Thermal Maturity Patterns in Pennsylvanian Coal-Bearing Rocks in Alabama, Tennessee, Kentucky, Virginia, West Virginia, Ohio, Maryland, and Pennsylvania

By Leslie F. Ruppert, Michael H. Trippi, James C. Hower, William C. Grady, and Jeffrey R. Levine

Chapter F.2 of

Coal and Petroleum Resources in the Appalachian Basin: Distribution, Geologic Framework, and Geochemical Character

Edited by Leslie F. Ruppert and Robert T. Ryder

Professional Paper 1708

U.S. Department of the Interior
U.S. Geological Survey

Suggested citation:
Ruppert, L.F., Trippi, M.H., Hower, J.C., Grady, W.C., and Levine, J.R., 2014, Thermal maturity patterns in Pennsylvanian coal-bearing rocks in Alabama, Tennessee, Kentucky, Virginia, West Virginia, Ohio, Maryland, and Pennsylvania, chap. F.2 *of* Ruppert, L.F., and Ryder, R.T., eds., Coal and petroleum resources in the Appalachian basin; Distribution, geologic framework, and geochemical character: U.S. Geological Survey Professional Paper 1708, 13 p., oversized material, http://dx.doi.org/10.3133/pp1708F.2.

Contents

Figures

[Figures 1–9 as separate files; click link to access]

Conversion Factors

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
nanometer	$3.93700787 \times 10^{-8}$	inch (in.)
kilometer (km)	0.6214	mile (mi)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$°F=(1.8\times°C)+32$

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Thermal Maturity Patterns in Pennsylvanian Coal-Bearing Rocks in Alabama, Tennessee, Kentucky, Virginia, West Virginia, Ohio, Maryland, and Pennsylvania

By Leslie F. Ruppert,[1] Michael H. Trippi,[1] James C. Hower,[2] William C. Grady,[3] and Jeffrey R. Levine[4]

Abstract

Thermal maturation patterns of Pennsylvanian strata in the Appalachian basin and part of the Black Warrior basin were determined by compiling previously published and unpublished percent-vitrinite-reflectance (%R_o) measurements and preparing isograd maps on the basis of the measurements. The isograd values range from 0.6 %R_o in Ohio and the western side of the Eastern Kentucky coal field to 5.5 %R_o in the Southern field in the Pennsylvania Anthracite region, Schuylkill County, Pa. The vitrinite-reflectance values correspond to the American Society of Testing Materials (ASTM) coal-rank classes of high-volatile C bituminous to meta-anthracite, respectively. In general, the isograds show that thermal maturity patterns of Pennsylvanian coals within the Appalachian basin generally decrease from east to west. In the Black Warrior basin of Alabama, the isograds show a circular pattern with the highest values (greater than 1.6 %R_o) centered in Jefferson County, Ala. Most of the observed patterns can be explained by variations in the depth of burial, variations in geothermal gradient, or a combination of both; however, there are at least four areas of higher ranking coal in the Appalachian basin that are difficult to explain by these two processes alone: (1) a set of west- to northwest-trending salients centered in Somerset, Cambria, and Fayette Counties, Pa.; (2) an elliptically shaped, northeast-trending area centered in southern West Virginia and western Virginia; (3) the Pennsylvania Anthracite region in eastern Pennsylvania; and (4) the eastern part of the Black Warrior coal field in Alabama. The areas of high-ranking coal in southwestern Pennsylvania, the Black Warrior coal field, and the Pennsylvania Anthracite region are interpreted here to represent areas of higher paleo-heat flow related to syntectonic movement of hot fluids towards the foreland associated with Alleghanian deformation. In addition to the higher heat flow from these fluids, the Pennsylvania Anthracite region also was buried more deeply than other parts of the Appalachian basin. The area of high rank coal in southwestern Virginia probably was controlled primarily by overburden thickness, but may also have been influenced by higher geothermal gradients.

Introduction

This report presents a series of thermal maturity maps for the Pennsylvanian coal-bearing strata in Alabama, Tennessee, Kentucky, Virginia, West Virginia, Ohio, Maryland, and Pennsylvania (figs. 1, 2) based on measurements of vitrinite reflectance (in percent, denoted as %R_o) for Appalachian basin coals. Four thermal maturity maps were produced, one for all Pennsylvanian coals (fig. 3) and one each for Lower Pennsylvania coals (fig. 4), Middle Pennsylvanian coals (fig. 5), and Upper Pennsylvanian coals (fig. 6).

The thermal maturity patterns of the Pennsylvanian coals are evaluated here because coal rank, or the degree of coalification or maturation, is an important factor in determining coal usage and evaluating the coalbed-methane potential of an area. Coalification patterns may be used to interpret some aspects of the geologic history of sedimentary basins, notably the temperature and burial history of the sediments and the relative timing of thermal and deformational events. The most commonly used physical method to determine the maturity of a coal body is to measure the reflectance of the coal maceral, vitrinite, which is accomplished by measuring the percentage of vertical incident light (546-nanometer (nm) wavelength) reflected from a polished vitrinite surface immersed in oil (Rimmer, 1985; Gluskoter, 1991). Other parameters that may be used to determine coal maturity include the percentage of fixed carbon (Heck, 1943; Damberger, 1974), equilibrium moisture capacity (Damberger, 1991), and calorific value; however, vitrinite reflectance offers advantages over these other parameters because of the following: (1) it is applicable

[1]U.S. Geological Survey, Reston, Va.

[2]Center for Applied Energy Research, University of Kentucky, Lexington, Ky.

[3]West Virginia Geological and Economic Survey, Morgantown, W. Va.

[4]Consultant, Richardson, Tex.

over a broader interval of coal rank, (2) its reflectance responds quickly to temperature, (3) it records the maximum temperature increases in the geological environment (Levine, 1993), (4) it is independent of heating duration, and (5) heating events shorter than 1,000 years can be recorded (Barker, 1991; Hulver, 1997). These properties make vitrinite reflectance a very powerful tool in unraveling the thermal history of Pennsylvanian coal-bearing strata within the Appalachian basin.

The use of vitrinite reflectance as a rank parameter is complicated by anisotropy, which is a manifestation of a preferred orientation of the molecular structure of the organic matter and is caused by directional stresses applied to the coal during maturation. The three-dimensional pattern of reflectance anisotropy can be represented by an ellipsoid, the magnitude and orientation of each indicating the thermal and stress history of the rock. The simplest reflectance pattern is represented by a uniaxial negative ellipsoid (an oblate spheroid), where the minimum principal reflectance is approximately perpendicular to bedding, and the maximum reflectance lies in the bedding plane and is nearly equal in all directions. This pattern is typical of coals in the mildly deformed Appalachian Plateaus (Hower and Davis, 1981; Zhang and Davis, 1993). In more strongly deformed terranes (for example, the Pennsylvania Anthracite region), reflectance fabrics are much more complex and are represented by biaxial reflectance ellipsoids that have various orientations relative to bedding, which can result in differences between the maximum and the random vitrinite reflectance of several percent (Levine and Davis, 1989a,b).

In an effort to reduce the impact of optical anisotropy on the precision and accuracy of the vitrinite-reflectance measurements, the maximum vitrinite reflectance is measured by a 360° rotation of the microscope stage under polarized light. Between 30 and 50 individual reflectance measurements typically are recorded for each sample, yielding a mean maximum vitrinite reflectance (%$R_{o(max)}$). In contrast, the mean random vitrinite reflectance, which typically is used for dispersed organic matter, is measured in nonpolarized light with no stage rotation. The difference between the mean maximum and the mean random vitrinite reflectance is negligible for coals of a low rank but can become quite significant for coals of higher ranks (Levine and Davis, 1989a).

The increases in coal rank, or maturation, are driven primarily by elevated temperatures during burial, hence the term “thermal maturation.” The influence of time on coal rank is subject to various interpretations, but the (interpreted) exponential influence of temperature on reaction rates implies that the highest temperatures sustained by the strata have the strongest impact on the final rank attained. Although the burial history of Pennsylvanian coal-bearing strata in the Appalachian basin and eastern part of the Black Warrior basin allows for the possibility of slow heating over the course of millions of years, the cumulative impact of the lower temperatures is interpreted to be minimal, irrespective of duration. Moreover, there is evidence that even thermal events as short as 1,000 years may be sufficient to produce elevated vitrinite-reflectance values (Barker, 1991; Hulver, 1997). Thus, variations in the values may be interpreted as a direct indicator of the highest temperatures experienced during burial, particularly in cases that compare strata that have experienced similar burial histories, as in the Appalachian basin and eastern part of the Black Warrior basin.

