-1995, there is a clear increase in the percentage of CBM being produced in the central and northern Appalachian basin as compared with the Black Warrior Basin. In 1992, this percentage was 8% of the combined central and northern Appalachian and Black Warrior Basin CBM production as compared with 22% in 1995. These trends imply that the

Appalachian states, except for Alabama and Virginia, are in their infancy with respect to CBM production.

Total in-place CBM resources in the central and northern Appalachian basin have been variously estimated at 66-76 trillion cubic feet (Tcf), of which an estimated 14.55 Tcf (3.07 Tcf for central Appalachian basin and 11.48 Tcf for northern Appalachian basin) is technically recoverable according to Rice' s (1995) report. This compares with 20 Tcf in place and 2.30 Tcf as technically recoverable CBM for the Black Warrior Basin. These estimates should be considered preliminary because of unknown CBM potential in Ohio, Maryland, Tennessee, and eastern Kentucky. The largest potential for CBM development in the central Appalachian basin is in the Pocahontas coal beds, which have total gas values as much as 700 cf/ton, and in the New River coal beds. In the northern Appalachian basin, the greatest CBM potential is in the Middle Pennsylvanian Allegheny coal beds, which have total gas values as much as 252 cf/ton. Rice (1995) estimated a mean estimated ultimate recovery per well of 521 MMcfg for the central Appalachian basin and means of 121 and 216 MMcfg for the anticlinal and synclinal areas, respectively, of the northern Applachian basin.

There is potential for CBM development in the Valley coal fields and Richmond basin of Virginia, the bituminous region of southeastern Kentucky, eastern Ohio, northern Tennessee, and the Georges Creek coal field of western Maryland and adjacent parts of Pennsylvania. Moreover, the Anthracite region of eastern Pennsylvania, which has the second highest known total gas content for a single coal bed (687 cf/ton) in the central and northern Appalachian basin, should be considered to have a fair to good potential for CBM development where structure, bed continuity, and permeability are favorable.

CBM is mainly an undeveloped unconventional fossil-fuel resource in the central and northern Appalachian basin states, except in Virginia, and will probably contribute an increasing part of total Appalachian gas production into the next century as development in Pennsylvania, West Virginia, Ohio, and other Appalachian states continue. The central and northern Appalachian basins are frontier or emerging regions for CBM exploration and development, which will probably extend well into the next century. On the basis of CBM production trends in these two parts of the Appalachian basin, annual CBM production may exceed 70 Bcf by the turn of the century. This Appalachian CBM development will decrease the nation's dependence on high-sulfur coal and would supply a cleaner source of fossil fuel in the eastern United States where the energy demand is high. There will be some environmental impact resulting water disposal and extension of gas lines.

Introduction

Over the past decade in the United States, coalbed methane (CBM) has become an increasingly important unconventional source of fossil fuel, which also includes gas shales and tight gas sands. In 1994, unconventional natural gas accounted for 3,609 billion cubic feet (Bcf) and about 20 percent of U.S. gas production; of this total, tight gas sands contributed 2,492 Bcf (~14%), CBM 858 Bcf (~5%), and gas shales 259 Bcf (1%)

(Kuuskraa and Stevens, 1995). According to Rogers (1994), CBM accounts for a significant part of the gas reserves of the United States, which has been estimated by Rice (1995) as 6 percent..

For many years CBM was primarily an underground coal-mine safety problem and a large body of literature exists on this subject (e.g., see Finfinger, 1995). Over the last decade there has been a rapid acceleration of symposia, conferences, literature, and technological and scientific studies on CBM as an unconventional fossil fuel. In addition, a new periodical--Quarterly Review of Methane from Coals Seams Technology, which is produced by the Gas Research Institute--emerged about a decade ago. These activities have paralleled accelerated exploration and development of CBM in the United States. CBM exploration and development during this decade was stimulated by the federal Windfall Profit Act of 1980 (Nonconventional Fuels Tax Credit under Section 29) for wells drilled between December 31, 1979 and December 31, 1992. Coalbed methane (also called "coalbed gas" by Rice et al., 1993) represented in 1994 approximately 3% of natural gas production. The most significant CBM production occurs in the San Juan Basin, Colorado and New Mexico and Warrior Basin, Alabama, which collectively accounted for about 94% of CBM production in the United States in 1995 (Stevens et al., 1996). According to the latter authors, the Appalachian basin accounted for 4% of U.S. CBM production during 1995, and, according to these authors, accounts for an estimated 12% of the U.S. reserves of CBM. Thus, Appalachian CBM deserves special attention as a mainly undeveloped, clean-burning fossil fuel.

In addition, decreasing the venting of CBM to the atmosphere from coal mines by extracting it through wells may help to reduce global warming (Rogers, 1994). According to Clayton et al. (1995), methane is an important greenhouse gas and ventilation from underground coal mines is the largest source of atmospheric methane from coal. Kelafant and Boyer (1988) reported several coal mines in their study area in the central Appalachian basin venting 3 million cubic feet of gas per day, which is equivalent to 6 Bcf of CBM per year lost to the atmosphere. This loss to the atmosphere does not include natural degassing along hillsides with outcropping coal beds.

This paper is an overview of the potential of coal beds of the central Appalachian basin (Virginia, West Virginia, Kentucky, and Tennessee) and northern Appalachian basin (Pennsylvania, West Virginia, Ohio, and Maryland) for CBM exploration and development (see also Stevens et al., 1996). The Cahaba coal field of Alabama in the southern Appalachian basin also contains CBM at depths of about 2500-9000 ft (Rice, 1995; Pashin et al., 1995). The Cahaba coal field is usually considered with the Black Warrior Basin of Alabama, which has a similar section of Pottsville strata. Various aspects of Appalachian CBM are summarized in this paper including legal and economic constraints, CBM fields and stratigraphy, depth to coal beds and coalification, cleats, CBM composition and desorption data, production, and CBM potential of different areas of the central and northern Appalachian basin. Additional references on the subject appear in a selected bibliography of Appalachian coalbed methane by Lyons and Ryder (1995).

Legal, economic, and environmental constraints

Coal is both the source and reservoir of CBM. Thus, because methane could be considered in the terms “coal” and “gas”, legal conflicts have arisen among surface owners, owners of coal rights, and owners of oil and gas rights. Ownership of coalbed methane has been a source of legal contention in several states (see “Who owns the gas in coal?--A legal update”, Farrell, 1987).

In 1977, Virginia enacted a statue that all migratory gases are the property of the coal owner rather than that of the gas lessee or surface owner. In Pennsylvania, in U.S. Steel v. Hage, methane ownership was considered passed with the coal rights, but the landowner retained rights on the methane that migrated from the coal bed. As noted later in this paper, this migrated CBM may not be a small matter because most of the thermogenic methane generated in coal has probably migrated out of the coal and may be partly trapped in surrounding strata in tight sands or has escaped to the surface.

In 1991 with the passage of the Gas and Oil Act in Virginia, ownership rights and regulation has spurred development of CBM in Virginia (see Table 1). This act states: “When there are conflicting claims to the ownership of coalbed methane gas, the Board, upon application from any claimant, shall enter an order pooling all interests or estates in the coalbed methane gas drilling unit for the development and operation thereof.” In April 1995, about 650 wells in Virginia were producing CBM (Jack Nolde, Virginia Division of Mineral Resources, Department of

Natural Resources, personal commun., May, 1995). Similar laws in West Virginia and probably other Appalachian states are expected to be enacted in order to foster CBM exploration and development.

"The Energy Policy Act of 1992 requires the Interior Secretary to administer a federal program to regulate coalbed methane in states where ownership disputes have impeded development (Petroleum Research Institute, 1995, p. 11). These states in 1995 included Kentucky, Pennsylvania, and Tennessee; Ohio was recently removed from the list of affected states (Petroleum Information Corporation, 1995). In the northern Appalachian basin, gas ownership and environmental problems (mainly disposal of water) have hindered CBM development (Rice, 1995).

The economic parameters for CBM development are outlined in Kuuskraa and Boyer (1993). The economics of CBM recovery is discussed at length by Rogers (1994). According to Rogers (1994), the critical factors for CBM development of Appalachian coals are gas content, permeability, and reservoir pressure. Hunt and Steele (1991b) suggested that a minimum gas content of coals of 125-150 Mcf/ton was necessary for profitable development in the Appalachian and Warrior basins. In addition, permeability of at least 0.1-0.5 millidarcies (md) are necessary to be economically attractive, but hydraulic and other types of fracturing can greatly enhance the permeability, which is particularly true for the Pittsburgh coal bed (Rogers, 1994). An additional factor in CBM recovery is the cost of water disposal.

In the Appalachian basin, lower rock pressures and shallower depths of CBM recovery, as compared with the San Juan and Warrior basins, should help keep the drilling costs down. Also, a substitution of state-of-the-art technology for stimulation treatments (see Hunt, 1991) may also enhance future CBM production in the central and northern Appalachian basin. In addition, gas prices, existing pipeline infrastructure, and proximity of the Northeastern U.S. gas markets should favor continued development of CBM in the central and northern Appalachian basin (Hunt and Steele, 1991c). Also, it is likely the demand for gas in the Northeast will increase and cost-effective CBM recoverability technology could keep CBM competitive with conventional gas prices (Steele, 1990).

Attanasi and Rice (1995) predicted on the basis of economic analysis that CBM will continue to contribute to the future gas supply of the United States. For the Appalachian basin, they suggested costs (based on 1993 prices) of about $2-6 per thousand cubic ft (Mcf) for confirmed CBM resources and about $6-9 per Mcf for hypothetical resources. In 1994 in Virginia, the average price for CBM was $2.16 Mcf, as compared with $2.29 Mcf in 1993, a slight drop in prices (Jack Nolde, Virginia Division of Mineral Resources, personal commun., March, 1996). Flaim et al. (1987, p. 153) estimated that the cost of "Coalbed methane appears to be substantially less than exploration for conventional resources." Federal tax credits under Section 29 of the Windfall Profit Act of 1980 spurred exploration and development of CBM in the United States, particularly in the San Juan and Warrior basins (Rogers, 1994). On December 31 1992, when this tax credit end for new CBM wells drilled, major production of CBM was accomplished in the San Juan and Warrior basins, and 6,000 wells were producing CBM in the United States (Kuuskraa and Boyer, 1993). For 1981-1992, these tax credits for CBM increased with inflation from $0.25 to $0.95/Mcf. The tax credit program will continue until the end of 2002 for CBM wells drilled near the end of 1992 (Rogers, 1994).

