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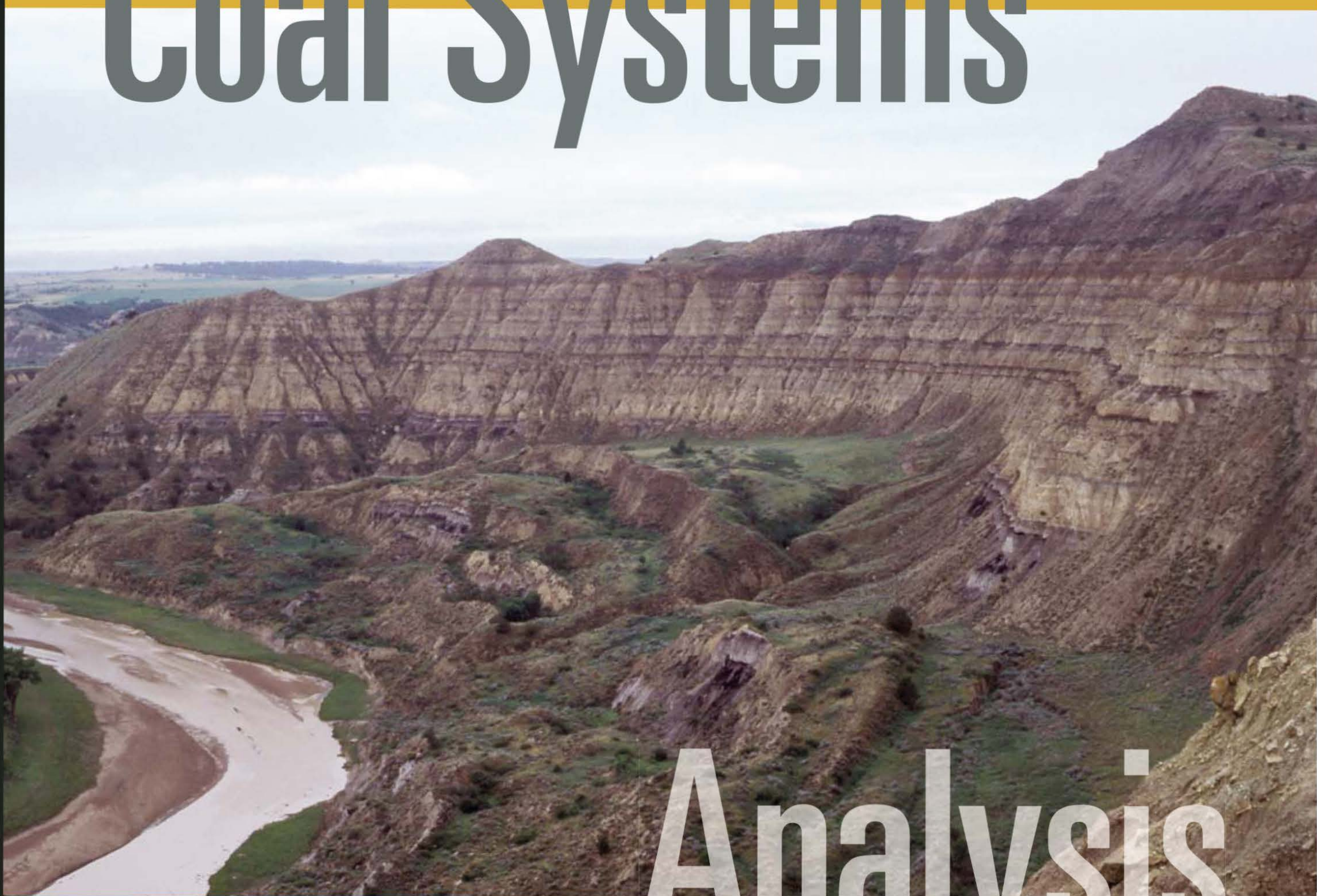

Edited by Peter D. Warwick

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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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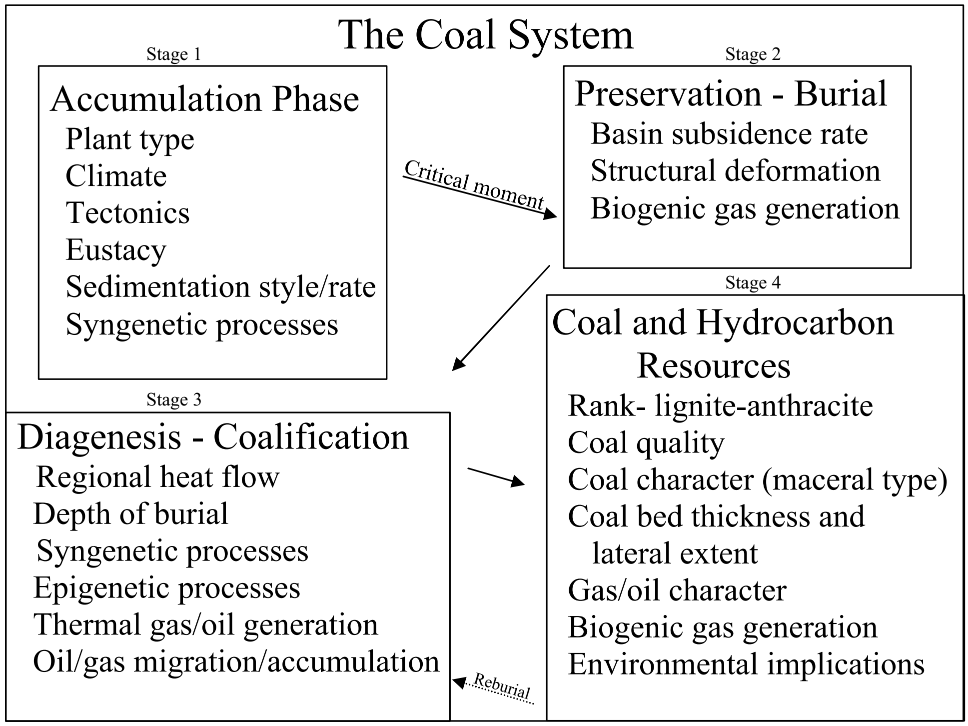

Figure 1. Outline of the components of coal systems analysis.

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.

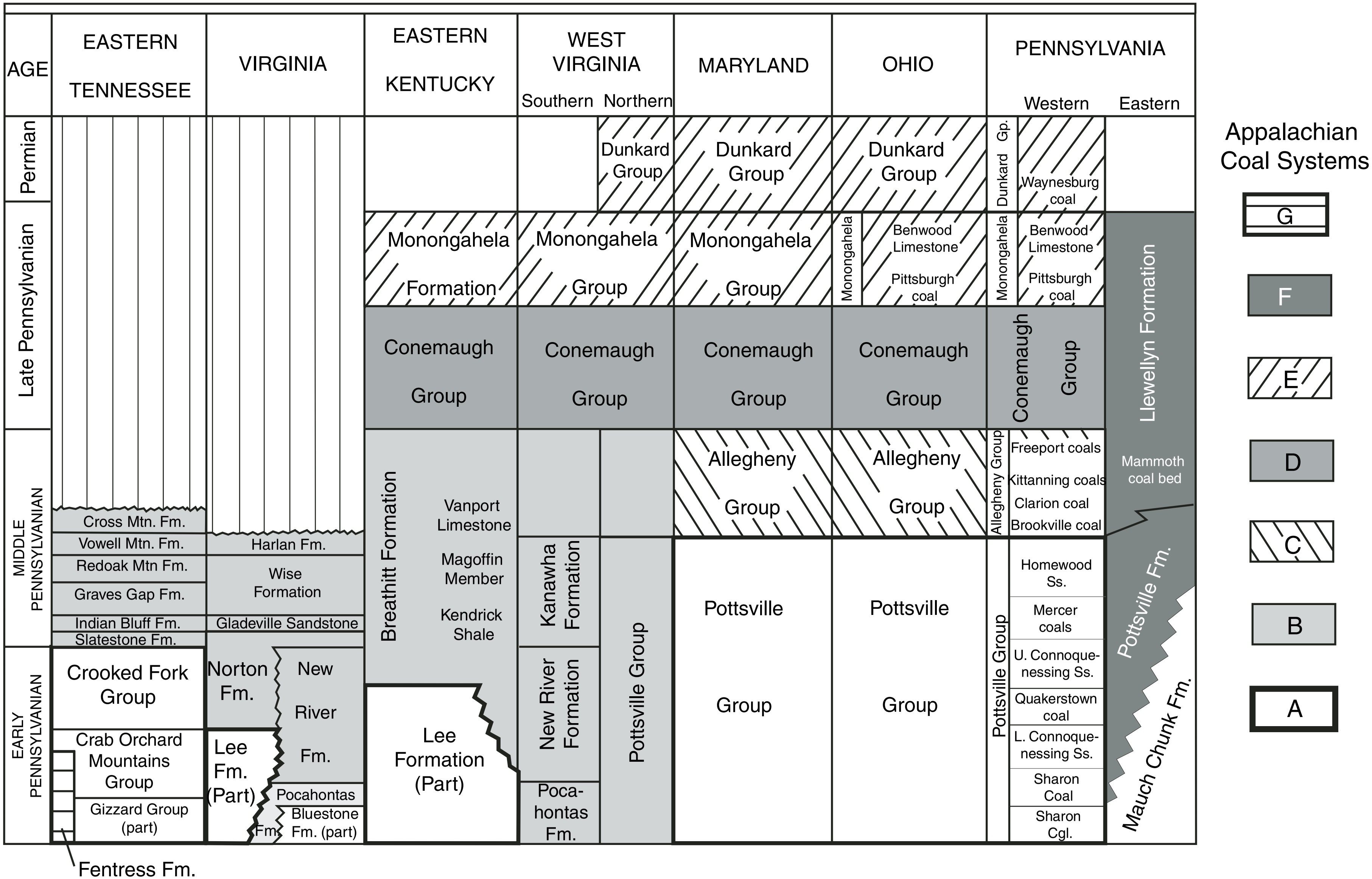

TABLE 2. MAJOR COAL SYSTEMS OF THE CENTRAL AND NORTHERN PARTS OF THE APPALACHIAN BASIN

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).

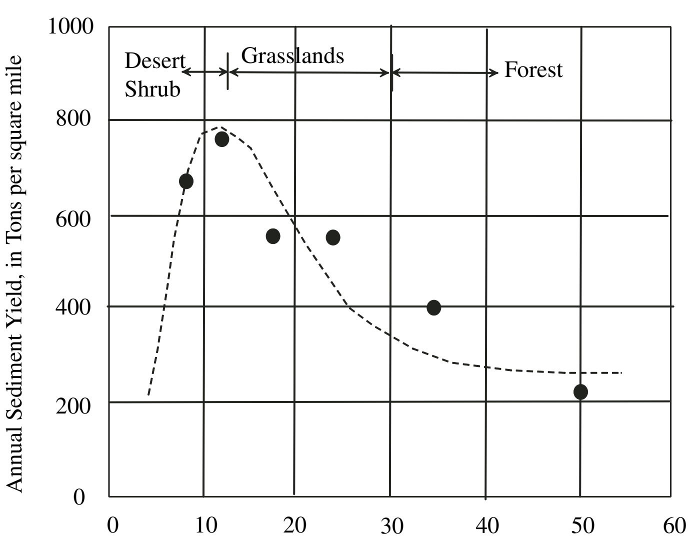

Figure 1. Sediment yield versus effective precipitation (Langbein and Schumm, 1958). Note maximum sediment yield at ~12 in. (30.5 cm) annual precipitation (1 mi^2 = 2.59 km^2; 1 short ton = 0.907 tonnes; 1 in = 2.54 cm).

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).

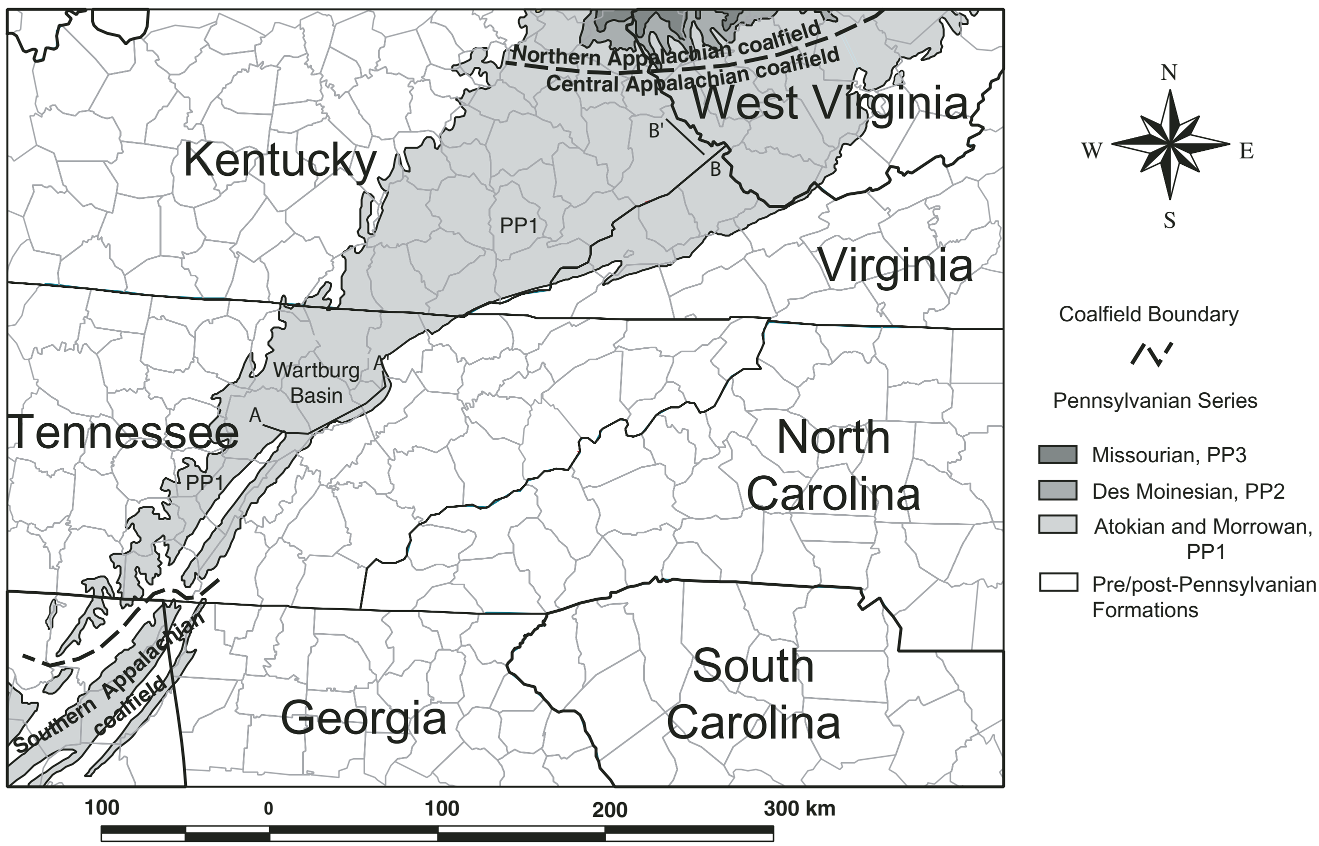

Figure 2. Generalized geologic map of central part of Appalachian Basin (after King and Beikman, 1974).

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

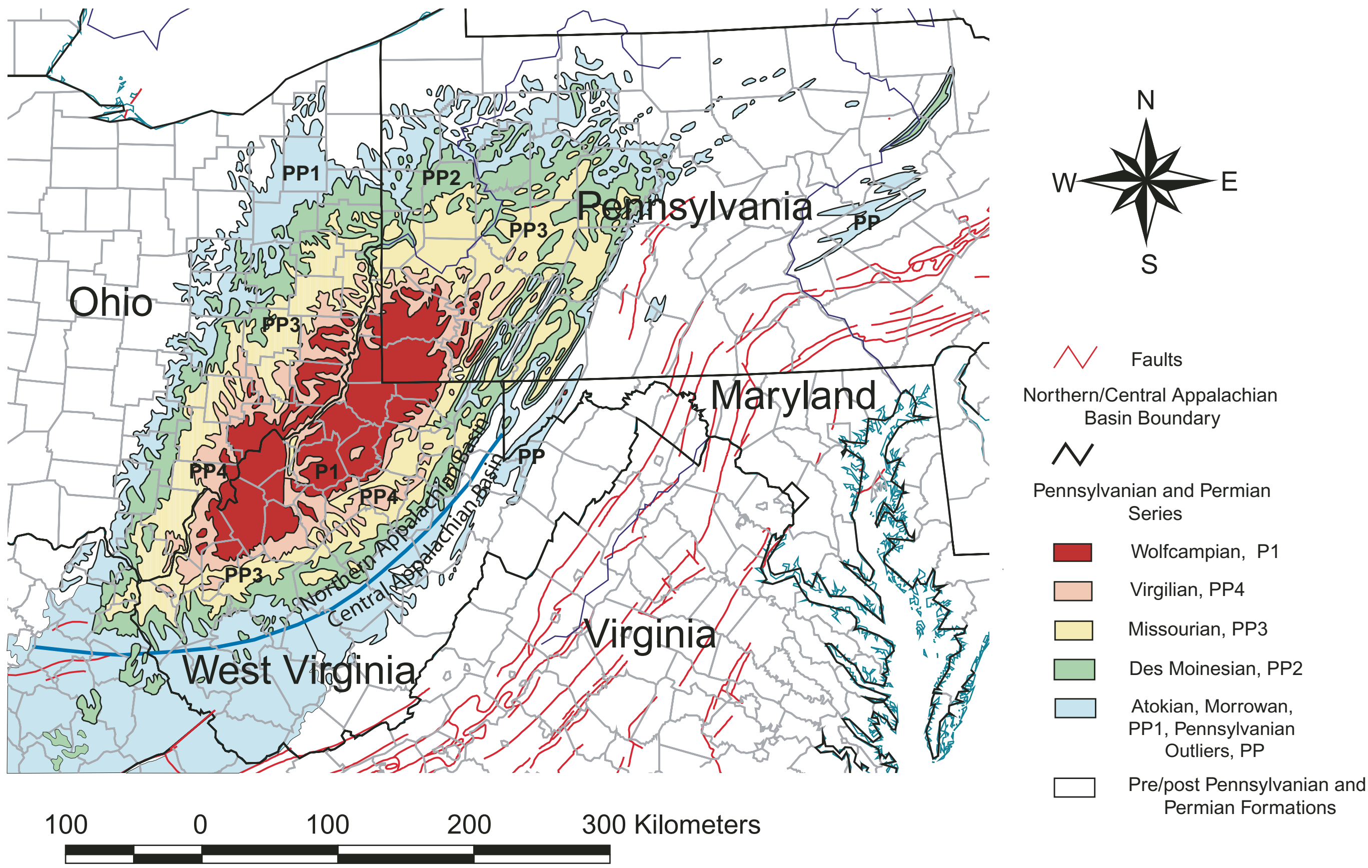

Figure 3. Generalized geology of the northern part of the Appalachian Basin, showing boundary between the northern and central parts of the basin (after King and Beikman, 1974).

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

Appalachian coal measures. (4) Sulfur content of the coal beds ranges widely, which suggests that mixed processes are involved. (5) The rank of the coal beds is bituminous.

Tennessee

The stratigraphic section that comprises Coal System A is ~305 m (1000 ft) thick in the southern Cumberland Plateau of Tennessee and up to 460 m (1500 ft) thick in the northern Tennessee Plateau (Fig. 4). In the southern part of the Plateau, several mineable coal beds of the Sewanee coal zone (including the Sewanee and Richland coal beds and their riders) are located within the Whitwell Shale in the lower part of the Crab Orchard Mountains Group. In general, the sulfur content of these coal beds ranges from less than 1% to almost 6%, and ~60% of available analyses indicate more than 1% sulfur (Fig. 5) (Williams et al., 1955b, 1955c; Hershey et al., 1956a, 1955c, 1955d; Williams and Hershey, 1956). The relatively high sulfur content of the Sewanee and Richland coal beds and their riders apparently reflects the deposition of Gizzard, Crab Orchard Mountain, and Crooked Fork Groups in and near littoral to marginal-marine environments (Milici, 1974; Knox and Miller, 1985; Miller and Knox, 1985). Mineral-rich waters from these strata thus could provide chemical impurities to the paleopeat deposits during burial, compaction, and diagenesis.

Virginia and Southern West Virginia

In Virginia and southern West Virginia, the Lee Formation consists primarily of ~460 m (1500 ft) of quartzose sandstone and quartz-pebble conglomerate formations that are interstratified with coal-bearing shale, siltstone, and lithic sandstone formations. The Lee is in a complex facies relationship with equivalent strata within the Pocahontas, Norton, and New River Formations and the upper part of the Mississippian Bluestone Formation (Table 1) (Englund, 1979; Englund and Thomas, 1990; Nolde, 1994). Englund (1979) interpreted the depositional environments of the Lee and the overlying New River Formation as being "dominated by coastal and near-coastal deltaic processes." Greb and Chestnut (1996), however, have described similar strata in Kentucky as multistory fluvial sand bodies, which are capped, in succession, by estuarine sand facies, coal, and marine or brackish-water carbonaceous shales

The overall sulfur content of coal beds within the Lee Formation in Virginia is generally greater than those in the New River and Norton Formations. This suggests that Lee coals were somewhat more contaminated during diagenesis by marine connate waters than were the coal beds in overlying formations (Fig. 6).

Eastern Kentucky

A similar relation exists between the Lee and Breathitt Formations in eastern Kentucky, where the overall sulfur content of coal beds within the Lee Formation is greater than that of the coal beds in the Breathitt Formation (Fig. 7). The Lee ranges from less than 30 m (100 ft) of quartzose sandstone and quartz pebble conglomerate on the western side of the Appalachian Basin in eastern Kentucky to 460 m (1500 ft) or more of quartzose sandstone and quartz-pebble conglomerate formations that are interstratified with coal-bearing siltstone and shale formations in easternmost Kentucky (Englund and Thomas, 1990, Plate 1) (Fig. 8). Although Chestnut (1992, 1996) recognized the significant lithologic differences between Lee strata and the Breathitt Formation in Kentucky, he chose to abandon the name "Lee" and include all of the Pennsylvanian formations below the Conemaugh within one group, the Breathitt Group. Rather than raise the Lee Formation to group status, Chestnut (1992, 1996) defined several of the members of the Lee Formation of Kentucky as formations and assigned to them the names used for lithologically similar formations in southern Tennessee and southwestern Virginia. Although Chestnut (1992, 1996) simplified the stratigraphic terminology in eastern Kentucky by abandoning the name "Lee," it is clear from the work of others (e.g., Englund and Thomas [1990] in Virginia and Milici [1974] in Tennessee) that some of the quartzose sandstone units in the lower part of the Pennsylvanian section in Virginia and those within the Gizzard Group of southern Tennessee are only mappable locally and cannot be correlated with certainty into Kentucky. In order to highlight the significant lithologic differences between the basal Pennsylvanian quartzose sandstone stratigraphic units and the overlying subgraywacke-dominated units, the name "Lee" is retained herein for eastern Kentucky and adjacent states as used by Englund and Thomas, 1990.

Pennsylvania

The Pottsville Formation ranges between ~6 and 106 m (20–350 ft) thick in western Pennsylvania (Patterson, 1963; Edmunds et al., 1979; Edmunds et al., 1999). There, the formation is divided generally into a lower unit dominated by sandstones and an upper unit that consists of the Mercer coal beds and overlying sandstones (Table 1). The lower unit is generally ~30 m (100 ft) thick and consists of the Sharon Conglomerate at the base, a shaly unit that includes the Sharon coal bed; the Lower Connoquenessing Sandstone, a shaly unit that includes the Quakerstown coal bed; and the Upper Connoquenessing Sandstone. In Pennsylvania, the pre-Mercer part of the Pottsville Formation is entirely nonmarine.

The upper part of the Pottsville Group ranges from ~6 to 25 m (20–80 ft) thick. It contains three coal beds in its shaly lower part (Lower Mercer, Middle Mercer, Upper Mercer), which in places are interbedded with marine limestones (Lower Mercer Limestone, Upper Mercer Limestone) and shale beds that contain marine or brackish-water fossils. Overlying beds commonly consist of one or more sandstone units, including the Homewood Sandstone (Patterson, 1963; Van Lieu and Patterson, 1964; Edmunds et al., 1999). In Ohio and Pennsylvania, sulfur content of 33 samples from the Mercer coals averaged 3.21%, which reflects contamination from associated marine deposits. In contrast, the sulfur content of 16 samples from coal beds in the lower, nonmarine, part of the Pottsville section averaged 1.75% sulfur.

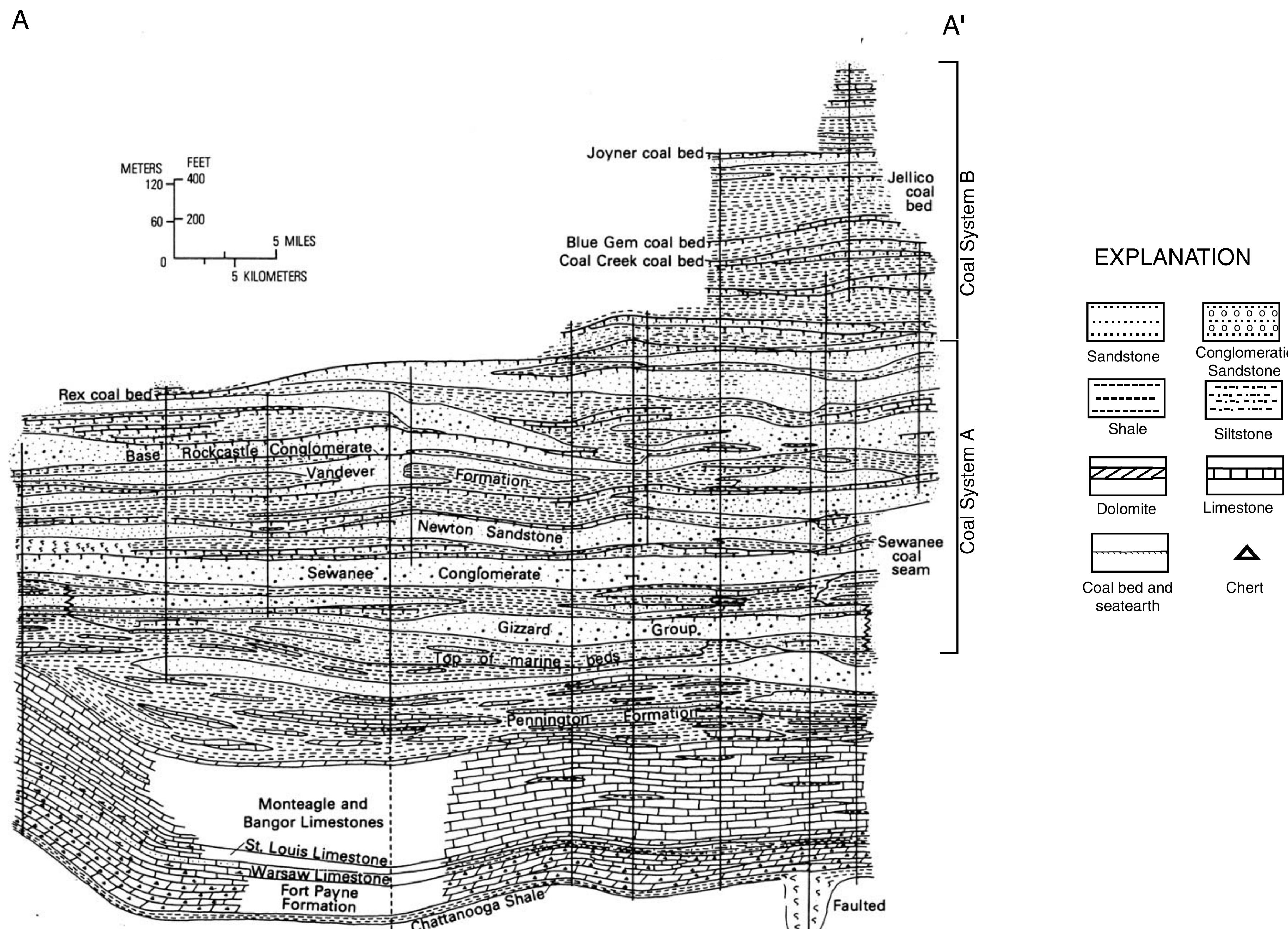

Figure 4. Northeast-southwest cross section, A–A′, through Carboniferous strata in northern Cumberland Plateau of Tennessee. See Figure 2 for location (Milici et al., 1979).

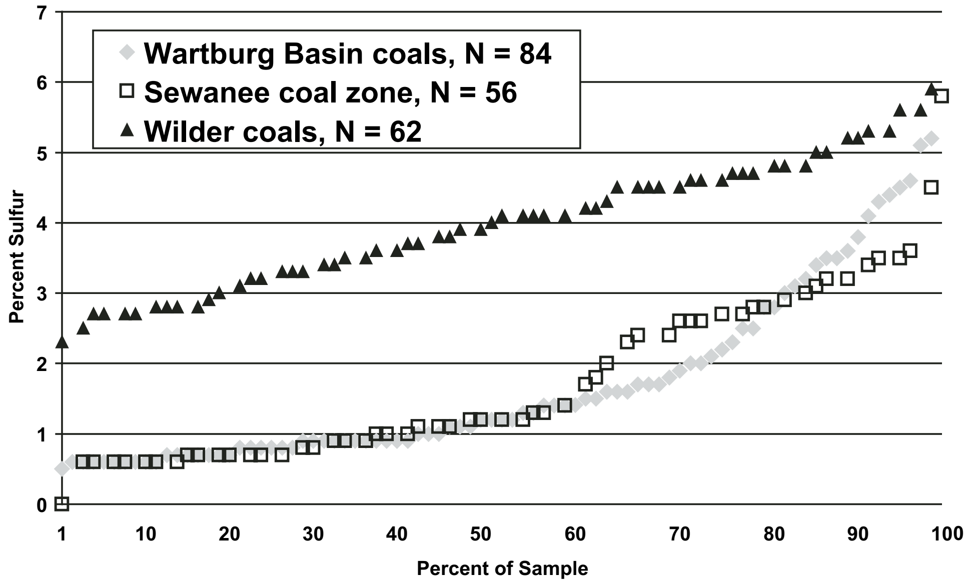

Figure 5. Sulfur content of Tennessee Coals (dry and as received). Data from U.S. Bureau of Mines (Hershey et al., 1956a–1956d; Williams and Hershey, 1956; Williams et al., 1954, 1955a–1956d, 1956a–1956c) (dry), and from Bragg et al. (1998, as received). Wilder coals are in the Fentress Formation; Sewanee coal zone is in the lower part of Crab Orchard Mountains Group; Wartburg Basin includes coals within the Slatestone Formation and above (Table 1). Approximately 40% of the coal in the Sewanee coal zone (southern Cumberland Plateau) and in the Wartburg Basin (northern Cumberland Plateau) contains 1% sulfur or less.

Ohio

The Pottsville is ~75 m (250 ft) thick in Ohio. The relatively high sulfur content of Pottsville coal beds there (Fig. 9) appears, to a large degree, to be related to the incursion of 11 marine limestone and shale units into the region (Collins, 1979). Although Pottsville of Ohio generally consists of stratigraphic units similar to those in nearby Pennsylvania, marine limestones and ironstones (“ores”) are much more common throughout the Ohio section and persist downward into the basal Sharon Conglomerate (Collins, 1979; Slucher and Rice, 1994).

Discussion

Appalachian Coal System A is interpreted to have accumulated under climatic conditions that were generally everwet tropical in the Central Appalachian coal field and perhaps more seasonal in the northern part of the Appalachian basin (Cecil et al., 1985). Sulfur content of coal beds in Lee-equivalent strata in Tennessee and Virginia is relatively low when compared with the coal beds in the Lee of eastern Kentucky, Pennsylvania, and Ohio. These differences apparently reflect the greater influence of marine environments on coalbed composition to the north and west, and perhaps regional differences in the paleoclimate under which the original peat deposits had accumulated (Table 3). Connate fluids from marine beds apparently provided relatively large amounts of sulfur to the coal beds throughout the Pottsville section in Ohio and only to the Mercer coal beds in the upper part of the Pottsville Group in Pennsylvania.

Appalachian Coal System B

This coal system includes the Pocahontas, New River, and the Kanawha Formations in Virginia and West Virginia, the Norton and Wise Formations in Virginia, and the Breathitt Formation in Kentucky and its approximate lateral equivalents in the Wartburg Basin of Tennessee (Milici et al., 1979; Rice, 1986; Englund and Thomas, 1990; Blake et al., 1994). (1) Appalachian Coal System B is confined to the central Appalachian coal field and contains domed to mixed domed and planar, generally low- to medium-sulfur coal beds (Cecil et al.,

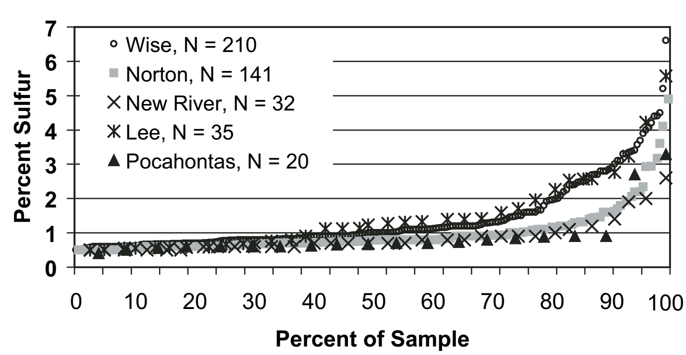

Figure 6. Sulfur content of Virginia coals, by formation (as received) (Bragg et al., 1998). N = number of samples. About 75% of the coal beds in the Pocahontas, Norton, and New River Formations contain 1% sulfur or less.

1985; Eble and Grady, 1993; Grady et al., 1993). (2) The coal system includes a number of named formations in several states. In some places it is dominated lithologically by subgraywacke sandstone, siltstone, and shale; in other places it contains large amounts of quartzose sandstones and quartz pebble conglomerate. (3) Coal beds are relatively abundant, and the system provides much of the resource base for low-sulfur coal in the central Appalachian coal field. (4) Sulfur content is generally low except where marine beds occur within the section. (5) Coal rank ranges from bituminous to semianthracite in the Pocahontas No. 3 coal bed in southern West Virginia (Milici et al., 2001).

Tennessee

The stratigraphic terminology used herein for Tennessee is modified slightly from that of Wilson et al. (1956). Above the quartzose sandstone-dominated part of the Pennsylvanian section, Breathitt equivalents in the Wartburg Basin of Tennessee consist of the upper part of the Crooked Fork Group and the Slatestone, Indian Bluff, Graves Gap, Redoak Mountain, Vowell Mountain, and Cross Mountain Formations (Table 1, Fig. 4) (groups of Wilson et al., 1956) (Milici et al., 1979; Patchen et al., 1985a, 1985b).

In general, coal beds in these formations collectively exhibit the same range of sulfur content as do the coal beds in the Sewanee coal zone in southern Tennessee; ~40% of available samples test greater than 1% sulfur (Fig. 5) (Tables 3 and 4) (Williams et al., 1955a, 1956a; Hershey et al., 1956b). Marine zones are documented as occurring above the Big Mary coal bed in the lower part of the Redoak Mountain Group (Hershey et al., 1956b; Williams et al., 1956a; Glenn, 1925), within the lower part of the Indian Bluff Group, and at or near the base of the Vowell Mountain Formation (Glenn, 1925). Accordingly, the relatively high sulfur content of some of the coal deposits in the Wartburg Basin appears to be related to contamination by fluids from associated marine strata.

Eastern Kentucky

The Breathitt Formation ranges from ~245 m (800 ft) thick in northeastern Kentucky, where its entire thickness is preserved, to ~915 m (3000 ft) thick in southeastern Kentucky, where its upper beds have been removed by erosion. The Breathitt consists largely of interbedded impure sandstones (subgraywackes), siltstones, shale, and ironstones (Fig. 8). Coal is common throughout the formation. The formation contains several conspicuous marine zones, the Betsie Shale Member, the Kendrick Shale Member (Kendrick Shale of Jillson, 1919), Magoffin Member, Stony Fork Member (Chestnut, 1991, 1992), and the Lost Creek Limestone of Morse (1931) (Rice et al., 1979, 1994; Rice, 1986). In addition, numerous marine fossils occur in thin, more or less continuous to discontinuous beds or zones scattered throughout the formation. The limited extent and scattered distribution of these fossils suggest that they accumulated in the headwaters of tidal estuaries, rather than in large, open bays such as that which gave rise to the Magoffin (Rice et al., 1979). Approximately half of the analyses

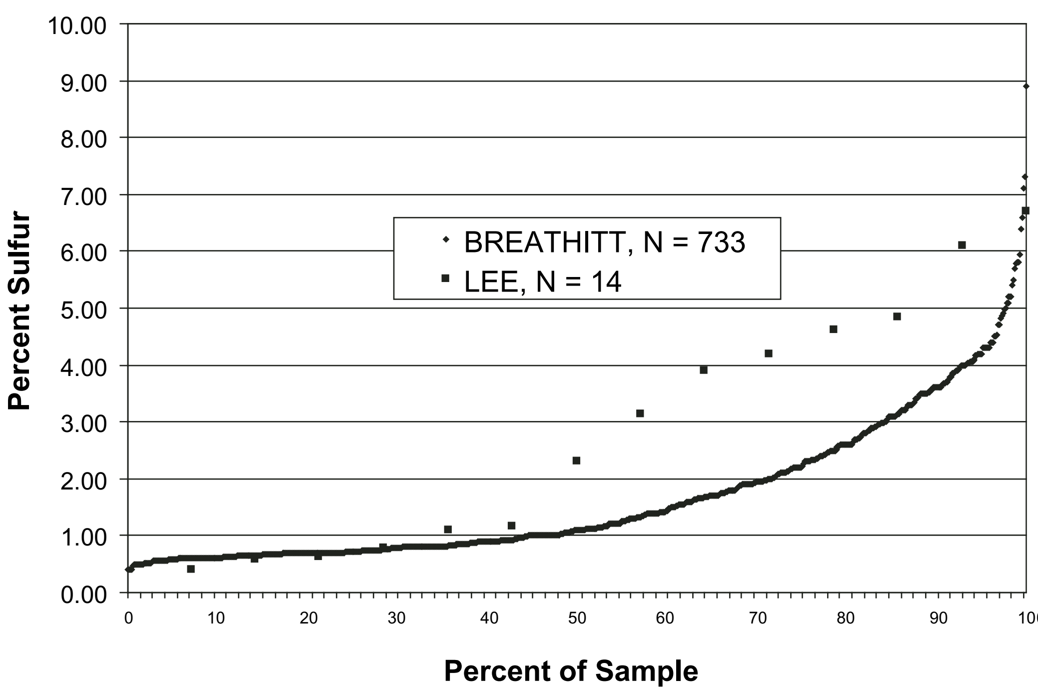

Figure 7. Sulfur content of eastern Kentucky coals (as received) (Bragg et al., 1998). N = number of samples. About 45% of the coal beds in the Breathitt Formation contain 1% sulfur or less.

