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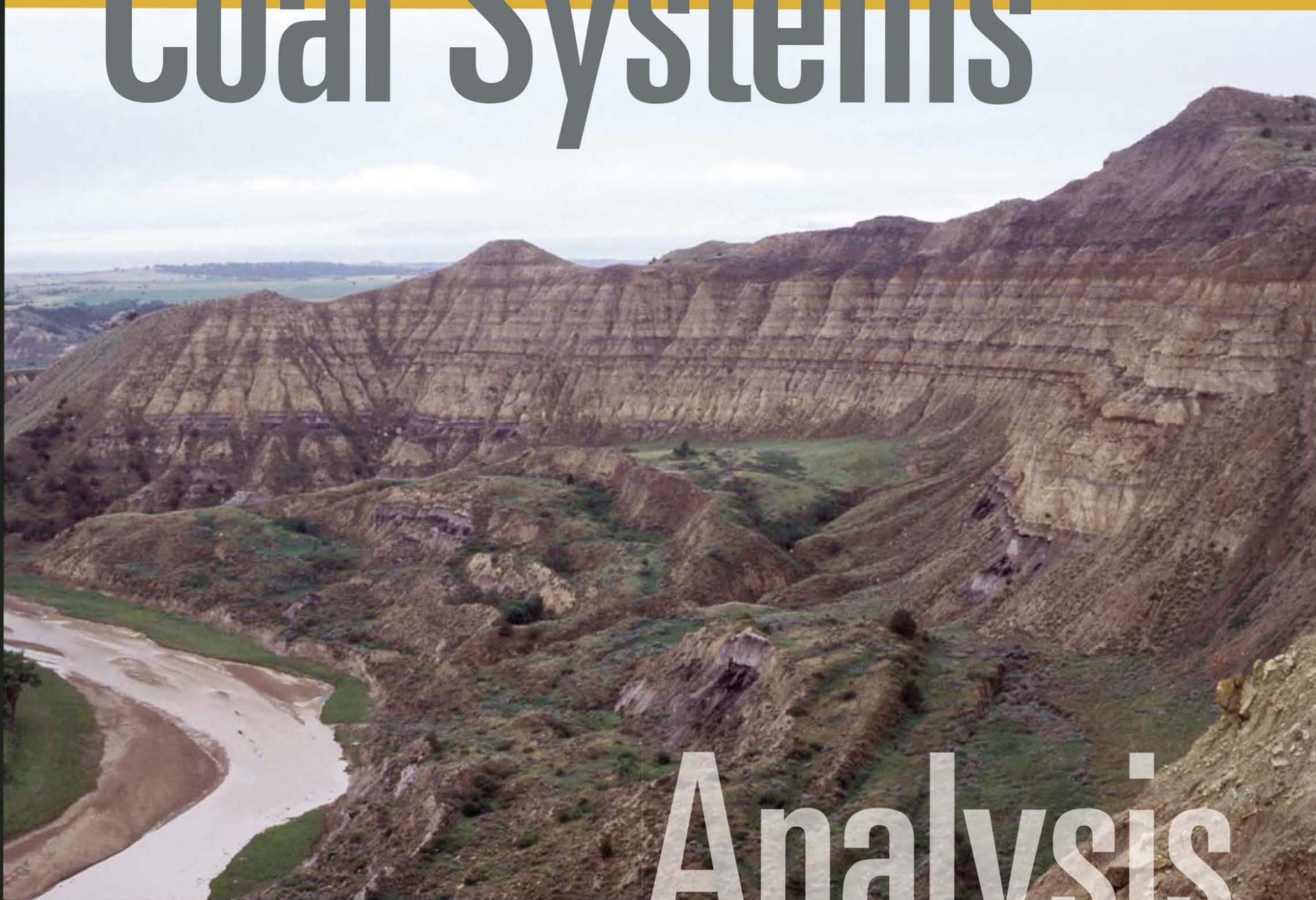
Coal Systems Analysis



Edited by Peter D. Warwick

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Cover: Exposure of the coal-bearing Fort Union Formation (Paleocene) along the Little Missouri River in southwestern North Dakota. Photographed by P.D. Warwick, U.S. Geological Survey.

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Coal systems analysis: A new approach to the understanding of coal formation, coal quality and environmental considerations, and coal as a source rock for hydrocarbons

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ABSTRACT

Coal is an important and required energy source for today's world. Current rates of world coal consumption are projected to continue at approximately the same (or greater) levels well into the twenty-first century. This paper will provide an introduction to the concept of coal systems analysis and the accompanying volume of papers will provide examples of how coal systems analysis can be used to understand, characterize, and evaluate coal and coal gas resources. Coal systems analysis incorporates the various disciplines of coal geology to provide a complete characterization of the resource. The coal system is divided into four stages: (1) accumulation, (2) preservation-burial, (3) diagenesis-coalification, and (4) coal and hydrocarbon resources. These stages are briefly discussed and key references and examples of the application of coal systems analysis are provided.

Keywords: coal, coal systems, coalbed gas, geology, energy.

INTRODUCTION TO THE COAL SYSTEM

Coal is perhaps the most abundant fossil fuel resource in the world. Frozen gas hydrate trapped in tundra or near the seafloor is the only other potential energy source that may be more abundant than coal. Gas hydrates, however, are just beginning to be evaluated as an energy resource, and the extent of which this resource will be utilized in the future is uncertain (Collett, 2002). Coal, on the other hand, is expected to be a vital component of the world's energy resource mix for the foreseeable future (National Petroleum Council, 2003; Energy Information Administration, 2004). This paper introduces the concept of coal systems analysis, and this volume of papers provides examples of how coal systems analysis can be used to understand, characterize, and evaluate coal and coal gas resources.

Any evaluation of coal resources should consider the evolutionary process that takes coal from its origin as peat to its eventual use a resource. This approach can be described as coal systems analysis, which incorporates, among other things, an understanding of coal formation, coal quality and environmental considerations, and coal as a source rock for hydrocarbons. The components of the coal system are illustrated in Figure 1.

In recent years, the concept of petroleum systems (Magoon and Dow, 1994) has evolved into an integrated multifaceted predictive model that utilizes diverse aspects of petroleum geology. A petroleum systems model usually includes an evaluation of source rocks, a review of hydrocarbon thermal maturation and generation pathways, and an assessment of the migration and

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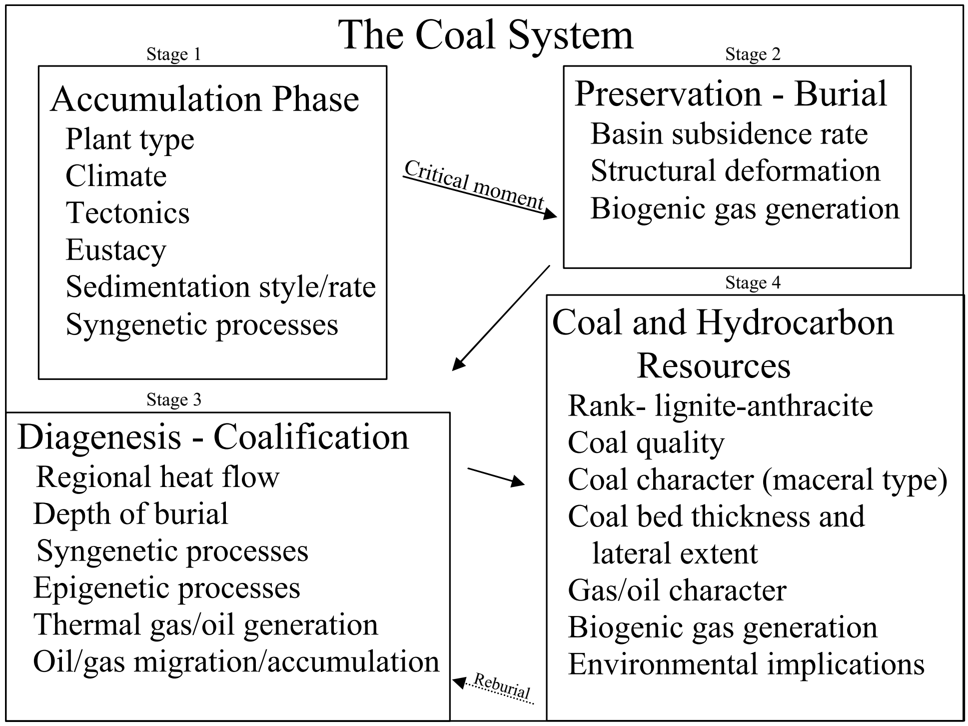

Figure 1. Outline of the components of coal systems analysis.

entrapment processes to understand and explore for these resources. Ayers (2002) employed the petroleum systems concept to evaluate coalbed gas systems in the San Juan and Powder River basins in the western United States. This paper expands the systems concept to include all the disciplines of coal geology.

