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Assessment of Appalachian Basin Oil and Gas Resources: Carboniferous Coal-bed Gas Total Petroleum System

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Abstract

The Carboniferous Coal-bed Gas Total Petroleum System, lies within the central and northern parts of the Appalachian coal field. It consists of five assessment units (AU): the Pocahontas Basin in southwestern Virginia, southern West Virginia, and eastern Kentucky, the Central Appalachian Shelf in Tennessee, eastern Kentucky and southern West Virginia, East Dunkard (Folded) in western Pennsylvania and northern West Virginia, West Dunkard (Unfolded) in Ohio and adjacent parts of Pennsylvania and West Virginia, and the Appalachian Anthracite and Semi-Anthracite AU in Pennsylvani and Virginia. Of these, only the Pocahontas Basin and West Dunkard (Folded) AU were assessed quantitatively by the U.S. Geological survey in 2002 as containing about 3.6 and 4.8 Tcf of undiscovered, technically recoverable gas, respectively (Milici and ithers, 2003).

In general, the coal beds of this Total Petroleum System, which are both the source rock and reservoir, were deposited together with their associated sedimentary strata in Mississippian and Pennsylvanian (Carboniferous) time. The generation of biogenic (microbial) gas probably began almost immediately as the peat deposits were first formed. Microbial gas generation is probably occurring at present to some degree throughout the basin, where the coal beds are relatively shallow and wet. With sufficient depth of burial, compaction, and coalification during the late Paleozoic and Early Mesozoic, the coal beds were heated sufficiently to generate thermogenic gas in the eastern part of the Appalachian basin.

Trap formation began initially with the deposition of the paleopeat deposits during the Mississippian, and continued into the Late Pennsylvanian and Permian as the Appalachian Plateau strata were deformed during the Alleghanian orogeny. Seals are the connate waters that occupy fractures and larger pore spaces within the coal beds as well as the fine-grained siliciclastic sedimentary strata that are intercalated with the coal. The critical moment for the petroleum system occurred during this orogeny, when deformation created geologic structures in the eastern part of the basin that enhanced fracture porosity within the coal beds. In places, burial by thrust sheets (thrust loading) within the Appalachian fold-and-thrust belt may have resulted in additional generation of thermogenic CBM in the anthracite district of Pennsylvania and in the semianthracite

deposits of Virginia and West Virginia.

Introduction

Coalbed methane (CBM) occurs in coal beds of Mississippian and Pennsylvanian age in the Appalachian basin, which extends almost continuously from Pennsylvania to Alabama (Lyons, 1998, Markowski, 1998, Nolde and Spears, 1998, Attanasi, 1998, Pashin and Groshong, 1998). In general, the basin consists of three structural sub-basins, the Dunkard basin in Pennsylvania, Ohio, and northern West Virginia; the Pocahontas basin in southern West Virginia, eastern Kentucky, and southwestern Virginia; and the Black Warrior basin in Alabama (fig. 1). Although there is a considerable difference in detail, the overall stratigraphic framework of Carboniferous strata within the basin is remarkably similar from one end to the other.

By far, most of the coalbed methane produced in the Appalachian basin has come from the Black Warrior basin. During the 2002 National Oil and Gas Assessment (NOGA), the U.S. Geological Survey (USGS) assessed the hydrocarbon resources of the Black Warrior basin separately from the remainder of the Appalachian basin, however, and this discussion is restricted almost entirely to the assessment of the coalbed methane resources of the bituminous coal fields in the Dunkard and Pocahontas basins, and to the CBM potential of the anthracite and semianthracite districts in the Appalachian fold and thrust belt.

In general, coalbed gas accumulations are assessed as continuous accumulations and, for assessment purposes, are not designated as discrete fields. Nevertheless, in some areas the economic viability of an accumulation may be enhanced by local stratigraphy or geologic structure, and may result in a drilling entity that would be defined as a field, even though its boundaries are gradational with surrounding areas that contain gas. For the most part, CBM fields are designated by state regulatory agencies more for administrative and regulatory convenience, rather than for their geologic viability.

Methane degasification in advance of underground mining commenced in the early 1970’s in the Black Warrior basin, and in the late 1970’s and early 1980’s in the Pocahontas basin, initially as an effort to improve mine safety conditions in deeply buried coal beds. At first, vertical ventilation holes were drilled into the Blue Creek coal bed in Alabama and Pocahontas No. 3 coal bed in Virginia. At first, the gas produced from coal beds in advance of mining or from gob wells drilled into old works after mining was vented into the atmosphere. Upon recognition of the value of the resource and resolution of ownership issues, production of CBM commenced in Alabama in 1980 (Pashin and Hinkle, 1997) and in Virginia in 1988 (Nolde and Spears, 1998). Coalbed methane production from the Pocahontas No. 3 coal bed began in southern West Virginia in 1995 (Avary, 2003).

By 2002, annual production of CBM had increased to more than 110 billion cubic feet of gas (Bcf) from 3,357 wells in the Black Warrior Basin of Alabama (Alabama State Oil and Gas Board, 2002); 2,359 wells in the Pocahontas basin of Virginia and southern West Virginia produced 65.8 Bcf (Virginia Division of Gas and Oil, 2002; Avary, 2003); and 252 wells in Pennsylvania and northern West Virginia produced 1.4 Bcf of CBM in the Dunkard basin (Avary, 2003; Markowski, written communication, 2003). As of 2002, about 1.4 trillion cubic feet (Tcf) of CBM had been produced from the Black Warrior Basin, 439 Bcf from the Pocahontas basin, and 8.5 Bcf from the Dunkard basin (Table 1). In the Appalachian basin, the gas produced from coal beds is chiefly methane, with small amounts of other gasses. Gob gas produced from previously mined areas (coal mine methane) commonly contains relatively large amounts of gaseous impurities from mine atmospheres. Markowski (2001) provides numerous analyses of gas produced from both conventional CBM completions and gob wells in Pennsylvania.

East Dunkard and West Dunkard Assessment Units.

Introduction:

The Dunkard basin occupies much of the northern part of the Appalachian coalfield in Pennsylvania, eastern Ohio, and northern West Virginia (fig. 2). The basin, as defined generally by the crop line of the base of the Pennsylvanian Conemaugh Group, occupies an area that is about 300 miles long parallel to Appalachian regional strike, and is 100 miles wide. The former U.S. Bureau of Mines recognized both the safety problems and economic potential of coalbed methane released by coal mines in the Freeport and Kittanning coal beds in Indiana and Cambria Counties, Pennsylvania (fig. 3)

(Puglio and Innacchione, 1979; Innacchione and Puglio, 1979). In 1976, three mines in Cambria County produced an average of 2.6, 2.7, and 3.1 thousand cubic feet per day (Mcfd) of coalbed methane (Innacchione and Puglio, 1979, table 1). In Indiana County, a coalbed methane test in the Lower Kittanning coal bed yielded a gas content of 352 cubic feet per ton (cf/ton) under ambient conditions, one of the highest then ever measured from a coal bed in the bituminous coal fields of Pennsylvania (Puglio and Innacchione, 1979, table 8). In Ohio, Wolfe (1997) reported that in a mine in Harrison County had produced up to 500 Mcfd of methane; and in 1998, a well produced about 56.5 MMcf of gas for local use in six months (Steve O'Pritza, Ohio Division of Oil and Gas, verbal communication 6/2000).

Figure 2 illustrates the extent of the Carboniferous Coalbed Gas Total Petroleum System (TPS) (Magoon, 1988) in the northern part of the Appalachian coalfield, the extent of the Minimum Petroleum System (MPS) (the area in which the petroleum system is demonstrated to be active by the occurrence or production of hydrocarbons) in that region, and the extent of the area where Allegheny Group coal beds are buried deeply enough beneath the Conemaugh Group (≥ 500 feet) to be considered as potential sources and reservoirs for CBM. Shows, relatively small amounts of coal bed gas, and coal mine methane (most likely of microbial origin, Laughrey and Baldassare, 1998) occur well beyond the area selected for the minimum petroleum system, the area in which most of the gas produced is probably of thermogenic methane (vitrinite reflectance, Ro, ≥ 0.8).

The stratigraphic nomenclature for the major groupings of Pennsylvanian strata in the region is shown in Table 2, and coal bed nomenclature is presented in Table 3. The principal coal beds targeted for CBM exploration in this region are within the Monongahela and Allegheny Groups (figs. 3 - 7). Although all of the major coal beds are extensively mined along their outcrop, much unmined coal remains in the deeper part of the basin.

Stratigraphy:

Pottsville Group:- The Pottsville Group (or Formation) consists of the coal-bearing siliciclastic strata that are between older Mississippian strata and the top of the

Homewood sandstone or the base of the Brookville coal bed in the Allegheny Formation, where present (Table 2). The basal contact of the Pottsville with underlying strata is unconformable (fig. 3); accordingly, its thickness ranges greatly, generally from about 20 to 350 feet thick (Arkle and others, 1979; Collins, 1979; Edmunds and others, 1999). In Ohio and West Virginia, the Pottsville consists of primarily of conglomerates, sandstones, siltstones, and shale that contain a few thin and irregular coal beds. Marine limestone, shale, and calcareous ironstones are common, although in relatively small amounts. In Pennsylvania, the formation consists of a lower sequence of conglomerate, sandstone, and shale, with minor amounts of coal; and an upper succession that is composed of the Mercer coal zone and shale, and the overlying Homewood sandstone (fig. 3).

Allegheny Group:- The Allegheny Group (or Formation) includes all strata between the base of the Brookville coal bed to the top of the Upper Freeport coal bed (Table 2, fig. 3) (Arkle and others, 1979; Collins, 1979; Edmunds and others, 1999). In general, the group is an anastomosing mixture of sandstone, siltstone, shale and claystone, and coal (fig. 3) that ranges in thickness from about 100 feet to 330 feet. Nevertheless, some coals, marine shales, and limestones are very widespread (figs. 4 and 5) (Edmunds, and others, 1999). The lower half of the group contains several marine or brackish-water units, such as the Vanport Limestone; the upper part of the group is entirely non-marine. There are six major coal zones within the Allegheny Group, which makes it an important target for coalbed methane development (Table 3, figs. 3, 4 and 5). In ascending order, these include the Brookville-Clarion coal zone, the Lower Kittanning coal zone (Milici and others, 2001b), the Middle Kittanning coal, the Upper Kittanning coal, the Lower Freeport coal zone, and the Upper Freeport coal bed (Ruppert and others, 2001). Of these, the Upper Freeport and the Lower Kittanning are the second and third most important coal beds in Pennsylvania (behind the Pittsburgh) in terms of potential coal resources (Edmunds and others, 1999).

Conemaugh Group:- The Conemaugh Group consists of those strata between the top of the Upper Freeport coal bed and the base of the Pittsburgh coal (Table 2). In

Pennsylvania, the Conemaugh Group is divided into the Glenshaw Formation at the base and the Casselman Formation at the top (Table 2) (Flint, 1965). The boundary between these two units is the top of the marine Ames Limestone. The Conemaugh Group contains several named sandstone formations (or members), including the Mahoning Sandstone at the base of the Glenshaw Formation. The thickness of the Conemaugh Group averages about 400 feet in Ohio, and it ranges from 450 feet on the Ohio River in West Virginia to 520 feet in Washington County, Pennsylvania, and then to 890 feet in Somerset County, Pennsylvania (Arkle and others, 1979; Collins; 1979; Edmunds, and others, 1999).

The Conemaugh Group is dominated by siliciclastic strata, including claystone, shale, siltstone, and sandstone. In West Virginia, the Conemaugh consists primarily of red shales and mudstone, with some subgraywackes, thin limestones (both marine and non-marine), and thin coal beds. Red beds occur scattered throughout the stratigraphic section in Pennsylvania, and coal beds are generally thin and have little economic value. The Glenshaw Formation contains several marine units and the overlying Casselman Formation is almost entirely non-marine. In Ohio, the Conemaugh consists mostly of sandstones, siltstones, and shales. Thin coal beds occur scattered throughout much of the section; as in Pennsylvania, marine zones are common in the lower part of the Group, and red beds are abundant in the upper part of the section, which is generally non-marine (Arkle and others, 1979; Collins; 1979; Edmunds, and others, 1999).

Because the Upper Freeport coal bed and the overlying Mahoning Sandstone are discontinuous or absent in the subsurface of southwestern Pennsylvania and northeastern West Virginia, Bruner and others (1995, republished in 1998), in their study of the coalbed methane potential of the area, used the base of the Brush Creek marine zone within the lower part of the Glenshaw Formation as their key marker horizon to define the top of their coal-bearing "operational" Allegheny Formation. In effect, this definition includes about 110 feet of the Conemaugh Group, including the Mahoning Sandstone and the Mahoning coal bed, within their operational Allegheny Formation. The operational Allegheny Group of Bruner and others (1995, 1998) contains most of the target coal beds for CBM production in the northern Appalachian coalfield.

Monongahela Group:- The Monongahela Group extends from the base of the Pittsburgh coal bed upward to the Waynesburg coal bed (figs. 6, 7; table 2). Edmunds (1999a) and Edmunds and others (1999), included the Waynesburg coal bed within the Dunkard Group in Pennsylvania, whereas Arkle and others (1979) and Collins (1979) placed the Waynesburg within the Monongahela Group in West Virginia and Ohio. The Monongahela Group averages about 250 feet thick in Ohio. To the east, its thickness ranges from about 250 feet on the Ohio River to 400 feet in north-central West Virginia and adjacent Pennsylvania (Arkle and others, 1979; Collins; 1979; Edmunds and others, 1999). In Pennsylvania, the Monongahela is divided into two formations, the Pittsburgh Formation at the base, and the Uniontown Formation at the top. The boundary between the Pittsburgh and Uniontown Formations is placed at the base of the Uniontown coal bed (fig. 6) (Edmunds, and others, 1999).

In Ohio, the Monongahela Group is generally non-marine. It consists of a gray facies composed of gray shales, limestones, and thick coal beds in the northern and central part of the basin, a red facies composed of red and yellow mudstone and little coal in the southern part of the basin, and a transitional facies of mixed lithologies in between (Collins, 1979). In West Virginia as in Ohio, coal-bearing gray shale, mudstone, and limestone in the northern part of West Virginia grade southwestward into red shales and mudstone that contain little coal and limestone (Arkle and others, 1979). In Pennsylvania, the Monongahela consists mostly of limestones, calcareous mudstones, shales, siltstones, and silty sandstones. The principal sandstone of the Group, the Pittsburgh sandstone, overlies the Pittsburgh coal bed in the lower part of the section (fig. 7) (Edmunds, and others, 1999).

Four coal beds, the Pittsburgh, Redstone, Sewickley, and Waynesburg, occur in the Monongahela Group in the northern part of the Dunkard basin. Of these, only the Pittsburgh is laterally persistent and thick (4-12 feet) (Tewalt and others, 2001); the others, although locally important are not as thick and continuous as the Pittsburgh (fig. 8) (Edmunds, 1999a). In places, the Sewickley coal bed may be up to 6 feet thick in southern Green and Fayette Counties, Pennsylvania, and nearby counties in West Virginia. The Pittsburgh and, locally, the Sewickley coal beds are among the principal targets for CBM exploration and development in this region. Where the Pittsburgh has been mined in southwestern Pennsylvania, wells drilled into mine breakdown (gob) produce coal mine methane.

Geologic Structure:

The East Dunkard and West Dunkard Assessment Units (AUs) are entirely within the Dunkard basin synclinorium (fig. 2). The coal beds are both the source rocks and the reservoirs for methane. Depths to producing and potential coal beds range from several hundred feet around the perimeter of the Dunkard basin to 2,000 feet near its axis. Natural fractures related to regional geologic structure, as well as the more common cleats in coal, are essential for increasing the porosity and permeability of the coal beds to the extent required for commercial production of methane.

The East Dunkard AU is in the folded part of the synclinorium (fig. 2), where surficial folds in Pennsylvanian-age strata are the result of shortening above regional subhorizontal decollement in the Silurian salt and/or Ordovician shale formations (Frey, 1973). Structural intensity increases progressively to the east, to where the west-verging folds become increasingly asymmetrical; and near the Allegheny structural front their western limbs are steeply dipping to overturned. In general, deformation decreases progressively to the west as shortening above decollement decreases. There, the folds within the Plateau region are broad and have relatively low amplitudes related to their extent, so that their limbs have relatively low dips (fig. 9) (Edmonds, 1999a).

In general, current (2003) CBM exploration in the northern Appalachian coalfield is in the synclinal areas, where greater thicknesses of coal-bearing strata are preserved. Aside from wells drilled into mined Pittsburgh gob in Greene County, Pennsylvania, much of the recent drilling in Pennsylvania has occurred along the Uniontown (Latrobe) syncline, in Fayette, Westmoreland, and Indiana Counties (fig. 10; Table 4, pool numbers 18-25).

In contrast, historical production of CBM in adjacent Wetzel County, West Virginia, chiefly from the Pittsburgh and Sewickley coal beds in the Big Run and Pine Grove fields, has been primarily from the anticlines rather than from synclines (Table 4) (Patchen and others, 1991). CBM was discovered in the Big Run Field in 1932, and the Pine Grove CBM field was discovered in 1955. Patchen and others (1991) recognized the structural control on CBM production and on the occurrence of water within the Pittsburgh coal bed in these Wetzel County fields. Although gas occurs as a continuous accumulation in both anticlinal and synclinal areas, the Pittsburgh coal bed is generally wet, rather than dry, below a depth of about 260 feet above sea level in the Big Run and Pine Grove fields. The wells that encountered free gas in dry coal beds along the anticlinal axes were preferentially completed by the early operators, whereas wet and non-producing coal beds were generally not tested for gas. In the anticlinal traps in this area, free gas occurs in intermaceral porosity, open fractures, and cleats within the coal bed reservoir; because of the lack of interstitial water, however, the amount of gas may have been diminished by leakage. In the synclinal occurrences, the water serves as a seal so that the amount of the methane per ton within the coal bed may be greater than in the anticlines. However, because of the water it is likely that it would take a greater time to desorb an equivalent amount of gas from wells drilled in synclines than in anticlinal areas (Patchen and others, 1991).

Coalbed Methane Fields and Pools:

The major fields and pools in Pennsylvania and northern West Virginia are described in Table 4 and illustrated on Figure 10. All of the fields are located in the East Dunkard Assessment Unit. As of late 2003, there are about 225 commercial CBM wells in Pennsylvania. Of these, 132 wells drilled in unmined seams were completed using hydraulic fracturing and stimulation. The other wells tested and produced gas from gob in active and abandoned mines (coal mine methane) (Markowski, 2003, written communication). Production in Pennsylvania is currently from four fields, Blairsville field in Indiana County, Munster field in Cambria County, Waltersburg field in Fayette County, and Lagonda field in Washington County (fig. 10). In addition, gob gas is currently being produced from several wells in Greene County. By far, the most productive area in Pennsylvania is in Indiana County, from the Campus Mill pool in the Blairsville field, primarily from coal beds in the lower part of the Conemaugh, Allegheny, and the upper part of the Pottsville Groups (Markowski, 2001; Markowski, A. K., CBM Activities in Pennsylvania: Unpublished presentation, October, 31, 2001, to the Fall Session of the North American Coalbed Methane Forum, Morgantown, WV). In

2002, Indiana County produced about 865 million cubic feet of CBM (Markowski, 2003, written communication). Two wells are producing CBM from multiple coal horizons in Wetzel County, West Virginia. In Monongahela County, West Virginia, 23 wells are producing from the gob of the Pittsburgh coal bed in the Blacksville mine, and 4 wells are producing from multiple coal beds in the St. Leo field (Avary, 2003) (Table 4, fig. 10). In Ohio, CBM of probable microbial origin is being produced for local uses from several gob wells in Harrison County (West Dunkard Assessment Unit).

Assessment Data:

The principal factors taken into consideration during the USGS 2002 assessment of CBM in the northern Appalachian coalfield are: (1) maximum reported gas-in-place data (fig. 11), (2) thermal maturation data (figs. 8-10), (3) timing of generation and migration of hydrocarbons, (4) porosity and permeability, (5) cumulative coal thickness, (6) known distribution of major coal beds, (7) depth of burial, (8) water production, and (9) cumulative production data (fig. 12).

Coal as a Source Rock for CBM:

Gas-in-place data:- In autogenic (self-sourced) accumulations, such as coalbed methane, the source rocks and the reservoirs are the same stratigraphic unit. Accordingly, gas-in-place (desorption) data may provide a direct indication of potential production. Almost all of the gas-in-place data, measured in cf/ton, used in this report were compiled and published by the former U.S. Bureau of Mines (Diamond and others, 1986). The gas values reported by Diamond and others, 1986 are at ambient field and laboratory conditions, and have not been corrected to standard temperature and pressure (STP). In the northern Appalachian bituminous coal fields, gas-in-place data range from 10 to 442 cf/ton, with the largest values in Indiana, Westmoreland, and Greene Counties, Pennsylvania, and Barbour County, West Virginia (fig. 11). Because of the great differences in the numbers of gas desorption samples from different counties, the largest available value, in cf/ton, was plotted for each county in figure 11, rather than an average value for each county. In counties for which there are few samples, however, it is very likely that larger desorption values would be obtained from additional tests. Where the number of samples is large (say 50 or more), the largest value currently observed may be approximating the upper end of the sample size distribution. Available data, however, indicate that the average gas content for the Pittsburgh coal bed is about 140 cf/ton; about192 cf/ton for the Freeport coals, and about 252 cf/ton for the Kittanning coal beds (Bruner and others, 1995, 1998).

Thermal maturity:- The coal beds are considered thermally mature with respect to methane generation at %Ro values that exceed 0.6 to 0.8 (fig. 8). Much of the coal bed gas to the east of the 0.8 %Ro isoline in the eastern part of the East Dunkard (Folded) AU is probably of thermogenic origin. In southwestern Pennsylvania, adjacent to the 0.8% Ro isoline, microbial gas in Pennsylvanian coal beds has been reported mixed with thermogenic gases (Laughrey and Baldassare, 1998). However, it is expected that much of the CBM to the west of the 0.8% Ro isoline would be of microbial origin.

Although there is considerable potential for the generation and accumulation of microbial CBM in the southern part of the East Dunkard (Folded) AU, and generally throughout the area of the West Dunkard (Unfolded) AU, the area that is thermally mature (>0.8 %Ro) is considered to have a greater potential for CBM development than the areas that are immature. The thermally mature area includes almost all of the area of current development (figs. 8, 10; %Ro isoline based upon unpublished data supplied by Leslie Ruppert, 2002).

Generation and migration:- Microbial methane almost certainly has been generated from the formation of the first Pennsylvanian peat deposits to the present day, where surface waters interact with shallow coal beds (Laughrey and Baldassare (1998). Thermal maturation commenced toward the end of the Paleozoic to the east, in the deeper part of the Appalachian Plateaus region, where it may have been enhanced by Alleghanian folding and faulting. Thermal maturity probably was reached in the eastern half of the basin during the latest Paleozoic and earliest Mesozoic (fig. 13), prior to erosion associated with regional uplift and crustal extension during the early Mesozoic.

In autogenic CBM accumulations, only local desorption of gases from coal macerals into micropores and natural fractures is needed to charge the reservoir.

However, long distance migration of CBM along coal beds is unlikely, especially if the coal beds are wet, because formation waters would inhibit desorption of methane into a fracture network. In contrast, relatively porous sandstone beds adjacent to coal source rocks may provide a network of fractures and pore spaces sufficient to support long-distance migration of desorbed gases.

Coal as a Reservoir for CBM:

Porosity and permeability:- Coal beds are structurally weak when compared to the enclosing strata. As a result, coal beds are highly susceptible to deformation when they are folded or faulted. In order for gas production to occur, desorbed methane in small pore spaces (micropores, macropores) must first migrate into fracture systems, either natural or man- induced, on the way to a well bore. Effective methane production, thus, depends upon the development of an extensive fracture system within coal bed reservoirs. Natural fractures include face and butt cleats, as well as fractures formed by structural deformation.