This report presents a set of thermal maturity maps for Pennsylvanian coal-bearing strata in the Appalachian basin and eastern part of the Black Warrior basin that is based on vitrinite-reflectance measurements of coals. The maps can be used to aid in determining (1) the temperature and burial history of the coals and associated sediments, (2) the relative timing of the thermal and deformational events, (3) an estimate of the thermal maturation of underlying shales, and (4) the potential for coalbed-methane resources.

Several previously published thermal maturity maps of Pennsylvanian coals are available for evaluating thermal maturity patterns in the Appalachian basin and eastern part of the Black Warrior basin, but they either have been limited to smaller areas than the present study or are based on fewer sample locations, or both. Examples include Trinkle and others (1978), Cole and others (1979), Hower and Davis (1981), Levine (1986), Chyi and others (1987), Winston (1990), Hower and Rimmer (1991), Zhang and Davis (1993), Carroll and others (1995), Hulver (1997), and Harrison and others (2004).

The Pennsylvanian thermal maturity maps compiled in this study complement the conodont color alteration index- (CAI-) based and dispersed-vitrinite-reflectance-based thermal maturity maps for the Ordovician and Devonian rocks of the Appalachian basin shown in Repetski and others (this volume, chap. F.1). Their maps are based on new conodont CAI data for Upper Ordovician to Middle Devonian carbonate rocks and dispersed-vitrinite-reflectance data for Middle to Upper Devonian black shales in the central Appalachian basin. The maps in Repetski and others (this volume, chap. F.1) are based almost entirely on subsurface samples and they complement the maps of Harris and others (1978), which are based on outcrop samples.

Methods

A total of 2,845 vitrinite-reflectance values were collected from published and unpublished reports and databases and entered into a database. All available data were used and no attempt was made to classify it according to reliability and quality. Almost all of the vitrinite-reflectance measurements collected for this study record the maximum vitrinite reflectance of a sample (denoted as %$R_{o(max)}$), which is measured using plane-polarized light at 45°, a wavelength of 546 nm, and reflected-light oil-immersion optics in a 360° rotation of the microscope stage; however, the measurement technique from one of our sources (U.S. Geological Survey, unpub. data, 2005) was not specified. Therefore, we are reporting all of the measurements simply as a nonspecific percentage (%R_o).

The primary records include one published database maintained by The Penn State Earth and Mineral Sciences Energy Institute (2011, although this report only uses its data through 2005) and several unpublished databases (John C. Crelling, Southern Illinois University at Carbondale, unpub. data, 2005; William C. Grady, West Virginia Geological and Economic Survey, unpub. data, 2005; James C. Hower, unpub. data, 2005; J.C. Hower and Cortland F. Eble, Kentucky Geological Survey, unpub. data, 2005; U.S. Geological Survey, unpub. data, 2005). The data from all of these databases are available in appendix 1 of this report; in published reports by Winston (1990) and Hower and Rimmer (1991); and in unpublished doctoral dissertations by Hower (1978) and Rimmer (1985). The records include (1) sample identifiers, (2) latitude and longitude of sample locations, (3) the maximum mean percentage of vitrinite reflectance (except for the data from the U.S. Geological Survey (USGS)), and (4) the coal-bed or coal-zone name.

In addition, 147 inferred values are included in the database (appendix 1), primarily to supplement data in areas where records were absent or sparse. The inferred values were generated by digitizing points along the vitrinite-reflectance contours (isograds) of the Pittsburgh coal bed (shown in a report by Chyi and others (1987)) and of Lower Pennsylvanian coal beds in the Black Warrior basin (shown in a report by Winston (1990)). Additionally, Cole and others (1979) show maps of sample locations (accompanied by their latitude and longitude data) and vitrinite-reflectance isograds with labeled values for unidentified Pennsylvanian coals of eastern Kentucky, Virginia, West Virginia, Ohio, Maryland, and southern Pennsylvania; points along the isograds on these maps were digitized to provided inferred data for this report; these values were assigned a general age of Pennsylvanian. The resulting database, which includes information on Lower, Middle, and Upper Pennsylvanian coal, is provided in appendix 1.

A mean arithmetic vitrinite-reflectance value was substituted for multiple measurements of samples that were in close geographic and stratigraphic proximity (within a mine or a core). Of the 2,849 records in the database, about half (1,418) of the records were tied to 397 unique point locations, resulting in a usable database of 1,868 vitrinite-reflectance values. The data density was highest in eastern Kentucky, where 1,172 values are indexed to unique geographic locations, followed by 358 in West Virginia, 141 in Pennsylvania, 66 in Alabama, 42 in Virginia, 38 in Ohio, 5 in Maryland, and 2 in Tennessee. No records for the northern extensions of the Sand Mountain and Lookout Mountain coal fields in Georgia were available for inclusion in the dataset.

The entire database of 1,868 values was used to construct the principal map, which depicts vitrinite-reflectance values and isograds for the undivided Pennsylvanian System (fig. 3; appendix 1). Three additional maps were generated, representing the Lower, Middle, and Upper Pennsylvanian Series (figs. 4–6; appendix 1). The Lower Pennsylvanian thermal maturity map was constructed using 376 values, the Middle Pennsylvanian using 1,200 values, and the Upper Pennsylvanian using 102 values. The total number of samples for the individual Lower, Middle, or Upper Pennsylvanian data subsets is smaller than the number of samples in the dataset (that is, covering all of the Pennsylvanian; fig. 1; appendix 1) because 171 samples are reported simply as Pennsylvanian and 19 samples spanned the series boundaries.

The data for all 1,868 samples were imported into a geographic information system (ArcGIS) as a database file, plotted over a digital base map, and then grouped and color coded into 0.2-%R_o intervals (except in the Pennsylvania Anthracite region where a 0.5-%R_o interval was used because data were sparse). The color-coded map was exported to Adobe Illustrator where it was magnified and the isograds were constructed (fig. 3). The Lower, Middle, and Upper Pennsylvanian data subsets were treated similarly (figs. 4–6). In general, all data points were honored, except for occasional "outliers." There are a number of significant irregularities in the contour lines, which may be indicative of measurement error rather than actual regional differences in reflectance. In the absence of corroborative evidence, however, all the data points were honored.

Stratigraphy of Pennsylvanian Coal Beds and Coal Zones

The coal-bearing strata within the Appalachian basin are informally subdivided into three coal regions: the northern, central, and southern (fig. 2) on the basis of the character of the sedimentary strata and coals therein (Ruppert and others, this volume, chap. D.2). The boundary between the northern and central coal regions was adapted from the approximate position of the structural and depositional hinge line of Arkle (1974), which separates the older (Lower to lower Middle Pennsylvanian) and relatively low sulfur and low ash coals of southern West Virginia, western Virginia, and eastern Kentucky from the younger (upper Middle to Upper Pennsylvanian) and relatively high sulfur and high ash coals of northern West Virginia, eastern Ohio, western Maryland, and Pennsylvania to the northeast. The boundary between the central and the southern coal regions (which includes the eastern part of the Black Warrior basin) (fig. 2) was placed at the southern boundary of the Wartburg basin of Tennessee on the basis of structural and sedimentological continuity (Milici, this volume, chap. G.1; Ruppert and others, this volume, chap. D.2). The coal-bearing strata within the Wartburg basin are relatively thin and plunge and thicken northward into deeper parts of the basin in eastern Kentucky and southwestern Virginia. Southwest of the Wartburg basin, the relatively thin coals extend into the Black Warrior, Cahaba, and Coosa coal fields of Alabama, where they thicken and increase in number.

The Pennsylvanian coal-bearing strata are further subdivided into formally and informally named coal fields as shown in figure 2. The primary coal fields in the northern Appalachian coal region include the Main bituminous field, the Pennsylvania Anthracite region (which contains the North-Central, Western Northern, Southern, Northern, Eastern Middle, and Western Middle fields); the Broad Top coal field, and the northern extension of the Upper Potomac coal field in Pennsylvania; the Lower Youghiogheny basin, Upper Youghiogheny basin, Castleman basin, Georges Creek basin, and Upper Potomac basin coal fields and the Upper Potomac coal field in Maryland; and the Northern West Virginia coal field in West Virginia. The coals of Ohio are not subdivided into fields or regions.