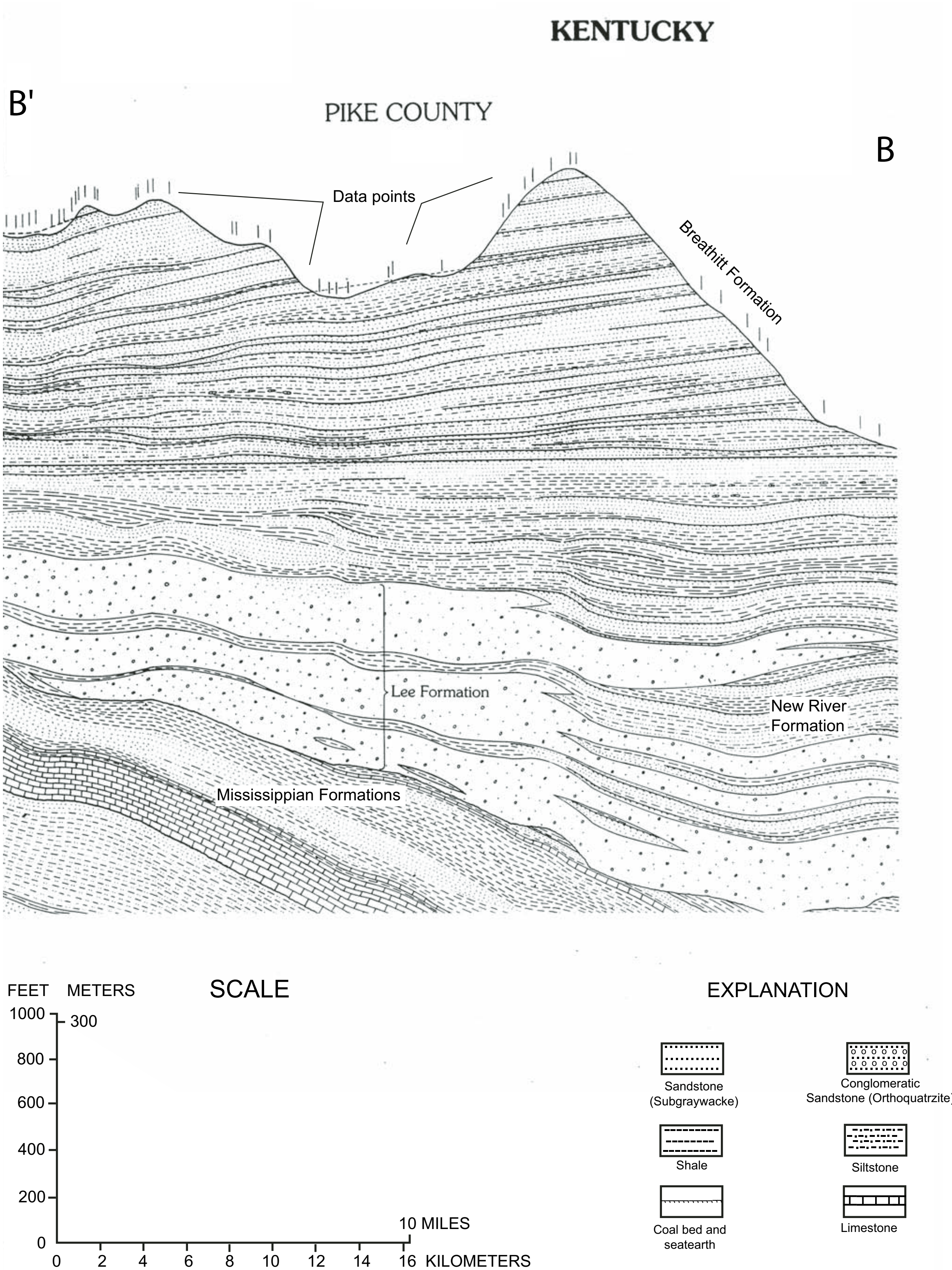

Figure 8. Northwest-southeast cross section, B–B′, through Pennsylvanian strata of Pike County, Kentucky. See Figure 2 for location (after Englund and Thomas, 1990).

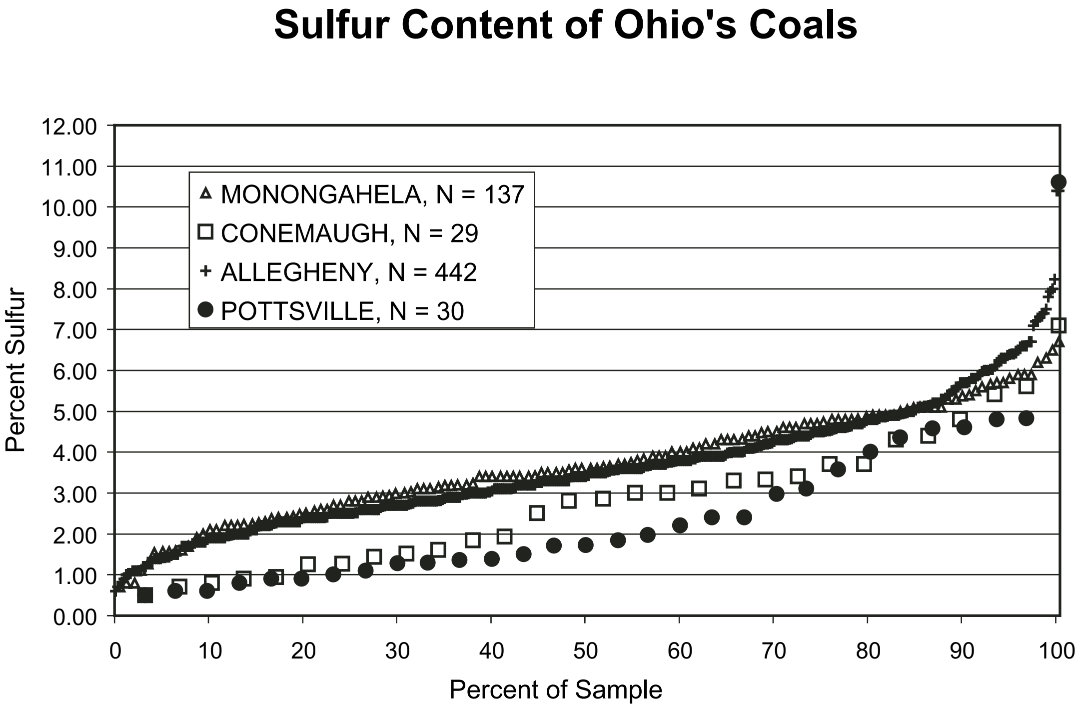

Figure 9. Sulfur content of Ohio coals (as received) (Bragg et al., 1998). N = number of samples. Less than 20% of the coal beds in the Pottsville and Conemaugh Formations contain 1% sulfur or less. The relatively high sulfur content of coal in Ohio is the result of both climatic effects and relative proximity of peat-forming environments in the lower part of the delta to marine depositional environments.

of Breathitt coal contain more than 1% sulfur, and the average sulfur content of 733 samples is ~1.66%. In places, the relatively high sulfur content of the coal beds apparently resulted from contamination by connate waters from associated marine zones (Fig. 7).

Virginia and Southern West Virginia

The Pocahontas Formation, which is the lowest Pennsylvanian stratigraphic unit in the central Appalachian Basin, extends from the eastern part of the Virginia coal field into adjacent West Virginia. In some places the Pocahontas is laterally equivalent to the Lee; in other places the Lee overlies it, and elsewhere it is overlain by the New River Formation (Englund, 1979). The formation contains the highest quality low-sulfur coking coal in the central part of the Appalachian Basin.

In Virginia and West Virginia, the Pocahontas, New River, and Kanawha Formations (and their equivalents in Virginia, the Norton and Wise Formations) (Table 1) are generally similar lithologically, and their coal beds contain relatively low amounts of sulfur and ash (Fig. 6, Table 4) (Cecil et al., 1985). The Pocahontas Formation is a sandstone-dominated sequence that consists of up to 300 m (980 ft) of sandstone, siltstone, shale, and low-sulfur coal along its outcrop in Virginia. The formation thins to the northwest, to where it is as much as 760 m (2500 ft) deep and is truncated by a regional unconformity (Englund, 1979; Englund et al., 1986; Englund and Thomas, 1990; Milici et al., 2001).

Englund et al. (1986) showed that the formation was deposited in a series of northwest-trending delta lobes that extend from the eastern margin of the Appalachian coal basin in southwestern Virginia and adjacent West Virginia, northwestward deeply into the subsurface. The Pocahontas coal beds accumulated on these lobes in several thick domal bodies (up to 4 m thick), which in places have been mined extensively. Shale-dominated interlobe areas contain relatively thin, discontinuous coal beds. Although the sulfur content of these coal beds increases to the northwest, toward marine depositional environments, the amount of sulfur in the Pocahontas coals is generally less than 1%, which is consistent with the interpretation that the paleomarshes in which they formed were nourished in an everwet tropical climate by rainfall low in dissolved chemicals, rather than by chemical-rich surface and/or ground waters (Cecil et al., 1985; Englund et al., 1986).

The overlying New River Formation is up to 535 m (1750 ft) thick in southwestern Virginia and southern West Virginia, and in places it contains up to 16 named coal beds. In Virginia, the New River is lithologically similar to the Pocahontas Formation except for several widespread, thick beds of quartzose sandstone and quartz pebble conglomerate (tongues of the Lee Formation) in the western part of the coal field (Englund and Thomas,

TABLE 3. AVERAGE SULFUR CONTENT (AS RECEIVED) OF LEE/POTTSVILLE COAL BEDS IN APPALACHIAN COAL SYSTEM A

Area	Coal bed	Samples	Average %S	Marine influence
Tennessee		19	1.67	Yes
Virginia		35	1.50	Yes
E. Kentucky		14	2.89	Yes
Pennsylvania, Ohio	Mercer (upper)	33	3.21	Yes
	pre-Mercer	16	1.75	Less

Note: Data from Bragg et al. (1998), U.S. Bureau of Mines.

TABLE 4. AVERAGE SULFUR CONTENT (AS RECEIVED) OF COAL BEDS IN APPALACHIAN COAL SYSTEM B

Area	Formation	Samples	Average %S	Marine influence
Tennessee		39	1.60	Yes
Kentucky	Breathitt	733	1.66	Yes
Virginia	Wise	210	1.37	Yes
Virginia	Norton	141	0.99	No
West Virginia	Kanawha	261	1.06	Yes
Virginia/West Virginia	New River	150	0.81	No
Virginia/West Virginia	Pocahontas	85	0.82	No

Note: Data from Bragg et al. (1998), U.S. Bureau of Mines.

1990; Nolde, 1994). Nolde (1994) regarded the New River as transitional between the quartzose sandstones and conglomerates of the Lee Formation to the south and west and the subgraywacke sandstones of younger Pennsylvanian formations. Marine fossils have been reported from near the base of the New River in Virginia (Arkle et al., 1979; Englund, 1979; Nolde, 1994).

In Virginia, the Norton Formation consists of up to 600 m (1970 ft) of shale, siltstone, and lesser amounts of sandstone. At least four beds within the Norton contain fresh- or brackish-water fossil invertebrate fauna. The fossiliferous beds generally consist of 2–3 m (5–10 ft) of dark gray shales that in places contain thin beds, lenses, or nodules of limestone (Nolde, 1994).

The Wise Formation, up to 600 m (2268 ft) thick, is composed of fine- to coarse-grained siliciclastic strata, predominantly siltstone and sandstone. The shale beds that occur above several of the coal beds may contain invertebrate fossils. The Wise contains two widespread marine zones, the Kendrick Shale of Jillson (1919) and the Magoffin Member of the Wise Formation (Miller, 1969) (originally the Magoffin Beds of Morse, 1931). In Virginia, the Kendrick Shale ranges 3–6 m (10–20 ft) thick, is dark gray to black, and contains calcareous lenses with cone-in-cone structures and brackish-water to marine fossils. The Magoffin Member consists of 6–9 m (20–30 ft) of fossiliferous gray shale, thin beds of limestone, and calcareous siltstone (Nolde, 1994). The Wise is overlain by the Harlan Formation, which is the uppermost Pennsylvanian formation in the state. The Harlan is thickest on the mountaintops near Kentucky, where it consists of ~200 m (655 ft) of sandstone with minor amounts of siltstone and shale and several beds of coal (Englund, 1979).

The Kanawha Formation, the West Virginia equivalent of the Norton and Wise Formations, consists of up to 640 m (2100 ft) of subgraywacke sandstone, shale, and mudstone. It contains numerous marine limestones and shale beds. In some places, marine zones consist of shales and siltstones that contain marine and brackish- to freshwater invertebrates; in other places, they consist of 30-m-thick (100 ft) coarsening-upward units of fossiliferous shale, siltstone, and sandstone that are widespread across the basin (Blake et al., 1994). Offshore facies are characterized by dark gray laminated shales that contain "calcareous brachiopods, cephalopods, bivalves, gastropods, and echinoderms" (Blake et al., 1994). Nearshore and littoral deposits are interlaminated to interbedded shales, siltstones, and sandstones that exhibit the flasered bedding of tidal sedimentary environments. These beds may contain inarticulate brachiopods and a variety of shallow water trace fossils (Martino, 1994).

Discussion

The relatively high sulfur content of some of the coal beds in the Breathitt, Wise, and Kanawha, as well as the sulfur content of the coal beds in the Wartburg Basin of Tennessee (Figs. 6, 7, 10; Table 4), clearly reflects the postdepositional influence of marine environments that occur within these formations. Where marine beds are few or absent in the stratigraphic section, such as in the Pocahontas, New River, and Norton, sulfur content averages less than 1% (Fig. 6, Table 4). Nevertheless, when compared with the northern part of the Appalachian Basin, coal beds from the central Appalachian region have a relatively low sulfur content overall. Accordingly, these Central Appalachian Basin formations may collectively be considered a part of one thick, widespread, generally low-sulfur coal system, Appalachian Coal System B, which extends from the Wartburg Basin in Tennessee through eastern Kentucky and southwestern Virginia to southern West Virginia. Low-sulfur coal beds of Coal System B apparently accumulated under tropical everwet conditions (Cecil et al., 1985), and those coal beds with somewhat greater amounts of sulfur reflect a relatively greater influence of marine paleoenvironments locally within the stratigraphic section. Indeed, there may be some relationship between the domed topology of the low-sulfur coal beds in the Pocahontas Basin of southwestern Virginia and the planar-to-domed topology of Breathitt coals in eastern Kentucky, where there are more marine zones in the stratigraphic section (Eble and Grady, 1993; Grady et al., 1993).

Appalachian Coal System C

Appalachian Coal System C consists of the Allegheny Group (Formation) of Ohio, Pennsylvania, western Maryland, and northern West Virginia. The system is characterized by numerous relatively thick, mineable coal beds, almost all of which have a moderate to relatively high sulfur content. (1) Coal System C was deposited within the northern Appalachian coal field, in the area dominated by Type B coal beds, which were deposited under seasonal tropical climates (Cecil et al., 1985). (2) The system is coincident with the Allegheny Group in this region. (3) The Allegheny Group contains several widespread, thick, mineable coal beds and is a major coal-producing interval in the northern Appalachian coal field. (4) Some of the coal beds have a relatively high sulfur content, which is apparently related to the occurrence of marine beds in the stratigraphic section. (5) The coal is bituminous in rank.

Pennsylvania

In Pennsylvania, the Allegheny Formation, which ranges from ~80 to 100 m (270–330 ft) thick, includes all of the economically producible coal beds in the upper Middle Pennsylvanian part of the Carboniferous sequence (Edmunds et al., 1999). The Allegheny Formation contains the Brookville, Clarion, and Kittanning coal beds in its lower part and the Freeport coal beds in its upper part. There are several persistent marine beds within the Kittanning sequence. All of the Allegheny marine beds are below the Upper Kittanning coal bed and underclay, and the Allegheny beds above the Upper Kittanning are generally nonmarine. The most distinctive marine zone in the Allegheny of western Pennsylvania is the Vanport Limestone Member. This unit is ~3 m (10 ft) thick, and it separates the thin coals in the lower part of the Allegheny from the middle and upper parts of the section that contain the Kittanning and Freeport coals (Patterson, 1963). Some of the coal beds or zones and the marine shales and limestones of the Allegheny in the northern part of the Appalachian basin appear to persist over thousands of square miles (Edmunds et al., 1999).

Discussion

Average sulfur content of 1093 samples from Allegheny coal beds (including the 5 Block coal in the Kanawha Formation) is 2.84% (Figs. 9 and 11). About two-thirds of the samples in the northern part of the Appalachian Basin are in the lower part of the formation (Brookville, Clarion, Kittanning), where marine beds are common, and they average ~3.05% sulfur. Analyses of Freeport coal beds from the nonmarine, upper part

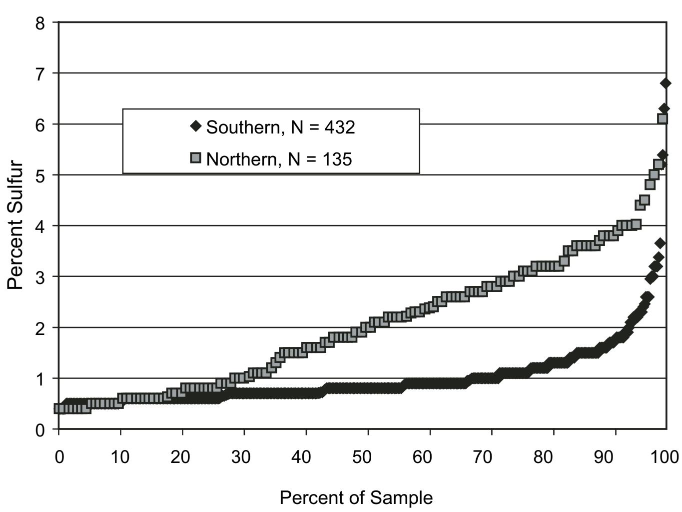

Figure 10. Sulfur content of West Virginia coals (as received) (Bragg et al., 1998). N = number of samples. This plot illustrates the regional differences in sulfur content that are related to the overall effects of climate on paleopeat environments, from everwet tropical in the central part of the Appalachian Basin to more seasonal, wet and dry in the northern part of the basin. Coal beds in southern West Virginia include those in the Pocahontas, New River, Kanawha Formations, and Allegheny Group; those coal beds in northern West Virginia are within the Allegheny, Monongahela, and Dunkard Groups.

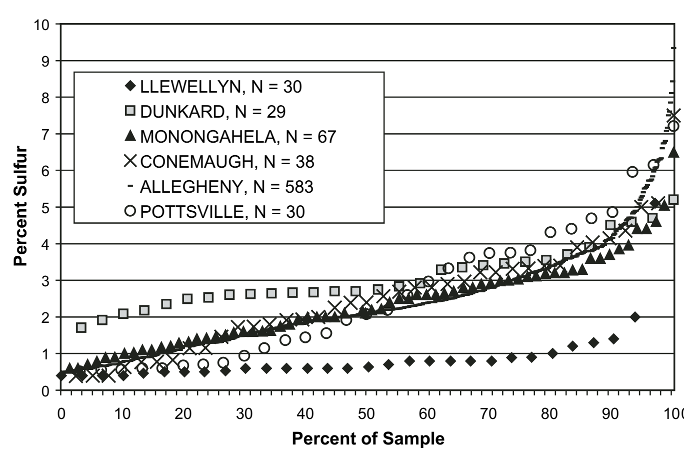

Figure 11. Sulfur content of Pennsylvania coals (as received) (Bragg et al., 1998). N = number of samples. Except for the coal beds in the Llewellyn Formation, only ~10–15% of Pennsylvania's coals contain 1% sulfur or less, thus reflecting both the effects of deposition under alternating wet and dry seasons and the proximity of marine environments. Llewellyn coal beds were deposited far to the east, away from marine environments, and probably in regions that had more rainfall.

TABLE 5. AVERAGE SULFUR CONTENT (AS RECEIVED) OF COAL BEDS IN APPALACHIAN COAL SYSTEMS C, D, E, F, AND G

Coal System	Group or formation	Number of samples	Average %S	Marine influence
C	Allegheny, upper part	370	2.56	No
C	Allegheny, lower part	658	3.05	Yes
D	Conemaugh	81	2.54	Yes
	Pennsylvania	38	2.55	Yes
	Ohio	29	2.79	Yes
E	Monongahela	276	3.10	Yes
	Pennsylvania	67	2.37	No
	Ohio	137	3.79	Yes
E	Dunkard	39	2.81	No
F	Llewwllyn	36	0.86	No
G	Fentress	62	4.00	Yes

Note: Data from Bragg et al. (1998), U.S. Bureau of Mines.

of the Allegheny Formation average ~2.56% sulfur, which may be considered as background for this area (Table 5). The generally medium to high sulfur content of Allegheny coal beds and their relatively planar topology, when combined with the paleogeographic location of the northern Appalachian coal field, indicate that peat deposits in Coal System C accumulated within planar, topogenous swamps under the seasonal, wet-dry tropical climates (Cecil et al., 1985). The greater sulfur content of the coal beds in the lower part of the Alleghany section appears to have been enhanced by contributions from the marine zones nearby within the stratigraphic section.

Appalachian Coal System D

The Conemaugh Formation or Group extends from northeastern Kentucky through Ohio, West Virginia, and Maryland into Pennsylvania. The base of the Conemaugh is placed at the top of the Upper Freeport coal bed, and its top is at the base of the Pittsburgh coal bed. (1) In general, the Conemaugh Group contains Type B, relatively high-sulfur coal beds that were derived from peat that accumulated in planar, topogenous swamps under a seasonal tropical climate (Cecil et al., 1985). (2) Coal System D, the Conemaugh Formation or Group ("Lower Barren"; Edmunds et al., 1979), is generally characterized by red-bed sequences of mudstone, shale, siltstone, sandstone, and some fossiliferous marine limestones and shales. (3) The system contains relatively few, erratically occurring, thin, medium- to high-sulfur coal beds. (4) The lower and middle parts of the Conemaugh contain marine zones that may have been the sources of additional sulfur in some coal beds. (5) The coal is of bituminous rank.

Eastern Kentucky

In Kentucky, where the Pittsburgh horizon is not easily identified, the Conemaugh and overlying Monongahela are commonly mapped together. Their combined thickness is ~575 ft. There, the Conemaugh and Monongahela consist chiefly of red, green, and gray shales, siltstones, and sandstones, with some marine siliciclastic and limestone strata (Rice et al., 1979; Chestnut, 1992). The Conemaugh Group contains little coal. The overlying Monongahela contains fewer red beds and more coal than does the Conemaugh.

Ohio, West Virginia, and Pennsylvania

In Ohio, West Virginia, and Pennsylvania, the Conemaugh consists generally of gray shales; red and green mudstones and siltstones; and marine shales, siltstones, and limestones. The name "Lower Barren" was originally used for the group because of its general lack of widespread, high-quality coal (Table 5). Nevertheless, several coal beds have been mined, both by surface and underground methods, in northeastern West Virginia and in the panhandle of Maryland (Lyons et al., 1985), where their sulfur content ranges from medium to low (Arkle et al., 1979). The Group averages ~120 m (400 ft) thick in Ohio, and ranges from ~165 to 275 m (550–900 ft) thick in Pennsylvania. In West Virginia, it is ~260 m (850 ft) thick along the Maryland border and thins to ~150 m (500 ft) thick in central West Virginia.

In Ohio, the Conemaugh consists generally of thick sandstones, mudstones, and shales that are intercalated with thin coal beds, marine- and freshwater limestones, clays, and marine shales. Marine beds occur generally in the lower and middle parts of the group, and the upper beds were generally deposited in continental environments. In contrast with underlying Pennsylvanian formations, red beds are common throughout the Conemaugh of Ohio (Collins, 1979).

In West Virginia, the Conemaugh consists of red and gray mudstones and shales that are interbedded with subgraywacke sandstone and thin beds of limestone. As in Ohio, the limestones are commonly of marine origin in the lower part of the group. Although the coals tend to be thin and irregular, several beds have been mined in places, and their sulfur content ranges from low in a few places, to high (Arkle et al., 1979).

In Pennsylvania, the Conemaugh Group is dominantly a siliciclastic sequence that contains discontinuous red beds and nonmarine limestones within much of the section. Several widespread marine zones occur in the Glenshaw Formation (Flint, 1965), interspersed with other strata in the lower part of the

Group (Edmunds et al., 1999). These include, from bottom to top, the Brush Creek, Pine Creek, Nadine, Woods Run, Noble, and Ames marine zones. The top of the Ames is the boundary between the Glenshaw and overlying Casselman Formation. The Casselman Formation (Flint, 1965) is almost entirely nonmarine and contains only the locally distributed Skelly marine zone near its base. Edmunds et al. (1999) noted an abundance of mottled red and green beds throughout the Conemaugh, many of which were identified as caliche paleosols that formed in alternating, wet-dry semiarid climates. Although Conemaugh coal beds in the western part of the basin are few in number, generally less than 28 in. thick, and are discontinuous, they are thick enough to mine in a few places (Patterson, 1963; Patterson and Van Lieu, 1971). To the east, however, some of the Conemaugh coal beds are thicker and more readily mined (Edmunds et al., 1999).

Discussion

In general, the "barren" nature of the Conemaugh has been attributed to deposition under drier climatic conditions than the underlying Allegheny and overlying Monongahela Groups (White, 1913; Cecil et al., 1985). The average sulfur content of 81 samples from Conemaugh coal beds lies within the middle of the medium sulfur range (Bragg et al., 1998) (Table 5). More than 80% of the coal samples from the Conemaugh coal beds in Ohio and Pennsylvania contain over 1% sulfur, and ~45% of these samples are high in sulfur content (>2% S) (Figs. 9, 11, 12). The relatively high sulfur content of Conemaugh coals, as well as the stratigraphy and depositional features of the group suggest that it was deposited under seasonal, wet-dry climatic conditions (Cecil et al., 1985), with local occurrence of brackish and marine strata near some coal beds. The similarity of the sulfur content of Conemaugh coal beds in Pennsylvania and Ohio (Fig. 12) suggests that climatic and depositional conditions were relatively uniform across the area.

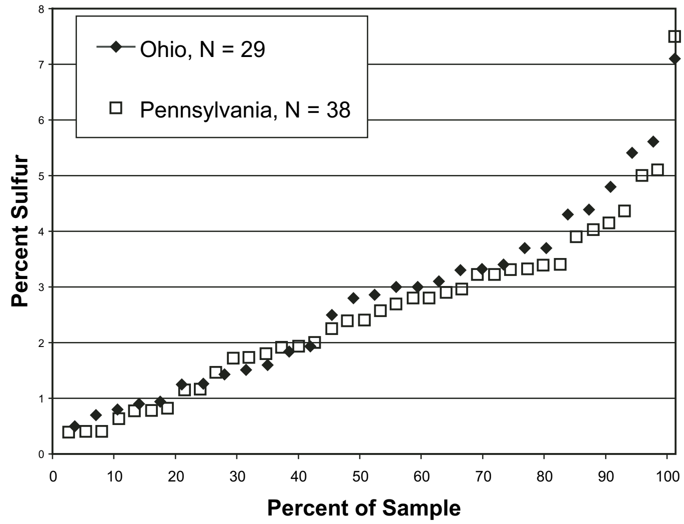

Figure 12. Sulfur content of coal beds in the Conemaugh Group of Pennsylvania and Ohio (as received) (Bragg et al., 1998). N = number of samples. The "Upper Barren" is characterized by locally distributed coal beds, red and green siliciclastic strata, and marine to nonmarine limestones. The close relationship of the sulfur content of the coal beds suggests that climatic and depositional conditions were relatively uniform across the area. More than 80% of the coal samples contain more than 1% sulfur, a result of the seasonal, wet-dry climatic conditions and the local influence of brackish and marine waters on peat-forming environments.

Appalachian Coal System E, Monongahela Group

Coal System E contains the formations and coal beds of the Monongahela and Dunkard Groups. In general, the Monongahela Group extends stratigraphically from the base of the Pittsburgh coal bed to the base of the Waynesburg coal bed. It ranges from ~75 to 120 m (250–400 ft) thick in West Virginia, is ~75 m (250 ft) thick in Ohio, and generally ranges from 85 to 115 m (275–375 ft) thick in Pennsylvania. Although the base of the Dunkard Group is commonly placed at the base of the Waynesburg coal bed (Edmunds et al., 1999), in the places where the coal bed is absent, the contact of the Monongahela with the overlying Dunkard Group is gradational, both lithologically and paleontologically. Nevertheless, there is a general increase in the proportion of Permian flora upward, and most of the Dunkard is considered to be of Permian age. The Dunkard is ~190 m (625 ft) thick in Ohio and is up to ~335 m (1100 ft) thick in West Virginia and southwestern Pennsylvania. (1) Coal System E contains Type B, relatively high-sulfur coal beds that were deposited under a seasonal tropical climate. (2) Coal System E generally consists of sandstone, gray shales and siltstones, and mudstone. (3) The Monongahela Group ("Upper Productive") contains several important medium- to high-sulfur coal beds. (4) Marine zones in the Ohio part of the section may be responsible for greater amounts of sulfur in the coal beds there. (5) The coal is of bituminous rank.

Ohio, West Virginia, Pennsylvania

In northern Ohio, Pennsylvania, and northern West Virginia, the Monongahela Group ("Upper Productive") consists generally of gray shales and mudstone, subgraywacke sandstone, and lacustrine limestone, together with thick coal beds, such as the Pittsburgh, Meigs Creek (Sewickley), and Pomeroy (Redstone). In southern Ohio and adjacent West Virginia, the Monongahela consists of variegated red and yellow shale and mudstone, with much less coal, and there is a transitional facies between these northern and southern areas where the gray and red beds mix and the coal beds are thin and impure (Arkle et al., 1979; Collins, 1979; Edmunds et al., 1999). Edmunds et al. (1999) concluded that the Monongahela Group was deposited in a low-energy alluvial plain environment that had extensive lake and swamp development, which suggests that during that time, water tables would have been relatively high during a sea-level highstand. Glascock and Gierlowski-Kordesch (2002) provided additional evidence of marine incursions into Monongahela environments in their detailed study of the Benwood Limestone in Ohio. They concluded that the Benwood was deposited in a fresh- to brackish-water lake system that was intermittently affected by marine storm surges.

Discussion

Although the overall climatic regime under which the Conemaugh and Monongahela Groups were deposited appears to be much the same, a generally higher water table during the deposition of Monongahela coal beds apparently enhanced the development of several extensive peat mires. Nevertheless, the overall sulfur content of the coal beds in these groups is generally higher than that in the coal beds in the central Appalachian Basin. Unlike the Conemaugh, however, the Monongahela coal beds in Ohio have significantly more sulfur than do their equivalents in Pennsylvania (Fig. 13), which reflects the greater abundance of marine and brackish-water strata within the coal-bearing section to the west. The average sulfur content of 276 samples from Monongahela coal beds is 3.10% (Table 5). About 70% of the Monongahela coal samples from Ohio and 27% of the samples from Pennsylvania tested in the high sulfur range (Figs. 9, 11, 13).

Appalachian Coal System E, Dunkard Group

Ohio and Pennsylvania

With more detailed information about its stratigraphy, depositional environments, and coal chemistry, the Dunkard Group ("Upper Barren") would probably have been justifiably classified as a separate coal system, generally similar to the Conemaugh ("Lower Barren"), rather than included with the Monongahela. The boundary between the Monongahela and the Dunkard is transitional, however, and for the purposes of this paper it is included with the Monongahela as one coal system. The Dunkard Group consists of interbedded mudstone, shale, siltstone, graywacke sandstone, lacustrine limestone, and coal. In Ohio, red shales and mudstones, which in some places contain selenite crystals, are common in the Dunkard. In Pennsylvania, much of the Dunkard appears to have accumulated as fine- to coarse-grained siliciclastic fluvial to deltaic sediments that invaded lacustrine environments, with the siliciclastic sediments grading laterally into carbonate deposits and peat swamps (Edmunds et al., 1999).

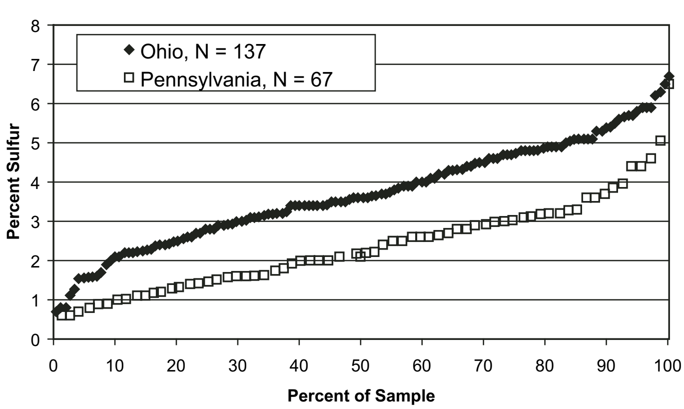

Figure 13. Sulfur content of coal beds in the Monongahela Group of Pennsylvania and Ohio (as received) (Bragg et al., 1998). N = number of samples. Even though the Monongahela contains no significant marine zones, a greater proximity to brackish-water and marine (?) environments appears to have introduced larger amounts of sulfur into Ohio paleopeat deposits than are in the Monongahela coals of Pennsylvania.

West Virginia

In West Virginia, the Dunkard is composed primarily of red shale, mudstone, and graywacke. In southwest Pennsylvania and adjacent West Virginia, in the axis of the syncline, it is ~335 m (1100 ft) thick. Relatively thin (up to 1 m thick) coal beds in the lower part of the formation are interbedded with gray shale, mudstone, and lacustrine limestone (Arkle et al., 1979).

Discussion

Dunkard coals are Type B coal beds that are high in ash and sulfur content, which has been interpreted to be the result of their deposition under a more seasonal, wet-dry, tropical climate (Arkle et al., 1979; Collins, 1979; Cecil et al., 1985; Edmunds et al., 1999). About 40% of the Dunkard coal samples from Pennsylvania contain greater than 3% sulfur (Fig. 11) and the average of 39 samples from Dunkard coal beds in the USGS Coal Quality database (Bragg et al., 1998) is 2.81% (Table 5). The selenite crystals in red beds, together with the general decrease in widespread mineable coal beds in the Dunkard, suggest that climatic conditions may have been somewhat drier, with lower water tables than in the Monongahela.

Appalachian Coal System F

Pennsylvania

In Pennsylvania, Coal System F includes the Pottsville and Llewellyn Formations (Pennsylvanian) in the anthracite region of Pennsylvania (Wood et al., 1986). The region is extensively folded, and bituminous to anthracite rank coals occur in one small and four large coal fields. Although the Pottsville contains several mineable coal beds, most of the resources are within the Llewellyn. (1) Although the topology of the peat deposits is generally not known, the low sulfur nature of the anthracite deposits suggest that they may have been formed, at least in part, as type A paleopeat deposits. (2) The anthracite region contains thick, relatively coarse-grained siliciclastic deposits. (3) Coal beds are relatively abundant and some are unusually thick for the Appalachian Basin. (4) The very low sulfur content of the coal beds in this region suggests that they may have been deposited in an everwet environment, even though the anthracite region is located near the northern Appalachian bituminous coal field. Locally, higher sulfur values occur in coal beds that are associated with marine zones. (5) The rank of the coal beds ranges from bituminous to anthracite (Hower and Gayer, 2002).

The Pottsville Formation overlies Mississippian-age strata and ranges from ~15 to 457 m (50–1500 ft) thick. It consists chiefly of conglomerate, conglomeratic sandstone, sandstone, siltstone, and shale, and contains about a dozen named coal beds. The top of the Pottsville is placed at the base of the seat earth beneath the Buck Mountain coal bed (Wood et al., 1986).

The Llewellyn, which is ~1065 m (3500 ft) thick, consists of fine- to coarse-grained and conglomeratic siliciclastic strata, minor marine limestone in the northwestern part of the district, and some 40 coal beds. The thickness of the major coal beds commonly ranges from a few feet to a dozen feet or more. In places, the Mammoth coal bed is as much as 20 m (65 ft) thick (Wood et al., 1986).

Discussion

The anthracite district is noted for its low-sulfur coal. Available coal analyses average less than 1% sulfur for Llewellyn coals (Table 5, Fig. 11). Sulfur and ash content generally increase to the northwest across the district and are generally highest in the Northern Field, where the marine limestones are known to occur. Wood et al. (1986) noted that the low sulfur content of the coal beds was most likely related to the predominantly freshwater depositional environment of the region and that perhaps, in some way, the metamorphism reduced the overall amount of sulfur. Alternatively, the relatively low amount of sulfur in the anthracite region may have been related to an everwet environment caused by the orographic effects of the early Appalachian Mountains, nearby (Otto-Bleisner, 2003). Gas-in-place values for coalbed methane are unusually high in the anthracite region, and measurements of 21.6 and 18.3 cm^3/g (691 and 586 ft^3/ton) have been obtained from the Peach Mountain and Tunnel coal beds, respectively, in the upper part of the Llewellyn Formation (Diamond et al., 1986).