In general, abundant, closely spaced orthogonal cleat systems, which form relatively early in the coalification process, are widespread in the Appalachian bituminous coal fields (Bruner and others, 1995, 1998). In many places, however, coal beds contain additional natural fractures that are related to Appalachian structural deformation and have been superimposed upon previously existing cleats. Although tectonically-induced fractures may destroy the fabric of previously formed cleats in some places, they commonly increase the fracture porosity of the deformed coal beds. Pashin and Hinkle (1997) maintain that where the dip of folded coal measures exceeds 10 degrees, cleat is commonly destroyed and is replaced by closely spaced inclined fractures and normal faults within the coal beds. Accordingly, large-scale folding in the eastern part of the coal field in Pennsylvania and West Virginia very likely has increased the fracture porosity of target coal beds in those areas as the coal beds were preferentially deformed by interstratal slip during deformation. Furthermore, Harris and Milici (1977), Milici and Gathright (1985), and Milici and others (1982, 1986) have described the occurrence of bedding parallel faults and associated structures within coal beds in

Tennessee and Virginia that may significantly increase fracture porosity, both within the coal beds and in the enclosing strata.

Coal bed distribution:- Figure 8 illustrates the known distribution of the three major coal-producing beds in the northern coal fields, the Lower Kittanning, Upper Freeport, and Pittsburgh coal beds, together with the areas of known mining (Northern and Central Appalachian basin Coal Regions Assessment Team, 2001). Each of the maps shows that their respective coal beds do not appear to extend to the southwest, from Pennsylvania into central West Virginia. Although the map of the Pittsburgh coal bed reflects the distribution of this bed in the deep part of the basin with a reasonable degree of certainty, the maps of the Upper Freeport and Lower Kittanning coal beds do not. The correlations of Allegheny Group coals with their equivalents in southern West Virginia, easternmost Ohio, and eastern Kentucky were not well enough understood to justify their extension into those areas.

The principal area of the Dunkard basin that was assessed quantitatively by the USGS in the 2002 assessment is that designated as the minimum petroleum system in western Pennsylvania and adjacent West Virginia (figs. 2, 8, 10, 11, 12). The southwestern part of the East Dunkard (Folded) AU and the West Dunkard (Unfolded) AU were not assessed (Milici and others, 2003). The West Dunkard AU area is immature with respect to thermogenic methane generation and contains little structure that would enhance coal bed porosity. The gas that is being produced in this area from an underground mine complex in Harrison County, Ohio may be mostly of microbial origin. It should be noted, however, that any significant discovery in this relatively untested area could impact future CBM assessments greatly.

Cumulative Coal Thickness:- A cumulative coal thickness of 15 to 20 feet or more, distributed over several coal beds, is considered favorable for CBM development. Bruner and others (1995, 1998, fig. 41) have shown that much of the area in southwestern Pennsylvania and northern West Virginia is underlain by a cumulative coal thickness, in their operational Allegheny Group, that exceeds 15 feet (their net coal isolith map).

Seals:

Depth of Burial:- Much of the CBM production in the northern Appalachian coal field is in the deeper part of the basin. A depth of burial to the target coal beds of 500 feet or more is considered important to seal the gas within potential reservoirs (see Markowski, 2001 for a summary). Although the possibility of obtaining large amounts of microbial gas from shallow, wet reservoirs cannot be disregarded, those areas may require a cumulative coal thickness of 15 to 20 feet, or more, in order to generate an economic volume of gas.

Water Production:- Connate water contained within the natural fractures of the coal beds is an effective seal. In many CBM reservoirs this water must be removed by pumping to reduce reservoir pressure and initiate gas production. For example, in the Blairsville field, Pennsylvania, CBM wells completed in wet coal beds may produce as much as 15 to 30 thousand barrels of water during their first few years (Markowski, 2000). The water is sent to a treatment facility and discharged into nearby surface drainage (Markowski, 1998).

Cumulative Production and Estimated Ultimate Recovery Data:

Cumulative production data provide another indicator of potential in this greatly under-explored region. The counties that have produced a Bcf of gas, or more, include Wetzel and Monongahela counties in West Virginia, and Washington and Indiana counties in Pennsylvania (Table 1, fig. 12). These counties are in or near the area that is thermally mature ($R_o \geq 0.8$) and are in the deeper part of the basin. Although much of the historical CBM production in Greene and Washington Counties, Pennsylvania, and in Monongahela County, West Virginia, was from gob associated with the mining of the Pittsburgh coal bed, CBM wells were successfully completed in unmined coal beds in the now-abandoned Pine Grove and Big Run gas fields and in a new unnamed field in Wetzel County, and in the St. Leo field in Monongahela County, West Virginia. The Blairsville field, which produces almost all of the gas in Indiana County, Pennsylvania, had produced approximately 3.4 Bcf as of 2002 (Table 1).

Patchen and others (1991, fig. 24), in their study of the Big Run Field plotted the average annual CBM production per well of seven wells for their 35-year history. The average estimated ultimate recovery (EUR) for these wells is about 120 MMcf of methane. Rice and Finn (1996) used an EUR of 121 MMcf for the Northern Appalachian Anticline Play and 216 MMcf for the northern Appalachian Syncline Play. Both of these plays were assessed as analog plays. In the current assessment (Milici and others, 2003) we used a mean value of 160 MMcf for the EUR for the minimum petroleum system area of the East Dunkard AU.

Assessment Results:

Given the 30-year time frame of this assessment, the area that was considered most likely to be developed is within the MPS of the East Dunkard (Folded) AU (fig. 8). This area was assessed at the mean as containing about 4.8 Tcf of technically recoverable methane. This value is significantly less than the CBM assessment of Rice and Finn (1996) for the northern Appalachian coal field; they reported an undiscovered resource of about 11.6 Tcf for a much larger area in the coal field. Furthermore, Rice and Finn (1996) used an analog methodology for the Appalachian CBM assessment, primarily because they had little or no exploration and production data on which to base their assessment, and their assessment was not constrained by a 30-year time frame. The results of the current assessment are shown in Table 5.

Pocahontas basin and Central Appalachian Shelf Assessment Units

Introduction:

For assessment purposes, the central Appalachian coal field was divided into two AUs, the Pocahontas basin Assessment Unit, and the Central Appalachian Shelf Assessment Unit (fig. 14). In general, the CBM resources of the Pocahontas basin have been well developed during the past several decades, whereas the Central Appalachian shelf has been little explored.

The Pocahontas basin lies along the eastern margin of the Appalachian Plateaus, where it extends along regional structural strike for about 200 miles, from eastern Kentucky, through southwestern Virginia, to southern West Virginia. Because of its location along the eastern margin of the Appalachian foreland basin, the Pocahontas basin contains the greatest thickness of Pennsylvanian strata and the largest number of bituminous coal beds in the central part of the Appalachian basin. Coal has been produced from the Pocahontas basin for more than 150 years, and there are about 30 major named coal beds in the basin that are commercially mined for coal. The boundary between the Pocahontas basin and Central Appalachian Shelf AUs lies generally along the western limit of the Pocahontas Formation in the subsurface, which occurs from near the Virginia-Kentucky state line to a few miles into eastern Kentucky from Virginia. (Englund and Thomas, 1990).

The Central Appalachian Shelf, which occupies an area about 270 miles long and 50 to 75 miles across, extends from the Wartburg basin in Tennessee (Milici and others, 1979) across eastern Kentucky, to the broad structural arch in West Virginia that lies between the Dunkard basin on the north and the Pocahontas basin on the south (fig. 14). In eastern Kentucky and Tennessee, the predominant structure of this region is the regional dip of the Appalachian Plateaus, from the Cincinnati arch on the west, eastward into the Appalachian basin. In general, the arch has been a positive structural element since its inception in the Ordovician (Wilson, 1949), so that Ordovician and younger strata thin westward away from the Appalachian basin, and commonly wedge out over the arch. Accordingly, the preserved thickness of the coal-bearing Pennsylvanian rocks decreases from several thousand feet to a few hundred feet generally from southeast to northwest across the basin. There are about 30 major coal beds or coal zones along the eastern side of the Central Appalachian Shelf AU, where it is near the deeper part of the basin. To the west, where the Pennsylvanian stratigraphic sequence laps onto the Cincinnati arch and is partly truncated by erosion, there are relatively fewer coal beds and they are much less deeply buried (Englund and Thomas, 1990; Rice, 1986). Although this part of the Appalachian basin has been extensively explored for conventional oil and gas, at present there is no commercial production of CBM from the Central Appalachian Shelf AU.

Stratigraphy:

The Pennsylvanian stratigraphic nomenclature of the Central Appalachian Shelf AU (Tennessee, eastern Kentucky, and southern West Virginia) and Pocahontas basin AU (Virginia and southern West Virginia) is shown in Table 6. It is anticipated that the greatest potential for CBM development in the shelf area may be in the lower part of the Breathitt Formation in eastern Kentucky and its equivalents in Tennessee, as well as from coal beds in the Lee and equivalent, formations. Similarly, most of the CBM production in the Pocahontas basin in Virginia and West Virginia has been from coal beds in the Pocahontas and New River Formations and their lateral equivalents.

Pocahontas Formation: - The Pocahontas Formation, which is the lowest Pennsylvanian stratigraphic unit in the central Appalachian basin, extends generally northeastward from the Virginia coalfield into adjacent West Virginia; it extends northwestward from its crop line along the eastern margin of the Appalachian coal basin into the subsurface to where it is as much as 2,500 feet deep. To the west, deep in the subsurface of Virginia and southern West Virginia, the Pocahontas Formation is truncated by a regional unconformity that cuts downward through Pennsylvanian strata (Englund, 1979; Englund and Thomas, 1990). In some places the Pocahontas is laterally equivalent to the Lee; in other places the Lee overlies it, and elsewhere it is overlain unconformably by the New River Formation. The Pocahontas Formation contains the highest quality low-sulfur coking coal in the central part of the Appalachian basin, which is produced from the Pocahontas No. 3 coalbed (McColloch, 1995).

The Pocahontas Formation is a sandstone-dominated sequence that consists of up to 980 feet of sandstone, siltstone, shale, and low-sulfur coal along its outcrop in Virginia and West Virginia (Englund, 1979; Englund and others, 1986; Englund and Thomas, 1990; Milici and others, 2001a). Englund and others (1986) showed that the formation was deposited in a series of northwestward-prograding delta lobes. The Pocahontas coal beds apparently accumulated on the lobes of the paleodelta in several thick peat domes (up to 13 feet thick after compaction), which in places have been mined extensively

(Milici and others, 2001a). Shale-dominated inter-lobe areas contain relatively thin, discontinuous coal beds.

Because of its high gas content, the mined areas in the Pocahontas No. 3 coal bed contain many gob wells. Some of these gob wells had their origin as "vertical ventilation holes" that had vented methane into the atmosphere in advance of mining prior to 1988, when CBM was first produced economically in Virginia (Nolde, 1995). Elsewhere, in unmined areas, numerous wells have been completed within the Pocahontas No. 3 coal bed as well as in several of the overlying coal beds (Table 6).

New River Formation:- The New River Formation is 1,400 – 1,750 feet thick in southwestern Virginia and southern West Virginia. It contains up to 16 named coal beds, many of which have been completed for CBM (Nolde, 1994a; Nolde and Spears, 1998) (Table 7). In Virginia, the New River is lithologically similar to the Pocahontas Formation, except that it contains several widespread, thick beds of quartzose sandstone and quartz-pebble conglomerate (tongues of the Lee Formation) in the western part of the coalfield (Englund and Thomas, 1990; Nolde, 1994a). Nolde (1994a) regarded the New River as transitional between the quartzose sandstones and conglomerates of the Lee Formation and the subgraywacke sandstones of overlying Norton Formation (Table 6). Marine fossils have been reported from near the base of the New River in Virginia (Nolde, 1994a; Arkel et al, 1979; Englund, 1979).

Kanawha Formation:- The Kanawha Formation, the West Virginia equivalent of the upper part of the Norton Formation, the Gladeville Sandstone, and the Wise and Harlan Formations in Virginia (Nolde, 1994b) (Table 6), consists of up to 2100 feet of subgraywacke sandstone, shale, and mudstone. It contains several marine limestones and shale beds that contain marine to brackish-water invertebrates. In some places, marine zones consist of 30m-thick coarsening-upward units of fossiliferous shale, siltstone, and sandstone that are widespread across the basin (Blake and others, 1994). Offshore facies consist of dark-gray, fossiliferous laminated shales. Nearshore and littoral deposits are interlaminated to interbedded shales, siltstones and sandstones that exhibit the flasered bedding of tidal sedimentary environments. These beds may contain inarticulate brachiopods and a variety of shallow-water trace fossils (Martino, 1994). In West Virginia, the War Eagle, Gilbert, and Douglas coal beds within the lower part of the Kanawha Formation have been completed locally for CBM (Avary, 2003).

Lee Formation:- In Virginia, southern West Virginia, and eastern Kentucky, the Lee Formation, of Upper Mississippian and Lower Pennsylvanian age, consists of 800 to 1,650 feet of quartzose sandstone and quartz-pebble conglomerate formations that are interstratified with coal-bearing shale, siltstone, and sandstone units. The Lee is in part equivalent to the Upper Mississippian-Lower Pennsylvanian Bluestone Formation and to the Lower Pennsylvanian Pocahontas, Norton, and New River Formations (Table 6) (Englund, 1979, Englund and Thomas, 1990; Nolde, 1994a).

There are several interpretations concerning the depositional environment of the Lee Formation. Ferm (1974) concluded that the Lee Formation was deposited as a northwestward migrating beach- and back-barrier complex; similarly, Englund (1979) interpreted the depositional environments of the Lee and the overlying New River Formation as being "dominated by coastal and near-coastal deltaic processes." Rice and others (1979), however, suggested that the sandstone members of the Lee "were large sand-filled distributary channels of a dominantly southwest-prograding delta." More recently, Greb and Chestnut (1996) described the Lee in Kentucky as consisting of multistory braided fluvial sand bodies, which are capped by estuarine sand facies, coal, and then by carbonaceous shales that contain marine or brackish-water fauna. Regardless of its interpreted depositional environment, the Lee Formation is time-transgressive and becomes progressively younger to the northwest.

In general, the Lee Formation does not contain an abundance of coal beds, except in the deeper part of the basin. There, in the central part of the Virginia coalfield, many of the coal beds recognized within the New River Formation (Table 7) extend laterally into the Lee Formation (Nolde, 1994a), where they are completed for CBM.

Norton Formation:- In Virginia, the Norton Formation generally overlies the Lee Formation conformably and consists of up to 1,970 feet of gray shale, siltstone and lesser amounts of feldspathic and micaceous sandstone (Englund, 1979; Nolde, 1994a; Nolde and Spears, 1998). At least four beds within the Norton contain fresh or brackish-water fossil invertebrates. The fossiliferous beds generally consist of 5-10 feet of dark-gray shales that in places contain thin beds, lenses, or nodules of limestone. The Norton Formation is widely distributed in southwest Virginia and contains 20 coal beds (more or less) that may be completed for gas. These coal beds include most of those listed in Table 7, as well as the overlying Raven, Aily, Kennedy, Big Fork, Lower Banner, Upper Banner, Splash Dam, Hagy, and Norton coal beds.

Gladeville Sandstone:- The Gladeville Sandstone consists of about 75 to 120 feet of quartzose to feldspathic sandstone (Englund (1979); Nolde, 1994a, Nolde and Spears, 1998). It overlies the Norton Formation with a conformable, but sharp contact, and is in turn overlain by the Wise Formation (Table 6).

Wise Formation:- The Wise Formation (Table 6), up to 2,268 feet thick (Miller, 1969), is comprised of fine- to coarse-grained siliciclastic strata, predominantly siltstone and sandstone. Shale beds that occur above several of the coal beds may contain invertebrate fossils. The Wise contains two widespread marine zones, the Kendrick Shale of Jillson (1919), and the Magoffin Member of the Wise Formation (Miller, 1969) (originally the Magoffin Beds of Morse, 1931). In Virginia, the Kendrick Shale ranges from 10 to 20 feet thick, is dark gray to black, and contains calcareous lenses with cone-in-cone structures and brackish-water to marine fossils. The Magoffin Member consists of 20 to 30 feet of fossiliferous gray shale, thin beds of limestone, and calcareous siltstone (Nolde, 1994a). Coal beds in the lower part of the Wise Formation include the Dorchester, Lyons, Blair, Clintwood, and Addington. Coal beds higher in the section are not widely distributed in this mountainous terrain and have little chance for development of CBM resources.

Harlan Formation:- The Wise is overlain by the Harlan Formation, which is the uppermost Pennsylvanian formation in Virginia (Table 6). The Harlan is thickest on the mountaintops along the state line near Kentucky, where it consists of about 650 feet of sandstone with minor amounts of siltstone and shale and several beds of coal (Englund, 1979).

Breathitt Formation:- The Breathitt Formation overlies the Lee Formation (both formations were included in the Breathitt Group by Chestnut, 1992) over much of the area of the eastern Kentucky coalfield. It ranges from as much as 3,000 feet thick in southeastern Kentucky, where it is only partly preserved, to about 800 feet thick in northeastern Kentucky, where it is overlain by the Conemaugh Formation (Rice and others, 1979). The Breathitt consists of shale, siltstone, impure sandstone (subgraywackes), coal, limestone, and ironstone. It contains about 30 mineable coal beds or coal zones. Shales and siltstones are commonly carbonaceous and contain plant fossils. Marine fossils occur in some thin zones. The Kendrick Shale of Jillson (1919), the Magoffin Member, and the Lost Creek Limestone of Morse (1931) are major marine zones that serve to subdivide the Breathitt locally. These zones, up to 115 feet thick, represent regional marine transgressions that apparently were deposited in large, open bays (Rice and others, 1979). Relatively thin and locally distributed marine zones occur throughout the Breathitt, and these may represent local bay-fills or estuarine deposits.

Several wells have been successfully completed in the Breathitt Formation for coalbed methane in Clay and Bell Counties, Kentucky (Table 1) (Kentucky Division of Oil and Gas, 2004). These wells were probably completed in Lower Elkhorn coals (Brandon Nuttall, Kentucky Geological Survey, written communication, 2001).

Geologic Structure:

In general, the major geologic structures of the central Appalachian coalfield are the regional dip to the southeast from the Cincinnati arch into the basin, and the Pine Mountain block (Cumberland Overthrust block) in Tennessee, Virginia, and eastern Kentucky (fig. 15). Numerous other structures have been mapped in this area, and were summarized by Harris and Milici (1977), and more recently by Chestnut (1992) and Henika (1994).

The Pine Mountain block is a major Alleghanian structure that is terminated on its ends by cross faults, the Jacksboro fault in Tennessee and the Russell Fork fault in

Virginia. To the southeast, the block is bounded by the Powell Valley anticline, which was formed above a major structural ramp that transfered displacement from decollement in the underlying Rome Formation (Cambrian) up into Paleozoic shales of Silurian and Devonian age.

Young (1957) documented explosive gas production that resulted from drilling into deformed and greatly fractured Devonian black shale at the base of the Pine Mountain Block in southwestern Virginia. Gas production in these wells, which were drilled with cable tools, was almost instantaneous, and in many cases blew the drilling tools up the hole. Similarly, Harris and Milici (1977) described bedding decollement in coal beds and associated fracture systems in their hanging walls from extensive exposures in southern Tennessee. Subsequently, Milici and others (1982), Milici and Gathright (1985), and Milici and others (1986) documented decollements in southwestern Virginia that were localized within coal beds and associated shales, either in shale partings within the coal beds or in shale beds immediately overlying the coal beds. Henika (1994) provided additional examples of coal-bed decollement. Without question, decollement in hydrocarbon-rich rocks, whether black shales or coal beds, is a mechanism that may enhance porosity in these rocks. Where deformation is great, however, the gas may be released explosively and production will be short lived, as it was beneath the Pine Mountain Block. Where deformation is slight or moderate, however, production may be enhanced by additional networks of fractures that intersect joints in shales or cleats in coal, as it may be in some CBM reservoirs in the Pocahontas basin.

Coalbed methane fields:

For the purposes of this paper, the principal coalbed methane accumulations in the Pocahontas basin in Virginia are grouped into the Buck Knob field in Wise County, and the Nora and Oakwood fields (fig. 14). The Nora field is mostly in Dickenson and Russell Counties, whereas the Oakwood field is mostly in Buchanan and Tazewell Counties. In West Virginia, the named fields are the Bradshaw, Welch, McGraw, and Slab Fork fields (fig. 14). Jack E. Nolde, Consulting Geologist, compiled the (unpublished) Virginia well data used in this assessment for the USGS from the files of the Virginia Division of Gas and Oil. Avary (2003) compiled the data for West Virginia.

Lewis (1999) described the Buck Knob anticline field thusly:

"The Buck Knob anticline of Wise County represents the southwestern extent of coalbed methane production in Virginia. The anticline at depth is a ramp structure developed as a result of overthrusting of the Devonian Shale during the Alleghanian orogeny. Approximately 400 feet of structural closure is expressed at the Pennsylvanian level.

Numerous temperature anomalies and natural gas shows (5-620 MCFPD) were encountered while drilling and logging through the coal section. Reservoirs belong to the Norton and Lee Formations (Morrowan) and range from 650-2450 feet in depth. The coals are of high volatile A to medium volatile bituminous rank. Gas contents range from 60-150 SCF/ton. A typical completion contains 6 coal seams with an aggregate thickness of 120 inches. Stimulation is achieved through single stage limited entry fracture treatment.

Average open flow is 50 MCFPD. Average peak rate is 95 MCFPD and is reached within 9-12 months. Exceptional wells have production rates above 200 MCFPD. Current field rate exceeds 1500 MCFPD. Estimated ultimate recoveries are 425 MMCF per well based on 80 acre spacing. Total field recoveries are expected to reach 25-30 BCF.

The field serves as an analog for low rank/low gas content coals producing at economic rates due to enhancement of permeability by natural fractures."

The natural fractures in the Buck Knob field may be related to interstratal slip along the limbs of the fold, or to limited bedding decollement within the coal beds that occurred before and during folding. Target coal beds are in the Lee, Norton, and Wise Formations and depths to the tops of completed zones range from about 635 to 2,480 feet. In recent years, CBM production from Wise County, Virginia, mostly from the Buck Knob field, has declined from 1.1 Bcf in 1999 (62 wells) to 978.5 MMcf in 2001 (67 wells) (Virginia Center for Coal and Energy Research, 2004).

CBM production in Buchanan County, Virginia, mostly from the Oakwood field, appears to have peaked in 2000 at 41.7 Bcf (1,328 wells) and was down a little, to 41.5 Bcf in 2001 (1,696 wells). Target beds in Buchanan County range from the Seaboard coal bed, in the New River or Norton Formation, down to the Pocahontas No. 1 coal bed in the Pocahontas Formation, with the largest number of completions in the Pocahontas No. 3 coal bed (Table 7). CBM is produced from gob in mined areas of the Pocahontas No. 3, as well as from the unmined coal, which is fractured and hydraulically stimulated in advance of mining. Although depths to the tops of completed zones in Buchanan County range from as little as 325 feet to over 2,400 feet, most of the completions are a thousand feet, or more deep.

Dickenson County CBM production, mostly from the Nora field, peaked in 1999 at 9.5 Bcf (373 wells) and declined to 8.5 Bcf in 2001 (444 wells). Target coal beds are generally from the Jawbone to the Pocahontas No. 1 coal bed, with most of the completions within deeper coals of the Lee Formation. Depths to completed coal zones are, in places, as shallow as 375 feet. Most of the completions, however, have been effected at depths greater than 1,000 feet.

Production declines in Buchanan and Dickenson County, Virginia, were offset by new discoveries in Russell County, Virginia, in 2002, where CBM production increased from 484.5 MMcf (45 wells) in 2000 to 3.5 Bcf (110 wells) in 2002. There, Pocahontas and Lee coals are commonly completed at depths that range from about 600 feet to 1,500 feet, or more. Altogether, Virginia's annual CBM production reached 58.6 Bcf (2,235 wells) in 2002 (Virginia Center for Coal and Energy Research, 2004).