Coal systems analyses are concerned with the study of the geologic factors that control the formation and thermal maturation of coal from peat to anthracite, its overall quality as a fuel, its potential to generate and store hydrocarbons (such as methane), and the factors that control the environmentally important impurities within the coal bed. In this paper, a brief discussion describes the various components of the coal systems model. The components are organized into four stages: (1) accumulation, (2) preservation and burial, (3) diagenesis and coalification, and (4) coal and hydrocarbon resources. In this discussion, a few key supporting references are provided so that the reader can refer to existing coal geology literature for more detailed discussions of the various components of the coal system. In addition, example applications of the coal systems model are provided. Unlike the petroleum systems model, which was primarily developed as an exploration and resource evaluation tool for hydrocarbons, the coal systems model is a tool that will help scientists understand the complex nature of the many different types of coal and how the various disciplines of coal geology may be used together to address exploration and resource evaluation, production, and the environmental problems associated with coal utilization.

DEFINITION OF A COAL SYSTEM

Stage 1. Accumulation Phase

Peat, the precursor (or parent material) of coal, accumulates in many environments, ranging from subarctic marshes to tropical rain forests. In all cases, accumulation of organic matter must exceed the oxidation or biodegradation of the organic matter. Most coal deposits were formed in ancient depositional systems that include river flood plains, deltas, and other coastal process areas (e.g., Rahmani and Flores, 1984; Mial, 1985; Walker and James, 1992; Diessel, 1992; Thomas, 1994; Galloway and Hobday, 1996; Reading, 1996; Gayer and Pašek, 1997; Papp et al., 1998). An understanding of depositional influences on peat during the accumulation stage is a valuable tool to help predict coal quality and seam continuity. For example, high ash yields in coal may be the result of the original peat deposit's proximity to an active sediment-laden river channel that periodically flooded and introduced waterborne sediment into the peat mire. Windblown silt and volcanic ash may also be a contributor to the ash content of a peat and resulting coal deposit. Although depositional conditions during peat accumulation no doubt influence the properties of the resultant coal, there is no set of parameters that can adequately describe coal deposits formed in one environment verses another. For a discussion of the inadequacies of using depositional environments as a predictive tool for coal character and quality, see Crosdale (1993); Holdgate and Clarke (2000); Wüst et al. (2001), and Moore and Shearer (2003).

Petrographic, paloebotanical, and palynological evidence indicates that coal is composed of the fossilized remains of plants that, depending on the paleolatitude at the time of deposition, range from tropical to subarctic vegetation that grew millions of years ago (Teichmüller, 1989; Cross and Phillips, 1990; Scott, 1991). The vegetable material includes tree trunks, roots, branches, leaves, grass, algae, spores, and a mixture of all plant parts accumulated in mire environments that were subsequently buried by sediments derived from rivers or seas that ultimately filled in subsiding basins (Taylor et al., 1998). Through time, the weight of the overlying sediment and inherent temperature in Earth's crust transformed the organic matter into coal. This process begins with peatification, and, with continued heat flow and pressure, proceeds into coalification and eventually graphitization. Hydrocarbons (gas and oil) may be generated during the coalification process (Tissot and Welte, 1984; Boreham and Powell, 1993; Wilkins and George, 2002). Nichols (this volume) and O'Keefe et al. (this volume) utilize palynology to investigate plant type variation in paleo–peat mires and relate their findings to modern coal characteristics.

Many factors are important to consider when reconstructing how a particular coal deposit might have formed. Not only are there chemical and biological processes active during peat deposition, but the climate, the relative position of sea level, and the local geologic setting may also strongly influence the shape and form of the peat, and ultimately the coal deposit. Peat requires a wet environment to form, so the amount of rain a particular location receives will limit or enhance the formation of peat (Cecil et al., 1985), although some peat mires can have a wide tolerance of rainfall if it is seasonal (Moore and Shearer, 2003). If an area receives too little rain and a local sediment source is available, the peat mire may receive too much sediment to allow large quantities of organic material to accumulate. If sediment accumulation rates are greater than peat accumulation rates, then organic-rich shale or mudstone may form instead of peat.

Many research papers have been written to evaluate the effects of climate, eustacy, and tectonics on coal formation. The papers contained in a volume compiled by Given and Cohen (1977) address the interrelationships between peat and coal character and quality. A collection of papers edited by Lyons and Rice (1986) focuses on tectonic controls on coal-bearing basins. A recent collection of papers edited by Pashin and Gastaldo (2004) explores the eustatic and tectonic affects on coal-bearing sequence formation, whereas a collection of papers edited by Cecil and Edgar (2003) focuses on the climatic affects on coal-bearing stratigraphy. Milici (this volume) and Greb et al. (this volume) discuss the influence of depositional environments, tectonics, and climate on coalbed continuity and quality in the Appalachian basin.

Syngenetic processes are primarily chemical reactions that occur within the peat-forming environment, which affect the overall quality of the resulting coal deposit. An example of a syngenetic process is the formation of pyrite nodules in the poorly oxidized reducing environments of a peat mire. A listing of common minerals in coal can be found in Taylor et al. (1998, p. 258). Other types of secondary minerals, such as calcite and quartz, can form in this manner. Factors such as nutrient supply, acidity, bacterial activity, sulfur supply, temperature, and redox potential in the peat during deposition strongly influence the character of the resulting coal deposits (Raymond and Andrejko, 1983; Taylor et al., 1998). Within an individual peat deposit, variation of these parameters results in recognizable facies variation within coal beds (Cecil et al., 1979; Swaine, 1990; Finkelman, 1993; Taylor et al., 1998; Schatzel and Stewart, 2003; Hámor-Vidó, 2004).

Stage 2. Burial and Preservation: The Critical Moment

In order for thick, widespread accumulations of peat to be preserved in the rock record, they have to form in persistent basins that at some time in the history of their formation subside into the earth and are filled with siliciclastic sediments and carbonate rocks. The rate at which a sedimentary basin subsides will affect the type and amount of peat that can accumulate in the basin. If the basin subsidence rate is very low, even relatively low rates of sediment accumulation may be sufficient to fill the basin, and the wet, swampy areas that are conducive to peat accumulation may not be able to form. On the other hand, if the basin subsidence rate is too great, freshwater or seawater may inundate the basin, and peat deposits may not be able to form. Examples of this relationship can be found in the modern Mississippi delta where relatively rapid subsidence rates prevent significant peat accumulation (Kosters et al., 1987). The rate of basin subsidence must be intermediate, not too high or too low, to allow peat to accumulate.

Once peat has accumulated, it has great potential to be eroded by encroaching rivers or seas. If this encroachment and erosion happens shortly after the peat is deposited, the peat will not be preserved in the sedimentary rock record. The point in time at which the peat is buried and preserved in the geologic record is described in this paper as the *critical moment*. The critical moment is the time that the geologic conditions allow the peat to start the process to become a coal deposit. This idea is very similar to the critical moment in the petroleum system, where appropriate geologic processes converge to allow hydrocarbon generation, migration, and accumulation (Magoon and Dow, 1994).