Appalachian Coal System G

Appalachian Coal System G occurs in the northwestern part of the Tennessee Cumberland Plateau. (1) The location of this coal system, in a region that is considered to have been located geographically under everwet tropical conditions at the time the paleopeat beds and enclosing strata were deposited (Cecil et al., 1985), suggests that these coal beds should have had a relatively low sulfur content. Instead, Wilder coals consistently test greater than 2% sulfur, and the average for 62 samples is 4% sulfur, the highest in the Appalachian Basin (Fig. 5, Table 5) (Glenn, 1925; Williams et al., 1954, 1955d). (2) In the northwestern Plateau of Tennessee, formations of the Gizzard and Crab Orchard Mountains Groups below the Rockcastle Conglomerate grade laterally into the dark-colored shales and siltstones of the Fentress Formation, which contains the coal beds of the Wilder coal zone. (3) The stratigraphic sequence is relatively thin and contains relatively few coal beds. (4) The chemistry of the Wilder coals appears to have been strongly influenced by proximity to marine beds in the stratigraphic section. (5) The coal rank is bituminous.

On the basis of a detailed study of trace fossils, Miller (1984) and Miller and Knox (1985) concluded that that the Fentress Formation and the lower part of the Rockcastle Conglomerate (uppermost Crab Orchard Mountains Group, Table 1) were deposited in "back-barrier, tidal flat, and tidal channel or delta subenvironments within a barrier or marine-dominated deltaic system."

Discussion

The high sulfur content of the Wilder coal beds and abundant bioturbation within the Fentress Formation are evidence that the peat deposits accumulated in near-coastal mires, so that slight changes of sea level resulted in the deposition of marine deposits in the adjacent stratigraphic record. It is likely that sulfur was transferred from these marine connate waters into the Wilder paleopeat beds during diagenesis.

In this coal system, the negative effects of marine zones in the coal-bearing section appear to have overwhelmed the positive effects of an everwet climate on paleopeat quality. Because of their geographic location, however, it is expected that these coal deposits would be domed or perhaps mixed planar and domed. This coal system may be considered a variant of Coal System A. Because of its unusually high sulfur content and location within the low-sulfur coal region of the central Appalachian Basin, it is considered as a separate coal system.

SUMMARY AND CONCLUSIONS

Appalachian coal systems may be defined by the primary characteristics of their paloepeat deposits (Type A, everwet; or Type B, more seasonal), the regional stratigraphic framework, the relative abundance of mineable coal beds, the amount of introduced sulfur, and the coal rank. The relative abundance of sulfur in central and northern Appalachian Basin coal beds is primarily the result of the interaction of temporal and regional differences in paleoclimate as the principal cause, with the more local effects of associated marine depositional environments a secondary, but important, factor.

Coal System A extends over almost all of the central and northern parts of the Appalachian Basin. The sulfur content of coal beds in this system averages greater than 1%, regardless of location within the Appalachian Basin. The coal beds in the areas most affected by marine depositional environments in this coal system, such as eastern Kentucky and the upper part of the Pottsville in Pennsylvania, average well above the high sulfur limit (>2%). The largest average sulfur content in this coal system occurs in the Mercer and associated coals of Pennsylvania and Ohio, which may be the result of both a relatively unfavorable climate during peat formation and marine influence on the coal-bearing strata. Although this coal system has produced a significant amount of coal, it probably should be assigned a low to medium priority for assessment purposes.

Coal System B is located entirely within the central part of the Appalachian Basin. In formations that exhibit few or no marine beds, such as the Pocahontas, New River, and Norton Formations, the sulfur content of coal beds averages less than 1%, which is apparently the result of little or no marine influence on the domed peat deposits that had accumulated under tropical everwet environments. Those formations in this coal system that contain marine zones, which includes the Kanawha, Wise, and Breathitt Formations, and the Breathitt equivalents in Tennessee, generally average from >1% to <2% sulfur (Table 4). This coal system, however, would be given a high priority for assessment because of its remaining potential for producing low-sulfur coal.

Even though all of the sulfur analyses of coal beds in Coal Systems C, D, and E, which are located almost entirely within the northern part of the Appalachian Basin, average >2% S, the local to regional effects of marine deposits on the sulfur content of coal beds are evident. The sulfur contents of coal beds within the lower part of the Allegheny Group, which contains marine beds, are greater than those in the upper part of the group, which is almost entirely nonmarine; coal beds in the Conemaugh and Monongahela Groups of Ohio, which contain more marine units than those groups in Pennsylvania, have a greater sulfur content than their counterparts in Pennsylvania. Coal Systems C and E would be given a relatively high priority for assessment because of the remaining potential of their widespread, thick coal beds to produce large amounts of coal, even though the sulfur content is relatively high.

Coal System F, the anthracite region, contains a large amount of low sulfur coal that may be difficult to mine because of the geologic structure in the region. The system may be given a moderate priority for assessment because this low sulfur coal exhibits very high gas-in-place values for coalbed methane.

The greatest average sulfur content of any of the coal systems designated herein occurs within the coal beds of the Fentress Formation in Tennessee (Coal System G), which averages >4% sulfur. There, the effects of adjacent marine zones on paleopeat chemistry clearly override the location of these mires within a tropical, everwet climatic zone. Although academically interesting, this system would be assigned a low priority for assessment because its coal beds are relatively thin and their sulfur content is unusually high.

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Subtle structural influences on coal thickness and distribution: Examples from the Lower Broas–Stockton coal (Middle Pennsylvanian), Eastern Kentucky Coal Field, USA

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ABSTRACT

The Lower Broas–Stockton coal is a heavily mined coal of the Central Appalachian Basin. Coal thickness, distribution, composition, and stratigraphic position were compared with basement structure, gas and oil field trends, and sequence stratigraphic and paleoclimate interpretations to better understand the geology of the Stockton coal bed in eastern Kentucky. The thickest coal occurs south of the Warfield structural trend and east of the Paint Creek Uplift, two basement-related structures. Along the Warfield trend, coal beds in the underlying Peach Orchard coal zone locally merge with the Stockton coal to form a seam more than 3 m thick. Other areas of thick coal occur in elongate trends. Two pairs of elongate, conjugate trends in Stockton coal thickness are interpreted as regional paleofractures that influenced paleotopography and groundwater during peat accumulation.

Compositional group analyses indicate that the Stockton peat infilled depressions in the paleotopography as a topogenous to soligenous mire codominated by tree ferns and lycopsid trees. Flooding from adjacent paleochannels is indicated by partings and seam splits along the margins of the mineable coal body. One or more increments of low-vitrinite coal, dominated by tree ferns and shrubby, *Densosporites*-producing lycopsids occur at all sample sites. Similar assemblages have been previously used to identify ombrogenous, domed mire origins for Early and Middle Pennsylvanian coals in which ash yields were less than 10%. It is difficult, however, to reconcile ombrogenous conditions with the partings in the Stockton coal in this area. Low-ash, low-vitrinite increments may have been formed in topogenous to soligenous mires with periodic drying or water-table fluctuations, rather than widespread doming. This is consistent with interpretations of increasingly seasonal paleoclimates in the late Middle and Late Pennsylvanian and fracture-influenced groundwater conditions.

Keywords: coal, petrography, palynology, fracture, bench-architecture, paleoecology.

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INTRODUCTION

Numerous allocyclic (e.g., river avulsion, flooding) and autocyclic (e.g., climate, tectonics, eustacy) processes may influence the thickness, distribution, and quality of coals. These processes are dynamic, and their influence can change temporally and spatially before, during, and after peat burial. Understanding the spatial and temporal influences on a mineable coal seam can aid in resource analyses through the recognition of trends that allow for more reasonable interpolation of existing data or more ordered collection of new data within a framework defined by the interpreted trends.

The Stockton coal is a late Middle Pennsylvanian (Bolsovian), high volatile A bituminous coal of the Central Appalachian Basin (Fig. 1). The Stockton coal and its equivalent produce more than 18,000 short tons annually, which ranks, by bed, ninth in the nation, fourth in the eastern United States, and third in the Central Appalachian Basin (U.S. Department of Energy, 2003). Most of this production is from West Virginia. In eastern Kentucky, the Stockton is equivalent to the Lower Broas and Hazard No. 9 coal beds of the Four Corners Formation, Breathitt Group (Alvord, 1971; Rice and Hiett, 1994). In Kentucky, Broas coal mining is mostly concentrated in an area centered in Martin County, where the coal ranges from 0 to more than 2 m in thickness (Huddle and Englund, 1962a, 1962b; Rice, 1963, 1964).

Several tectonic structures appear to have influenced Carboniferous sedimentation in the Martin County area. Past interpretations of structural control have been inferred for older coals on the basis of trends of regional coal thickening coincident with structures, inferred coincidence of paleochannels to structures, and channel stacking toward structures (Horne, 1979; Powell, 1979; Andrews et al., 1996; Greb et al., 2002b). Herein, coal thickness and coal-bench architecture are compared with known structures in order to determine potential structural influences on Stockton thickness in part of the Eastern Kentucky Coal Field. Data from previous studies are examined as parts of compositional groupings within the context of the coal's bench architecture to interpret paleomire ecology. Because the late Middle Pennsylvanian spans a time of fluctuating climatic (e.g., Cecil, 1990), marine (e.g., Chesnut, 1996), and tectonic (e.g., Greb et al., 2002b) influences in the Central Appalachian Basin, Stockton (Lower Broas) paleomire interpretations are discussed in the context of broader basinal changes by using a variety of data and analyses: a coal systems approach.

Structure

The study area is located in the Eastern Kentucky Coal Field of the Central Appalachian Basin (Fig. 1A), a foreland basin. The study area is located along the southern margin of a basement aulocogen called the Rome Trough (McGuire and Howell, 1963; Ammerman and Keller, 1979; Drahovzal and Noger, 1995). The southeastern margin of the Rome Trough is marked by a series of faults, monoclines, and arches, cumulatively called the Warfield structures (Figs. 1C and 1D; Gao and Shumaker, 1996).

Displacement along the Warfield Fault at the surface cannot be measured very far into Kentucky (Huddle and Englund, 1962a), although magnetic and structural contours on the base of the middle Pennsylvanian Magoffin Shale indicate that a monocline, named the Warfield Monocline (Fig. 1C), extends westward along the trend of the fault (Black, 1989). Several faults have also been mapped in the subsurface west of the surface expression of the Warfield Fault on the basis of data from Devonian gas shale exploration (Fig. 1D; Lowry et al., 1990). In addition, the Warfield Anticline is located north of, and parallel to, the Warfield Fault (Figs. 1C and 1D). The anticline is a prominent feature in West Virginia, where it is the border between the northern and southern West Virginia coal fields (Arkle et al., 1979; Gao et al., 2000). A basement fault has been inferred on the north margin of the anticline in West Virginia (Neal and Price, 1986). Local structural influences along the Warfield trend have been inferred in Kentucky on the basis of the stacking of sandstones above the Taylor coal at the base of the Magoffin Shale member, Four Corners Group (Andrews et al., 1996). A recent study just west of the study area in Mingo County, West Virginia, however, found no evidence of syndepositional structural influences along that segment of the Warfield Fault in Coalburg coal mines (Coolen, 2003).

The Coalburg Syncline of West Virginia (Fig. 1C) is another structure that occurs south of, but parallel to, the trend of the Warfield structures (Arkle et al., 1979). The Coalburg Syncline is continuous with the Eastern Kentucky Syncline (Chesnut, 1992). The syncline is steeply dipping on the north adjacent to the Warfield Fault, and gently dipping on the southeastern limb of the Eastern Kentucky Syncline (Fig. 1C). Carboniferous strata do not thicken into the syncline so it is interpreted as a post- to late Middle Pennsylvanian structure (Chesnut, 1992).

The Warfield structures are interrupted and offset by several north-south–oriented structures. The southern margin of the Rome Trough is interrupted just west of Martin County by a basement graben called the Floyd County Channel (Figs. 1B and 1D; Ammerman and Keller, 1979; Drahovzal and Noger, 1995). The Paint Creek Uplift overlies this structure (just west of the western edge; Figs. 1C and 1D) and continues northward along the same trend, which suggests reactivation and tectonic inversion at some time during the Middle to Late Paleozoic. On the other side of Martin County, two subparallel strike-slip faults have been interpreted in the Devonian shale based on seismic analyses and gas-production trends (Shumaker, 1987; Lowry et al., 1990). Just east of the study area, in West Virginia, a southeast bend in the Warfield Fault and the eastern boundary fault of the Rome Trough may indicate a northeast-southwest–trending transcurrent fault at depth (Fig. 1D; Gao et al., 2000).

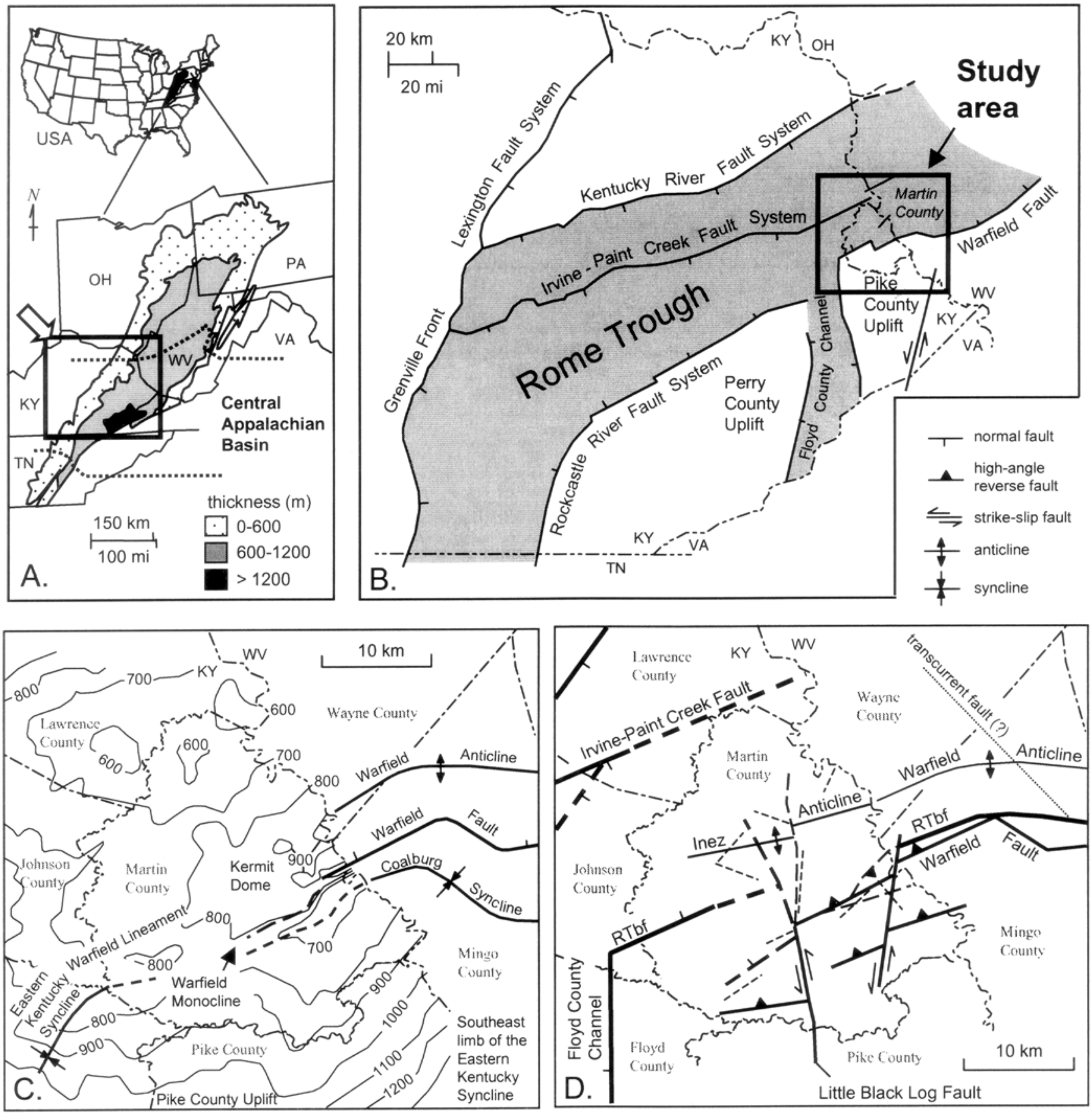

Figure 1. Location and structural geology of the study area. (A) Thickness isopach of the Central Appalachian Basin (modified from Wanless, 1975). KY—Kentucky; OH—Ohio; PA—Pennsylvania; TN—Tennessee; VA—Virginia; WV—West Virginia. (B) Major basement structures in eastern Kentucky and the location of the study area (after Drahovzal and Noger, 1995; Gao et al., 2000). (C) Near-surface structures in the study area drawn on the base of the Middle Pennsylvanian Magoffin Shale, Four Corners Formation (Black, 1989). Contour interval is 100 ft (30.5 m). Strikes of structures in West Virginia from Arkle et al. (1979). (D) Deep structures in the study area. Major structures from Drahovzal and Noger (1995) in Kentucky, and from Gao et al. (2000) in West Virginia are shown with thick, solid lines. RTbf—Rome Trough boundary fault. Structures inferred from seismic data and production data of the Devonian gas shale by Lowry et al. (1990) are shown with a thin solid line. Structures inferred from Devonian gas production data by Shumaker (1987) are shown by thin, long, dashed lines. Short dashed lines indicate trends of production presented in Shumaker (1987) but are not shown as definite structures. KY—Kentucky; TN—Tennessee; VA—Virginia.

Stratigraphy

The Breathitt Group is subdivided into formations on the basis of widespread marine-shale members (Chesnut, 1992, 1996). The Stockton (Lower Broas) coal occurs at the top of the Four Corners Formation (Fig. 2) and is equivalent to the Hazard No. 9 coal to the south. Both coals are overlain by the Stoney Fork Member, which is one of the formation-bounding marine shale units. In parts of the Eastern Kentucky Coal Field, the Stoney Fork Member contains a discontinuous limestone with open marine fauna at its base (Chesnut, 1981).

Because Chesnut (1992, 1994, 1996) defined formations on the basis of marine fossil-bearing shales, the formations generally conform to intervals between major marine flooding events, the bases of which approximate maximum marine flooding surfaces. The Four Corners Formation, therefore, can also be interpreted as a third-order genetic sequence (sensu Galloway, 1989), with a maximum flooding surface at the base of the Magoffin Shale member and at the base of the Stoney Fork Member or equivalents in the overlying Princess Formation (Fig. 2). By means of sequence stratigraphic techniques, the Four Corners Formation, in which the Stockton coal occurs, has also been interpreted as a third-order composite sequence. The coal is positioned at the top of a lowstand sequence set, which is overlain by the transgressive sequence set that contains the Stoney Fork Member (Aitken and Flint, 1994).

On 7.5′ geologic quadrangles in the study area, the Stockton coal is mapped as (1) the Broas coal (Outerbridge, 1963; Rice, 1963, 1964; Alvord, 1971), (2) the Broas coal split into Upper and Lower Broas coal beds (Huddle and Englund, 1962a, 1962b), (3) separate Upper and Lower Broas coal beds (Outerbridge, 1964), and (4) the Broas coal zone, comprising as many as three distinct beds (Jenkins, 1966; Sanchez et al., 1978). Where an Upper and Lower Broas coal are mapped, the lower bed is considered equivalent to the Stockton coal. In at least some cases, the Upper Broas coal is equivalent to coal beds above the Stoney Fork Member to the south of the study area (Fig. 2; Rice and Hiett, 1994).

Coal-Bench Architecture Analyses

Where coal seams contain persistent partings or durain layers, the seam can be analyzed as subsets called coal benches (e.g., Staub, 1991). Coal benches are increments of coal seams and beds bound by underlying (floor) rock, overlying (roof) rock, clastic partings, or persistent and subtle durain (dull coal) layers. Analyses of the stacking and lateral juxtaposition of benches is termed coal-bench architectural analysis (Greb et al., 1999, 2002a). This type of analysis can be used to better constrain interpretations of existing data sets, to interpret the depositional history of a coal, and to plan for a wide variety of mineability applications. Recent research in the Central Appalachian Basin indicates that many coal seams have multiple-bench architectures. Multiple-bench seams are composed of different combinations of benches at different places across the coal field (e.g., Thacker et al., 1998), each of which can have its own distribution, quality, and thickness characteristics. Because the Stockton (Lower Broas) coal in the study area locally consists of multiple benches, coal-bench architecture analyses can be used to provide a framework for interpreting previously col-

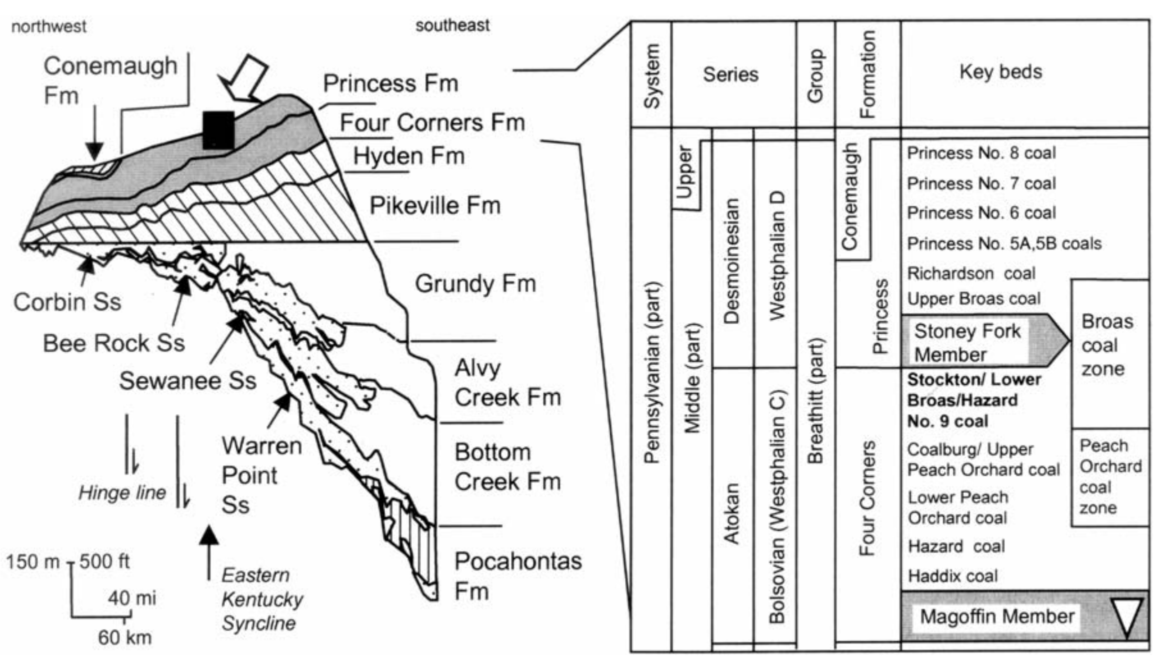

Figure 2. Pennsylvanian stratigraphy in the Central Appalachian Basin showing the position of the study area and Stockton (Lower Broas) coal.

lected quality, petrographic, and palynological data relative to the spatial distribution of coal and tectonic structures.

Compositional Groups

Numerous types of data (e.g., ash yield, sulfur contents) can be used to interpret the depositional origin of a coal seam. If increment data are available or collected such that it can be meaningfully analyzed relative to the coal's bench-architectural framework, variation between and within the benches that comprise a seam can be tested. One type of increment data collection that can be used to interpret the depositional environment of a coal uses compositional groups (e.g., Eble and Grady, 1990). Compositional groups use combinations of ash yield, sulfur content, and palynologic and petrographic data to derive sets of characteristics that should be analogous to the characteristics of modern rheotrophic, ombrotrophic, and transitional mires. Rheotrophic mires are low-lying (usually topogenous) mires that receive their moisture from groundwater. Ombrotrophic mires (usually raised or domed) receive their moisture from rainwater (Moore, 1989). A better understanding of the original paleomire can aid in understanding coal thickness, distribution, and quality characteristics. For Middle Pennsylvanian coal beds of the Appalachian Basin, four compositional groups, (1) mixed palynoflora–high ash, (2) *Lycospora*-vitrinite dominant, (3) mixed palynoflora–vitrinite dominant, and (4) mixed palynoflora–low vitrinite–low ash, have been developed as analogies, respectively, to (1) clastic-influenced and mire-margin topogenous-rheotrophic mires, (2) topogenous-rheotrophic mires, (3) topogenous to soligenous-mesotrophic mires, and (4) ombrogenous-ombrotrophic domed (raised) mires (Eble and Grady, 1990, 1993; Eble et al., 1994).

In this study, compositional groups are used to interpret Stockton paleomire ecology. Qualifications on the use of the previously interpreted Middle Pennsylvanian compositional groups are discussed relative to changing paleoclimate and flora in the late Middle to Late Pennsylvanian. Examination of the changing influences of autocyclic and allocyclic factors is consistent with the type of coal systems approach advocated in this volume.

RESULTS

Stockton (Lower Broas) Coal

Figure 3 is a map of the study area, centered on Martin County, Kentucky. The map shows the locations of 447 coal-exploration boreholes, as well as the location of underground mines and surface mines. Borehole data was obtained from the Kentucky Geological Survey's borehole database. Mine map data were examined at the Kentucky Department of Mines and Minerals. At least one thickness and elevation data point was available for each of the underground mines, and in many cases, more data were available. Thickness and structure maps were compiled for each mine, and then those mine-scale isopachs were compiled into the larger-scale maps used in this study. Because of the difference in scale, individual data points in the mine areas are not shown in Figure 3, but more than 725 data points were used to map coal thickness and structure in the area of mined coal. This information was concentrated in mining areas of the Inez, Offutt, Lancer, and parts of the Thomas 7.5′ quadrangles. The locations of four seam samples for which increment samples were collected for quality and other compositional data are also indicated on Figure 3. Data for three of the four samples were illustrated in a previous study of Stockton lithotypes and geochemical variation (Hower et al., 1996). Increments from all four samples are herein examined with compositional group analyses. Results are discussed for these sites relative to their position in the overall seam architecture.

Martin County Sections

Cross sections across the study area (Fig. 4) indicate that the stratigraphic interval between the Magoffin Shale member and Stockton (Lower Broas) coal thins northward (90–100 m to 50–60 m). In both sections, the interval between the Stockton and Peach Orchard coal zone thins northward from the Thomas and Varney quadrangles to a point near the Warfield Fault trend (southeastern boundary fault of the Rome Trough). In section E–E″, the Stockton (Lower Broas) coal is thick across much of the area where the underlying Peach Orchard coal is thick. The Stockton splits north toward the Warfield Fault trend and southeast toward the Martin County border (Figs. 3 and 4). In section D–D″, coals in the Peach Orchard coal zone locally merge with the Stockton (Lower Broas) coal to form a composite seam 3.2 m thick (with partings). Northward from the point of merger, it is difficult to determine if the Stockton remains merged with a coal bed in the Peach Orchard zone, is split into several thin coals, or is cut out.

Coal-Bench Architecture

Detailed coal sections of the Stockton coal indicate that it is a single- to multi-benched coal seam (Fig. 5). Partings are reported in many areas, with a persistent shale to bone coal parting toward the middle of the seam in eastern and southern Martin County (Fig. 5, A–A″, E–E″). There is an abrupt split on the eastern and southeastern margin of the mined coal that separates the coal into two beds more than 15 m apart (Fig. 5, A–A″, E–E″). The split is continuous with the middle parting, which is noted as shale or rock or bone (coaly shale) on mine maps and boreholes. Several seam splits are noted along the northern margin of the mined coal. These seam splits also appear to continue into the coal body as a parting toward the middle of the seam (Fig. 5, B–B″, C–C″, D–D″, E–E″).

As was shown in Figure 4 (D–D″), the Stockton coal locally merges with coal beds in the underlying Peach Orchard coal zone along the Warfield structures trend in central Martin County. Figure 5 shows a detailed section of the coal bench

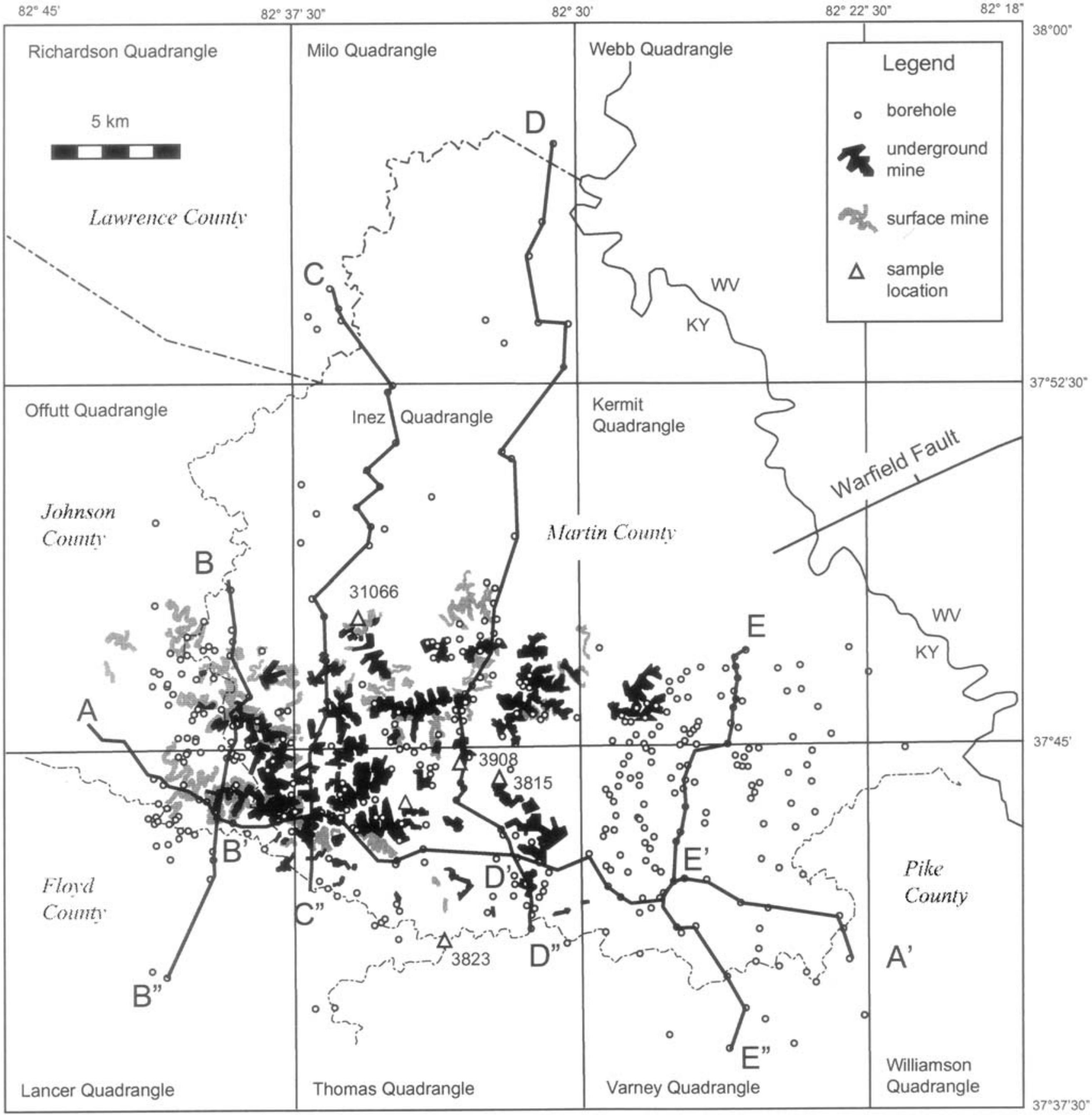

Figure 3. Map of the study area showing the locations of mines, data, and cross sections in Figures 4 and 5. Locations of the four increment-sample sites of Hower et al. (1996) used in this study and shown in Figures 9 and 11 are shown with a triangle. WV—West Virginia; KY—Kentucky.

architecture along line D–D″. Three distinct coal beds come together, the Stockton (Lower Broas), the upper Peach Orchard coal or an upper bench of the main Peach Orchard coal, and a bench of the main Peach Orchard coal. Northward, the composite coal abruptly thins and separates into several thin beds. Splitting on the northern margin of the mined coal body is complex and associated with the development of several additional coals in a zone (Fig. 5, C–C″, D–D″). All of the coals in the Broas and Peach Orchard coal zones tend to be thin and split in northern Martin County. Some coals have thicker than average underclays (paleosols). Because there are no consistently thick coals or key beds, correlation of individual beds is difficult north of the Warfield trend. The thickest, most uniform coal corresponds to the area of mining in the southern part of Martin County (Fig. 6).

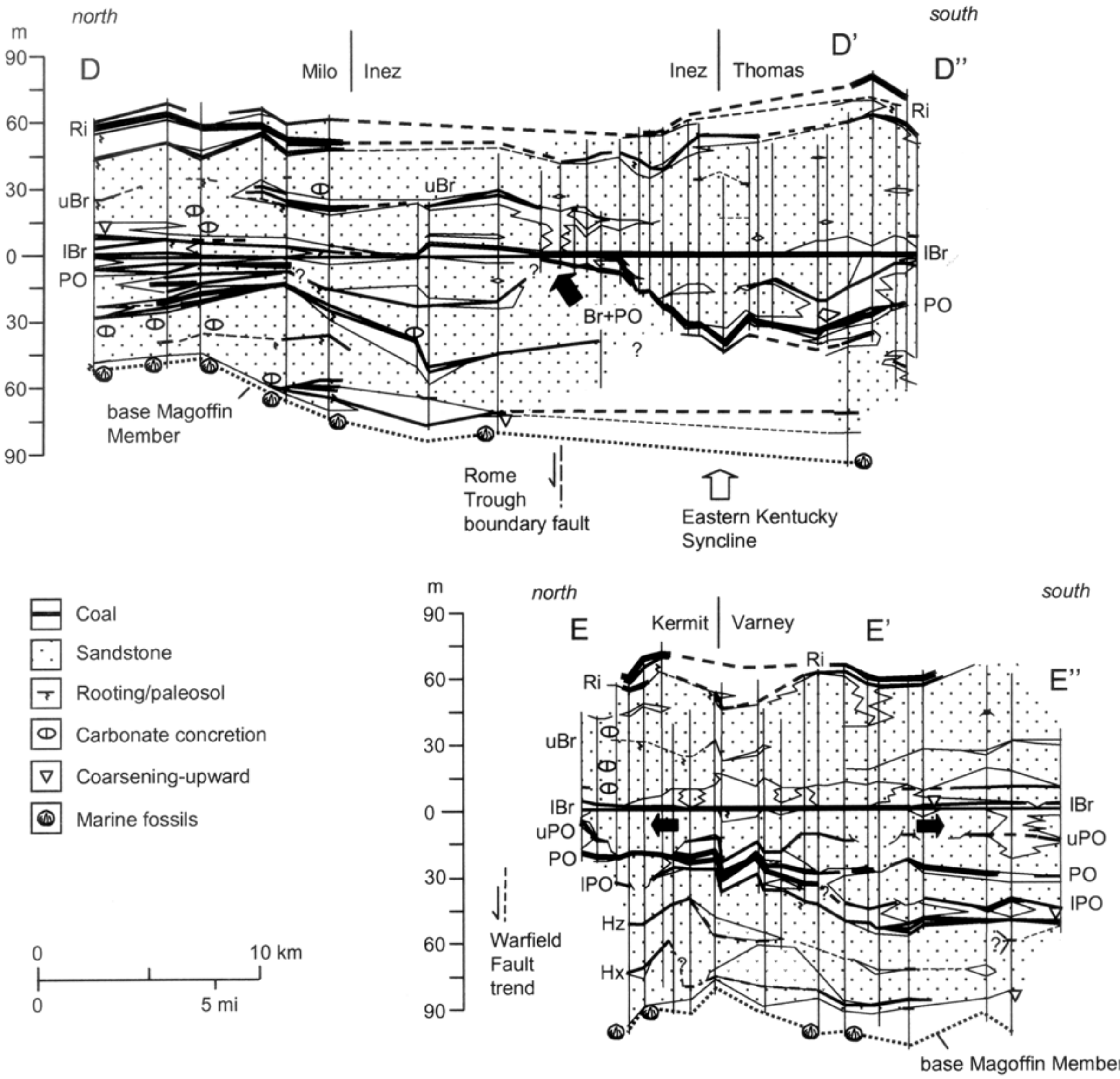

Figure 4. Cross sections across Martin County from the base of the Magoffin Shale member to the Richardson coal. Datum is the Stockton (Lower Broas) coal. Location of sections shown in Figure 3. Black arrow in section D–D″ shows area where coals in Peach Orchard coal zone merge with the Broas coal (Br + PO). Black arrow in line E–E″ show directions of splitting in the Stockton (Lower Broas) coal. The two sections are aligned along quadrangle boundaries at 37°45′. Hz—Hazard coal; Hx—Haddix coal; lBr—Loer Broas coal; uBr—Upper Broas coal; lPO—Lower Peach Orchard coal; PO—Peach Orchard coal (main seam); uPO—Upper Peach Orchard coal; RI—Richardson coal zone.

Coal Thickness and Structure

A structure map on the base of the Stockton coal shows several trends (Fig. 7). There is a series of anticlines and synclines along the Warfield structural trend. A prominent anticline is located north of the Warfield Fault along the Warfield structural trend. The strike of the structure corresponds to the Warfield Lineament (Fig. 1C) of Black (1989) and may be a continuation of the Warfield Anticline of West Virginia, although it is slightly south of the projected trend of that structure in Figure 1D. The anticline appears to split in the Inez quadrangle into two branches. The northern branch parallels the Warfield structures trend. The southern branch has a northeast-southwest trend that curves to an east-west orientation parallel to the Warfield structures trend. One mine noted a "fault" and "hill" along this part of the anticline (Fig. 7).

The Coalburg Syncline of West Virginia is well developed in the eastern part of the study area south of the Warfield Fault.