In the central Appalachian basin, low well costs and attractive wellhead gas prices spurred development without tax supports after 1992 (Stevens et al., 1996). In the northern Appalachian basin, extremely low costs of CBM production historically have been due to shallow wells (less than 1000 ft) in an anticlinal structure (Patchen et al., 1991).

Water is an important economic and environmental factor in CBM projects. Water must be removed from the coal to lower the pressure for CBM desorption (Rogers, 1994). This is the bulk moisture that is in the cleat system of coal. In some cases, underground mining such as in the Pittsburgh coal bed, may have greatly reduced water saturation. Water disposal techniques may include well injection and discharge into surface streams. Injection wells, which require suitable formations for disposal, are the preferred method of disposal in the San Juan Basin and central Appalachian basin (Rice, 1995), whereas discharge into surface streams, after treatment in ponds to meet water-quality regulations, occurs in the Black Warrior basin (Rogers, 1994). Total dissolved solids in water in CBM wells from the central Appalachian basin have been reported at 30,000 ppm as compared with 3,000 ppm for the Black Warrior Basin (Rice, 1995).

Coalbed methane fields

Central Appalachian Basin

CBM production in the central Appalachian basin is virtually all from CBM fields of Virginia (Fig. 1), where it comes mainly from the Nora (Dickenson and Russell Counties) and Oakwood (Buchanan County) fields; four smaller CBM fields of more limited CBM production occur in Wise and Buchanan Counties (Nolde, 1995). The Nora field contains a relatively larger number of conventional gas wells (R.C. Milici, U.S. Geological Survey, written commun., 1996) The Valley coal fields and the Richmond and Taylorsville Basins of Virginia do not produce commercial CBM.

Northern Appalachian Basin

Historically, CBM from the Pittsburgh coal bed has been produced in commercial quantities since 1932 and 1956 from the Big Run and Pine Grove fields, respectively, of Wetzel County, West Virginia (Repine, 1990; Patchen et al., 1991). Wells in these historic fields have been shut in. There was also historic CBM production from the Freeport coal zone in Carroll County, Ohio.

As shown in Figure 2, there are six CBM fields in southwestern Pennsylvania and two in the northern West Virginia (West Virginia Geol. Survey and Pennsylvania Topographic and Geologic Survey, 1993; Bruner et al., 1995). These are the Oakford, Gump, New Freeport, Lagonda, Waynesburg and Blairville fields in Pennsylvania, and the Big Run and Pine Grove fields in West Virginia. The multipurpose borehole in Monongalia County, West Virginia, as shown in Figure 2, was used for horizontal degasification from the Pittsburgh coal bed from 1972 to1980.

Coalbed methane stratigraphy

The most important coal beds with CBM production and(or) potential for production in the central and northern Appalachian basin are shown in Figure 3. The coal stratigraphy of the Southwest Virginia coalfield, where most of the 1995 CBM production in the central Appalachian basin exists, can be found in Englund and Thomas (1990) and Nolde (1994). In northern West Virginia and southwestern Pennsylvania, the coal stratigraphy is summarized in Arkle et al. (1979), and the coal beds of importance for CBM exploration and development are given in Bruner et al. (1995). For Ohio, the coal-bed stratigraphy is summarized in Collins (1979). For Tennessee, the coal stratigraphy is summarized in Glenn (1925) and Wilson et al. (1956), and for Maryland in Swartz and Baker (1920) and Lyons and Jacobsen (1981).

Depths to coal beds and coalification

In most CBM studies, coal beds less than 500 ft and more than 6,000 ft below the surface are excluded in resource calculations (Kelafant and Boyer, 1988; Patchen et al., 1991; Rice, 1995), although there are rare cases of CBM production at shallower depths. In Virginia, the principal known CBM reservoirs are the Lower Pennsylvanian Pocahontas and Lee coal beds at depths of 500-3000 ft (Fig. 3; Stevens et al., 1996, p. 43). A summary of depths to individual CBM target beds in the central Appalachian basin is in Rogers (1994). In the Big Run and Pine Grove fields of northern West Virginia, CBM was being produced from the Pittsburgh coal bed at depths from 475 to 997 ft (Patchen et al., 1991). Target coal beds in three coal tests in Greene County by Equitrans Inc.(a subsidiary of Equitable Resources Exploration) were at depths of 2,100 to 2,350 ft (PRI, 1991).

The CBM fields in northern West Virginia and southwestern Pennsylvania are in areas where the cumulative coal thickness varies from 10 to 30+ ft (generally 10-19 ft) and where single coal beds of mainly high volatile B/A bituminous rank are as much as 12 ft thick. The Pittsburgh coal bed, which was the principal CBM producer in West Virginia in 1994, is a thick and laterally extensive Appalachian coal bed (Cross, 1952).

Stach et al. (1982, p. 242) distinguished four coalification jumps in bituminous and anthracitic coals. The first and second coalification jumps correspond to the start and end of oil generation--vitrinite reflectance of 0.6% and 1.3% Rm, respectively. The third and fourth coalification jumps, which correspond to the release of large amounts of methane and aromitization of vitrinite, are at 2.3% and 3.7% Rm (Stach et al., 1982) respectively. Important economic gas deposits first appear where the vitrinite refelectance is 1.0% Rm (high volatile A bituminous coal) and peak at about 2.0% Rm, which corresponds to semianthracite, according to

Stach et al. (1982, p. 45, 402-403). The gas 'death line' is unknown according to these authors. However, it is clear that much of the economic CBM is generated between the first and fourth coalification jumps, which correspond mainly to high volatile bituminous coal to semianthracite.

It is generally assumed that most of the thermogenic methane comes from liptinite macerals when they reach a maturation of high volatile A bituminous coal (e.g., see Rogers, 1994). Although liptinite macerals are certainly an important source of CBM, they cannot account for the comparatively larger amounts of CBM in low volatile bituminous coal and anthracite that must have produced substantial amounts of CBM from non-liptinite macerals, probably from the cleaving of aliphatic chains from vitrinite during aromitization. Rogers (1994) has shown that 80-95% of the CBM thermally generated in coals of low volatile bituminous and anthracitic ranks escaped when CBM exceeded the adorptive capacity of the micropores. This author suggested that CBM retention is about an order of magnitude less in Appalachian coals than methane generated at bituminous ranks and that as much as 30,000 cf/ton of CBM could be generated through the anthracite rank. If the gas content of coals in the Anthracite region of eastern Pennsylvania is at a maximum of 687 cf/ton (see section on desorption data), then these anthracites are retaining only a few percent of their original thermogenic CBM.

The target coal beds for CBM in the central Appalachian basin are dominantly low volatile bituminous coal and a smaller amount of medium volatile bituminous coal (Nolde, 1995). The shallower coal beds such as the War Creek, L. Seaboard, and Jawbone (Fig. 3) are mainly of low and medium volatile bituminous rank, but high volatile A bituminous rank is also known (Kelafant and Boyer, 1988).

In the bituminous coal fields of the northern Appalachian basin, the rank of the coal ranges from high volatile B bituminous coal to low volatile bituminous coal, generally increasing in rank in an eastward direction towards the Allegheny Front. Lyons (1988) has suggested that the rank of the coal in Maryland follows structure, the highest ranks following the axial trends. This may be an important consideration in CBM development just west of the Allegheny Front in Maryland and Pennsylvania.

In Virginia, the Valley coal fields contain low volatile bituminous coal and semianthracite (Merrimac and Langhorne coal beds, Price Formation, Lower Mississippian) (Englund et al., 1983; Simon and Englund, 1983). The total gas from these coals from two test wells averages about 220 cf/ton at depths from 1,110-1,462 ft; total coal thickness for the Merrimac and Langhorne coal bed intervals varied from 0.45-6.70 ft) (Stanley and Schultz, 1983). The Merrimac and Langhorne coal beds average 5 ft and 3 ft thick, respectively, where they have been historically mined (see data in Campbell et al., 1925). At the time of their report, these beds reportedly did not have any economic potential for CBM development . However, these gas data indicate that there is a CBM economic potential for these two coal beds if thick and continuous coal beds can be located in these coal fields.

Cleats in Appalachian coal beds

Natural fractures in coal (cleats) are the principal conduits for the transfer of methane from coal reservoirs (Diamond et al., 1988; Close, 1993; Law, 1993; Rice et al., 1993; Rogers, 1994). Face and butt cleats are the primary and secondary cleat systems in coal, respectively, and these are a function of regional structure, coal rank, coal lithotype, bed thickness, and other factors. Diamond et al. (1988) suggested that closer fracture spacing results in higher permeability of coal beds for CBM. Conversely, Law (1993) reported that the spacing of face and butt cleats are similar and, therefore, the well-known permeability anisotropy of these cleat systems is due to connectivity and not cleat spacing (see also Jones et al., 1984). The permeability of face and butt cleats in the San Juan basin are generally different (Young, 1992), averaging about 12-20 md and 4-5 md, respectively. The greater permeability of face cleats is supported by stimulation experiments using fluorescent paint (Diamond, 1987).

In the central and northern Appalachian basin, face and butt cleats are perpendicular and parallel, respectively, to fold axes (McCulloch et al., 1974). Kelafant and Boyer (1988) reported two dominant cleat trends in the central Appalachian basin--a northeast-southwest set and a north-south set (see also Colton et al, 1981). For the Pocahontas No. 3 coal bed in Buchanan County, Virginia, the face and butt cleats strike N 18° W and N67° E , respectively. In Wise County, Virginia, Law (1993) reported similar cleat spacings of 1.02-1.32 cm for face and butt cleats.

In the northern Appalachian basin, the face cleat of the Pittsburgh coal bed rotates from N 80° W in northwestern West Virginia to N 57° W in southwestern Pennsylvania, following a shift in the axial trend (McCulloch et al., 1974). This set of face cleats corresponds to the regional system of N70-80°W face cleats mapped by Kulander et al. (1980). Cleat spacings of 0.5-9.7 cm were reported by Law (1993) in the northern Appalachian basin. McCulloch et al.(1974) and Kulander et al. (1980) reported that horizontal drill holes perpendicular to the face cleats yielded much higher gas yields (up to ten times) as compared with drill holes perpendicular to butt cleats, thus suggesting that face cleats are the primary conduit for CBM. In the Anthracite region of eastern Pennsylvania, Law (1993) reported that cleat systems are poorly developed and mineral-filled, and this will undoubtedly be a major factor in preventing CBM development in that region.