Once a peat deposit is preserved and starts into the coalification process, folding, faulting, or compaction may deform the strata that contain the peat or coal bed. Faults may serve as conduits for mineral-rich geothermal fluids to enter the coal bed and cause the deposit to be enriched in undesirable minerals or elements (such as arsenic or mercury; for examples from China and the southeastern United States, see Finkelman et al., 2003, and Goldhaber et al., 2003). Deformation of the coal-bearing strata, if intense enough, can render a coal deposit unmineable, cause mining complications, or compress much or all of the pore space for storage and the cleat system of potentially producible coalbed methane (Milici and Gathright, 1985; Coolen, 2003; Phillipson, 2003). On the other hand, folding-induced fractures in the coal can enhance permeability, a key factor determining the producibility of coalbed gas (Laubach et al., 1998). There is always compaction that is associated with the transition from peat to coal. The original composition of the peat and the depth of burial can cause the amount of compaction to vary between coal deposits. Some wood-rich coals may not have compacted very much from the thickness of the original peat deposit, whereas a coal composed of primarily decomposed organic matter mixed with wood fibers may compact by factors as much as or 7:1 (or greater) from the thickness of the original peat deposit (Shearer and Moore, 1996; Taylor et al., 1998). Water loss associated with the peat-to-coal transformation probably accounts for most of the compaction. For a discussion of coal compaction, see White (1986), Littke (1993), Shearer and Moore (1996), Taylor et al. (1998), and Laubach et al. (2000).

Naturally occurring bacteria in peat or coal can generate significant amounts of methane. Gas generated from the decay of organic matter in the peat stage is generally referred to as swamp gas and is not thought to be preserved in the resulting coal beds (Clayton, 1998). Such bacterial gas generation (a process known as methanogenesis) continues throughout the various coal rank stages, and if significant amounts of the gas are trapped in the coal or in an adjacent reservoir, such as porous sandstone beds, it may eventually become an economic gas resource. Many low-rank coal deposits, such as those of the Powder River basin in Wyoming, owe their coalbed methane resources to bacteria activity (Rice, 1993; Clayton, 1998).

Stage 3. Diagenesis and Coalification

Diagenesis and coalification are processes by which buried plant material is altered or metamorphosed to form coal. During this process the original organic material is geochemically altered by heat and pressure during relatively long periods of geologic time. Heat is the most important of these variables and if readily available can cause even geologically young coal to reach elevated ranks. Pressure mainly contributes to reduction of coal porosity, and time is important in the sense of how long a particular coal has been exposed to an elevated heat source. Heat increases with the depth of burial and is associated with Earth's natural geothermal gradient (Levine, 1993; Taylor et al., 1998).

Regional heat flow refers to the amount of geothermal heat that is available in a particular sedimentary basin. Some sedimentary basins have an elevated heat flow because of their proximity to tectonic or igneous activity. Elevated heat flow in sedimentary basins may be associated with deep-seated igneous intrusive bodies. This heat may be sufficient to alter the mineralogy of adjacent sediments or rocks. Heat flow may also be influenced by the proximity to folding or faulting. For example, hot fluids or gasses may flow more easily through deep-seated basin faults. Rock composition of the sedimentary layers within a basin also influences the thermal conductivity of the sediments. Salt and other evaporates have higher thermal conductivity than do sandstone or claystone (Deming, 1994). Formation overpressure may also contribute to increases in regional heat flow of deep sedimentary basins (Mello and Karner, 1996).

The average geothermal gradient in Earth's crust is ~25 °C per 1000 m depth (Tissot and Welte, 1984). The temperatures necessary to form bituminous coal are usually no higher than 100–150 °C, so coal can serve as an important tool to measure paleo–heat flow within a basin (Levine, 1993). This fact is also important in hydrocarbon exploration, because oil and natural gas generation depend on the sediments reaching a certain temperature to facilitate hydrocarbon generation (Taylor et al., 1998).

Natural fractures in coal are very important features that must be considered in coal mining and in coal-gas production. A fractured or cleated coal may be more easily mined than a non-cleated coal. In coalbed methane applications, coal gas has to be able to move though the coal bed to the borehole to allow gas to flow to the surface. Without the natural fracture system, coal gas would not be able to be produced using conventional technologies. However, horizontal drilling techniques may help improve gas production in low-permeability coalbed reservoirs (Von Schoenfeldt et al., 2004). Fractures in coal are controlled by bed thickness, coal type (compositional facies), quality, rank, and tectonic deformation and stress. Tectonic forces are the primary cause for cleat and fracture formation in coal. Coal compaction and water loss may also contribute to cleat and fracture formation. The factors that control the ability of water or gas to move through the coal cleat system are cleat (or fracture) frequency, connectivity, and aperture width (Close, 1993; Kulander and Dean, 1993; Law, 1993; Laubach et al., 1998). Riese et al. (this volume) investigate, among other things, the influence of cleat and fracture systems on coal gas production in the San Juan Basin of Colorado and New Mexico.

The rank of the coal increases as depth of burial becomes greater and the overburden pressure increases (Hilt's Law, see Taylor et al., 1998). In the bituminous coal stage, organic material is heated to where the hydrogen-rich components generate bitumen, which is a gelatinous mixture of hydrocarbons similar to oil. These bitumens fill open pore spaces in the coal, or they can be expelled and can migrate away from the coal bed to become trapped in conventional oil reservoirs (Littke and Leythaeuser, 1993; Wilkins and George, 2002). Because of this change in chemical properties, the physical nature of the coal also changes. The internal microporosity of the coal decreases while the density increases. As the coal is buried deeper and/or subjected to increased heat, the bitumen cracks into smaller molecules, and gases such as methane and carbon dioxide are released. These gases can be adsorbed into the coal structure, and, in the case of methane, can become an economic source of natural gas. This type of methane is described as thermogenic because it was generated by thermal (heating) processes and accounts for most of the gas currently being produced from the

San Juan, Warrior, and Pocahontas basins in the United States. For a detailed discussion of coal rank and the coalification process see Levine (1993) and Taylor et al. (1998).

Epigenetic processes are those processes that affect the peat or coal after deposition and preservation. Examples are groundwater or geothermal fluid flow that can introduce mineral-rich solutions into the buried peat or coal deposit. Many coal deposits become enriched in environmentally sensitive trace elements (such as arsenic and mercury) by epigenetic activity (Goldhaber et al., 2003).

Stage 4. Coal and Hydrocarbon Resources

Coal is the most abundant fuel source currently known on Earth. Estimates of total coal resources range from 10 to 30 trillion metric tons. According to the Knapp (2004), world recoverable coal resources total ~1 trillion metric tons. Coal basins are distributed around the world, with Europe, North America, and Asia having the greatest coal resources. The U.S. Energy Information Administration (2004) reports that the top ten countries with the greatest amount of recoverable coal in decreasing order are: United States, Russia, China, India, Australia, Germany, South Africa, Ukraine, Kazakhstan, and Poland.

The U.S. Geological Survey Coal Resource Classification System (Wood et al., 1983) defines coal resources as "naturally occurring concentrations or deposits of coal in the Earth's crust, in such forms and amounts that economic extraction is currently or potentially feasible." This should not be confused with coal reserves that are "Virgin and (or) accessed parts of a coal reserve base which could be economically extracted or produced at the time of determination considering environmental, legal, and technologic constraints" (Wood et al., 1983).

Typically, coal resource evaluations employ subsurface drilling to obtain information on coal thickness and coal depth, which is combined with similar information from coal outcrops, to calculate coal tonnages over a given area. Most modern coal assessments use geographic information system computers to calculate coal resources. Certain resource assurance levels are employed based on the density and distribution of the data points. Such terms as measured, indicated, inferred, and hypothetical are commonly used to describe estimates of resources (Wood et al., 1983).