The central Appalachian coal region includes the Southern West Virginia coal field in West Virginia; the Southwest Virginia coal field in Virginia; the Eastern Kentucky coal field in Kentucky; and the northeastern part of the Northern Tennessee coal field in Tennessee. The southern Appalachian coal region includes the Southern Tennessee coal field in Tennessee; the Black Warrior, Cahaba, Coosa, Sand Mountain, and Lookout Mountain coal fields in Alabama; and the northeastern extension of the Lookout Mountain coal field in Georgia.

The placement of the boundaries between the Lower, Middle, and Upper Pennsylvanian rocks between States and coal regions is discussed in detail in Ruppert and others (this volume, chap. D.2). On the basis of that paper, the boundary between the Lower and Middle Pennsylvanian Series is placed at the top of the Quakertown coal bed in Pennsylvania, Maryland, and Ohio and equivalent horizons in West Virginia, Kentucky, and Tennessee (see fig. 1). The boundary between the Middle and Upper Pennsylvanian Series is placed above the Upper Freeport coal bed near the top of the Mahoning coal bed. All of the coal beds in Alabama are Early Pennsylvanian in age. The Lower, Middle, and Upper Pennsylvanian vitrinite-reflectance databases used to model thermal maturation patterns for this report were subdivided on the basis of these boundaries.

Thermal Maturity of Pennsylvanian Strata Within the Appalachian Basin and Eastern Part of the Black Warrior Basin

Distribution of Pennsylvanian Vitrinite-Reflectance Isograds

The distribution of the undivided Pennsylvanian vitrinite-reflectance isograds is based on the vitrinite reflectance values at various geographic points and is shown on figure 3, along with selected structural features. The isograd values range from 0.6 %R_o on the western side of the Appalachian basin to 5.5 %R_o in the Pennsylvania Anthracite region (fig. 1), which corresponds to a coal rank of high-volatile C bituminous to meta-anthracite. Isograd values generally increase from west to east across the basin as coal rank increases. The maximum mean vitrinite-reflectance values of coal samples range from 0.47 %R_o in the upper split of the Princess No. 3 coal bed in Greenup County, Ky., to 5.65 %R_o in the Primrose coal bed in Schuylkill County, Pa. (appendix 1; see figure 1 for county names and Ruppert and others, this volume, chap. D.2, for coal-bed stratigraphy). These values correspond to a coal rank of high-volatile C bituminous and meta-anthracite, respectively.

The Pennsylvania Anthracite region is both physically and thermally isolated from the adjoining Main bituminous coal field of Pennsylvania, as indicated by the anomalously high vitrinite-reflectance values (greater than 2.0 %R_o; figs. 2, 3). The values within the Pennsylvania Anthracite region range from 2.6 %R_o in the Mammoth No. 8 and Mammoth No. 8½ coal beds in Northumberland County, Pa., to 5.65 %R_o in the Primrose coal bed in Schuylkill County, Pa. (appendix 1). These values correspond to semianthracite and meta-anthracite coal ranks, respectively. The isograd values increase sharply southeastward from Sullivan and Northumberland Counties to Schuylkill County, Pa. (figs. 1, 3). Meta-anthracite-rank coals (vitrinite reflectance is greater than 5.0 %R_o) occur in the eastern end of the Southern field in Schuylkill County, Pa., and in the Eastern Middle field in Lucerne and Carbon Counties, Pa. (figs. 2, 3). The coal rank of the Western Northern field (fig. 2) is semianthracite.

The Pennsylvanian coals west of the Pennsylvania Anthracite region decrease eastward in rank (figs. 2, 3) from anthracite to low- and medium-volatile bituminous (equivalent to 1.0–1.8 %R_o; Lea, 1841). Isograd values between 1.6 and 1.8 %R_o flank the easternmost edge of the northern Appalachian coal region in Pennsylvania southward to the easternmost edge of the central Appalachian coal region in southern West Virginia and Kentucky. The 1.6-%R_o isograd also surrounds a circular area in the Black Warrior coal field (figs. 2, 3).

The 1.4-%R_o isograd roughly parallels the 1.6- to 1.8-%R_o isograds (fig. 3). The isograd values decrease progressively westward from 1.4 to 0.6 %R_o. The 0.8-%R_o isograd generally parallels the higher isograds through the Main bituminous coal field in Pennsylvania and both the Northern and Southern West Virginia coal fields, but the greater density of data points in Kentucky shows additional maturation detail (fig. 3). The 0.6-%R_o isograd extends along the western part of the coal-bearing strata in the Appalachian basin from northeastern Kentucky (fig. 3), through southern Ohio and northward to Portage County, Ohio.

Coals in the Northern and Southern Tennessee coal fields were not modeled because only two vitrinite-reflectance values (0.9 %R_o in Morgan and Sequatchie Counties, Tenn.; fig 1) were located in that area. The vitrinite-reflectance values in the Black Warrior, Cahaba, and Coosa coal fields of Alabama range from 0.8 to 1.6 %R_o and generally increase toward the southeast with a pronounced circular trend (fig. 3).

Several prominent areas of high thermal maturity are defined by the isograds. The 1.6-%R_o isograd defines the eastern edge of a set of northwest-protruding salients centered in Somerset and southern Cambria Counties, Pa. The salients continue westward to approximately the Pennsylvania-West Virginia State boundary and are outlined by the 1.4- to 0.8-%R_o isograds; the wider 0.6-%R_o isograd extending through Jefferson County, Ohio, appears to mimic the isograds with higher values to the east. A second area of high thermal maturity is defined by the 1.8-%R_o isograd in the Southern West Virginia coal field and the Southwestern Virginia coal field. The area is elliptically shaped and trends to the northeast through Raleigh, Wyoming, and McDowell Counties, W. Va.; Buchanan, Dickenson, and Wise Counties, Va.; and Letcher County, Ky.

Distribution of Lower Pennsylvanian Vitrinite-Reflectance Isograds

Vitrinite-reflectance values from 376 Lower Pennsylvanian coal beds and coal zones were used to construct the isograds shown in figure 4 (appendix 1). Although the values range from 0.53 %R_o in the Stearns No. 2 coal bed in McCreary County, Ky., to 2.98 %R_o in the Lykens Valley No. 2 coal bed in Northumberland County, Pa. (fig. 4; appendix 1), the Lykens Valley No. 2 coal bed was not used in contouring because there are no other data points near it. Isograds range from 0.6 to 1.8 %R_o. With the exception of the Lykens Valley No. 2 coal bed, all of the Lower Pennsylvanian coals in the database are in West Virginia, Kentucky, Tennessee, and Alabama. Although Lower Pennsylvanian coals do occur in the Main bituminous field in Pennsylvania and Ohio, vitrinite-reflectance values were not found for them in the literature for inclusion in the database.

The locations of the 0.6- and 0.8-%R_o isograds are approximately located (except for the 0.6-%R_o isograd in the western part of the Pennsylvanian outcrop extent in Kentucky) because few data points were available for modeling. The approximately located isograds decrease progressively westward from central West Virginia and eastern Kentucky; however, the isograds with higher values (1.0 to 1.8 %R_o) are better defined. In McDowell and Raleigh Counties, W. Va., and the coal-bearing areas of Mercer and Summers Counties, W. Va., the isograd distribution is similar to that shown in the all-Pennsylvanian map (fig. 3), with an elliptical pattern centered on the 1.8-%R_o isograd. There is no change in the isograd values for the Black Warrior, Cahaba, and Coosa coal fields between figures 3 and 4 because all of the coals within these fields are Lower Pennsylvanian.

In Wayne, McCreary, and Whitley Counties, Ky., the 0.6- to 1.0-%R_o isograds appear to bend gently eastward. This eastward trend cannot be verified because of the lack of data points in Tennessee.

Distribution of Middle Pennsylvanian Vitrinite-Reflectance Isograds

Vitrinite-reflectance values from 1,200 Middle Pennsylvanian coal-bed and coal-zone samples were used to construct the isograds shown in figure 5 (appendix 1). The values range from 0.47 %R_o in the upper split of the Princess No. 3 coal bed in Greenup County, Ky., to 5.2 %R_o in the Buck Mountain coal bed in Luzerne County, Pa. The isograd values range from 0.6 to 5.5 %R_o throughout the northern and central Appalachian coal regions (fig. 5), from the southern part of the Eastern Kentucky coal field to the Pennsylvania Anthracite region.