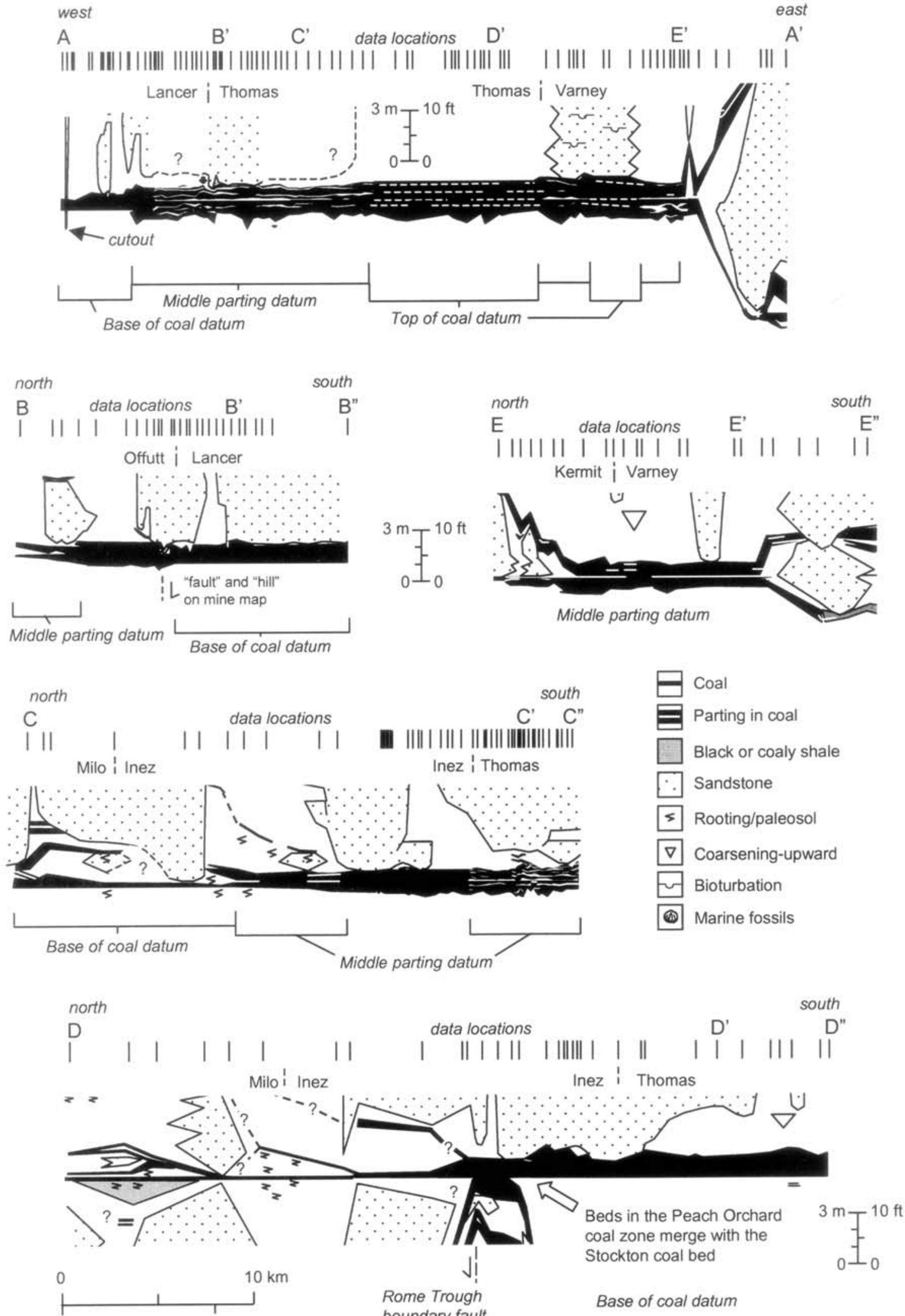

Figure 5. Cross sections of the Stockton (Lower Broas) coal. Locations shown in Figure 3. All sections to same scale. Midseam parting used as datum where possible (as shown) in order to illustrate relation to lateral splits and relative thickness changes in the coal above and below the parting.

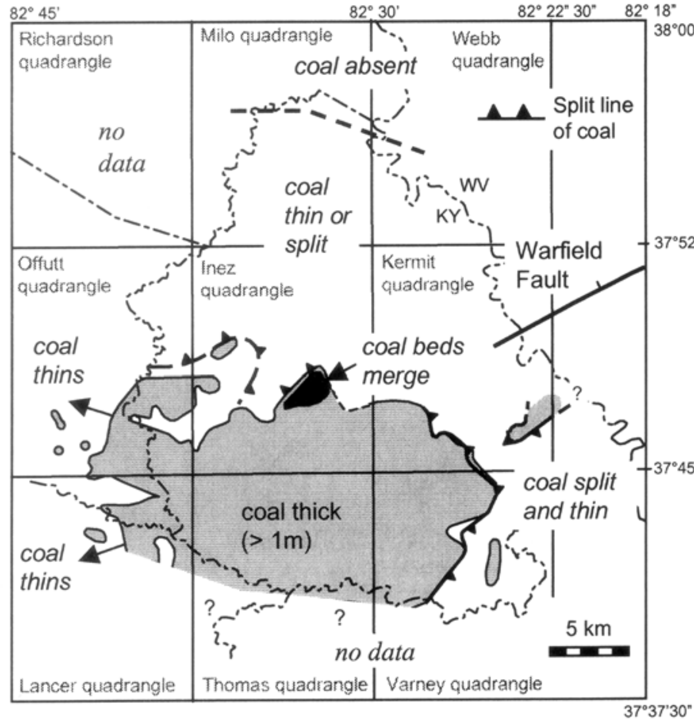

Figure 6. Generalized distribution of the Stockton coal in the study area. The area of thicker mineable coal is shown in more detail in Figure 8. Map can be compared with Figure 3, which shows locations of mines.

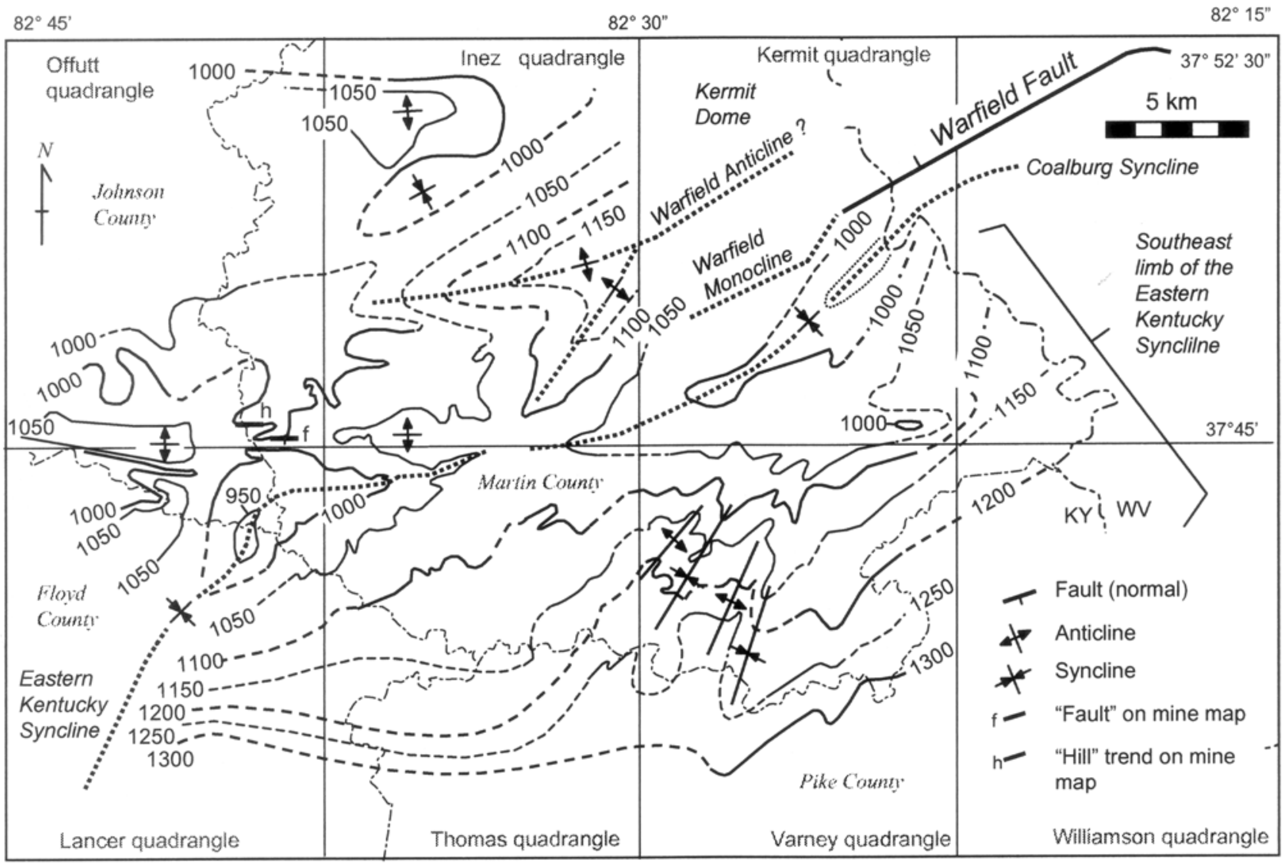

Figure 7. Structural elevation on the base of the Stockton coal in the mining area. Contour interval is 50 ft (15 m).

The Coalburg Syncline connects to the Eastern Kentucky Syncline across southern Martin County (Fig. 7). Where the synclines connect, their axes parallel the Warfield structures trend.

The Stockton coal isopach shows that coal thickness of more than 92 cm is mostly restricted to an area in southern Martin County (Fig. 8). The coal thins and splits into thinner benches or beds of coal northward, westward, and eastward. Southward, data density decreases, and it is difficult to determine trends. Coal thickness is greatest in two areas. The first is along the northern margin of mining where the Peach Orchard and Stockton coals merge to form a composite seam more than 3 m thick (Figs. 4 and 5, D–D″). The second area of thick coal occurs in the southeastern part of the study area, where several narrow, subparallel trends of northeast-southwest–oriented coal more than 152 cm thick are mapped (Fig. 8).

Local offset and a steep down-to-the-south ramp in a mine near the Offutt-Lancer 7.5′ border are located along a persistent east-west trend of structural arches on the base of the Stockton coal as well as roof rolls noted in several underground mines. Areas of thin coal noted as “rolls” on mine maps (Fig. 8) are mostly parallel to local structure trends on the base of the coal (Fig. 7). Rolls near the Warfield structural trend are oriented parallel to the Warfield trend. Farther south and west, rolls are oriented in northeast-southwest orientations, subparallel to the strike of the southeast limb of the Eastern Kentucky Syncline (Fig. 8).

Palynology, Petrography, and Geochemistry

The palynology, petrography, and geochemistry of the Stockton coal bed have previously been discussed by Eble and Grady (1993) and Hower et al. (1996). Figure 9 illustrates palynologic, petrographic, and geochemical variation within the Stockton coal for four sample sites previously collected by Hower et al. (1996) in the study area. Compositional group analyses of four sites indicates the existence of three compositional groups. They are as follows: (1) mixed palynofora–high vitrinite group (MPHV), (2) mixed palynoflora–low ash group (MPLA), and (3) mixed palynoflora–high ash (MPHA) group. The groups are similar to, but in two cases slightly different than, compositional groups developed for older Middle Pennsylvanian coals in the basin (Eble and Grady, 1990, 1993; Eble et al., 1994; Greb et al., 2002a). Table 1 shows the average,

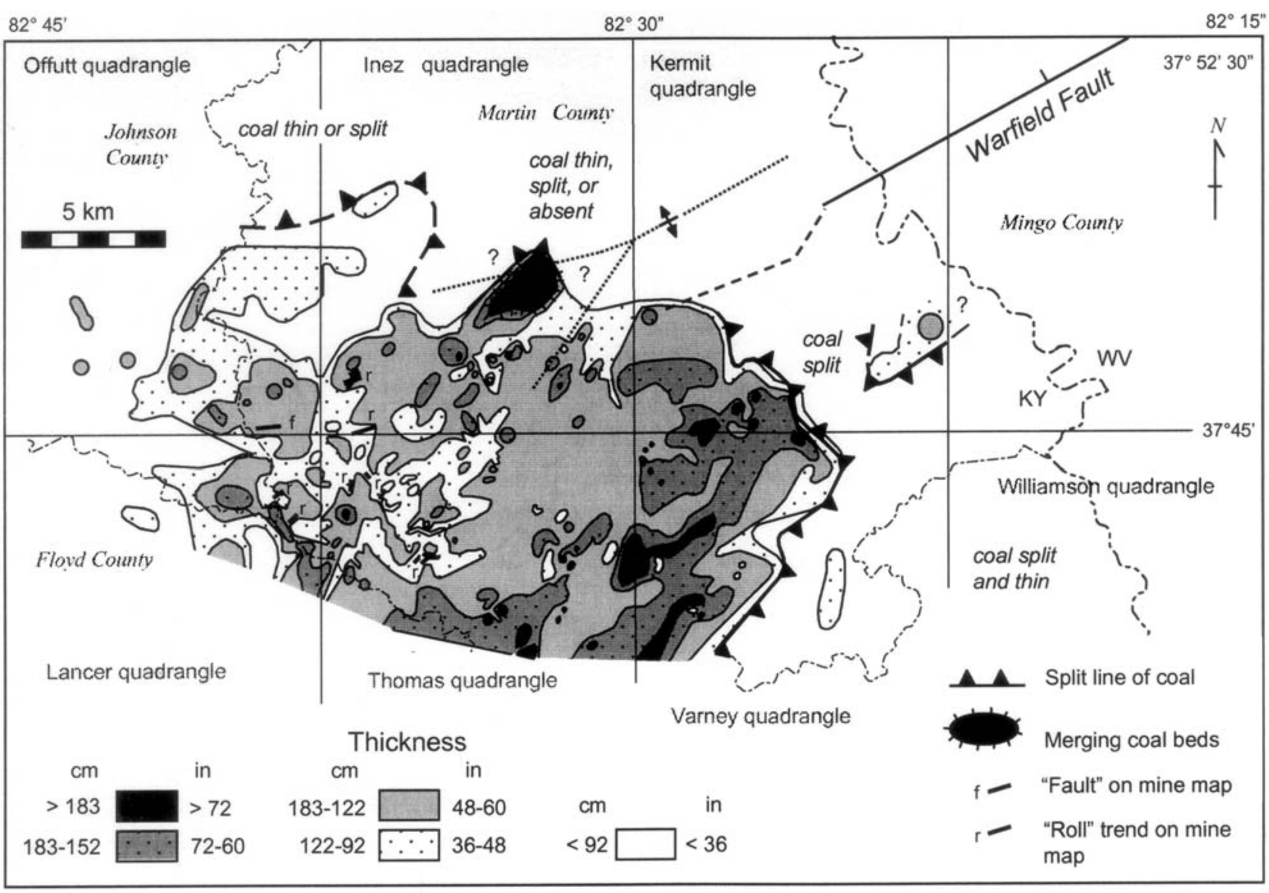

Figure 8. Isopach of the Stockton coal in the mining area. Dotted line shows trace of anticline as shown in Figure 7. The anticline just north of the Warfield Fault trend is likely a continuation of the Warfield Anticline, although a lack of data in the northern part of the Kermit quadrangle and sparse data in the northern part of the Inez quadrangle make absolute correlation of the trend difficult.

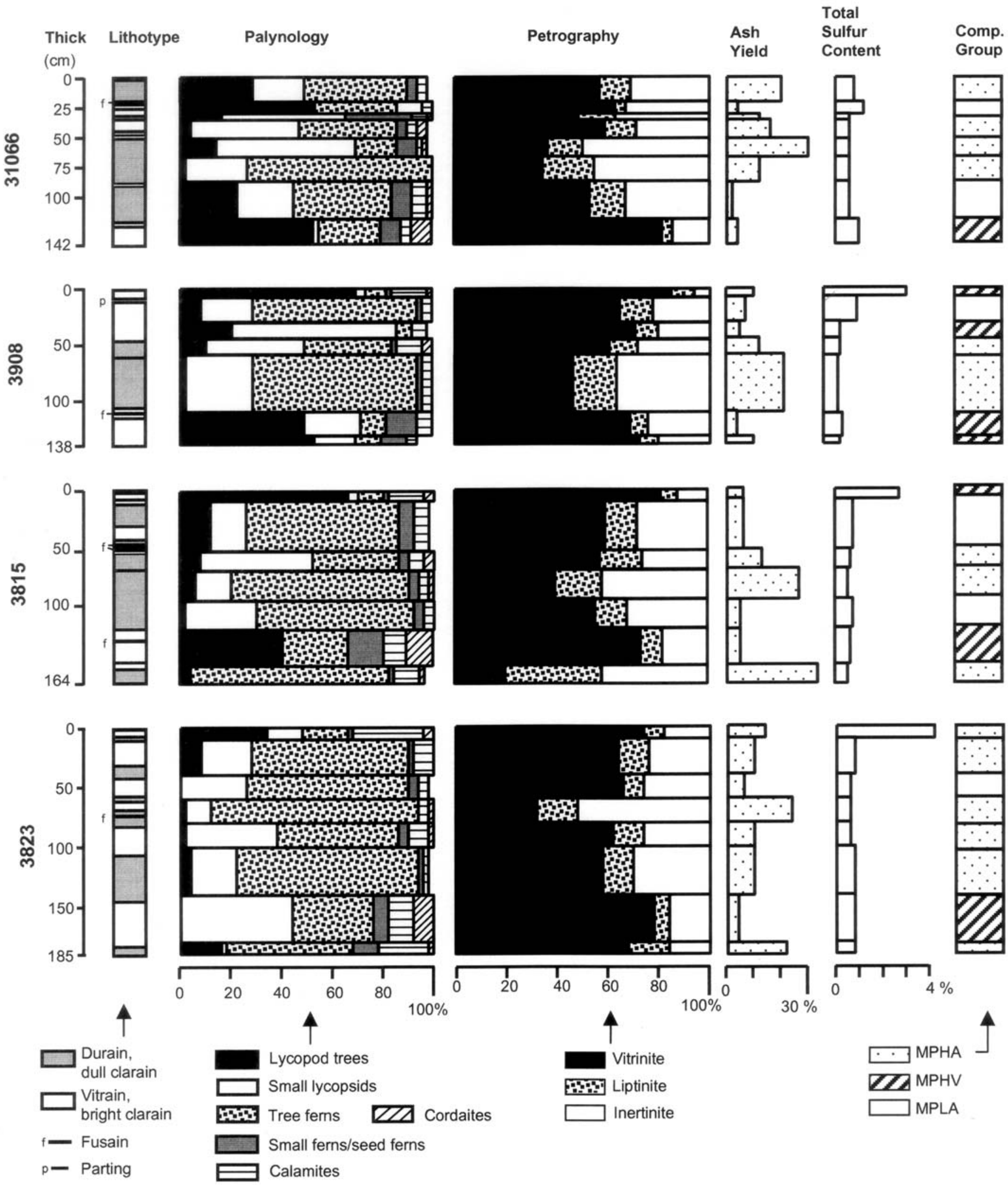

Figure 9. Composition of the Stockton coal at four sample locations (data from Hower et al., 1996). Each division reflects a sample interval. MPHA—mixed palynoflora–high ash compositional group; MPHV—mixed palynofora–high vitrinite group; MPLA—mixed palynoflora–low ash group. Locations shown on Figure 3.

TABLE 1. PALYNOLOGICAL, ASH YIELD, SULFUR CONTENT, AND PETROGRAPHIC DATA FOR THE STOCKTON COAL FROM FOUR STUDY SITES (30 INCREMENT SAMPLES) IN THE STUDY AREA ARRANGED BY COMPOSITIONAL GROUP

	MPHV			MPLA			MPHA		
	avg	max	min	avg	max	min	avg	max	min
Total lycopsid trees	46.7	69.6	20.8	15.2	53.2	1.2	8.8	27.2	0.4
Total small lycopsids	2.5	14.0	0.0	14.4	27.6	0.0	27.1	57.2	0.0
Total tree ferns	25.3	66.8	8.8	60.8	72.8	33.2	51.7	81.2	15.2
Total small ferns	6.5	13.2	1.2	4.9	9.6	2.0	3.5	10.1	0.4
Total calamites	12.8	28.0	5.6	4.1	7.6	2.0	6.5	20.4	0.0
Total cordaites	5.3	10.4	0.0	0.5	1.2	0.0	1.6	3.6	0.0
Ash yield (% dry)	6.7	13.4	3.6	5.9	9.5	2.8	18.9	33.9	10.1
Sulfur content (% dry)	1.6	4.2	0.6	0.9	1.5	0.6	0.6	0.9	0.5
Vitrinite	76.9	86.4	70.6	60.5	66.0	54.4	49.0	67.1	19.0
Liptinite	6.4	8.0	4.1	10.6	15.4	4.3	16.2	37.6	10.6
Inertinite	16.7	24.2	6.1	28.9	32.6	21.9	34.7	51.6	17.4
Structured/unstructured	1.5	2.4	0.9	1.3	1.8	0.8	0.8	1.2	0.4

Note: MPHV—mixed palynoflora–high vitrinite group; MPLA—mixed palynoflora–low ash group; MPHA—mixed palynoflora–high ash group.

maximum, and minimum values for palynologic, petrographic, and geochemical parameters of the groups based on 30 increment samples from four sites.

The MPHV group has the highest percentages of lycopsid tree and calamite spores, and cordaite pollen (Table 1, Fig. 9). Vitrinite contents are the highest of the three groups, greater than 70%. Ash yields are less than 10%. The MPHV group differs slightly from the mixed palynoflora-vitrinite dominant group previously used for Middle Pennsylvanian coal analyses in the basin in that the cutoff for vitrinite was lowered from 80% to 70%. There is an overall decrease in vitrinite in Grundy Formation (Late Langsettian) coal beds, through coal beds in the lower part of the Princess Formation (Bolsovian), such that 70% is a high vitrinite content for coals of this time. Also, 70% vitrinite was a natural break among the increment samples that had substantial vitrinite content and low ash yield.

The MPLA group in the Stockton coal bed is defined for increments that have less than 10% ash on a dry basis, similar to the mixed palynoflora–low vitrinite–low ash group previously used for Middle Pennsylvanian coal analyses in the basin. The MPLA has palynoflora codominated by small lycopsid and tree-fern spores (Table 1, Fig. 9). Ash yields are low and uniform, as are total sulfur contents. Inertinite and liptinite contents are high (collectively, they average 39.5%). Differences between the MPLA in this study and the previously defined mixed palynoflora–low vitrinite–low ash include the general decrease in vitrinite in younger coals mentioned above and in the MPLA group's relation to other factors in the overall seam architecture, which are discussed later.

The third group in the Stockton coal, the MPHA group, is palynologically and petrographically similar to the MPLA group, but is defined where ash yields are greater than 10% (average 18.9% ash). This group is essentially the same as the MPHA group previously used for Middle Pennsylvanian coal analyses in the basin.

A comparison of the sample sites (Fig. 9) shows that the seam is dominated by the MPHA compositional group, with lesser amounts of the MPHV and MPLA groups. Samples 3908 and 3815, which occur toward the center of the mined area, are thinner and more alike than samples 31066 and 3823, which are located on the margins of the mined area. Samples 3908 and 3815 also have more MPHV increments than the other two sites. In contrast, samples 31066 and 3823 have the most MPHA increments. MPHV increments are most common near the base of the seam at all sites. Likewise, MPHA increments occur in the center of the seam at all sites. The highest sulfur contents occur at the top of the seam.

Bench-Scale Comparisons

The Stockton (Lower Broas) coal is a single to multiple bench coal in the study area (Fig. 5). As previously noted, the coal merges with the Peach Orchard coal zone along the Warfield structure trend to form a composite seam, composed of different beds or benches of coal separated by shale partings. Just as the rock intervals between each coal bed can be used to correlate the beds that form the composite seam, thinner partings within the Stockton coal itself can be used to define benches and test for in-seam thickness and quality variability.

Incremental measurements of partings and coal were noted on some mine maps so that detailed cross sections can be made to show the extent of partings in the main Stockton (Lower Broas) coal. Partings were marked as shale, rock, or bone (generally equivalent to a high-ash durain or coaly shale), or simply as a parting on mine maps, such that each may consist of laterally gradational shale, coaly shale, and shaly coal or durains. These partings were persistent across a large part of the southern and eastern study area and increased in thickness and abundance toward the margins of the mineable coal area. On the eastern margin of the mined area the coal is split into two distinct benches. Laterally, where the split comes together, one parting is consistent through the middle of the seam (Fig. 10). If this parting is continuous with one of the partings to the west, the seam can be divided into two benches across the study area and intraseam variation can be analyzed. It is logical to infer that the midseam parting is equivalent to the highest ash durains at the four sample sites (Fig. 10) collected by Hower et al. (1996), which are all in a similar position in the coal. Because there was one obvious MPHA increment at all sites, it was treated separately, and benches were defined informally above and below this persistent high-ash durain increment (Fig. 11). No samples were available in the older mine areas where a midseam parting was recorded or along the split margin of the coal. Because sample thickness is based on lithotypes, sample size is not uniform.

A comparison of the upper and lower benches shows that they are similar in overall quality (Figs. 5, 9, 11). At three of four locations, the lower bench has slightly higher ash yield than the upper bench and the upper bench has slightly higher sulfur content than the lower bench. Much of the sulfur in the upper bench is concentrated in the uppermost increment of the upper coal bench irrespective of its palynoflora (Fig. 9). In terms of compositional groups, both benches contain all three groups. The thickest mixed palynoflora–high vitrinite increments are toward the base of the lower bench at all sites. The greatest number of high-ash increments is located in the site

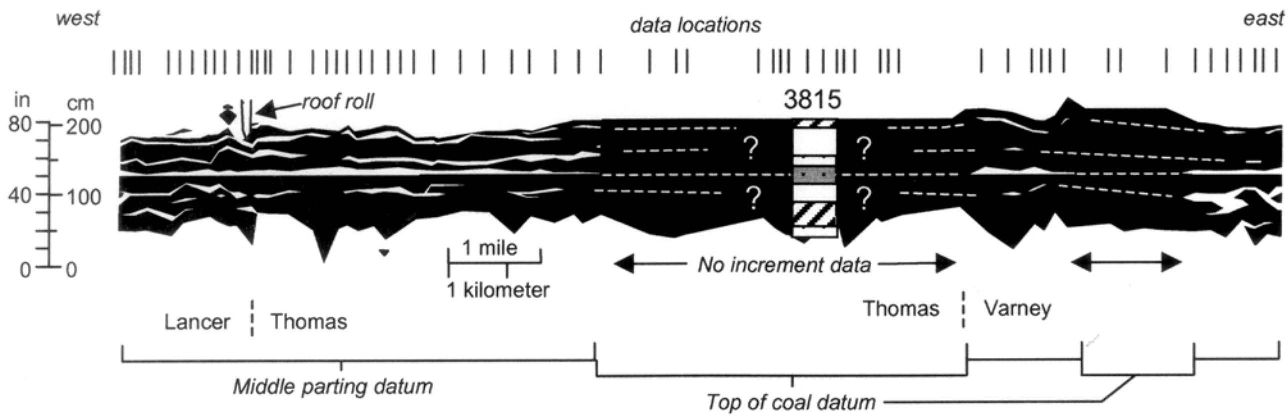

Figure 10. Bench architecture of the Stockton (Lower Broas) coal based on mine data along parts of cross section A–A″ showing possible correlations of partings and in-seam thickness variability. Sample location 3815 is placed in its relative position to show relationship to lateral partings noted in the coal.

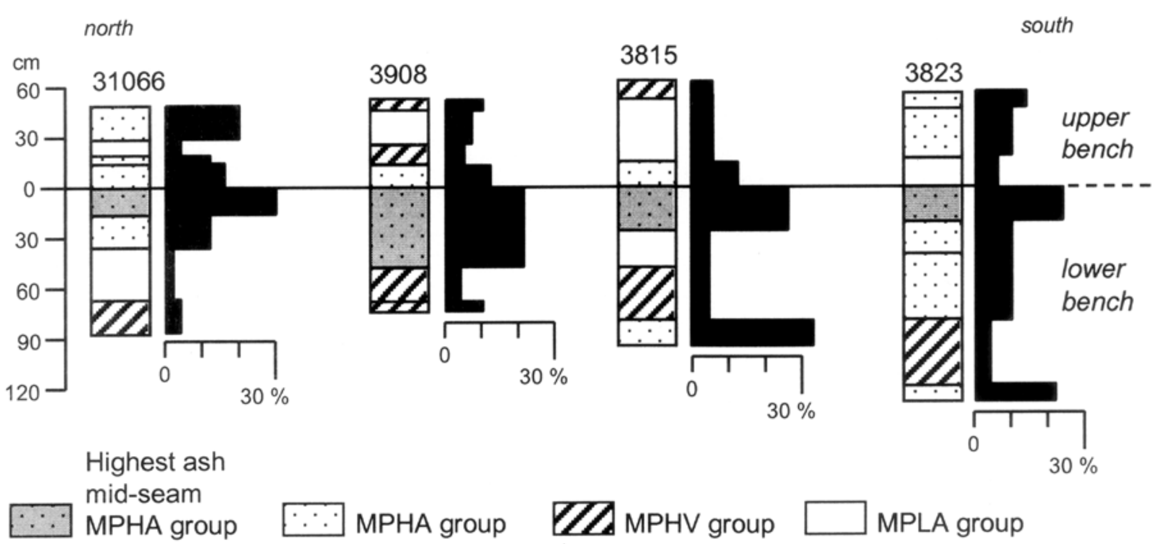

Figure 11. Comparison of ash yields and compositional groups in a bench architectural analysis of the four sample sites of Hower et al. (1996). Datum is the top of the highest ash parting in the middle of the seam. The parting and equivalent high ash increment can be used to define informal benches (upper and lower) composed of multiple sample intervals, in order to compare intraseam variability. MPHA—mixed palynoflora–high ash compositional group; MPHV—mixed palynofora–high vitrinite group; MPLA—mixed palynoflora–low ash group.

along the northern and southern margin of the mineable coal area. These results should be tempered with the fact that this is a small sample set.

DISCUSSION

Structural Controls

Obvious sandstone stacking is not apparent in Figure 4, although it would be difficult to discern because much of the interval between the Magoffin Shale member and Richardson coal is dominated by sandstones. Likewise, there is no large-scale thickening of the interval across mapped structures. This does not mean, however, that there were not structural influences on Lower Broas (Stockton) coal. Several scales of structural influence on coal thickness and distribution can be inferred from a comparison of the structure map (Fig. 7) and coal isopach (Fig. 8). The northern limit of coal greater than 92 cm thick, which generally defines the limit of mining (Fig. 3), occurs along a trend that represents a continuation of the Warfield structures (Figs. 1C and 1D) westward from the Kentucky–West Virginia border (Fig. 12). The western limit of thick coal is the eastern margin of the Floyd County Channel–Paint Creek Uplift. Areas of coal greater than 122 cm thick are almost completely limited to the area south and east of these basement structures. Likewise, the area in which the Stockton and Peach Orchard coals merge (Figs. 4 and 5, D–D″) is between branches of the anticline along the Warfield Lineament (dotted lines in Fig. 8), which is the inferred bounding fault of the Rome Trough (Fig. 12). Northward splitting is coincident with the direction of throw on the inferred fault and opposite the overall trend of southward accommodation into the basin.

Seismic analyses of the Warfield Fault in Kentucky (Lowry et al., 1990) and neighboring West Virginia (Gao and Shumaker, 1996; Gao et al., 2000) indicate flower structures above the fault along its strike. Many of the small-scale, unnamed faults, anticlines, and synclines that parallel the overall Warfield trend on the Stockton structure map (Fig. 6) probably represent the small-scale, mid-Pennsylvanian expression of those flower structures.

Westward thinning occurs toward the Floyd County Channel and Paint Creek Uplift. If the Paint Creek Uplift was active before or during accumulation of the Stockton paleomire, it

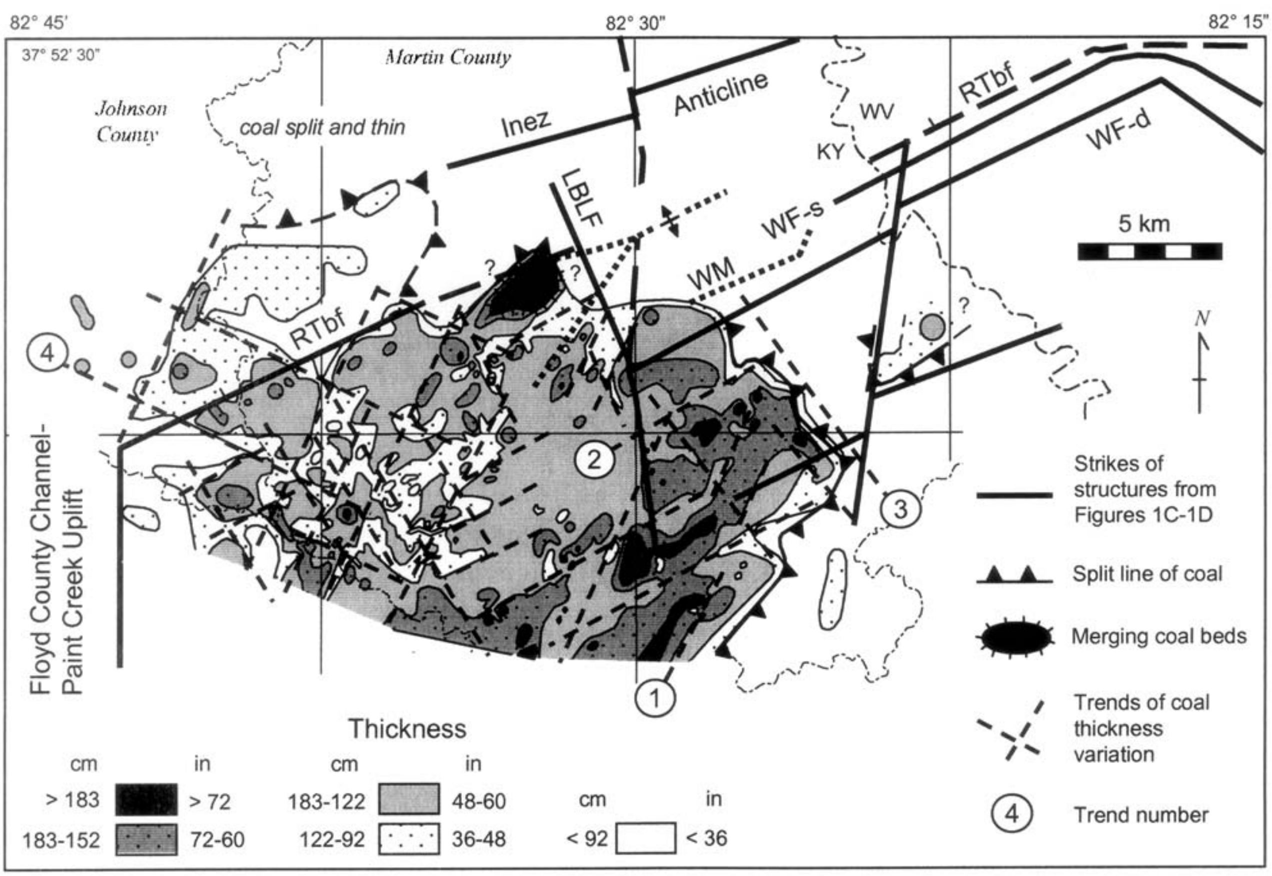

Figure 12. Comparison of coal thickness to structures in the study area. Four elongate trends of coal thickness are defined. See text for explanation of trends by numbers. LBLF—Little Black Log fault; RTbf—Rome Trough bounding fault; WF-s—surface trace of the Warfield Fault; WF-d—trace of the Warfield Fault at depth; WM—Warfield Monocline.

may have been manifested as a topographic high toward which the peat thinned. The bench architecture appears to indicate westward thinning from the bottom of the seam (Fig. 5, A–A′), which would be consistent with a peat infilling the topography and onlapping toward a topographically higher area. To the northwest, north, and east, coal splits suggest syndepositional drainages and paleotopographic lows.

There is also a slight correspondence of coal greater than 152 cm thick to the eastern side of the Little Black Log fault (Fig. 1D) in the southern Kermit and northern Varney 7.5′ quadrangles (Fig. 12). This structure is not defined at the surface but appears to influence production in deeper Devonian gas shales (Shumaker, 1987; Lowry et al., 1990). The eastern split margin of the mined Stockton coal in Martin County is located between this strike-slip fault and another unnamed strike-slip fault that offset the Warfield structures at depth (Fig. 12). Synsedimentary movement of the faults or fractures related to the faults may have influenced the position of a northwestward-flowing drainage to the area between the faults rather than elsewhere. Paleofractures and faults have been interpreted as controlling the position of paleochannels in many parts of the coal field (Horne et al., 1978; Powell, 1979; Greb et al., 1999).

A second scale of possible structural influences involves elongate trends in coal thickness. At least two subtle trends of northwest-southeast and northeast-southwest coal thickness variation can be inferred from the coal thickness map (Fig. 12, short dashed lines). The first northeast-southwest trend (N20–25°E) is apparent in the eastern part of the mineable coal area as elongate trends of thick coal (183–152 cm thick), and in the western mined area, as the linear western limit of coal greater than 92 cm thick, and more subtle, narrow trends of coal thinning in southeastern Martin County, which approximate a rectangular trend (Fig. 12, trend 1). This trend parallels a series of small anticlines and synclines at the base of the Stockton structure map in the Varney 7.5′ quadrangle (cf. Fig. 7). The area of merging Peach Orchard and Lower Broas coal may be partly related to this trend.

The second northeast-southwest trend (N60–65°E) is represented by the limit of widespread thick coal south of the eastern boundary fault of the Rome Trough, a series of small trends of coal thinning in the center of the mined coal area, and the orientation of coal greater than 183 cm thick along the eastern split margin of the coal (Fig. 12, trend 2). The trend of the area in which the Peach Orchard and Lower Broas coals merge into a thick composite seam is also along this trend. Trend 2 is parallel to the Warfield structural trend, two unnamed faults between the strike-slip faults shown in Figure 1D, and to the strike of the southeast limb of the Eastern Kentucky Syncline (Figs. 1C and 7).