Coal as a source rock for CBM:

Gas-in-place data:- Within the Pocahontas basin AU, maximum gas-in-place data, by county, range from 282 cf/ton in Dickenson County, to 688 cf/ton in Buchanan County Virginia (fig. 16) (Diamond and others, 1986). One sample from Wyoming County, West Virginia, has yielded a value of 285 cf/ton. The number of samples in Dickenson (4) and Wyoming (1) Counties is relatively small and their values almost certainly understate the in-place CBM potential for those counties. Gas-in-place values for the Central Appalachian Shelf AU are conspicuously smaller, and maximums, by county, range from a low of 54 cf/ton in Perry County, Kentucky (one sample), to 144 cf/ton in Mingo County, West Virginia (30 samples). In general, the area is under-sampled and the values shown in figure 16 understate the in-place-gas potential for the area, except perhaps for Mingo County.

Thermal maturity:- The 0.8 %Ro isoline illustrated in Figure 17 is based on a composite of all %Ro data in the area, from core and outcrop samples of numerous coal beds. Areas with values less than 0.8 %Ro generally to the west of the isoline are considered to be relatively immature with respect to gas generation; areas with values equal to or greater than 0.8 %Ro, generally to the east of the isoline, are considered to be mature with respect to commercial gas generation. Although all of the coal samples to the west of the 0.8 %Ro isoline are immature, coal samples to the east of the isoline exhibit a mixture of both mature and immature values.

In general, coal rank (and thermal maturation) varies with maximum depth of burial. For example, the apparent rank of the Pocahontas No. 3 coalbed, in the deeper part of the Pocahontas basin, ranges from high-volatile A bituminous coal to semianthracite (fig. 18) (Milici and others, 2001a); whereas, the rank of the stratigraphically higher Fire Clay coal zone (Tewalt and others, 2001), which is in the Wise Formation (Virginia) and Breathitt Formation (eastern Kentucky) on the shelf to the west (Table 6; fig. 19), is almost entirely high-volatile A-bituminous.

Generation and migration:- Microbial methane almost certainly was generated during the accumulation of peat during the Pennsylvanian, and may be continuing today where shallow coal beds interact with surface waters. Thermal maturation commenced toward the end of the Paleozoic in the deep Pocahontas basin, probably to the northeast near the Appalachian Valley and Ridge, where semianthracite occurs in the Pocahontas No. 3 coalbed at depth. Structural deformation (and perhaps structural loading) in the Valley coalfields of Virginia, 30 to 50 miles to the east and north of the Pocahontas basin, has metamorphosed the Mississippian-age coal there to semianthracite (Campbell and others, 1925). Thermal maturity ($\geq$ 0.8% Ro) was probably reached in the Pocahontas basin during the latest Paleozoic and earliest Mesozoic, prior to Early Mesozoic uplift and erosion (fig. 13).

Coal as a reservoir for CBM:

Porosity and permeability:- Porosity and permeability of natural cleat systems in coal beds in the Pocahontas basin have been enhanced by structural deformation and limited decollement within coal beds on and near the Pine Mountain block (Milici and others, 1982, 1986). In general, deep coal beds in the Pocahontas basin contain less water than the coals in the northern Appalachian coalfields and production rates and yields per well are generally greater in the Pocahontas basin than in the Dunkard basin.

Coal bed distribution:- In general, coal beds suitable for the development of CBM are 500 feet, or more, deep in the Pocahontas basin, are 14 or more inches thick, are charged with thermally-generated methane, and are not mined extensively. Nolde and Spears (1998) presented maps of 10 coalbeds in the Pocahontas basin of Virginia that occur at depths of 500 feet, or more, from the Upper Seaboard down to the Pocahontas No. 3 coalbed (Table 6). Similar data was compiled by the USGS for the Fire Clay and Pond Creek coal beds, which are mostly in the Central Appalachian Shelf AU, and for the Pocahontas No. 3 coalbed, in the Pocahontas basin AU, in Virginia, West Virginia, and Kentucky (Ruppert and others, 2001; Tewalt and others; 2001, and Milici and others 2001a). These USGS reports include maps of the coal bed and mined out areas, coal isopachs, structure contours, and depth of overburden, which collectively provide the geological framework for CBM exploration and development in those areas.

Drahovzal and others (2002) designated an area in eastern Kentucky centered about the eastern Kentucky syncline (fig. 15) as having the best potential for CBM development on the Central Appalachian Shelf. This area contains up to 1,500 feet of Pennsylvanian strata and up to 30 feet of cumulative coal thickness, with the thickest overburden and the highest rank coals in eastern Kentucky (Drahovzal and others, 2002).

Cumulative coal thickness:- In general, in the Pocahontas basin AU, CBM wells are commonly completed in several coal beds, with a cumulative coal thickness of 15 to 25 feet. However, where the vertical ventilation holes that were drilled into coal beds for mine safety (degasification) purposes were converted to gob wells, only that one bed may produce gas. As cited in the previous section, the Central Appalachian Shelf AU contains sufficient coal within the Eastern Kentucky Syncline to permit up to 30 feet of coal to be completed in a single CBM test well (Drahovzal and others, 2002).

Seals:-

Depth of burial:- In many places, water within coal beds serves as an effective seal to gas migration (fig. 13), and gas may be produced from relatively shallow coal beds once the water is removed. Because of the relatively small amounts of water associated with

CBM production in southwestern Virginia, however, the coal beds that are completed for gas generally are at depths that approach 1,000 feet (Nolde and Spears, 1998) and shallow coals in the upper part of the section may contain insufficient gas for development. In the Pocahontas basin, CBM is effectively produced from coal beds buried 500 feet, or more, beneath the surface. There is sufficient shale within the Pennsylvanian section to serve as local seals (fig. 13).

Water Production:- Water production per well is relatively low in the Pocahontas basin. In general, in 2001, a sample of 1,718 wells produced an average of about 533 barrels of water per well per annum. Average water production was somewhat greater in 1990, when a sample of 54 wells produced about 633 barrels of water (Nolde, 2003, unpublished Wellsum database).

Cumulative Production and EUR Data:

Deep production of coalbed gas associated with the degasification and mining of the Pocahontas No. 3 coal bed provided the initial impetus for much of the CBM development in Virginia. Through 2002, the Pocahontas basin has produced about 433.9 Bcf of coalbed methane (exclusive of pre-mine and mine drainage). Almost three-quarters of the CBM produced in the Pocahontas basin AU is from Buchanan County, Virginia, which had produced 321.5 Bcf by 2002. Much of the remainder comes from Dickenson County, Virginia (71.8 Bcf), Wyoming County, West Virginia, (19.3 Bcf), and Russell County, Virginia (10.7 Bcf) (Table 1).

Production data is available for fourteen years from the first nine wells drilled in the Pocahontas basin, in Dickenson County, Virginia (Nolde, unpublished Wellsum database). Second-year production, which averaged 34.1 MMcf, declined sharply during years three and four to a little more than 25 MMcf for economic reasons (1991, 1992), and then rebounded in the fifth year to 38.4 MMcf. By the 14^{th} year, average production for the seven wells had declined to 20.3 MMcf. Cumulative production for these wells ranged from 135.3 MMcf to 591.1 MMcf, with an average of 376.5 MMcf for the nine wells over a 14-year production history.

Assessment Results:

The area that is considered most likely to be developed during the next 30 years is coincident with that of the minimum petroleum system within the Pocahontas basin AU. In 2002, the USGS assessed this area (at the statistical mean) as containing about 3.58 Tcf of technically recoverable undiscovered methane (Table 5) (Milici and others, 2003). This value is a little larger than the amount assessed by Rice and Finn (1996), who reported an undiscovered resource of about 3.07 Tcf for the central Appalachian play. Rice and Finn (1996), however, had little drilling and production data at the time of their assessment and used an analog assessment methodology.

Appalachian Anthracite and Semi-Anthracite Assessment Unit:
Pennsylvania Anthracite

Introduction:

The anthracite region of Pennsylvania is within the folded and faulted Appalachians, in the Valley and Ridge and Appalachian Plateaus physiographic provinces (Fenneman, 1938). The mining district consists of four main fields, from south to north the Southern Anthracite field, the Western Middle Anthracite field, the Eastern Middle anthracite field, and the Northern Anthracite field (fig. 20) (Wood and others, 1962, 1969, 1986). In general, the anthracite fields consist of Pennsylvanian strata that are complexly folded, faulted, and preserved in structural synclines within older Paleozoic strata.

Most of the historical anthracite production in Pennsylvania has been from the Northern and Western Middle fields (Eggleston and Edmunds, 1981). As of 2000, approximately 5.5 billion short tons (bst) had been produced from the Pennsylvania anthracite region. Total remaining resources in synclines that may be as much as 5,000 feet deep, are estimated to be about 19.6 bst and the potential recoverable resource, down to depths of about 1,000 feet, is estimated to be about 7.3 bst. About 68% of the remaining resources are in the Southern field, 14% in the Northern field, 17% in the Western Middle field, and the remainder in the Eastern Middle field (Eggleston and Edmunds, 1981; Eggleston and others, 1999).

Stratigraphy:

The Pennsylvanian stratigraphic section includes three formations in this region, the upper part of the Mauch Chunk Formation (Lower Pennsylvanian), the Pottsville Formation (Lower and Middle Pennsylvanian, and the Llewellyn Formation (Middle and Upper Pennsylvanian) (fig. 21). The Mauch Chunk Formation ranges from about 3000 to 4000 feet thick in the Southern Anthracite Field, and generally thins to the north and west across the Pennsylvania coal fields. In general, the formation contains mudstone, siltstone, sandstone, and conglomerate of various hues of red and brown, which are interbedded with similar lithologies of gray and green colors. The Mauch Chunk apparently accumulated as flood plain deposits on a broad coastal plain. The upper part of the Mauch Chunk, which is about 650 feet thick in the Southern Anthracite Field, is interbedded with the Pottsville and is classified with the Pottsville as Pennsylvanian in age (Wood and others, 1962, 1969; Edmunds and others, 1999).

The thickness of the Pottsville Formation ranges from about 1,600 feet in the Southern Anthracite field, where it contains about 14 coal beds, to less than 100 feet in the Northern field, where it contains little or no coal (Edmunds and others, 1999, Eggleston and others, 1999). The overlying Llewellyn Formation is thickest in the Southern field, where about 3,500 feet of strata are preserved, and thinnest in the Eastern Middle field, where about 1,000 feet are preserved.

Pottsville Formation:- In the anthracite fields, the Pottsville Formation extends from the top of the red beds of the Mauch Chunk Formation (Mississippian) to the base of the clay bed or shale beneath the Buck Mountain (No. 5) coal bed (White, 1900). The Pottsville consists mostly of conglomerate, conglomeratic sandstone, and sandstone. Some of the conglomerates in the Pottsville and underlying Mauch Chunk Formation contain clasts of igneous and metamorphic rocks and minerals, which indicates that crystalline rocks were exposed in the source area (Wood and others, 1969). Only about 25 to 40 percent of the formation is siltstone, shale, and coal (Edmunds and others, 1999).

The Pottsville is entirely nonmarine in this area and is divided into three units, the Tumbling Run, Schuylkill, and Sharp Mountain Members. Each of these members consists generally of multiple fining-upward alluvial cycles, which contain conglomerates and conglomeratic sandstones at the base and shales and coal beds at the top (Wood and others, 1956, 1969).

Llewellyn Formation:- In general, the Llewellyn Formation extends from the base of the Buck Mountain (No. 5) coal bed to the present day erosion surface. The formation consists predominantly of subgraywacke conglomerate and conglomeratic sandstone, sandstone, siltstone, shale, and coal, with local deposits of marine limestone. The maximum thickness of the Llewellyn Formation, about 3,500 feet, occurs in the central part of the southern anthracite field. There are about 40 named coal beds in the formation that have been identified by both name and number (Wood and Trexler, 1968a, b; Wood and others, 1969). Although the lateral distribution and thicknesses of rock units in the Llewellyn ranges greatly from place to place, intervals between the major coal beds tend to be more consistent. In general, the thicker, more widespread coal beds occur in the lower 1,500 feet of the Llewellyn (Wood and others, 1986).

Geologic Structure:

The anthracite region of Pennsylvania consists of four major synclinoria that extend from within a tightly compressed, greatly folded and faulted part of the Appalachian Valley and Ridge Province northwestward into the Appalachian Plateaus Province. In general, structural deformation, which is greatest in the Southern Anthracite field, decreases to the northeast, so that the Northern (Lackawana) basin is the least deformed of the four (Wood and Bergin, 1970).

These superficial structures of the folded and faulted Appalachians are underlain by a basal decollement within the lower part of the Paleozoic section, from which major southeastward-dipping tectonic ramps splay upward, generally as blind thrusts, to where they “tip-out” in the overlying Paleozoic section. The anthracite region lies in structural lows adjacent to or between the major first order ramp anticlines that were formed by movement along the splay thrusts (Faill, 1998). The Northern (Lackawanna) Anthracite coalfield, which is the least deformed of the four, is nestled between two first order anticlines (Faill, 1998). Although there are no first order anticlines in the Southern, Western Middle, and Eastern Middle Anthracite fields, this area is one of the most severely deformed, relatively large regions of the Appalachian Valley and Ridge. Several stages of deformation have been recognized by different writers (Arndt and Wood, (1960), Nickelsen, (1979); see Wood and others, 1969, for a detailed discussion of anthracite structure in the southern field, and Faill, 1998, for a general summary). In general, the early stages of Alleghanian deformation resulted in the formation of ubiquitous coal cleats followed by layer-parallel shortening of strata above the basal decollement. Later stages of deformation apparently resulted in the development of multiple levels of decollement from which numerous imbricates splayed upward into overlying strata.

Arndt and Wood (1960) described five structural stages that ranged from broad folding and faulting to the development of recumbent folds and nappes. Nickelsen (1979) recognized seven stages of deformation in the Western Middle field. Wood and others (1969) placed an hypothetical decollement (Pottchunk fault) at or near the base of the upper member of the Mauch Chunk Formation and, among others, Arndt (1971), Wood and Arndt (1973), Faill and Nickelsen (1999) interpreted faults exposed at the surface in the Southern Anthracite field as splays (or tectonic ramps) from the underlying hypothetical Pottchunk fault. Wood and others (1986) noted that coal in the anthracite region was, in some places, structurally overthickened by flowage into the cores of synclines and in other places duplicated by faults. Furthermore, geologic structure locally affects the rank of the coal so that fixed carbon content generally increases towards the core of tightly folded synclines and greatly deformed thrust faults (Wood and others, 1969).

Nevertheless, in spite of the complex geologic structures, there are relatively large areas where subhorizontal to moderately inclined coal beds may be accessed by the drill in the Southern Anthracite district. For example, the detailed maps of Wood (1972) illustrate several areas in Schuylkill County, Pennsylvania, that may be suitable for coalbed methane exploration.

Coal as a source rock for CBM:

Gas-in-place-data: U.S. Bureau of Mines gas-in-place data for the anthracite district (Diamond and others, 1986; Trevits and others, 1988) range from 6.4 cf/ton in the Orchard coal bed to 691.2 cf/ton from the Peach Mountain coal bed in the Southern Anthracite field, which is the largest in-place value in the USBM database, nationwide (Table 8). Of the 19 cores tested for gas-in-place values in the Northern Anthracite field, the largest value obtained was 70.4 cf/ton, for the Upper New County (No. 7) coal bed. Adsorption data (Langmuir isotherms) for Pennsylvania anthracite published by Lyons and others (2003) range from about 290 cf/ton in the Buck Mountain coal bed to 900 cf/ton in the Mammoth and Seven-foot beds.

Thermal maturation:- Thermal maturation (coal rank) of the coals in the anthracite district ranges from low-volatile bituminous coal to anthracite (Hower and Gayer, 2002). In general, vitrinite reflectance values increase from 2% or less in the southwestern-most part of the anthracite fields to 6% or more in the northeastern part of the Southern field. Vitrinite reflectance values in the Northern field range from a little less to a little more than 4% (Hower and Gayer, 2002).

Generation and migration: Thermal maturation commenced toward the end of the Paleozoic as the paleopeat deposits of the anthracite coal fields were buried by overlying sediments. Thermal maturity probably was reached during the latest Paleozoic, when the area was under the greatest sedimentary cover and, perhaps, beneath now-eroded Appalachian thrust sheets. In the southern, western middle, and eastern middle fields several writers noted a temperature inversion whereby the older (lower) coal beds are of a lower rank than the younger (upper) coal beds (Edmunds and others, 1979; Levine, 1986; Levine and Davis, 1989). Explanations range from differential warming of the younger coal beds by means of hydrothermal fluids, to the effects of a relatively warm, newly emplaced overthrust sheet (now eroded) (see Faill, 1998, for a summary). Wood and others (1969), however, noted that rank was closely related to local structural deformation, thus explaining the apparent “temperature inversions”, more simply. Furthermore, Edmunds and others (1979) show that the fixed carbon content of

Pennsylvanian coals increases from west to east across Pennsylvania and is, in general, greatest within the center of the anthracite coal fields, where the depth of burial would have been the greatest.

As with the coals in the other assessment units, methane generation probably began microbially during the first formation of peat and continued thermogenically as the paleopeat deposits were progressively buried during the Pennsylvanian (fig. 13) . Progressive metamorphism, thus, has transformed the original paleopeat deposits from a complex mixture of organic chemicals to relatively pure carbon (anthracite) and methane.

Coal as a reservoir for CBM:

Porosity and permeability: Fracture porosity is well developed in anthracite and semianthracite coal beds. Pennsylvanian anthracite commonly breaks with a conchoidal fracture. In some places, however, fractures may be prismatic and rectangular. In contrast, semianthracite commonly breaks with closely spaced rectangular and prismatic fractures, and is rarely conchoidal (Wood and others, 1969).

Coal bed distribution: Although anthracite is widely distributed throughout the synclinal coal fields, structural deformation may be so intense locally that it would inhibit the orderly development of CBM drilling units. Areas most suitable for CBM development would be in the relatively broad anticlinal and synclinal folds, and perhaps in regions of gently to moderately inclined beds.

Cumulative coal thickness: The principal coal beds mined in the Southern, Eastern Middle, and Western Middle fields are the Lykens Valley coal zone (up to 11 coal beds) in the Pottsville Formation, and the Buck Mountain, Seven Foot, Skidmore, Mammoth, Holmes, Primrose, and Orchard coal beds in the Llewellyn Formation (fig. 21) (Eggleston and Edmonds, 1981). Where these beds occur together, they are in a stratigraphic section that ranges from about 700 to 1000 feet thick and their average cumulative thickness may total 75 feet or more. The thickest coal bed is the Mammoth, which averages about 30 feet thick (maximum about 65 feet). The others are commonly in the 4- to 6-foot range in thickness. Where younger beds are present, including the

Peach Mountain (No. 18) and Tunnel (No. 19), cumulative coal thickness may approach 100 feet in a stratigraphic section that is 1,500-1,700 feet thick (Wood and others, 1969; Eggleston and Edmonds, 1981).   .

Seals: In relatively unfaulted areas, seals would consist of shales interbedded with the coals. The amount of interstitial water in the coal beds is unknown.

Depth of burial: Depth of burial of anthracite coal beds in geologic structures potentially suitable for coalbed methane production ranges from several hundred feet to 2,000 feet, or more. In some places the synclines may extend to depths of 5,000 feet, or more (Eggleston and Edmunds, 1981).

Appalachian Anthracite and Semi-Anthracite Assessment Unit: Virginia Semianthracite

Introduction:

The coal-bearing strata of the Valley coal fields are of Mississippian age and extend discontinuously within the folded and faulted strata of the Appalachian Valley and Ridge from Rockingham and Augusta Counties, Virginia, on the north to Wythe, Bland, Smyth, and Washington Counties, Virginia, on the south (fig. 22). Campbell and others (1925) divided these Valley coal fields into several groups based on their relative importance: (1) the fields of Montgomery and Pulaski counties, Virginia; (2) the fields of Wythe County, Virginia; (3) the fields of Morgan and Berkley counties, West Virginia; (4) the fields of Bland and Smyth counties, Virginia; (5) the fields of Roanoke and Botetourt counties, Virginia; (6) the fields of Augusta and Rockingham counties, Virginia; and (7) scattered fields of little or no economic importance. Historical prospecting and mining of coal beds has occurred to some extent in many of these areas (Campbell and others, 1925). Only the fields of Montgomery and Pulaski counties, Virginia, are considered herein.

In 1983, the Virginia Division of Mineral Resources evaluated the coalbed methane potential of the coal fields in Montgomery County, Virginia (fig. 23) (Stanley and Schultz (1983). In this area, Mississippian coal beds are exposed within a structural window (fenster) through the Pulaski thrust sheet and along the western margin of the thrust sheet (fig. 22). Of the three core holes drilled, two encountered coal, which was desorbed using the method described by Diamond and Levine (1981).

Stratigraphy:

Cambrian formations of the Pulaski thrust sheet:- In the coal-bearing area of Montgomery and Pulaski Counties, the stratigraphic units may be divided into two general groupings, the older rocks of the Pulaski thrust sheet and the younger rocks of the footwall in the Saltville thrust sheet (Table 9) (Bartholomew and Lowry, 1979). Pulaski thrust sheet rocks include calcareous and phyllitic mudstones and argillaceous dolomites and limestones of the Rome Formation (Lower Cambrian), and the Elbrook Formation (Middle Cambrian). The combined thickness of these units, now greatly deformed on the thrust sheet, may range from 2,300 feet to nearly 3,000 feet. An unusually thick tectonic breccia (tens to hundreds of feet thick), the Max Meadows breccia (Schultz, 1986), is widely exposed on the thrust sheet. The breccia occurs primarily in the upper part of the Rome Formation and lower part of the Elbrook Formation. It consists generally of dolomite and mudstone clasts that are in a matrix of crushed dolomite or sheared phyllite (Stanley and Schultz, 1983; Schultz, 1986).

Mississippian formations of the foot wall:- Footwall strata range in age from Cambrian to Mississippian (Table 9) and are exposed on the Saltville thrust sheet along the western edge of the Pulaski thrust sheet and in several anticlinal windows (fensters) that have been eroded through the Pulaski thrust sheet. Strata of Mississippian age, which include the Price and Maccrady Formations (Mississippian), are exposed within the Price Mountain window and in the footwall along the trace of the Pulaski thrust sheet (fig. 23).

The Maccrady Formation, at the top, consists of two members. The upper member, 180 feet thick, consists of interbedded mudstones, siltstones, conglomeratic sandstones, and quartz-pebble conglomerates. A lower member of grayish-red and greenish-gray mudstones, a few gray to black mudstones, and massive to cross-bedded sandstones is about 1,150 feet thick. The contact of the Maccrady with the underlying Price Formation is gradational and is placed where the grayish-red siltstones of the

Maccrady give way to the gray siltstones and sandstones of the Price (Stanley and Schultz, 1983).

In general, the Price Formation (Lower Mississippian) represents a westward-prograding delta shoreline complex related to the Acadian orogeny (Kreisa and Bambach, 1973). The Price Formation consists of two members: an upper coal-bearing member, and a lower member that includes the basal Cloyd Conglomerate (Stanley and Schultz, 1983). The contact between the two members is placed at the top of the first sandstone below coal-bearing mudstones. The coal-bearing upper member is about 900 feet thick. It consists of grayish-red to greenish-gray mudstones, gray to black mudstones, quartzose sandstones, and coal. The mined coal beds, the Merrimac and Langhorne, occur in the lower part of the upper member and range in thickness from 5 to 12 feet and from 1 to 3 feet, respectively (Campbell and others, 1925, Stanley and Schultz, 1983). Kreisa and Bambach (1973) recognized three lithofacies within the upper member: (1) distributary channel sandstones; (2) delta plain sandstone and shale; and (3) coal and carbonaceous shales that were deposited in mires. In places, the channel sandstones contain plant fossils and some burrows; plant fossils are commonly associated with both the delta plain deposits and carbonaceous shale, and coal.

The marine lower member is about 1,500 feet thick. It consists of shale, siltstone, sandstone, and quartz-pebble conglomerate, with some bioturbated, fossiliferous beds of sandy shale. Kreisa and Bambach (1973) recognized five lithofacies within the lower member: (1) fossiliferous marine shales; (2) interbedded prodelta slope sandstones with sole markings, (3) massively bedded bar and barrier deposits of quartz arenites and quartz-pebble conglomerates (Cloyd Conglomerate); (4) barred bay deposits of fossiliferous sandstones and mudstones; and (5) washover deposits of sandy conglomerates. The Cloyd Conglomerate, in the lower part of the lower member, is a conspicuous marker bed that consists of white sandstone and quartz pebble conglomerate, some with marine fossils and comminuted plant debris. In places, the Cloyd is up to 20 feet thick (Campbell and others, 1925).