CBM composition and desorption data

The composition of CBM has been generally treated by Rice (1993). These data come from sampling of underground mines, desorption tests of coals, and samples from active reservoirs. These gases are of both biogenic and thermogenic origin, the latter originating during coalification beginning at high volatile C bituminous coal and increasing into low volatile bituminous coal and anthracitic ranks. Methane is usually the major component, but carbon dioxide, ethane, and higher hydrocarbon gases are important components of some coals (Rice, 1993). There are reports of up to 10% CO_2 in the CBM of the Appalachian basin (Rice, 1995).

In Virginia, CBM contains an average of 96.6% methane and has a calorific value of about 990 Btu/cf (Nolde, 1995). Rice (1995) reported CBM composed of 97.0% methane, 2.5% ethane and heavier gases, and 0.5% CO_2 in this same state; he also reported as much as 2% CO_2. In Greene County, Pennsylvania, CBM contains 94% methane with a similar calorific value of 979 Btu/cf was reported from a CBM well (Markowski, 1993; WVGES and PTGS, 1993; Bruner et al., 1995); the remaining 6% consists of ethane, propane, butane, and pentane, carbon dioxide, and nitrogen.

As much as 98% of the CBM is adsorbed in the micropores of coal, which generally have diameters less than 40 angstroms (Rogers, 1994), rather than being in intergranular pores as in conventional gas reservoirs. Methane and ethane have molecular diameters of 4.1 and 5.5 angstroms, respectively (Rogers, 1994, p. 169). The micropores in high volatile A/B bituminous coal to anthracite are mainly less than 12 angstroms in diameter; the percentage of these less than 12 angstroms micropores increases with rank to 75% in anthracite (Gan et al., 1972).

The volume of gas contained in a core sample (i.e., total gas content) is the sum of three measured components--desorbed gas, residual gas, and lost gas (Rice et al., 1993). The desorbed gas is measured in a sealed canister over days, weeks, or months, and the residual gas is measured after the desorption tests by crushing the sample to a very small size and measuring the volume of evolved gas. The residual gas in some northern Appalachian coals may be relatively high and, in some cases, exceeds 50 percent of the total gas content (Hunt, 1991). Finally, the lost gas, which represents the amount of gas lost from the core sample before it was placed in the canister, is determined by linear extrapolation. Most of the water in the cleat system of coal must be removed before the CBM can be desorbed (Rogers, 1994).

The average amount of total gas by rank for bituminous and anthracitic coals ranges from about 39-430 cf/ton (Eddy et al., 1982). The highest average is for low volatile bituminous coal, and the lowest average is for high volatile C bituminous coals.

CBM samples have seldom yielded more than 600 cf/ton and estimates of the amount of methane generated during the coalification process exceeds 5,000 cf/ton through the rank of low volatile bituminous coal (Rightmire and Choate, 1986). This implies that the bulk amount of CBM has escaped or has been lost into the surrounding strata. Kelafant et al. (1988) reported the following desorption data for high volatile bituminous A coal beds of the northern Appalachian basin, which shows a general increase of CBM with depth:

135 cf/ton at 500 ft
196 cf/ton at 1,000 ft
231 cf/ton at 1,500 ft

At the same depths, the gas values are about twice as much for low volatile bituminous coal from the central Appalachian basin (see data in Kelafant and Boyer, 1988). This partly explains the greater productivity of CBM wells in the central Appalachian basin where the principal CBM producing coals are mainly of low volatile bituminous rank.

Central Appalachian Basin

The Pocahontas No. 3 coal bed was previously reported to be one of the gassiest coals in the United States (Irani et al., 1977). In 1985, The Pocahontas No. 3 mines of Virginia ranked in the top 15 for having the highest methane liberations in the United States (Grau, 1987). Methane emissions of 135-304 Mcf/day were reported from the Beckley Mine in Raleigh County, West Virginia (Adams et al., 1984). In 1985, the Beckley coal mines of West Virginia and a mine in the Jawbone coal bed of Virginia ranked in the top 25 for methane liberation among U.S. coal mines (Grau, 1987).

For desorption tests for 109 samples from 12 coal beds in the central Appalachian basin (Diamond and Levine, 1981), a range of 6-573 cf/ton was determined. In their study area in the central Appalachian basin, Kelafant and Boyer (1988) reported a minimum of 86 cf/ton The highest desorption values reported were for the Pocahontas No. 3 coal bed, which ranged from 285-573 cf/ton at depths of 778-2143 ft; Hunt and Steele (1991a) reported a high value of 660 cf/ton for this coal bed. In Virginia, the gas content of the target beds for CBM development range from 249 to 408 cf/ton (Nolde, 1995). The Sewell coal bed in Raleigh County, West Virginia, had total gas contents of 130-296 cf/ton at depths of 680-981 ft, as compared to considerably lower values of 6-143 cf/ton at depths of 684-1,037 ft and an average total gas content of 51 cf/ton for the L. Cedar

Grove coal bed (high volatile A bituminous coal) in Mingo County, West Virginia (Adams, 1984). Desorption tests for three coal samples from Clay County, Kentucky, indicated 25 and 45 cf/ton (after 3-4 months) from depths from 643 to 869 ft (Adams, 1984), which indicates poor potential for CBM development in that area. For the Jawbone coal bed (see Fig. 3), approximately 280 cf/ton was reported by Adams et al. (1984). The Pond Creek coal bed in Pike and Martin Counties in eastern Kentucky, at depths of 125-500 ft, showed very low total gas contents of 38 to 67 cf/ton). Such low gas contents would be expected at depths less than 500 ft unless there were enhanced structural conditions for CBM retention.

In Tennessee, there are very scanty data on gas contents of coal beds. (Diamond et al., 1986). In Morgan County, the total gas for three samples from the Sewanee coal bed (low volatile bituminous coal) at depths from 821-825 ft varied from 32 to 83 cf/ton. The sample set is very inadequate to be able to predict the CBM potential in Tennessee.

Northern Appalachian Basin

In 1985, The Lower Kittanning, Lower Freeport, Upper Freeport, and Pittsburgh coal beds of West Virginia and Pennsylvania were among the 10 highest methane liberating coal beds from coal mines in the United States(Grau, 1987). In general, desorption and total gas values for the northern Appalachian basin are lower than those for the central Appalachian basin. These data probably reflect higher ranks and greater depths for coal beds of the central Appalachian basin. According to Rice (1995), coals in the northern Appalachian basin have much longer desorption times (as much as 600 days); in contrast, CBM in southwestern Virginia in the central Appalachian basin desorbs in a few days probably due to lower hydrostatic pressure.

Hunt and Steele (1991a) postulated CBM values of 100-150 cf/ton for the Pittsburgh coal in the northern Appalachian basin. A low gas value of less than 50 cf/ton at a depth of 520 ft was reported for the Pittsburgh coal (WVGES and PTGS, 1993). An average gas content of 140 cf/ton for the Pittsburgh coal bed, as compared with 192 cf/ton and 252 cf/ton for the Freeport and Kittanning coal beds (Fig. 3), respectively, was reported (WVGES and PTGS, 1993; Bruner et al., 1995). These values reflect increased CBM with depth. Markowski (1993) reported 95-216 cf/ton for seven Monongahela samples in this part of the basin, which is in general agreement with previous reports. Adams et al. (1984) reported 100 cf/ton for the western part of the northern Appalachian basin and 150-200 cf/ton for the eastern part. In Ohio County in the panhandle of West Virginia, Hunt and Steele (1991a) reported 112 cf/ton for the Pittsburgh coal bed at 722 ft, which may have been affected by some CBM depletion from nearby coal mining; Hunt and Steele (1991c) reported a reservoir pressure of only 75 psi in this well, which is now shut in. In Greene County, Pennsylvania, three CBM coal tests were staked (Petroleum Information Corporation, 1991). Twenty-one coal core samples for desorption measurements were taken from six drill holes in Beaver, Lawrence, Somerset, and Washington Counties, Pennsylvania, but the results were not reported (Markowski, 1995). In Ohio, there are a limited amount of desorption data (Couchot et al., 1980; Diamond et al., 1986). For 23 core samples of the Brookville, Middle Kittanning, Lower and Upper Freeport, and Pittsburgh coal beds of

Belmont, Guernsey, Monroe, Noble, and Washington Counties, Ohio, the desorption values ranged from 11 to175 cf/ton) at depths as much as 786 ft. The highest value (175 cf/ton) was for the Upper Freeport was from a depth of 667 ft. Diamond et al. (1986) reported similar low desorption values ranging from 9.5 to 95.4 cf/ton for the Upper Freeport and Kittanning coal beds of Harrison County, Ohio.

There is a lack of information on methane emissions from Maryland coal mines. However, Maryland coal beds are not known to be gassy (R.H. Grau and W.P. Diamond, Bruceton Research Center, Department of Energy, Pittsburgh, personal commun., March, 1996). This information is consistent with mine-safety information from bottled gas samples taken quarterly at fans in the Mittiki A, B, C, and D mines (all mining Upper Freeport coal bed) in the southern part of the Upper Potomac coal field, the largest mines in Maryland; the Mittiki mines show generally low CBM emissions (less than 100,000 cf/day, March 1, 1996; Barry Ryan, Mine Safety and Health (Department of Labor), mining inspector, Oakland, Maryland, personal commun., March,1996). However, from the Mittiki C Mine (circa 1989) there were a few quarters that year when the C mine, which is now sealed, in the southernmost part of the Upper Potomac coal field had high emissions in the range of 250,000-300,000 cf/day and was put on a 15-day spot check (Barry Ryan, personal commun., March, 1996). Another deep mine in Garrett County near Steyer and owned by the Patriot Mining Company (Permit DM-90-109), which mines the Bakerstown coal bed (Fig. 3), also has low methane emissions (Barry Ryan, personal commun., March, 1996). These data do not represent mined coal beds with the greatest amount of overburden, so they are probably misleading with respect to the CBM potential of deeply buried beds in the Maryland coal fields.