All coals contain some amount of coalbed gas. It follows that the regions in the world with the greatest amount of coal in the ground would also contain the greatest coalbed gas resource. Worldwide testing of coals for their coalbed gas content has not been performed systematically, so comprehensive world coalbed gas resource estimates are generally not available at this time. Given these restraints, preliminary worldwide coalbed gas resources are estimated to range between 164 and 686 trillion cubic meters (Scott, 2004). It is projected that coalbed gas will become an important source of natural gas worldwide in the near future. To give a sense of the importance coalbed gas in overall natural gas production, the Energy Information Administration (2004) reports that in 2003, coalbed gas contributes to ~8% of annual natural gas production in the United States.

Coalbed gas estimates can be divided into two types. One type of resource assessment for coal gas is called "gas in place," which utilizes coal resource tonnage multiplied by measured gas content (Mavor and Nelson, 1997). The gas content estimates are determined from coal gas desorption measurements done in the field and in the laboratory. Estimates of coal gas in place indicate the amount of gas in the ground, but not the amount that might be recoverable. The second type of gas resource estimate is that of recoverable gas resources. This methodology employs past production history, field size, and geological data to estimate the recoverable gas from a field (Schmoker, 1999, 2004). If no production data are available for a given field, then field analogues are used.

Coal beds below the regional water table are usually water saturated. The level of permeability within the coal bed will determine if it is an aquifer. In many coal-bearing regions, the coal beds serve as regional aquifers and supply drinking and irrigation water. In some places, in the production of coalbed gas, a large amount of water is produced in order to recover the coal gas. There is some concern that overproduction of the water stored in the coal beds may eventually harm the aquifer systems (Harrison et al., 2000). Therefore, water produced from coalbed aquifers during the coalbed gas production process has to be managed. Some common practices are to release the water in surface drainage systems, let the water evaporate from evaporation ponds, or to re-inject the water into subsurface disposal wells. The method that is used to dispose of the produced water depends on the water quality (Nuccio, 2000).

"Coal quality" is a term used to describe coal chemical and physical properties that influence its utilization. There are a number of laboratory tests (such as for ash, moisture, sulfur, and calorific value) that help determine the quality of coal (Berkowitz, 1979; Ward, 1984; American Society for Testing and Materials, 2003). Coal quality is important because it helps predict how a particular coal might be used or how it might behave when it is combusted in a boiler, for example. Furthermore, coal quality parameters are important to help determine if a particular coal, when used in any number of ways, will cause environmental damage (Ward, 1984; Finkelman, 1997). Coal quality should not be confused with coal rank, which is a measure of the coalification process in coal.

Coal is largely composed of organic matter, but it is the characterization of the inorganic material in coal, both mineral and trace elements, that have important ramifications in the technological aspects of coal use and in understanding the environmental and health problems that may result from coal utilization. Detailed analytical procedures are available for testing coal samples for various trace elements, but most recent attention has focused on determining the concentrations in raw coal of the potentially environmentally harmful trace elements such as mercury, lead, arsenic, and selenium. It is these elements that may cause environmental damage if concentrations are great enough and if the ash and smoke resulting from the burned coal is not treated or disposed of properly.

Another possible mode of release for the potentially environmentally harmful trace elements may be the prolonged exposure of the coal to weathering effects or groundwater runoff commonly know as acid mine drainage. For the most part, the concentrations of these elements are generally too small in most power plant feed stocks to cause significant short-term damage to the environment. However, with continued and increased use of coal as a fuel for generating electricity in conventional power plants, levels of mercury and possibly other harmful trace elements may accumulate in the environment sufficiently so that they will have to be regulated in the future (Finkelman et al., 2002). Alternatively, the use of Clean Coal Technology may help reduce or eliminate these potential pollutants in the future (Abelson, 1990; Department of Energy, 2004).

Geologic sequestration of carbon dioxide in coal beds may be an environmentally attractive method of reducing the amount of greenhouse gas emissions generated from fossil fuel combustion (Stevens et al., 2000; Stanton et al., 2001). In addition, carbon dioxide may be used to enhance coalbed gas production. Many scientific studies are now being conducted on the chemical, physical, and technological aspects of the possibility of future geologic sequestration of carbon dioxide in coal beds (e.g., Busch et al., 2003; Karacan and Mitchell, 2003). Other potential targets for geologic sequestration of carbon dioxide include the deep ocean, and in underground saline aquifers and depleted hydrocarbon reservoirs (Burruss and Brennan, 2003).

CONCLUSIONS

Coal is an important and required energy source for today's world. Current rates of coal consumption are projected to continue well into the twenty-first century. This review of coal geology and resources employs the concept of coal systems analysis, which ranges from the study of peat-accumulating environments to the ultimate end use of coal as a fuel or other industrial applications. The use of this approach integrates multiple geologic, geochemical, and paleontological fields of study into one common approach to understand the complex nature of a coal deposit and its associated resources. The papers in this volume provide examples of how coal systems analysis can be used to better incorporate the diverse aspects of coal geology into one usable tool.

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Appalachian coal assessment: Defining the coal systems of the Appalachian basin

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ABSTRACT

The coal systems concept may be used to organize the geologic data for a relatively large, complex area, such as the Appalachian basin, in order to facilitate coal assessments in the area. The concept is especially valuable in subjective assessments of future coal production, which would require a detailed understanding of the coal geology and coal chemistry of the region. In addition, subjective assessments of future coal production would be enhanced by a geographical information system that contains the geologic and geochemical data commonly prepared for conventional coal assessments.

Coal systems are generally defined as one or more coal beds or groups of coal beds that have had the same or similar genetic history from their inception as peat deposits, through their burial, diagenesis, and epigenesis to their ultimate preservation as lignite, bituminous coal, or anthracite. The central and northern parts of the Appalachian basin contain seven coal systems (Coal Systems A–G). These systems may be defined generally on the following criteria: (1) on the primary characteristics of their paleopeat deposits, (2) on the stratigraphic framework of the Paleozoic coal measures, (3) on the relative abundance of coal beds within the major stratigraphic groupings, (4) on the amount of sulfur related to the geologic and climatic conditions under which paleopeat deposits accumulated, and (5) on the rank of the coal (lignite to anthracite).

Keywords: coal, coal systems, Appalachians, resource assessment.

INTRODUCTION

Current federal and state coal assessments (herein called conventional coal assessments) estimate original and remaining resources in the ground, coal resources available for mining, and economically recoverable coal resources (coal reserves). Although these types of assessments provide valuable information about the nation's coal resources, they do not predict the amount of coal that may be mined in the near future (e.g., for an assessment period of ~20 yr) from an area selected for assessment. Predictive assessments of coal production would be subjective. In general, subjective coal assessments would be based on an understanding of the regional coal geology (coal systems), the potential demand for the coal resource, and knowledge of the mining history of the region. As in conventional coal assessments, compilation of the geology of coal beds or coal zones into a geographic information system (GIS) is essential for predictive assessments. In general, the GIS would be used to illustrate coal crop lines and the extent of the coal bed underground, the extent and type of mining, geologic structure, coalbed thickness, and depth of overburden, together with the point data used to make the GIS covers. The GIS would be used to calculate the volumes of the original and remaining coal resources for the assessed coal beds or zones. In addition to the work required for conventional coal assessments, subjective assessments of coal production would require estimates of the

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amount of coal expected to be produced from existing mines as well as the numbers and sizes of new mines expected to be opened during the assessment period. These values would be combined in an appropriate computer software program to produce probability distributions that illustrated the amount of coal expected to be produced from current and new mines during the selected assessment period (Charpentier and Klett, 2000).