Geologic Structure:

The principal geologic structure of the region is the Pulaski thrust sheet, which consists of complexly folded and faulted rocks of the Rome and Elbrook Formations. This fault carries deformed and brecciated Cambrian formations westward to where they overlie Mississippian-age strata within the underlying Saltville thrust sheet. In places, the Pulaski thrust sheet, which ranges up to about 5,000 feet thick, contains several structural windows that expose strata that range in age from Cambrian to Mississippian. The windows are of two general types; those that contain horses of severely deformed Cambrian to Devonian strata (Schultz, 1988), and the Price Mountain window, which exposes the relatively undeformed strata of the Mississippian footwall as well as a complexly deformed horse of older rocks. Schultz (1988) hypothesized that 12 horses of greatly deformed Cambrian to Devonian strata exposed along the trace of the Pulaski fault and in the windows eroded through the eastern part of the Pulaski thrust sheet were rootless and overlay Mississippian-age strata at depth. If Schultz (1988, fig. 3) is correct, Mississippian strata and their contained coal beds may extend buried in the footwall of the Pulaski thrust sheet eastward beneath the leading edge of the Blue Ridge thrust sheet.

Coal as a source rock for CBM:

Gas-in-place-data: Three State core holes and six commercial CBM tests were drilled in and near the Pulaski thrust sheet, respectively, by the Virginia Division of Mineral Resources, and by Mr. John Goldsmith of Radford, Virginia (Toms Creek Energy Co., New River Gas Co., and Valley Basin Gas Associates in a joint venture with AMOCO) (Tables 10, 11, 12, 13 and fig. 23) (Stanley and Schultz, 1983; J. L. Coleman, written communication 2004). The first State core hole, located half way between the Price Mountain window and the leading edge of the Pulaski thrust sheet (Prices Fork test), failed to penetrate the deformed hanging wall rocks and was terminated at 1,773 feet. A second well, (VDMR Well W-6534; Sunnyside test) was drilled in the western footwall of the thrust sheet and penetrated two named coal-bearing zones in the Price Formation: the Merrimac coals from 1,110.05 feet to 1,120.8 feet, and the Langhorne coals from 1,134.22 to 1,139.18 feet and 1,194.9 to 1,198.6 feet. A third well, (VDMR Well W-6535; Merrimac test) drilled near the northwestern side of the Price Mountain window, went through the Pulaski thrust sheet at about 104 feet, and encountered the Merrimac coal in three thin beds between 1,403.5 and 1411.9 feet. Seven thin coals of the Langhorne interval were encountered between 1420 and 1,481 feet (Stanley and Schultz, 1983).

Of the six commercial wells drilled for CBM in the mid- 1980's, (Tables 12 and 13) four encountered coal of considerable thickness and gas content and, of these, two wells were hydraulically fractured and tested. Although the gas content of coals in two of the wells ranged from 508 to 664 scf/Ton (Table 13), the wells yielded non-economic flows of gas, most likely because of very low permeability (J.L. Coleman, written communication, 2004).

Table 11 summarizes the desorption data from the Merrimac and Langhorne coal beds in the Sunnyside (W-6534) and Merrimac (W-6535) wells, which yield a weighted average of 202.2 cf / ton and 230.6 cf / ton, respectively. An economic analysis conducted by Gruy Petroleum Technology Incorporated (Stanley and Schultz, 1983) assumed that the original gas-in-place to be 3,220 Mcf / acre, which was consistent with these desorption values. They concluded, however, that the coal thicknesses measured in the two cores were not great enough to supply an economic amount of gas relative to the costs of exploration and development, and suggested that twice that amount of coal may be needed for the successful development of a CBM field. Although Campbell and others (1925) have reported coal thicknesses as great as 22 feet in Pulaski County coal fields, thicknesses this great appear to be exceptional and not widespread across the region.

Thermal maturation:-Thermal maturation of Mississippian-age coal from surface locations in the Valley and Ridge ranges from a vitrinite reflectance of 1.41 (medium-volatile bituminous) in Wyth County, Virginia to 2 (semianthracite) in Montgomery County, Virginia (unpublished data courtesy of L. Ruppert, USGS). In Pulaski County, the vitrinite reflectance values for coals in the New River Gas, Neuhoff Farms No. 1 well were a little greater and ranged from 2.5-2.7 percent (J.L. Coleman, written communication, 2004, Table 13).

Generation and migration:- Methane was first generated by microbial activity when the Mississippian paleopeat deposits first formed. Although much of this "swamp gas" was lost to the atmosphere, microbial generation of methane continued at depth until the ambient temperatures became too great. When the coal beds were buried sufficiently deep by overlying sediments, temperatures became high enough to support the formation of thermogenic gas, probably sometime in the late Mississippian and Early Pennsylvanian (fig. 13). Alleghanian folding and faulting has deformed the coal beds and their enclosing strata. Methane may well have been lost from the coal beds in areas of intense deformation. Where deformation is moderate, so that seals have not been broken, increased fracture porosity may result in more rapid desorption of the gas into the fracture network and thence into the well bore once the coal beds are drilled.

Coal as a reservoir for CBM:

Porosity and permeability: In general, porosity and permeability are enhanced in areas of moderate deformation and fracturing. Where deformation is intense, however, seals may be broken and CBM lost. Following commercial exploration in the area in the mid-1980’s, AMOCO discontinued exploration in the area. They concluded that the relatively high thermal maturation of the coal, combined with bedding-parallel faulting in the coal beds resulted in the very low permeability observed (J.L. Coleman, written communication, 2004).

Coal bed distribution: In Pulaski and Montgomery Counties, the coal-bearing strata of the Price Formation are exposed along the trace of the Pulaski fault and in the Price Mountain window. The coal-bearing zone may extend at depth from its exposure eastward beneath the Pulaski thrust sheet to the leading edge of the Blue Ridge thrust sheet (Schultz, 1988).

Cumulative coal thickness: Cumulative coal thickness may range from about 6 or 7 feet to 22 feet or more (Campbell and others, 1925).

Seals: The coal beds occur within black, carbonaceous mudstones, with subordinate amounts of sandstone and siltstone. The fine-grained rocks may serve as effective seals for CBM (Stanley and Schultz, 1983).

Depth of burial: Coal beds of the Price Formation may extend eastward from their cropline in the footwall of the Pulaski fault, beneath the thrust sheet to depths of 5,000 feet or more.

Assessment results: The Appalachian anthracite and semi-anthracite Assessment Unit was not qualitatively assessed and should be regarded as hypothetical until the successful demonstration of a commercially active petroleum system.

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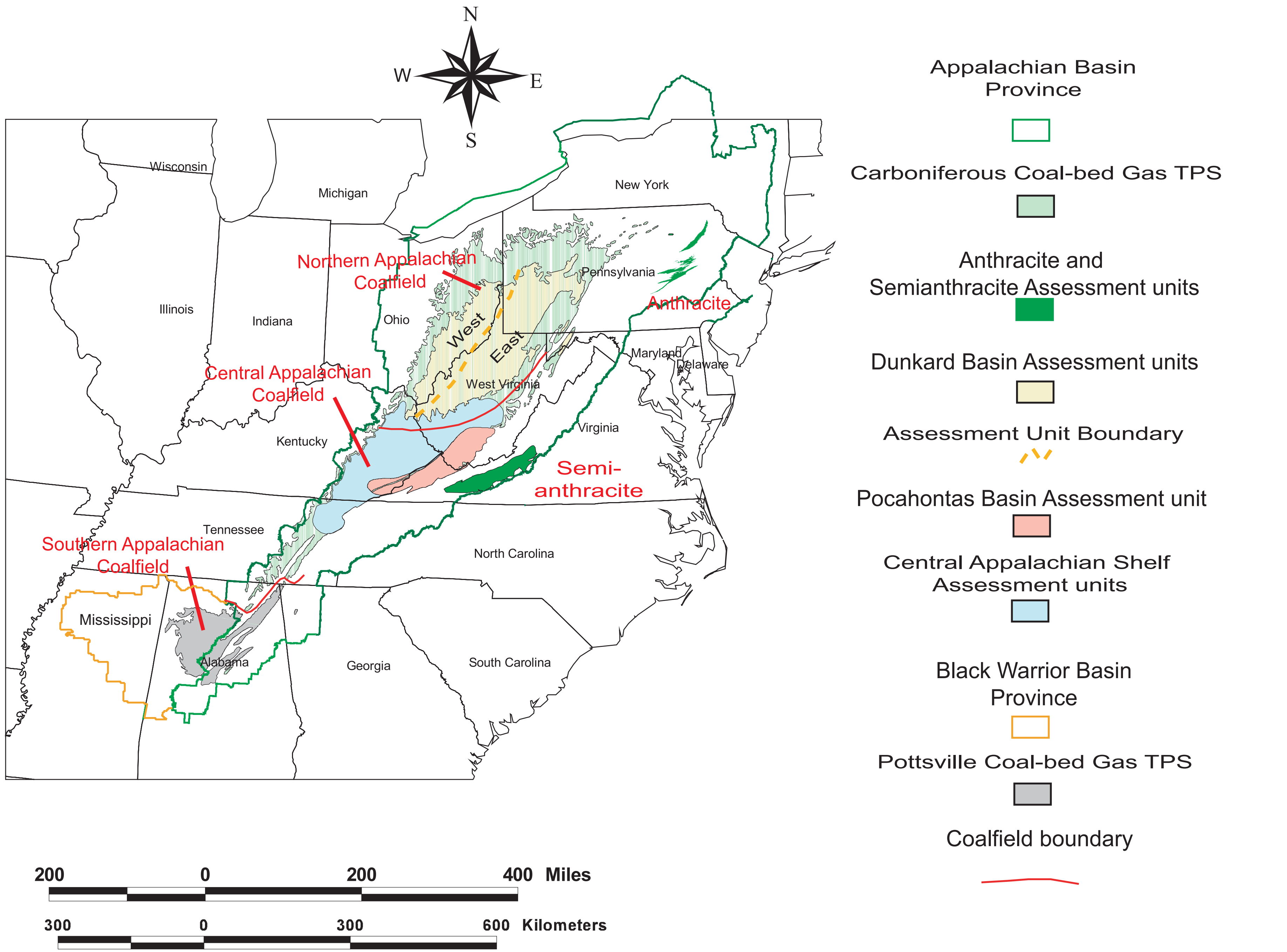

Figure 1. Appalachian basin coal field, major sub-basins, and oil and gas assessment provinces

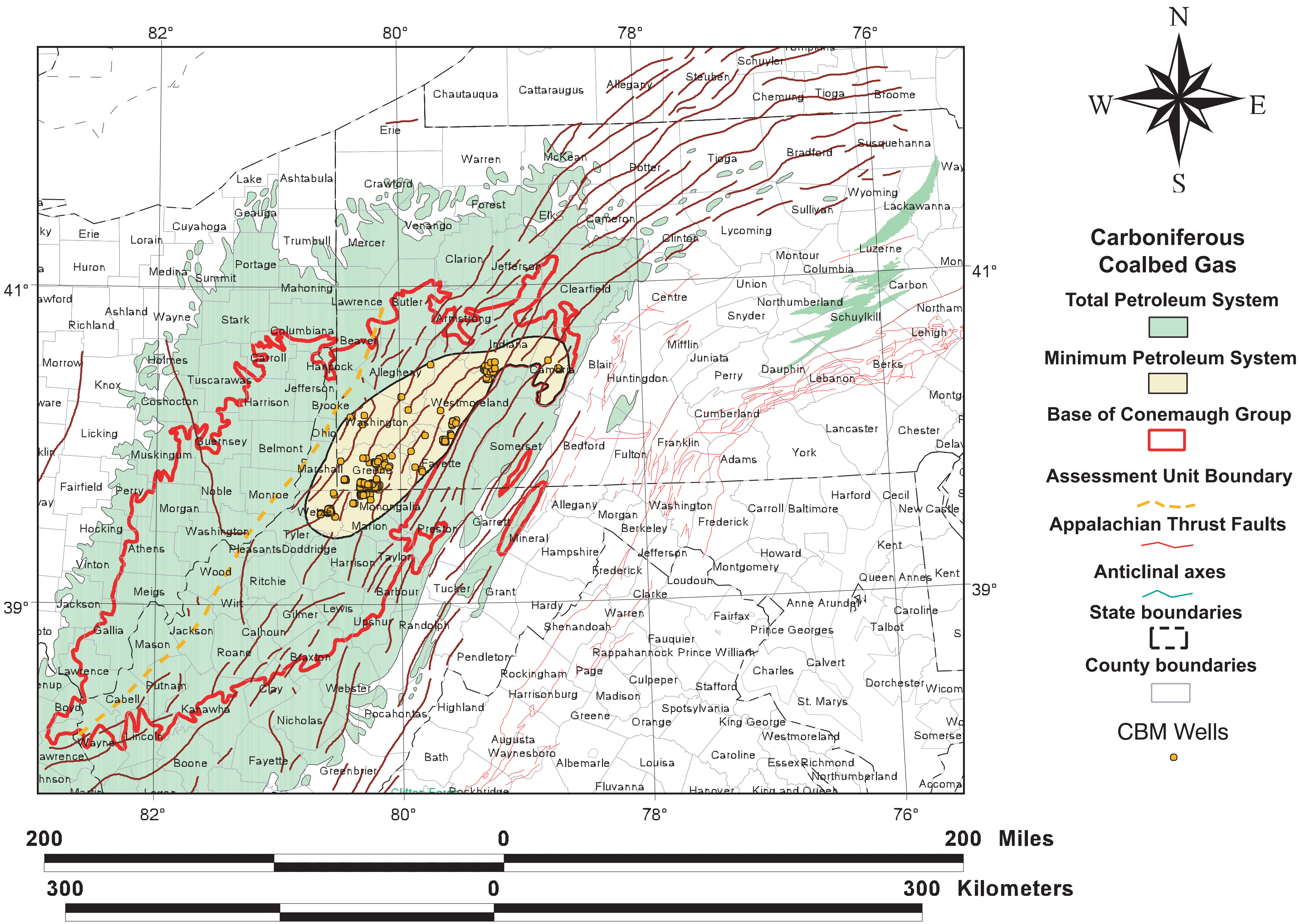

Figure 2. Map of the Carboniferous Coal-bed gas Total Petroleum and Minimum Petroleum Systems, northern part of the Appalachian coalfield, showing the location of the East Dunkard (folded) and West Dunkard (unfolded) assessment units (CBM well locations from Avary, 2003 and Markowski, 2000).

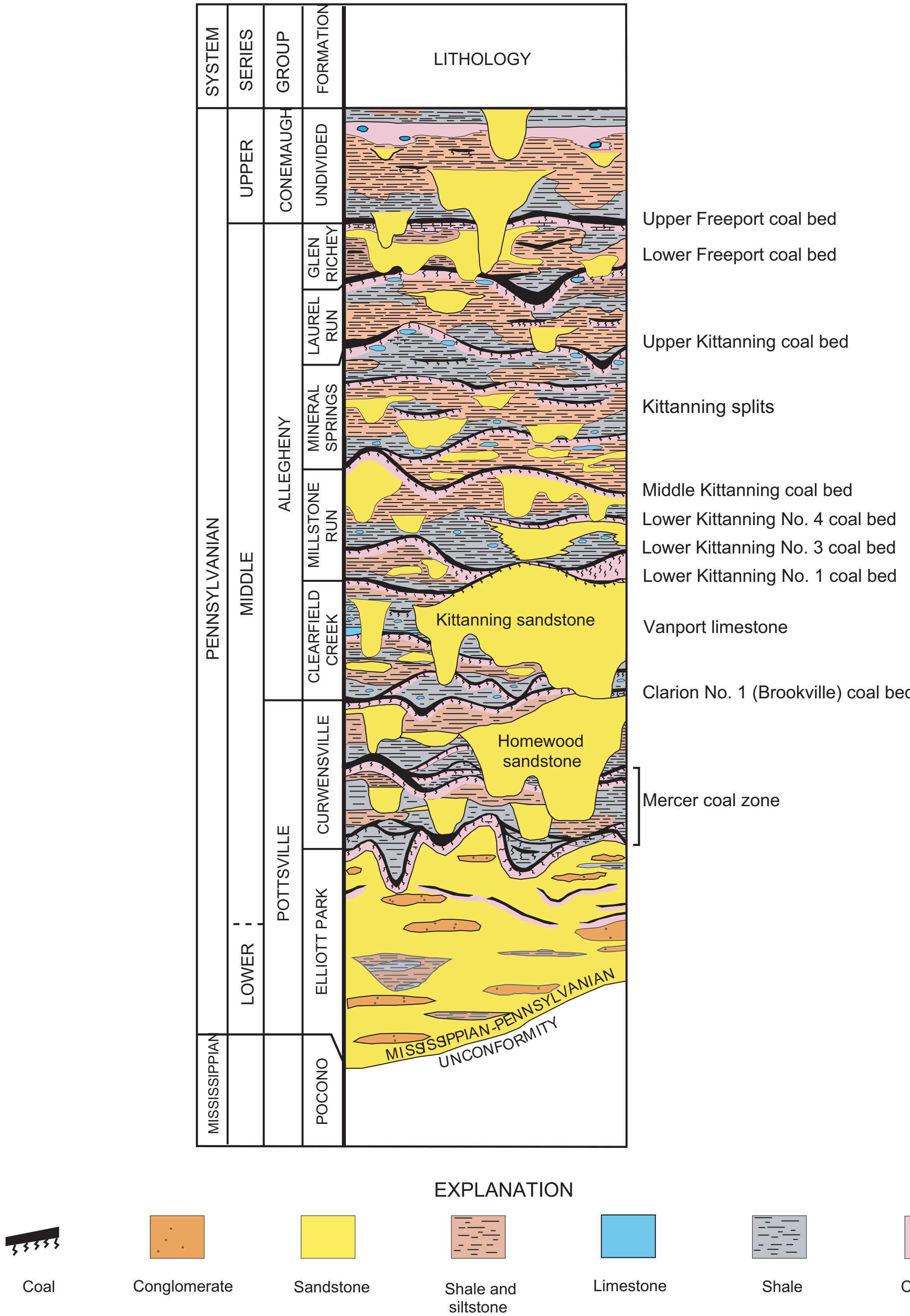

Figure 3. Generalized stratigraphic column of the Pottsville and Allegheny Groups in Clearfield and adjacent counties, Pennsylvania (adapted from Glover and Bragionier, 1987) (from Milici and others, 2001b).

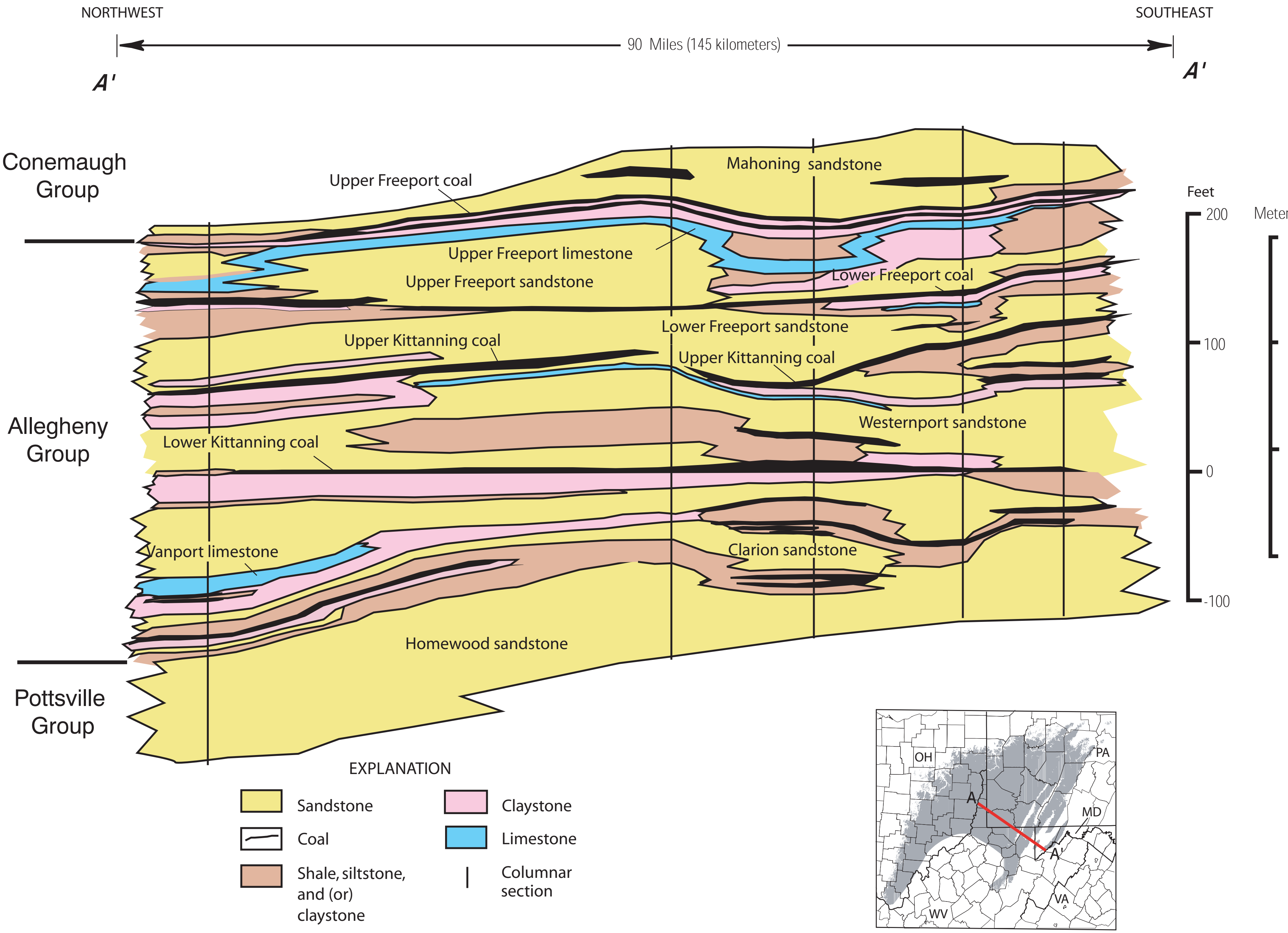

Figure 4. Cross section A-A' showing the Allegheny Group from Ohio County, W. Va., southeast to Garrett County, Md. Vertical exaggeration X 594 (adapted from Swartz and others, 1922) (from Milici and others, 2001b).