The Middle Pennsylvanian vitrinite-reflectance isograds decrease in value from east to west and tend to roughly parallel the Lower Pennsylvanian isograds (fig. 5), where data points are available. There are, however, some differences between the positions of the Middle and Lower Pennsylvanian isograds; for instance, the Middle Pennsylvanian 0.6- and 0.8-%R_o isograds may be shifted farther to the west in the Southern West Virginia coal field compared to the Lower Pennsylvanian isograds, perhaps due to the shallower burial depth of the Middle Pennsylvanian coals.

The pronounced northwest-protruding salients observed in figure 4 (centered in Somerset, Cambria, and Fayette Counties, Pa.) are controlled by the vitrinite-reflectance values of the Middle Pennsylvanian coal beds and coal zones (fig. 5). One of the salients is centered between, but not aligned with, the Pittsburgh-Washington structural discontinuity and the Tyrone-Mount Union structural discontinuity and the associated Akron-Suffield-Highlandtown fault zone to the west (figs. 3, 5). Another salient occurs south of the Pittsburgh-Washington structural disconformity.

Distribution of Upper Pennsylvanian Vitrinite-Reflectance Isograds

A total of 102 Upper Pennsylvanian coal bed and coal zone vitrinite-reflectance values were used to construct the vitrinite-reflectance isograds shown in figure 6 (appendix 1). Vitrinite-reflectance values range from 0.47 %R_o in the Pittsburgh No. 8 (equivalent) coal bed in Boyd County, Ky., to 5.65 %R_o in the Primrose coal bed in Schuylkill County, Pa. Isograd values range only from 0.6 to 1.6 %R_o (fig. 6) because the vitrinite-reflectance values of 4.5 and 5.65 %R_o for the Primrose and Peach Mountain coal beds in Schuylkill County, Pa., were not used during isograd construction due to a lack of nearby control points.

The Upper Pennsylvanian coals in the Appalachian basin are located in the Pennsylvania Anthracite region; the southwestern part of the Main bituminous field of Pennsylvania; southwestward to Lawrence and Boyd Counties, Ky.; and westward to the eastern edge of the coal-bearing strata in Ohio, from Columbiana County southward to Gallia County.

In West Virginia, the majority of the Upper Pennsylvanian samples in the database (appendix 1) are from the northern Appalachian coal region, from Pennsylvania southward to Braxton County, W. Va. (fig. 4). The isograd distribution for the Upper Pennsylvanian coals (fig. 6) is similar to that shown on the map of Middle Pennsylvanian isograds (fig. 3) where data points are available, but the 0.8-%R_o isograd in figure 6 may fall somewhat east of the 0.8-%R_o isograds on the Lower and Middle Pennsylvanian maps (figs. 4, 5). The shift to the east may indicate the shallower burial depths of the Upper Pennsylvanian coals compared with those of Lower and Middle Pennsylvanian coals, but there are insufficient control points for verification.

Discussion

Coalbed-Methane Resources and Distribution of Pennsylvanian Vitrinite-Reflectance Isograds

One of the primary reasons to study and model the vitrinite reflectance of coal is to obtain information on the thermal and depositional history of a basin. A secondary reason is to obtain information on areas within the basin that may contain sufficient coalbed-methane resources for commercial production. In an assessment of undiscovered Pennsylvanian and Upper Mississippian coal-bed-gas resources of the Appalachian basin (Milici and Hatch, 2004; Milici, this volume, chap. G.1), the USGS estimated that the Appalachian basin contains a mean coal-bed-gas resource of approximately 15.5 billion cubic feet (BCF). The resource volume is likely to be much larger because only the currently producing assessment units (AUs) (the Pocahontas Basin, East Dunkard (Folded), and Black Warrior Basin AUs; fig. 7) were quantitatively assessed. Four other AUs that have potential for commercial production (the West Dunkard (Unfolded), Central Appalachian Shelf, Appalachian Anthracite and Semi-Anthracite, and the Cahaba Basin AUs) were recognized, but they were not quantitatively assessed because of a lack of reliable data. See Milici (this volume, chap. G.1) for the stratigraphic and structural documentation of coalbed-methane resources within the Appalachian basin and Milici and Polyak (this volume, chap. G.2) for coalbed-methane production by county.

Methane is contained within the pore spaces and fractures in coal and is generated during the coalification process. During early diagenesis, methane is primarily produced by methanogenic bacteria, but as coalification progresses and temperatures and pressures increase, methane is produced by thermal processes. Within the Appalachian basin, three types of coalbed methane are present: biogenic, thermogenic, and mixed biogenic and thermogenic methane. All of the currently produced methane in the Appalachian basin is thermogenic in origin (Milici, this volume, chap. G.1), although some methane from mixed sources has been identified (Ruppert, Fedorko, and others, this volume, chap. G.3; Ruppert, Trippi, and others, this volume, chap. G.4). The 0.8-%R_o isograd (figs. 3–6) roughly defines the boundary between coal-bed gas that is predominately microbial in origin (less than 0.8 %R_o) and coal-bed gas that is thermogenic in origin (0.8 %R_o and greater). The westward shift of the 0.8-%R_o isograd on both the Middle and Upper Pennsylvanian maps (figs. 5, 6) may, therefore, have implications for coalbed-methane production potential in the basin because the maximum production of coalbed methane occurs east of the Upper Pennsylvanian 0.8-%R_o isograd (fig. 6), but all of the coal beds within the Pennsylvanian section east of the 0.8-%R_o isograd are sufficiently mature for the production of thermogenic methane.

Presently, there are over 10,000 coalbed-methane wells producing over 1.0 trillion cubic feet (TCF) of thermogenic methane within the basin, and the potential for additional production is high (Milici and Hatch, 2004; Milici, this volume, chap. G.1). The less thermally mature coals west of the 0.8-%R_o isograd (figs. 3–6) are currently under evaluation for commercial production in the western part of the Eastern Kentucky coal field and in Ohio.

Geological Controls on Observed Thermal Maturation Patterns

The major structural elements that affect the Pennsylvanian coal-bearing strata in the Appalachian basin are shown on figures 3 through 6, and several of them also may have affected the thermal maturation patterns observed in those strata. The structural features and the tectonic and sedimentation events that affected the thermal maturation patterns of Ordovician and Devonian strata within the basin are discussed in detail in Repetski and others (this volume, chap. F.1), and they will not be repeated here. Only the structural features that appear to directly affect the distribution of the Pennsylvanian vitrinite-reflectance isograds will be addressed.

Harris and others (1978) and Repetski and others (this volume, chap. F.1) concluded that present-day subsurface temperatures and depth of burial do not account for their observed conodont-CAI and vitrinite-reflectance-isograd patterns for the Ordovician and Devonian strata within the Appalachian basin. Similarly, present-day subsurface temperatures and depth of burial do not account for the observed vitrinite-reflectance-isograd patterns for the Pennsylvanian strata of the Appalachian basin (fig. 3). There are three mechanisms that can explain the discrepancy (either alone or combined): the Pennsylvanian strata were more deeply buried in the past, either the paleotemperatures or paleogeothermal gradients were higher in the past, or the introduction of hot fluids increased the coal rank.