As assessors, coal geologists should understand and be conversant with the coal geology of the region to be assessed. This information may be organized first by defining coal systems and then by selecting assessment units within them—the coal beds or zones that, in the view of the assessors, would have a considerable potential to produce economic amounts of coal during the selected time frame. In general, coal systems are one or more coal beds or groups of coal beds that have had the same or similar genetic history from their inception as peat deposits, through their burial, diagenesis, and epigenesis to their ultimate preservation as lignite, bituminous coal, or anthracite.

The purpose of this paper is to define and briefly describe the major coal systems of the central and northern parts of the Appalachian coal fields in order to provide a general geologic framework for subjective assessment of future coal production. These systems may be defined generally: (1) on the primary characteristics of their paleopeat deposits, including regional differences in sulfur content (Bragg et al., 1998; Cecil et al., 1985), (2) on the stratigraphic framework of the Paleozoic coal measures, (3) on the relative abundance of coal beds within the major stratigraphic groupings, (4) on the amount of sulfur related to the geologic and climatic conditions under which paleopeat deposits accumulated, and (5) on the rank of the coal (lignite to anthracite) (Tables 1 and 2) (this outline is used in the description of Appalachian coal systems that follow). Once defined, coal systems may be divided into assessment units of one or more closely related coal beds or coal zones on the basis of their inferred potential to produce relatively large volumes of coal in the future.

The coal quality data used herein is primarily from Bragg et al. (1998) and is supplemented with data obtained from publications of the U.S. Bureau of Mines. Although there are several thousand analyses available for the central and northern parts of the Appalachian basin, there are fewer than a hundred analyses available for several of the stratigraphic units discussed herein. The numbers of samples for each stratigraphic unit described are indicated on accompanying figures and tables. Many of these samples were collected from coal mines that were in operation during the past several decades and are not necessarily representative of coal that is currently (2004) being mined (Bragg et al., 1998).

Although the coal system approach is preferred for subjective assessments of future coal production, it should be noted that, historically, conventional coal assessments have not been based on coal system analyses. For example, the U.S. Geological Survey completed conventional assessments of several of the major coal beds in the northern and central Appalachian coal regions in 2001 (Northern and Central Appalachian Basin Coal Regions Assessment Team, 2001). The priorities for the coal beds to be assessed were established in consultation with other agencies, including state geologic surveys, industry, and academia, rather than through the use of an established coal system/assessment unit protocol. Although the geologic data were not organized by coal systems at the time of the assessments, these GIS-based conventional assessments provide sufficient data for follow-on subjective estimates of future coal production from the assessed beds.

COAL SYSTEMS

Coal is the product of many complex, interrelated processes (see Warwick, this volume). Coal beds are described geologically by their rank (lignite to anthracite), thickness, aerial extent, geometry, petrology (maceral type), and chemistry, as well as by their potential to generate biogenic and thermogenic gases (coalbed methane) and liquids. When the processes that produce coal are viewed collectively as a coal system, they describe the geologic, biologic, and climatic events that formed its precursor, peat; they continue with the diagenitic events that affect the peat during its burial and preservation and end with the relative amounts of metamorphism of the coal bed (coalification) that form the lignite-to-anthracite commodities used by humans.

In general, coal formation occurs under the umbrella of plate tectonics. Plate tectonics play a direct (although not exclusive) role in the evolution of climate and sea-level changes as landmasses, such as Pangea, drifted into and out of climatic regimes that range from arctic to tropical. For example, as the Appalachian region of Pangea moved northward across the equator, paleoclimates changed from arid in the Early Mississippian to tropical in the Pennsylvanian, and once again to arid in the Early Triassic (Scotese, 2003a–2003f).

Regional subsidence, in part caused by thrust loading during continental collision (Tankard, 1986), produced the Appalachian foreland basin in which a great thickness of coal-bearing Carboniferous and Permian strata accumulated. In contrast, the continental breakup that followed in the early Mesozoic produced numerous, relatively small, extensional basins in the Appalachian Piedmont and Atlantic Outer Continental Shelf in which peat accumulated, was buried, and was then preserved within graben and half-graben structures. In addition, the collisional and extensional events that occurred in the eastern United States at the end of the Paleozoic and during the early Mesozoic created the mountainous source regions for the siliciclastic sediments that are so commonly associated with these coal beds. Under optimal climatic conditions, however, thick, widespread deposits of peat will accumulate and be preserved only during relatively long periods of tectonic stability. Even though climatic conditions may be ideal for the formation of thick accumulations of peat (Cecil et al., 1985; Cecil, 2003), tectonic instability and rapidly changing local depositional environments may result in the erratic distribution of discontinuous coal beds (Edmunds, 1968).

TABLE 1. GENERALIZED PENNSYLVANIAN AND PERMIAN STRATIGRAPHIC NOMENCLATURE FOR THE CENTRAL AND NORTHERN PARTS OF THE APPALACHIAN BASIN, SHOWING MAJOR COAL SYSTEMS.