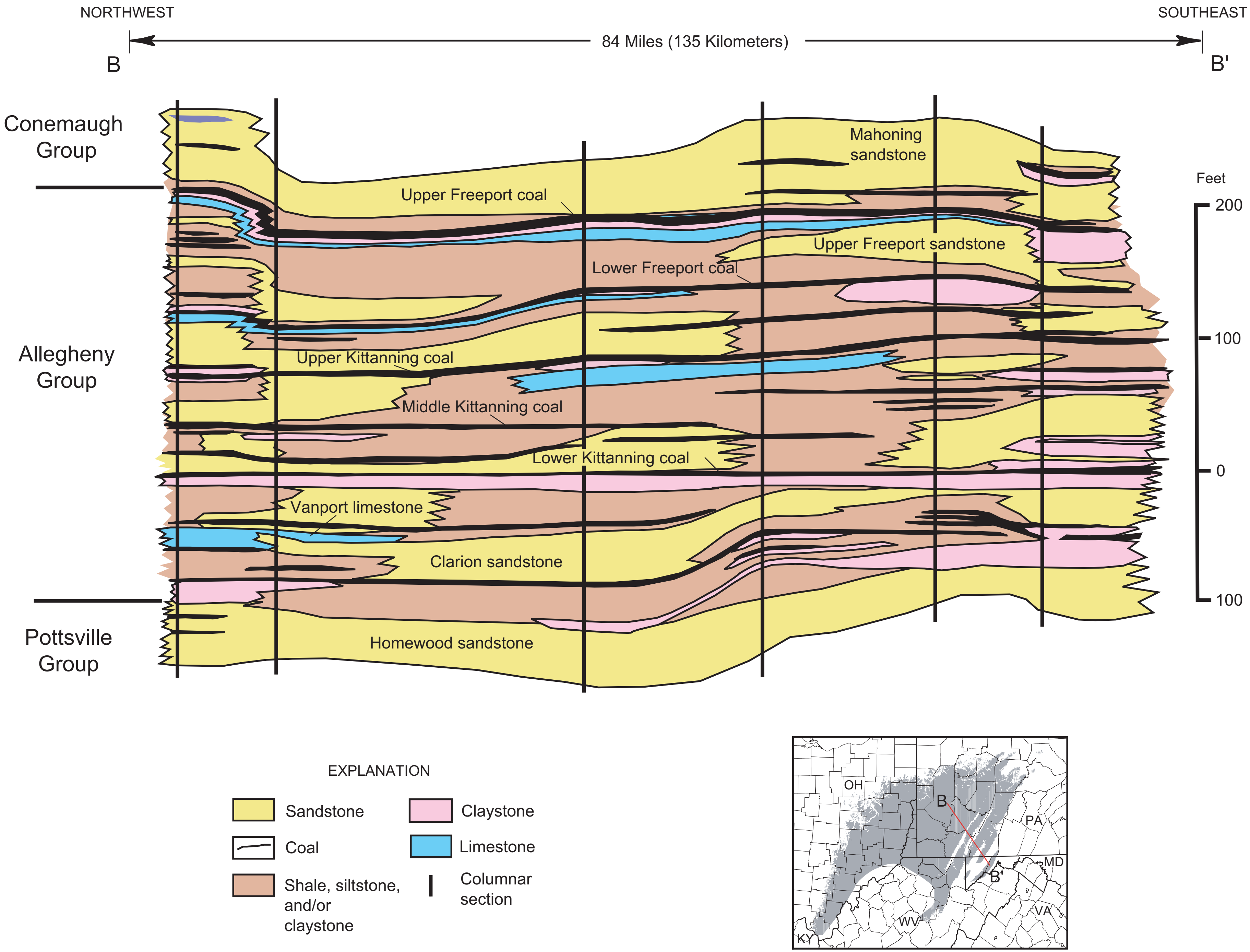

Figure 5. Cross section B-B' from Allegheny County, Pa., southeast to Allegheny County, Md. (adapted from Swartz and others, 1922) (from Milici and others, 2001b), vertical exaggeration X 652.

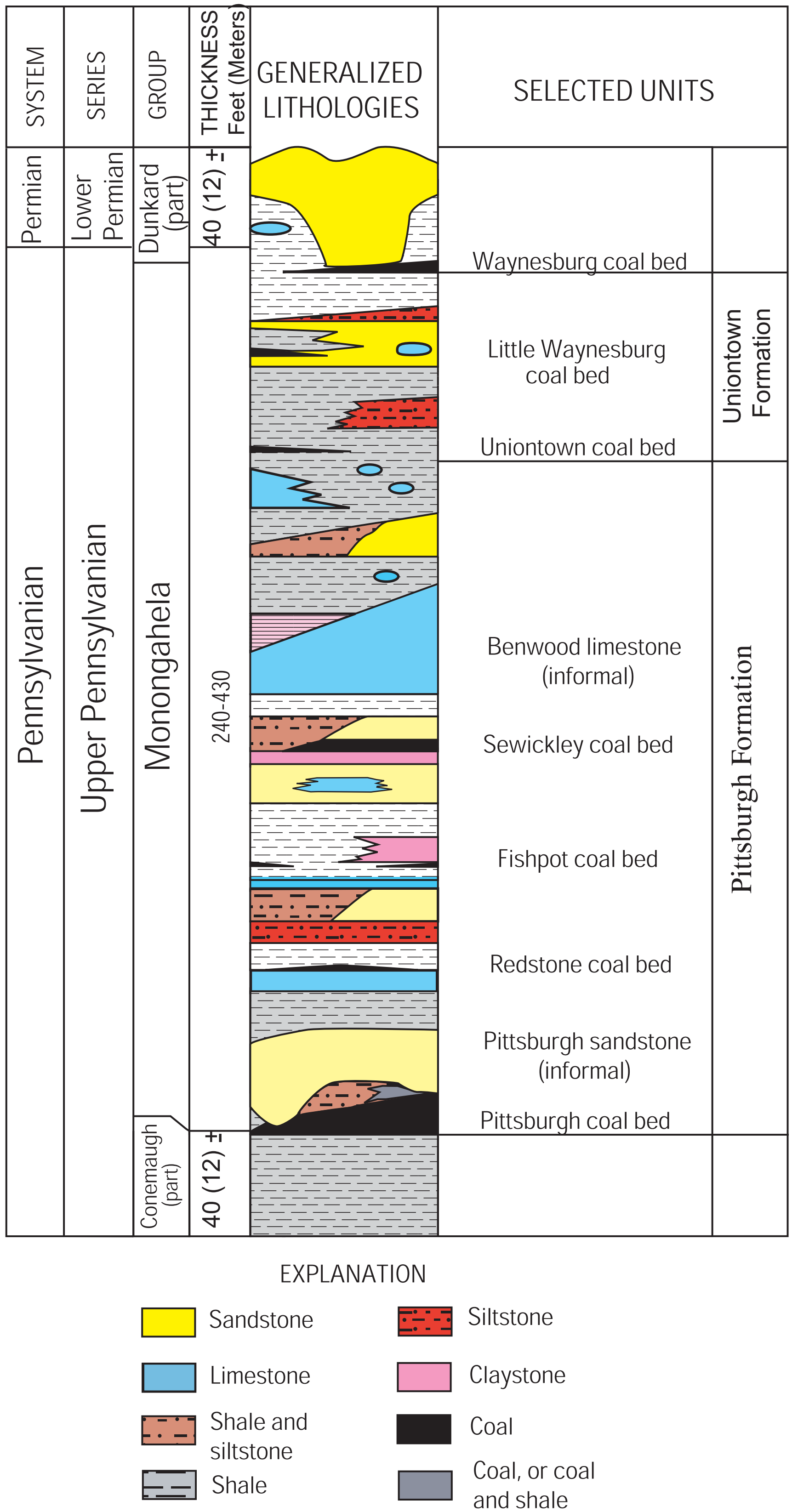

Figure 6. Generalized stratigraphic column of the Upper Pennsylvanian Monongahela Group, showing major coal beds and informal stratigraphic units (from Ruppert and others, 2001).

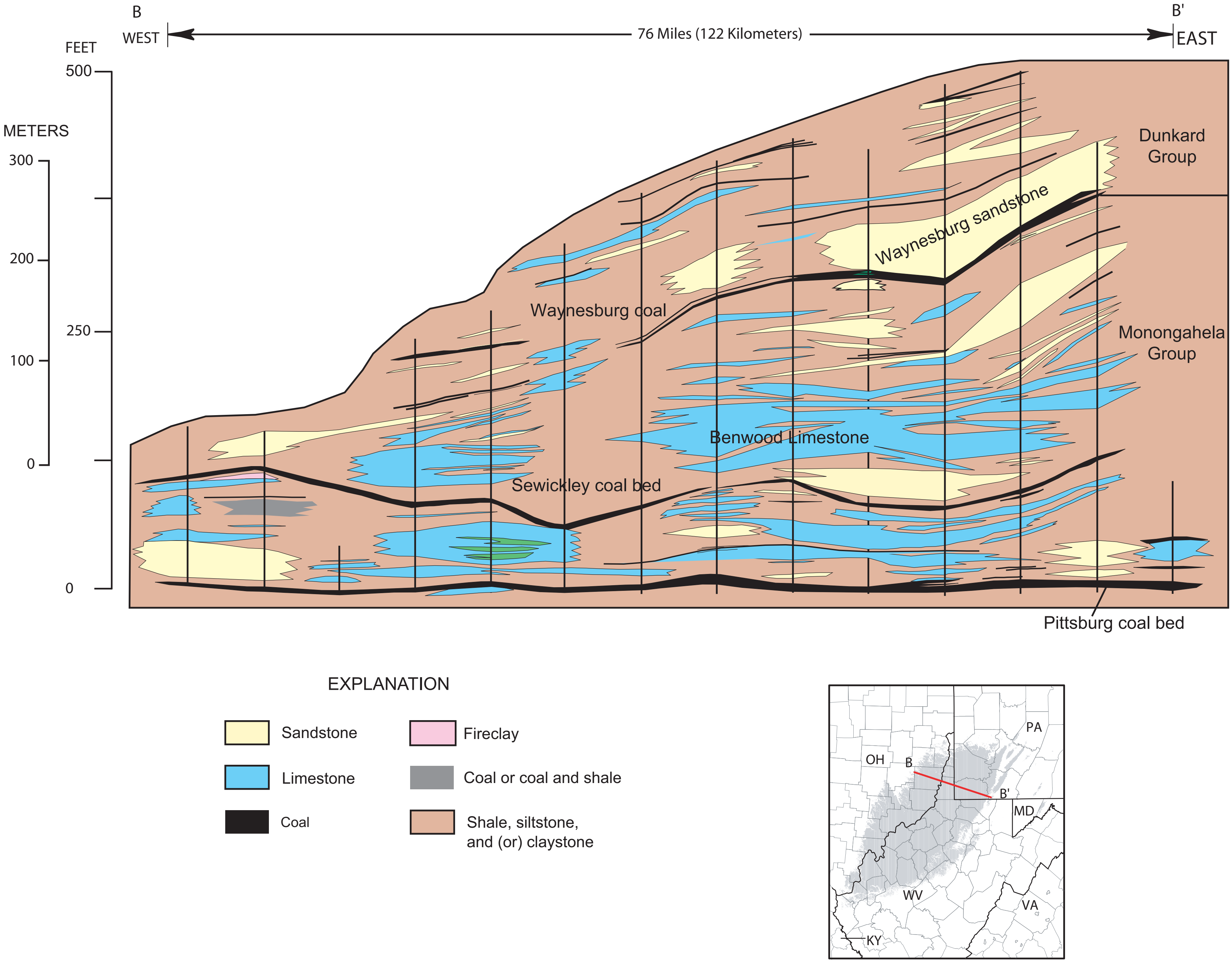

Figure 7. Generalized cross section trending east-west through the Pittsburgh coal bed. Vertical lines represent individual coal cores on line of section B-B'. Vertical exaggeration X398. (from Ruppert and others, 2001).

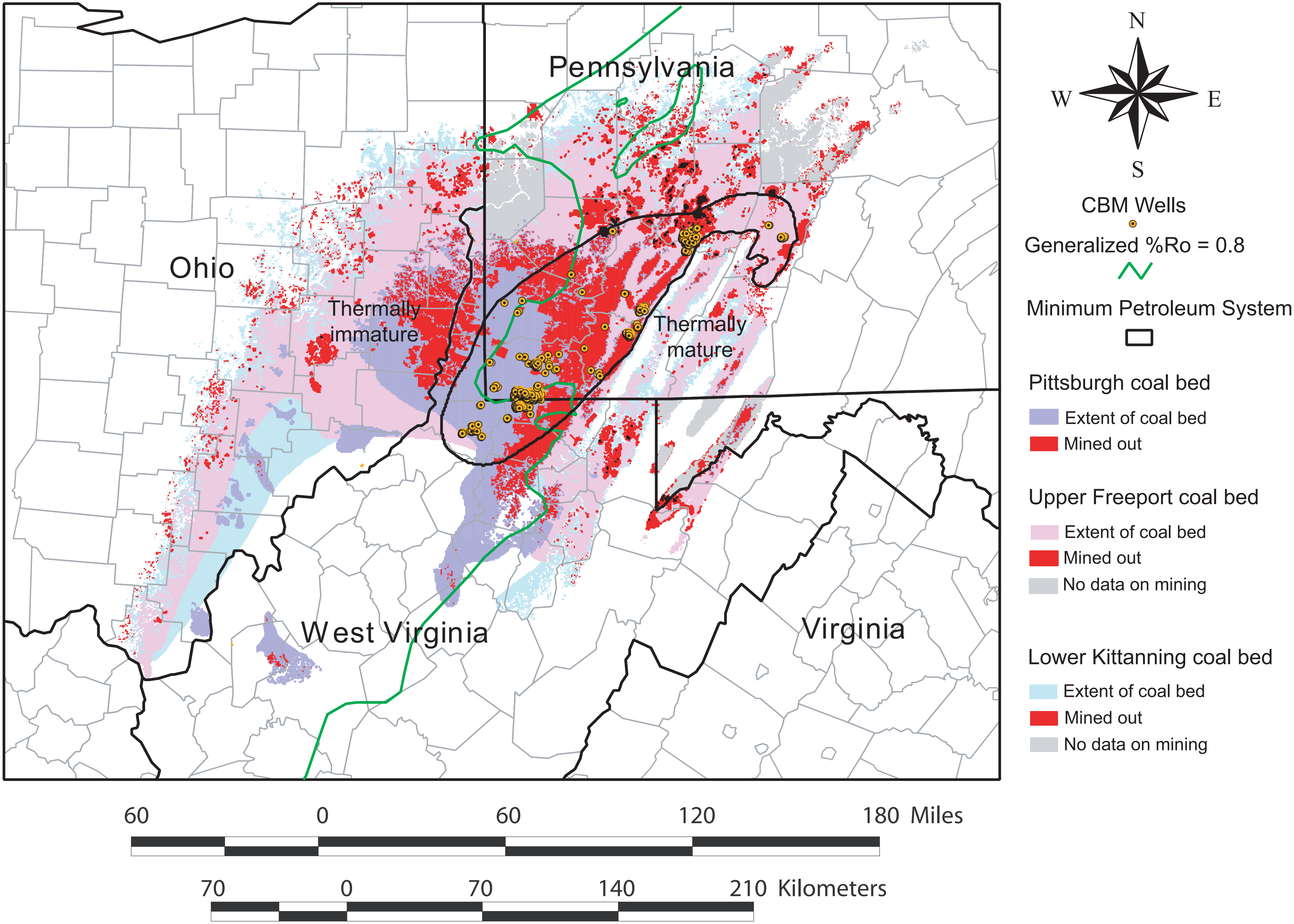

Figure 8. Location of CBM wells with respect to major coal beds in the northern coal field (%Ro isoline based on unpublished data provided by Leslie Ruppert in 2002) (from Ruppert and others, 2001; Tewalt and others, 2001; and Milici and others, 2001b).

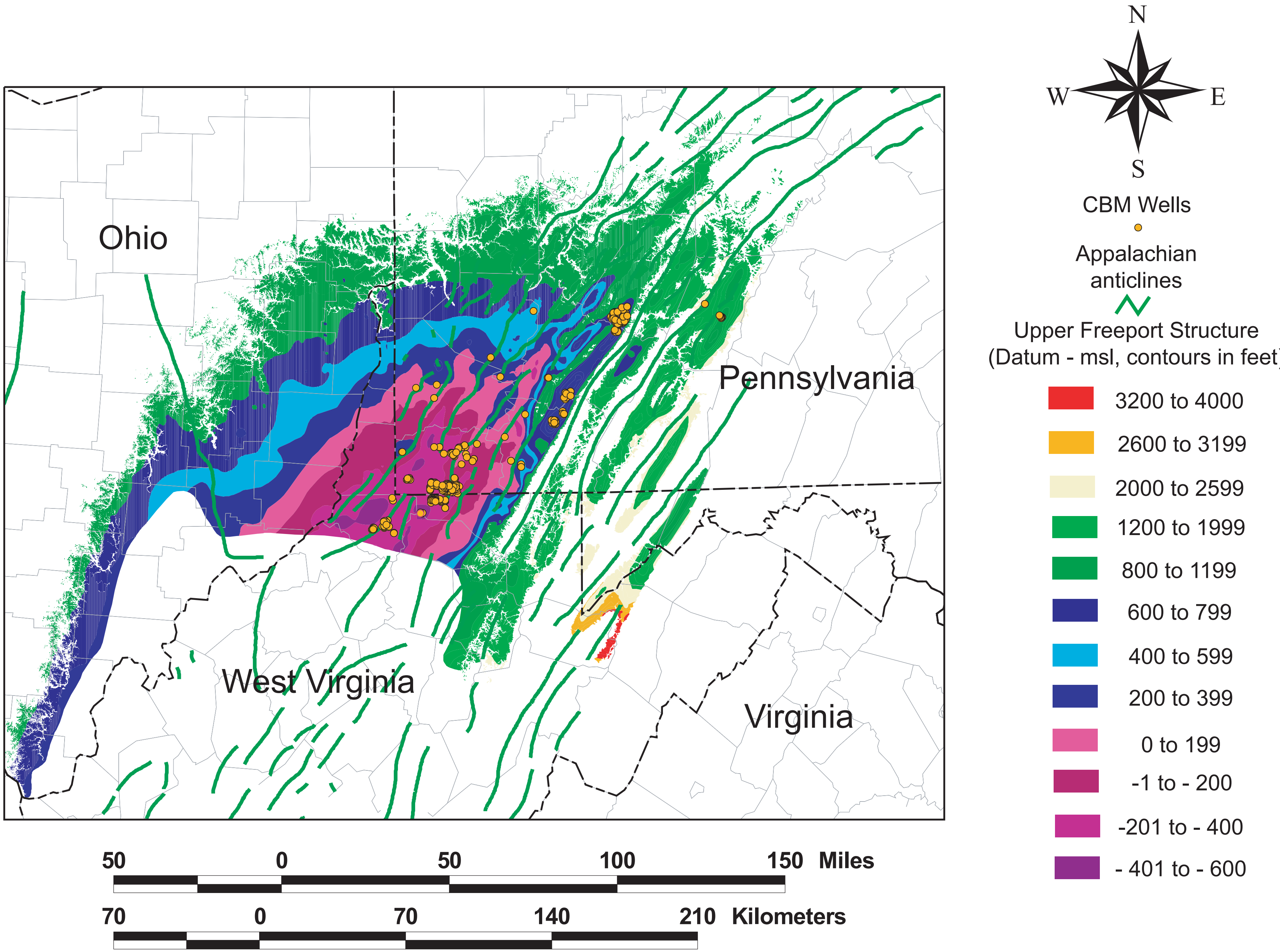

Figure 9. Structural contour map on the top of the Upper Freeport coal bed, showing thermal maturation in percent Ro; contours are relative to mean sea level (from Tewalt and others, 2001)

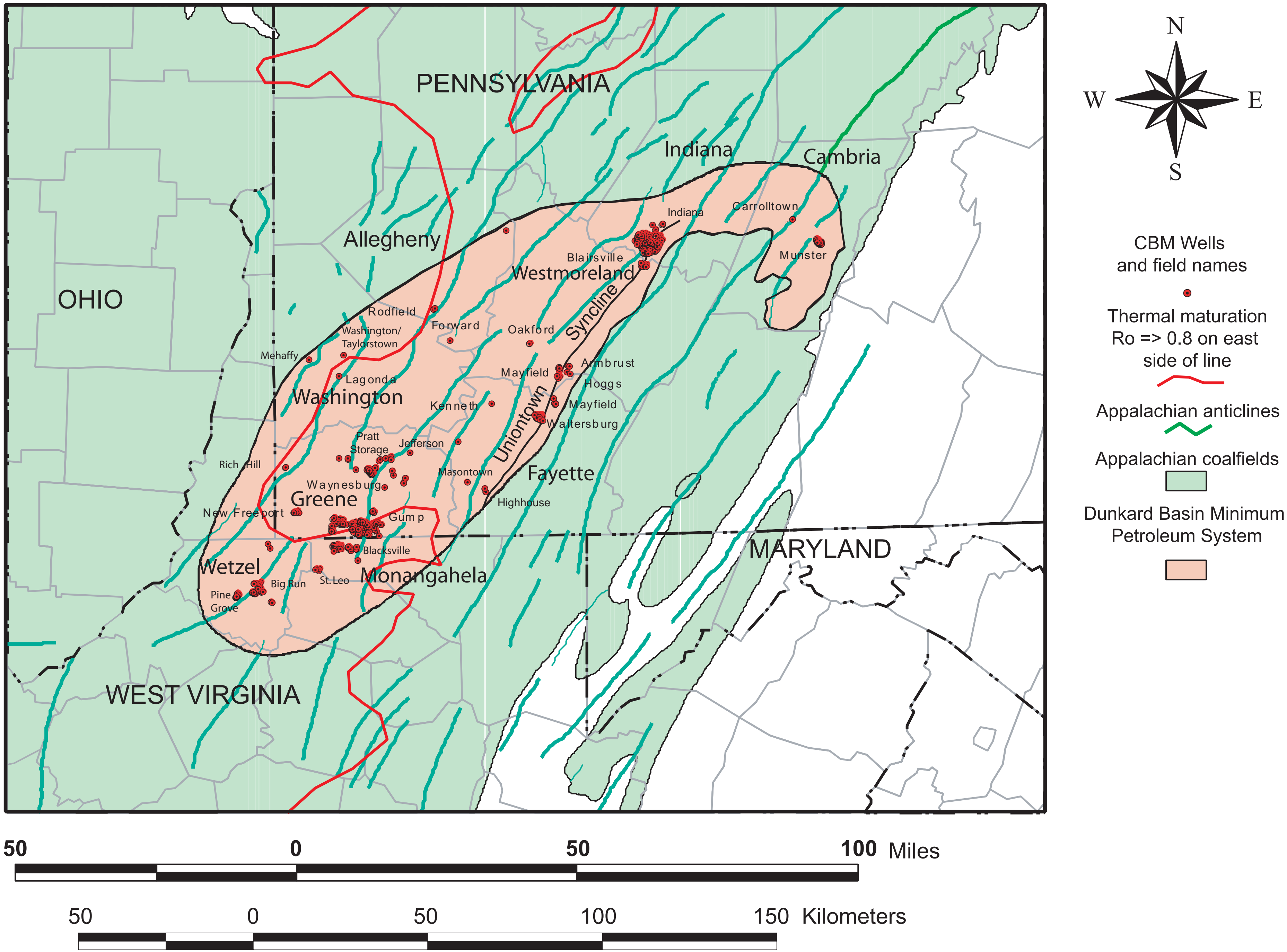

Figure 10. Major CBM fields of northern Appalachian coalfield (CBM well locations from Avary, 2003 and Markowski, 2000).

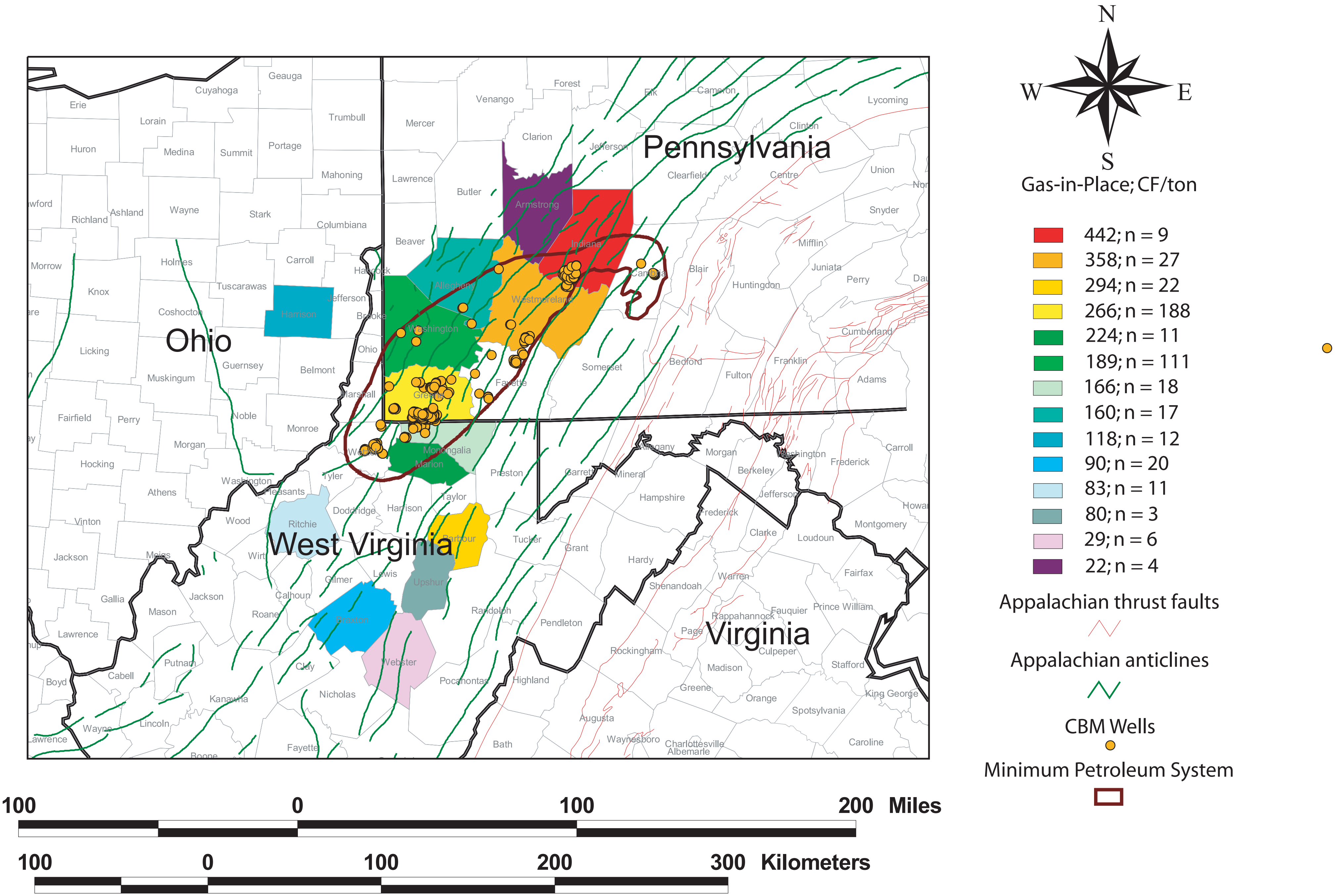

Figure 11. Direct measurement of gas content in coal beds (data from Diamond and others, 1986); n = number of samples. Largest gas determination in CF/ ton value is plotted on map for each county.