In the Anthracite region of eastern Pennsylvania there are limited known gas-content data (Diamond and Levine, 1981; Diamond et al., 1986). However, the data available from these two sources suggest very high amounts of CBM in some parts of the Anthracite region. For the Peach Mountain coal bed (Llewellyn Formation) in Schuylkill County in the Southern Anthracite field, at a depth of 685 ft, the total gas content was measured at 598 to 687 cf/ton, the second highest total gas content known to me for Appalachian basin coal beds. For the Tunnel coal bed at depths of 604-608 ft in Schuylkill County, the total gas content of three samples ranged from 445 to 582 cf/ton. These gas contents can be contrasted with very low total gas contents of 6 to 29 cf/ton for the Orchard coal bed and 13 cf/ton for the Mammoth coal bed in Schuylkill County (Diamond et al., 1985). Similar low total gas contents of 16 to 70 cf/ton were reported for the New County coal bed in Lackawanna County (Diamond et al., 1986) in the Northern Anthracite field These extreme differences in total gas contents may represent structural and permeability problems due to the absence of cleats or mineral-filled cleats (Law, 1993) and other local factors. These will be an important consideration that may prevent development in some areas. Nevertheless, the very high total gas contents of some coal beds in the Anthracite region indicate that CBM exploration should be carried out in this region.

Appalachian CBM production data

CBM production from coal reservoirs is affected by gas content, sorption rate, saturation, pressure, permeability, and other factors. Hunt and Steele (1991b) suggested the following hypothetical minimum values for economic development from multiple seams in CBM reservoirs:

1. Gas content 125-150 cf/ton
2. Permeability 0.1-0.5 md
3. Pressure 125-175 psi

The gas contents of coal beds in the central and northern Appalachian basin, as given in the section on desorption data, range from 6-660 cf/ton. In general, the central Appalachian basin has higher values (as much as 660 cf/ton), as compared with as much as 252 cf/ton for the bituminous coals in the northern Appalachian basin. Hunt and Steele (1991b) noted that the Pocahontas No. 3 coal bed has a high average permeability (5 to 27 md), which is probably related to its high CBM productivity. According to these authors, coal beds in both parts of the Appalachian basin are underpressured probably due to geological history, extensive coal mining, and many nearby conventional oil and gas wells. Kelafant and Boyer (1988) reported a minimum reservoir pressure of 215 psi in their study area in the central Appalachian basin.

In 1995, CBM production in the United States was 973 Bcf, of which the central and northern Appalachian basin accounted for an estimated 32 Bcf (see Table 1). CBM production data for the central and northern Appalachian basin are summarized by state in Table l; the data for the

Black Warrior basin and the Cahaba coal field (Alabama) in the southern Appalachian basin are shown for comparison.

Central Appalachian Basin

Historic production (1970-1988) for this part of the Appalachian basin is summarized in Hunt and Steele (1991b). The early wells were producing from the Pocahontas No. 3 coal bed, Beckley, and Jawbone coal beds. In 1992, about 272 new Virginia CBM wells were permitted and completed (Fig. 4; Jack Nolde, Virginia Division of Mineral Resources, personal commun., 1995) through casing perforations and fractures stimulation with sand, water, and nitrogen foam; production from invididual wells at depths to 2,680 ft was as much as 356 Mcf/day.

In 1994 in Virginia, 649 wells (see Fig. 4) produced about 28.33 Bcf of CBM (Fig. 5; Jack Nolde,Virginia Division of Mineral Resources, personal commun., 1995; see Fig. 1 and Table 1). This is an average of 119.6 Mcf/d (thousand cubic feet/day) for CBM wells in Virginia, which is about two to four times the average daily production rate for CBM wells in the northern Appalachian basin. In April 1996, there were 708 producing CBM wells in Virginia (Jack Nolde, Virginia Division of Mineral Resources, personal commun., April, 1996). The principal producers in Virginia are Equitable Resources Exploration (EREX), Pocahontas Gas Partnership, OXY USA, Consol, Inc., and Island Creek Coal Company. In Virginia, CBM has been produced in commercial quantities in the Southwest Virginia coalfield since 1988 (Nolde, 1995).

In southern West Virginia, there is no record of CBM production in 1992, 1993, and 1994 (K.L. Avary, West Virginia Geological and Economic Survey, personal commun., April, 1996). However, in southern West Virginia, 17 CBM wells were permitted in 1995 (K.L. Avery, West Virginia Geological and Economic Survey, personal commun., April, 1996). These include 15 wells in the Welch field--2 in McDowell County and 13 in Wyoming County-- and 2 wells in Raleigh County in the Slab Fork field (Fig. 1). The Raleigh and Wyoming Counties wells reportedly produce from the Pocahontas No. 3 and 4 coal beds at depths of 655 to 1,650 ft. Production data for these wells were not available in April, 1996. It is interesting to note in Cardwell and Avary (1982, p. A-43) a record of an inactive gas well in the Welch field, Browns Creek District, in McDowell County that was producing from an 80-ft-thick Pocahontas sandstone.

CBM information in Kentucky comes from B.C. Nuttall (Kentucky Geological Survey, personal commun., April, 1996). Three wells were completed in coals in Harlan County in 1957, and one of these remained as a domestic gas supply until 1980 or later. There was no public record of any CBM production in southeastern Kentucky for the period 1992-1994 . In Letcher County, Equitable Resources Exploration completed in 1990 a CBM test well (KF1300 Fee well), but production data for this well were not available at the time of this report. Also there is a report of another company that has drilled CBM test wells in eastern Kentucky, but further details were not available.

A large part of the CBM production in the central Appalachian basin comes from Consol and Equitable Resources with a combined production of 12 to 16 Bcf annually (Ayers, 1996). Consol's Oakwood field in Buchanan County, Virginia, is the largest field and had 209 fractured wells in 1995 (Stevens et al., 1996). Cumulative CBM production in southwestern Virginia for the period 1988 through 1994 was 97,844,896 Mcf (Jack Nolde,Virginia Division of Mineral Resources, personal commun., April, 1996). The 85 early CBM wells operating in Virginia in 1991 and early 1992 had an average production of 100 Mcf/d (Quarterly Report of Methane from Coal Seams Technology, 1992).

In 1995, Virginia had the following CBM production by county:

County	Annual Production (Mcf)
Buchanan County:	24,300,209
Dickenson County	5,227,176
Russell County	569,549
Wise County	258,936
Total:	30,355,870

The Virginia production statistics for 1995 (Fig. 5, Table 1) indicate that CBM production is 61% of the state's gas production (Jack Nolde, Virginia Department of Mines, Minerals and Energy, written commun., June, 1996). In 1995, Buchanan County accounted for 80% of the production in Virginia and for most of the CBM production in the northern and central Appalachian basin. For 1994 there were 52 new CBM gas wells in Virginia, which averaged 2,240 ft in depth and cost $79.06/ft to drill and complete (Oil and Gas Journal, March 11, 1996).

There is scarcely any record of CBM production in southeastern West Virginia for the period 1992-1994 (K.L. Avary, West Virginia Geological and Economic Survey, personal commun., April, 1996). One well (Permit 912) produced 2,592 and 5,308 Mcf in 1992 and 1994, respectively. However, 12 new CBM wells were permitted in this area in 1995. These wells, except for one in the Beckley (War Creek in Virginia) coal bed (Fig. 3), will be producing from the Pocahontas No. 3 (9 wells) and from both the No. 3 and No. 4 coal beds (2 wells). For 1996 (as of May 24), four new CBM wells were permitted (3 in Wyoming County and 1 in McDowell County), all to be drilled by U.S. Steel Mining (K.L. Avary, West Virginia Geological and Economic Survey, written commun., June, 1996). These four wells are expected to be producing from the Pocahontas No. 3, 4, and 6 coal beds.

Northern Appalachian Basin

CBM production from eight historic projects (1932-1980), from the Pittsburgh and Clarion/Kittanning coal beds, and from mutiple coal beds in the northern Appalachian basin, is summarized in Hunt and Steele (1991b). The Pine Grove and Big Run fields in northern West Virginia were producing CBM from shallow depths along the axes of anticlines in the Pittsburgh-Huntington Synclinorium (Dunkard Basin) along what has been called “structurally high and dry” features (Patchen et al., 1991). The cumulative unstimulated gas production (1932 to1982) from about 52 wells in the Big Run field (Wetzel County, West Virginia; Fig. 2), mainly from the Pittsburgh coal bed 2-10 ft thick, was about 2.0 Bcf. The production rates ranged from 8-121 Mcf/d with a mean of about 38.5 Mcf/d (Hunt and

Steele, 1991a; Patchen et al., 1991; Rogers, 1994). The Pittsburgh wells in the Big Run field have now been abandoned.

In 1994, CBM production in northern West Virginia was from 8 wells in three different fields in Monongalia County (K.L. Avary, West Virginia Geological and Economic Survey, personal commun. April, 1996). All of these wells are producing from the Pittsburgh coal bed. Total production from the 8 wells in 1994 was 97,372 Mcf (average about 33.4 Mcf/d)(see Table 1). In the Pine Grove field, 16 wells have had production from 8-60 (average 28) Mcf/d from Pittsburgh coal 1 to 7 ft thick. For these fields, the total CBM production, all from the Pittsburgh coal bed, for 1992, 1993, and 1994 are 198,428; 223,554; and 97,372 Mcf, respectively (K.L. Avary, West Virginia Geological and Economic Survey, personal commun., April, 1996). In northern West Virginia, there is a record of production from seven CBM wells, all producing from the Pittsburgh coal bed, for the period 1992-1994 (K.L. Avary, West Virginia Geological and Economic Survey, personal commun., April, 1996). In 1995 in northern West Virginia, 8 new coalbed methane ventilation wells in Monongalia County (CNG Development, operator) were permitted for Pittsburgh coal bed at depths of 750 to 1,090 ft (K.L. Avary, personal commun., April, 1996). Production data for these 8 wells are not available at the time of this report; however, it is estimated here that they are producing at an average of about 40 Mcf/day. According to Rod Biggs (CNG Producing, personal commun., May, 1996), initial production on all these CNG ventilation wells was about 100$^{\pm}$ Mcf/d declining to 20 or less Mcf/day. There is an unknown amount of CBM coming from overlying coal beds, including the the Redstone, Sewickley, and Waynesburg coal beds. For 1996 (as of May 24), three new CBM wells in Monongalia County, which are planned by CNG Producing, have been permitted (K.L. Avary, June, 1996).

