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Coalbed methane resource potential and current prospects in Pennsylvania

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Abstract

Coalbed methane gas content analyses from exploratory coal cores and existing data indicate that gas content generally increases with increasing depth and rank. The coal beds studied are from the Main Bituminous field of Pennsylvania (which currently contains 24 coalbed methane pools) and the Northern and Southern Anthracite coal fields. They range from the Middle Pennsylvanian Allegheny Group to the Late Pennsylvanian–Early Permian Dunkard Group. Previous US Bureau of Mines studies revealed gas contents from 0.4 to 13.8 cm^3/g at depths of 99 to 432 m for the bituminous coal beds of the Allegheny Group. More recent core data from the Allegheny Group yielded gas contents from 2.2 to 8.9 cm^3/g at depths from 167 to 387 m. In the Anthracite region of eastern Pennsylvania, the little data that are available show that gas content is anomalously high or low. Gas yields from test holes in eastern Pennsylvania are low with or without artificial stimulation mainly due to the lack of a good cleat system. Overall estimates of coalbed methane resources indicate there may be 1.7 Tm^3 (61 Tcf) of gas-in-place contained in the Northern Appalachian coal basin. The amount of technically recoverable coalbed methane resources is projected by the US Geological Survey National Oil and Gas Resource Assessment Team [US Geological Survey National Oil and Gas Resource Assessment Team, 1996. 1995 National assessment of United States oil and gas resources—results, methodology, and supporting data, US Geological Survey Digital Data Series DDS-30, CD-ROM, Denver, CO, 80 pp.] and Lyons [Lyons, P.C., 1997. Central-northern Appalachian coalbed methane flow grows. Oil and Gas Journal 95 (27) 76–79] at 0.3 Tm^3 (11.48 Tcf). This includes portions of Pennsylvania, Ohio, West Virginia, and a small part of Maryland. Consequently, a mapping investigation was conducted to evaluate the regional geology of the bituminous coal-bearing intervals in southwestern Pennsylvania and its influence on coalbed methane potential. Phase I of this study involved the entire Pennsylvanian coal-bearing interval of southwestern Pennsylvania. Phase II focused on a stratigraphic delineation and evaluation of Allegheny Group coal beds and associated sandstones.

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Several prospective coal beds and associated facies relationships with channel–fill sandstones were determined. Possible non-coal scenarios for coalbed methane include erosional contacts between coal beds and overlying channel–fill sandstones and areas of stacked channel–fill sandstones. Repetitive sequences of coal accumulation are stacked, commonly with shale interburden, and are also potential coalbed methane targets. Additional Pennsylvania Geological Survey drilling/coalbed methane sampling occurred in Armstrong, Beaver, Cambria, Greene, Lawrence, Somerset, and Washington Counties. Raw coalbed methane desorption data tables/graphical displays of gas contents versus depth, thickness, and time, and average composition and heating values from coal beds of the Allegheny Group to the Dunkard Group are available at the Pennsylvania Geological Survey. Further information on cross-sections, isopleth maps, isopach maps, raw drillhole data, and ownership issues can also be obtained from the same source. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: coalbed methane; resources; bituminous coal; anthracite; Allegheny Group; Middle Pennsylvanian

1. Introduction

Coalbed methane (the gas emitted from coal which is primarily methane, with minor amounts of heavier hydrocarbons, carbon dioxide, nitrogen, oxygen, hydrogen, and helium) in the Northern Appalachian coal basin has long been considered a mining and safety problem. Until recently, it has also generally been overlooked as a resource by the oil and gas industry. In the 1970s, coalbed methane got its start in Pennsylvania with the drilling of degasification holes prior to mining. The gas was mainly used for local mine operations. In the late 1980s, interest in the economic value of gas from coal beds expanded to the extent that now the oil and gas industry is developing commercial quantities of this unconventional natural gas.

Companies are also becoming interested in converting ventilation holes in gob to production wells. Gob is the coal and surrounding strata above the coal that has collapsed due to longwall mining. Gob gas is a major contributor to coalbed methane emissions released to the atmosphere. It is often contaminated with oxygen and nitrogen from ventilation air, making it less desirable for use as a pipeline-quality natural gas, which is approximately 1,054,350 J (1000 Btu). A mean composition for gob gas is 78% methane (varies from 65 to 95%), 16% nitrogen (varies from 9 to 26%), 3% oxygen (varies from 2 to 6%), 3% carbon dioxide (varies from 3 to 9%), and saturated (amount not stated) with water vapor (U.S. Department of Energy, 1994). With new technology (pressure swing adsorption), gob gas can be enriched to at least 95% hydrocarbon in the product (Shirley and Porto, 1997). According to the U.S. Department of Energy (1994), gob gas flows vary greatly, from less than 2.8 Mm^3/d (100 Mcf/d) to over 0.2 MMm^3/d (8 MMcf/d). Diamond et al. (1993) found that cumulative production from 82 holes on seven longwall panels in the Lower Kittanning coal bed range from less than 0.03 to 10.1 MMm^3. In general, gob wells are expected to produce for 20 years based on reservoir characteristics of the fractured gob and engineering of the gob wells.

Overall estimates of coalbed methane resources indicate there may be 1.7 Tm^3 (61 Tcf) of gas-in-place contained in the Northern Appalachian coal basin. The amount of technically recoverable coalbed methane resources is projected at 0.3 Tm^3 (11.48 Tcf)

(U.S. Geological Survey National Oil and Gas Resource Assessment Team, 1996; Lyons, 1997). This includes portions of Pennsylvania, Ohio, West Virginia, and a small part of Maryland.

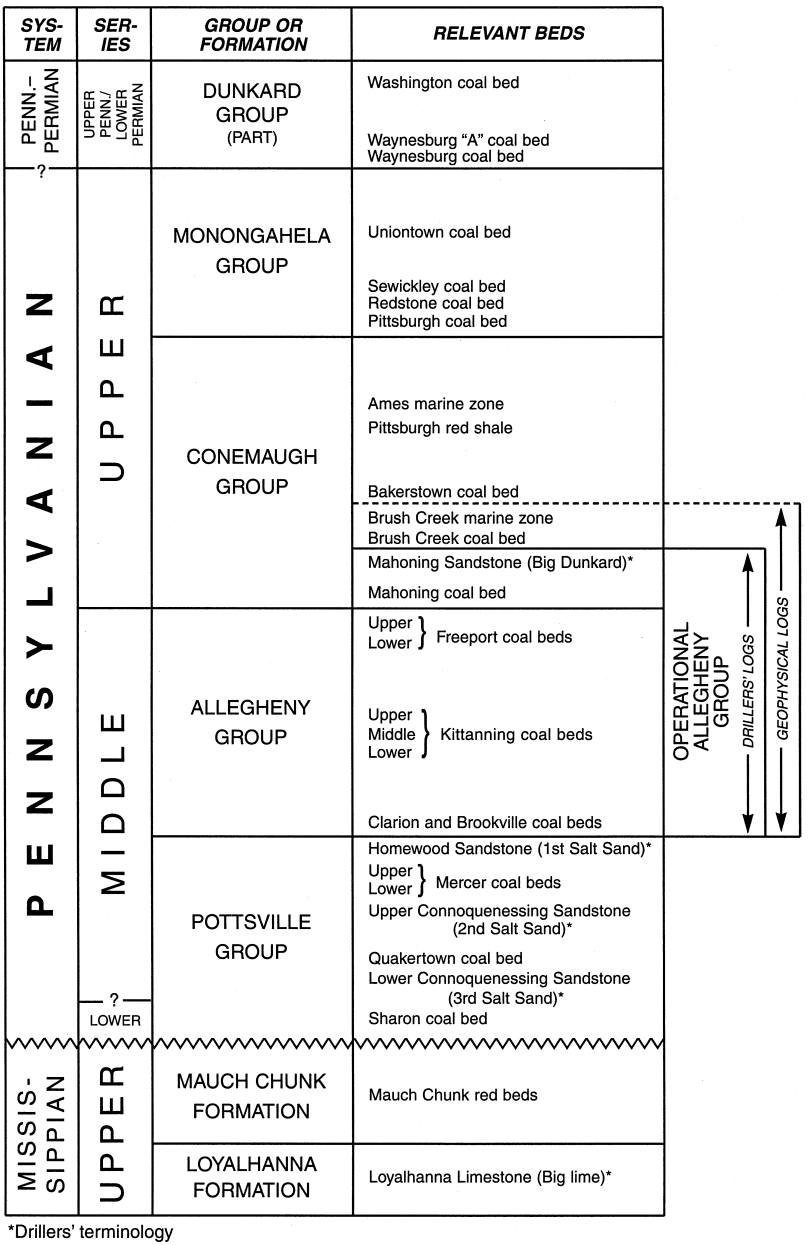


Fig. 1. Subdivisions of the Pennsylvanian System and the stratigraphic position of beds important to this study (modified from Bruner et al., 1995).