The third and fourth trends of coal thickness variation (Fig. 12, trend 3, 4) are subordinate to the first two trends. Both are oriented along northwest-southeast trends. Trend 3 (N35–40°W) is at near right angles to trend 2, and trend 4 (N60–65°W) is at right angles to trend 1. In the eastern area, trend 3 is most visible as the orientation of the northeastern part of the split line of mined coal (Fig. 12, trend 3). In the western area, trend 4 is most visible as a projection of coal 92–122 cm thick into southern Johnson County, and as part of a crudely rectangular thickness trend (with trend 1) in southwestern Martin County (Fig. 12, trend 4). Trend 3 is close to the trend of the northern part of the Little Black Log fault (LBLF in Fig. 12), and an inferred transform fault that offsets the southeastern margin of the Rome Trough in neighboring West Virginia (Fig. 1D, Gao et al., 2000). Trend 3 is at near right angles to the Warfield structures trend. Trend 4 is similar to trends of Devonian gas shale production, which are probably fracture controlled (Shumaker, 1987).

Subtle northeast-southwest and northwest-southeast structural trends have previously been interpreted for older coals southwest of the study area (Weisenfluh and Ferm, 1991; Greb et al., 1999). Trends in these previous studies are slightly different than the trends in this study, although trend 4 is close to one of the trends seen in the Fire Clay coal (Greb et al., 1999). In all cases, closely spaced data were needed to define the trends because they document thickness variation on the scale of centimeters across large areas. Because the four trends form two conjugate pairs, the orientations are interpreted as paleofracture trends. If the Warfield structural trend and bounding fault of the Rome Trough was a structural hingeline during peat accumulation, the arching effect may have exerted local tensional forces on preexisting fracture trends, which could have influenced surface water and groundwater flow.

Areas of thin coal noted as “rolls” on mine maps probably represent truncation or compaction of the coal beneath sandstones in the mine roof. In the mined area, rolls noted on mine maps are parallel to local structure trends on the base of the coal (Figs. 7 and 8), indicating that fracture trends, topographic expression of local structures, or peat thickness and compaction trends related to underlying structures influenced the position of postpeat drainages. Rolls near the Warfield structures trend are oriented along trend 2, parallel to the Warfield trend. Farther south and west, sandstone roof rolls are oriented along trend 1.

Paleoecology of the Stockton Paleomire

Interpretations of original mire paleoecology can be inferred from the compositional groups identified in measured sections and from the vertical stacking and lateral juxtaposition of compositional groups to seam architecture (especially relative to bench thickness and partings in the coal).

Mixed Palynoflora–High Vitrinite Group

The relative abundance of lycopsid tree spores and vitrinite macerals in the mixed palynoflora–high vitrinite group (Table 1, Fig. 9) suggests topogenous mire conditions with standing surface water, at least some of the time, similar to previous interpretations of mixed palynoflora–vitrinite-dominant groups in older coals of the basin (Eble et al., 1994; Greb et al., 2002b).

Lycopod trees had specialized megasporangium (*Lepidocarpon, Achlamydocarpon*), which were designed for dispersal in water (Phillips, 1979; DiMichele and Phillips, 1994). A waterlogged substrate would also favor the formation of vitrinite and pyrite, both of which are promoted by anaerobic conditions (Teichmüller, 1989). The fact that the mixed palynoflora–high vitrinite group is thickest and most common in the lower part of the lower bench of the coal is consistent with an interpretation of a relatively wet substrate developing in topographic lows.

All of the benches in this group contain 70% or more vitrinite on a mineral-matter-free basis. In previous studies of coals where 80% vitrinite was used as the cutoff for a mixed palynomorph vitrinite-dominant group, the vitrinite dominant group was inferred to represent a transitional (mesotrophic) mire (Eble et al., 1994; Greb et al., 2002a). In contrast, topogenous (rheotrophic) mires (sometimes called planar mires), in which the peat obtained all of its water from groundwater and the peat surface was supersaturated to submerged, were interpreted for "*Lycospora*-vitrinite dominant" compositional group because it had high vitrinite (>80%) and also high *Lycospora* (>70%) percentages. None of the increments analyzed herein contains enough *Lycospora* to indicate similar supersaturated conditions in the Stockton paleomire. Likewise, if the average amount of lycopsid tree spores in the mixed palynoflora–vitrinite dominant (80.6%) for the older Fire Clay coal (Eble et al., 1994) is compared with the mixed palynoflora–high vitrinite group (46.7%) in the Stockton coal, it can be seen that even in the compositional groups in which there is significant vitrinite, the percentage of arborescent lycopod tree spores is significantly reduced. A relative decrease in wetness or saturation of the peat mire could very well be climate related. Previous interpretations of Bolsovian paleoclimates have suggested more seasonally wet climates, as opposed to the more everwet conditions earlier in the Pennsylvanian (e.g., Cecil, 1990).

Mixed tree-fern, lycopsid, and cordaite spore assemblages in coals from other basins have been interpreted as representing planar mires with seasonal or periodically high water tables (Calder, 1993). The mixed palynoflora–high vitrinite group for the Stockton coal is interpreted as representing topogenous (planar) to soligenous mire conditions with fluctuating or relatively high water tables. Soligenous mires are mires in which water seeps from springs or slopes laterally through the peat. In the local study area, where fractures appear to have influenced groundwater flow and subsequent peat thickness, it is possible that springs and seeps influenced peat accumulation. The mixed palynoflora–high vitrinite group is also indicative of mesotrophic to rheotrophic (minerotrophic) nutrient conditions because nutrients were probably supplied to the peat through groundwater, especially in the lower bench where this group is best developed.

MPLA Group

The MPLA group is dominated by tree ferns with few arborescent lycopsid spores (Table 1, Fig. 9). Ecologically, the paucity of arborescent lycopsid spores in the MPLA group indicates that persistent water cover was rare in the mire when this group accumulated. Tree ferns and *Omphlophloios* were the dominant vegetation. These plants did not require a flooded surface for reproduction (DiMichele and Phillips, 1994). Hower et al. (1996) noted that lithotypes with common tree ferns (some corresponding to MPLA and some to MPHA compositional groups) have high fusinite and semifusinite and low telinite/gelocollinite ratios, suggesting that aerial root bundles of the tree ferns were subject to oxidation (either through fire or biodegradation). Tree-fern–dominated, dull lithotypes also were noted in the Stockton coal in West Virginia (Eble and Grady, 1993; Pierce et al., 1993). These factors in combination with high inertinite contents and low sulfur contents of the MPLA group were previously used to interpret an ombrogenous (domed) origin for the Stockton paleomire (Eble and Grady, 1993; Pierce et al., 1993; Hower et al., 1996). Architectural analysis, however, indicates that these attributes are not equally distributed in the coal at this location.

At three locations, MPLA increments occur in both the upper and lower bench, separated by the midseam durain, MPLA increment (Figs. 9 and 11). Although this juxtaposition could be interpreted as representing a stacked domed mire succession, the parting and high-ash increment between the low-ash increments is problematic. The type of domed mires generally used as analogs for mid-Pennsylvanian peats are the ombrogenous peats of modern Indonesia and Malaysia (e.g., Cecil et al., 1993). These peats obtain their water from precipitation in tropical climates where precipitation greatly exceeds evapotranspiration. Tropical ombrogenous domes commonly build to heights in excess of 10 m above base level for areas of hundreds of square kilometers (Anderson, 1983; Esterle et al., 1992; Cecil et al., 1993). The peat domes are protected from fluvial encroachment by their height. For a high-ash increment or parting, which is laterally equivalent to relatively close by seam splits, to be emplaced between two "domed" increments in the Stockton coal, the original peat dome would have to have been flooded by excessively high flooding and then continue as an ombrogenous peat after flooding. This is unlike the development of ombrogenous-ombrotrophic peats in modern tropical analogs.

Thick MPHA group increments occur in the lower bench of the coal at three locations (Figs. 9 and 11). The thickest increments in the lower bench occur at the two locations where the lower bench is thickest (Fig. 11). This relationship suggests topographic control on at least the lower MPHA increments. Although MPLA group increments occur in the upper bench in all four sample locations and could indicate a widespread peat dome, the relative position of MPLA increments in the upper bench when compared with lateral areas of coal with numerous persistent partings (Fig. 10) indicates that any domed phase of the mire would have been significantly less widespread than the type of ombrogenous domes seen in modern tropical analogs.

The parting-free area of the upper bench in the mined area of the Stockton coal in eastern Kentucky is difficult to ascertain because of a lack of bench-scale increment data in some of the mines, but is certainly less than 100 km^2. Therefore, a qualification is needed for interpreting low-ash, low-vitrinite compositional groups as originally formed from tropical, ombrogenous peat domes. That qualification is that the increment should be widely correlatable and occur in a part of the bench that is free of partings. If ombrogenous conditions developed in the Stockton paleomire at all, they were relatively short-lived in the upper bench of the mire.

If MPLA increments were not formed in large, widespread ombrogenous domed mires, then they must have accumulated in low-ash topogenous (planar) to soligenous mires. Staub and Cohen (1979) documented low-ash planar mires in the southeastern United States. In these mires, pH differences in water chemistry between mire waters and lateral drainages caused clay to flocculate adjacent to the channel margin and limited extensive inundation of mineral-laden waters into the mire. This analogy has been used in several studies that have interpreted low-ash coal beds as ancient planar, low-ash peats (Littke, 1987; Cairncross and Cadle, 1988; Staub and Richards, 1993). Another possibility is that the peats were spring or seep fed and that seasonal variations in mineral-poor spring waters resulted in periodic oxidation, without significant sediment contribution to the peat.

MPHA Group

The dominant compositional group at the study sites is the MPHA group. The high ash yields in the MPHA group (Table 1, Fig. 9) reflect times when clastic influx into the paleomire was active and resulted in high-ash increments and inorganic partings. The dominance of this group in the coal is consistent with the abundant partings seen in the coal along at least the southwestern and eastern margins of the coal (Figs. 10 and 11).

The MPHA group is common at the base of the seam where the lower bench of the seam is thick (Fig. 10). Hower et al. (1996) noted variability in durain layers at the base of the seam, which were interpreted to have resulted from the Stockton (Lower Broas) paleomire infilling an uneven topographic surface. Variable and locally high ash yields would be expected in topogenous (planar) peats that were infilling topographic depressions as these same depressions would tend to be the loci for local clastic sedimentation. Such peats would have been rheotrophic (minerotrophic) because they would have obtained their nutrients mostly from groundwater. Mineral-rich floodwaters from lateral channel flooding or percolation from groundwater through underlying fractures could have formed these increments at the base of the seam.

The MPHA increment also occurs in a durain toward the middle of the seam at all four locations. In detailed bench architecture sections of the coal in the study area, there appears to be a widespread bone coal or shale parting toward the middle of the seam in several areas (Fig. 10). The midseam rock partings, bone coal or durain layers, and high-ash increments appear to be continuous with splits on at least three margins of the mined coal area and indicate a period of widespread flooding from lateral channels. The high-ash durain and lateral partings mark a surface in the peat in which the paleotopography was essentially flat.

Where the MPHA group is common at the top of the seam (Figs. 9 and 12), it undoubtedly reflects clastics introduced during the drowning phase of the mire. MPHA and MPHV increments at the top of the seam generally have increased arborescent lycopsids as compared with underlying increments and have the largest percentage of calamites spores of all increment samples (Fig. 9). As previously mentioned, arborescent lycopsids required standing water, which is consistent with a rise in base level and mire flooding. Likewise, calamites are typically associated with riparian flora (Scott, 1978; Gastaldo, 1987) and sediment incursions (Smith, 1962; DiMichele and Phillips, 1994).

Flooding, Sulfur Content, and Sequence Complications

The greatest sulfur contents at three of the four sample sites occurred at the top of the seam, either in the uppermost MPHA or in mixed palynoflora–high vitrinite increment (Table 1, Fig. 9). Hower et al. (1996) inferred that high sulfur contents resulted from marine flooding of the paleomire. The Stockton (Lower Broas) coal occurs at the top of the Four Corners Formation (Fig. 2), which is a third-order genetic sequence (Greb et al., 2002b). There is a tendency toward higher sulfur coals beneath maximum flooding surfaces in each of the Breathitt formations–genetic sequences (Cobb and Chesnut, 1989; Greb et al., 2002b), which supports the idea of marine flooding somewhere above the Stockton (Lower Broas) coal.

A complication to that idea, however, with regards to the Stockton (Lower Broas) coal, is that the Stoney Fork marine zone is not well developed in the study area. Marine fossils were noted in one core above a split in the Broas coal zone in northern Martin County, and locally a bioturbated sandstone occurs above the Stockton (Lower Broas) coal (Fig. 5, A–A″; Huddle and Englund, 1962a, 1962b). Neither horizon can be widely correlated. The poor development of the Stoney Fork horizon suggests that either this transgression was not as extensive as earlier transgressions or that sediments deposited during the transgression were removed by subsequent lowstand incision in a low accommodation setting. The limited bioturbation and high sulfur contents at the top of the coal are the only evidence of the marine incursion in this part of the basin. Where the Stoney Fork pinches out or is truncated, the equivalent of the marine flooding surface would be predicted to occur between the upper and lower coals in the Broas coal zone.

SUMMARY

The Stockton (Lower Broas) coal in the Martin County area of eastern Kentucky is a good example of the different scales at which basin structures can influence coal distribution and thickness as well as the benefits of a coal systems approach to geologic analyses of coal-bearing strata. Trends of thickness and coal splitting are related to different types and scales of structures. The overall southeastern thickening trend reflects subsidence into the basin. The northern and western limits of the mined coal are related to faults bounding basement grabens and uplifts. Two conjugate, northeast-southwest and northwest-southeast thickness trends are interpreted as reflecting paleo-fracture trends. Fractures are interpreted to have influenced the paleotopography that was infilled by the Stockton paleomire, and possibly groundwater flow during peat accumulation. If the latter, parts of the Stockton might have accumulated as spring- or seep-fed soligenous mires. Accurate delineation of subtle structure and thickness trends requires detailed mapping at the mine scale or closely spaced well data, but can be useful for projecting thickness trends in advance of mining.

Coal-bench architecture analyses of the Stockton (Lower Broas) coal shows that the thickest coal results from the merging of the Peach Orchard coal with the Stockton coal along the Warfield structure trend. Recognition of merging coal beds or benches can be important to understanding both thickness and quality trends because the composite seam is a combination of distinctly different beds. Architectural analyses also indicates that splits on the margins of the mined coal can be traced into the seam as a midseam parting or high-ash durain. The durain or parting can be used as a datum for testing intraseam variation. In some seams in the basin, there is significant thickness and quality variability within seams (between benches). In the study area, Stockton (Lower Broas) thickness variation is mostly concentrated in the lower bench. Limited data indicate similar quality characteristics between benches with slightly more ash in the lower bench and slightly higher sulfur content in the upper bench. Most of the sulfur is concentrated in the uppermost increment of coal, such that differential mining of the seam could be used to high-grade the quality of the mined coal in a surface mine.

Compositional group analyses of the coal indicates that the Stockton paleomire was dominantly a topogenous-planar to possibly soligenous-transitional mire with a mixed plant assemblage dominated by tree ferns. Some parts of the coal contain low-ash, low-vitrinite increments with common *Densosporites* spores. Similar assemblages have been interpreted as indicative of ombrogenous, domed peats. If representative of doming, the relative abundance of the low-ash increments, and the extent at which they occur in the upper bench in the absence of lateral partings, indicate that peat domes would have been relatively short-lived. Rather than domed mires, the occurrence of numerous partings and high-ash durains lateral to low-ash compositional groups indicate that the low-ash increments in this part of the Stockton paleomire could represent (1) topogenous to soligenous mires that had relatively high water tables and/or (2) topogenous mires in which water chemistry was significantly different from bounding drainages so that clastics were partly prevented from entering the mire center. High and variable water tables may have been spatially related to structurally controlled fractures and groundwater flow, and temporally related to changing climates, which are inferred to have been more seasonal in the late Middle Pennsylvanian than earlier.

The Stockton paleomire was subsequently flooded during the Stoney Fork transgression. Sulfate-bearing waters filtered into the top of the buried peat. High sulfur contents in the top of the coal may be the only evidence of the transgression in this part of the basin. Low accommodation brought the Stockton (Lower Broas) coal into close proximity with a coal that accumulated in the next genetic sequence, the Upper Broas coal, to form the Broas coal zone. Such complications to sequence stratigraphy would be expected on the margins of foreland basins.

Understanding regional tectonic, eustatic, and climatic changes at the time of peat accumulation is critical to understanding the possible controls on peat paleoecology and subsequent coal distribution and thickness. Such an understanding can be achieved through analyses of different types and scales of data (a coal systems approach), including mine-scale data, which can then be used to more accurately address a wide variety of mining issues, from regional resource analyses to mine-scale prediction of coal thickness and quality trends. Detection of subtle paleofracture-related thickness trends requires closely spaced data across a broad area.

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Palynology in coal systems analysis—The key to floras, climate, and stratigraphy of coal-forming environments

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ABSTRACT

Palynology can be effectively used in coal systems analysis to understand the nature of ancient coal-forming peat mires. Pollen and spores preserved in coal effectively reveal the floristic composition of mires, which differed substantially through geologic time, and contribute to determination of depositional environment and paleoclimate. Such applications are most effective when integrated with paleobotanical and coal-petrographic data. Examples of previous studies of Miocene, Carboniferous, and Paleogene coal beds illustrate the methods and results. Palynological age determinations and correlations of deposits are also important in coal systems analysis to establish stratigraphic setting. Application to studies of coalbed methane generation shows potential because certain kinds of pollen are associated with gas-prone lithotypes.

Keywords: palynology, coal, paleoecology, paleoclimatology, palynostratigraphy.

INTRODUCTION

First Principles

Coal is formed from accumulations of plant matter in mire environments (the term "mire" includes swamps, marshes, moors, fens, and bogs). The kinds of plants inhabiting coal-forming mires have changed through geologic time but can also differ with the diverse ecological settings of mires. Different kinds of plants can form coal deposits with a variety of compositional characteristics. Understanding the kinds of plants that formed a particular coal deposit contributes to understanding the properties of the coal (other than rank) that may have economic significance in coal utilization.

The coalification process involves the structural and chemical decomposition of plants. Consequently, the kinds of plants that formed a particular coal deposit cannot be directly identified by examination of the coal. However, spores and pollen produced by plants inhabiting ancient coal-forming mires are well preserved in all but the most highly altered coal deposits. Therefore, study of the fossil spores and pollen preserved in coal can be the key to understanding the nature of the plant communities of ancient mires. Knowledge of the vegetation of ancient mires leads to interpretations of their paleoecological settings and of paleoclimates, which are major factors affecting "coal systems" as defined elsewhere in this volume. Palynological studies of coal also provide valuable data on age and correlation of coal beds and coal zones, which are important features of coal systems.

Palynology in Coal Systems Analysis

Warwick (this volume) explains that the development of a coal system from the initial deposition of peat to the ultimate utilization of a coal resource involves several phases, including accumulation, burial, and preservation, and diagenetic to epigenetic coalification. The accumulation phase includes five fundamental components: plant type, peat mire type, climate,

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sedimentation style, and syngenetic processes. Palynology is the key to determining the first three of these components in a particular coal system. Pollen and spores preserved in coal are primary evidence of the kinds of plants that formed the deposit. The type of mire can be interpreted largely through an understanding of the plant communities that inhabited the mire, critical data on which comes from palynological analyses. The climate in which the mire existed influenced the nature of its plant community, and in the absence of megafossil paleobotanical data, palynological determination of the dominant vegetation of the mire is basic data for interpretation of paleoclimate. Examples that follow demonstrate the application of palynology to analyses of these three components of coal systems (see also O'Keefe et al., this volume). The final phase in the analysis of a coal system concerns the resource itself—coal and associated hydrocarbon resources such as methane gas. Palynology may also contribute to investigations of coalbed methane generation, as shown by one intriguing example presented here.

Also important in studies of coal systems and the exploitation of coal deposits are the geologic age and stratigraphic correlation of coal beds or coal zones. The use of stratigraphic palynology in conjunction with the essentially paleoecologic investigations outlined above have a long history in coal geology. This history is not reviewed here, but some complications and a successful methodology are briefly discussed.

It is a given that analyses of coal systems will benefit most from integrated studies that incorporate coal-geologic, coal-petrographic, and available paleobotanical data together with palynological data. Examples of such studies are those of Pierce et al. (1993) and Hower et al. (1996), both on a Pennsylvanian coal seam in the Appalachians, and Demchuk et al. (1993) and Kalkreuth et al. (1993), on Paleogene coal beds of Canada. These studies integrate palynological data with paleobotany, coal petrography, geochemistry, sedimentology, and stratigraphy, and this is clearly the most effective approach; it is not the intent of this paper to suggest otherwise. The purpose of this paper is to focus on the value of palynology in coal systems analysis, especially in revealing the nature of the types of plants and the plant communities that inhabited coal-forming peat mires. The types of plants that inhabited coal-forming peat mires have varied greatly through Paleozoic, Mesozoic, and Cenozoic time (Cross and Phillips, 1990; cf. Traverse, 1988). The floristic composition of coal floras is known from comprehensive paleobotanical analyses of plant fossils preserved either within coal (e.g., coal balls) or more commonly in associated strata, but as DiMichele and Phillips (1994) have noted, palynology is the backbone of paleobotanical studies of coal beds themselves.

The earliest examples of palynological studies in coal geology certainly well precede the recent development of the concept of coal systems. Anything approaching a comprehensive historical review is certainly beyond the scope of this paper. Examples are drawn selectively from the literature to illustrate the manner in which established palynological methods can be applied to the analysis of coal systems.

SELECTED EXAMPLES

Reconstructing Ancient Mires

A seminal palynological study of a coal deposit leading to an interpretation of the flora of the mire from which it was derived is that of Traverse (1955) on the Brandon lignite, a non-commercial coal of early Miocene age (Traverse, 1994). In his 1955 study, Traverse documented the pollen and spore flora of the lignite and related it to modern plant genera and families to reconstruct the ancient mire flora. The palynoflora of the Brandon mire is numerically dominated by pollen of flowering plants (angiosperms), especially fossil species referable to the living beech and cyrilla families (Fig. 1a). The modern affinities of certain other fossil plants represented by pollen in the coal enabled Traverse (1955) to reach important conclusions about the subtropical to tropical paleoclimate of the Brandon deposit. Traverse's research was supplemented by a megafossil paleobotanical study of the Brandon lignite (Barghoorn and Spackman, 1949). The identification of the early Miocene plant genera and families was aided by comparisons of paleobotanical and palynological data, but significantly, Traverse (1955, p. 19) observed that a survey of the Brandon mire flora could have been accomplished on the basis of palynology alone.

Although there were important floristic differences, Traverse (1955) found the closest modern analog to the Brandon lignite mire in the swamps of Florida. Cohen and Spackman (1972) later studied the peat deposits of southern Florida with the goal of reconstructing the ancient environments in which they formed; these peat deposits were viewed as precursors to coal deposits. Several distinctive types of peat were identified in this work, including those formed predominantly or largely of mangroves, saw grass, water lilies, and ferns or admixtures of these plants. The depositional environments of these peats ranged from marine (the mangroves) through brackish to freshwater (saw grass and water lilies). Cohen and Spackman's (1972) analyses of peat types were primarily paleobotanical in nature but were supplemented by unpublished palynological data of Riegel (1965). Riegel's data could be used to distinguish the peats of marine and freshwater origin.

Teichmüller (1958) studied other coal beds of Miocene age in Germany. Teichmüller defined four mire plant communities that had contributed to the accumulation of coal-forming peat deposits: reeds in a broad sense (including rushes, sedges, and water lilies), forested swamp, wetlands with shrubs, and redwood forest. This is a classic study reconstructing ancient mires and their floras, but the recognition of these distinctive communities was based more on paleobotanical data than palynology. Teichmüller evidently regarded the reliability of palynological data as somewhat uncertain, despite the fact that Traverse (1955) had previously established the validity of such an approach. The significance of Teichmüller's (1958) study from the perspective of coal systems analysis is that the different kinds of peat formed Miocene brown coals (lignites) of differ-

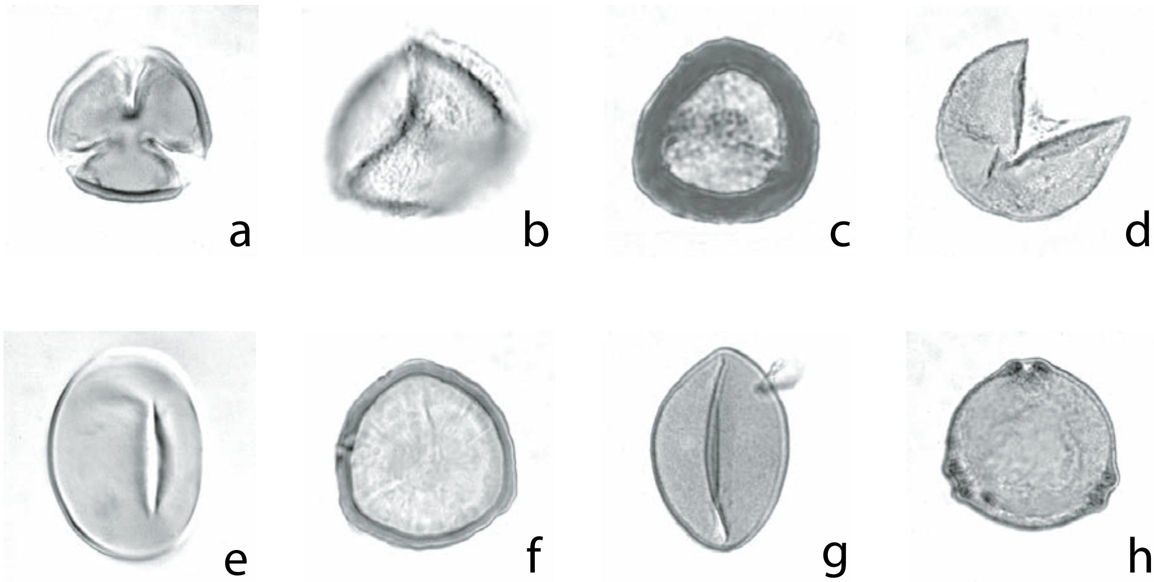

Figure 1. Some pollen and spores types mentioned in the text: (a) cyrilla pollen, (b) lycospore, (c) densospore, (d) conifer pollen, (e) fern spore, (f) sphagnum spore, (g) palm pollen, (h) birch pollen. Average size of specimens is ~35 μm.

ing quality. Differences in the peat could be traced back to the plant communities in which it accumulated.

A more recent interpretation of Miocene brown coal floras that relies more on palynological data is that of Sluiter et al. (1995). This is a comprehensive study that also incorporates paleobotany along with neobotanical data on the climatically controlled distribution of living relatives of the mire flora, and it summarizes a large body of previous research on these important deposits of southeastern Australia. A new model for the origin of coal lithotypes within the coal-bearing interval is proposed that challenges a sequence-stratigraphic model for the same coal beds (Holdgate et al., 1995). The sequence-stratigraphic model also utilizes palynology, but primarily for age control. The two models invoke, respectively, either changes in sea level or changes in paleoclimate to account for variations in coal lithotypes. Both studies are good examples of the concept of coal systems analysis; that of Sluiter et al. (1995) appears preferable because it accommodates the extensive body of data on the vegetation of the mires. Other palynologically based studies of these Miocene coals include Kershaw and Sluiter (1982) and Kershaw et al. (1991), both of which make reference to the work of Teichmüller (1958). It is important to note that the floristic compositions of the Miocene floras of Germany and Australia were thoroughly different, due to profound differences in the floras of the Northern and Southern Hemispheres in late Cenozoic time.

The studies of floras of Holocene peat mires of Florida and Miocene coal-forming mires of Vermont, Germany, and Australia cited above could utilize paleobotanical data to supplement or confirm palynological identifications of plants in the respective paleoenvironments because coalification processes had not advanced beyond the point at which megafossil remains could be recognized. In most coal deposits of Paleozoic age, however, such an approach would not be possible. In most such deposits, only pollen and spores are preserved well enough to provide evidence of the plants that inhabited the ancient mires. A major study of Carboniferous coal beds serves as a good example of an exclusively palynological approach.

Smith (1962) conducted detailed palynological analyses of bituminous coal seams in the Carboniferous of England and defined four "associations" of spores (assemblages containing ecologically related species) that represent different phases in the development of the coal-forming mires. Within the vertical profiles of individual seams, distinctive associations of spores are present in what Smith dubbed the lycospore phase, the densospore phase, the transition phase, and the incursion phase. The incursion phase is associated with increases in ash content of the coal and appears to represent flooding events within the ancient mires; it occurs randomly within seams. In contrast, there is a pattern in the occurrence of the other phases. The lycospore phase is usually at the base of a seam, but the densospore phase never is, and the transition phase is always present between these two, which are never directly superjacent to one another. Smith interpreted the shifts in mire communities (and hence in spore associations) to changes in water table and/or paleoclimate that affected ecological successions within the mires. The parent plants of these spores are known to be various species of arborescent or herbaceous lycopods and ferns (e.g., Traverse, 1988), but the paleobotanical relationships are of minor importance in this study. Smith also found that the four palynologically defined phases were related to petrographic differences within the coal seams. Later he used the combined data from palynology and coal petrography to develop a model for interpretation of the depositional history of seams that placed more emphasis on changes in the water table than on paleoclimate (Smith, 1968). In a review of Smith's 1962 work, Chaloner and Muir (1968) emphasized the manner in which the sequence of phases Smith described reflected ecological succession within the Carboniferous mires. The densospore phase was seen as representing the ecological "climax community," which failed to be attained in some mires due to repeated marine incursions that disrupted the succession.

Lycospores (Fig. 1b) and densospores (Fig. 1c) are prominent in two of five distinctive palynological assemblages (associations in the terminology of Smith) in a Carboniferous (Pennsylvanian) coal in North America described by Habib (1966). Habib observed apparent ecological successions reflected by these assemblages at numerous localities where he sampled the same coal seam over a laterally extensive area. He attributed differences in completeness of the successions from locality to locality to varied conditions of freshwater and saline water in the depositional environment from place to place in the ancient environment. These differences were due to changes in the water table and to marine incursions, which were determined from analyses of the shale overlying the coal. Habib's interpretations are not in complete accord with those discussed above for the Carboniferous of England, placing as they do more importance on changes in the paleoenvironment than on ecological succession within a mire plant community. They serve to illustrate how detailed palynological analyses of coal can reveal much about its origin in a coal system, including the stratigraphic setting.

A more recent palynological analysis of Pennsylvanian coal is that of Eble and Grady (1990), who studied the palynology and petrography of stratigraphically equivalent coal deposits in West Virginia and Kentucky. In a palynoflora that included 180 species, lycospores tended to be numerically dominant; the lycopod spores occur along with spores of ferns, calamites, and cordaites. In their interpretation of the mire flora, Eble and Grady distinguished four groups or associations of plants and related them to the petrographic characteristics of the coal (maceral abundances and ash content). From these data, they developed a model of the ancient mire as a domed peat. These authors also applied their model to a reinterpretation of Habib's (1966) data, suggesting a similar origin for that coal in a domed mire, rather than in a mire that was controlled by being gradually drowned by marine transgression. The final resolution of which interpretation is correct for the origin of these and other Carboniferous coal beds requires application of the coal-systems concept, taking into account all aspects of the geology of the deposits, including stratigraphy, petrography, geochemistry, and paleobotany—the last as revealed primarily through palynological analyses.

About the time that Smith (1962) was investigating the palynofloristic nature of Carboniferous coal beds in England, Kremp et al. (1961) began research on rather different coal beds, the Paleogene lignite of the western United States. The palynology of these deposits indicated that they had originated in mires inhabited by completely different kinds of vegetation from that which existed in the Carboniferous. Kremp et al. (1961) identified two distinct floral groups as the dominant plants of the geologically much younger mires: coniferous trees related to the living bald cypress of the southeastern United States and angiosperms related to the living wax myrtle and birch families. They noted a correlation between the pollen assemblages and the petrographic constituents of the coal, especially a correlation between abundance of the conifer pollen (Fig. 1d) and "anthraxylous material" (vitrain). It is now well established that woody components in peat contribute to the formation of exceptionally thick coal beds (Shearer et al., 1995), but this relationship was just beginning to be understood in the early 1960s. In retrospect, the work of Kremp et al. (1961) can be seen as an early attempt to understand coal systems.

The coal beds studied by Kremp et al. (1961) were Paleocene lignite from North and South Dakota. Recent detailed studies on coal of this age in the Dakotas and correlative coal beds in Montana and Wyoming were summarized by the Fort Union Coal Assessment Team (1999). Palynology was utilized in compiling these data, although more for biostratigraphy (age determination and correlation) than for paleoecological analyses of Paleocene mires. The mire palynoflora of one Wyoming coal bed more than 20 m thick was analyzed, however. Figure 2 summarizes the results of that analysis. The conifer pollen is characteristic of the living family that includes the bald cypress, and the angiosperm pollen consists largely of species Kremp et al. (1961) attributed to the wax myrtle and birch families, among others. Ecological changes within the mire are suggested by the shifts in relative abundance, analogous to the ecological succession observed in some Carboniferous mires by Smith (1962) but involving a totally different flora.

Nichols (1995) compared the palynological assemblages in six Paleogene coal beds in Wyoming and Colorado, one of which is correlative with the bed discussed above. Conifer pollen is present in great abundance in only two of the six, and in one of these, the abundance of spores of sphagnum moss (Fig. 1f) indicates that two differing mire floras are represented. In an earlier, more comprehensive analysis of the same two Wyoming coal beds, Moore et al. (1990) reached a similar conclusion about the floristic composition of the mire floras. In his study, Nichols (1995) also distinguished mire floras evidently dominated by ferns in two of the other coals analyzed, and mire floras dominated by palms in the other two. Clearly, dissimilar plant communities inhabited Paleogene mires of similar ages in the same part of the world. The mires inhabited by palms are especially interesting because their palynofloras carry a paleoclimatic signal. One of them is early Paleocene in age and has a dicot angiosperm as the codominant species, and the other is early Eocene in age and has ferns as codominant species; both mires evidently developed in tropical or subtropical temperature regimes, as indicated by the presence of palm pollen (Fig. 1g).

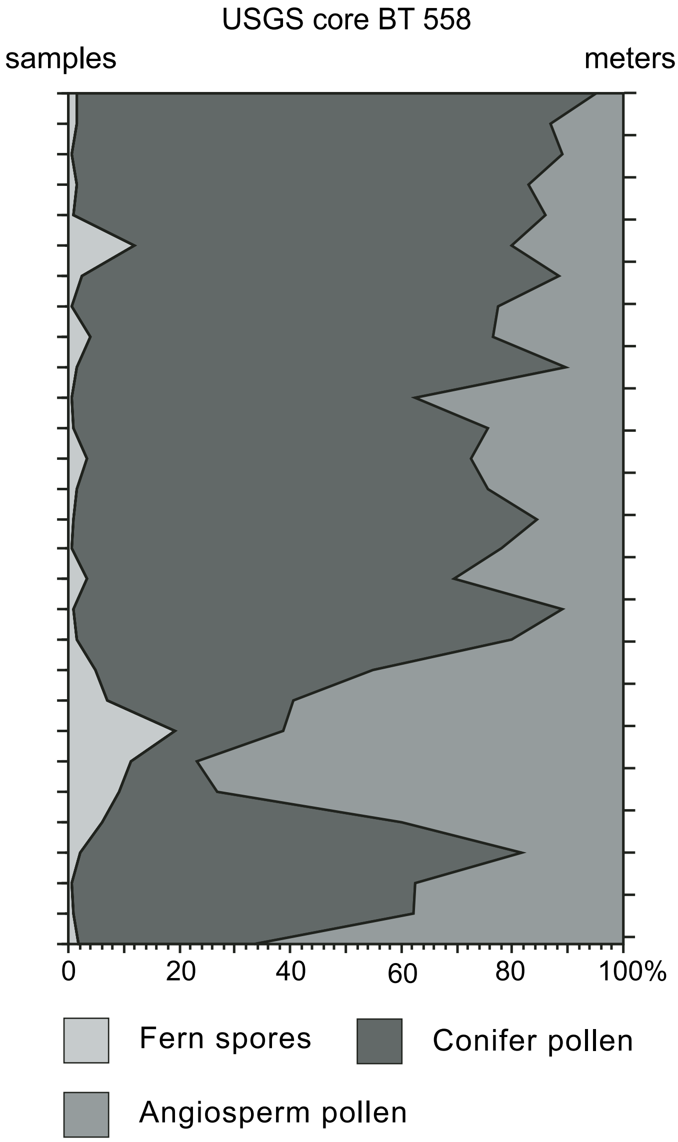

Figure 2. Palynological analysis of the composition of a Paleocene coal bed from Wyoming. As indicated by the relative abundances of pollen and spores of major groups of plants, conifers were the most common kind of plant that contributed to development of this coal bed. Modified from Nichols (1999b, Fig. PB-7).

In his comparison of mire palynofloras in the western United States, Nichols (1995) also discussed two assemblages of late Paleocene age in the Gulf Coast region of Texas that reflected two distinct mire plant communities, both of which were quite different from the age-equivalent mire communities of Wyoming. The coal-forming mires of the Gulf Coast in late Paleocene time were dominated not by conifers as in Wyoming, but by various communities in which angiosperms tended to be the most abundant. Nichols and Pocknall (1994) defined four palynofacies by selecting certain ecologically significant pollen and spore taxa within palynological assemblages, species that were not necessarily the most common in occurrence. Four distinct plant communities were thus distinguished, whose distribution matched that of coal beds that were deposited in contemporaneous fluvial, delta plain, and marginal-marine lagoonal paleoenvironments. Nichols and Pocknall then applied this method of analysis to a reexamination of the palynofloras of the late Paleocene mires of Wyoming. There they defined four other palynofacies that respectively represent raised mire, riverbank, heath, and lacustrine paleoenvironments. They noted that the coal beds that formed in these varied settings differed in qualities such as thickness, woody versus nonwoody composition, presence of partings, and ash content. This study exemplifies the palynological approach to what can now be thought of as coal systems analysis.

Correlating Coal Deposits

Age determination and correlation of coal beds and coal zones is perhaps the oldest practical application of palynology to coal geology, beginning with the work of Reinhardt Thiessen in the 1920s. Such studies are fundamental to understanding the stratigraphic setting of coal deposits. It should be evident, however, that difficulties in accurate correlation are created by similarities in palynological assemblages produced by similar, ecologically controlled mire floras. Two examples from literature already cited will suffice to illustrate this point.