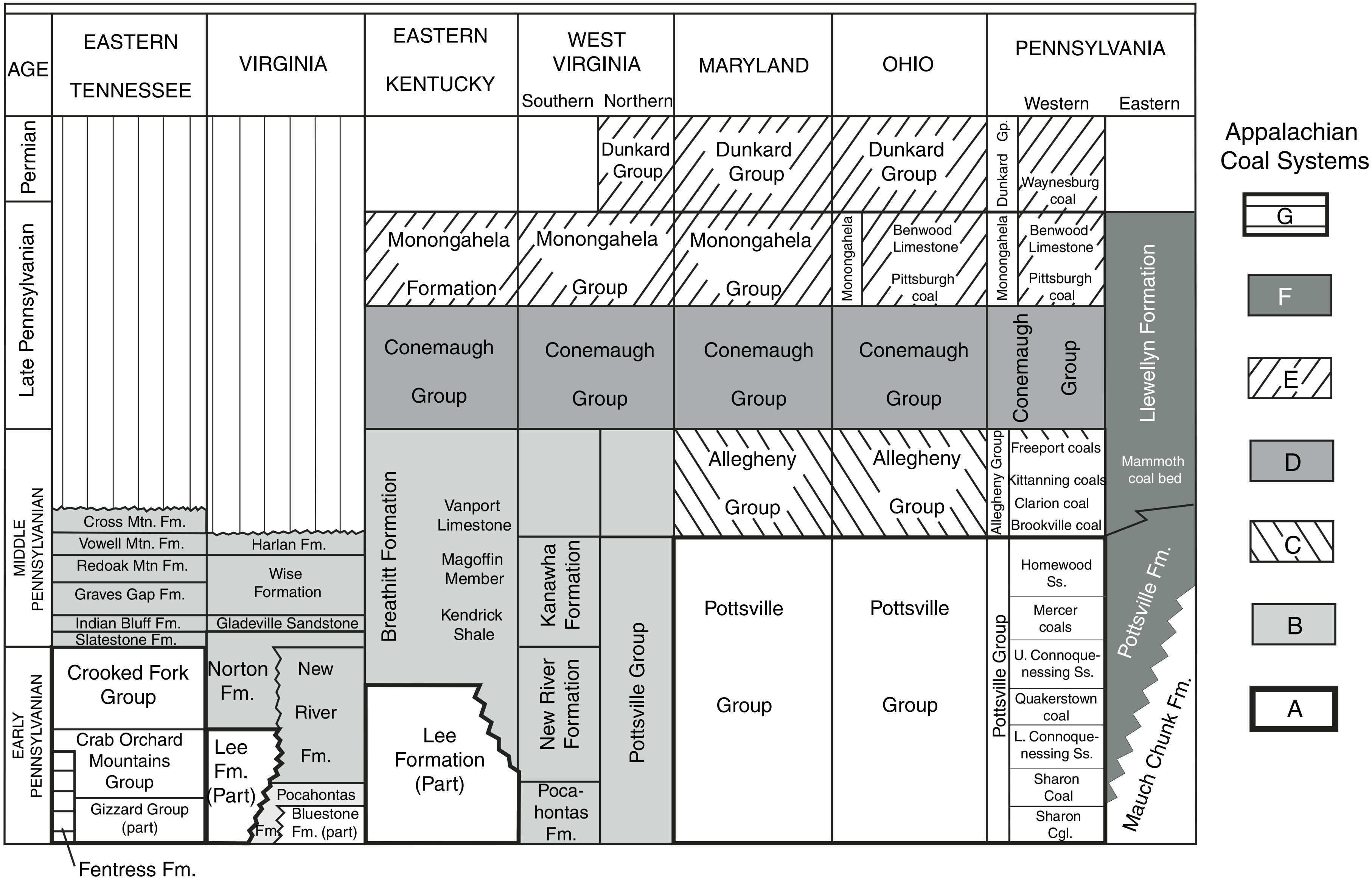

TABLE 2. MAJOR COAL SYSTEMS OF THE CENTRAL AND NORTHERN PARTS OF THE APPALACHIAN BASIN

DATA						
		Southern Tennessee	**Northern Tennessee**	**Northern Tennessee**	**Eastern Kentucky**	**Eastern Kentucky**
	COAL SYSTEM	**A**	**G**	**B**	**A**	**B**
		Sewanee coal zone	**Wilder coal zone**	**Wartburg Basin**	**Lee**	**Breathitt**
(Measured)	**Sulfur content**	Low to high	High	Low to high	Low to high	Low to high
(Inferred)	**Climate**	Everwet, tropical	Everwet, tropical	Everwet, tropical	Everwet, tropical	Everwet, tropical
(Inferred)	**Peat Topography**	Planar to domed?	Planar to domed?	Planar to domed?	Planar to domed?	Planar to domed
(Measured)	**Lithology**	Qtz ss., sh., sltst., coal	Sh., siltst., ss., coal	Sh., siltst., ss., coal	Qtz ss., sh., sltst., coal	Sh., siltst., ss., coal
(Inferred)	**Marine influence**	Low to high	High	Low to medium	Low to high	Low to high
		Southwest Virginia	**Southwest Virginia**	**Southwest Virginia**	**Southwest Virginia**	**Southwest Virginia**
	COAL SYSTEM	**A**	**B**	**B**	**B**	**B**
		Lee coals	**Pocahontas coals**	**New River coals**	**Norton coals**	**Wise coals**
(Measured)	**Sulfur content**	Low to high	Low	Low to high	Low to high	Low to high
(Inferred)	**Climate**	Everwet, tropical	Everwet, tropical	Everwet, tropical	Everwet, tropical	Everwet, tropical
(Measaured to inferred)	**Peat Topography**	Planar to domed?	Domed	Planar to domed?	Planar to domed?	Planar to domed?
(Measured)	**Lithology**	Qtz. ss., slst., sh, coal	Ss., slst., sh, coal	Sh., sltst., ss., coal	Sh., siltst., ss., coal	Sh., siltst., ss., coal
(Inferred)	**Marine influence**	Low to high	Low	Low to medium	Low to medium	Low to high
			Southern West Virginia	**Southern West Virginia**	**Southern West Virginia**	**Southern West Virginia**
	COAL SYSTEM		**B**	**B**	**B**	**B**
			Pocahontas coals	**New River coals**	**Kanawha coals**	**Allegheny coals**
(Measured)	**Sulfur content**		Generally low to medium	Generally low to medium	Low to high	Low to high
(Inferred)	**Climate**		Everwet, tropical	Everwet, tropical	Everwet, tropical	Everwet, tropical
(Measaured to inferred)	**Peat Topography**		Planar to domed?	Planar to domed?	Planar to domed?	Planar to domed?
(Measured)	**Lithology**		Sh., sltst., ss., coal	Sh., sltst., ss., coal	Sh., sltst., ss., coal	Sh., sltst., ss., coal
(Inferred)	**Marine influence**		Generally low to medium	Generally low to medium	Low to high	Low to high
		Northern Appalachian Basin (Bituminous coal field)			**Northern Appalachian Basin (Bituminous coal field)**	
	COAL SYSTEM	**A(2)**	**C**	**D**	**E**	**E**
		Pottsville	**Allegheny**	**Conemaugh**	**Monongahela**	**Dunkard**
(Measured)	**Sulfur content**	Low to high	Generally med. to high	Generally med. to high	Generally med. to high	Generally med. to high
(Inferred)	**Climate**	Everwet, tropical?	Seasonal, wet/dry	Seasonal, wet/dry	Seasonal, wet/dry	Seasonal, wet/dry
(Measaured to inferred)	**Peat Topography**	Planar to domed?	Planar	Planar	Planar	Planar
(Measured)	**Lithology**	Qtz. ss., slst., sh, coal	Ss., sltst., sh, coal	Red/green sh., sltst., ss., coal	Red/green sh., sltst., ss., coal	Red sh., sltst., ss., coal
(Inferred)	**Marine influence**	Generally high	Generally high	Low to high	None	None
		Northern Appalachian Basin (Anthracite district)				
	COAL SYSTEM	**F**	**F**			
		Pottsville (PA)	**Llewellyn**			
(Measured)	**Sulfur content**	Low	Generally low to medium			
(Inferred)	**Climate**	Everwet, tropical?	Everwet, tropical?			
(Measaured to inferred)	**Peat Topography**	Planar to domed?	Planar to domed?			
(Measured)	**Lithology**	Cgl., Ss., slst., sh, coal	Cgl., Ss., slst., sh, coal			
(Inferred)	**Marine influence**	None	Local			
(Measured)	**Metamorphism**	Anthracite	Anthracite			

Note:

Low sulfur coal. <1% S
Medium sulfur coal, 1 - 2% S
High sulfur coal, > 2% S

Paleoclimate

The paleoclimate under which a coal (paleopeat) deposit formed is a significant controlling factor in defining coal systems (Cecil et al., 1985; Cecil et al., 2003). Among others, Langbein and Schumm (1958) (Fig. 1) and Cecil and Dulong (2003) have related the amount of siliciclastic sediment yield to precipitation, and Langbein and Schaumm (1958) have shown that the greatest amounts of sediment are eroded in relatively dry climates, in areas with ~10 in. (25.4 cm) of rainfall annually (Fig. 1). Progressively wetter climates stimulate plant growth, which retards erosion and sedimentation and enhances the formation and preservation of peat. Progressively drier climates do not provide sufficient runoff to transport clastic sediments (Cecil and Dulong, 2003; Cecil et al., 2003).

In the northern and central Appalachian coal fields, coal quality (primarily ash and sulfur content; Bragg et al., 1998) is related regionally to the climatic conditions under which their paleopeat precursors formed, and locally to fluids derived from adjacent marine sediments during the compaction, dewatering, and diagenesis of peat-bearing strata subsequent to deep burial. Cecil et al. (1985) classified Appalachian peat-forming environments into two general types, which they labeled Type A and Type B. Type A paleopeat deposits were formed in everwet tropical environments, were fed by the nutrient-poor waters of rain, and tended to be topographically domed. Because of the relatively low amount of introduced nutrients, these paleopeat deposits were generally low in ash and sulfur content. Type A coal beds generally occur in the central part of the Appalachian coal field. Type B paleopeat deposits formed in more seasonal tropical environments, obtained most of their moisture from ground and surface waters that were relatively enriched in nutrient content, and tended to be planar in their topographic expression. As a result, coal beds derived from these paleopeats are relatively high in their ash and sulfur contents. Type B coal beds generally occur in the northern Appalachian coal field. In places where marine environments are common in the stratigraphic sections in both the central and northern parts of the Appalachian basin, however, the sulfur content of coal beds is greater than it is where marine beds are absent. This supports a general cause-and-effect relationship between marine zones and the sulfur content of coal beds regardless of the climatic regime under which the paleopeat deposits were formed (everwet versus seasonal).