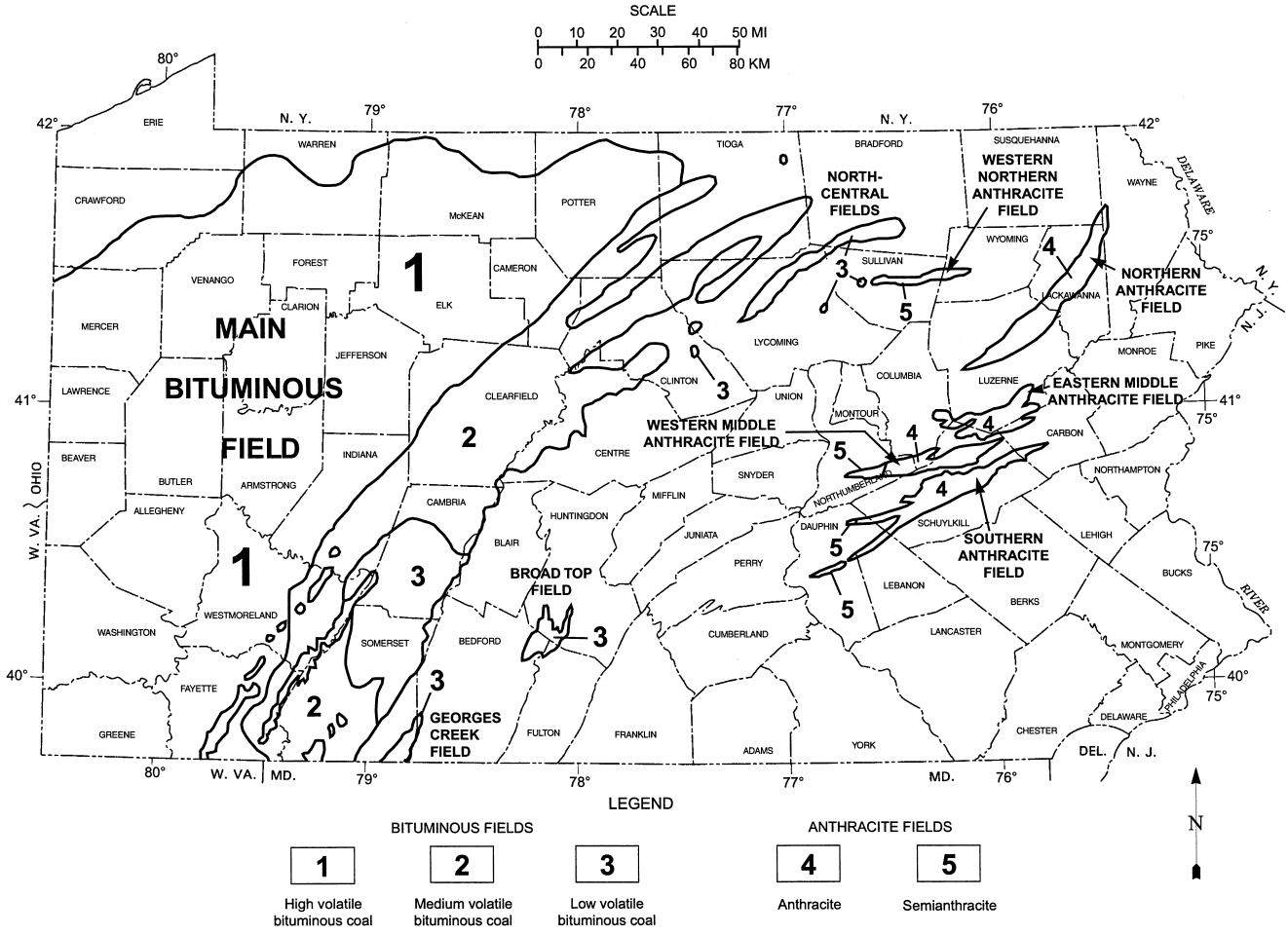


Fig. 2. Location of coal-bearing rocks and coalfields across Pennsylvania (modified from the Pennsylvania Geological Survey, 1992).

1.1. Objectives

The principal objective of this report is to identify and evaluate the coalbed methane potential and current prospects of the major coal beds in southwestern Pennsylvania from existing and new data. Additional objectives include: (1) identification of key areas with a high coalbed methane content; (2) subsurface delineation of the coal-bearing intervals, especially the Allegheny Group coal beds and associated reservoir-quality sandstones; (3) interpretation of coal data and coal-sandstone relationships; and (4) assessment of the implications of exploiting coalbed methane as a supplemental and/or alternative unconventional energy source for Pennsylvania.

1.2. Scope

This report is a summary of previous and new work on coalbed methane in Pennsylvania, some of which was completed in a cooperative study with the West Virginia Geological and Economic Survey (Bruner et al., 1995). The primary emphasis was to collect information from the Allegheny Group of the Main Bituminous coal field (Figs. 1 and 2). The data provided in this report indicates the presence of very gassy coals in certain parts of the Northern Appalachian basin. The resource potential of these coals deserves serious consideration.

Raw coalbed methane data/graphical displays of gas contents versus depth, thickness, and time, and information on average composition and heating values from coal beds of the Allegheny Group to the Dunkard Group are available from an expanded report (Markowski, Pennsylvania Geological Survey, unpub. report).

2. Regional geology

The Northern Appalachian coal basin is a symmetrical, oval basin covering approximately 113,183 km^2 (Fig. 3). Structure controls the basin configuration on the east with late Middle Pennsylvanian coal cropping out on the flanks of northeast/southwest trending folds (Adams et al., 1984). The major coal-bearing units of the study area include the Pennsylvanian-age Pottsville, Allegheny, Conemaugh, Monongahela, and the Late Pennsylvanian-and/or Early Permian Dunkard Group (Fig. 1). Although most of the coals in the basin are only locally continuous, some coal beds, like the Pittsburgh, are regionally continuous in Pennsylvania.

2.1. Regional setting and structure

The primary study area, the Main Bituminous field, is located in southwestern Pennsylvania (Figs. 2 and 3), which is in the central part of the Appalachian Plateaus Province. Late Paleozoic rocks in and around the study area have been deformed into long, gently plunging open folds. Fractures and faults, the presence or absence of which are so important in the transmission and storage of gas in coal beds, formed before, during, and after the main phase of Alleghany folding.