The lycospore phase observed by Smith (1962) in the Carboniferous coal measures of England tended to occur repeatedly in different beds. Obviously, detailed correlations of individual beds on the basis of the presence of abundant lycospores would not be possible. Correlation would be possible only by reliance on the occurrence of stratigraphically restricted species of spores, which would tend to be rare rather than common in the assemblages. A disparate circumstance exists in the case of the Paleocene coal beds in the Gulf Coast of Texas discussed by Nichols and Pocknall (1994). There, different pollen and spore assemblages characterize contemporaneous deposits in genetically related paleoenvironmental systems. The age equivalence of these coal beds is not immediately obvious. In practice, the species in an assemblage from coal that are most useful for correlation were derived not from the mire flora but from plants living adjacent to the mire or even at some greater distance. Usually such species are more commonly found in associated noncoal clastic rocks than in the coal beds.

An example of the use of palynology to provide a stratigraphic framework for coal deposits is shown in Figure 3. Individual coal beds that developed in five different depositional basins through about 10 m.y. of Paleocene time are placed in stratigraphic context by using the palynology of the coal and associated clastic rocks for age determination and correlation. Applications of this framework in the Rocky Mountains and Great Plains region are discussed in Fort Union Coal Assessment Team (1999) and Nichols (1999a).

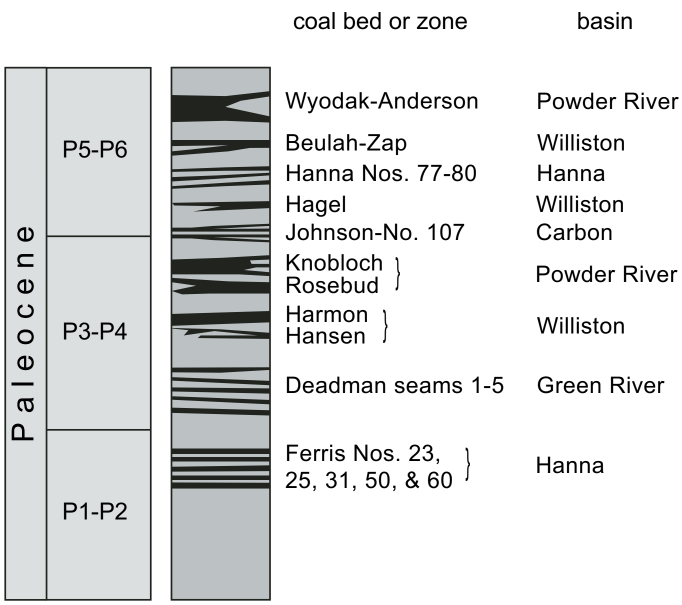

Figure 3. Composite stratigraphic section of Paleocene rocks in coal basins in Wyoming, Montana, and North Dakota showing palynologically determined ages of principal coal beds and zones. Designations P1 through P6 are palynostratigraphic biozones based on pollen species having restricted stratigraphic ranges. See Fort Union Coal Assessment Team (1999) for details.

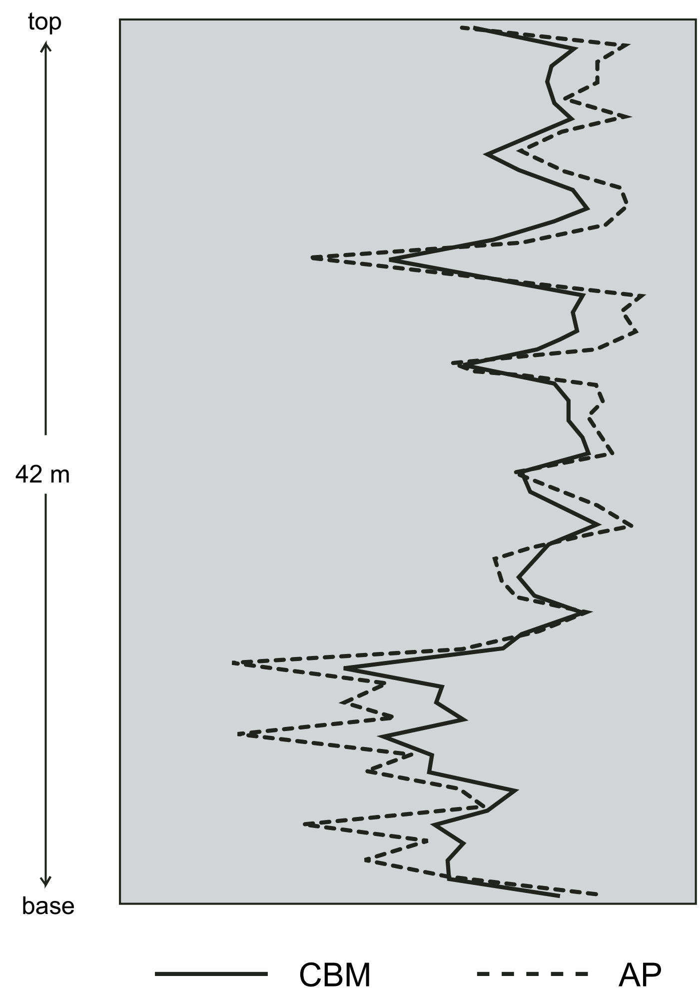

Figure 4. Coalbed methane (CBM) production and relative abundance of arboreal pollen (AP) in a Paleocene coal bed. Horizontal scales are not numerically comparable. To assist in visual comparison of the curves, CBM data measured as standard cubic feet per ton are exaggerated to place that curve adjacent to the one for percentage AP. Details of stratigraphy and location are omitted because of the proprietary nature of the data.

PALYNOLOGY AND COALBED METHANE

The final example of an application of palynology to coal systems analysis discussed here concerns the final component of coal systems as defined by Warwick (this volume)—the resource itself. In this example, the resource is not coal per se, but methane gas produced by coal beds. There is much current interest in coalbed methane as a resource, and its mode of generation is under study (e.g., Rice, 1993; Scott, 1993; Flores et al., 2001a; Meissner and Thomasson, 2001; Schenk et al., 2002; Riese et al., this volume). The reader is referred to those papers and others cited therein for details about coalbed methane as a resource. Here, an example is presented of methane generation apparently related to the composition of a coal bed, as it was determined by the original vegetation of the coal-forming mire.

Figure 4 shows diagrammatically the correlation of coalbed methane production and the relative abundance of arboreal pollen analyzed in a coal core. Arboreal pollen is that part of the palynoflora that was produced by trees in or adjacent to the ancient mire. Fluctuations in the abundance of arboreal pollen indicate that the floristic composition of the mire was not uniform through time. Fluctuations in the curve measuring methane desorbed from the coal indicate that the amount of methane produced from various intervals within the bed is also irregular. The curves measuring these properties are strikingly parallel. This result is interpreted to mean that abundance of arboreal pollen reflects the volume of woody vegetation in the mire, and evidently, the woody (vitrinitic) macerals in the coal are gas-prone. The arboreal pollen present in this coal bed (a Paleocene coal from Wyoming) is essentially the same as the two groups of pollen identified by Kremp et al. (1961) in coal of similar age from the Dakotas, although in the Wyoming coal, arboreal angiosperm pollen can be referred to additional living families (cf. Nichols and Pocknall, 1994).

Palynological analyses of this and other coal beds cored for testing methane production in an ongoing research program of the U.S. Geological Survey are indicative of varied plant communities in the mires that formed the coal (e.g., see Fig. 2 and Nichols, 1995). The arboreal pollen that appears to be correlated with methane production was derived from conifers related to living bald cypress and from angiosperm (hardwood) trees related to living birch, walnut, and others. This pollen represents the vegetation of a forested swamp, and is most common in lithotypes characterized by an abundance of vitrain. Other plant communities recognizable by their palynological content in these coal beds include heath or moor vegetation consisting largely of shrubs, ferns, and sphagnum moss. The coal formed by such deposits is considerably lower in methane content than that from woody vegetation, presumably because these plants tended to produce coal with lesser amounts of vitrain. In a petrographic analysis of two methane-producing coal cores, Flores et al. (2001b) found a relationship between methane content and the proportion of vitrain in the coal. From the results of that study and the close correlation of methane desorbtion data and pollen abundance shown in Figure 4, it appears that arboreal pollen is a proxy for woody vegetation in mires, and hence vitrain in coal. See also Chiehowsky et al. (2003) for similar results from another Paleocene coal from Wyoming.

Only routine palynological analysis is required to estimate the percentages of groups of pollen and spore types present in coal samples. Because of differential production of pollen by different species of trees, shrubs, and herbs, there is not a direct relation between abundance of pollen and the plants that produced it, but a useful approximation can be made. In any event, as shown by the analyses of Nichols and Pocknall (1994), the numerically dominant kinds of pollen and spores present in coal beds may not be the most important in deciphering the nature of ancient plant communities.

To produce the data depicted in Figure 4, the same segments of coal core from which methane was desorbed were analyzed palynologically, and pollen and spores present in each sample were identified, counted, and assigned to assemblages interpreted as representing distinctive plant communities. Variations in relative abundance of these assemblages within the coal seam were then plotted against methane production data. The intriguing correlation shown in Figure 4 resulted. The degree to which floristic composition of coal-forming mires—as revealed by pollen and spores—may have influenced the potential of certain coal beds or intervals within coal beds to produce methane gas is a new area in the application of palynology to coal-systems analysis. These kinds of analyses are likely to be most instructive when combined with coal-petrographic analyses conducted on the same coal-core intervals.

CONCLUSIONS

Palynology is the key to determining the floristic composition of peat mire floras, which is fundamental to understanding the origin of coal deposits. Other aspects of coal-forming paleoenvironments such as climate may also be deciphered from palynological data, and the age, correlation, and stratigraphic setting of coal deposits can be established palynologically. Selected examples from the literature on palynology and coal geology illustrate this. There are indications that palynology may also contribute to the interpretation of the cause of variations in methane production from coal beds. Thus, palynology is valuable in coal systems analysis, especially when integrated with paleobotany, coal petrography, and other coal-geologic studies.

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A comparison of late Paleocene and late Eocene lignite depositional systems using palynology, upper Wilcox and upper Jackson Groups, east-central Texas

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ABSTRACT

Lignites of the Wilcox and Jackson Groups in east Texas were deposited in marginal marine depositional complexes during times of cyclic sediment deposition. Thick upper Wilcox lignites occur within cycles of estuarine strata. Thin upper Jackson lignites occur within strandplain/shoreface deposits. Palynology of the lignites and enclosing sediments reveal two distinct climatic regimes: warm and equable during Wilcox deposition versus variable warm-cool during Jackson deposition. Four palynologic assemblages have been recovered from lignite-bearing upper Wilcox strata, and six palynologic assemblages have been recovered from upper Jackson nonmarine and marine strata. Wilcox lignites contain assemblages indicating change from closed-canopy freshwater swamps populated by a community dominated by chestnut and walnut family trees, to open-canopy swamps that add ferns to the community, to a community of palms and ferns that extends into the overlying marine-influenced mudstones, and capped by marine siliciclastics containing an assemblage of dinoflagellates and transported cypress pollen and fern spores. The Jackson assemblages indicate a transition from a palm-dominated community in the sands and silts to a fern marsh community in the silty mudstones and base of the lignites, to closed-canopy freshwater communities in the lignite populated by a tropical walnut and swamp tupelo, to an open-canopy community populated where ferns replace the tupelo, capped by a swamp community dominated by a chestnutlike tree and leatherwood, especially in lignites overlain by marine sediments; marine sediments contain an assemblage of dinoflagellates and transported pollen. The dominant tree in Wilcox swamp communities is chestnut, whereas Jackson swamps are dominated by a tropical walnut; ferns are common in both settings. The dominance of cypress in the estuarine-marine transition sediments of the Wilcox suggests an open-water transition between peat swamp and marginal marine environments. The dominance of the chestnutlike tree in the swamp-marine transition of the Jackson indicates a sharp boundary between peat swamp and marine environments.

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Keywords: Wilcox Group, Jackson Group, Tertiary, lignite, coal, palynology, paleoecology, paleoclimatology, environmental change.

INTRODUCTION

Coal systems analysis is an integrative approach to studying coal geology. One of the many ways to analyze a coal system is to combine stratigraphic studies of coal and coal-bearing rocks with palynologic studies, yielding a detailed determination of the depositional environment and paleoecology of the mire (Demchuck, 1992; Nichols, this volume).

This paper presents a comparison of the stratigraphic and palynologic studies of two early Tertiary coal systems: the late Paleocene upper Wilcox Group coals of Big Brown Mine near Fairfield in north-central Texas and the late Eocene upper Jackson Group coals of the Lake Somerville Spillway section near Somerville in south-central Texas (Figs. 1 and 2). These sections were studied because they span an important period of climate change (Yancey et al., 2002) and are relatively complete sections. Lignites from the Wilcox and Jackson Groups in east-central Texas have been interpreted as having been deposited in a variety of nearshore depositional environments, most often deltaic (Nichols and Traverse, 1971; Elsik, 1978; Ayers and Kaiser, 1987; Galloway et al., 2000). Work during the past 15 yr has challenged the deltaic interpretation for these units using stratigraphic, sedimentologic, and palynologic evidences (Breyer and McCabe, 1986; Gennett et al., 1986; Breyer, 1987;

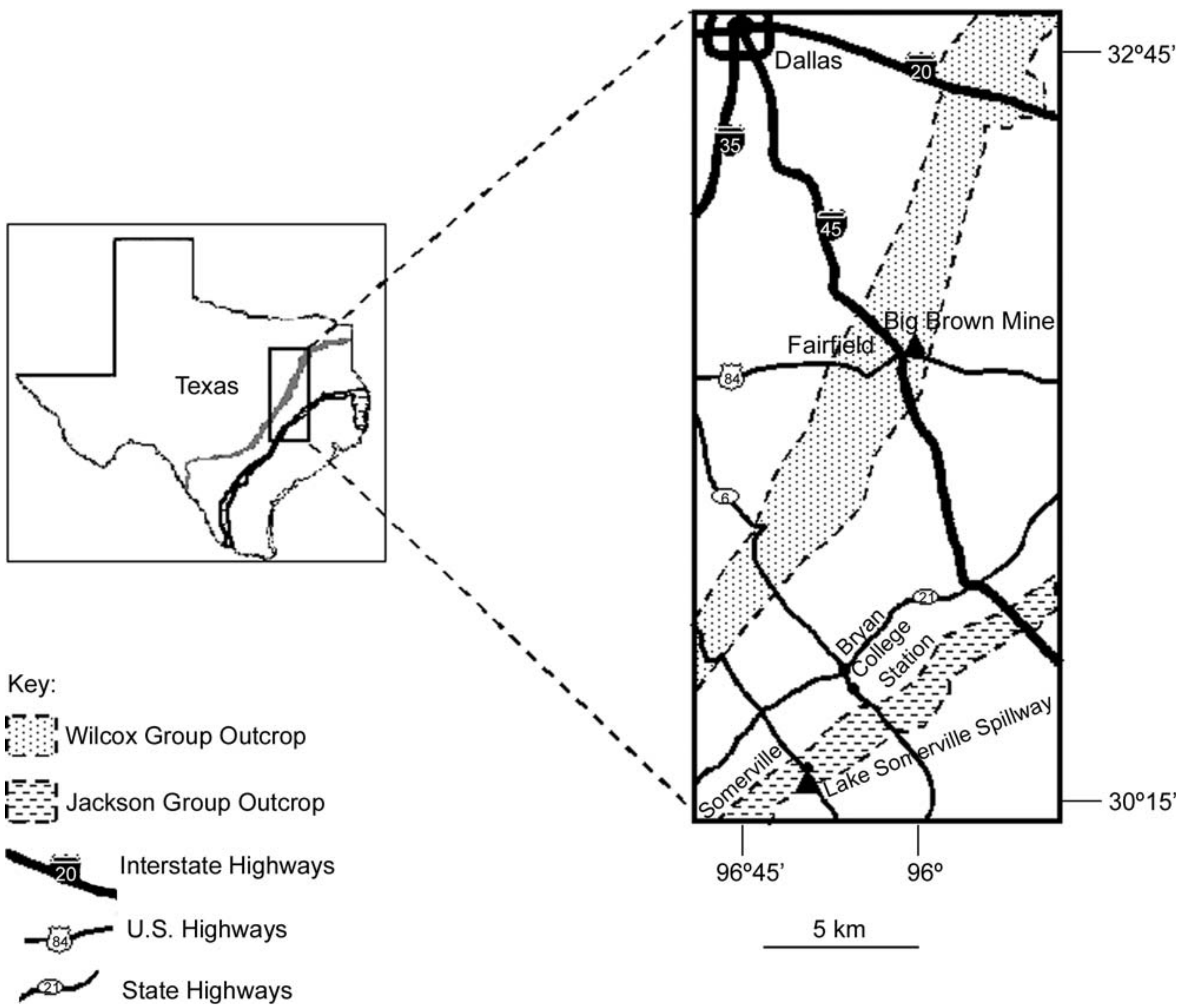

Figure 1. Location of study areas.

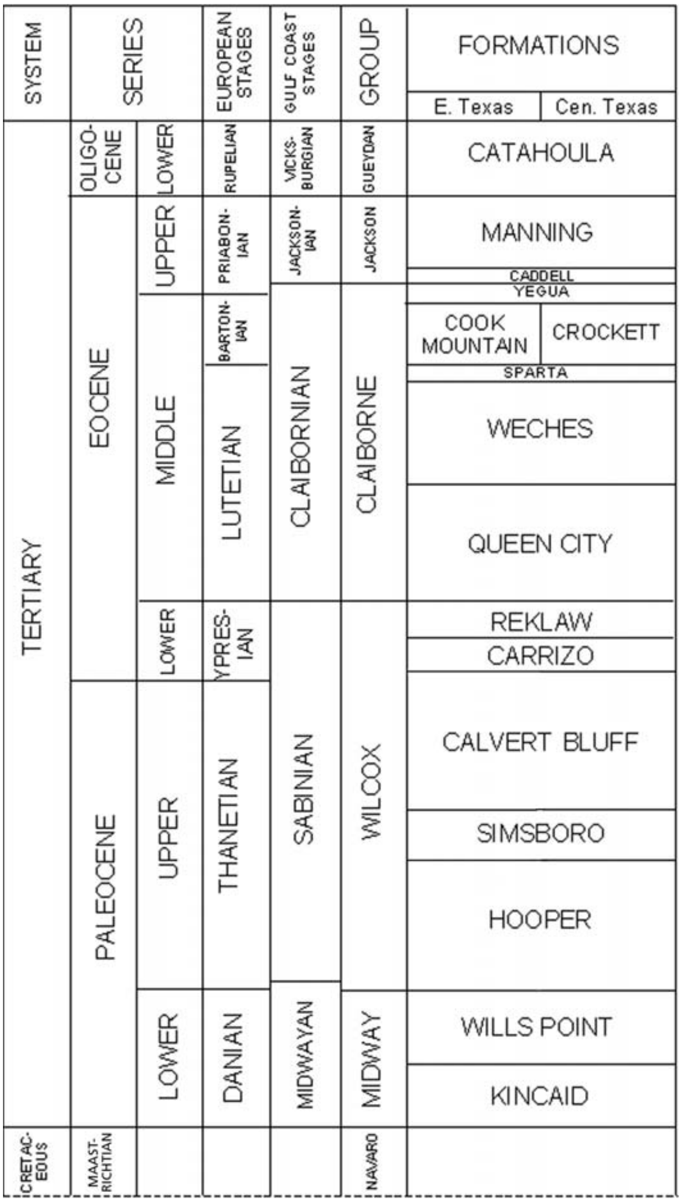

Figure 2. Geologic timescale and formational chart for central and east Texas (adapted from Sams and Gaskell, 1990; Yancey, 1997; Berggren et al., 1998; Graham, 1999; Warwick et al., 2000).

Yancey and Davidoff, 1991; Gennett, 1993; May, 1994; Raymond et al., 1997; Yancey, 1997; Klein, 2000; Sancay, 2000; Yancey et al., 2002).

The coal systems analyses presented here are the culmination of two master's theses that built on these early works (Klein, 2000; Sancay, 2000). Both used stratigraphy and palynology to study the paleoecology and depositional environments of the mires that developed into the upper Wilcox and upper Jackson lignites. Supporting information from maceral analyses comes from English (1988) and Mukhopadhyay (1987, 1989).

BIG BROWN MINE COAL SYSTEMS ANALYSIS

Stratigraphy

Breyer and McCabe (1986) and Breyer (1987) interpreted the deposits at Big Brown Mine as estuarine in origin, with the lignites deposited in reed-marsh complexes, on the basis of their interpretations of the stratigraphy and maceral analyses by Mukhopadhyay (1987). English (1988) expanded upon this and interpreted the lignites as originating in freshwater mire settings that grade up into reed-marsh complexes. Klein's (2000) work on the stratigraphy of the Tertiary section in the mine area is in agreement with these previous studies, except in finding that the upper portion of the lower lignite is not composed of reed and fern remains.

The two main lignite seams exposed in Big Brown Mine are contained in a cyclic unit and are overlain by coarsening upward successions of strata (Fig. 3). The cycles contain deposits of five facies: channel-overbank, tidal flat, salt marsh, marine, and mire. Channel-overbank deposits are characterized by trough cross-bedded sands that infill channels with high width:depth ratios and rolled slump blocks that infill channels with low width:depth ratios that are cut into planar laminated sands and silts. Tidal-flat deposits are composed of flaser and planar laminated muds and sands with vertical burrows and minor rooting. Salt-marsh deposits are made up of highly rooted clays, muds, and silts with small vertical burrows. Marine deposits are characterized by burrowed, laminated silts, which may have minor rooting at the top of the unit, indicating later exposure. Mire facies are characterized by lignites with compressed fern remains and partially compressed to uncompressed logs. The laminated sediments between the lignites are laterally extensive and contain rhythmic tidal sedimentary structures in the form of horizontal mud and sand laminae and rippled/wavy bedding bundled into tidal sets (Fig. 3). This is indicative of rapid sedimentation after the cessation of mire conditions (Klein, 1998). The lignites in the high-wall exposures of the Big Brown Mine are laterally continuous, even where the upper lignite splits around a channel-fill deposit.

Palynology

Twenty-three samples from two cores and three mine high-wall sections were chosen as representatives of each sedimentary facies, with the high-wall samples concentrated in the organic-rich zones. All samples were first mixed with water and two lycopodium tracer tablets, then treated with concentrated hydrochloric acid. Each sample was passed through a 500 μm mesh screen to remove large particles. Excess water was removed and the samples were treated with 70% hydrofluoric acid overnight. This treatment was deemed necessary for all samples because of common silicification of woody remains in the Big Brown Mine. The next day, warm hydrochloric acid was added to remove fluorosilicates. Then the residue was diluted

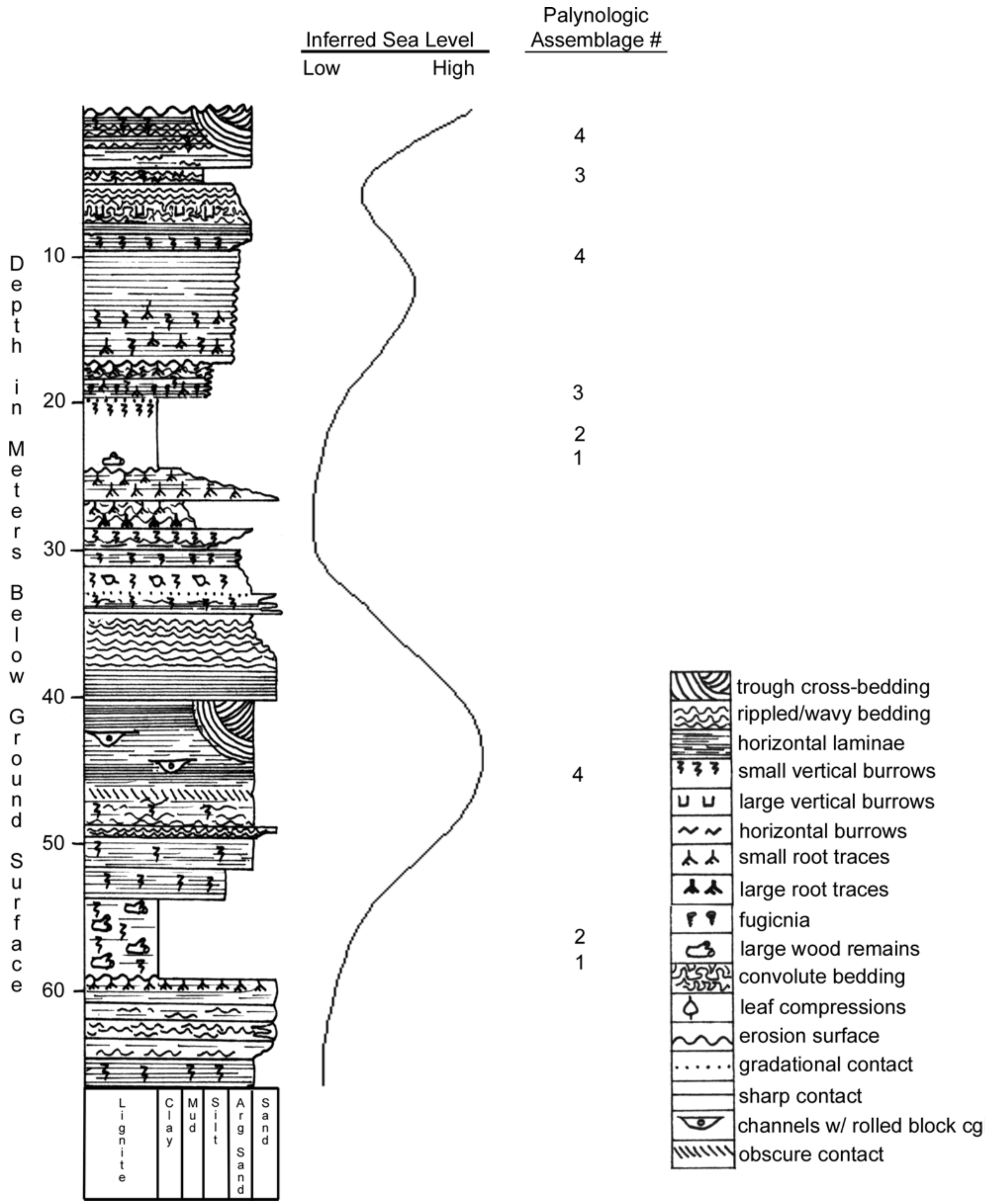

Figure 3. Composite stratigraphic column for the Big Brown Mine area showing maximum thickness in relation to inferred sea level and palynologic assemblages.

with water and allowed to settle before being drawn down and rinsed into 15 mL test tubes, where treatment with a zinc bromide solution (specific gravity = 2) to remove any remaining heavy-density minerals occurred. After this heavy-density separation, all samples were oxidized with nitric acid and neutralized with potassium hydroxide. After these treatments, the samples were examined, and all save the lignite samples were found to be in good condition. The lignite samples still contained abundant woody remains. Splits were taken and carefully treated with bleach to reduce the number of woody remains. No change was noted in comparing palynomorph content of the bleach-treated and non–bleach-treated splits. Samples were mounted in glycerin and counted under 500× magnification. After the counts, concentration values were calculated according to the methodology of Benninghof (1962) (tracer added/tracer counted × nontracer palynomorphs counted per gram of sample = concentration value).

The high-diversity Paleocene and Eocene palynofloras present in the Big Brown Mine and Lake Somerville areas occurred in the context of relatively high rates of angiosperm evolution associated with climatic transitions from equable warm and wet to seasonably variable temperature and rainfall (Berggren and Prothero, 1992; Berggren et al., 1998). Taxa present in abundances as low as 5% can be considered to be important components of the flora, especially when referring to rare or insect-pollinated taxa in samples with a generic diversity between 80 and 100 taxa. All 23 samples examined were found to be statistically valid (i.e., more than 1000 nontracer palynomorph grains per gram recovered) (Table 1). Concentration values ranged from 1258 grains/g to 6,672,000 grains/g, with highest concentrations in the lignites and lowest concentrations in the sands. Cluster analysis, a methodology that is considered to be successful at identifying ecological groupings with palynology data (Gennett et al., 1986; Oboh et al., 1996), was used to identify ecologic groupings in assemblages from both the Big Brown Mine and Lake Somerville Spillway study areas.

Four palyno-assemblages were identified at Big Brown Mine, each correlative with a portion of the overall stratigraphy (Figs. 3 and 4). This reflects a transition from freshwater mire communities to marine-influenced plant communities that follows the stratigraphic transition from mire deposits to channel and overbank deposits containing tidal structures.

Assemblage 1, preserved at the base of the major lignite seams, is dominated by chestnut (*Castanea* sp.) and *Engelhardia* (*Momipites* sp., a tropical juglandaceous hardwood) and contains a high diversity of low-abundance background taxa (Klein, 2000). This dominance is indicative of a closed-canopy freshwater hardwood swamp containing a diverse but sparse understory. Assemblage 2 is similar to Assemblage 1 but is characterized by greater abundances of both monolete (*Laevigatosporites* sp.) and trilete (*Deltoidospora* sp.) ferns. This is indicative of an open-canopy hardwood mire, possibly with marine influence,

TABLE 1. CONCENTRATION VALUES FOR SAMPLES FROM BIG BROWN MINE

Sample no.	Description	Tracer lycopodium added	Grams of sample processed	Total tracer grains counted	Total palynomorphs counted	Concentration value
17BBS3	Argillaceous silt and sand	24,000	20	45	313	8,347
17BBS4	Carbonaceous mudstone	24,000	10	1	336	806,400
17BBS5	Lignite	24,000	5	7	267	183,086
17BBS6	Silty carbonaceous mudstone	24,000	10	37	275	17,838
17BBS7	Laminated silty mudstone	24,000	10	8	333	99,900
17BBS8	Lignite	24,000	5	5	307	294,720
17BBS9	Lignite	24,000	5	1	350	1,680,000
17BBS10	Sand	24,000	20	79	250	3,798
18BBS4	Carbonaceous mudstone	24,000	10	2	284	340,800
18BBS5	Muddy sand	24,000	10	39	300	18,462
18BBS6	Muddy sand	24,000	10	21	287	32,800
18BBS7	Sand	24,000	20	290	304	1,258
18BBS8	Muddy sand	24,000	10	5	235	112,800
SSBBS3	Lignite	24,000	1	2	276	3,312,000
SSBBS4	Lignite	24,000	1	289	300	24,914
SSBBS5	Lignite	24,000	1	3	287	2,296,000
SSBBS6	Dirty lignite	24,000	5	2	293	703,200
SSBBS7	Carbonaceous mudstone	24,000	10	1	306	734,400
SSBBS8	Lignite	24,000	1	1	278	6,672,000
SSBBS9	Sand	24,000	20	279	300	1,290
SSBBS10	Argillaceous sand	24,000	20	24	271	13,550
SSBBS11	Silt	24,000	20	54	221	4,911
SSBBS12	Carbonaceous mudstone	24,000	10	25	245	23,520

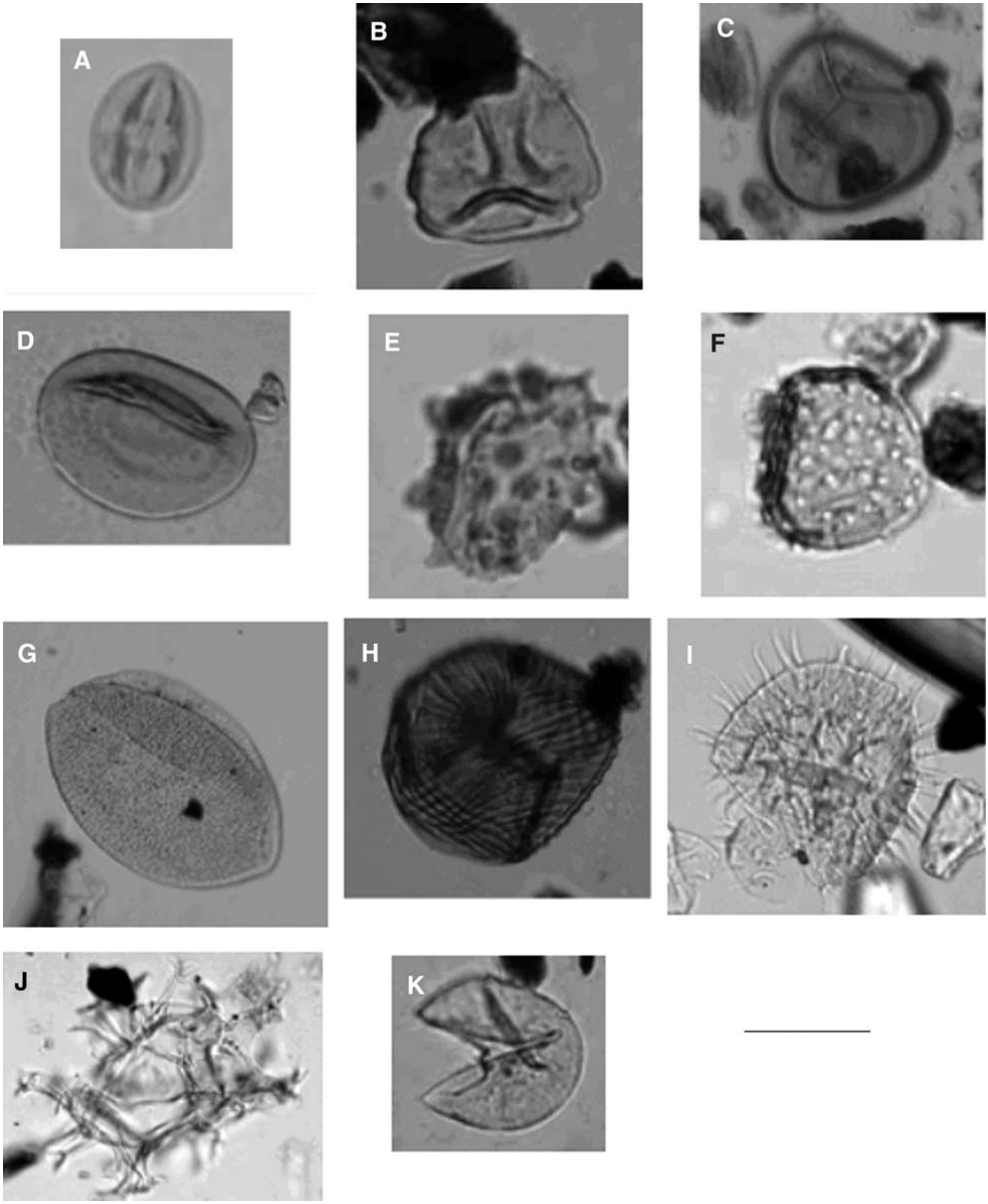

Figure 4. Dominant palynomorphs for each assemblage in Big Brown Mine (scale bar, 15 μm). Assemblage 1: *Castanea* sp. (A), *Momipites* sp. (B); Assemblage 2: *Castanea* sp. (A), *Momipites* sp. (B), *Deltoidospora* sp. (C), *Laevigatosporites* sp. (D); Assemblage 3: *Deltoidospora* sp. (C), *Nypa* sp. (E), *Pandaniidites* sp. (F), *Arecipites* sp. (G), *Cicatricosisporites* sp. (H); Assemblage 4: *Cleistosphaeridium* sp. (I), *Spiniferites* sp. (J), *Taxodiaceaepollenites* sp. (K).

because *Deltoidospora* is morphologically similar to *Acrostichum aureum*, which is common in mangrove communities (Graham, 1995). This assemblage appears in the lower to middle portions of both of the major lignite seams. Assemblage 3, preserved in the uppermost portions of the lignites and overlying mudstones, is characterized by palm pollen (*Nypa* sp., *Arecipites* sp.), *Pandanus* (screw pine) pollen (*Pandaniidites* sp.), and fern spores (*Cicatricosisporites* sp. and *Deltoidospora* sp.). This assemblage is indicative of a mangrove-type community, as associations of *Nypa* sp., *Pandanus* sp., and *Acrostichum* sp. grow in modern Old World tropical mangrove swamps and salt-tolerant marshes where *Rhizophora*, *Avicennia*, *Laguncularia*, and other mangrove taxa are absent (Graham, 1995, 1999). *Nypa*-type pollen grains are known from the New World in late Cretaceous through Eocene sediments (Graham, 1995). Assemblage 4, preserved in tidal laminated sediments and cross-bedded sands, is characterized by dinoflagellates, cypress pollen (*Taxodiaceaepollenites* sp.), and fern spores (*Laevigatosporites* sp.). Dinoflagellates within this assemblage are indicative of marine or brackish conditions.

Coal System Model

The paleoecologic transition from closed-canopy freshwater mire to marine or brackish conditions mirrors the stratigraphic transition from swamp to tidal channel deposits (Fig. 3). Upsection, the stratigraphic successions from mire to tidal channels become thinner and tend to become increasingly marine, reflected in skips of the first or first two palynologic assemblages in each sequence. Lignite maceral analysis follows this trend, showing a decrease in woody material (English, 1988). Additionally, the lack of cold-indicator taxa such as pine or spruce and presence of taxa that are today restricted to the tropics (*Nypa, Engelhardia, Acrostichum,* etc.) suggest that growth and deposition in the mine area took place under warm, equable conditions.

The stratigraphic facies, maceral analyses, and palynologic assemblage information presented above can be tabulated into an idealized coal systems model for the Big Brown Mine area (Table 2). This model can be used to predict coal characteristics in similar depositional settings in the lower Tertiary.

TABLE 2. GENERALIZED COAL SYSTEM MODEL FOR ESTUARINE-ASSOCIATED LIGNITES BASED ON DATA FROM BIG BROWN MINE

Sediment size, type	Sedimentary structures/macrofossils	Dominant or significant palynomorphs	Mean organic petrology % (where applicable)	Depositional environment
Silt	Laminae Burrows	*Dinoflagellates* *Taxodiaceaepollenites*		Marine
Sand, silt	Trough cross-beds Rolled slump blocks Planar laminae	*Dinoflagellates* *Taxodiaceaepollenites*		Tidal channel/overbank
Sand, mud	Flasar laminae Planar laminae Vertical burrows Minor rooting	*Dinoflagellates* *Taxodiaceaepollenites*		Tidal flat
Clay, mud, silt	extreme rooting small vertical burrows	*Cicatricosisporites* *Deltoidospora* *Arecipites* *Pandaniidites* *Nypa*		Salt marsh/mangrove community
Lignite	compressed ferns	*Cicatricosisporites* *Deltoidospora* *Arecipites* *Pandaniidites* *Nypa*	Humaninite: 66.8% Liptinite: 23.4% Inertinite: 9.4%	Mangrove swamp
		Castanea *Momipites* *Laevigatosporites* *Deltoidospora*	Humaninite: 67.9% Liptinite: 23.3% Inertinite: 8.0%	Open-canopy swamp with marine influence
	Logs common	*Castanea* *Momipites*	Humaninite: 68.7% Liptinite: 22.5% Inertinite: 8.9%	Closed-canopy freshwater swamp

Note: Organic petrology data averaged from Mukhopadhyay (1987, 1989) and English (1988).