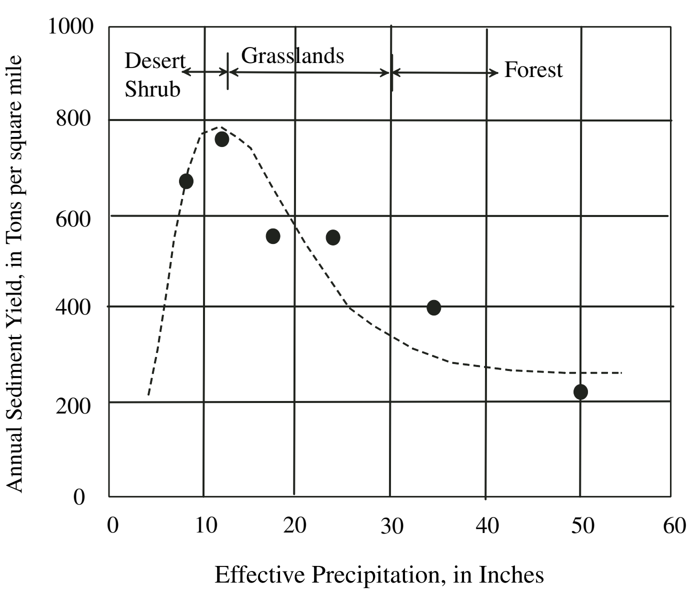

Figure 1. Sediment yield versus effective precipitation (Langbein and Schumm, 1958). Note maximum sediment yield at ~12 in. (30.5 cm) annual precipitation (1 mi^2 = 2.59 km^2; 1 short ton = 0.907 tonnes; 1 in = 2.54 cm).

Much of the low- to medium-sulfur coal produced in the central Appalachian coal field is from the Lower and Middle Pennsylvanian part of the stratigraphic section, from the Pocahontas, Norton, Wise, New River, and Kanawha Formations in Virginia and southern West Virginia, and from the lower and middle parts of the Breathitt Formation in eastern Kentucky (Fig. 2, Tables 1 and 2). In contrast, the major coal-producing beds in the northern Appalachian coal field, which generally produce medium- to high-sulfur coal, are from stratigraphically higher units, from the upper part of the Kanawha Formation (or Group), and from the Allegheny, Conemaugh, Monongahela, and Dunkard Groups (Middle Pennsylvanian to Permian; Fig. 3, Table 1).

In general, the major differences in coalbed topology and the sulfur and ash contents of coal beds in the Appalachian Basin are separated both in location and time, with everwet tropical conditions occurring in the central Appalachian coal field in Early and Middle Pennsylvanian time and more seasonal, wet and dry (monsoonal?) conditions occurring in the northern Appalachian coal field from the latter part of the Middle Pennsylvanian into Permian time (Cecil et al., 1985). These regional climatic differences apparently reflect both the northward migration of Pangea across the equator during the late Paleozoic and the orographic effects of the Appalachian mountain chain as it was progressively elevated during the Alleghenian orogeny in the latter part of the Pennsylvanian (Wood et al., 1986; Heckel, 1995; Otto-Bleisner, 2003). The location of this tectonically formed topography with respect to ambient winds during the Late Paleozoic and Early Mesozoic may have affected the amount of rainfall in which these ancient coal-bearing deposits formed. The apparent change in climate during the Pennsylvanian, from tropical everwet to more seasonal, wet and dry (monsoonal?) suggests that, by the latter part of the Pennsylvanian the mountains had affected atmospheric circulation sufficiently so that the paleoclimate in Pennsylvania and Ohio to the north (west) became generally drier (Otto-Bleisner, 2003).

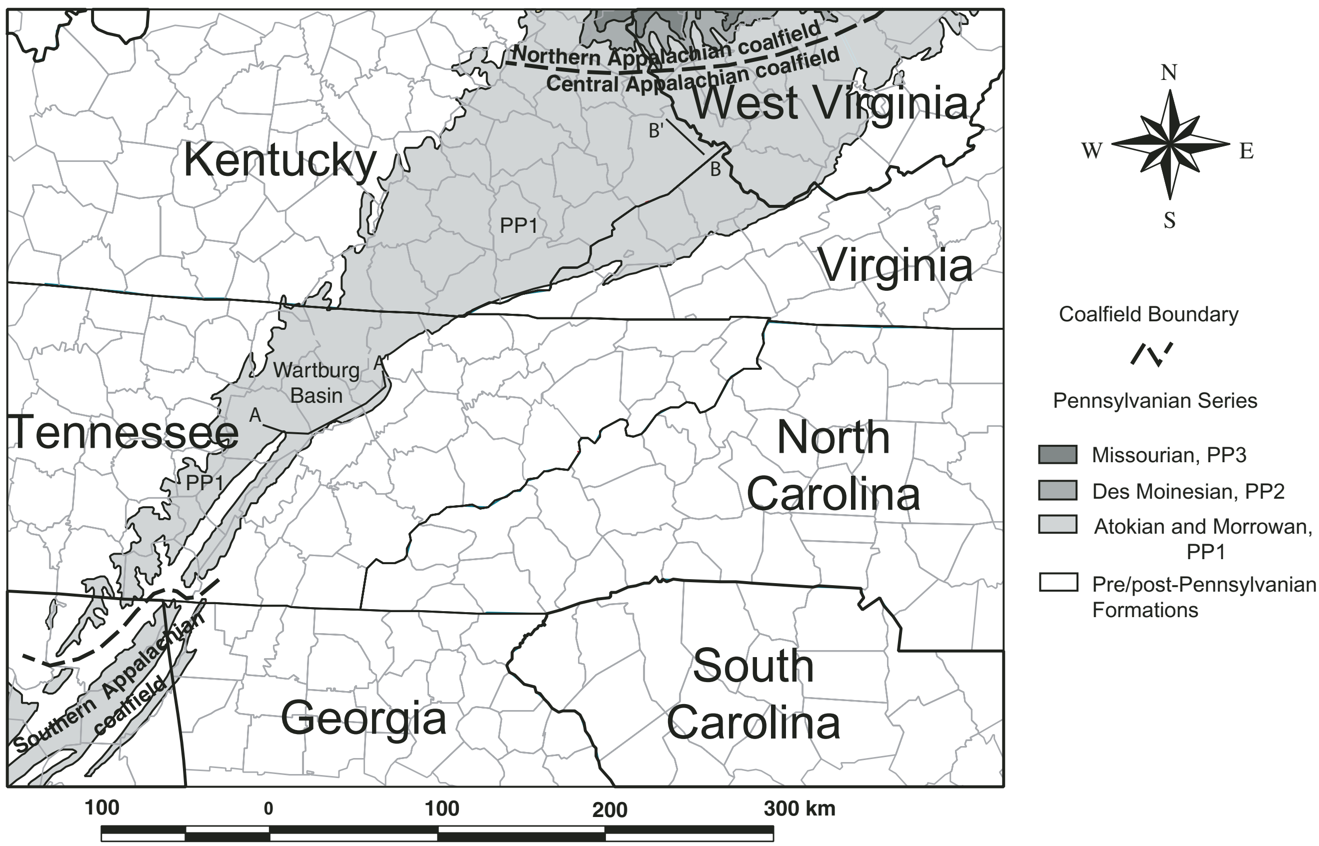

Figure 2. Generalized geologic map of central part of Appalachian Basin (after King and Beikman, 1974).

Diagenetic and Epigenetic Processes

Although paleoclimate may have directly influenced the regional differences in the sulfur content of coals in the Central and Northern Appalachian coal fields, local differences may be related to other factors. Cecil et al. (2003) present a conceptual model that relates late Middle Pennsylvanian climates to glacial maxima (sea-level lowstands) and glacial minima (sea-level highstands) in the southern hemisphere (Gondwana). In their model (Cecil et al., 2003, their figs. 22 and 23), the Appalachian region is described as generally wet during glacial lowstands (10–12 mo. of rainfall) and more seasonal during interglacial intervals (7–9 mo. of rainfall). This climate change, from relatively wet to relatively dry, should have caused a cyclic change in the sulfur content in Appalachian coal beds, with the accumulation of higher sulfur coals occurring during the relatively dry highstands. During these interglacial highstands, water tables would have been high and marine environments would have episodically intruded into the coal basins, thereby affecting both the stratigraphy and the sulfur content of the coal-bearing strata. Thus, glacially driven changes in sea level in the Pennsylvanian should be reflected both by cyclic stratigraphy and by cyclic coalbed geochemistry.