Many workers have concluded that burial depth alone is responsible for increased temperature. For example, Cole and others (1979) speculated that burial depth was the primary factor responsible for the increases in coal rank that were observed in West Virginia coals and noted that the calculated temperatures of the most deeply buried coals increased from northwest to southeast on the basis of coal rank and assumed temperatures of maturation. Cole and others (1979) used the time-temperature nomogram of Hood and others (1975) to show that the temperatures ranged from approximately 85°C to 90°C near the northwestern boundary of the Northern West Virginia coal field (fig. 2) to 160°C to 170°C in central McDowell County, W. Va. Zhang and Davis (1993) constructed detailed stratigraphic vitrinite-reflectance profiles for nine boreholes in western and south-central Pennsylvania and found that the vitrinite-reflectance values of those coals ranged from 0.7 to 1.9 %R_o, which corresponds to late Paleozoic to Mesozoic maximum burial depths of almost 9,800 to 16,000 feet (ft) and paleotemperatures between 90°C and 155°C. A burial beneath about 19,840 to 29,500 ft of overburden (sedimentary or tectonic) was proposed by Levine (1986) to account for the high-rank coals in the Pennsylvania Anthracite region. Rowan (2004) modeled the geothermal paleogradients from a subset of the vitrinite-reflectance values used in this report and determined that the Pennsylvanian and Permian rocks within the basin formed a northeastward-thickening wedge with thicknesses ranging from 10,000 ft in central West Virginia to 12,500 ft in south-central Pennsylvania, which provided sufficient thickness to account for the observed coal rank. Furthermore, Hulver (1997) concluded that between approximately 2 and 6 miles (mi) of Appalachian basin sediment has been eroded since the end of Alleghanian tectonic activity. Using a combination of data (including conodont CAI, vitrinite reflectance, equilibrium moisture, volatile matter, and apatite fission-track analyses), he calculated that there were substantial increases in the geothermal gradients (14°C±4°C/kilometer (km) in Magoffin County, Ky., to 41°C±6°C/km in the Pennsylvania Anthracite region) and paleotemperatures (100°C in the western portion of the coal-bearing strata of Ohio to more than 300°C in the Pennsylvania Anthracite region) across the basin. The calculated temperatures within the Black Warrior basin in Alabama range from 250°C/km to 300°C/km with geothermal gradients of approximately 40°C±3°C/km (Hulver, 1997). In comparison to the calculated paleogradients, the present-day geothermal gradients are somewhat higher in eastern Kentucky (15.8°C/km; Staub, 1980) and much lower in the North-Central field in Lycoming County, Pa. (21.8°C/km; Renner and Vaught, 1979).

Other workers suggest that a combination of burial depth, pressure caused by thrusting and faulting, or hot fluids is responsible for coal rank within the Appalachian basin. Winston (1990) and Carroll and others (1995) examined coalification patterns in the Black Warrior basin in Alabama and suggested that they were controlled by localized fluid flow and high regional geothermal gradients of 29°C/km, a gradient that is close to the average of four different paleogradients (26°C–34°C/km) calculated by Hulver (1997) in the Black Warrior coal field. In the Pennsylvania Anthracite region, several different hypotheses have been suggested for the high vitrinite-reflectance values (fig. 3). One discredited mechanism is metamorphism pressure from thrusting and folding, which was based on a high incidence of faulting in the anthracite fields, particularly in the Southern field (Wood and others, 1969); Hower (1997) suggested that this hypothesis originated from a misinterpreted chemical analysis of coals in the Bernice coal field in Sullivan County, Pa. (see White, 1925). Later, Faill (1998) argued for burial by a crystalline thrust sheet, which would have buried the coal deeply enough to reach anthracite rank. The concept of rank advancement as high as anthracite by means of frictional heating (O'Hara and others, 2006) may be locally valid, but it is not known if it can be applied to the whole basin. There is evidence that there was sufficient burial to explain coal rank within the anthracite region (see Hulver, 1997), but work by Daniels and Altaner (1990), Hower and Gayer (2002), and Harrison and others (2004) suggests that the migration of hot fluids during the Alleghanian orogeny, not just the depth of burial, is also responsible for the increase of coal rank in the anthracite region. Daniels and others (1990, 1994, 1996) hypothesized that the fluids originated at or near the Alleghanian orogenic core and migrated westward along regional imbricate thrust-sheet décollement zones into the sediments that eventually became anthracites; however, there is no direct evidence of igneous activity in the Pennsylvania Anthracite region.

Harrison and others (2004) used illite-crystallinity studies and fluid-inclusion analyses to suggest that the maximum burial for the Pottsville and Llewellyn Formations, which both contain coal beds in the Northern field of Pennsylvania (fig. 2), was greater than 5 km. They proposed that a detachment fault (Pottchunk fault, fig. 3) located at the base of the Pottsville Formation in the Lackawanna synclinorium in the Northern field served as a conduit for the migration of hot fluids during the Alleghanian orogeny and effectively elevated the rock temperatures to anthracite-rank conditions.

A comparison of the vitrinite-reflectance values and the isograd patterns for Pennsylvanian coal beds in the Pennsylvania Anthracite region with those of the dispersed vitrinite in the underlying Middle and Upper Devonian black shales (Repetski and others, this volume, chap. F.1) (fig. 8) provides further support for the role of fluid flow in coal rank attainment, not just in the Northern field, but throughout the Pennsylvania Anthracite region. Although the Middle and Upper Devonian black shale sample locations do not directly underlie the Pennsylvanian coal sample locations (fig. 8), the dispersed vitrinite-reflectance isograds of the Devonian shales are as much as 2.0 %R_o lower than those of Pennsylvanian coals in Carbon and Schuylkill Counties, Pa.; however, in Wyoming, Sullivan, and Lycoming Counties, Pa., the placement of the Middle and Upper Devonian 3.0-%R_o isograd is roughly the same as the placement of the Pennsylvanian 2.0-%R_o isograds in the North-Central field. Although vitrinite-reflectance anisotropy could explain the lower vitrinite-reflectance values measured in the Middle and Upper Devonian black shales of Carbon and Schuykill Counties, anisotropy alone does not explain the fact that Devonian vitrinite-reflectance values are lower than or equal to those of younger Pennsylvanian rocks. Also, the conodont CAI values of the Lower and Middle Devonian carbonate rocks within the region (Harris and others, 1978; Repetski and others, this volume, chap. F.1; fig. 9) show a similar pattern, which suggests that the Pennsylvanian rocks have a higher level of thermal maturation than the underlying Lower and Middle Devonian rocks. Furthermore, conodonts obtained from Upper Ordovician strata as much as 10,000 ft below the anthracites have conodont CAI values that are roughly equivalent to the vitrinite-reflectance values of Pennsylvanian coals, which implies that the Lower and Middle Devonian strata in the Pennsylvania Anthracite region are approximately as thermally mature as the overlying Pennsylvanian strata.

Several other examples of vitrinite-reflectance inversion with depth have been observed in the Illinois basin and the Appalachian foreland basins, but it is not certain whether they are related to burial temperature or other factors. Nuccio and Hatch (1996) suggested that the phenomenon of vitrinite-reflectance suppression, rather than differences in burial temperature, may have been responsible for a decrease in vitrinite-reflectance values with depth in the New Albany Shale in the Illinois basin. Rowan and others (2004) used a subset of the Pennsylvanian vitrinite-reflectance values that are used in the present study together with the Devonian dispersed vitrinite-reflectance values of Repetski and others (this volume, chap. F.1) to model the burial history of part of the central Appalachian basin. They found that the vitrinite-reflectance values of the Devonian black shales in eastern Ohio were lower than the vitrinite-reflectance values of the overlying Pennsylvanian coals, which also suggests suppression. Although they noted that the mechanisms causing suppression are not well understood, Nuccio and Hatch (1996) and Smith and Smith (2007) postulated that vitrinite that was high in hydrogen (oil-prone) was more likely to show suppression than vitrinite that was low in hydrogen (gas-prone), particularly for coals within the rank interval of those in the Illinois basin. The relatively low-rank Devonian dispersed vitrinite and Pennsylvanian vitrinite on the western side of the Appalachian basin are high in hydrogen (Repetski and others, this volume, chap. F.1), so suppression is a realistic mechanism to explain the abnormally low values of vitrinite reflectance. Although it is possible that the Devonian vitrinite that underlies the Pennsylvanian coals in the Pennsylvania Anthracite region was suppressed, it is unlikely because the isograd patterns of Repetski and others (this volume, chap. F.1) show a systematic increase in vitrinite reflectance from the Main bituminous field in Pennsylvania eastward to the Pennsylvania Anthracite region. If suppression occurred in the Devonian and Pennsylvanian vitrinite, then it would be reasonable to assume that it occurred systematically throughout the Appalachian basin, which is unlikely. Also, suppression of dispersed vitrinite does not appear to occur at a thermal maturation level greater than 0.75 $\%R_o$ (Nuccio and Hatch, 1996). Furthermore, the Ordovician to Middle Devonian conodont CAI values from the Pennsylvanian anthracite region (Repetski and others, this volume, chap. F.1) were unlikely to be suppressed because the analyzed conodonts were largely from carbonate grainstones and not from organic-rich shales (Harris and others, 1978; Repetski and others, this volume, chap. F.1), where suppression most likely can occur (Rejebian and others, 1987). The Ordovician to Middle Devonian conodont CAI values record maturation levels that are close to those of the overlying Pennsylvanian coals.