LAKE SOMERVILLE COAL SYSTEM ANALYSIS

Stratigraphy

Yancey and Davidoff (1991) suggested that the lignites in the Lake Somerville section accumulated in forested coastal swamps and that the surrounding nonmarine sediments accumulated in coastal lakes, fluvial channels, and as overbank deposits. Yancey (1997) placed the lignites within a cyclic nearshore marine and strandplain succession on the basis of detailed stratigraphic studies. Mukhopadhyay's (1989) analysis of the coals from Lake Somerville indicate a freshwater origin for these lignites, consistent with a terrestrial shore-zone peat, and elevated sulfur, consistent with other evidence (foraminifera, *Gyrolithes* burrows) for marine sedimentation directly above the lignites (Raymond et al., 1997).

Yancey's cycles are composed of five facies: coastal mire, transgressive shore zone, offshore, regressive shore zone, and exposure surface/paleosol (Fig. 5). Coastal mire deposits are characterized by lignites that sometimes contain lignified logs. Deposition in one of the lignite mires was interrupted by ash falls, resulting in two tonstein partings. The tops of the mire deposits are often burrowed. Transgressive shore-zone deposits are characterized by thin sands that fine upward into siltstones. Offshore deposits are characterized by burrowed mudstones and interbedded mudstones and siltstones. Offshore deposits grade up into regressive shore zones. Regressive shore zones are characterized by cross-bedded sands that coarsen upward. Exposure surfaces/paleosols are highly rooted clay-rich sands and silts, which underlie most mire deposits and are well developed in the middle of the section. A meter-thick unit of volcanic ash is present in the middle of the section (23–24 m) and has been dated at 34.4 Ma (Guillemette and Yancey, 1996). There is an overall trend toward more marine influence upsection to the 10 m level, above which nonmarine conditions dominate. The section is capped with a fluvial facies with trough and planar cross-bedded sand channel-fill deposits.

Palynology

Forty-three samples were examined. Seven were found to be statistically invalid samples (<1000 grains/g) and were excluded from the cluster analysis. Of the 36 valid samples, concentration values range from 1530 grains/g to 994,400 grains/g (Table 3). Unlike the Paleocene study area, there was no observable correlation between grain size or depositional environment and concentration value.

Six assemblages were identified in the Lake Somerville section (Figs. 5 and 6), each correlative with a portion of the overall stratigraphy. These assemblages portray an ecological transition not unlike that of the perideltaic shore zones of western Louisiana today and mirror the stratigraphic facies.

Assemblage 1 is characterized primarily by palms (*Calamuspollenites* sp. and *Arecipites* sp.), but become enriched in gymnosperm pollen (*Pinus* sp., *Picea* sp.) in the upper portions of the section. This assemblage is indicative of freshwater, tropical conditions, which cooled slightly over time. It occurs in the regressive shore-zone sands and silts. Assemblage 2 is dominated by ferns (*Cicatricosisporites* sp., *Verrucatosporites* sp., and *Polypodium* sp.). It is indicative of open mires and occurs in the paleosols and lower portions of the lignites. Assemblage 3 is characterized by *Engelhardia* (*Momipites* sp.) and swamp tupelo (*Nyssapollenites* sp.). This assemblage is indicative of closed-canopy freshwater mires. It occurs in the lower to middle parts of the lignite seams. Assemblage 4 is composed of *Engelhardia* pollen (*Momipites* sp.) and fern spores (*Laevigatosporites* sp. and *Deltoidospora* sp.). It is indicative of an open-canopy mire and occurs in the middle part of the lignite seams. Assemblage 5 is characterized by pollen from a chestnutlike tree (*Cupuliferoipollenites* sp.) and leatherwood (*Cyrillaceapollenites* sp.). Leatherwood is indicative of freshwater mires (Rich, 2002), whereas the origin of *Cupuliferoipollenites* has been variably attributed to freshwater (Nichols, 1970; Jones and Gennett, 1991) and brackish-water settings (Gennett, 1993; Raymond et al., 1997). Given the variable tolerances of *Cupuliferoipollenites* and its association with *Cyrillaceapollenites*, this assemblage is thought to represent a standing-water, freshwater mire. This assemblage occurs in the upper portions of the lignite seams. Assemblage 6 is characterized by dinoflagellates and transported pollen. It is indicative of marine deposition and occurs in the transgressive shore-zone and offshore facies. In the transgressive shore-zone deposits, the dinoflagellates are most likely reworked or transported.

Coal System Model

The relationship between the paleoecologic transition and the stratigraphic transition in the Lake Somerville spillway section is not as clear as it is in the Big Brown Mine, although, they generally correspond to one another (Fig. 5). Upsection, the cycles become increasingly marine, reflected in decreasing lignite thicknesses. This transition may be related to the climate change observed by the influx of pine and spruce pollen.

The stratigraphic facies, maceral analyses, and palynologic assemblage information presented above can be tabulated into an idealized coal system model for the Lake Somerville Spillway section (Table 4). This model can be used to predict coal characteristics in similar depositional settings in the lower Tertiary.

DISCUSSION

The coal depositional settings of the Wilcox and Jackson Groups are at first glance remarkably similar. Both study areas contain lignites that have been determined to be primarily fresh-

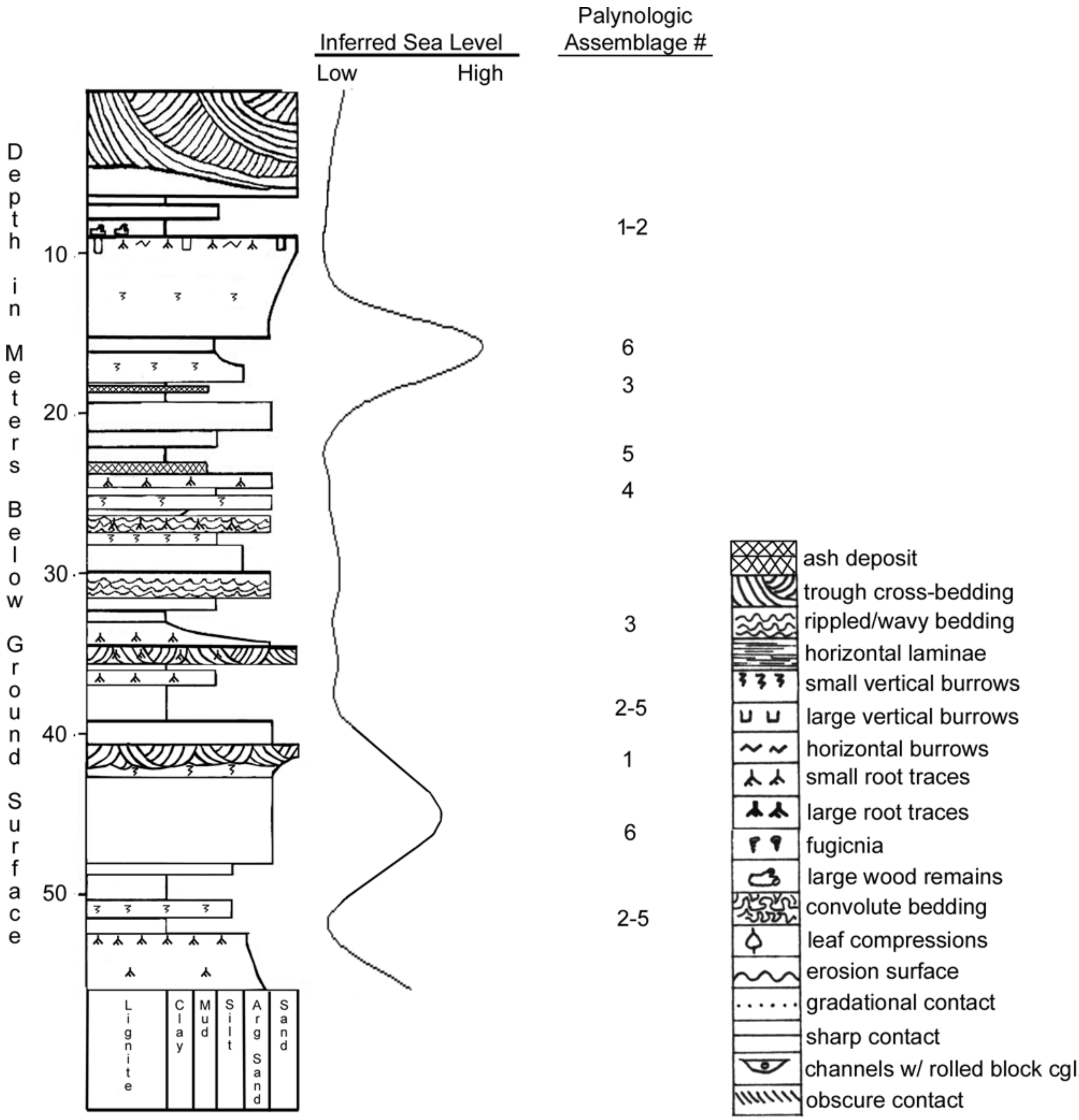

Figure 5. Composite stratigraphic column for the Lake Somerville Spillway showing maximum thickness in relation to inferred sea level and palynologic assemblages.

water in origin through maceral analysis, and both contain slightly elevated sulfur percentages, consistent with marine conditions after deposition. Both study areas contain cyclical packages of sediment. Both study areas contain clastic sediments that first fine, then coarsen upward. To a point, the two depositional settings can be differentiated by the sedimentary structures in and relative thicknesses of the clastic sediments. In the Wilcox, these sediments are flasar and planar laminated and represent a transition from mire to tidal flats to tidal channels. In the Jackson, these sediments are thick bedded to interbedded to cross-bedded and rippled and represent a transition from shore-zone to offshore to shore-zone deposition.

TABLE 3. CONCENTRATION VALUES FOR SAMPLES FROM LAKE SOMERVILLE SPILLWAY

Sample no.	Description	Tracer lycopodium added	Grams of sample processed	Total tracer grains counted	Total palynomorphs counted	Concentration value
PP#2	Sandy mudstone	24,000	10	65	44	1,625
PP#1	Lignite	24,000	5	8	200	120,000
PP#36	Mudstone	24,000	10	25	200	19,200
PP#37	Mudstone	24,000	10	6	200	80,000
PP#6	Ash	24,000	2	45	0	0
PP#7	Ash	24,000	2	57	2	421
PP#8	Sandstone	24,000	20	68	23	406
RHS-CS #1	Sandstone	24,000	20	16	57	4,275
RHS-CS #2	Mudstone	24,000	10	25	200	19,200
RHS-CS #3	Mudstone	24,000	10	35	154	10,560
RHS-CS #4	Sandstone	24,000	20	18	221	14,733
RHS-CS #5	Sandstone	24,000	20	7	200	34,286
RHS-CS #6	Mudstone	24,000	10	61	92	3,620
PP#10	Lignite	24,000	5	9	200	106,667
RHS-CS #7	Lignite	24,000	5	2	200	480,000
RHS-CS #8	Sandstone	24,000	20	130	14	129
PP#11	Mudstone	24,000	10	8	200	60,000
RHS-CS #9	Sandstone	24,000	20	177	6	41
RHS-CS #10	Mudstone	24,000	10	10	200	48,000
RHS-CS #11	Mudstone	24,000	10	35	200	13,714
RHS-CS #12	Siltstone	24,000	10	235	200	2,043
RHS-CS #13	Sandstone	24,000	20	64	54	1,013
RHS-CS #14	Sandstone	24,000	20	29	200	8,276
RHS-CS #15	Mudstone	24,000	10	28	200	17,143
PP#12	Mudstone	24,000	10	19	200	25,263
PP#13	Mudstone	24,000	10	54	200	8,889
RHS-CS #17	Mudstone	24,000	10	1	200	480,000
RHS-CS #16	Mudstone	24,000	10	3	200	160,000
PP#14	Lignite	24,000	5	4	200	240,000
RHS-CS #18	Lignite	24,000	5	1	200	960,000
RHS-CS #19	Lignite	24,000	5	1	200	960,000
RHS-CS #20	Ash	24,000	2	70	200	34,286
RHS-CS #21	Carbonaceous mudstone	24,000	10	25	56	5,376
RHS-CS #22	Sandstone	24,000	20	5	18	4,320
RHS-CS #23	Lignite	24,000	5	10	200	96,000
RHS-CS #24	Dirty lignite	24,000	5	15	200	64,000
RHS-CS #25	Carbonaceous mudstone	24,000	10	32	200	15,000
RHS-CS #26	Lignite	24,000	5	1	200	960,000
RHS-CS #27	Lignite	24,000	5	10	200	96,000
RHS-CS #28	Lignite	24,000	5	1	220	1,056,000
RHS-CS #29	Sandstone	24,000	20	438	137	375
RHS-CS #30	Sandy mudstone	24,000	10	29	200	16,552
RHS-CS #31	Lignite	24,000	5	13	200	73,846
RHS-CS #32	Lignite	24,000	5	7	200	137,143
RHS-CS #33	Lignite	24,000	5	8	214	128,400
RHS-CS #34	Carbonaceous mudstone	24,000	10	14	200	34,286
RHS-CS #35	Sandy mudstone	24,000	10	417	69	397

The overall palynology is remarkably similar in both settings, reflecting a transition from freshwater mire settings to marine-influenced or marine deposition. When the palynomorph assemblages of each setting are examined, distinct differences in mire community successions become apparent. In the Wilcox, this is a transition from closed-canopy swamps to open-canopy swamps, to a salt-marsh or mangrove-type community of palms and ferns, to an assemblage of dinoflagellates and transported pollen that reflects increasing salinity through time. In the Jackson, this is a transition from palm communities to fern marshes to closed-canopy swamps, to open-canopy swamps, to open-canopy wetland, to marine assemblages. In the Jackson, the transition from fresh to marine conditions appears to have been rapid as it lacks a

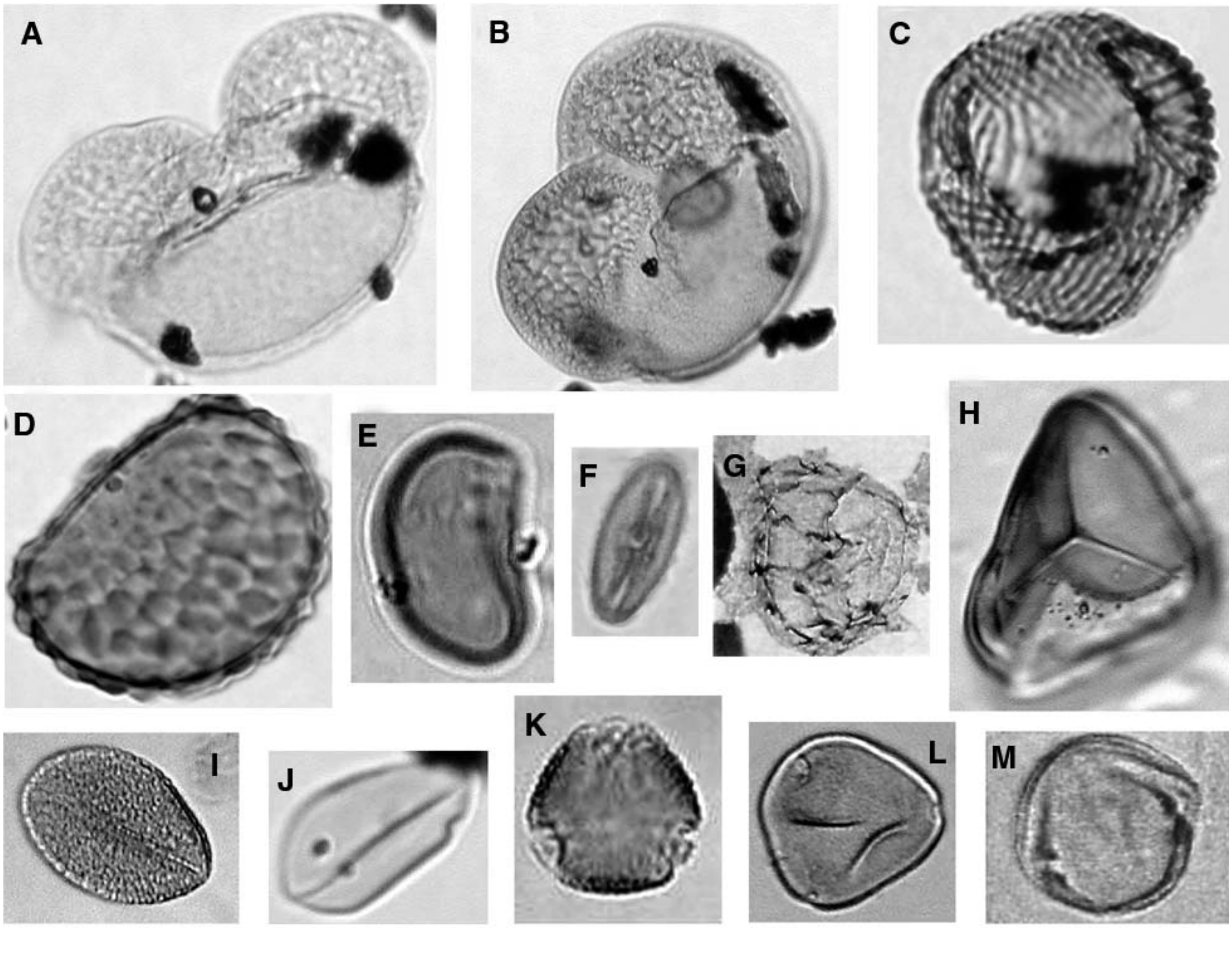

Figure 6. Dominant palynomorphs for each assemblage at the Lake Somerville Spillway (scale bar, 15 μm). Assemblage 1: *Calamuspollenites* sp. (I), *Arecipites* sp. (J), *Pinus* sp. (A), *Picea* sp. (B); Assemblage 2: *Cicatricosisporites* sp. (C), *Verrucatosporites* sp. (D); Assemblage 3: *Momipites* sp. (L), *Nyssapollenites* sp. (K); Assemblage 4: *Momipites* sp. (L), *Laevigatosporites* sp. (E), *Deltoidospora* sp. (H); Assemblage 5: *Cupuliferoipollenites* sp. (F), *Cyrillaceapollenites* sp. (M); Assemblage 6: *Wetzeliella* sp. (G).

brackish-water community, although this could indicate the presence of several unconformities, whereas in the Wilcox, several mangrove taxa are present, indicating a gradual freshwater-marine transition. Each community has a different dominant freshwater tree taxa. In the Wilcox, the dominant tree is chestnut (*Castanea* sp.). In the Jackson, it is *Engelhardia* (*Momipites* sp.). Modern *Engelhardia* occurs primarily in higher elevations in the tropics or in subtropical climates. It is possible that the predominance of *Engelhardia* in the Jackson Group sediments is another reflection of the relatively cooler climate in the late Eocene as opposed to the primarily tropical climate of the late Paleocene. The presence of *Pinus* sp. and *Picea* sp. pollen grains in the sands at the Lake Somerville spillway support this interpretation.

CONCLUSIONS

1. Palynology can be used to support depositional environment interpretations. In the Wilcox Group, palynology supports the estuarine depositional hypothesis. In the Jackson Group, palynology supported the strandplain/shoreface depositional hypothesis.

2. Palynology provides information about early Tertiary climate during lignite deposition. The upper Wilcox Group lignites were deposited during warm and equable conditions, whereas the upper Jackson Group lignites were deposited during increasingly cooling conditions.

3. Palynology provides a key to differentiating between coal system models for the early Tertiary.

TABLE 4. GENERALIZED COAL SYSTEM MODEL FOR SHOREZONE-ASSOCIATED LIGNITES BASED ON DATA FROM THE LAKE SOMERVILLE SPILLWAY SECTION

Sediment size/type	Sedimentary structures/macrofossils	Dominant or significant palynomorphs	Mean organic petrology % (where applicable)	Depositional environment
Clay-rich sand, clay-rich silt	Extreme rooting	*Cicatricosisporites Polypodium Verrucatosporites*		Exposure surface/paleosol
Sand	Cross-bedding	*Arecipites Calamuspollenites*		Regressive shorezone
Mudstone, interbedded mudstones and siltstones	Burrows	Dinoflagellates Transported pollen		Offshore
Sandstone, siltstone	Thin bedding fining upward	Transported pollen and transported or reworked dinoflagellates		Transgressive shorezone
Lignite		*Cupuliferoipollenites Cyrillaceaepollenites*	Humaninite: 66.3% Liptinite: 31.6% Inertinite: 2.1%	Standing-water freshwater mire
		Deltoidospora Laevigatosporites Momipites		Open-canopy mire
	Scattered logs	*Momipites Nyssapollenites*		Closed-canopy freshwater mire
		Cicatricosisporites Polypodium Verrucatosporites		Open mire

Note: Organic petrology data averaged from Mukhopadhyay (1989).

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New insights on the hydrocarbon system of the Fruitland Formation coal beds, northern San Juan Basin, Colorado and New Mexico, USA

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ABSTRACT

This investigation combines traditional and newly available investigative techniques to characterize the hydrocarbon system of the Fruitland Formation coals, both at outcrop and in the subsurface. These analyses indicate that the Fruitland coal hydrocarbon system began with Late Cretaceous–early Tertiary deposition and maturation of the coal source rocks; Late Cretaceous–early Paleocene tilting of the basin; Eocene uplift, exposure, and erosion of the basin margins; Eocene groundwater recharge, which maintained hydrodynamic pressure in the reservoirs; and continued uplift, which caused occlusion of permeability to occur ca. 35 Ma. Present-day erosion is slowly breaching biosome-scale reservoirs and allowing methane to escape to the atmosphere at the outcrop. Oligocene opening of the Rio Grande rift changed the stress regime of the San Juan Basin, allowing fractures to open and fluid to migrate from pre-Cretaceous rocks to the surface.

Outcrop seeps have been ongoing throughout Recent geologic time and probably have been active since the coals were first exposed at the outcrop. Methane production from the coal in deeper parts of the basin has not contributed to methane gas seeps at the outcrop. Our analysis calls into question hydrologic assumptions regarding the flow of water in coalbed aquifers and finds that a reexamination of coalbed aquifers in other basins is also warranted.

Keywords: Coal, methane, stable isotopes, I-129, Cl-36, Fruitland Formation, strontium, CT scan, XRD, cleat, San Juan Basin.

INTRODUCTION

The Cretaceous strata in the San Juan Basin of Colorado and New Mexico, USA, contain the world's largest, most productive coalbed methane (CBM) reserves. Within the Fruitland Formation alone, the coal beds constitute a resource base in excess of 1.4 trillion m^3 of natural gas (Kelso et al., 1988). Although thousands of wells targeting deeper reservoirs were drilled through the Fruitland coals between the 1950s and 1970s, the CBM resource was not thought to be of commercial importance. Early tests yielded large volumes of flowing water within the coals and hardly any methane in the free-gas phase. At the time, both of these characteristics were considered failure indicators when exploring for conventional gas reservoirs.

Amoco Production Company drilled the first well specifically targeting the coalbed reservoirs in the Cedar Hill field dur-

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ing 1977 and demonstrated the production potential of the Fruitland Formation (Whitehead, 1993). This well, the Amoco Cahn, marks the beginning of a CBM development trend in the basin that has seen more than 4000 wells drilled and that is continuing today as operators learn more about coalbed reservoirs and seek to drill more wells at closer spacings to capture additional reserves.

Because of its huge resource base and the prolific gas production rates of some wells (up to 280,000 Mcmd, or 10 MMcfd), the Fruitland and its high-rate "Fairway"—a narrowly focused cluster of high-rate wells with large recoverable reserves—have been the ongoing focus of intense geologic investigation. The Fairway is part of an overpressured area in a generally underpressured basin and, despite efforts to use the San Juan Basin as a predictive model for developing other such coalbed methane deposits, the cause of overpressure remains enigmatic. In many cases, adjacent wells show significant variations in production history of both natural gas and the coproduced waters, pointing to heterogeneities within the reservoir that continue to present challenges. The unanticipated variations in water production from well to well are significant and bring into question the relationship between production reservoirs and meteoric recharge at the coal outcrop. This assumed relationship is a critical component in several models of the San Juan Basin hydrocarbon system (Kaiser and Swartz, 1988; Scott et al., 1994), and these discrepancies may explain why such models have not been successfully extended to other coalbed systems.

Our investigative approach has been fourfold. First, we describe the spatial distribution and characteristics of the Fruitland Formation coals in the northern San Juan Basin. The logs from relatively closely spaced wells, when combined with field measurements at outcrop, provide a high-resolution database with which to determine overall stratigraphic relationships and basin structure. Using this data, we can infer whether or not there is enough continuity between the coals to provide macroscale hydraulic conductivity and can also assess the influence of basement fractures and contributions from adjacent aquifers. Second, we describe the composition and physical characteristics of the coals themselves since they serve as the principal reservoir as well as the probable source of the methane. Since the presence of coal structures known as cleats is a determining factor in the overall permeability of coals, we use a combination of computed tomography (CT) scanning, X-ray diffraction, and ion-microprobe petrography to describe the microscale characteristics and authigenic mineralization within the coals. Third, we look at the chemistry and isotopic composition of the waters associated with coalbed methane. The chemistry of the waters is a strong indicator of the interactions between water and the coals and provides an indicator of the duration with which hydrostatic pressure has maintained methane adsorption. Finally, we look at the chemical and isotopic composition of the produced gas, which permits the determination of the methane source, as well as the processes involved in its formation.

By looking at the distribution of coal, water, and gas properties across the study area, we can determine why some wells are very productive while adjacent wells are not. We can also determine the relationship between reservoir heterogeneity and well performance prior to production and ascertain whether the performance of wells can later be improved through innovative methods of enhanced methane recovery. In addition, the chemical and isotopic composition of the produced waters may be compared to the surface and near-surface formation waters at the edge of the basin in order to monitor the effect, if any, of natural gas production on local seepage.

This paper is the first to incorporate a comprehensive set of data and phenomena, some of which have at times been overlooked. These include subtle changes in gas-water ratios in the early stages of production and a comparison of the geochemistries of surface and near-surface formation waters at the edge of the basin to that of produced water. The methane seeps that punctuate the outcrop of Fruitland coals along the northern edges of the basin are also considered. All of these observations and phenomena are explained within the context of a clearly defined hydrocarbon system.

STRUCTURE AND STRATIGRAPHY OF THE SAN JUAN BASIN

Tectonic Framework

The San Juan Basin is a Laramide tectonic feature whose predominant structures formed beginning ca. 73–30 Ma (Fassett, 2000) and that is presently situated in Colorado and New Mexico (Fig. 1). The basin occupies an area that was part of a preexisting northwest-southeast striking, northwest plunging aulacogen whose southwestern flank contained numerous synthetic, down-to-the-north normal faults (Kelley, 1951, 1955; Kelley and Clinton, 1960). Very few similar faults are present on the northeastern flank. Although the basin did not form until the Late Cretaceous, these structures are dependent in part on preexisting Precambrian crustal fabrics (Cordell and Grauch, 1985; Huffman and Taylor, 1991), which are depicted in the gravity and magnetic data interpretations shown in Figures 2 and 3. These crustal fabrics influenced sedimentation during the Paleozoic, and cross sections of Pennsylvanian strata exhibit an interval that thickens to the northwest, apparently through the Four Corners Platform, and thins to the southeast, thus indicating the direction of plunge. The same isopachs and cross sections indicate thinning of Pennsylvanian strata to the northeast and southwest, the margins of the rift basin. Faulting continued slowly and subtly through the remainder of the Paleozoic and throughout the Mesozoic (Laubach and Tremain, 1994). This continuing movement created low amplitude monoclinal flexures in the overlying sediments and surface topography. This sloping, undulating topography provided the accommodation space that allowed accumulation of beach sands and back-barrier, marginal marine lagoonal sediments during the Creta-

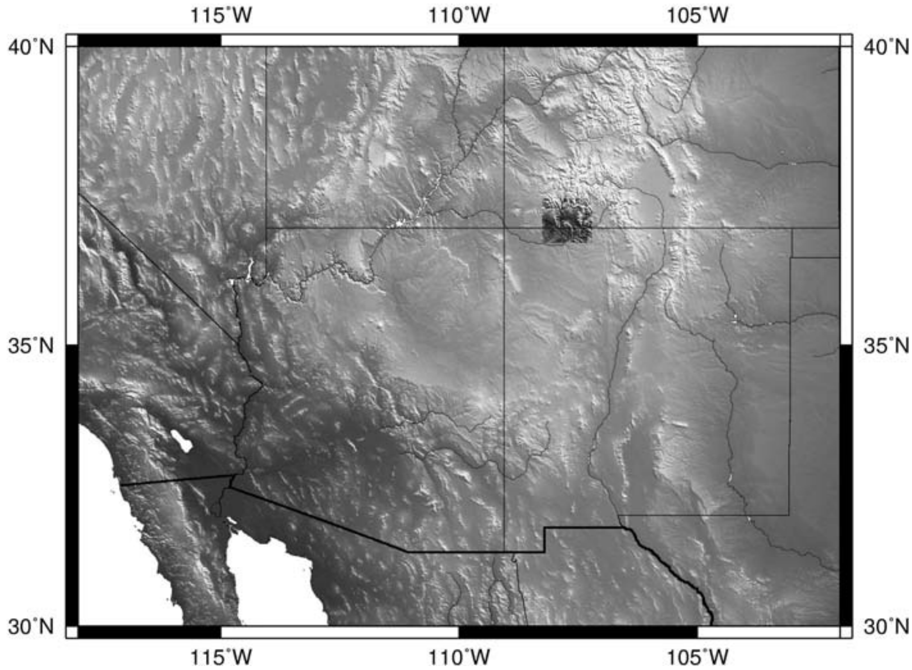

Figure 1. Regional map showing the San Juan Basin study area.

ceous (Silver, 1957). Where fault displacements did not propagate upward through the overlying stratigraphic section, fractures developed. The influence that these fractures would later have on the CBM hydrocarbon system will be discussed.

Cretaceous Stratigraphy

Oil and gas industry exploration of the Cretaceous interval of the San Juan Basin has been active since the 1920s. The thousands of wells that penetrated these strata provide data indicating that the beach sands in this sequence were deposited as time-transgressive strand plain sands, with the thickest accumulations occupying northwest-southeast–striking accommodation zones whose locations were determined by the previously described basement fault and fold architecture. The coal beds that were deposited during shoreline regression accumulated in deltaic and paludal environments in swamps behind the barrier beaches. Coals that accumulated during transgressive cycles of sedimentation are generally thin and often deeply eroded, and thus do not typically represent thick accumulations. The Fruitland coals were deposited during regressive cycles of sedimentation and are by far the most significant coals within the Cretaceous section, reaching thicknesses of 30 m (100 ft).

The stratigraphic sequence for the Cretaceous of the San Juan Basin is shown in column form in Figure 4. We also present a time-stratigraphic cross section based on detailed well logging in Plate 1 (a loose insert accompanying this volume). These rocks, of which the Fruitland Formation coals are a part, were deposited by a series of repeated marine transgressions and regressions of the Western Interior Seaway. The shoreline movements were a response to changes in the rate of sediment flux into the basin, a reflection of regional uplift and subsidence (Kaufman, 1977; Weimer, 1986; Fassett, 2000).

Coals were also deposited between channel margin settings of the streams and rivers that fed sand to the coastal environments. These streams were consequent streams, apparently utilizing a conjugate set of basement fractures and faults to establish themselves (Huffman and Taylor, 1991; Riese et al., 2000). The paludal channel-margin accumulations were protected by periodic over-levee flood and crevasse splay deposition and subsequently buried during basin subsidence. The thickness trends of these coal accumulations therefore often strike nearly perpendicular—northeast-by-southwest—to the paleoshorelines.

Present Basin Structure

Development of the present structural form of the San Juan Basin (Plate 2A [a loose insert accompanying this volume]) is a product of both the episodic subsidence of the Western Interior Basin and thrusting in the Cordilleran orogenic belt to the west. Together, these processes and events constituted the tectonic setting that gave rise to a series of intermontane basins and uplifts during the Laramide orogeny (Laubach and Tremain, 1994; Chapin and Cather, 1981). The asymmetric San Juan Basin with its northwest-trending axis in the north formed between 75 and 35 Ma (Fassett, 2000) and subsidence of the Western Interior Seaway led to the accumulation of several thousand feet of additional clastic sediments during the very latest Cretaceous, Paleocene, and Eocene. Sedimentation probably

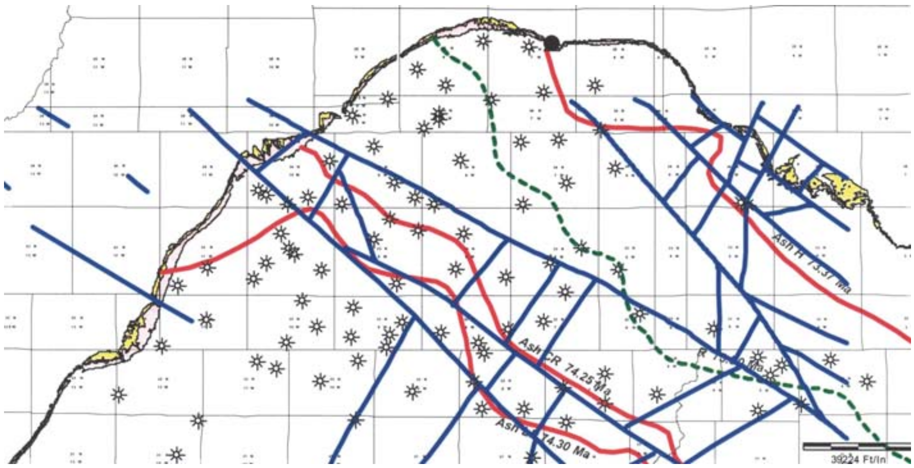

Figure 2. Paleoshorelines (after Fassett, 2000) and basement gravity linears.

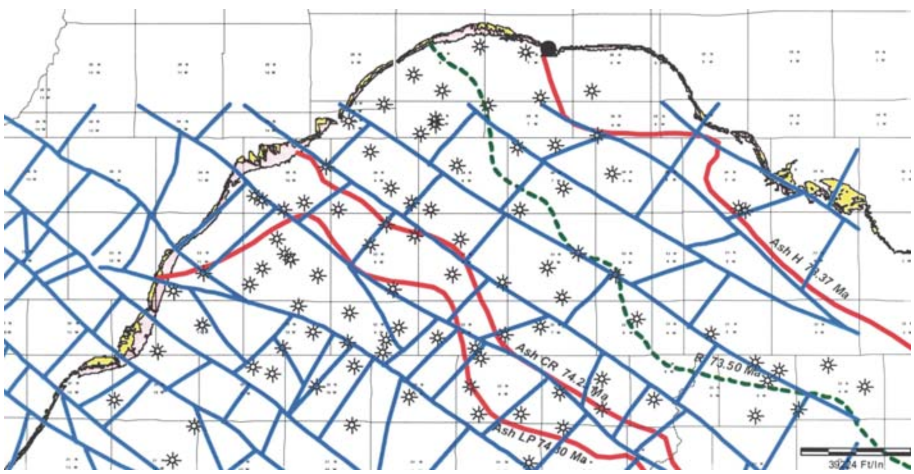

Figure 3. Paleoshorelines and basement magnetic linears.

continued until late Eocene or earliest Oligocene, when local uplift and erosion began. Precise timing of the cessation of subsidence-facilitated sedimentation and the onset of basin margin uplift is difficult because erosion has removed all of the strata that would have represented this time interval.

During the Oligocene, volcanics and intrusives were emplaced to the north of the basin (Steven, 1975; Lipman et al., 1978); these emplacements may have uplifted and begun the erosion of sediments on that margin. That erosion continued through the onset of uplift of the Colorado Plateau, of which the San Juan Basin is a part, in the early Miocene (Epis and Chapin, 1975), and continues today. The initial opening of the Rio Grande Rift to the east also began during the Oligocene, some time prior to 27 Ma (Aldrich et al., 1986; Moore, 2000), and caused minor east-west extensional fracturing to take place in the San Juan Basin. These fractures strike nearly north-south, parallel to the rift, and extend across the entire basin. Their presence is significant because they too, like the preexisting basement conjugate sets, may allow cross formational fluid flow and may locally enhance gross coal reservoir permeabilities.

Regional Coal Characteristics

The Fruitland Formation coals were deposited during the last marine shoreline regression from the basin area. These coals were deposited behind the beaches of the now underlying Pictured Cliffs Sandstone as the shoreline retreated to the northeast, between 76 and 73 Ma (Fassett, 2000), and were disrupted by stream channels (Flores and Erpenbeck, 1981). The Fruitland coals can reach individual bed thicknesses of 18 m (60 ft) or more, and may contain as much as 36 m (120 ft) of net coal in a gross interval of 60 m (200 ft) within which they interbed and interfinger freely with back-barrier, marginal marine facies (Ayers et al., 1994) (see Plate 2B and Plate 1).

Era	System	Series	Lithologic Unit	
Cenozoic	Quaternary	Pleistocene	Bridge Timber Gravel	
	Tertiary	Eocene	San Jose Formation	
		Paleocene	Nacimiento Formation	
			Animas Formation	Upper Member
Mesozoic	Upper Cretaceous			McDermott Member
			Kirtland Shale	Upper Member
				Farmington Sandstone Member
				Lower Member
			Fruitland Formation	
			Pictured Cliffs Sandstone	
			Lewis Shale	
			Mesaverde Group	Cliffhouse Sandstone
				Menefee Formation
				Point Lookout Sandstone
			Mancos Shale	
			Dakota Sandstone	
	Lower Cret.		Burro Canyon	
	Jurassic		Brushy Basin Member of Morrison Formation	

Figure 4. Stratigraphic column for the northern San Juan Basin (after Condon, 1988).