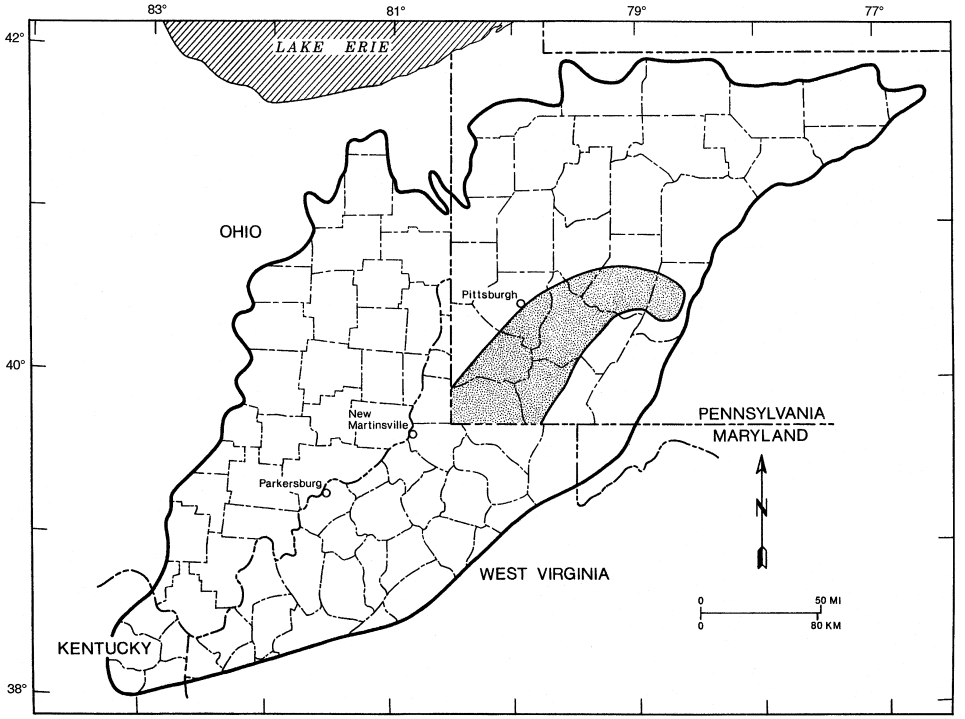
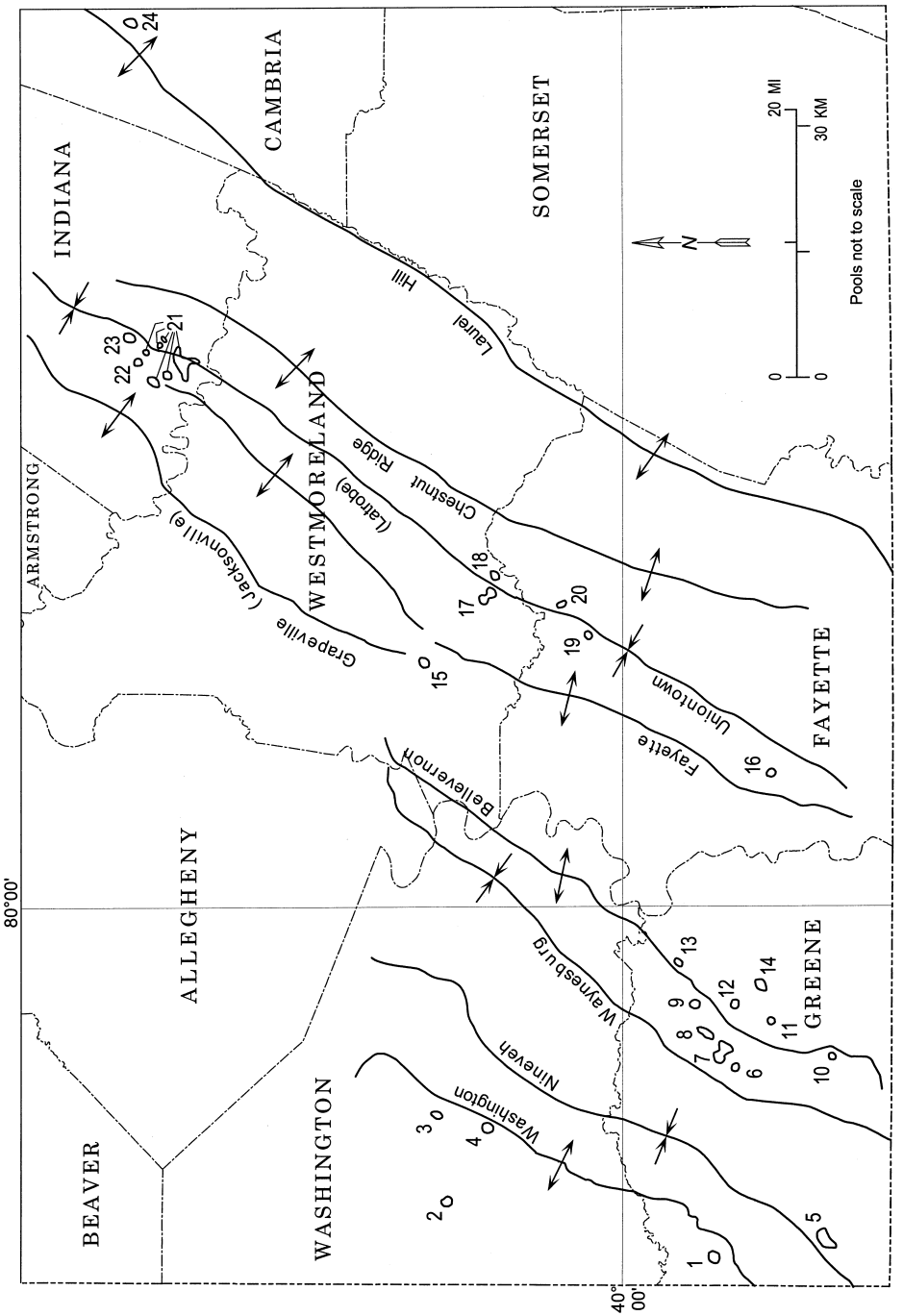


Fig. 3. Map of the Northern Appalachian coal basin showing the study area of a gas content reconnaissance, general target area for exploration (stippled), and county lines (modified from Adams et al., 1982).

Tight to moderately plunging folds interrupt the generally undeformed Northern Appalachian coal basin. These features trend northeast to southwest with dips generally between 10 and 20° (Kelafant et al., 1988). In some cases, these folds bring the coal beds to the surface, and over time the gas is lost by updip migration. Examples of this are the coal beds that lie near the Chestnut Ridge and Laurel Hill anticlines (Fig. 4). Coal-bearing strata in the central part of the basin are relatively flat and covered by a thick overburden of Dunkard strata.

Fig. 4. Coalbed methane pools and major fold axes in Pennsylvania (A.K. Markowski, Pennsylvania Geological Survey, unpub. report); fold axes from (Bragonier and Glover, 1996; Dodge and Glover, 1984; R.T. Faill, Pennsylvania Geological Survey, unpub. map; Glover, 1990; Skema, 1987, 1988). Explanation for pools and fields: 1 = Dunkard Fork pool, Rich Hill field; 2 = Unnamed pool, Mehaffy field; 3 = Unnamed pool, Washington–Taylorstown field; 4 = South Franklin pool, Lagonda field; 5 = Windy Gap pool, New Freeport field; 6 = Unnamed pool, Waynesburg field; 7 = Blairtown pool, Waynesburg field; 8 = Turner pool, Waynesburg field; 9 = Poverty Run pool, Pratt Storage field; 10 = Rudolph Run pool, Gump field; 11 = Unnamed pool, Waynesburg field; 12 = Unnamed pool, Waynesburg field; 13 = Unnamed pool, Jefferson field; 14 = Frosty Run pool, Waynesburg field; 15 = Waltz Mill pool, Oakford field; 16 = Smiley pool, Highhouse field; 17 = Morewood pool, Mayfield field; 18 = Orchard Hill pool, Hoggs field; 19 = Adelaide pool, Waltersburg field; 20 = Moyer pool, Mayfield field; 21 = Campbells Mill pool, Blairsville field; 22 = Unnamed pool, Blairsville field; 23 = Unnamed pool, Indiana field; 24 = Powell pool, Carrolltown field.


INDIANA
CAMBRIA
SOMERSET
ARMSTRONG
WESTMORELAND
FAYETTE
ALLEGHENY
BEAVER
WASHINGTON
GREENE
Laurel Hill
Chestnut Ridge
(Latrobe)
Grapeville (Jacksonville)
Uniontown
Fayette
Bellevernon
Waynesburg
Nineveh
Washington
80°00'
40° 00'
N
0 20 MI
0 30 KM
Pools not to scale
1
2
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The relatively high rank, total effective coal thickness, and deep burial of the coal beds, generally up to 457 m deep in the Dunkard basin (deepest part of the Northern Appalachian coal basin), suggest that this basin has good potential for coalbed methane production. The higher rank coals formed in a more deeply buried portion of the basin have experienced higher pressures and temperatures (Adams et al., 1984). Coal ranks in the Main Bituminous field increase generally from high volatile bituminous in the west to medium to low volatile bituminous coal in the east (Fig. 2). The bulk of the gas content reconnaissance study area contains high volatile bituminous coal with portions of medium to low volatile bituminous coal in the northeast part.