In Pennsylvania, CBM production data are summarized in Bruner et al., (1995). Three tests wells were staked in Greene County (PRI, 1991). A total of 22 new wells are expected to be drilled in 1996 by BTI Energy, Canton Oil & Gas Company, Belden and Blake, Equitable Resources, LAHD Energy, and the M.L. Minter Family (Toni Markowski, personal commun., 1996). CBM production is known from the Pittsburgh coal bed in the Gump and Waynesburg fields and from the Lower Freeport, Kittanning, Mercer, Quakertown, and Sharon coal beds (Fig. 3) in the Oakford field (WVGES and PTGS, 1993; Bruner et al., 1995). Also, gob gas (gas from underground mine waste) from the Pittsburgh coal bed is being produced in Pennsylvania and West Virginia through converted pre-mine ventilation wells (Bruner et al., 1995). The Sewickley and Waynesburg coal beds (Fig. 3) also have been reported to be CBM producers (Bruner et al., 1995). Permit numbers 30614, 30615, 30618, 30620, and 30622 in Blairsville, Indiana County, completed by O'Brien Methane Production in the Blairsville field (Fig. 2) in 1992 and 1994, have commingled gas production from Allegheny Formation coal beds (± Mahoning coal bed) (Petroleum Information Appalachian Basin Report, Section II, May 18, 1995 and August 10, 1995): Clarion (888-891 ft, fractured), L. Kittannning (802-805 ft), and U. Freeport (598-603 ft, fractured). The Mahoning coal bed in this well (546-549 ft) is not a CBM producer. In Fayette County, two CBM wells are producing CBM from the Kittanning coal zone at depths from 800 to 1,200 ft and 30 new wells are planned (Bruner et al., 1995). In Greene County, there are six CBM wells producing from the Kittanning, Freeport, Pittsburgh, and Waynesburg coal beds at depths from 750 to 1,865 ft and also two other wells producing from the Clarion and Kittanning interval and Clarion-Pittsburgh interval. One test well in Greene County penetrated a total of 28 ft of coal (Hunt, 1991). The Pottsville coal beds (Fig. 3), which are known to have CBM production in Westmoreland County (Bruner et al., 1995), have limited CBM potential because of their thinness and lack of continuity. The Brush Creek and Bakerstown coal beds in the lower part of the Conemaugh Formation (Fig. 3) may also have limited CBM production potential in local areas where they are thick and underlie a thick sedimentary cover.

In Ohio, there is no public record of CBM production for 1992-1995 (Ron Rea, Ohio Department of Natural Resources, personal commun. April, 1996). In Guernsey County, there were some old wells (pre-regulation days) that produced CBM. In November 1995, two CBM wells (permits nos. 936 and 937, Land Energy Inc.) were permitted in Harrison County (Cadiz quadrangle, Section 23, 1.1 mi WNW of Unionvale) and, once drilled in 1996, they will produce from the Freeport coal zone.

In Maryland and Tennessee, there is no CBM production at the present time (April, 1996).

The CBM production in Pennsylvania is mostly from Indiana County, in southwestern Pennsylvania. Twenty CBM wells (average production of 40 Mcf/day) producing from Allegheny coals (Brookville, Clarion, Kittanning, Lower Freeport and Upper Freeport) were in production in 1995 and 1996, and eight more new CBM wells were planned in 1996 (Jim Mills, Belden and Blake, personal commun., April, 1996).

The annual CBM production for the Appalachian basin is shown in Figure 6. For 1994, the estimated total of 29.5 Bcf of CBM, which is about 1 percent of the 2,492 Bcf for Appalachian tight gas sands production (Kuuskraa et al., 1996) A comparison of CBM production between and Appalachian basin and with the Black Warrior basin is shown in Figure 7.

Potential for undiscovered CBM

The CBM potential of coal beds for undiscovered CBM is related to thickness, rank, permeability, depth below the surface, and other factors. Within the Black Warrior and Appalachian basins, the gas content of coals increases with depth for coals of the same rank and also increases from high volatile A and B to low volatile bituminous coal. However, the CBM content of low volatile bituminous coals from various basins shows great differences in gas contents (McFall et al., 1986; Kelafant and Boyer, 1988), which suggests factors other than just rank are involved in CBM potential..

<u>Central Appalachian Basin</u>

Curiously, the central Appalachian basin--in contrast with the Black Warrior, northern Appalachian, San Juan, and Piceance basins--has the highest CBM content at depths between 1,500 and 3,000 ft (Kuuskraa and Boyer, 1993). This may be related to the greater permeability of central Appalachian basin coal beds due to structural or other regional factors.

A substantial part of Appalachian CBM technically recoverable CBM resources are in the central part of the Appalachian basin (Gautier et al., 1995; Rice, 1995; Attanasi and Rice, 1995). These resources using present-day technology were estimated at 14.84 Tcf (trillion cubic feet), including 4.43 Tcf confirmed and 10.41 Tcf hypothetical resources.

In the central Appalachian basin, six target seams of medium and low volatile bituminous rank are targeted for CBM production (Kelafant and Boyer, 1988). In stratigraphic order (see Fig. 3), with corresponding estimated gas in place (>500 ft depth, >1 ft coal), these are:

Coal bed (Wv./Va. names)		Gas in place (Tcf)
Iaeger/Jawbone		0.4
Sewell/Lower Seaboard		0.2
Beckley/War Creek		1.0
Fire Creek/ L. Horsepen		0.7
Pocahontas No. 4		1.1
Pocahontas No. 3		1.6
	Total	**5.0 Tcf**

Rice (1995) determined a mean estimated ultimate recovery per well of 521 MMcfg and 3.068 Tcf of technically recoverable CBM in the central Appalachian basin, which is at odds with the in-place CBM resources of 5.0

Tcf (Kelafant and Boyer, 1988), which should be a much higher value is Rice's (1995) estimate is reasonable. Earlier DOE estimates, as referred to in Kelafant and Boyer (1988), indicate 10-48 Tcf of CBM in place in the central Appalachian basin, and Rice's (1995) estimate of 3.068 Tcf is more compatible with the earlier estimates.

Kelafant and Boyer (1988) estimated an additional 0.6 Tcf in minor CBM coal beds in the Pocahontas and New River Formations. The great potential for CBM development in Virginia is shown by the growth in annual production (Fig. 5) which in 1994 is 28,331,817 Mcf, corresponding to a value of about $62,747,013 at $2.15/Mcf (Jack Nolde, Virginia Division of Mineral Resources, personal commun., April, 1996).

In the Valley Coal fields of southwestern Virginia (Fig. 8) in the Valley and Ridge Province, there is probably some CBM potential for recoverable CBM (Nolde, 1995; see also Stanley and Schultz, 1983). The chemical analysis of 20 samples from test drilling in 1982-83 (Englund et al., 1983) indicates the rank varies from medium volatile bituminous coal to semianthracite (Simon and Englund, 1983). These are among the optimum ranks for thermogenic generation of CBM (Das et al., 1991).

Nolde (1995) has estimated at least 0.3 Tcf of in-place CBM in the Richmond basin of Virginia (Fig. 8). This work was done by Virginia Polytechnic Institute. This Triassic basin is virtually unexplored as a basin for CBM development.

In southeastern West Virginia, there is a substantial potential for CBM development. The average gas content for deep coal beds in Wyoming and Rayleigh Counties, West Virginia (Kelafant and Boyer, 1988) is 385 and 322 cf/ton, respectively. There were no CBM gas-content data reported for nearby McDowell County (Diamond et al., 1986). These data suggest a CBM potential for these three counties similar to that in Buchanan and Dickenson Counties, Virginia, which have average gas contents of 514 and 200 cf/ton, respectively (Diamond et al., 1986; Kelafant and Boyer, 1988). These two Virginia counties have most of the current CBM production in the central Appalachian basin. Webster County to the north in central West Virginia has little or no potential for CBM development judging from the average gas content of 22 cf/ton (Kelafant and Boyer, 1988).

There is an unknown CBM potential in southeastern Kentucky. There is little published information on the CBM potential of that area of Kentucky (B.C. Nuttall, Kentucky Geological Survey, personal commun., April, 1996). However, judging from the average gas contents of 52-90 cf/ton (Kelafant and Boyer, 1988), the potential of this area for undiscovered recoverable CBM is limited.

In the Cumberland Plateau of Tennessee, there is an unknown potential for undiscovered recoverable CBM. Coal beds are up to 14 ft thick and occur at maximum depths from about 600 to 1,900 ft below the surface (Wilson et al., 1956; Luther, 1960). Some of the thicker coal beds are the Big Mary, Windrock, Joyner, Poplar Creek, Wilder, and Sewanee coal beds. The thicker beds generally average 3.5 to 4.5 ft thick, except for the Big Mary coal bed that averages 6 to 8 ft thick (Glenn, 1925). Chemical data in Glenn (1925) indicate that most of the coals are of high volatile B and A bituminous ranks. There is little known about the gas content of these coals. The Sewanee coal bed has a total gas content ranging from 32 to 83 cf/ton)at depths of 821-825 ft (Diamond et al., 1986), which are low gas contents. However, more gas tests need to be made in beds at greater depths in order to determine the CBM potential of these coal beds.

Northern Appalachian Basin

In the northern Appalachian basin, the in place CBM resources have been estimated by Adams et al., (1984). These are shown in stratigraphic order (see Fig. 3):

Coal bed or group (gp.)	Area (sq. mi)	Gas in place (Tcf)
Waynesburg coal bed	7,000	2.0
Redstone-Sewickley gp.	8,000	1.6
Pittsburgh coal bed	12,600	7.1
Freeport gp.	22,800	11.7
Kittanning gp.	28,000	30.5
Brookville-Clarion gp.	30,300	8.4
	Total	**61.3 Tcf**

Rice (1995) accepted this estimate of in-place CBM resources for his national assessment and reported 11.48 Tcf (10.41 Tcf for syncline play and 1.07 Tcf for anticline play) as technically recoverable gas. He used a mean estimated ultimate recovery per well of 121 and 216 MMcfg for the anticline and syncline plays, respectively. More work is necessary to refine these estimates. The greater CBM potential of the lower coal beds in the northern Appalachian basin is due to their higher rank and greater total gas content (Kelafant and Boyer, 1988; Hunt and Steele, 1991a; Markowski, 1993; Bruner et al., 1995).