Not all paleopeat deposits (coal beds) in the Appalachian basin that accumulated under everwet tropical conditions are low in sulfur content (1% sulfur or less by weight). In order to define the influence of one variable, climate, on coal composition, it is necessary to show that other variables, such as the introduction of sulfur into paleopeat deposits from adjacent marine sediments during burial, or the introduction of sulfur into coal beds by epithermal fluids, were or were not operative. Williams and Keith (1963) confirmed the relationship of the sulfur content of coal and the occurrence of marine roof rocks, which had been proposed by White and Thiessen (1913), by showing that the sulfur content of the Lower Kittanning coal bed in Pennsylvania was generally less than 2% where the overburden consisted of continental strata, to greater than 3% where the overburden was marine. In contrast, there was no statistical variation in the sulfur content of the Upper Freeport coal bed, which is overlain entirely by continental deposits. Furthermore, it is common knowledge amongst the field geologists who participated in the U.S. Geological Survey's (USGS) geological mapping program in the eastern Kentucky coal fields that coals relatively high in sulfur (>2% S) in the Breathitt Formation were invariably overlain by beds that contained marine fossils (William Outerbridge, USGS, retired, 2003, personal commun.; Greb and Chestnut, 1996). In their comparative study of the Eastern and Western Kentucky coal fields, Greb et al. (2002) concluded that although coal beds

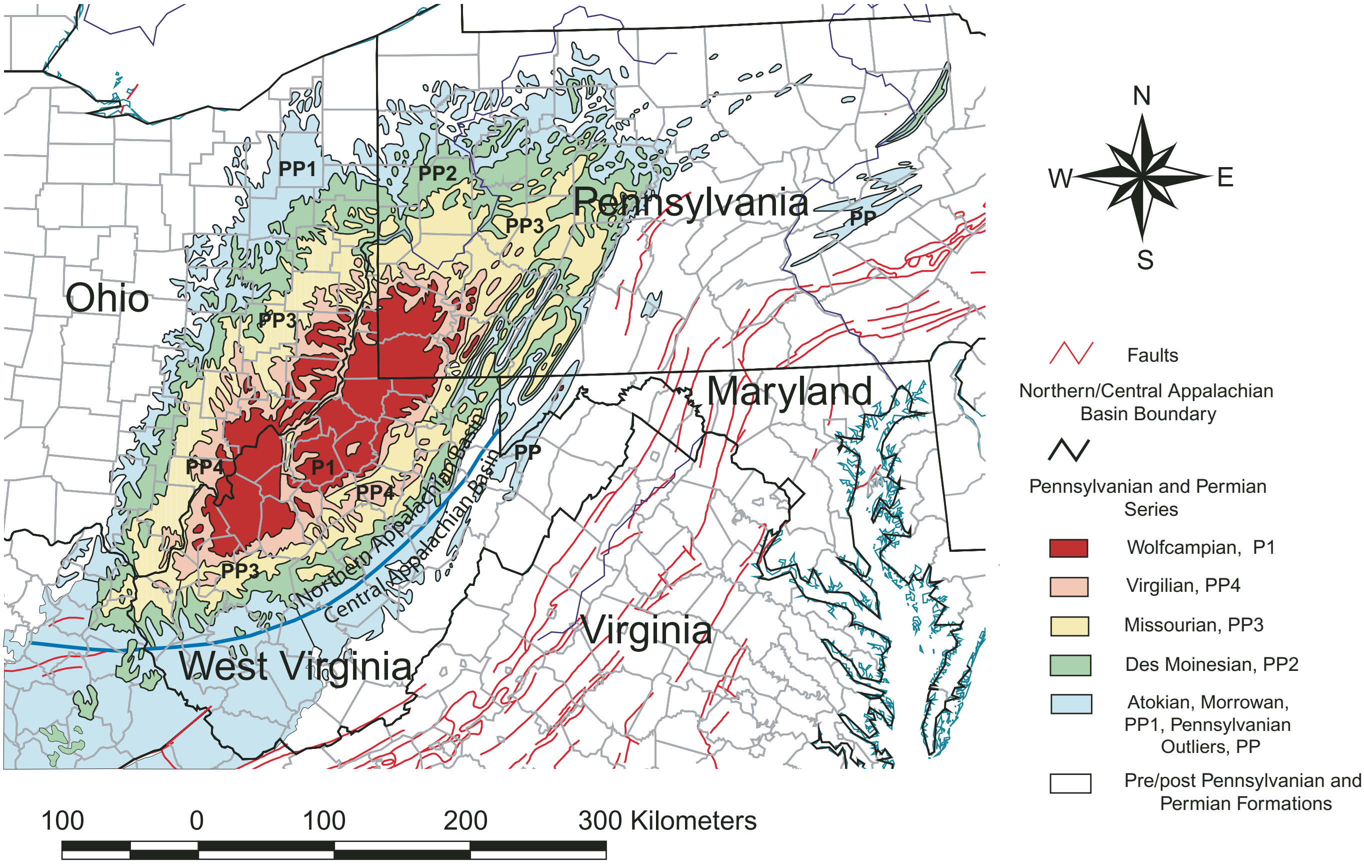

Figure 3. Generalized geology of the northern part of the Appalachian Basin, showing boundary between the northern and central parts of the basin (after King and Beikman, 1974).

may have an increased sulfur content where they occur beneath marine zones, paleoclimate and tectonic accommodation were important factors in determining overall coal quality. The glacially driven eustatic changes of sea level and associated invasions of marine environments into coal basins are, at least, examples of the influence of paleoclimate on coal chemistry, however indirect they may be.

In other places in the southern part of the Appalachian Basin, however, hydrothermal processes may have been responsible for elevated content of trace elements (e.g., arsenic) of coal deposits (Kolker et al., 1999). Where epigenesis is responsible for high sulfur content in coal beds that were deposited in tropical, everwet climates, it is expected that corresponding ash contents would be low, thereby reflecting a domed topology for these paleopeat deposits.

APPALACHIAN COAL SYSTEMS

There are at least seven major coal systems, designated A–G, in the central and northern coal fields of the Appalachian Basin (Tables 1 and 2). These systems may be defined generally on the following criteria: (1) on the primary characteristics of their paleopeat deposits, (2) on the stratigraphic framework of the Paleozoic coal measures, (3) on the relative abundance of coal beds within the major stratigraphic groupings, (4) on the amount of sulfur related to the geologic and climatic conditions under which paleopeat deposits accumulated, and (5) on the rank of the coal (lignite to anthracite).

Appalachian Coal System A

Appalachian Coal System A includes the Gizzard, Crab Orchard Mountains, and Crooked Fork Groups in Tennessee, the Lee Formation in Virginia and eastern Kentucky, and the Pottsville Group (or Formation) in Ohio, Maryland, and western Pennsylvania. (1) In the central Appalachian coal field, Coal System A probably was deposited in a tropical, everwet climate (Cecil et al., 1985). Pennsylvanian paleosols in the northern Appalachian coal field indicate that Pottsville climates there were also wet, although the climate was more seasonal, with wet periods alternating with dry periods (Cecil, 2003, personal commun.). (2) Lithologically, the system consists of quartzose sandstones and quartz-pebble conglomerates that are interstratified with coal-bearing siltstones and shales. (3) Coal beds are mined from within the Pottsville, but are not as abundant as they are elsewhere within other stratigraphic intervals in the