3. Coalbed methane in Pennsylvania

3.1. Southwestern Pennsylvania — existing coalbed methane pools and production

There are 24 coalbed methane pools in Pennsylvania (Fig. 4), but the number of reported pools and wells is changing as of this report. Eleven of the 24 pools are located in Greene County. There are three pools each in Fayette, Indiana, Washington, and Westmoreland Counties. One pool is in Cambria County. These pools contain wells drilled from 1938 to 1997.

Approximately 195 well permits are related to coalbed methane exploration, extraction, or production. The wells are classified as: (1) new, not drilled or completed yet; (2) active, not plugged or abandoned, at various stages of exploration, extraction, or production; (3) inactive, no production after one year or not equipped for production within 60 days after completion (this qualifies for a shut-in period of five years), the operator must demonstrate future well utility; (4) plugged and abandoned, little or no production, not equipped for production within 60 days after completion; (5) expired, not drilled within one year of permit issuance; or (6) cancelled, by the operator. Of the 195 well permits, there are 30 wells known to be commercial producers mainly from the Campbells Mill pool in Blairsville field, Indiana County, and South Franklin pool in Lagonda field, Washington County. The number of wells and their permit status as of December 1997 are: 78 new, 56 active (includes the 30 commercial producers), 27 expired, 26 plugged and abandoned, 4 cancelled, and 4 inactive.

These ‘coalbed methane wells’ exhibit the following criteria: (1) wells that penetrated coal beds or gob with reported gas shows or production; (2) wells converted from pre-mining degasification or ventilation boreholes; (3) wells that were targeted for the coal beds, but did not produce gas from either the coal beds or the associated sandstones (dry holes); (4) wells that were targeted for the coal beds, but produced from associated sandstones; and (5) unsuccessful coalbed methane wells that were re-targeted to deeper, conventional gas reservoirs.

There are many conventional and unconventional gas fields and pools in the target area. Commercial natural gas production is abundant and there is an existing, compatible pipeline infrastructure to bring the gas to market.

State regulations for spacing of coalbed methane wells are the same as for conventional natural gas wells in a coal area. The spacing requirements are 305 m (1000 ft)

between wells and not less than 101 m (330 ft) from the well to the boundary of the tract on which it is located. However, if the coal owner approves, the spacing between wells can be reduced to 274 m (900 ft). According to Commonwealth of Pennsylvania Act 214, the Coal and Gas Resource Coordination Act, the Bureau of Oil and Gas Management (Pennsylvania Department of Environmental Resources, 1991) (renamed the Department of Environmental Protection in 1995) can grant an exception from the minimum 305 m spacing ''where the vertical distance between the producing formation of the proposed gas well and the producing formation of any other well is 1000 ft or greater, where the permit applicant and the owner of the workable coal seam consent in writing.''

Selected pools from Cambria, Greene, Indiana, and Washington Counties are highlighted below for summary purposes. Production and interval depths were taken from public well records, well completion reports, and the Pennsylvania Geological Survey's Wells Information System (WIS).

3.1.1. Cambria County

Powell pool in the Carrolltown field is located about 1.2 km southeast of the Laurel Hill anticlinal axis (pool 24, Fig. 4). CNG Producing Company completed the Bilonick No. 1 well on June 12, 1993 in an abandoned mine. The exploratory well reached total depth in the Upper Freeport coal bed (Fig. 1) at 77 m. A natural open flow yielded 2.4 Mm^3/d. The well is reported to have sporadic production.

3.1.2. Greene County

Blairtown pool in the Waynesburg field, is located in north-central Greene County, about 0.8 km southeast of the Waynesburg synclinal axis (pool 7, Fig. 4). The main coal beds in this area are the Pittsburgh, Sewickley, and Waynesburg (Fig. 1). The main bench of the Pittsburgh coal bed is approximately 1.7 m thick with a thick lower bench accompanied by one or more thinner benches.

Emerald Mines Corporation (now known as Cyprus Emerald Resources Corporation) drilled 18 wells in the Blairtown pool between July 1970 and December 1979. These pre-mining degasification wells penetrated, in descending order, the Washington, Waynesburg, Uniontown, and Pittsburgh coal beds, and the coal beds of the Conemaugh Group (Fig. 1). Natural open flows ranged from 0 to 2.8 Mm^3/d after treatment mainly of the Pittsburgh coal bed. The deepest productive intervals ranged from 179 to 312 m. Production was not reported for about half of the wells. The 18 wells are now plugged and abandoned.

Windy Gap pool in the New Freeport field, is located in southwestern Greene County, about 0.8 km southeast of the Nineveh synclinal axis (pool 5, Fig. 4). CNG Producing drilled five coalbed methane wells in the New Freeport field in early 1991 as part of a project. The gas wells penetrated the Waynesburg to the Sharon coal beds (Fig. 1). Total depths ranged from 405 to 1097 m. Deepest productive intervals ranged from 348 to 535 m. Natural open flows were too small to test, but after hydraulic fracture stimulation, the open flows were estimated to be 1.4 Mm^3. The gas was relatively free of contaminants and yielded a Btu value acceptable for pipeline-quality control. Traces of fresh water were found at some of the shallower coal depths in three of the five wells.

CNG Producing reported brackish water near a deep coal bed in one of the wells. Cumulative production reported from 1991-92 ranged from 2.4 to 16.7 Mm^3 for approximately three months. The wells are now plugged and abandoned.

A new pilot pre-mining coalbed methane recovery program is underway at Cyprus Cumberland Resources Corporation to reduce the amount of methane on developmental mining sections. Two vertical boreholes will be converted into gob ventilation boreholes. Coalbed methane will be extracted from the Pittsburgh coal bed. According to a presentation by J.M. Reilly at the April 1997 North American Coalbed Methane Forum in Pittsburgh, Pennsylvania, Cyprus Cumberland Resources plans to continue the program which is proving to be cost-effective in reducing mining delays.

3.1.3. Indiana County

The most significant, commercial coalbed methane pool in Pennsylvania is the Campbells Mill pool in southern Indiana county. It is located in the Blairsville field (pool 21, Fig. 4). The Latrobe synclinal axis cuts through the eastern half of the pool and the Fayette anticlinal axis lies about 0.8 km west of the pool (Fig. 4). The pool contains 29 producing wells, all drilled as of April, 1997. Initially, twenty wells were drilled by O'Brien Methane Production, Incorporated prior to the end of 1992. The project was later sold to Belden and Blake Corporation. According to personal communication with David T. Bajek (Belden and Blake) on October 23, 1997, there are a total of twenty-seven producing coalbed methane wells. Eight additional wells are planned to be drilled for 1997. The Belden and Blake wells produce pipeline-quality gas at an average after-treatment open flow of 1.1 Mm^3/d and 23.9 m^3 (150 barrels) of fresh water per well per day. The water is pipelined to a treatment facility and discharged to Blacklick Creek. The quality of the treated water is within acceptable limits for discharge. According to the Bureau of Oil and Gas Management of the Department of Environmental Protection, the treatment design must incorporate the following: (1) flow equalization for optimum efficiency and minimization of water quality impacts; (2) chemical addition for pH control and metals removal, if needed; (3) aeration to reduce volatile petroleum hydrocarbons and oxidation for metals removal; (4) gravity separation and surface skimming to remove oil and grease; and (5) settling (retention) or filtration for removal of solids, including oxidized metals.

Three Lee E. Minter wells were also drilled in the Campbells Mill pool (two of the Minter wells are now owned by LAHD Energy, Incorporated). The Minter/LAHD Energy wells produce from the Pottsville to the Lower Conemaugh Group coal beds (Fig. 1). The deepest productive intervals in the Campbells Mill pool range from 145 to 345 m; natural open flows range from 0.1 to 4 Mm^3/d; and total depths range from 145 to 366 m. Cumulative production reports available from 1993-1994 show that 106 to 642 Mm^3 of coalbed methane was produced in approximately one year from southern Indiana County.

3.1.4. Washington County

South Franklin pool in Lagonda field (pool 4, Fig. 4) is located about 0.8 km northwest of the Washington anticlinal axis (Fig. 4). Jesmar Energy, Incorporated reported a natural open flow of 85 Mm^3/d from the Pittsburgh gob zone in the Ken

Varner No. 1 well, spudded on June 18, 1991. The productive interval ranged from 148 to 149 m, and the total depth reached 154 m to the Conemaugh Group. The well is producing and on-line with a natural gas pipeline.