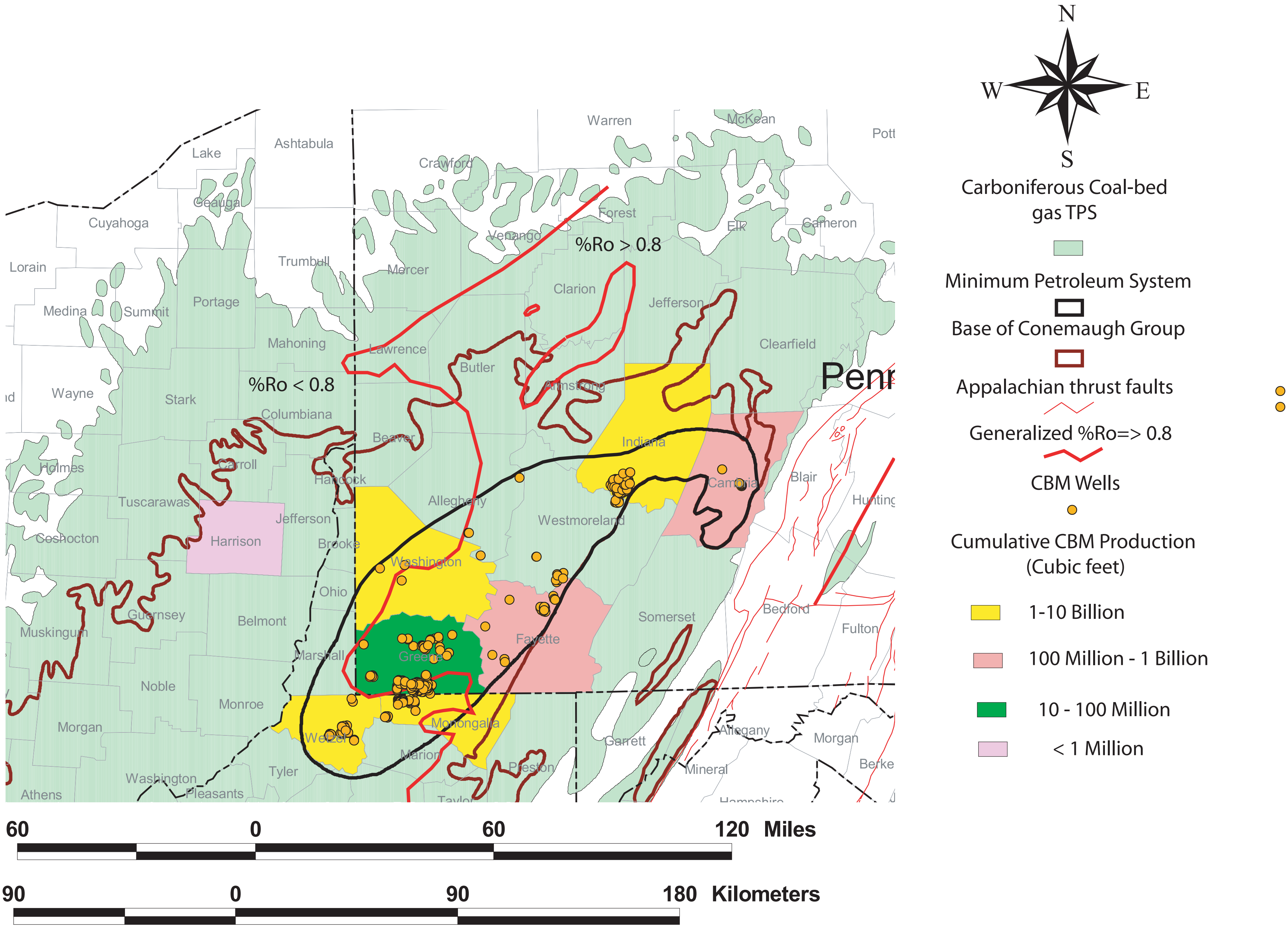

Figure 12. Cumulative production, by county, for northern Appalachian coalfield (see Table 1 for sources of data).

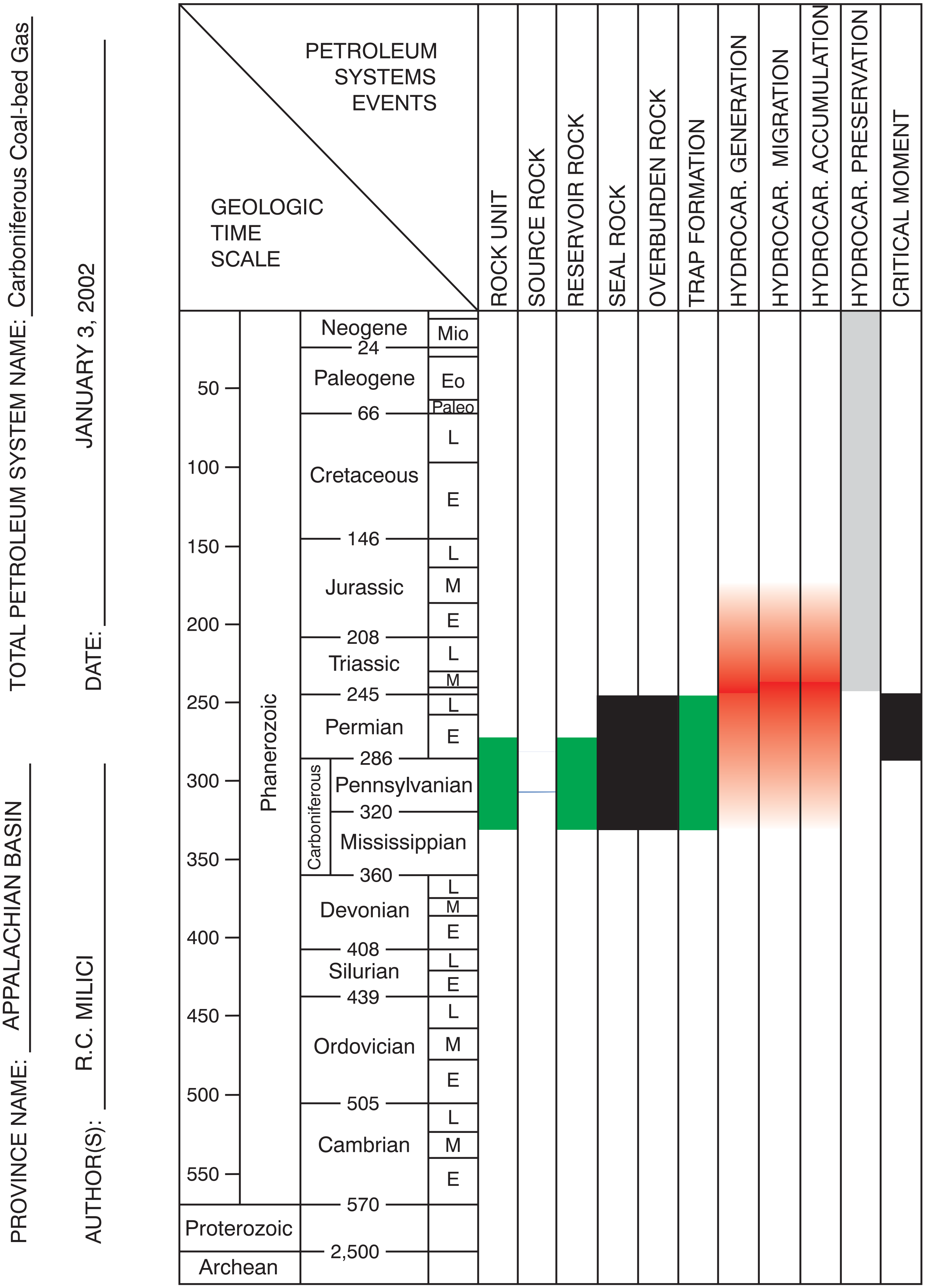

Figure 13. Appalachian Basin Province events chart for thermogenic CBM.

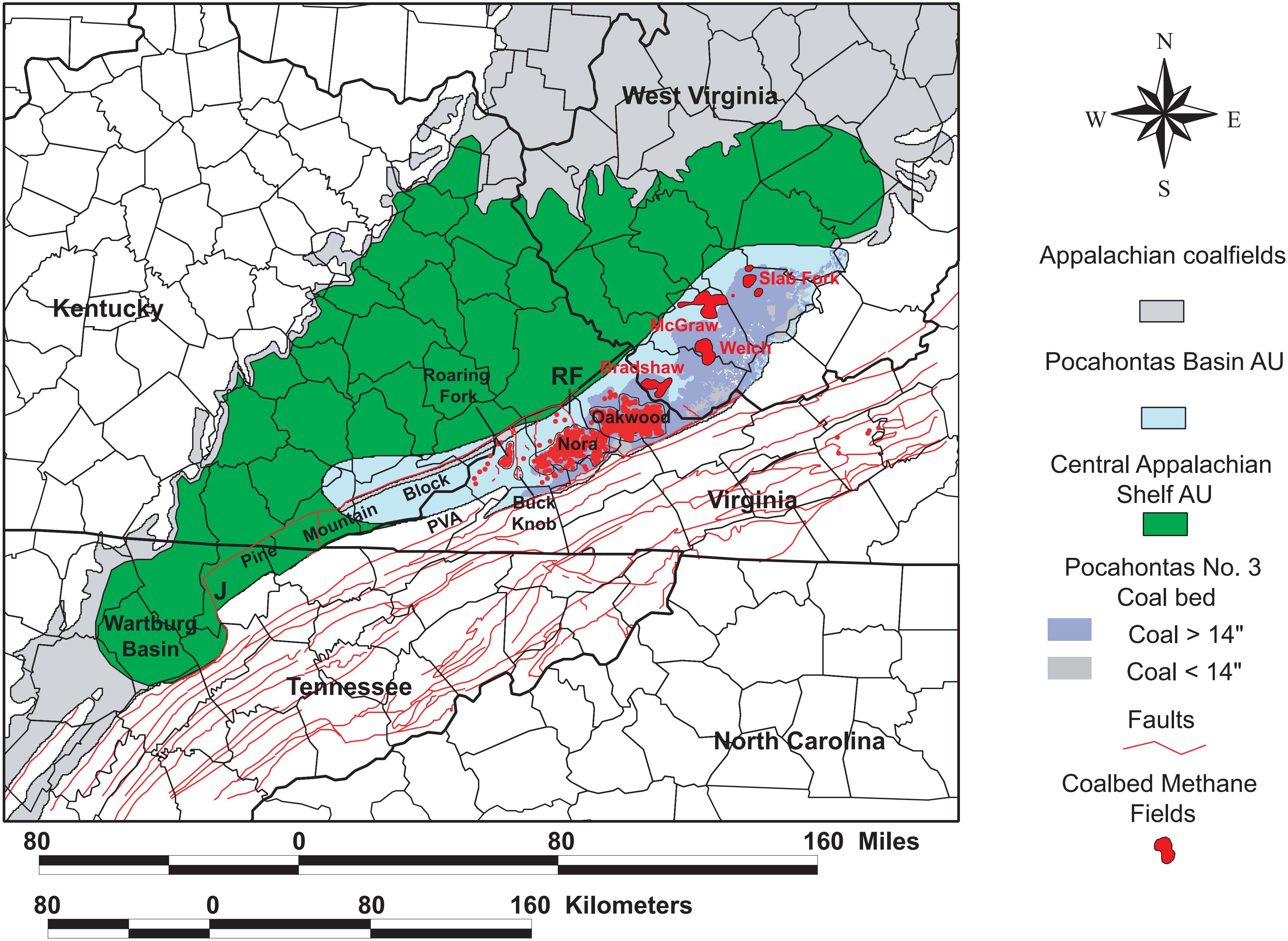

Figure 14. The Pocahontas Basin and Central Appalachian Shelf Assessment Units, showing major CBM fields and the Pocahontas No. 3 coal bed; J - Jacksboro fault; RF - Russell Fork fault; PVA - Powell Valley anticline. (data from Avary, 2003; Nolde, 2003). See figures 18,19 for selected county names.

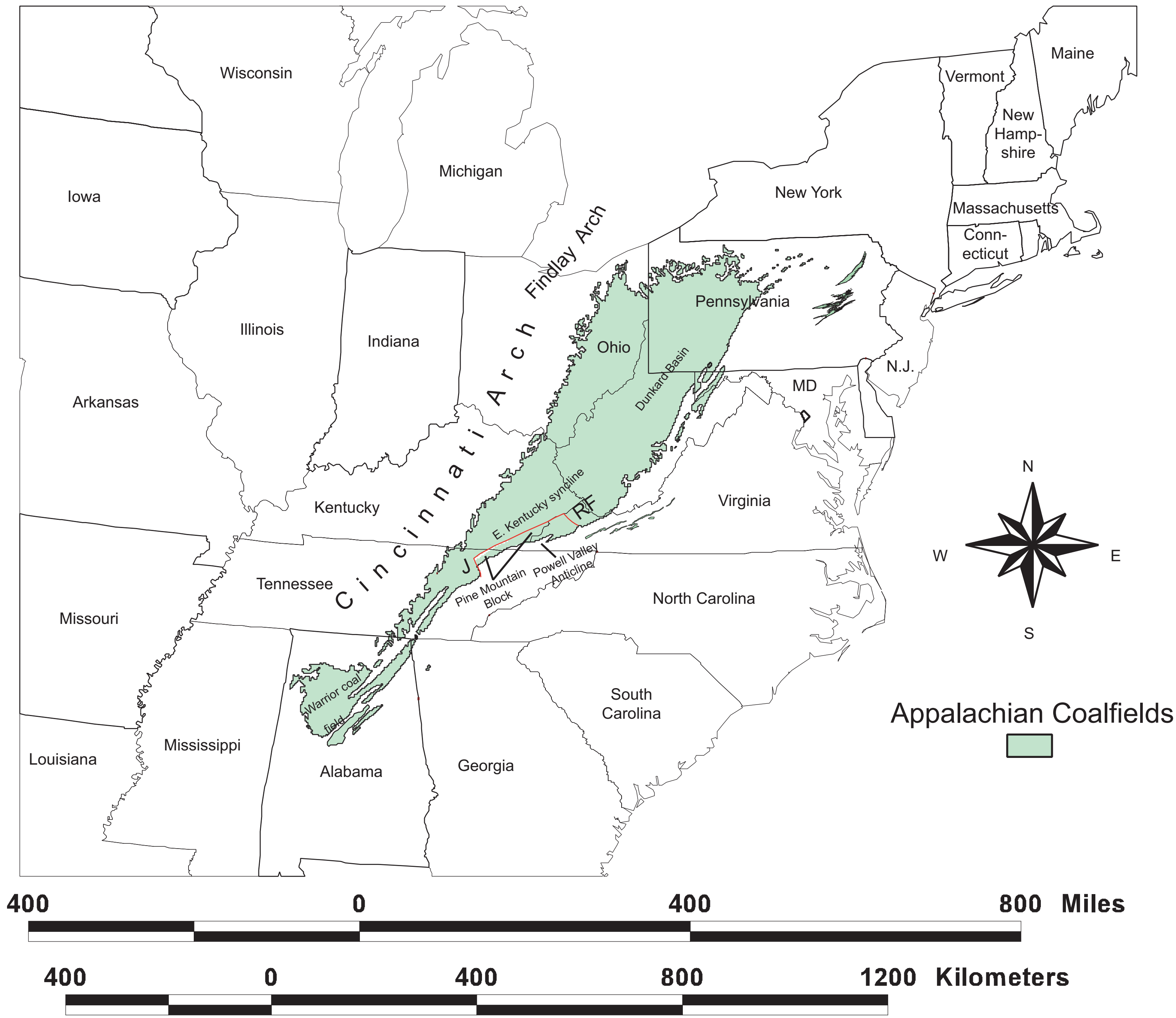

Figure 15. Major structural elements of the Appalachian Basin, showing Pine Mountain Block in Pocahontas Basin; J - Jacksboro fault; RF - Russell Fork fault.

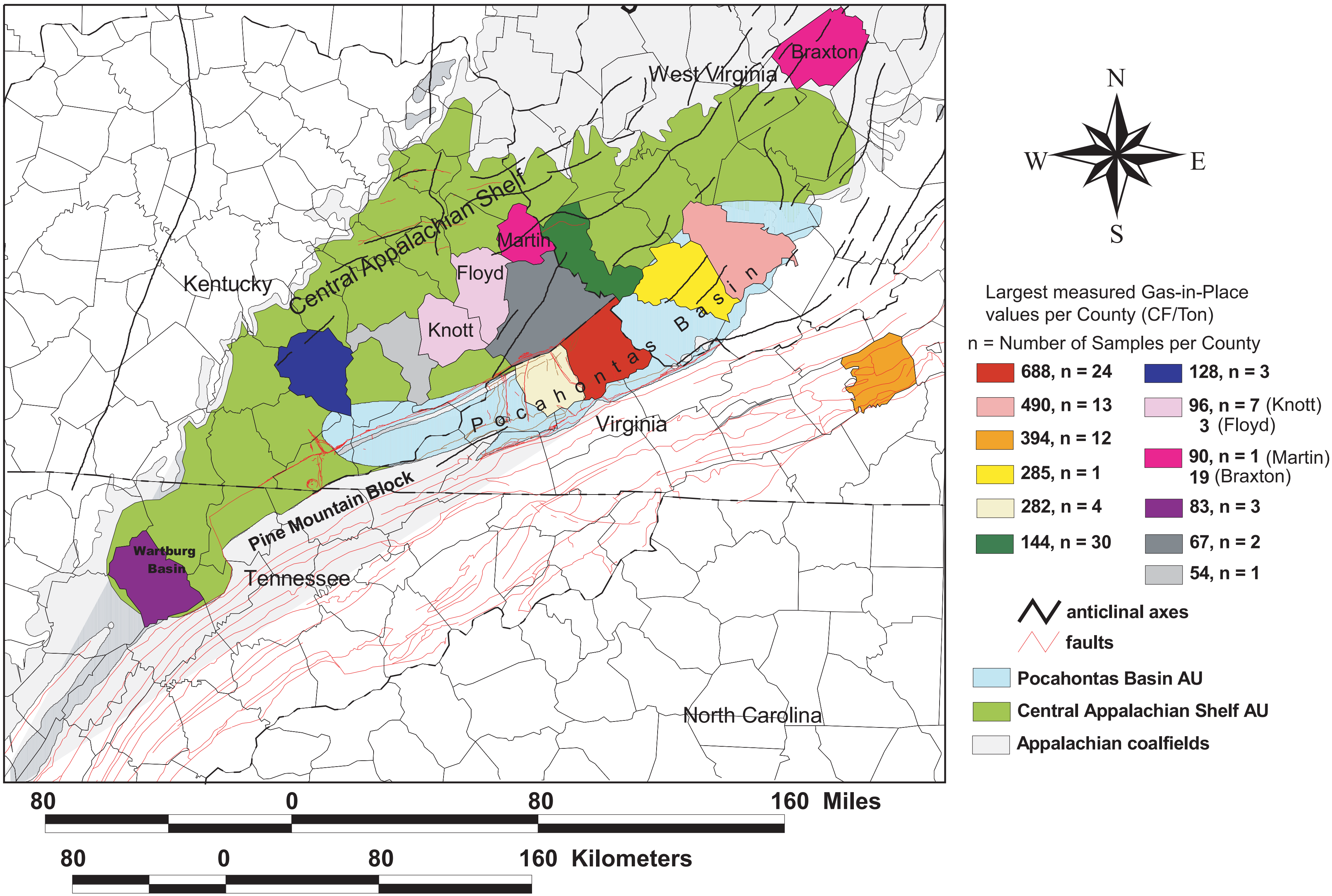

Figure 16. Gas-in-Place data for the Pocahontas Basin. Numbers represent the largest value tested per county; CF/ton = Cubic Feet per ton of coal; n = number of samples tested (data from Diamond and others, 1986). See figures 18 and 19 for additional county names.

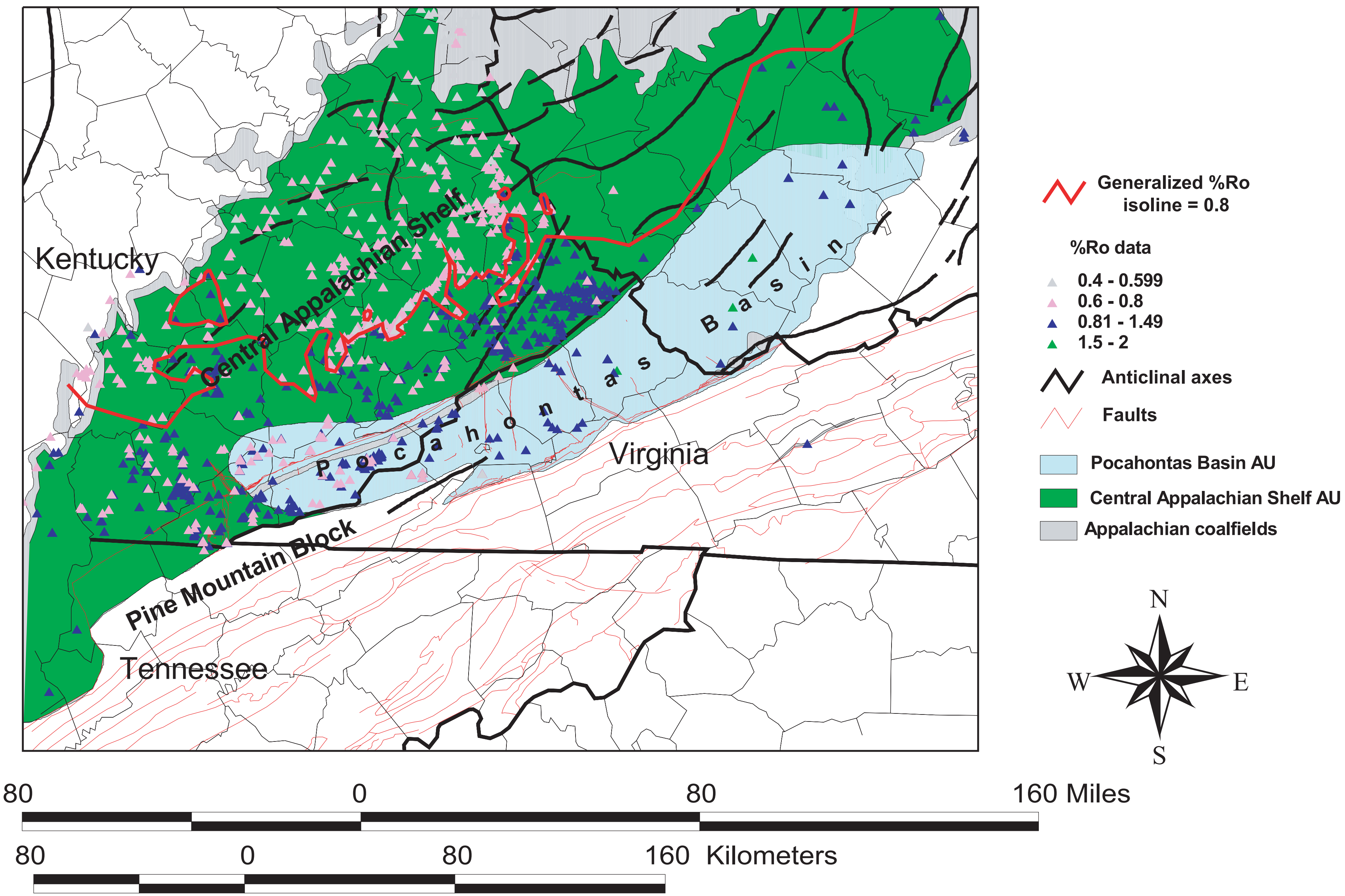

Figure 17. Thermal maturation data, in %Ro, for the Central Appalachian coalfield. The generalized 0.8 % Ro isoline separates thermally immature coalbeds on the west from coalbeds on the east that are immature to mature with respect to gas generation. Unpublished %Ro data courtesy of L.F. Ruppert, 2002.