The 1.6-$\%R_o$ isograd outlines a prominent set of salients in southern Cambria, Somerset, and Fayette Counties, Pa., on both the all-Pennsylvanian map (fig. 3) and the Middle Pennsylvanian map (fig. 5). These salients are not evident in the Upper or Lower Pennsylvanian maps (fig. 4, 6) where control points are absent. In the Main bituminous field in Pennsylvania, the isograd values decrease from as much as 1.6 $\%R_o$ (equivalent to a rank of low-volatile bituminous) in Somerset and Cambria Counties, Pa., to 0.6 $\%R_o$ (equivalent to a rank of high-volatile C bituminous) along the western outcrop extent of the Pennsylvanian in Ohio (fig. 1). The decrease in coal rank from the eastern margin of the Main bituminous field in Pennsylvania to the Ohio boundary has been attributed to a systematic decrease in geothermal gradients and burial depth (Hower, 1978, 1997; Hulver, 1997; Rowan, 2006); however, an examination of the Pennsylvanian vitrinite-reflectance isograds (fig. 3) shows that the decrease in rank from east to west is not systematic. The isograd values are highest between and south of (but not along) the Pittsburgh-Washington structural discontinuity and the Tyrone-Mount Union structural discontinuity and its associated Akron-Suffield-Highlandtown fault zone in Cambria and Somerset Counties, Pa., where they form a westward-bulging salient. Zhang and Davis (1993) suggested that the rank incursions could be caused by the lateral, westward-directed migration of hot fluids from Alleghanian orogenic activity. Repetski and others (this volume, chap. F.1) further concluded that the fluid flow was structurally controlled in part by the Pittsburgh-Washington structural discontinuity and the associated Akron-Suffield-Highlandtown fault zone (figs. 4, 6). The configuration of the Pennsylvanian vitrinite-reflectance isograd patterns and their apparent relationship to the structural discontinuities indicate that it is likely that late Paleozoic Alleghanian orogenic fluids produced the observed increase in coal rank in Somerset and Cambria Counties, Pa.

The salient may extend into eastern Ohio (fig. 3) as defined by the 0.6-$\%R_o$ isograd. It is interesting to note that in much of the coal-bearing area of northeastern Ohio, the Devonian vitrinite-reflectance values (Repetski and others, this volume, chap. F.1) are up to 0.3 $\%R_o$ less than the overlying Pennsylvanian vitrinite-reflectance values. We agree with Rowan (2006) that the difference in vitrinite-reflectance values is probably a function of vitrinite suppression.

The 1.8- to 1.4-$\%R_o$ isograds define a pronounced northeast-trending, elliptically shaped area of higher thermal maturation in Raleigh, Wyoming, and McDowell Counties, W. Va.; Buchanan, Dickenson, and Wise Counties, Va.; and Letcher County, Ky. (figs. 3, 4). As in Pennsylvania, some combination of greater overburden thickness and higher geothermal gradient could have produced this feature. The thermal high generally follows the outline of the Pocahontas basin (fig. 7), which is a Lower Pennsylvanian depositional center that reaches its maximum thickness of more than 1,600 ft along the border between Virginia and Kentucky (Rice and others, 1979). Hower and Rimmer (1991) examined the coal-rank changes from west to east in this area. On the basis of boreholes in Buchanan County, Va., they observed a vitrinite-reflectance gradient that is consistent with post-tectonic coalification at a paleogeothermal gradient of about 40°C to 45°C/km. Although this geothermal gradient is high for a typical foreland basin, it may represent a local area of increased heat flow.

Using an estimated maximum burial depth of about 16,000 ft and temperatures of 120°C to 160°C, Hulver (1997) showed that fluid flow was not necessary to explain the high thermal maturity in the Pocahontas basin; however, such a possibility cannot be dismissed. Hulver (1997) showed that fluid-inclusion data are similar to coal kinetic temperatures throughout the Appalachian basin, which suggests that coals and fluids can experience the same thermal regime. Although the calculated geothermal gradients and observed paleotemperatures were sufficient to explain the coal rank throughout the Pocahontas basin, Hulver's results do not dispute that fluid flow occurred and thus caused mineralization (Hearn and others, 1987; Evans and Battles, 1999; Goldhaber and others, 2003; Diehl and others, 2004, 2005), but they do suggest that the temperatures of the fluids and the strata were in equilibrium during the fluid-flow event(s). The temperature of the fluids in the Pocahontas basin was lower in contrast to that of the fluids in the Pennsylvania Anthracite region and in Somerset and Cambria Counties, Pa., which were hot enough to significantly increase coal rank.

The vitrinite-reflectance isograd patterns in the Black Warrior basin of Alabama are similar to the isograd patterns plotted by Winston (1990) because both interpretations are based on mostly the same data. The 1.4-%R_o isograd defines an elliptical area of increasing vitrinite-reflectance values in southern Jefferson County and northwestern Tuscaloosa County, Ala. Pashin and others (1999) found almost no correspondence between the patterns of coal rank and the regional structure because the strata increase in thickness away from the elliptical vitrinite-reflectance "high" rather than toward it. Winston (1990) suggested a westward flow of warm fluids along faults into the basin to explain the vitrinite-reflectance pattern, whereas Carroll and others (1995) hypothesized that thermal maturation was regulated by regional variations in the geothermal gradient and by locally higher geothermal anomalies. Goldhaber and others (2003) support the interpretation of Winston (1990) by demonstrating that arsenic in Black Warrior basin coals was distributed in a westward-directed fluid-flow system. The vitrinite-reflectance maturation patterns (fig. 1) support the conclusions of Winston (1990), Pashin and others (1999), and Goldhaber and others (2003) that warm fluids are responsible for the increased coal rank in the Black Warrior coal field.

Conclusions

A series of new thermal maturity maps for the Pennsylvanian coal-bearing strata in Alabama, Tennessee, Kentucky, Virginia, West Virginia, Ohio, Maryland, and Pennsylvania, based on measurements of percent vitrinite reflectance (%R_o) for coals in the Appalachian basin and eastern part of the Black Warrior basin, sheds light on the complex thermal history of the basin. Using vitrinite-reflectance values from published and previously unpublished data sources, we are able to show that a higher coal rank within the basin can be achieved from increases in burial depth and geothermal gradients alone; however, there are three areas where coal rank cannot be explained solely by these processes: (1) in the southwestern part of the Main bituminous field in Pennsylvania, (2) in the Black Warrior coal field in Alabama, and (3) in the Pennsylvania Anthracite region.

A pronounced westward-bulging set of salients centered in Somerset and Cambria Counties, Pa., and defined by the 1.6-%R_o isograd is centered between (not along) and south of the Pittsburgh-Washington and Tyrone-Mount Union structural disconformities. The westward-bulging salients also are observed in Devonian black shale dispersed-vitrinite-reflectance maps of Repetski and others (this volume, chap. F.1). Thermal maturation patterns in this area are thought to have been influenced by the lateral movement of hot water during the Alleghanian orogeny, which possibly was constrained and focused by the Pittsburgh-Washington structural discontinuity to the south and the Tyrone-Mount Union structural discontinuity to the northeast.

The vitrinite-reflectance maps of the eastern part of the Black Warrior basin confirm the work of Winston (1990), Carroll and others (1995), Pashin and others (1999), and Goldhaber and others (2003), all of whom suggested that the flow of warm, Alleghanian orogenic fluids helped to generate the observed coal rank within the basin. A comparison of the Pennsylvanian vitrinite-reflectance values in coals of the Pennsylvania Anthracite region with the dispersed vitrinite-reflectance values of the underlying Middle and Upper Devonian black shale and with the conodont color alteration indices in the underlying Lower and Middle Devonian carbonate rocks clearly shows that fluid flow is required to attain the observed coal rank. This finding expands on work by Harrison and others (2004) and is applicable to all of the anthracite fields in the Pennsylvania Anthracite region.

Coals within and adjacent to the Pocahontas basin in the Southern West Virginia and Southwest Virginia coal fields may have been influenced by metamorphic fluids originating in the east, but these fluids did not increase coal rank. The depth of burial alone can account for the observed increase in rank in a salient that is bounded by the 1.6%-%R_o isograd located in Mingo, Logan, and McDowell Counties in southern West Virginia and extending into Buchanan, Dickenson, and eastern Wise Counties in southern Virginia.