3.2. Northeastern Pennsylvania — anthracite coal fields

It is difficult to nearly impossible to evaluate the methane drainage potential in the Anthracite region of eastern Pennsylvania (Fig. 2). Few projects were initiated here due to the economics of drilling in a region of complex structure and stratigraphy (Diamond and Levine, 1981; Diamond et al., 1986). However, the variety of data presented from these sources reveal very high gas contents in localized areas of the Anthracite region. This suggests that further coalbed methane exploration should be conducted in this part of Pennsylvania (Lyons, 1997).

4. Selected sampling site — Cambria County

4.1. Cambria County

A drillhole in Cambria Township, Cambria County (Fig. 2) encountered the Upper and Lower Freeport coal beds (Fig. 1) at 221 and 235 m. Although this site is about 48.3 km east of the geological evaluation study area of Section 5 of this report, it is included

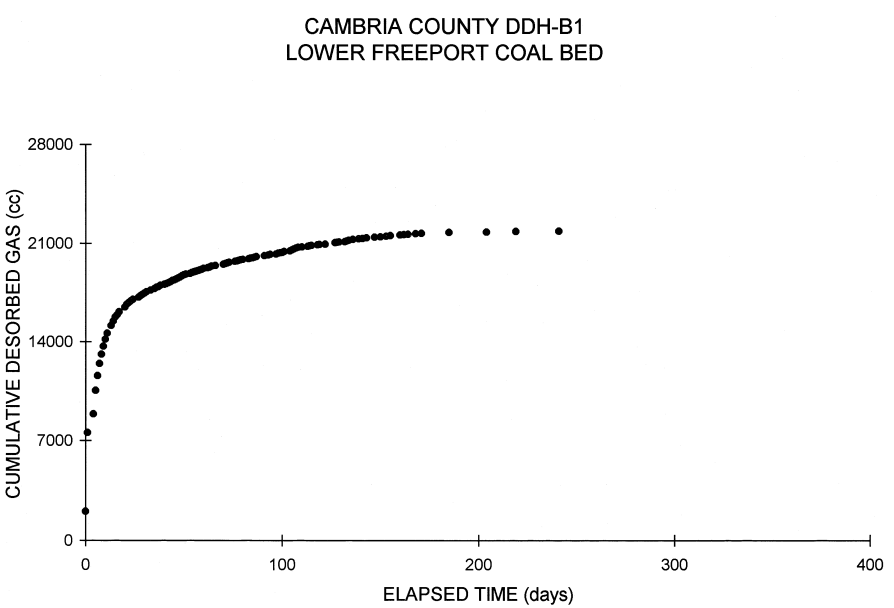


Fig. 5. Cumulative desorbed gas versus elapsed time for the Lower Freeport coal bed in Cambria County, Pennsylvania.

because the results are from the study area of a previous Pennsylvania Geological Survey gas content reconnaissance (Markowski, Pennsylvania Geological Survey, unpub. report). The site lies about 1.6 km west of the Wilmore synclinal axis, and 5.5 km east of the Ebensburg anticlinal axis (Glover, 1990). Locally, it is about 1.6 km from a mine dump and 7.2 km west-northwest of a strip mine. Total gas contents ranged from 6.3 cm^3/g for the Upper Freeport to 12.3 cm^3/g for the Lower Freeport. The Upper Freeport was the thicker of the two seams at 1.6 m compared to the Lower Freeport at 0.8 m. Coal rank is medium volatile bituminous. The gas composition averaged 99% methane for each coal bed.

Thickness of the coal and total gas content show no relationship. There also was no apparent correlation between total gas content and atmospheric pressure or ambient temperature. Cumulative desorbed gas appeared to increase slightly with an increase in atmospheric pressure and temperature. The amount of cumulative gas in the top part of the Lower Freeport coal bed also increased steadily with elapsed time, but stabilized after 200 days (Fig. 5).

4.2. Results of testing

Variables such as barometric pressure, temperature, and time were initially plotted against the cumulative gas calculated at standard temperature and pressure for data

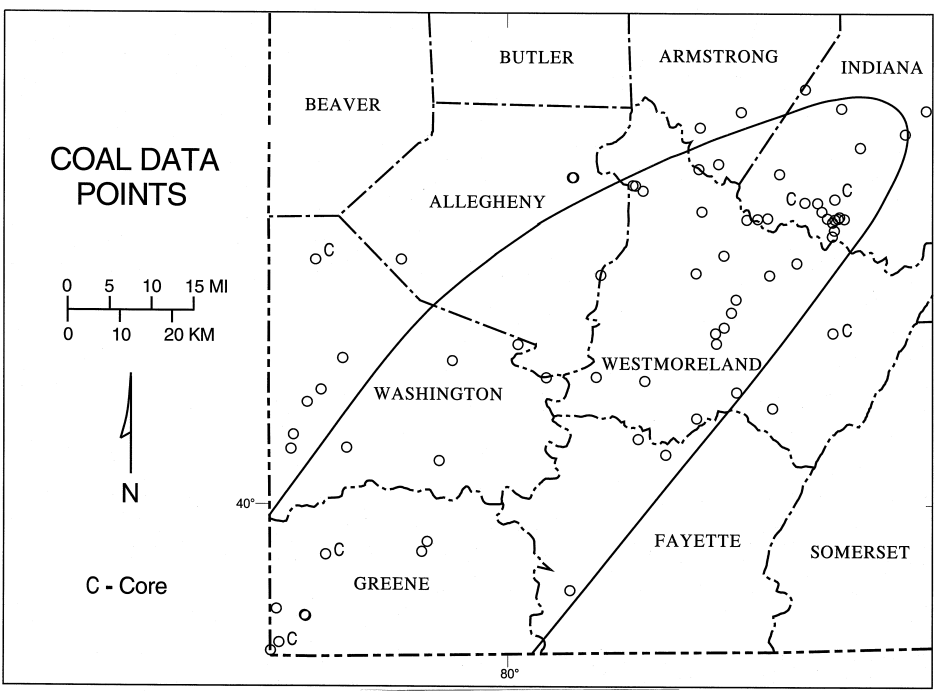


Fig. 6. Location of wells with core and gamma ray/density log suites used for coal mapping and cross-sections (modified from Bruner et al., 1995).

collected during this study. Thickness was also plotted against total gas content. Because there appeared to be no significant correlation between barometric pressure and temperature versus cumulative gas and coal bed thickness versus total gas content, these data are not included in this report. Previous U.S. Bureau of Mines studies and data from Markowski (Pennsylvania Geological Survey, unpub. report) suggest a direct correlation between depth of the coal bed and an increase in total gas content. Additional data on other coal beds can be obtained from the Pennsylvania Geological Survey.

The rate of cumulative desorbed gas versus time depends partly on the degree of cleat networking. That is, if the coal is blocky and dense with a poor cleat network, there will be a slow rate of cumulative desorption. If the coal is friable with a good cleat network, there will be a measurably rapid rate of cumulative gas released.