The CBM potential of the Anthracite region of eastern Pennsylvania (Fig. 8) has not been determined. Two core holes were drilled in the mid-1970s (J. R. Levine, Consulting geologist, Tuscaloosa, Alabama, personal commun., April, 1996) and desorption data were reported in Diamond and Levine (1981) and Diamond et al. (1986). High gas contents were measured for the Peach Mountain coal bed in Schuylkill County at 685 ft. There are also some data in Diamond et al. (1986) showing considerably lower CBM contents in the same county. These data suggest a possibility for CBM development in some parts of this region where permeability and structural factors are not a problem.

A potential for recoverable CBM may exist in the coal fields of western Maryland and adjacent parts of Pennsylvania. The most promising areas in Maryland are the Georges Creek (Fig. 8) and Upper Potomac (northern part) coal fields where the rank is highest and the total coal and overburden is greatest (Swartz and Baker, 1920; Lyons and Jacobsen, 1981). In these fields, the rank varies from medium volatile to low volatile bituminous coal. The most promising targets are Allegheny coals--Mount Savage, Kittanning and Freeport coals--which occur up to about 1500 ft below the surface along the axis of the synclines. These coals are commonly 2-5 ft thick in these fields; the Upper Freeport is as much as 11 ft thick in the southern part of the Upper Potomac coal field. The

Pottsville coals (Sharon, Quakertown, and Mercer; see Fig. 3) are thin (usually about 1-2 ft thick) and discontinuous, and, in spite of their greater depth, probably would not be good targets for CBM development in Maryland, except as part of mutiple-bed CBM production.

Ohio has a fair potential for CBM development from Allegheny coal beds underneath Monongahela and Dunkard strata (see Couchot et al., 1980, fig. 3) immediately west of the Ohio River. Data on deep coal resources of Ohio are in Struble et al. (1971), Collins and Smith (1977), and Couchot et al., (1980). In eastern Ohio, the counties with the greatest CBM potential are Belmont, Monroe, Washington, and Meigs Counties where there is the thickest and most areally extensive cover of Dunkard and Monongahela strata (see Couchot et al.,1980, fig. 3) above Allegheny coal beds at depths greater than 500 ft. The most promising coal beds for CBM recovery are the Bedford (in Upper Mercer coal zone) and Allegheny coals--Brookville, Lower and Upper Kittanning, and Lower and Upper Freeport--which collectively are as much as 18 ft thick or more in certain areas. These coals beds lie as much as 1,500 feet below the surface and are of high volatile A/B bituminous rank (Berryhill, 1963). There is a very limited CBM potential for the Meigs Creek coal bed (=Sewickley coal bed; Berryhill, 1963) and Pittsburgh coal bed in local areas where there is a thick Dunkard cover and where these coal beds are thickest, such as in Belmont and Washington Counties (Berryhill, 1963; Collins and Smith,1977; Couchot et al., 1980). In these counties these two beds occur in mineable thicknesses as much as 5.7 and 9.6 feet thick, respectively.

Conclusions

The central and northern Appalachian basin began significant CBM production in 1992 and, therefore, unlike the Black Warrior coal field, is probably in its infancy with respect to CBM production. Figure 7 shows for 1994 and 1995 the increasing share of CBM production in the central and northern Appalachian as compared with the Black Warrior Basin of Alabama,the second largest producing CBM basin in the United States (Rice, 1995).

The greatest CBM potential in the central and northern Appalachian basin is in West Virginia, Pennsylvania, and Virginia (including the Valley coal fields). There is too little CBM information in eastern Ohio, eastern Kentucky, and northern Tennessee to rank the CBM potential of these states with respect to each other. Maryland has no CBM information available, so its CBM potential needs to be determined; the Georges Creek coal field of Maryland holds the greatest CBM potential for Maryland coal fields because of its low volatile bituminous rank; thick coals, some up to 22 ft thick; and greatest overburden, as much as about 2,000 ft. locally.

About 95% of the 1994 CBM production in the central and northern Appalachian basin came from Virginia, where it is a growing multi-million dollar business. In view of this fact and 1994 and 1995 CBM production trends in Pennsylvania and West Virginia--the states with the greatest potential for CBM development--this implies that the central and northern Appalachian basin are frontier areas for CBM exploration and development. Current trends in these parts of the Appalachian basin indicate that CBM production could be over 70 Bcf annually by the turn of the century, which represents less than 1% of the estimated recoverable CBM resources in the central and northern Appalachian basin (Rice, 1995). CBM production in the Appalachian basin has become increasingly important because Appalachian tight gas sands production--the mainstay of Appalachian gas production--leveled off in 1993 and 1994 at 396 Bcf (Kuuskraa et al., 1996). Legal matters of CBM ownership and environmental problems such as water disposal will be important issues to resolve in the various states. Also, the abatement of the escape of methane, a well-known greenhouse gas, from coal beds and coal mines due to CBM production will have a beneficial affect on coal-mine safety and may also have a favorable influence on global warming. CBM development in the Appalachian states could reduce our dependence on high-sulfur coal and will provide a clean source of fossil fuel.

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(Advanced Resources International, Arlington, Virginia) provided some data on CBM production in Pennsylvania. A.K. Markowski of the Pennsylvania Geological Survey ably supplied CBM coal production information for Pennsylvania, which was used to estimate annual production in that state. B.C. Nuttall (Kentucky Geological Survey) provided information on CBM in Kentucky. K.L. Avary (West Virginia Geological and Economic Survey) supplied CBM production data for West Virginia. Rod Biggs (CNG Producing, New Orleans) supplied production data on the ventilation wells in Monongalia County, West Virginia. Jim Mills of Belden and Blake provided some general daily production data for CBM wells in Pennsylvania. Dave Uhrin of Coalbed Methane Consulting of Pittsburgh provided leads and general information on CBM in Pennsylvania.

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Table 1. Coalbed methane production (Mcf) by state, northern and central Appalachian basin, Cahaba coal field, and Black Warrior basin

State	1992	1993	1994	1995
	Northern and Central Appalachian Basin			
WV	198,428	223,554	97,372	n.a.[1]
VA	6,641,852	19,923,453	28,331,817	30,355,870
PA	350,000[2]	900,000[2]	1,000,000[2]	1,000,000[2]
OH	n.d.	n.d.	n.d.	n.d.
MD	n.d.	n.d.	n.d.	n.d.
TN[3]	n.d.	n.d.	n.d.	n.d.
KY[4]	32,850	32,850	32,850	32,850
Total	**7,223,130**	**21,079,857**	**29,462,039**	**31,388,720**
	Cahaba coal field, Alabama[5]			
AL	542,828	432,149	529,438	395,841
	Black Warrior Basin, Alabama[5]			
AL	91,381,930	104,702,828	110,571,369	112,109,853
Total AL	**91,924,758**	**105,134,977**	**111,100,807**	**112,505,694**

Footnotes to Table 1:

n.d., no data; n.a., not available

[1]Includes an estimated 175,200 Mcf from 13 mine ventilation wells (Rod Biggs, CNG Producing, personal commun., May, 1996). Estimated production on basis of 40 Mcf/day.

[2]Estimate based on data in Bruner et al., 1995, and data provided by Toni Markowski, Pennsylvania Topographic and Geologic Survey, personal commun., April, 1996; and Jim Mills, Belden and Blake, personal commun., April, 1996.

[3]No permitted CBM wells or activity; information courtesy of Mike Hoyal, Tennessee Oil and Gas Board, personal commun., April, 1996; and Ron Zurawski, Tennessee Geological Survey, personal commun., May, 1996.

[4]Estimate based on one well in production at estimated 90 Mcfd.

[5]Courtesy of Jack Pashin, Geological Survey of Alabama, personal commun., April and May, 1996.

FIGURE CAPTIONS

Figure 1. Map of part of southwestern Virginia showing coalbed methane fields in the central Appalachian basin. After Nolde (1995) and Cardwell and Avary (1982).

Figure 2. Map of northern West Virginia and southwestern Pennsylvania showing coalbed methane fields and pools in the northern Appalachian basin. After Bruner et al. (1995).

Figure 3. Stratigraphy of coalbed methane beds (bold) in the central and northern Appalachian basin. Scale, thickness and correlations of beds and units in the central and northern Appalachian basin are not implied. Other selected coal beds (not bold) are shown for stratigraphic reference.

Figure 4. Number of new coalbed methane wells in production in Virginia. Data from Jack Nolde, Virginia Division of Mineral Resources, personal commun., April, 1996. The federal tax credit under Section 29 ended on December 31, 1992.

Figure 5. Annual coalbed methane production in Virginia (Bcf). Data from Nolde (1995); Jack Nolde, Virginia Division of Mineral Resources, personal commun., April, 1996.

Figure Captions (continued)

Figure 6. Annual production (estimate) of coalbed methane in central and northern Appalachian basin. This report.

Figure 7. Comparison of coalbed methane production in the central and northern Appalachian basin with that of the Black Warrior basin. Note that the Black Warrior basin has reached production maturity, and the central and northern Appalachian basin began significant production on 1992 and, therefore, is a frontier area for coalbed methane development.