These maps may be useful for coalbed-methane exploration. The coalbed methane produced to date in the Appalachian basin is thermogenic in origin and is located east of the 0.8-%R_o isograds shown on the Pennsylvanian map (fig. 3). Areas to the east of the 0.8%-R_o isograds are prospective locations for thermogenic gas exploration throughout the coal-bearing strata. In addition, these maps, used in concert with the Ordovician and Devonian thermal maturity maps of Repetski and others (this volume, chap. F.1), may be useful in understanding the maturation of potential gas resources in shales of the Appalachian basin.

References Cited

Arkle, T., Jr., 1974, Stratigraphy of the Pennsylvanian and Permian Systems of the central Appalachians, *in* Briggs, G., ed., Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 5–29.

Barker, C.E., 1991, Implications for organic maturation studies of evidence for a geologically rapid increase and stabilization of vitrinite reflectance at peak temperature; Cerro Prieto geothermal system, Mexico: American Association of Petroleum Geology Bulletin, v. 75, no. 12, p. 1852–1863.

Carroll, R.E., Pashin, J.C., and Kugler, R.L., 1995, Burial history and source-rock characteristics of Upper Devonian through Pennsylvanian strata, Black Warrior Basin, Alabama: Geological Survey of Alabama Circular 187, 29 p.

Chyi, L.L., Barnett, R.G., Burford, A.E., Quick, T.J., and Gray, R.J., 1987, Coalification patterns of the Pittsburgh coal; their origin and bearing on hydrocarbon maturation: International Journal of Coal Geology, v. 7, no. 1, p. 69–83.

Cole, G.A., Williams, D.A., and Smith, C.J., 1979, Regional coalification patterns for the coals of eastern Kentucky, Virginia, West Virginia, Ohio, Maryland, and southern Pennsylvania: West Virginia Geological and Economic Survey Open-File Report 57, 23 p.

Damberger, H.H., 1974, Coalification patterns of Pennsylvanian coal basins in the eastern United States, *in* Dutcher, R.R., Hacquebard, P.A., Schopf, J.M., and Simon, J.M., eds., Carbonaceous materials as indicators of metamorphism: Geological Society of America Special Paper 153, p. 53–74.

Damberger, H.H., 1991, Coalification in North American coal fields, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., Economic geology: Boulder, Colo., Geological Society of America, The Geology of North America, v. P–2, p. 503–522.

Daniels, E.J., and Altaner, S.P., 1990, Clay mineral authigenesis in coal and shale from the anthracite region, Pennsylvania: American Mineralogist, v. 75, no. 7–8, p. 825–839.

Daniels, E.J., Altaner, S.P., Marshak, Stephen, and Eggleston, J.R., 1990, Hydrothermal alteration in anthracite from eastern Pennsylvania; implications for mechanisms of anthracite formation: Geology, v. 18, no. 3, p. 247–250.

Daniels, E.J., Aronson, J.L., Altaner, S.P., and Clauer, N., 1994, Late Permian age of NH4-bearing illite in anthracite from eastern Pennsylvania; temporal limits on coalification in the central Appalachians: Geological Society of America Bulletin, v. 106, no. 6, p. 760–766.

Daniels, E.J., Marshak, S., and Altaner, S.P., 1996, Use of clay-mineral alteration patterns to define syntectonic permeability of joints (cleat) in Pennsylvania anthracite coal: Tectonophysics, v. 263, no. 1–4, p. 123–136.

Diehl, S.F., Goldhaber, M.B., and Hatch, J.R., 2004, Modes of occurrence of mercury and other trace elements in coals from the Warrior field, Black Warrior Basin, northwestern Alabama: International Journal of Coal Geology, v. 59, no. 3–4, p. 193–208.

Diehl, S.F., Goldhaber, M.B., Tuttle, M.L.W., Ruppert, L.F., and Koenig, A.E., 2005, A comparison between concentrations of arsenic, selenium, and other trace elements in pyrite-filled structures in Appalachian coal basins in Alabama and Kentucky [abs.], *in* Coal-energy, environment and sustainable development, Twenty-second Annual International Pittsburgh Coal Conference, September 12–15, 2005, Pittsburgh, Pa.: Pittsburgh, Pa., University of Pittsburgh, School of Engineering, p. 44, 1 CD-ROM (Also available at http://www.engr.pitt.edu/PCC_Archive/2005/Abstract%20Booklet%202005.pdf.)

Dolton, G.L., Varnes, K.L., Gautier, D.L., and Barnett, D.L., 1995, Oil and gas resources assessment areas, 1995, lower 48 States: U.S. Geological Survey Open-File Report 95–75–I, 1 sheet, scale 1:5,000,000.

Evans, M.A., and Battles, D.A., 1999, Fluid inclusion and stable isotope analyses of veins from the central Appalachian Valley and Ridge province; Implications for regional synorogenic hydrologic structure and fluid migration: Geological Society of America Bulletin, v. 111, no. 12, p. 1841–1860.

Faill, R.T., 1998, A geologic history of the north-central Appalachians; Part 3, The Alleghany orogeny: American Journal of Science, v. 298, no. 2, p. 131–179.

Gluskoter, H.J., 1991, Coal; a brief overview, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., Economic geology, U.S.: Boulder, Colo., Geological Society of America, The Geology of North America, v. P–2, p. 463–467.

Goldhaber, M.B., Lee, R.C., Hatch, J.R., Pashin, J.C., and Treworgy, Julie, 2003, Role of large scale fluid-flow in subsurface arsenic enrichment, *in* Welch, A.H., and Stollenwerk, K.G., eds., Arsenic in ground water: Boston, Mass., Kluwer Academic Publishers, p. 127–176.

Harris, A.G., Harris, L.D., and Epstein, J.B., 1978, Oil and gas data from Paleozoic rocks in the Appalachian basin; Maps for assessing hydrocarbon potential and thermal maturity (conodont color alteration isograds and overburden isopachs): U.S. Geological Survey Miscellaneous Investigations Series Map I–917–E, 4 sheets, scale 1:2,500,000.

Harrison, M.J., Marshak, Stephen, and Onasch, C.M., 2004, Stratigraphic control of hot fluids on anthracitization, Lackawanna synclinorium, Pennsylvania: Tectonophysics, v. 378, no. 1–2, p. 85–103.

Hearn, P.P., Jr., Sutter, J.F., and Belkin, H.E., 1987, Evidence for late-Paleozoic brine migration in Cambrian carbonate rocks of the central and southern Appalachians; Implications for Mississippi Valley-type sulfide mineralization: Geochimica et Cosmochimica Acta, v. 51, no. 5, p. 1323–1334.

Heck, E.T., 1943, Regional metamorphism of coal in southeastern West Virginia: American Association of Petroleum Geologists Bulletin, v. 27, no. 9, p. 1194–1227.

Hood, A., Gutjahr, C.C.M., Heacock, R.L., 1975, Organic metamorphism and the generation of petroleum: American Association of Petroleum Geologists Bulletin, v. 59, no. 6, p. 986–996.

Hower, J.C., 1978, Anisotropy of vitrinite reflectance in relation to coal metamorphism for selected United States coals: University Park, Pa., The Pennsylvania State University, unpub. Ph.D. dissertation, 356 p.

Hower, J.C., 1997, Observations on the role of the Bernice coal field (Sullivan County, Pennsylvania) anthracites in the development of coalification theories in the Appalachians: International Journal of Coal Geology, v. 33, no. 2, p. 95–102.

Hower, J.C., and Davis, Alan, 1981, Application of vitrinite reflectance anisotropy in the evaluation of coal metamorphism: Geological Society of America Bulletin, v. 92, no. 6, p. 350–366.

Hower, J.C., and Gayer, R.A., 2002, Mechanisms of coal metamorphism; case studies from Paleozoic coalfields: International Journal of Coal Geology, v. 50, no. 1–4, p. 215–245.

Hower, J.C., and Rimmer, S.M., 1991, Coal rank trends in the central Appalachian coalfield; Virginia, West Virginia, and Kentucky: Organic Geochemistry, v. 17, no. 2, p. 161–173.