4.3. Gas composition and heating value

Fourteen coal cores (sampled from seven coal beds) retrieved from two exploratory drillholes were monitored for their gas composition from one to eleven months. Analyses of gas composition show that the coals sampled below at least 91 m generally have 90 to 99% methane content. Samples with low methane values indicate either a shallow coal sample or the introduction of nitrogen to the sample with time. For example, methane contents will be lower if the drillhole or well is within 610 to 914 m

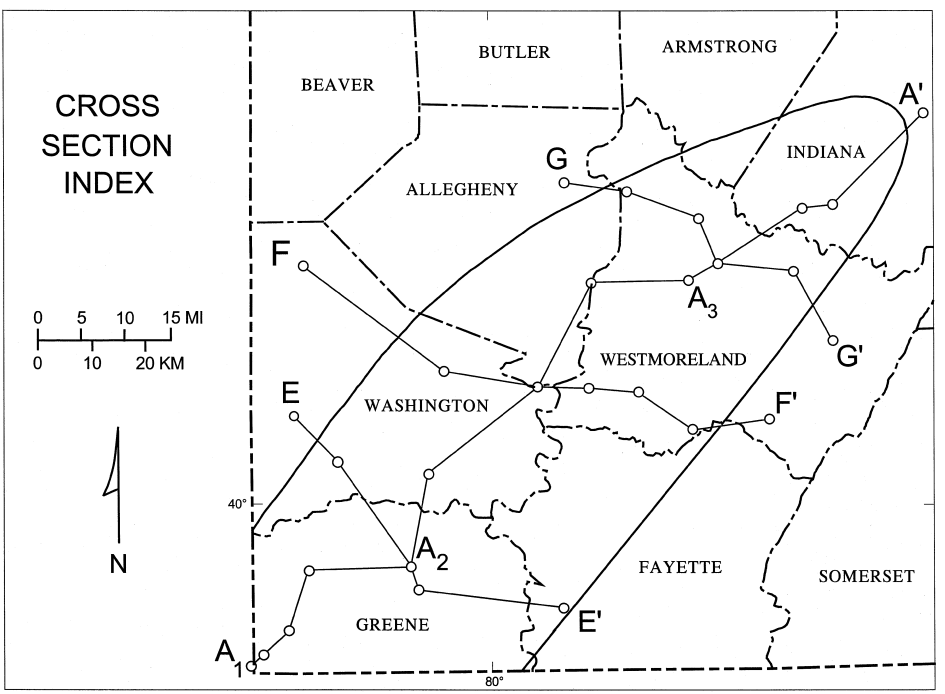
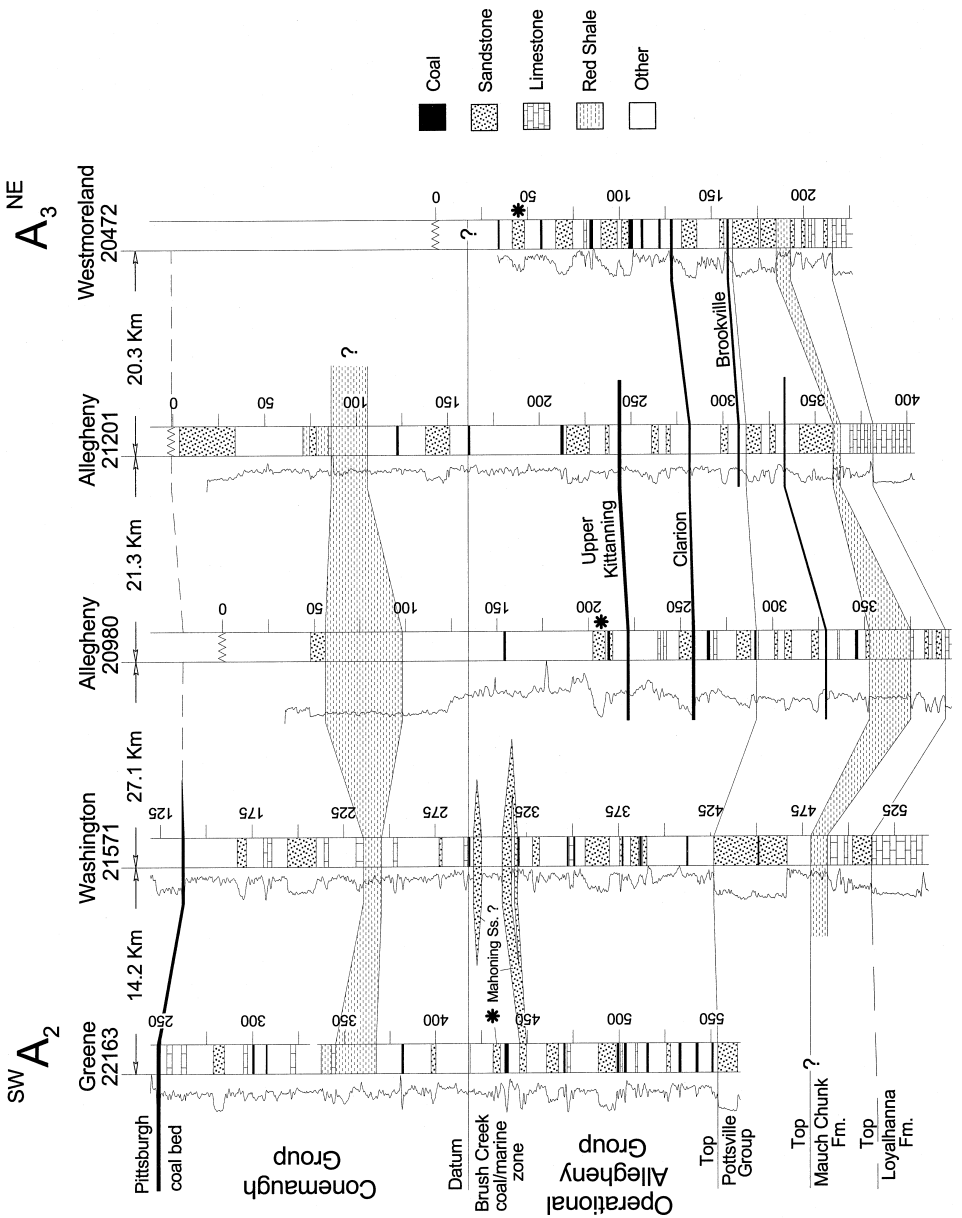


Fig. 7. Cross-section index map (modified from Bruner et al., 1995).


Coal
Sandstone
Limestone
Red Shale
Other
SW A2
NE A3
Greene 22163
Washington 21571
Allegheny 20980
Allegheny 21201
Westmoreland 20472
14.2 Km
27.1 Km
21.3 Km
20.3 Km
Pittsburgh coal bed
Conemaugh Group
Datum
Brush Creek coal/marine zone
Mahoning Ss. ?
Upper Kittanning
Clarion
Brookville
Operational Allegheny Group
Top Pottsville Group
Top Mauch Chunk Fm.
Top Loyalhanna Fm.

of an active mine. Previous studies from the U.S. Bureau of Mines revealed that over time, higher molecular weight hydrocarbons like ethane, propane, butane, pentane, and associated isomers tend to increase in the later stages of desorption. This suggests that large volumes of these gases might have been generated in certain coal beds, and in such cases would seem to desorb more slowly due to a larger molecule size (Ulery and Hyman, 1991). Samples from Greene County (Fig. 2), for example, contained from 0.03 to 2.91 normalized percent of the heavier hydrocarbons over a six month desorption period. Residual gas from some of these samples ranged from 0.10 to 5.94 normalized percent over an 11-month period.

Heating values of various ranks of coal from across the United States generally range from 4,744,575 to 15,129,923 J (4500 to 14,350 Btu) (Edmunds and Koppe, 1968). Coal samples from this study averaged 16,035,609 J (daf). Heating values from gas samples in this study averaged 1,054,350 J, comparable to conventional natural gas values. The samples with lower methane contents also have very low heating values and gas contents. On the other hand, high methane contents do not always guarantee high gas contents.