Figure 8. Technically recoverable cabled methane in the Appalachian region (map modified from Rogers, 1994; data from Rice, 1995)

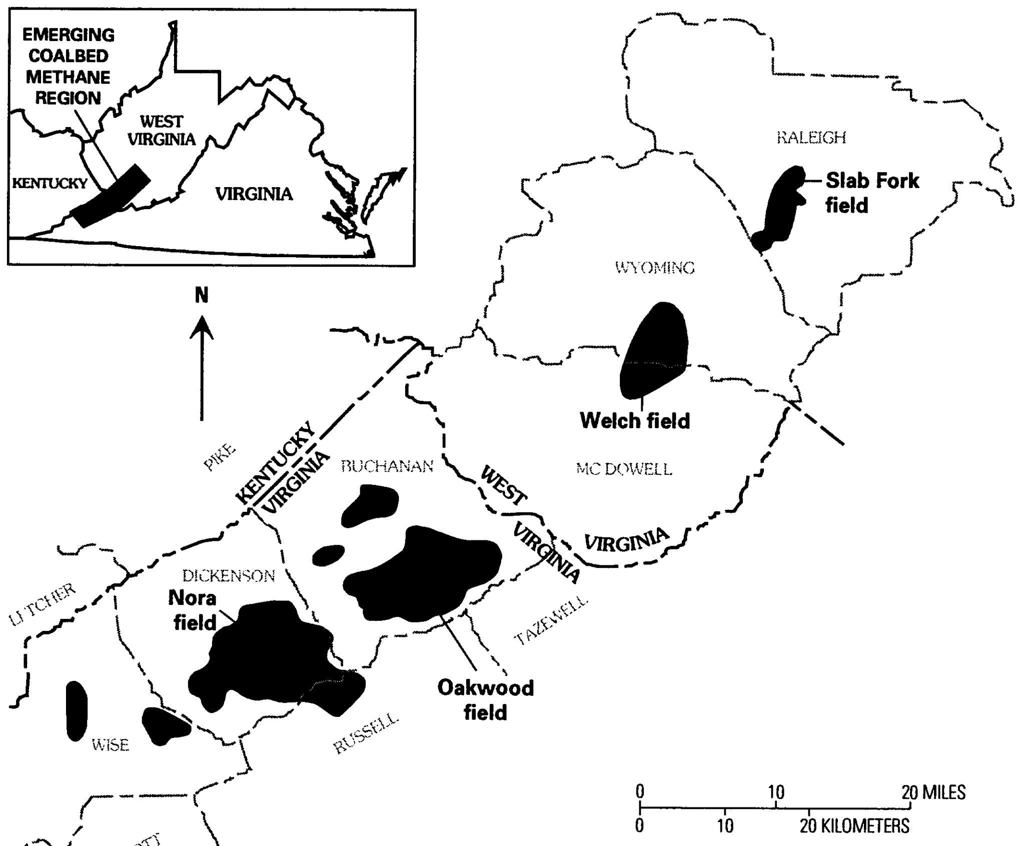
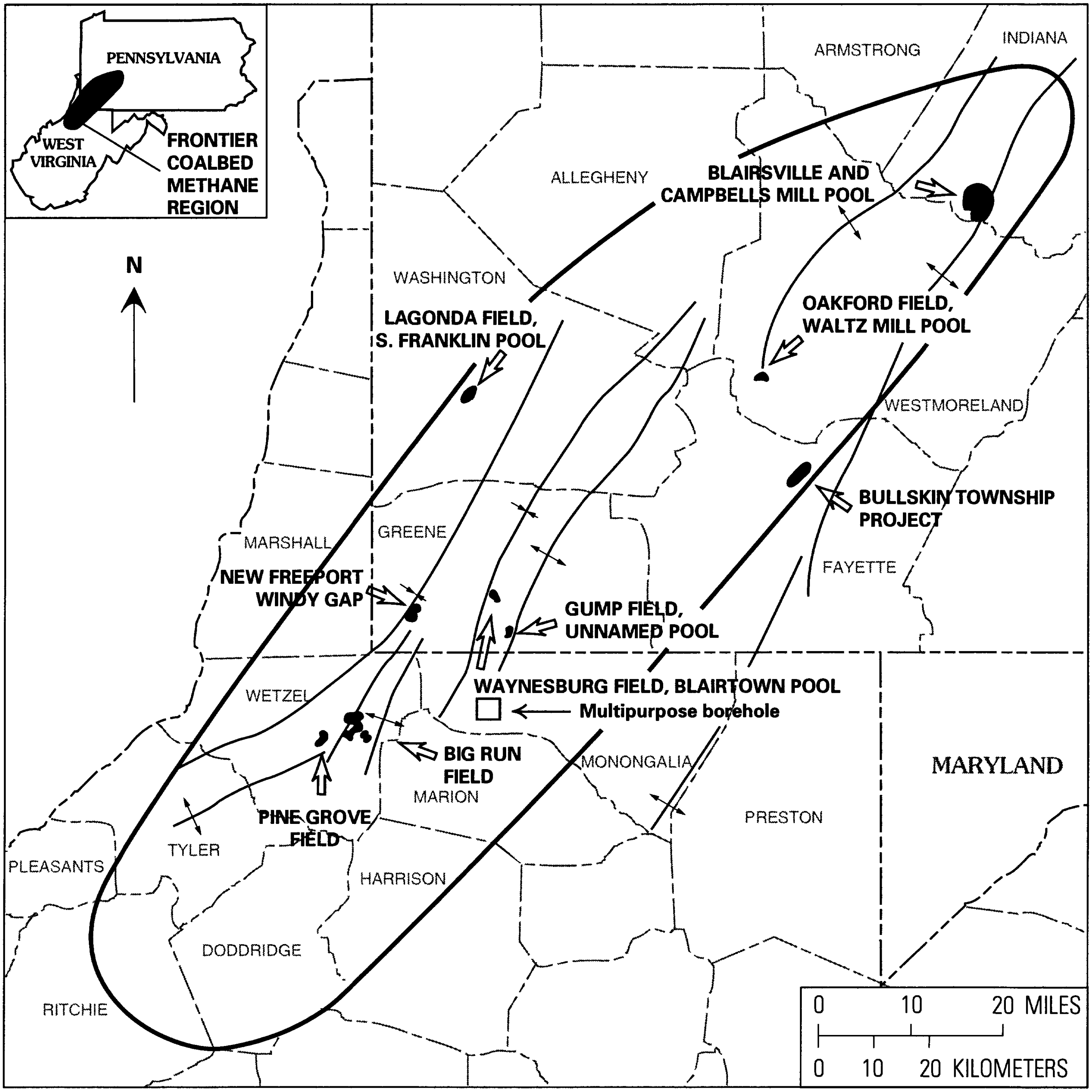

EMERGING COALBED METHANE REGION
WEST VIRGINIA
KENTUCKY
VIRGINIA
N
RALEIGH
Slab Fork field
WYOMING
Welch field
MC DOWELL
PIKE
KENTUCKY
VIRGINIA
BUCHANAN
WEST VIRGINIA
VIRGINIA
DICKENSON
Nora field
LETCHER
TAZEWELL
Oakwood field
WISE
RUSSELL
SCOTT
0 10 20 MILES
0 10 20 KILOMETERS

Fig. 1



PENNSYLVANIA
WEST VIRGINIA
FRONTIER COALBED METHANE REGION
N
ARMSTRONG
INDIANA
ALLEGHENY
BLAIRSVILLE AND CAMPBELLS MILL POOL
WASHINGTON
OAKFORD FIELD, WALTZ MILL POOL
LAGONDA FIELD, S. FRANKLIN POOL
WESTMORELAND
BULLSKIN TOWNSHIP PROJECT
MARSHALL
GREENE
FAYETTE
NEW FREEPORT WINDY GAP
GUMP FIELD, UNNAMED POOL
WETZEL
WAYNESBURG FIELD, BLAIRTOWN POOL
Multipurpose borehole
BIG RUN FIELD
MONONGALIA
MARYLAND
MARION
PINE GROVE FIELD
PRESTON
TYLER
PLEASANTS
HARRISON
DODDRIDGE
RITCHIE
0 10 20 MILES
0 10 20 KILOMETERS

Fig. 2

SERIES	NORTHERN APPALACHIAN BASIN Pa., Ohio, Md., nothern W.V. — Coal bed	NORTHERN APPALACHIAN BASIN — Group/Formation	CENTRAL APPALACHIAN BASIN Va. and southern W.V. — Coal bed		CENTRAL APPALACHIAN BASIN — Formation	
LOWER PERMIAN	Washington **Waynesburg**	**Dunkard Group**				
UPPER PENNSYLVANIAN	**Sewickley** **Redstone** **Pittsburgh**	**Monongahela Formation**				
	Duquesne Ames **Bakerstown** Brush Creek **Mahoning**	**Conemaugh Formation**				
MIDDLE PENNSYLVANIAN	**Upper Freeport** **Lower Freeport** **Upper Kittanning** **Middle Kittanning** **Lower Kittanning** **Clarion** **Brookville**	**Allegheny Formation**	**ERROSION LEVEL**			
			High Splint		**Harlan Formation**	Kanawha Formation
			Fire Clay tonstein		**Wise Formation**	Kanawha Formation
					Gladville Sandstone	Kanawha Formation
			Kennedy		**Norton Formation** (upper part)	Kanawha Formation
LOWER PENNSYLVANIAN	**Mercer** **Quakertown** Sharon	**Pottsville Formation**	**Jawbone**	Iaeger	**Norton Formation** (lower part)	Kanawha Formation
	MISSING SECTION		**L. Seaboard**	Sewell	**Lee Formation** or **New River Fm.**	
			War Creek	Beckley		
			L. Horsepen	Fire Creek		
			Pocahontas No.8			
			Pocahontas No.4 **Pocahontas No.3** Squire Jim		**Pocahontas Fm.**	

Fig. 3

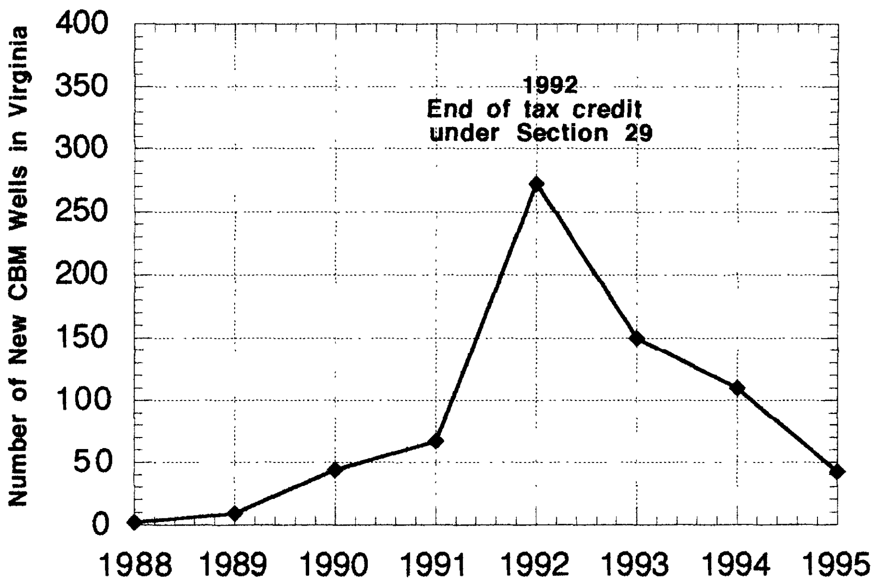
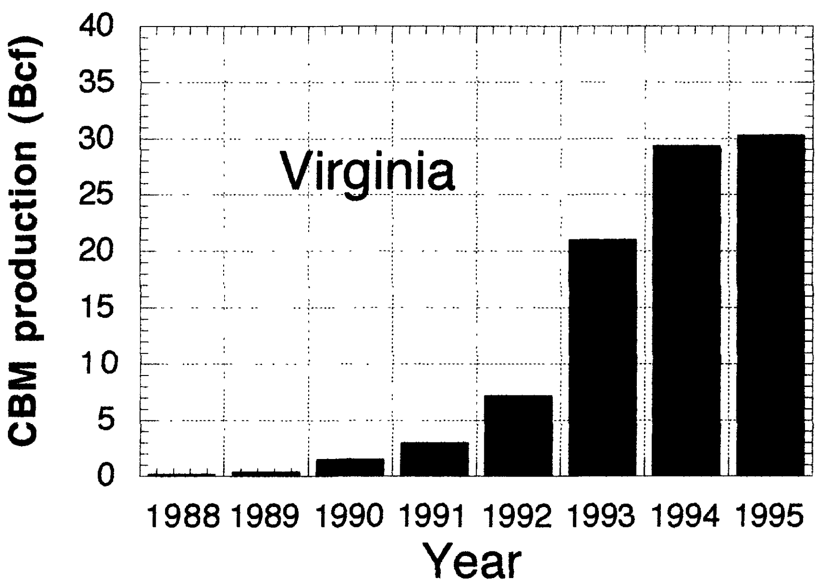