Hulver, M.H., 1997, Post-orogenic evolution of the Appalachian mountain system and its foreland: Chicago., Ill., The University of Chicago, unpub. Ph.D. dissertation, 1055 p.

Lea, M.C., 1841, On the first or southern coal field of Pennsylvania: American Journal of Science, v. 40, no. 2, p. 370–374.

Levine, J.R., 1986, Deep burial of coal-bearing strata, anthracite region, Pennsylvania; Sedimentation or tectonics?: Geology, v. 14, no. 7, p. 577–580.

Levine, J.R., 1993, Coalification; the evolution of coal as source rock and reservoir rock for oil and gas, chap. 3 *of* Law, B.E., and Rice, D.D., eds., Hydrocarbons from coal: American Association of Petroleum Geologists Studies in Geology 38, p. 39–77.

Levine, J.R., and Davis, Alan, 1989a, Reflectance anisotropy of Upper Carboniferous coals in the Appalachian foreland basin, Pennsylvania, U.S.A.: International Journal of Coal Geology, v. 13, nos. 1–4, p. 341–373.

Levine, J.R., and Davis, Alan, 1989b, The relationship of coal optical fabrics to Alleghanian tectonic deformation in the central Appalachian fold-and-thrust belt, Pennsylvania: Geological Society of America Bulletin, v. 101, no. 10, p. 1333–1347.

Milici, R.C., 1974, Stratigraphy and depositional environments of Upper Mississippian and Lower Pennsylvanian rocks in the southern Cumberland Plateau of Tennessee, *in* Briggs, G., ed., Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 115–133.

Milici, R.C., and Hatch, J.R., 2004, Assessment of undiscovered Carboniferous coal-bed gas resources of the Appalachian Basin and Black Warrior Basin Provinces, 2002: U.S. Geological Survey Fact Sheet 2004–3092, 2 p. (Also available at http://pubs.usgs.gov/fs/2004/3092.)

Nuccio, V.F., and Hatch, J.R., 1996, Vitrinite reflectance suppression in New Albany Shale, Illinois Basin; vitrinite reflectance and Rock-Eval data: U.S. Geological Survey Open-File Report 96–665, 37 p., accessed August 5, 2011, at http://pubs.usgs.gov/of/1996/0665/report.pdf.

O'Hara, Kieran, Mizoguchi, Kazuo, Shimamoto, Toshihiko, and Hower, J.C., 2006, Experimental frictional heating of coal gouge at seismic slip rates; evidence for devolatilization and thermal pressurization of gouge fluids: Tectonophysics, v. 424, nos. 1–2, p. 109–118.

Pashin, J.C., Carroll, R.E., Hatch, J.R., and Goldhaber, M.B., 1999, Mechanical and thermal control of cleating and shearing in coal; examples from the Alabama coalbed methane fields, USA, *in* Mastalerz, Maria, Glikson, Miryam, and Golding, S.D., eds., Coalbed methane; scientific, environmental, and economic evaluation: Dordrecht, Netherlands, Kluwer Academic Publishers, p. 305–328.

Penn State Earth and Mineral Sciences Energy Institute, 2011, Department of Energy coal sample bank and database: University Park, Pa., The Pennsylvania State University, Penn State Earth and Mineral Sciences Energy Institute database, accessed August 5, 2011, at http://www.energy.psu.edu/copl/doesb.html.

Rejebian, V.A., Harris, A.G., and Huebner, J.S., 1987, Conodont color and textural alteration; an index to regional metamorphism, contact metamorphism, and hydrothermal alteration: Geological Society of America Bulletin, v. 99, no. 4, p. 471–479.

Renner, J.L., and Vaught, T.L., 1979, Preliminary definition of the geothermal resources potential of Pennsylvania: Arlington, Va., Gruy Federal, Inc., 24 p. (Also available at http://www.osti.gov/geothermal/servlets/purl/5275354-KQvchE/5275354.pdf.) [Prepared under contract ET-78-C-08-1558 for the U.S. Department of Energy.]

Repetski, J.E., Ryder, R.T., Weary, D.J., Harris, A.G., and Trippi, M.H., 2008, Thermal maturity patterns (CAI and $\%R_o$) in the Upper Ordovician and Devonian rocks of the Appalachian basin; A major revision of USGS Map I–917–E using new subsurface collections: U.S. Geological Survey Scientific Investigations Map 3006, 1 CD–ROM disc. (Also available at http://pubs.usgs.gov/sim/3006/.)

Rice, C.L., Sable, E.G., Dever, G.R., Jr., and Kehn, T.M., 1979, Kentucky, *in* Mississippian and Pennsylvanian (Carboniferous) Systems in the United States: U.S. Geological Survey Professional Paper 1110–F, p. F1–F32.

Rimmer, S.M., 1985, Lateral and vertical variability in petrography and mineralogy of the Lower Kittanning seam, western Pennsylvania and eastern Ohio: University Park, Pa., The Pennsylvania State University, unpub. Ph.D. dissertation, 502 p.

Rowan, E.L., 2006, Burial and thermal history of the central Appalachian basin, based on three 2-D models of Ohio, Pennsylvania, and West Virginia: U.S. Geological Survey Open-File Report 2006–1019, 37 p. (Also available at http://pubs.usgs.gov/of/2006/1019/.)

Rowan, E.L., Ryder, R.T., Repetski, J.E., Trippi, M.H., and Ruppert, L.F., 2004, Initial results of a 2D burial/thermal history model, central Appalachian basin, Ohio and West Virginia: U.S. Geological Survey Open-File Report 2004–1445, 38 p. (Also available at http://pubs.usgs.gov/of/2004/1445/.)

Smith, J.B., and Smith, J.W., 2007, A relationship between the carbon and hydrogen content of coals and their vitrinite reflectance: International Journal of Coal Geology, v. 70, no. 1–3, p. 79–86.

Staub, W.P., 1980. A preliminary direct heat geothermal resource assessment of the Tennessee Valley region, *in* Berge, C.W., ed., Geothermal; energy for the eighties, Geothermal Resources Council annual meeting, Salt Lake City, Utah, September 9–11, 1980: Transactions, Geothermal Resources Council, v. 4, p. 137–140.

Trinkle, E.J., Sitler, J.A., Sasso, J.A., Kardosh, W.F., and Ting, F.T.C., 1978, Coalification pattern of West Virginia coals [abs.]: Geological Society of America Abstracts with Programs, v. 10, no. 7, p. 506.

Tully, John, comp., 1996, Coal fields of the conterminous United States: U.S. Geological Survey Open-File Report 96–092, 1 sheet, accessed August 5, 2011, at http://pubs.usgs.gov/of/1996/of96-092/index.htm.

White, C.D., 1925, Progressive regional carbonization of coals: Transactions of the American Institute of Mining and Metallurgical Engineers, v. 1414, no. 71, p. 253–281.

Winston, R.B., 1990, Vitrinite reflectance of Alabama's bituminous coal: Geological Survey of Alabama Circular 139, 54 p.

Wood, G.H., Jr., Trexler, J.P., and Kehn, T.M., 1969, Geology of the west-central part of the Southern anthracite field and adjoining areas, Pennsylvania: U.S. Geological Survey Professional Paper 602, 150 p. (Also available at http://pubs.er.usgs.gov/publication/pp602.)

Zhang, Etuan, and Davis, Alan, 1993, Coalification patterns of Pennsylvanian coal measures in the Appalachian foreland basin, western and south-central Pennsylvania: Geological Society of America Bulletin, v. 105, no. 2, p. 162–174.

Appendix 1. Percent Vitrinite Reflectance for Pennsylvanian Coal Samples From Coal Beds and Coal Zones in the Appalachian Basin

Sample identification numbers separated by an en-dash (–) represent groups of samples. Sample identification numbers separated by a slash (/) represent identical samples contained in multiple databases. Those databases can be found in the Source field. Reported coal bed, coal zone, formation, and group names were taken directly from the source databases and may not conform to U.S. Geological Survey nomenclature. Abbreviations are as follows: No., number; NA, not applicable or not available; $\%R_o$, percent vitrinite reflectance, as reported; $\%R_{omax}$, maximum percent vitrinite reflectance, as reported; $\%R_{omap}$, percent vitrinite reflectance used for contouring; L., Lower; M., Middle; U., Upper.

CLICK HERE TO ACCESS APPENDIX 1 DATA