5. Geological evaluation of previous studies

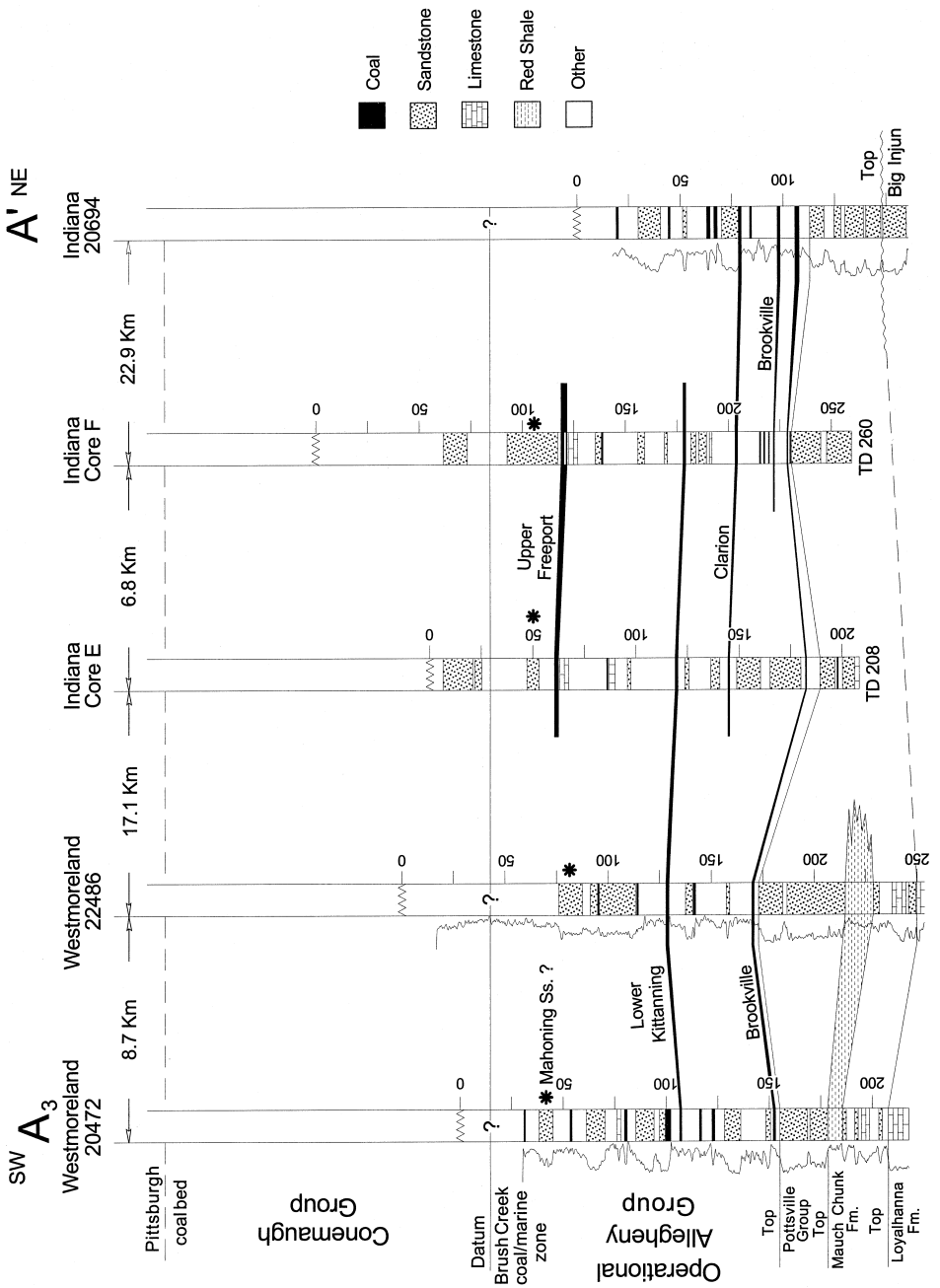
5.1. Introduction

The Pennsylvania Geological Survey and the West Virginia Geological and Economic Survey conducted a joint mapping investigation of coalbed methane resources in the Northern Appalachian (Dunkard) coal basin to better understand the influence of regional geology on coalbed methane potential. Methodology included the use of geophysical well logs, coal core logs, oil and gas records, correlation of coal beds and sandstones for regional cross-sections, and the interpretation of coal-sandstone relationships. Logs of oil and gas wells and coal cores (Fig. 6) were the source of data for the regional cross-sections shown in the cross-section index (Fig. 7) and as presented in Figs. 8 and 9. The cross-sections focus on the correlation of the operational Allegheny Group and associated strata.

5.2. Defining the operational Allegheny Group

The Allegheny Group extends from the top of the Pottsville Group to the top of the Upper Freeport coal bed (Fig. 1). Its thickness ranges from approximately 76 to 122 m in the study area. For mapping purposes, however, the need for definition of an ‘operational’ Allegheny Group arose because the Upper Freeport coal bed cannot always

Fig. 8. Cross-section A_2–A_3 showing the Loyalhanna Formation to Pittsburgh coal bed interval in Greene, Washington, Allegheny, and Westmoreland Counties, Pennsylvania (modified from Bruner et al., 1995).


SW
A3
A' NE
Coal
Sandstone
Limestone
Red Shale
Other
Westmoreland 20472
Westmoreland 22486
Indiana Core E
Indiana Core F
Indiana 20694
8.7 Km
17.1 Km
6.8 Km
22.9 Km
Pittsburgh coal bed
Conemaugh Group
Datum
Brush Creek coal/marine zone
Operational Allegheny Group
Top Pottsville Group
Top Mauch Chunk Fm.
Top Loyalhanna Fm.
Top Big Injun
Mahoning Ss. ?
Lower Kittanning
Brookville
Upper Freeport
Clarion
TD 208
TD 260

be identified from subsurface data or is not always present (Bruner et al., 1995). The 'operational' Allegheny Group as used here extends from the top of the Pottsville Group to the base of the Brush Creek marine zone and/or coal bed of the Conemaugh Group (Fig. 1). The mean thickness of the operational Allegheny Group is 137 m in southwestern Pennsylvania (Bruner et al., 1995).

The definition of the top of the Pottsville Group and the base of the Allegheny Group is also less clear because the Clarion sandstone (adjacent to the Clarion coal bed at the base of the Allegheny Group) commonly merges with the Connoquenessing and Homewood sandstones of the Pottsville Group (Fig. 1). Most of these thick sandstones were noted on drillers' logs and identified in cores and gamma ray logs as the 'Salt sands' or 'Homewood sandstone', depending on geographic region and the number of sandstones encountered. If a very thin sandstone or no sandstone is present, the top of the Pottsville was chosen by estimation through nearby control points.

5.3. Operational Allegheny prospect interval

The coalbed methane potential of the operational Allegheny Group is thought to exceed that of the other coal-bearing stratigraphic intervals in the study area because Allegheny Group coal beds have higher rank and greater total gas content per ton of coal (Diamond et al., 1986). Allegheny Group coals in Pennsylvania are typically thin and discontinuous and are commonly associated with sandstones. Most of the study area contains at least four Allegheny coal beds greater than 0.6 m thick, with an average total coal thickness of 3.1 to 4.6 m. The operational Allegheny Group prospect interval contains the following target coal beds: Brookville, Clarion, Lower, Middle, and Upper Kittanning, Lower and Upper Freeport, and Mahoning.

In their depositional model, Bruner et al. (1995) suggested that thick coal pods commonly occur offset from thick fluvial sandstone zones. Areas where differential compaction has been the primary influence tend to have offset channel systems. Erosional contacts have formed between coal beds and overlying channel–fill sandstones, thus forming potential non-coal methane traps (Bruner et al., 1995). Areas influenced by tectonics may exhibit stacked channel–fill sandstones. Repetitive sequences of coal accumulation are also stacked, commonly with shale interburden. These scenarios are prime targets for coalbed methane production (Bruner et al., 1995). Recent core data from the operational Allegheny Group yielded gas contents from 2.2 to 12.3 cm^3/g at depths from 127 to 387 m; average gas content for Allegheny Group coal beds ranged from 5.7 cm^3/g for the Kittanning coals to 7.1 cm^3/g for the Clarion/Brookville coals (Markowski, Pennsylvania Geological Survey, unpub. report). Rice and Finn (1996) concluded that the highest coalbed methane potential corresponds with the area where the Kittanning coal interval has more than 0.01 Bm^3/km^2 (0.5 Bcf $mile^{-2}$) of gas-in-place at depths greater than 91 m.

Fig. 9. Cross-section A_3–A' showing the Loyalhanna Formation to Pittsburgh coal bed interval in Westmoreland and Indiana Counties, Pennsylvania (modified from Bruner et al., 1995).

6. Cross-sections

Fig. 7 shows a cross-section index map of the geological evaluation study area and the cross-sections selected for this report (Figs. 8 and 9). The other cross-sections shown on Fig. 7 can be obtained from the Pennsylvania Geological Survey. Gamma-ray logs and corresponding strip logs showing lithologic selections are represented in the cross-sections (Figs. 8 and 9). These cross-sections show coal beds only where both gamma-ray and density logs, or coreholes, are used. They also show tentative correlations of the Mahoning Sandstone Member of the Conemaugh Group (upper sandstone pods and units in the operational Allegheny Group between the Upper Freeport coal bed and the Brush Creek coal bed/marine zone), individual Pottsville and Allegheny Group coal beds, and red beds of the Mauch Chunk Formation and Conemaugh Group (Figs. 1, 8 and 9). Wells with only gamma-ray logs were used to fill in areas where core and/or gamma-ray/density logs were unavailable (Bruner et al., 1995).