400
350
300
250
200
150
100
50
0
Number of New CBM Wells in Virginia
1992
End of tax credit
under Section 29
1988
1989
1990
1991
1992
1993
1994
1995

Fig. 4



40
35
30
25
20
15
10
5
0
CBM production (Bcf)
Virginia
1988
1989
1990
1991
1992
1993
1994
1995
Year

Fig. 5

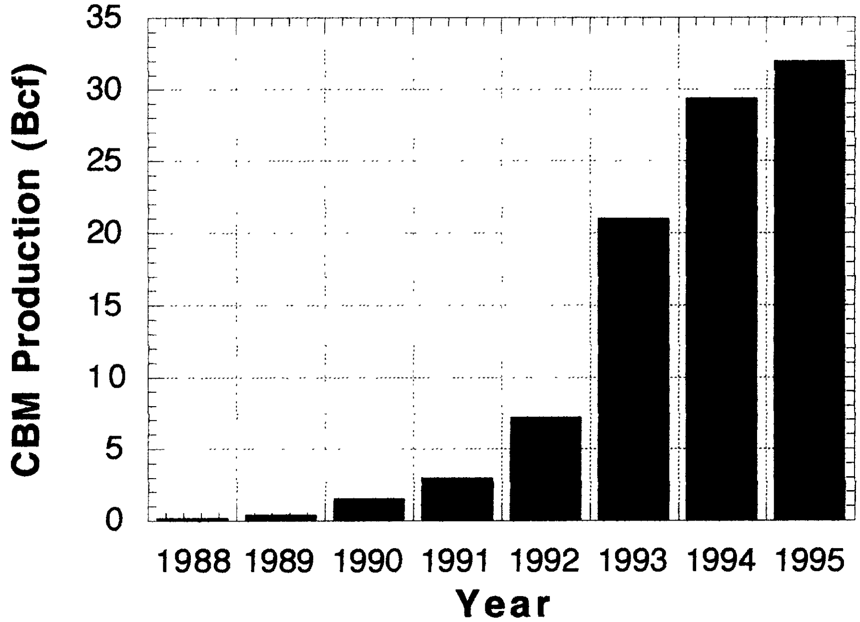

CBM Production (Bcf)
35
30
25
20
15
10
5
0
1988 1989 1990 1991 1992 1993 1994 1995
Year

Fig. 6

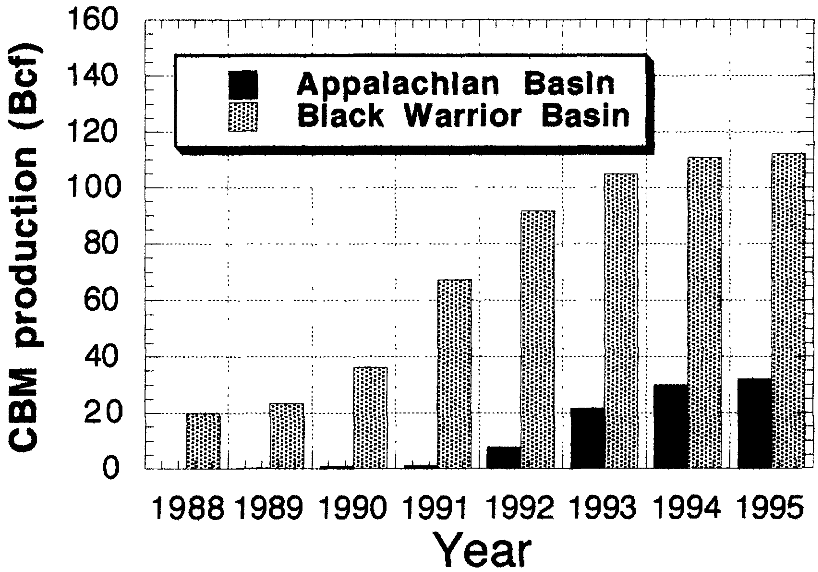
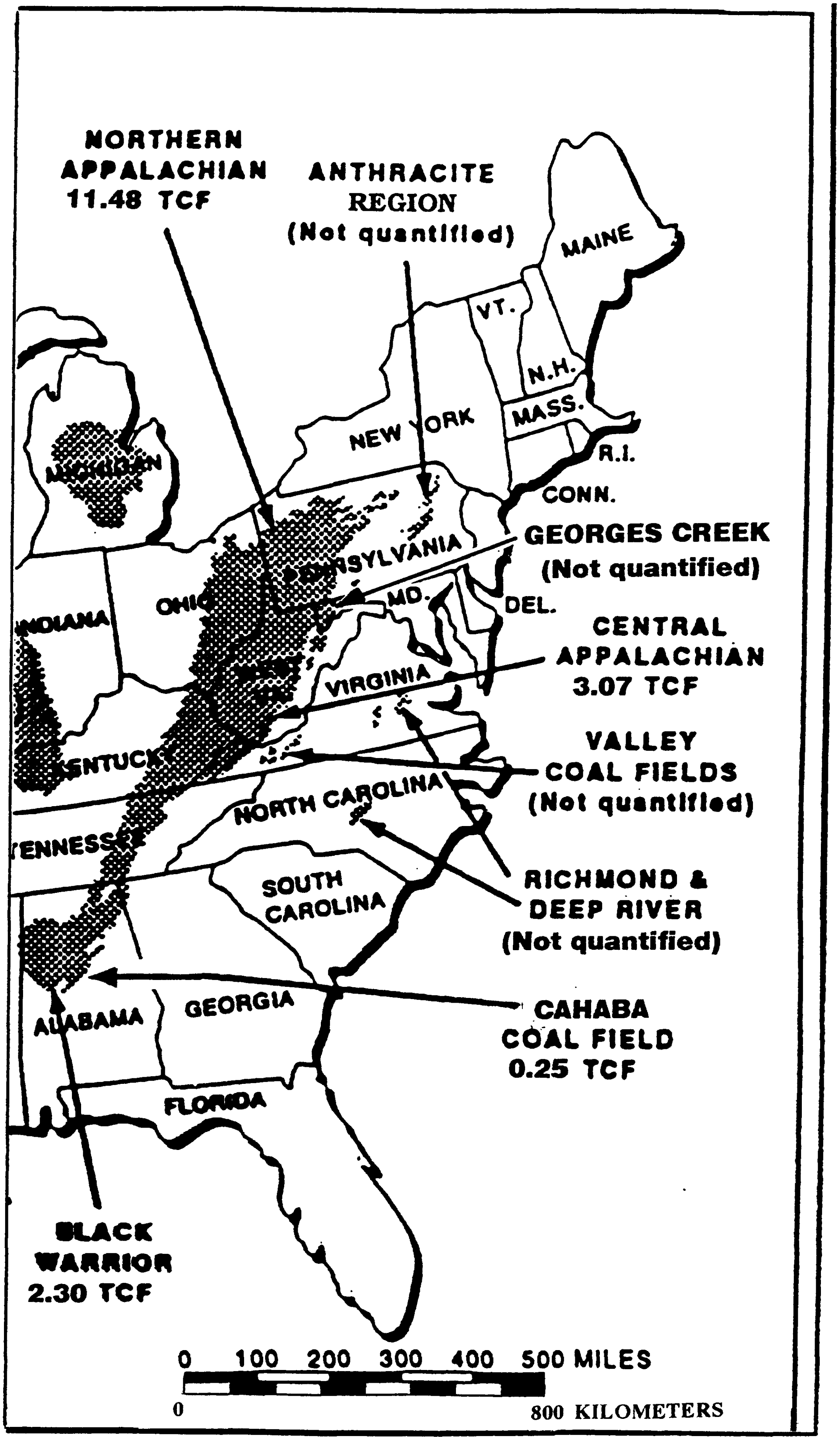

160
140
120
100
80
60
40
20
0
CBM production (Bcf)
Appalachian Basin
Black Warrior Basin
1988 1989 1990 1991 1992 1993 1994 1995
Year

Fig. 7



NORTHERN APPALACHIAN 11.48 TCF
ANTHRACITE REGION (Not quantified)
MAINE
VT.
N.H.
MASS.
R.I.
CONN.
NEW YORK
PENNSYLVANIA
GEORGES CREEK (Not quantified)
MD.
DEL.
OHIO
INDIANA
CENTRAL APPALACHIAN 3.07 TCF
VIRGINIA
VALLEY COAL FIELDS (Not quantified)
KENTUCKY
NORTH CAROLINA
TENNESSEE
RICHMOND & DEEP RIVER (Not quantified)
SOUTH CAROLINA
CAHABA COAL FIELD 0.25 TCF
ALABAMA
GEORGIA
FLORIDA
BLACK WARRIOR 2.30 TCF
0 100 200 300 400 500 MILES
0 800 KILOMETERS

Fig. 8