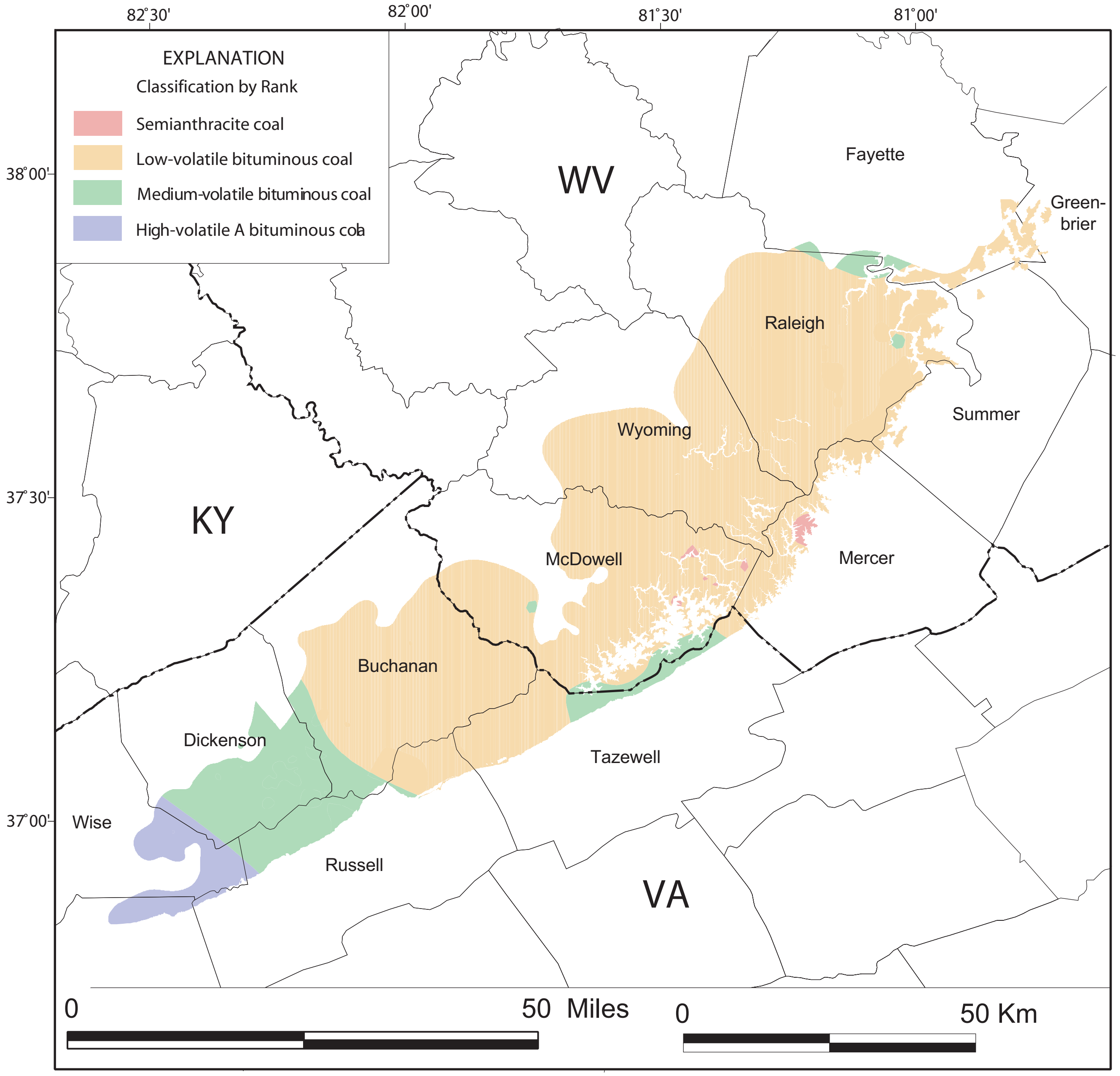

Figure 18. Map showing extent and apparent rank of the Pocahontas No. 3 coal bed based on 125 analyses. The coal tends to increase in rank fromhigh-volatile A bituminous in the southwest to low-volatile bituminous in the northeast, with small bulls-eye-shaped pods of semi-anthracite observed along the eastern front in McDowell and Mercer Counties, W. Va. Methodology for rank determinations is based on the percentage of fixed carbon in the sample. When dry mineral-matter-free (dmmf) fixed carbon is > 69 weight percent, rank is determined on dmmf fixed carbon; when dmmf fixed carbon is <69 weight percent, rank is determined from moist mineral-matter-free gross calorific values (American Society for Testing and Materials, 1996). (from Milici and others, 2001a).

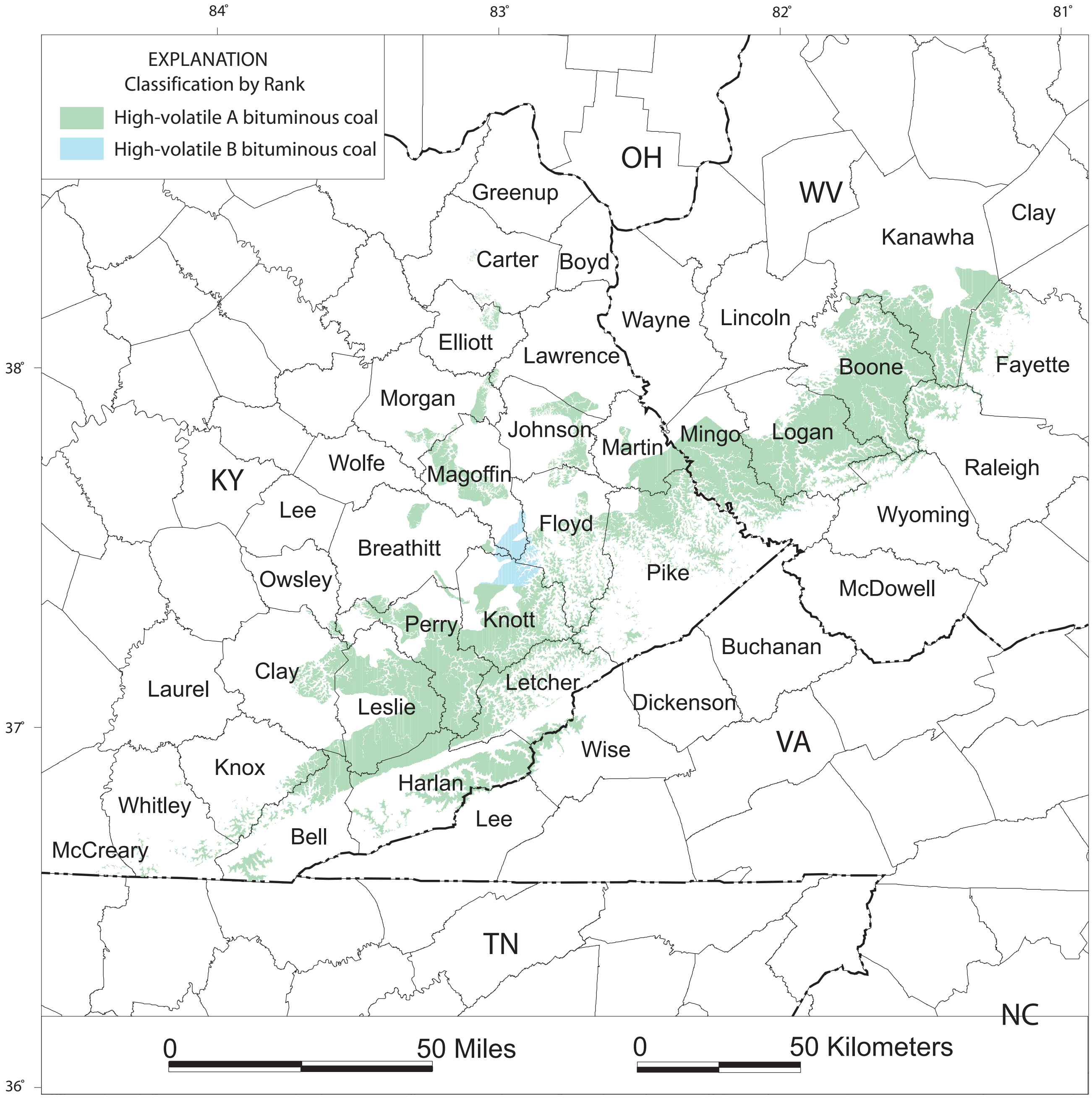

Figure 19. Map showing the extent and apparent rank of the Fire Clay coal zone in Kentucky, Virginia, and West Virginia based on 55 analyses. The coal is almost entirely high-volatile A bituminous. Only gross calorific values were used to determine the rank of the Fire Clay coal zone. The one area shown as high-volatile B bituminous rank reflects a decreasing trend in moist, mineral-matter-free (mmmf)-Btu/lb values, but is based on only one analysis and may be invalid (modified slightly from Tewalt and others, 2001).

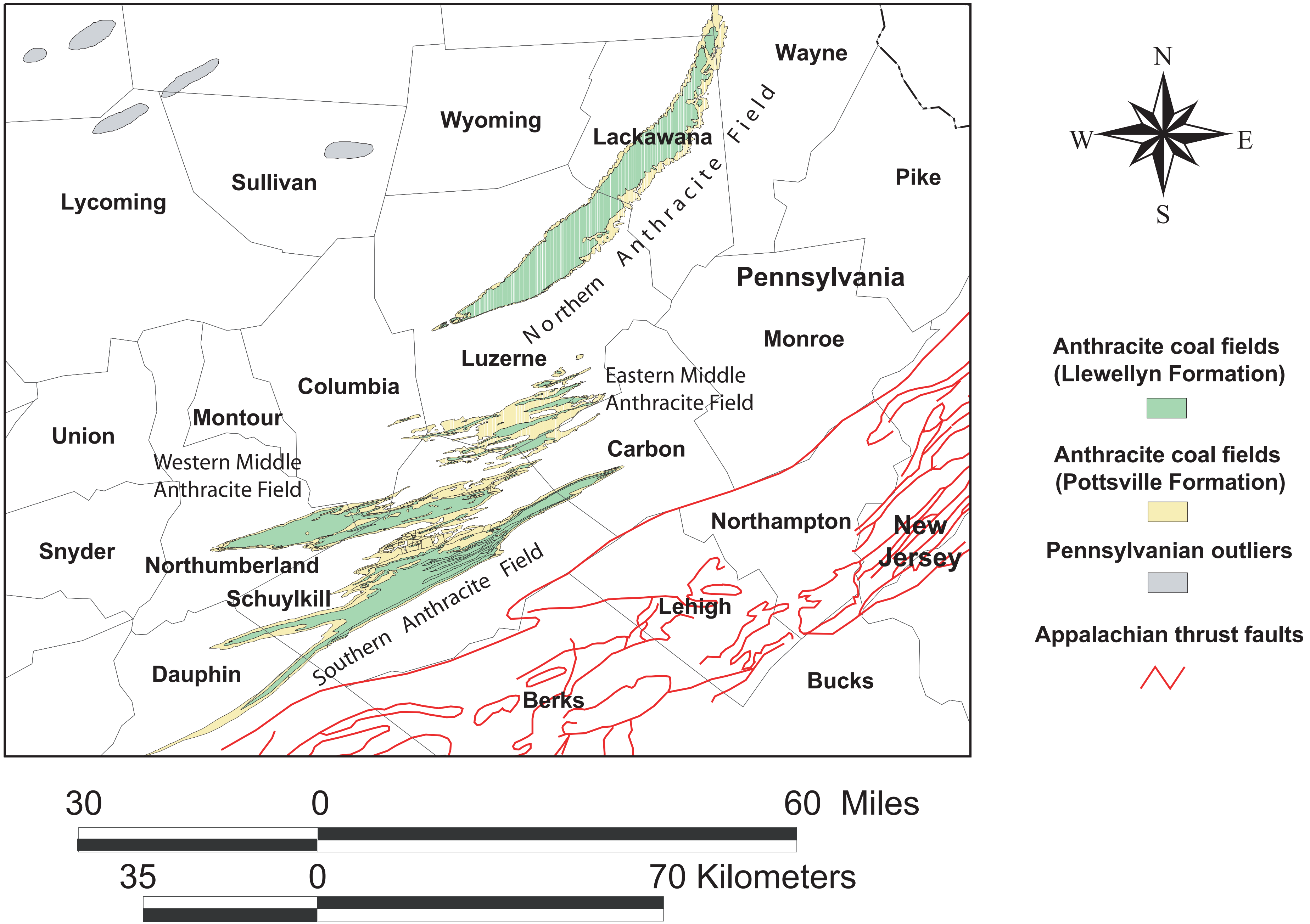

Figure 20. Location and generalized geology of the Pennsylvania anthracite district

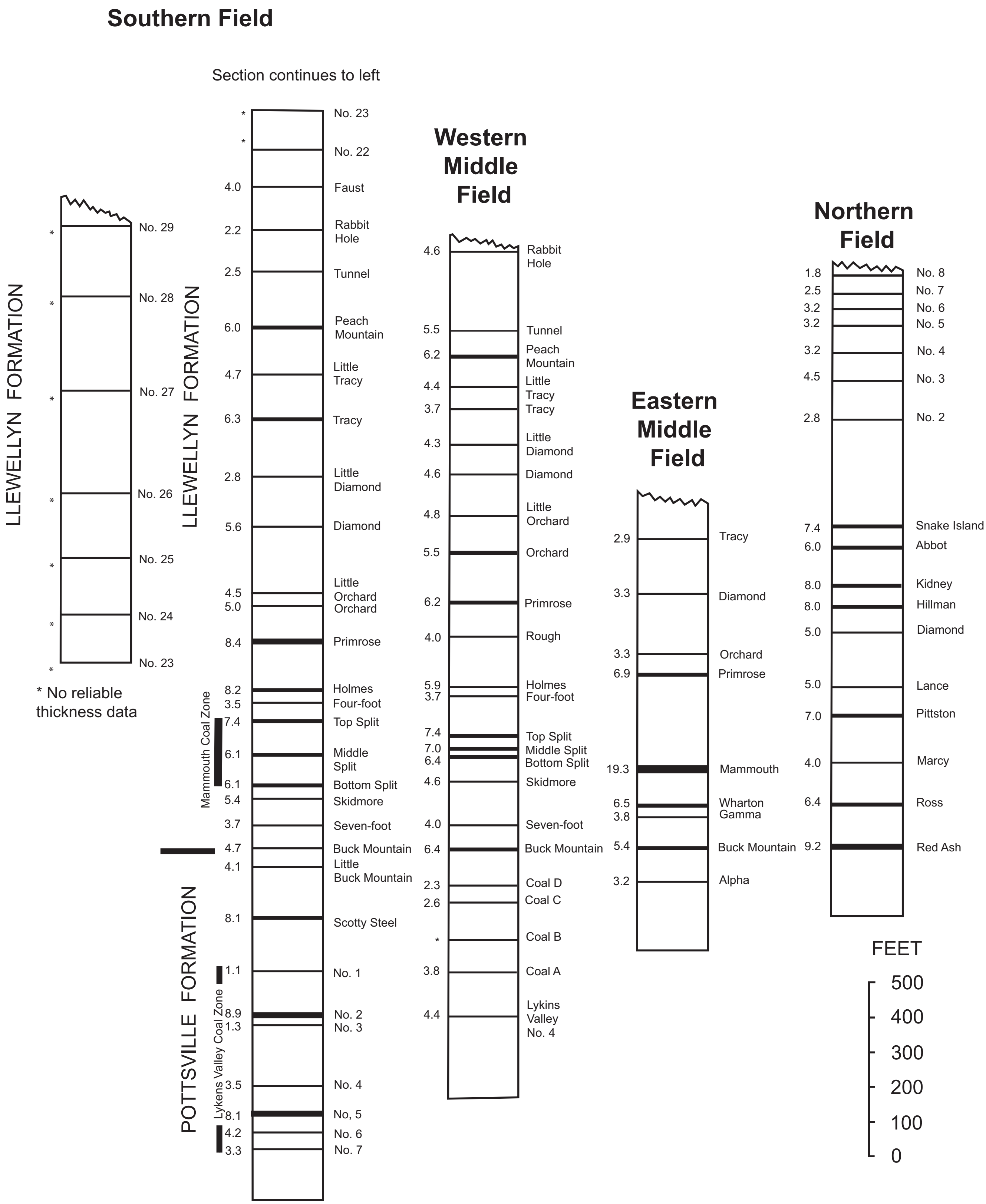

Figure 21. Generalized columnar sections showing the names of coal beds, the average thickness of each coal in feet, and the intervals between coal beds in the Pennsylvania anthracite fields (From Arndt and others, 1968, p. 130)

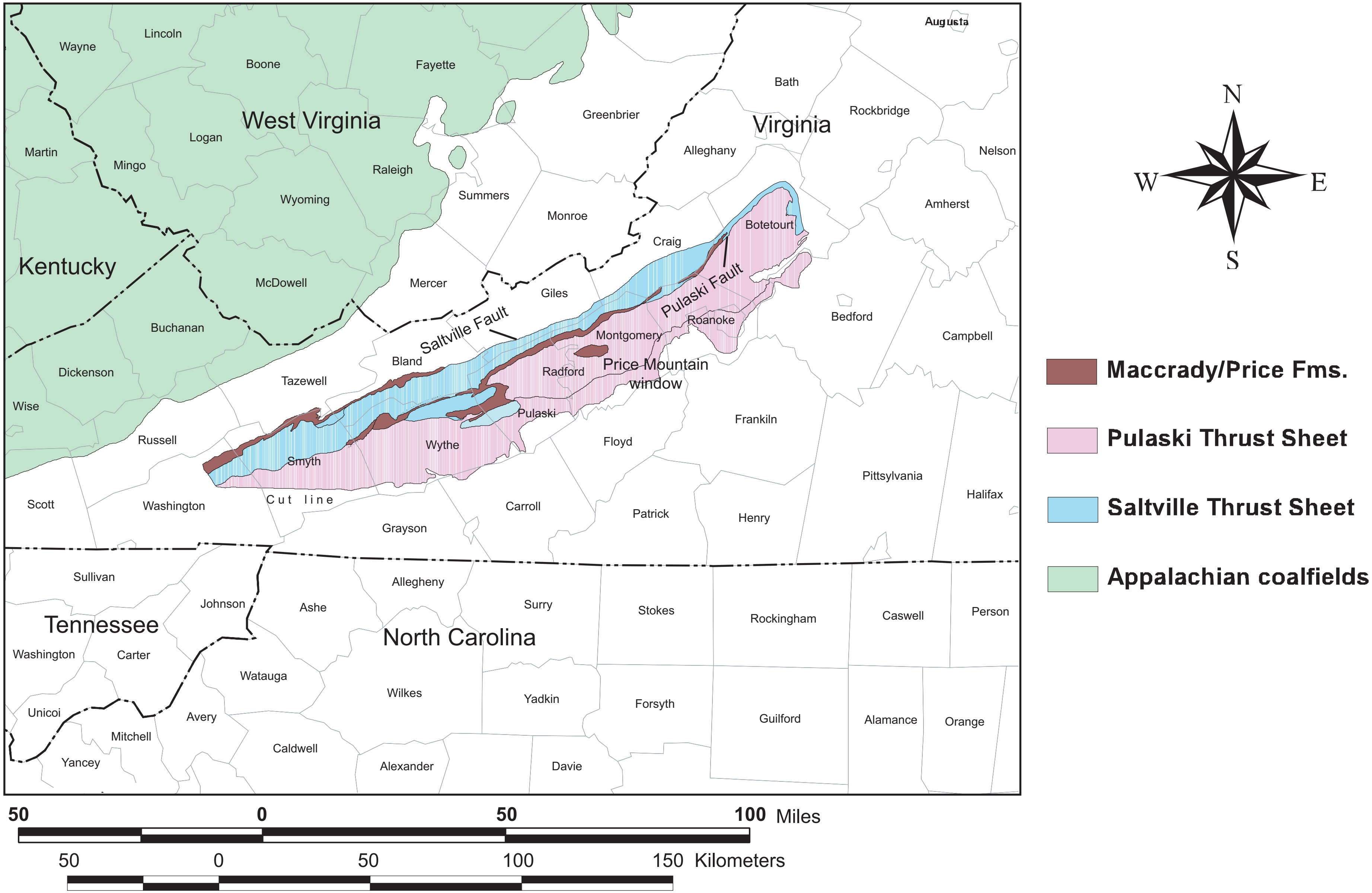

Figure 22. Virginia semianthracite district in southwestern Virginia. Coal beds of Mississippian age are exposed along the foot walls and in fensters through major Appalachian thrust sheets (map of thrust sheets from Virginia Division of Mineral Resources, 1993).