Cross-sections A_2–A' (Figs. 8 and 9) trend from north-central Greene County northeast to central Indiana County, Pennsylvania (Fig. 7) and include the interval from the Upper Mississippian Loyalhanna Formation to the Pittsburgh coal bed (Fig. 1). The operational Allegheny Group generally thickens to the northeast, whereas the Mauch Chunk Formation/Pottsville Group interval becomes thinner in the same direction. Several Allegheny Group coal beds appear to be present everywhere, but they are very discontinuous, making correlations difficult (Bruner et al., 1995). Tentative interval thicknesses between the top of each coal bed group from the study area are as follows: Upper Freeport to Upper Kittanning, 19 to 46 m; Lower Freeport to Upper Kittanning, 10 to 27 m; Upper Kittanning to Clarion/Brookville, 15 to 63 m; Lower Kittanning to Clarion/Brookville, 7 to 30 m.

The Conemaugh Group and Pittsburgh coal bed disappear along the line of cross-sections A_2–A_3 (Fig. 8) and A_3–A' (Fig. 9) because of erosion. Although the Mahoning Sandstone Member becomes more discontinuous along the lines of these sections, the lowermost Allegheny coal beds become more continuous. Mauch Chunk red beds occur between the Loyalhanna Formation and Pottsville Group sediments, providing alternative correlation tools (Bruner et al., 1995).

7. Results of coal-mapping data

A series of maps were constructed for the cooperative study from core-derived data and gamma-ray/density log combinations. Only coal beds greater than 0.6 m in thickness were used. Isopleth maps of the number of operational Allegheny Group coal beds, isolith maps of the net operational Allegheny Group coal thickness, and isopach maps of the thickest individual Allegheny Group coal beds can be obtained from one of the expanded versions of this report (Bruner et al., 1995) by contacting the Pennsylvania Geological Survey.

Most of the study area contains at least four coal beds greater than 0.6 m thick each, with as many as 10 individual coal beds in localized areas. Total thickness of all seams averages 3.1 to 4.6 m over much of the area with thicker pods in the northeastern part of the Pennsylvania study area.

The thickest individual coal bed in the operational Allegheny Group averages 1.2 to 1.5 m over much of the area, with localized thicknesses of up to 3.4 m. Field and core observations suggest that coal beds thicker than 2.1 m with many thin partings do not show up on oil and gas geophysical logs because of fast logging speed (Bruner et al., 1995).

8. Assessment of potential

Selected gas content data, correlations presented in this report (Figs. 8 and 9), and gas content results throughout the literature show that the total gas content of Pennsylvania's bituminous coal beds increases with increasing rank and depth. In general, the greater the depth of overburden, the higher the methane content. Most identified coal beds occurring in southwestern Pennsylvania between approximately 183 to 457 m deep are optimum economic targets for coalbed methane.

Thickness of the coal bed, according to communication from various industrial sources, is also important for economic production of coalbed methane, although it is not evident in this study. Combined production from stimulating multiple coal beds in a single well is common in Pennsylvania because of the prevalence of relatively thin cyclical beds.

Within different ranks of coal, variations in gas content are due to differences in matrix pore size distribution, coal maceral composition, and coal chemistry (Decker et al., 1986). The physical nature of the coal also dictates the rate of gas release. Friable coals having a more pronounced cleat network emit more gas during desorption than blocky, dense coals.

The presence of a cleat system in the coal bed is necessary for establishing permeability and hydrostatic/hydrodynamic conditions for coalbed methane generation. These may be faults, fold-induced fracturing, or stress fractures due to differential compaction properties of coal beds and adjacent shales. Favorable geologic structure and permeability occurs preferentially on the flanks of anticlines or synclines where the orientation and degree of jointing is more evident than on the crest of fold axes (Ayers and Kelso, 1989).

Coal in general is an effective reservoir rock because of its micropore structure. Its retention capacity is superior to that of a conventional natural gas sandstone or carbonate reservoir. Different ranks of coal have different capacities to store gas because of differences in their micropore system. In most cases, higher rank (and deeper) coals have a higher adsorptive or retentive capacity for methane gas storage than lower rank coals.

The target area for commercial development in Pennsylvania is a quasi-ellipse in the southwestern part of the state (Fig. 3). This is where the deepest, flat-lying coal beds occur compared to other parts of the state. Overall estimates of coalbed methane resources in the Northern Appalachian coal basin indicate there may be 1.7 Tm^3 of gas-in-place contained in the coal of the basin (Kelafant et al., 1988) and 0.3 Tm^3 of technically recoverable coalbed methane (U.S. Geological Survey National Oil and Gas Resource Assessment Team, 1996).

9. Conclusions

Over the last decade, the economic value of coal seam gas in Pennsylvania has attracted oil and gas industry interest. The information summarized in this report indicates the presence of very gassy coals in certain parts of the Dunkard basin of southwestern Pennsylvania. The resource potential of these coals deserves serious consideration because coalbed methane recovery is a cost-effective approach to achieving a range of energy, environmental, and safety goals. The target area for commercial development in Pennsylvania occurs in the southwestern part of the state, within a quasi-elliptical region of the Northern Appalachian coal basin. The deepest coals that exist here, and other coals near mines with known high methane emission rates, are potentially the most attractive for coalbed methane development.

Historically, the Pittsburgh coal bed of the Monongahela Group was once considered to be the prime target for coalbed methane. Gas shows from this bed are reported on many drillers' logs and estimated gas emission volumes are often large. Currently, gob gas from the Pittsburgh coal bed and the Allegheny Group coal beds are being produced via converted pre-mine ventilation wells.

Recent core data yielded gas contents from 2.2 to 12.3 cm^3/g at depths from 127 to 387 m; average desorbed gas content for Allegheny Group coal beds ranged from 5.7 cm^3/g for the Kittanning coals to 7.1 cm^3/g for the Clarion/Brookville coals. The highest coalbed methane potential corresponds with the area where the Kittanning coal interval has more than 0.01 Bm^3/km^2 of gas-in-place at depths greater than 91 m. Sandstones associated with the coal beds in southwestern Pennsylvania may also be targets for coalbed methane development.

It is difficult to nearly impossible to evaluate the methane drainage potential in the Anthracite region of northeastern Pennsylvania (Fig. 2). Few projects were initiated here due to the economics of drilling in a region of complex structure and stratigraphy (Diamond and Levine, 1981; Diamond et al., 1986). However, the variety of data presented from these sources suggest very high gas contents in localized areas of the Anthracite region. In Lackawanna and Schuylkill Counties, about 30 samples from nine coal beds were tested for their gas contents (Diamond et al., 1986). Results were quite different from those obtained in southwestern Pennsylvania. Refer to Edmunds et al., 1979 for the stratigraphic names of the following anthracite coal beds of Middle Pennsylvanian age (Dennison, 1978). The Big Bed of Lackawanna County yielded 1.7 cm^3/g at a basal depth of 31 m. The Mammoth coal bed of Schuylkill County had only 0.4 cm^3/g at the deepest basal depth of 524 m. Also in Schuylkill County, the Orchard coal bed at 414 m yielded the lowest total gas content at 0.2 cm^3/g, and the 209 m deep Peach Mountain coal bed of Schuylkill County yielded the highest at 21.6 cm^3/g. Although the Peach Mountain coal bed had the highest total gas content, the porosity and permeability were very low at this particular location (Trevits et al., 1986). Another drillhole indicated a high total gas content from the Tunnel coal bed at 15.1 cm^3/g. Even with stimulation and bottom-hole pumps, the presence of water in the hole and the low permeability inhibited further flow of gas for production. Localized pockets have anomalously high gas rates at shallow depths. The low gas rates at deep depths are due to complex folding and deformation in the region, and lack of cleat development. The

coalbed methane potential in the Anthracite region is uncertain because of the low permeability of the coal due to the absence of cleats or mineral-filled cleats (Law, 1993) and the high cost of exploration and production in a complex geologic setting. Despite this, the very high total gas contents of some of the anthracite coal beds suggest that further coalbed methane exploration should be conducted in this part of Pennsylvania.

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