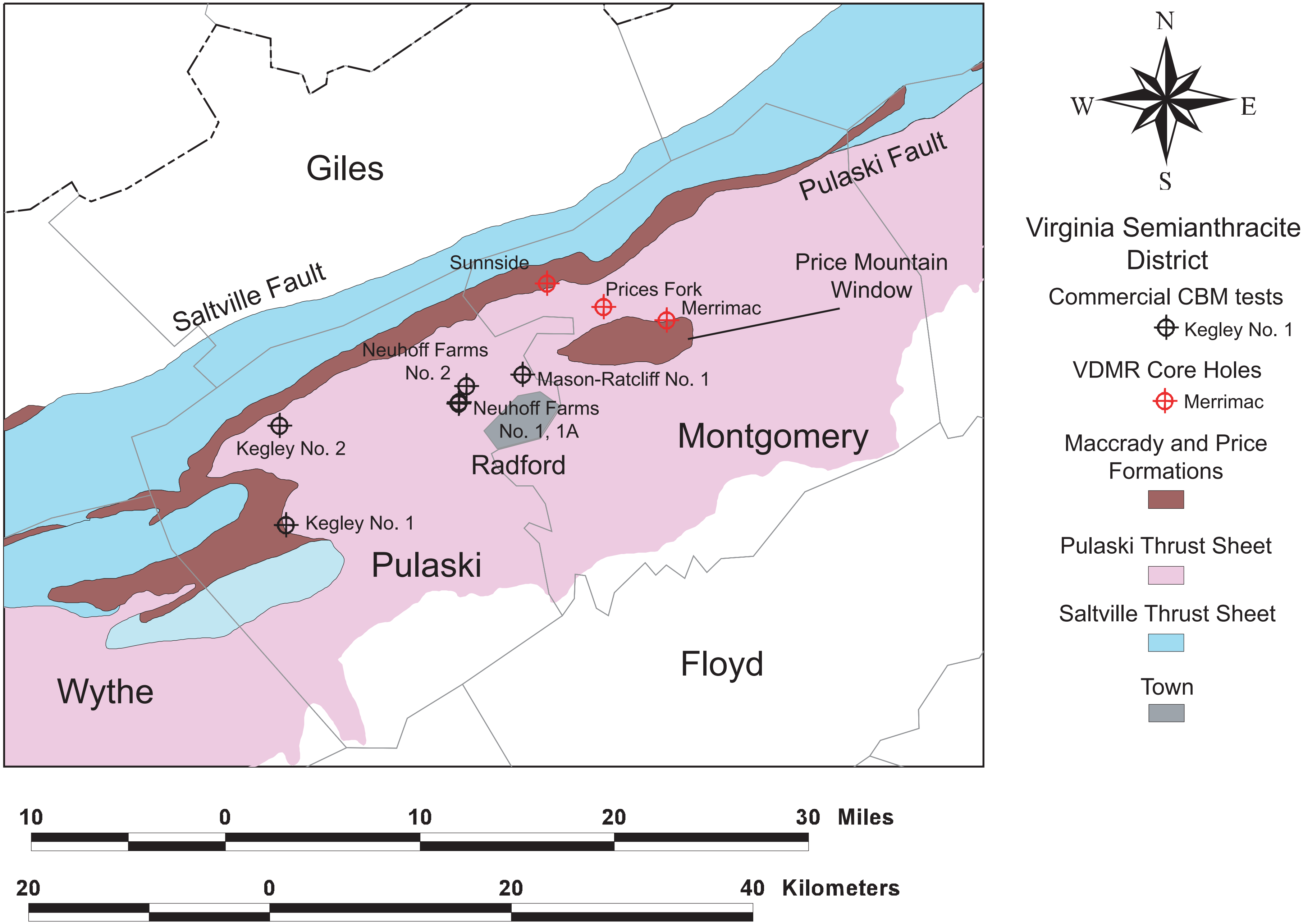

Figure 23. Virginia semianthracite district, showing locations of Virginia Division of Mineral Resources core holes and commercial CBM tests.

Table 1. Cumulative production of CBM from the Appalachian Basin (1999-2003 data). Source of data: Alabama State Oil and Gas Board (2004); Kentucky Division of Gas and Oil (2004); Markowski (2004); Virginia Center for Coal and Energy Research (2004); and Avary (2004).

State	County	Date of first Production	Cumulative Production Date	No. Currently Producing Wells	CBM Cumulative Production (Mcf)
Alabama	Greene	1992	10/31/2003	0	99,565
	Hale	1990	10/31/2003	0	111,543
	Jefferson	1980	10/31/2003	655	184,658,319
	Pickens	1990	10/31/2003	0	1,873
	Shelby	1990	10/31/2003	0	3,969,067
	Tuscaloosa	1981	10/31/2003	3,096	1,310,241,313
	Walker	1989	10/31/2003	102	18,937,713
Alabama	Subtotal			3,853	1,518,019,393
Virginia	Buchanan	1992	2002	1,492	321,535,042
	Dickenson	1988	2002	474	71,810,618
	Russell	1990	2002	110	10,694,923
	Tazewell	1990	2002	93	5,620,269
	Wise	1990	2002	80	6,577,583
Virginia	Subtotal			2,249	416,238,435
West Virginia	Logan	2002	2002	1	157
	Marshall	ND	ND	ND	ND
	McDowell	1995	2002	40	3,571,128
	Monongalia	1992	2002	22	1,443,617
	Raleigh	1992	2002	2	62,811
	Wyoming	1994	2002	67	19,335,467
	*Wetzel	1931	2002	2	1,328,862
West Virginia	Subtotal			133	25,742,042
Pennsylvania	Cambria	1997	2002	Confidential	166,950
	Fayette	1999	2002	Confidential	199,718
	Greene	1988	2002	Confidential	774,910
	Indiana	1993	2002	Confidential	3,433,679
	Washington	1993	2002	Confidential	1,184,125
Pennsylvania	Subtotal			225	5,759,382
Kentucky	Bell	1998	2002	3	7,674
	Clay	1998	2002	5	56,478
	Leslie	2000	2002	1	
	Letcher	1997	2002	1	
Kentucky	Subtotal			10	64,152
Appalachian Basin Total				6,470	1,965,823,404

* Big Run and new unnamed fields, only

Table 2. Generalized Pennsylvanian and Permian stratigraphic nomenclature of the northern part of the Appalachian Basin. L. = Lower; U. = Upper; ss. = sandstone; cgl. = conglomerate, Fm. = Formation; ls = limestone; informal units are in italics.

AGE	NORTHERN WEST VIRGINIA	MARYLAND	OHIO	PENNSYLVANIA Western	PENNSYLVANIA Eastern
Permian	Dunkard Group	Dunkard Group	Dunkard Group	Dunkard Group *Waynesburg coal*	
Late Pennsylvanian	Monongahela Group	Monongahela Group	Monongahela Group *Benwood limestone* *Pittsburgh coal*	Monongahela Group Uniontown Fm. *Uniontown coal* Pittsburgh Fm. *Pittsburgh coal*	Llewellyn Formation
Late Pennsylvanian	Conemaugh Group	Conemaugh Group	Conemaugh Group	Conemaugh Group Casselman Fm. *Ames ls.* Glenshaw Fm. *Brush Creek ls.* *Mahoning ss.*	Llewellyn Formation
MIDDLE PENNSYLVANIAN	Allegheny Formation	Allegheny Group	Allegheny Group	Allegheny Group *Freeport coals* *Kittanning coals* *Clarion coal* *Brookville coal*	Llewellyn Formation *Mammoth coal bed*
MIDDLE PENNSYLVANIAN / EARLY PENNSYLVANIAN	Pottsville Group	Pottsville Group	Pottsville Group	Pottsville Group *Homewood ss.* *Mercer coals* *U. Connoquenessing ss.* *Quakerstown coal* *L. Connoquenessing ss.* *Sharon coal* Sharon cgl.	*Pottsville Fm.* *Mauch Chunk Fm (part)*

Table 3. Major coal beds of the Dunkard Basin

SYSTEM	GROUP	COAL BED
PERMIAN	DUNKARD	WAYNESBURG
PENNSYLVANIAN	MONONGAHELA	SEWICKLEY REDSTONE PITTSBURGH
	CONEMAUGH	BAKERSTOWN MAHONING BRUSH CREEK
	ALLEGHANY	UPPER FREEPORT LOWER FREEPORT UPPER KITTANNING MIDDLE KITTANNING LOWER KITTANNING BROOKVILLE / CLARION
	POTTSVILLE	MERCER QUAKERSTOWN SHARON

Table 4: Coalbed methane (CBM) fields and pools in the Dunkard Basin, Pennsylvania and West Virginia (data from Markowski, 2001a; Patchen and others, 1991; and Avary, K. L., 2003, http://www.wvgs.wvnet.edu/www/datastat/datastat.htm). Mcfd = thousands of cubic feet per day; P&A = plugged and abandoned; ss. = sandstone; L. = Lower, M = Middle, U. = Upper;

PENNSYLVANIA					Field Ranges							
County	**Field (see fig. 10 for loction)**	**Pool name (pool no.)**	**No. Wells**	**Coal beds targeted**	**Perforation/ stimulation intervals (ft)**	**Natural open-flow (Mcfd)**	**After treatment open flows (Mcfd)**	**Target interval depths (feet)**	**Total depths (feet)**	**Water Production (barrels per day)**	**Well Type**	**Status**
Indiana	Blairsville	Campbells Mill (24)	50	Mahoning U. Freeport M. Freeport L. Freeport U. Kittanning M. Kittanning L. Kittanning Clarion Brookville Mercer	319-1,169.5	5-15	40-125	749-1,170	975-1,410	115	CBM	Producing
			3	U. Freeport		120-140		475-575	475-575		Gob	Non-producing*
	Indiana	Unnamed (25)	3	U. Freeport				622-638	655-670		Test/service	P&A
Greene	Gump	Rudolph Run (6)	1	Pittsburgh	674-680	0.19-14.9			828-1,250			P&A
			1	Pittsburgh								P&A
			1	Pittsburgh	755-760			680-695				P&A
	Jefferson	Unnamed (11)	1	Pittsburgh U. Freeport					934		CBM	Dry
	Waynesburg	Blairtown (8)	18	Waynesburg Sewickley Pittsburgh	0-?		Up to 100	582-1,022	616-1,022	Trace	CBM / degasification	P&A/ Non-producing*
		Unnamed (7)	1	Pittsburgh U. Freeport Freeport ss.				580, 1,220 1,249	1,420		CBM	Dry
		Unnamed (12)	1	Salt Sand	1,260-1,290	29	10	1,260-1,290	1,333			Dry
		Frosty Run (13)	1	Clarion Brookville	1,344.5-1,490.75		15		1,607	80		Dry
			1	Pittsburgh					862			Dry

	Waynesburg	Turner (9)	1	Waynesburg Sewickley Pittsburgh rider Pittsburgh Bakerstown U. Freeport U. Kittanning M. Kittanning Clarion Mercer	496.8-1,416.2	5	20-30	498.6-1,416.2	1,450	120-230	CBM	Non-producing*
			1							610	CBM	Dry; P&A
			1				10				CBM/Conventional	Shut-in
			1	Sewickley Pittsburgh Mahoning	688-1,589		50-10	688-1,589	1,902		CBM/Conventional	Shut-in
			1	Pittsburgh		450		531	571		Gob	Producing
	Pratt Storage	Poverty Run (10)	1	U. Freeport				1,305	1,305		Degasification	Non-producing*
	Rich Hill	Dunkard Fork (1)	1	Pittsburgh		1.1		347	392		CBM	P&A
	New Freeport	Windy gap (5)	5	Waynesburg “A” Waynesburg Sewickley Pittsburgh L. Freeport U. Kittanning	633-1,756		50	1,140-1.756	1,330-2,130	Trace	CBM	P&A
Fayette	Highhouse	Smiley (18)	2		747-770	100		747-770	2,707		CBM/Conventional	Non-producing*; P&A
	Waltersburg	Adelaide (19)	1	Clarion Brookville	1,053-1,389	8	84	1,053-1.389	1,540		CBM/Conventional	Non-producing*
			12	U. Bakerstown Brookville	679-1,459				1,315-1,653		CBM/Conventional	Producing
	Mayfield	Moyer (21)	1						45		CBM	Junked & plugged
			2	Pittsburgh	1.005-1,048	5	60-70		1,150-1,289	Excess	Conversion/ Gob	Non-producing*

	Masontown	Unnamed (15)	1					118	178		Conversion/ Gob	Dry
	Kenneth	Unnamed (16)	1					165	290		Conversion/ Gob	Dry
Westmoreland	Oakford	Waltz Mill (17)	1	U. Freeport Sharon and others				187-629	741		Observation/	Non-producing*
			1	L. Freeport U. Kittanning L. Kittanning Clarion Mercer Sharon	193-658		28-43	658	750	240-120	CBM	Non-producing*
	Mayfield	Morewood (20)	1	L. Kittanning Clarion	683-1,096		146		1,168		CBM	P&A
			1	U. Kittanning L. Kittanning Clarion Mercer			40	848-1,086	1,215		CBM	P&A
	Hoggs	Orchard Hill (22)	1	Brush Creek U. Freeport U. Kittanning Clarion Mercer			10	688-1,116	1,269		CBM	P&A
	Armbrust	Ramsey Terrace (23)	1	Pittsburgh				270	270		Conversion/ Gob	Dry
Washington	Mehaffy	Unnamed (2)	1	Pittsburgh				1,025	1,025		CBM	P&A
	Lagonda	South Franklin (4)	1	Pittsburgh		3,000		485-490	504		Gob	Producing
	Washington/ Taylorstown	Unnamed (3)	1	Pittsburgh				362-367	367		Gob	P&A

Cambria	Munster	Unnamed (27)	11	U. Freeport L. Freeport M. Kittanning L. Kittanning	440-550				547-1,052		Conversion/ Gob	2 wells online
	Carrolltown	Powell (26)	1	U. Freeport		84		254	254		Gob	Non-producing*
Allegheny	Forward	Detweiler	1	Freeport coals		327		1,002-1,006		2,347	CBM/Conventional	
WEST VIRGINIA												
Wetzel	Big Run		35	Sewickley Pittsburgh		8-121		370-1215			CBM	Non-producing*
	Pine Grove		16	Pittsburgh		8-60					CBM	Non-producing
Wetzel	Unnamed		2	Sewickley Pittsburgh Pittsburgh rider Bakersville Brush Creek Mahoning L. Freeport U. Kittanning M. Kittanning Clarion							CBM	Producing
Monongahela	Blacksville		23	Pittsburgh							Gob	Producing
	St.Leo		4	Sewickley Redstone Pittsburgh Bakersville Brush Creek U. Freeport M. Freeport M. Kittanning L. Kittanning Brookville U. Mercer							CBM	Producing

*Non-Producing wells may have production potential.

Table 5. Total undiscovered coalbed methane resources of the Carboniferous Coal-bed Gas Total Petroleum System				
Assessment unit	Total Undiscovered Resources of Gas (BCFG)			
	F95	F50	F5	Mean
Pocahontas Basin AU	2,929.57	3552.81	4,308.64	3,577.32
East Dunkard (Folded) AU	2,748.71	4,593.61	7,676.78	4,823.03
West Dunkard (Unfolded) AU	Not quantitatively assessed			
Central Appalachian Shelf AU	Not quantitatively assessed			
Appalachian Anthracite and Semi-Anthracite AU	Not quantitatively assessed			

Table 6. Generalized Pennsylvanian stratigraphic nomenclature of the central Appalachian coal field. Mtn. = Mountain; Fm. = Formation.

AGE	Central Appalachian Shelf Assessment Unit			Pocahontas Basin Assessment Unit	
	EASTERN TENNESSEE	EASTERN KENTUCKY	SOUTHERN WEST VIRGINIA	VIRGINIA	SOUTHERN WEST VIRGINIA
PERMIAN		Monongahela Group	Monongahela Group		Monongahela Group
UPPER PENNSYLVANIAN		Monongahela Group Conemaugh Group	Monongahela Group Conemaugh Group		Monongahela Group Conemaugh Group
MIDDLE PENNSYLVANIAN	Cross Mtn. Fm. Vowell Mtn. Fm. Redoak Mtn Fm. Graves Gap Fm. Indian Bluff Fm. Slatestone Fm.	Breathitt Formation Vanport Ls. Lost Creek Ls. Magoffin Mem. Kendrick Sh.	Allegheny Formation Pottsville Group	Harlan Fm. Wise Formation Gladeville Sandstone	Charleston Sandstone Kanawha Formation
LOWER PENNSYLVANIAN	Crooked Fork Group Crab Orchard Mountains Group Gizzard Group (part) Fentress Fm.	Breathitt Formation Lee Formation (part)	Pottsville Group	Norton Fm. New River Fm Lee Fm. (part) Pocahontas Fm. Bluestone Fm. (part)	New River Formation Pocahontas Formation

Table 7. Lower and Middle Pennsylvanian stratigraphic nomenclature of formations, sandstones, and of coal beds commonly completed in CBM fields of southwest Virginia and adjacent West Virginia.

Virginia and West Virginia

Continues at base of middle column

Formation	Unit
POCAHONTAS FORMATION	FLATTOP MOUNTAIN SANDSTONE
	Goodwill coal bed
	Pocahontas No. 7 coal bed
	QUARTZ ARENITE BED
	Pocahontas No. 6 coal bed
	QUARTZ ARENITE BED
	Pocahontas No. 5 coal bed
	Pocahontas No. 4 coal bed
	Pocahontas No. 3 coal bed
	Pocahontas No. 2 coal bed
	Pocahontas No. 1 coal bed
	Landgraff coal bed
	Simmons coal bed
	Squire Jim coal bed
BLUESTONE FORMATION	

Base section

Virginia

Top section

Formation	Unit
LEE, NEW RIVER AND NORTON FORMATIONS (PART)	Jawbone coal bed
	COUNCIL SANDSTONE MEMBER
	Tiller coal bed
	Castle coal bed
	Upper Seaboard coal bed
	Greasy Creek coal bed
	Middle Seaboard coal bed
	Lower Seaboard coal bed
	unnamed coal bed
	Upper Horsepen coal bed
	Middle Horsepen coal bed
	Unnamed B coal bed
	C Seam Rider
	C Seam
	War Creek coal bed
	Unnamed C coal bed
	Beckley coal bed
	Lower Horsepen coal bed
	Fire Creek coal bed
	Little Fire Creek coal bed
	X Seam
	Pocahontas No. 9 coal bed
	Pocahontas No. 8 coal bed

West Virginia

Formation	Unit
NEW RIVER FORMATION (PART)	Iager coal bed
	Lower Iager coal bed
	Castle coal bed
	Sewell B coal bed
	Sewell A coal bed
	Sewell coal bed
	Welch coal bed
	Little Raleigh A coal bed
	Little Raleigh coal bed
	Beckley Rider
	Beckley coal bed
	Fire Creek coal bed
	Little Fire Creek coal bed
	Pocahontas No. 9 coal bed
	Pocahontas No. 8 coal bed

Table: 8. Gas-in-place data for the Northern and Southern Anthracite fields, Pennsylvania (Diamond and others, 1986); cf = cubic feet; L. = Lower; U. = Upper.

Northern Anthracite	Southern Anthracite
Total gas (cf/ton)	Total gas (cf/ton)
U. New County	Tunnel
70.4	585.6
54.4	448
L. New county	403.2
48	
41.6	Peach Mountain
32	691.2
28.8	601.6
25.6	
16	Orchard
Big Bed (Pittston)	28.8
64	6.4
54.4	
44.8	Primrose
32	12.8
28.8 (2)	
Clark (Ross)	Seven Foot Leader
16 (2)	396.8 (2)
12.8	
9.6 (2)	

Table 9. Stratigraphic nomenclature of the Price Mountain area (adapted from Stanley and Schultz, 1983).

PERIOD	FORMATION	THICKNESS (feet)	
		Saltville thrust sheet	Pulaski thrust sheet
Mississippian	Maccrady	1605	
	Price (Merrimac coal, Langhorne coal, Cloyd Conglomerate)	975	
Devonian	Chemung	698	
	Brallier	2699	
	Millboro	850	
	Needmore	30	
	Huntersville	30	
	Rocky Gap	40	
Silurian	Keefer	140	
	Rose Hill	127	
	Tuscarora	100	
Ordovician	Juniata	165	
	Martinsburg	980	
	Moccasin	55	
	Middle Ordovician (undivided)	529	
Cambrian and Ordovician	Knox Group	2563	
	Conococheague		1800
Cambrian	Nolichucky	56	
	Honaker	826	
	Elbrook (Breccia)		1800
	Rome		600+

Table 10. Coalbed methane core holes drilled in Virginia semianthracite district by VDMR* (see fig. 23 for locations).

Number	Name	Quadrangle	Longitude	Latitude	Elevation (ft)	Total depth (ft)
W-6533	Prices Fork	Blacksburg	-80.48861111	37.21222222	2,037.0	1,773.5
W-6534	Sunnyside	Radford North	-80.54166667	37.23000000	2,015.0	1,672.0
W-6535	Merrimac	Blacksburg	-80.42972222	37.20222222	2,090.0	1,674.0

* Virginia Division of Mineral Resources

Table 11. Desorption data from the Valley Coal Fields, Virginia (Stanley and Schultz, 1983)							
Sample Number	Coal Thickness (feet)	Sample Weight (grams)	Total Gas (Cubic centimeters/ gram)	Weight X Gas Content (cubic centimeters/ sample)	Total Gas (Cubic centimeters/ gram; Weighted Average)	Total gas (Cubic Feet/ton)	
Well W-6534							
1933	2.4	2,121	5.7	12,089.7			
1934	1.5	2,173	7.1	15,428.3			
1935	2	1,350	7.6	10,260.0			
1936	0.8	480	8.9	4,272.0			
1937	1.8	1,222	2.5	3,055.0			
1938	1.2	984	4.6	4,526.4			
1939	0.75	501	12.3	6,162.3			
Totals	10.45	8,831		55,793.7	6.3	**202.2**	(Weighted Average)
Well W-6535							
1986	1.45	1,137	7.4	8,413.8			
1987	2.65	1,273	9.1	11,584.3			
1988	2.05	1,135	5.5	6,242.5			
1989	0.6	333	4.9	1,631.7			
1990	0.8	251	7.5	1,882.5			
	7.55	4,129		29,754.8	7.2	**230.6**	(Weighted Average)

Table 12. Basic location data for commercial wells drilled in Pulaski Conuty, Virginia. Data from unpublished database by J. E. Nolde and from J.L. Coleman

DGONumber*	API Number	Operator	Farm	Well Number	Status	Completion Date	WellClassID	WellTypeID	TD
PU-0001	45-155-19702	C.L. Hottle		1	D&A	12/31/1948	Exploratory	Conventional oil	1400
PU-0004	45-155-20723	Toms Creek Energy co.	Kegley	1	D&A	1/11/1985	New-Field Wildcat	CBM	1513
PU-0005	45-155-20739	New River Gas Co.	Neuhoff Farms	1	D&A	9/4/1985	New-Field Wildcat	CBM	4655
PU-0006	45-155-20964	New River Gas Co.	Neuhoff Farms	1A	D&A	4/21/1987	Extension	CBM	4525
PU-0007	45-155-21078	Valley Basin Gas Associates	Mason-Ratcliff	1	D&A	7/7/1987	Exploratory	CBM	4500
PU-0008	45-155-21139	Valley Basin Gas Associates	Neuhoff Farms	2	D&A	6/29/1988	New-Field Wildcat	CBM	4500
PU-0009	45-155-21140	Valley Basin Gas Associates	Kegley	2	D&A	6/29/1988	New-Field Wildcat	CBM	4988

DGONumber	API Number	Formation at Total Depth	Formation Age at TD	Well Elvevation	Latitude	Longitude	UTM E	UTM N	UTM Z
PU-0001	45-155-19702			2,360	37.12943654	-80.80206004	517582	4109046	17
PU-0004	45-155-20723	Elbrook Dolomite	Middle Cambrian	2,050	37.05061667	-80.78616033	519019	4100310	17
PU-0005	45-155-20739	Price Formation	Early Mississippian	1,964	37.14180269	-80.62424685	533372	4110470	17
PU-0006	45-155-20964	Price Formation	Early Mississippian	1,971	37.14093888	-80.62476819	533326	4110372	17
PU-0007	45-155-21078	Price Formation	Early Mississippian	1,862	37.16214036	-80.56473618	538643	4112745	17
PU-0008	45-155-21139	Price Formation	Early Mississippian	2,042	37.15393388	-80.61742846	533969	4111816	17
PU-0009	45-155-21140	Price Formation	Early Mississippian	2,068	37.12469157	-80.79163288	518510	4108520	17

* DGO refers to the Virginia Division of Gas and Oil

Table 13: Results of commercial CBM well tests in Pulaski County, Virginia. Data provided by J.L. Coleman										
API Number	Operator	Farm	Well Number	Geology	Depth	Approximate Thickness (feet)	Vitrinite reflectance	Results	Gas Content (scf/Ton)	Gas analyses (%)
45-155-20723	Toms Creek Energy Co.	Kegley	1	Did not penetrate Pulaski thrust sheet						
45-155-20739	New River Gas Co.	Neuhoff Farms	1	Pulaski fault Merrimac Coal Langhorne Coal	2,826 4,217 4,281	4.5 23	2.5% - 2.7%	Four zones hydraulically fractured with non-economic flow of gas		Methane: 98.2 Ethane: 0.2 Propane: 0.5 Carbon Dioxide: 0.5 Nitrogen: 0.6
45-155-20964	New River Gas Co.	Neuhoff Farms	1A	Pulaski fault Merrimac Coal Langhorne Coal	2,750 4,335 4,389	4 15		Several zones hydraulically fractured with non-economic flow of gas	508 - 664	
45-155-21078	Valley Basin Gas Associates	Mason-Ratcliff	1	Coal		17 - 20			580	
45-155-21139	Valley Basin Gas Associates	Neuhoff Farms	2	Pulaski fault Coal	2,700 4,220 - 4230	18		Low permeability		
45-155-21140	Valley Basin Gas Associates	Kegley	2	Pulaski fault				No coal		