As with most Late Cretaceous coals, the Fruitland coals are generally layered and discontinuous. This is principally due to the complexity of biological systems in paludal environments where the coal-forming peat accumulated. Heterogeneities within the present coal deposits reflect both the spatial and temporal diversity in vegetation associated with the Late Cretaceous swamps. The variations in vegetation types from one biofacies to another resulted in the formation and abundance of different coal macerals in different places (Cohen and Spackman, 1980). This collection of stacking and lateral variability in biofacies units and biosomes is further punctuated by numerous clastic interbeds of fluvial and marginal marine origin, depending on proximity to paleoshorelines, and by bentonites, which are the devitrification products of volcanic ash-falls. Although these ash-fall bentonites are commonly only a few millimeters thick, they form very effective barriers to vertical fluid migration.

Subsidence and the accumulation of overburden from the time of sedimentation in the Late Cretaceous through the Eocene resulted in thermal maturation of the paludal deposits to low volatile bituminous coals, with a vitrinite reflectance of up to 1.5% (Stach et al., 1982). Areas of greatest vitrinite reflectance (Plate 2C) are situated in what was the structurally deepest portion of the basin (Law, 1992) although subsequent uplift has shifted the basin axis significantly (Fassett, 2000). The degree of maturation of peat to coal also has an influence on the chemical and hydrologic properties of the coals themselves (Snyder et al., 2003), which is likely to be reflected in the production capability of wells within the basin.

PHYSICAL AND CHEMICAL PROPERTIES OF THE COALS

Significance of Microscale and Mesoscale Properties

The coal beds as methane reservoirs bear a number of unique characteristics that collectively differentiate them from other natural gas reservoirs. Whereas the gas contained in most conventional reservoirs is sourced elsewhere and has migrated from its original location, most of the gas in a coalbed methane reservoir evolved in situ (Schraufnagel and Schafer, 1996). Although conventional gas reservoirs contain gas as a free phase, or dissolved in other reservoir fluids, most coalbed methane gas is held in a sorbed state in the coal matrix (Zuber, 1996). Because hydrodynamic pressure provides the "trapping" mechanism that keeps the gas sorbed in the reservoir rock matrix, facies changes and structural discontinuities are not required for this type of trap to be operative. The overall reservoir permeability is provided by diagenetic, fracture-like networks known as "cleats" (Bailey et al., 1999; Cohen et al., 1999, 2000; Riese et al., 2000). An understanding of the collective properties of the coals is therefore critical in the development of natural gas production wells and provides a requisite understanding that is necessary prior to developing large scale basin modeling and management plans.

Core Coal Petrology

Cores from seven wells were classified using a lithotype approach (Clarkson and Bustin, 1997) that is similar to the lithofacies approach used to describe clastic and carbonate rocks. In this classification (Table 1), dull coals contain less than 10% bright bands (a few mm thick), and dull-banded coals contain 10%–40% bright bands a few millimeters thick in a matrix of otherwise massive dull coal. Banded coals contain subequal amounts of bright and dull bands, and bright-banded coals contain 60%–90% bright bands. Bright coals are uniformly bright with little indication of banding (Jenkins, 1999). Brightness was found to correlate with cleating intensity. Dull

TABLE 1. COAL LITHOTYPE CLASSIFICATION

Lithotypes	Characteristics
Bright coal	>90% bright bands. Mineral matter varies from 7% to 15%. Intensely cleated with very well-developed orthogonal cleating system
Bright banded coal	60–90% bright bands contained in a dull to relatively bright matrix. Bright bands typically had a 3–5 mm cleat spacing. Mineral matter varies from 6% to 27%.
Banded coal	Subequal amounts of bright and dull bands. Bright bands are up to 10 mm thick and cleat spacing is typically 2–10 mm. Mineral matter varies from 15% to 46%.
Dull banded coal	10–40% bright bands. Bands are thicker and more laterally extensive than in dull coals. Cleat spacing is slightly greater than in bright coals but the cleats are more discontinuous and there is little butt cleat development. Mineral matter varies from 9% to 52%.
Dull coal	<10% bright bands. Very dull luster, sparse and thin bright bands generally <1 mm thick. Poorly developed incipient face cleats. Mineral matter varies from 32% to 66%.

Note: After Jenkins (1999).

coals have cleats that are poorly developed and widely spaced. In addition, the cleats of dull coals tend to be short, discontinuous, unidirectional, and lack orthogonal connections (Tremain et al., 1994). In contrast, bright coals have closely spaced cleats (1–3 mm) with well developed orthogonal sets of face and butt cleating (Tremain et al., 1994). All bands, whether bright or dull, reflect variations in original swamp vegetation assemblages and are referred to as biosomes.

Patches of calcite cement were observed in many of the coals. In rare instances authigenic calcite fills a significant portion of the total cleat network. Up to 67% of the face cleats contain calcite in core from the SU27-1,33-10 well (Jenkins, 1999; Jenkins et al., 2001) (Table 2).

TABLE 2. COAL LITHOTYPE CLASSIFICATION

API #	Coal interval containing cleat-face calcite cement (%)	Coal interval containing joints (%)
05067072880000	6	14
05067073130000	10	11
05067070950000	49	30
05067081510000	15	21
05067081560000	67	31
05067070220000	10	24
05067071060000	67	36

CT Scanning

CT scanning is an X-ray imaging technique that allows three-dimensional characterization and depiction of internal structure. It relies on variations in X-ray attenuation, or X-ray capture density, to delimit boundaries in rock or other media. When applied to well cores, it produces a qualitative view of the proportion made up of coal, as well as a clear view of how the cleats are organized and distributed within the coal fabric. Differences in lithology and structural architecture can be further quantified in processed CT images. Three cores were available for reservoir characterization (Plate 1D), and each was collected specifically to examine reservoir properties in fresh, unaltered samples. The images were enhanced to bring out the proportion of interbedded clastics as well as the internal cleat structure (Plate 3 [a loose insert accompanying this volume]). The various axial images illustrate the differences in cleat density and orientation from core to core.

Despite the fact that the lithologies of the cores change rapidly and the cores themselves represent only a small portion of the reservoir, they do permit several generalizations. Samples from core #27-1 contain fully developed orthogonal cleat patterns as well as irregular fractures. Both of these types of structural discontinuities appear to be open and are not mineralized. Samples from core #5-2 contain less densely packed orthogonal cleat sets and many of those present do not appear to be open. A number of the cleats in core #5-2 show signs of secondary mineralization, and the samples do not have the same density of irregular fractures observed in core #27-1. Samples from the third core, #32-4, contain fewer cleats and fractures than the previous two cores and completely lack orthogonal cleat sets. As with core #5-2, many of the fractures appear to be closed.

X-ray Diffraction

X-ray diffraction (XRD) analyses were performed on a number of residual mineral separates in order to determine ash composition or mineral constituents in the coals (Table 3). They suggest that the total amount of mineral matter present in the coals is not a determinant in the development of cleating, but rather that the type of mineral matter may be important. A simple zoning of clay phases, iron-bearing phases (pyrite), and carbonate is present and appears to empirically and crudely correlate spatially with the amount of cleating present and with apparent permeability. Kaolinites dominate the clay-mineral phase in the westernmost 27-1 core, but are less common further east in the 32-4 well; smectites are not present in the 27-1,

TABLE 3. X-RAY DIFFRACTION ANALYSIS OF MINERAL MATTER

API number	Well name	Description	Mineral matter (%)	Quartz (%)	Total CO_3 (%)	Pyrite (%)	Smectite (%)	Kaolinite (%)
05067081560000	16-5, 32-8	Dull band	42	48	N.A.	12	N.A.	36
		Dull band	23	44	13	N.A.	N.A.	43
		Bright band	27	4	81	N.A.	N.A.	11
		Band	29	34	7	10	14	28
		Bright band	33	30	15	3	15	30
05067081510000	18-4, 32-8	Dull band	34	74	N.A.	N.A.	N.A.	21
		Bright	8	37	N.A.	N.A.	N.A.	63
		Bright band	19	53	N.A.	N.A.	N.A.	42
		Dull band	19	16	53	N.A.	N.A.	32
05067070220000	32-4,33-8	N.D.	12	30	<1	10	5	50
		N.D.	80	70	2	4	<1	20
		N.D.	8	30	10	5	0	50
		N.D.	11	30	12	0	3	50
		N.D.	2	40	3	0	0	50
		N.D.	22	30	10	5	0	50
		N.D.	52	40	48	0	2	10
		N.D.	64	55	<1	0	<1	40
		N.D.	96	50	<1	0	5	40
		N.D.	12	30	<1	10	5	50
		N.D.	80	70	2	4	<1	20
		N.D.	8	30	10	5	0	50
		N.D.	11	30	12	0	3	50
		N.D.	2	40	3	0	0	50
		N.D.	22	30	10	5	0	50
		N.D.	52	40	48	0	2	10
		N.D.	64	55	<1	0	<1	40
		N.D.	96	50	<1	0	5	40
05067073130000	5-2,32-9	N.D.	25	50	2	0	0	40
		N.D.	15	60	0	0	0	40
		N.D.	50	35	2	0	<1	55
		N.D.	20	97	1	0	<1	2
		N.D.	50	20	43	0	2	25
		N.D.	50	100	0	0	0	0
		N.D.	10	20	43	0	1	30
		N.D.	5	50	14	4	30	5
		N.D.	25	50	2	0	0	40
		N.D.	15	60	0	0	0	40
		N.D.	50	35	2	0	<1	55
		N.D.	20	97	1	0	<1	2
		N.D.	50	20	43	0	2	25
		N.D.	50	100	0	0	0	0
		N.D.	10	20	43	0	1	30
		N.D.	5	50	14	0	4	30
05067072880000	27-1, 33-10	N.D.	45	25	3	0	0	72
		N.D.	7	15	2	0	0	83
		N.D.	40	25	3	0	0	72
		N.D.	6	30	<1	0	0	70
		N.D.	90	25	1	0	0	74
		N.D.	90	25	<1	0	0	75
		N.D.	98	20	0	0	0	78
		N.D.	6	25	3	0	0	72
		N.D.	7	25	0	0	0	75
		N.D.	45	25	3	0	0	72
		N.D.	7	15	2	0	0	83
		N.D.	40	25	3	0	0	72
		N.D.	6	30	<1	0	0	70
		N.D.	90	25	1	0	0	74
		N.D.	90	25	<1	0	0	75
		N.D.	6	25	3	0	0	72
		N.D.	7	25	0	0	0	75

Note: N.D.—not determined

but do occur in the 5-2 and 32-4; and pyrite is more abundant in the easternmost 32-4 well. The mineral matter is indicative of the geochemical environment that contributed to cleat formation and to the subsequent infilling of cleats. The XRD data of samples from these three wells suggests that oxidizing fluids moved through the coals at some point in time, promoting authigenic mineralization.

Electron Microprobe Petrography

Cleat and incipient cleat systems were imaged using electron microprobe, in order to reveal variations in ash mineralogy in the near-cleat environment. Variations in mineral content and the locations of authigenic phases should be indicative of the chemical processes associated with cleat formation. These analyses can also potentially provide valuable information about the portions of the basin that have received input of meteoric water recently or in the past.

Photomicrographs of samples were taken at 969.87 m (3182.0 ft) depth in the 27-1 core (Plate 3). Open fractures are clearly visible, as is late-stage calcite, kaolinite, and quartz cementation. The orthogonal cleat sets that tend to characterize samples from this well are not readily apparent; however, dark areas in another portion of the core represent areas with abundant microporosity. The broad, dark areas of the image are the product of agglomerations of micropores. Microfractures or microcleats are also present. The presence of this open space suggests that the network of effective porosity that allows gas to reach the wellbore extends to a very fine scale.

Photomicrographs of samples taken at 1148.27 m (3767.3 ft) depth in the 32-4 core show open, epoxy-filled fractures and dark zones of microporosity (Plate 3). Also visible is a network of fractures filled with kaolinite. It is not clear whether these kaolinite-filled features are diagenetically or stress induced. In either case, they represent open space that appears to be almost uniformly filled by authigenic phases.

Comparative analysis of these images permits several generalizations. The coals in the eastern part of this study area generally appear to be “dirtier,” or to contain more authigenic phases, than those from the west. Microporosity is present in samples from across the area sampled and has character suggestive of incipient cleating and phyteral preservation. Open fractures are present across this entire portion of the field.

Photomicrographs were also taken of samples from 969.87 m (3182.0 ft) depth in the 27-1 core, the westernmost core available and the one closest to the previously described production “Fairway” (Plate 3). These figures show the open fracture and cleat network that characterizes samples from that portion of the field. They also reveal a texture that suggests that dissolution has occurred either along the faces of these fractures or that might be concurrent with and contributing to their formation. These dissolution textures are perhaps the result of the oxidizing solutions as suggested by the XRD data (Riese et al., 2000).

WATER CHEMISTRY IN THE FRUITLAND FORMATION COALS

The chemical and isotopic makeup of the waters associated with coalbed methane is influenced by a variety of factors including contributions from connate waters that were originally deposited with the peats, the expulsion of certain elements during the coalification process, water-rock interactions both locally and along the path of flowing groundwater, and microbially mediated reactions involving both methanogenesis and anaerobic oxidation of methane (AOM). Despite their complex origin, formation waters associated with coalbed methane in different basins around the world bear remarkable resemblance to each other, and are generally sodium chloride–bicarbonate dominated and depleted in calcium and sulfate (Van Voast, 2003). The presence of relatively conservative ions Na and Cl is due to the marginal marine origin of the formation waters, while the abundance of the reactive constituents is modified by microbial activities associated with both methanogenesis and anaerobic methane oxidation (Rice, 1993). The extent to which these processes are distributed spatially and evidenced in production well brines provides a direct measure of the presence or absence of throughflow in these systems, since the movement of dissolved solutes into the basin is a precursor for some of the observed biogeochemical reactions.

Nearly 100 production wells were analyzed for their chemical and isotopic composition within the Fruitland Formation coals during an initial phase of the study from 1997 to 2000 (Table A1). The compositional distributions are mapped in Plate 1E–1L. Subsequently, rivers and streams, as well as shallow monitoring wells in areas near the outcrop of the Fruitland Formation, were sampled on a bimonthly basis between 2001 and 2002 in order to assess seasonal variations and the presence or absence of effective recharge (Table A2).

Isotopes: Stable, Radiogenic, and Cosmogenic

Deuterium and Oxygen-18

Production well waters, shallow monitoring wells, and rivers were analyzed for δD and $\delta^{18}O$, and most of the samples plotted along the global meteoric water line (GMWL; Fig. 5). Production wells were consistently less depleted in deuterium and ^{18}O than the monitoring wells and rivers, with most plotting slightly above the GMWL. Deuterium enrichments were noted in a number of production wells and are likely the product of either the reequilibration of subsequent groundwater incursions with hydrocarbons associated with the coals (Snyder et al., 2003) or the preferential removal of light hydrogen during biogenic methanogenesis through CO_2 reduction. Likewise, well waters that fall below the GMWL may reflect the inclusion of connate seawater, as well as hydrogen expelled from the peats during coalification, resulting in a net deuterium depletion (Polya et al., 2000; Snyder et al., 2003; Schimmelmann et al., 2001).

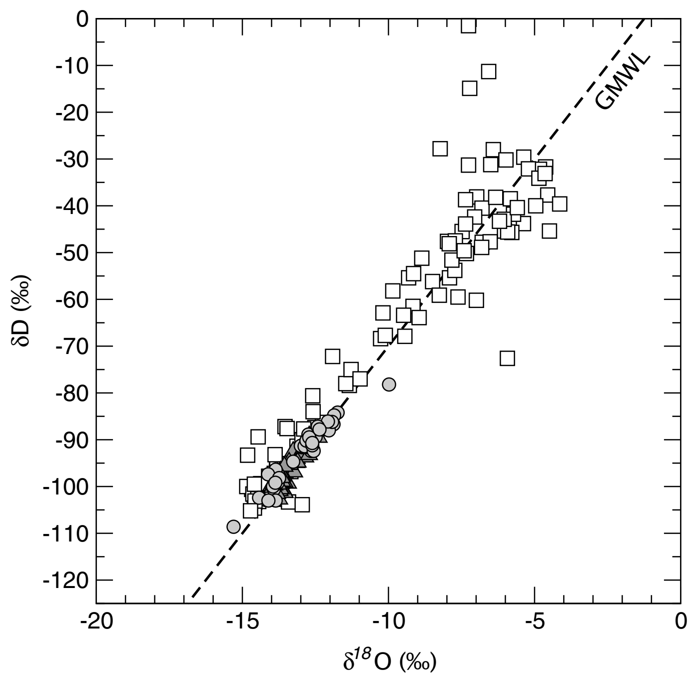

Figure 5. A cross plot of deuterium versus $\delta^{18}O$ generally follows the global meteoric water line (GMWL). White squares—production wells; light gray circles—streams and rivers; dark gray triangles—shallow monitoring wells. Production wells are generally more enriched in deuterium and ^{18}O than surface waters. Shallow monitoring wells show similar values as the surface waters.

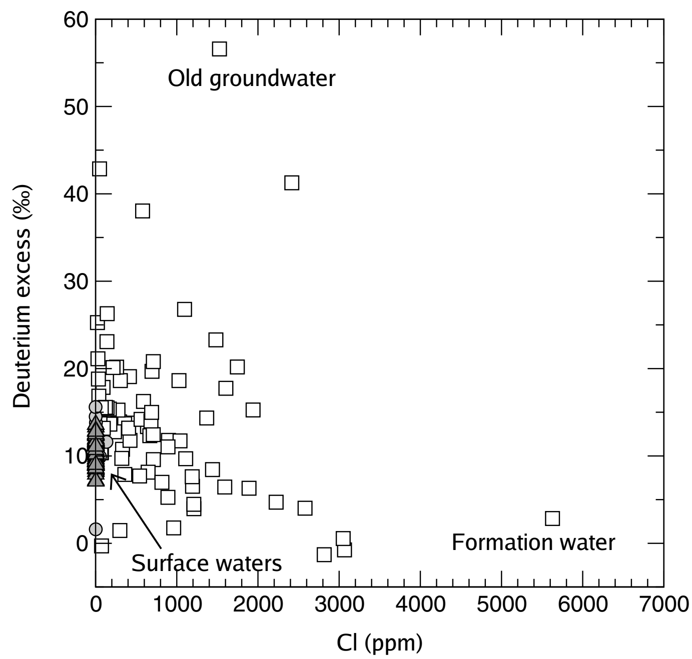

Figure 6. Formation waters are characterized by high chloride content as well as low deuterium, a relict of the initial seawater contributions rather than halite dissolution, which would still preserve a deuterium excess of ~10‰. White squares—production wells; light gray circles—streams and rivers; dark gray triangles—shallow monitoring wells.

The deviation from the GMWL can be quantified as a single value, or deuterium excess:

$$D_{excess} = \delta D - 8\ \delta^{18}O \quad (1)$$

Generally, deuterium excesses are a result of the kinetic isotopic effect during seawater evaporation in regions of low humidity, such as the Mediterranean (Sheppard, 1986; Criss, 1999; Gat and Carmi, 1970). Nonetheless, deuterium enrichments observed in several of the Fruitland Formation production wells are much greater than can be explained by low atmospheric humidity. They do, however, originate from water with much lower chloride concentrations than the low excess deuterium formation waters (Fig. 6). As will be discussed, the high excess deuterium is likely the product of near-outcrop methanogenesis through carbon dioxide reduction during a period of groundwater incursion.

Strontium

Dissolved strontium and ratios of $^{87}Sr/^{86}Sr$ were also measured for the same waters (Fig. 7). Because the timescales associated with the deposition and formation of the Fruitland Formation are relatively short compared to the half-life of ^{87}Rb (48.8 Gyr; Faure, 1986), the $^{87}Sr/^{86}Sr$ ratios observed in these groundwaters are either the result of a marine source—connate waters or weathering of associated carbonates—or the ratios are a product of weathering of old continental crust that has accumulated ^{87}Sr as a daughter product from the decay of ^{87}Rb. Some of the production wells have high strontium concentrations and show mixing between a marine end-member with ratios somewhat lower than modern seawater, but typical for the Late Cretaceous ($^{87}Sr/^{86}Sr$ = ~0.7075; Hess et al., 1986), and a high-strontium end-member with $^{87}Sr/^{86}Sr$ = ~0.713, which is possibly due to upward migration of brines from basement fractures. This mixing trend is similar to well waters observed elsewhere by Dowling et al. (2003) who attributed it to weathering of strontium-rich micas in basement rocks.

River water samples also show binary mixing. In this case, one of the end-members has low $^{87}Sr/^{86}Sr$ ratios and high dissolved strontium and may represent the weathering of secondary carbonates or the direct recharge to the rivers from springs containing strontium-rich connate brines. The second end-member is represented by strontium-depleted waters with $^{87}Sr/^{86}Sr$ = ~0.715, which is indicative of a source where the predominant form of chemical weathering is of silicic basement rocks rather than carbonates (e.g., Faure, 1986). Shallow monitoring wells located along the Pine River have strontium concentrations and $^{87}Sr/^{86}Sr$ ratios that fall along the same mixing trend as river waters, although the range is restricted to higher Sr concentrations and lower isotopic ratios. In general, there is also an overlap between surface waters and monitoring wells when comparing deuterium excess and $^{87}Sr/^{86}Sr$ ratios (Fig. 8).

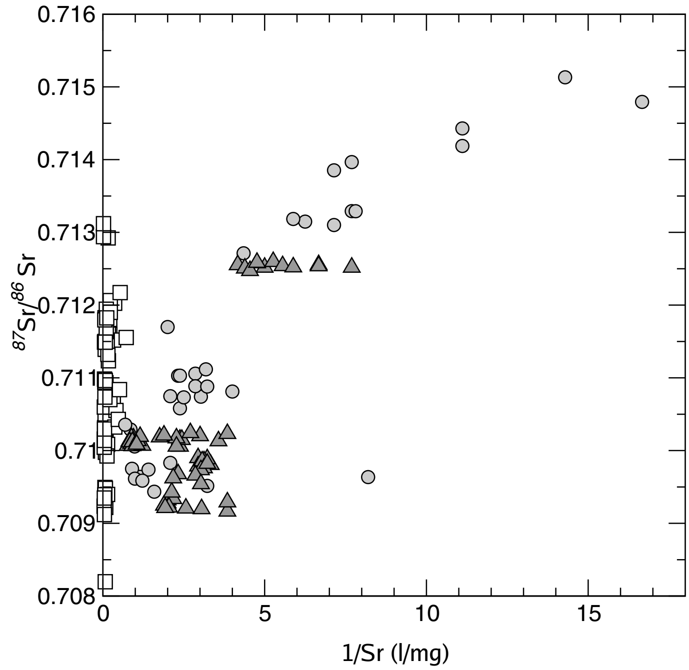

Figure 7. The strontium isotopic composition of surface waters shows clear mixing between two end-members. The first end-member is strontium-rich, with $^{87}Sr/^{86}Sr = 0.708–0.709$, which is typical for seawater and dissolved carbonates. The second is a low strontium end-member, with $^{87}Sr/^{86}Sr$ representing strontium derived from the weathering of silicic rocks. The monitoring wells show similar values. The production wells, on the other hand, show mixing between the seawater-carbonate end-member with a third strontium-rich end-member with $^{87}Sr/^{86}Sr = 0.713$. White squares—production wells; light gray circles—streams and rivers; dark gray triangles—shallow monitoring wells.

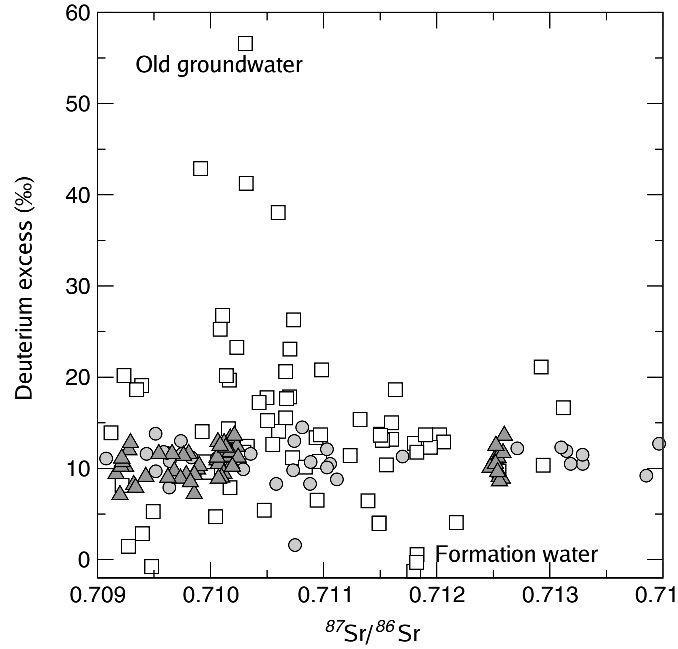

Figure 8. Water samples cover a broad range of $^{87}Sr/^{86}Sr$ ratios depending on whether the strontium source is from carbonate or silicic sources. Production wells with high deuterium excess tend to trend toward lighter strontium ratios, indicating a carbonate source. Surface waters show the greatest input from silicic rocks. White squares—production wells; light gray circles—streams and rivers; dark gray triangles—shallow monitoring wells.

Waters associated with the production wells show a much higher variation in deuterium excess than is observed in rivers and monitoring wells, with low values (0–10‰) similar to those commonly associated with connate waters. High values, which are also present ($\delta D > 20‰$), reflect the infiltration of groundwater into the coals at some point in time, and/or isotopic effects related to anaerobic methanogenesis. The infiltration of groundwater is also suggested by a noticeable drop in chloride concentration (Fig. 9). Formation waters that have been mixed with groundwater associated with carbonate weathering show no appreciable change in $^{87}Sr/^{86}Sr$ ratios during dilution, and groundwater that has come into contact with silicic crustal rocks increases $^{87}Sr/^{86}Sr$ ratios significantly during the process of dilution. The data we present suggest that both of these mixing processes may have been operative to some extent.

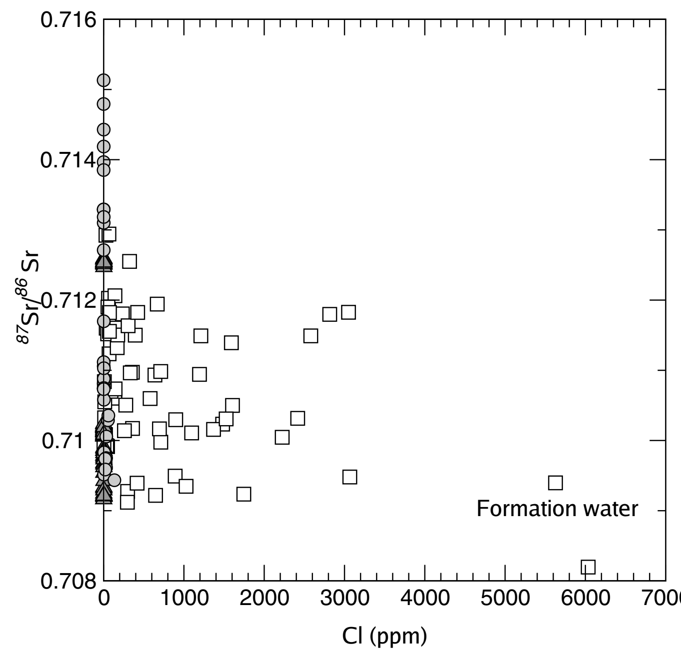

Figure 9. Strontium ratios plotted against chloride content indicate mixing between formation water and waters derived from weathering of carbonates and silicic rocks. Surface waters show a greater contribution of strontium from a chloride-depleted silicic source. White squares—production wells; light gray circles—streams and rivers; dark gray triangles—shallow monitoring wells.

Iodine-129

The iodine-129 composition in hydrocarbon-related brines has been used as an indicator of age and source since the early 1990s (Fabryka-Martin et al., 1991; Moran et al., 1995; Fehn et al., 2000). More recently, both the ^{129}I and ^{36}Cl systems were also applied to the Fruitland Formation brines (Snyder et al., 2003). In this paper, we describe some of the relationships that occur between these two isotopic systems and the overall water chemistry.

The ^{129}I that is present in the brines is predominantly derived from iodine that was sorbed onto organic matter associated with the coal-forming peats prior to burial. This ^{129}I was derived from the interaction between cosmic rays and atmospheric xenon. Based on the age of the coals (73–74 Ma; Fassett, 2000), the half-life of ^{129}I (15.7 m.y.), and the initial marine-cosmogenic ratio of ^{129}I to stable ^{127}I (^{129}I/I = 1500 × 10^{-15}, Moran et al., 1998; Fehn et al., 1986), we can determine the ^{129}I/I ratio for formation waters derived from the early expulsion of iodine and other elements during the coalification process. Given reasonable assumptions, and a minor correction for fissiogenic in situ production of brines, the ratio of ^{129}I/I is presently 120 × 10^{-15} (Snyder et al., 2003). The combined ^{129}I contribution to the environment from bomb tests of the 1960s and ongoing nuclear reprocessing has led to anthropogenic ^{129}I/I ratios in North American streams and rivers that are presently 3–5 orders of magnitude greater than pre-anthropogenic ratios (Moran et al., 2002; Fehn and Snyder, 2000; Rao and Fehn, 1999).

In the case of the Fruitland Formation, meteoric waters presently have ratios exceeding 2.5 × 10^{-9}). Because iodine concentrations in surface reservoirs are much lower that those of formation waters, the iodine isotopic ratios are generally inversely correlated to the total iodine concentration (Fig. 10). The observed iodine isotopic ratios cannot be explained by simple binary mixing of anthropogenic and formation waters, nor can they be described as the product of mixing pre-anthropogenic and formation waters. Somewhat more dilute waters in the production wells tend to have higher ^{129}I/I ratios than expected and likely were derived from long-term accumulations of ^{129}I produced in situ through the spontaneous fission of ^{238}U. As has been discussed, formation waters have low deuterium excess, and are, for the most part, observed to have low ^{129}I/I ratios (Fig. 11). In addition, the group of old groundwaters associated with deuterium excess in Figures 6 and 7 is also the group of groundwaters with somewhat elevated ^{129}I/I ratios. As will be discussed, this group of waters may represent upward migration of fluids into the Fruitland Formation along basement fractures.

Chlorine-36

A limited number of production wells, test wells, and surface waters were also analyzed for ^{36}Cl (Fig. 12). The ^{36}Cl system is discussed in detail in the context of the Fruitland Formation in Snyder et al. (2003). As with ^{129}I, the isotope ^{36}Cl

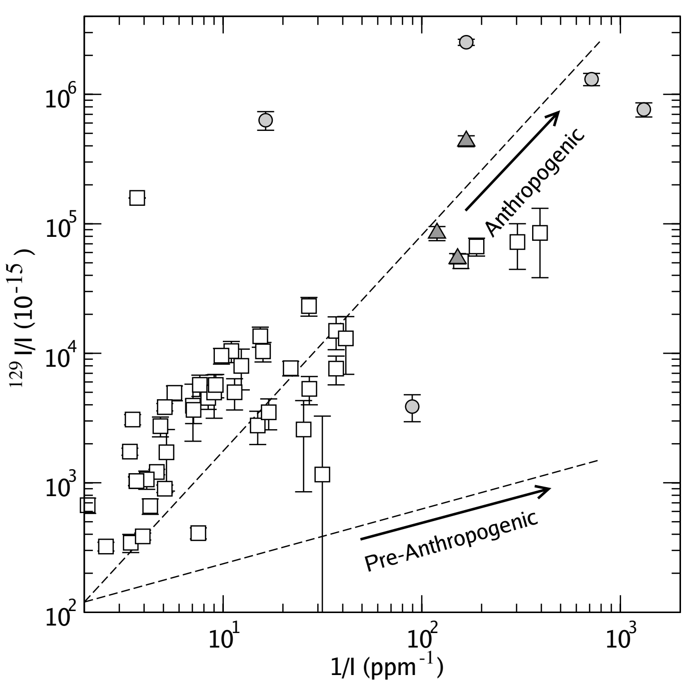

Figure 10. Iodine ratios plotted against the inverse of iodine concentration show dilution by an end-member with low iodine and high ^{129}I, caused by minor dilution form anthropogenic source or in situ ^{129}I production in the coals. White squares—production wells; light gray circles—streams and rivers; dark gray triangles—shallow monitoring wells. Error bars are 1σ.

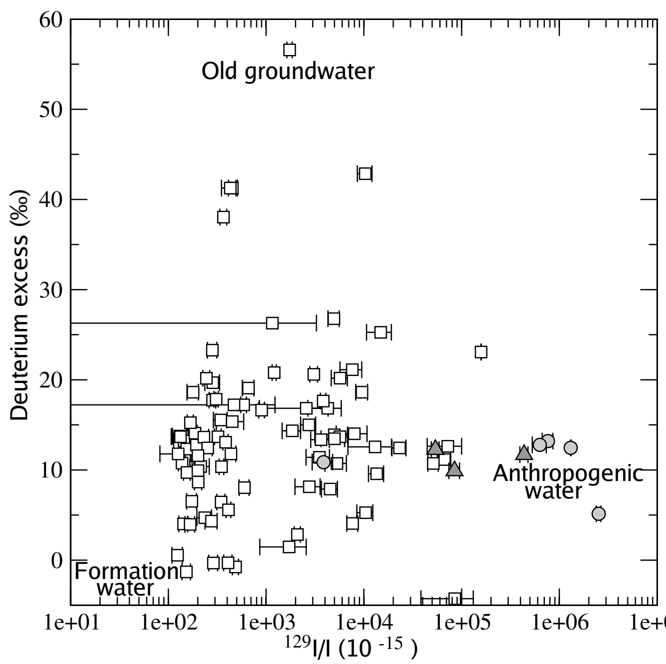

Figure 11. Plot of deuterium excess versus iodine isotopic composition, showing three predominant end-members. Formation waters have seawater deuterium-excess values of 0‰ and ^{129}I/I = 120 × 10^{-15}. Surface waters have typical deuterium-excess values of ~10‰ and a strong anthropogenic signature of ^{129}I/I = 2.55 × 10^{-9}. A third end-member, representing old groundwater, has an intermediate iodine isotopic composition and elevated deuterium-excess due to a combination of reequilibration between the water and hydrocarbons. White squares—production wells; light gray circles—streams and rivers; dark gray triangles—shallow monitoring wells. Error bars are 1σ.

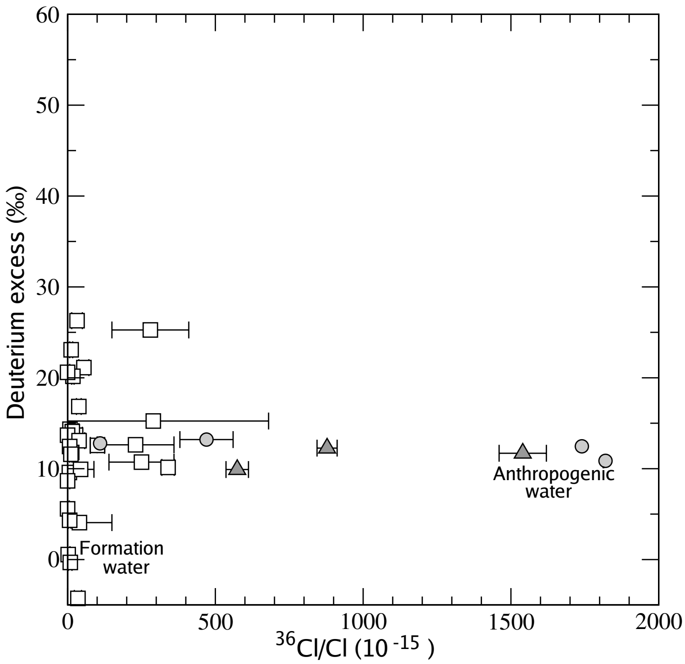

Figure 12. Ratios of $^{36}Cl/Cl$ show similar trends to Figure 11. In this case, the cosmogenic ^{36}Cl has decayed away in both the formation water and old groundwater end-members, and elevated $^{36}Cl/Cl$ ratios are seen only in surface waters and the shallow test wells. White squares—production wells; light gray circles—streams and rivers; dark gray triangles—shallow monitoring wells. Error bars are 1σ.

is also produced through cosmogenic interactions, as well as radiogenically (Andrews et al., 1989). Unlike ^{129}I, the relic marine ^{36}Cl signature is below the limits of AMS detection, and present $^{36}Cl/Cl$ ratios are a function of distance from coastal regions and dilution from sea spray–derived chloride (Davis et al., 2001). The half-life of ^{36}Cl is only 0.3 m.y., and any ^{36}Cl found within the Fruitland Formation must be a product of either infiltration of groundwater less than 2 Ma or in situ production (Bethke et al., 2000; Park and Bethke, 2002). Another difference with the ^{36}Cl is that the bomb test component has been largely diluted by the marine chloride signature, and nuclear reprocessing has not resulted in further dispersal of this nuclide, such that $^{36}Cl/Cl$ ratios have returned to pre-anthropogenic levels in surface reservoirs (Cornett et al. 1997).

The present ratio for surface waters associated with the San Juan Basin is 1600×10^{-15} (Snyder et al., 2003). Appreciable amounts of ^{36}Cl are present in river samples and in the monitoring wells (Fig. 12). Unfortunately, there is not enough coverage of the production well samples with high deuterium excess to determine their age. Ratios of $^{36}Cl/Cl$ do indicate the absence of recent surface waters involved in the dilution of formation waters. Discrepancies between ^{129}I and ^{36}Cl ages (Table A1) are discussed in Snyder et al. (2003). Because the half-life of ^{36}Cl is much shorter than that of ^{129}I, the chlorine isotopic system reaches secular equilibrium with respect to in situ production in the central part of the basin. At the northern margin of the basin, discrepancies between ^{129}I and ^{36}Cl ages reflect hydrodynamic, or mechanical, dispersion of formation water chloride with surface waters (Park and Bethke, 2002), rather than halite dissolution (Davis et al., 2000).

Microbial Influences on Water Chemistry

The chemistry of Fruitland Formation waters, as well as water-rock interactions within the coals themselves, is influenced by microbial organisms that derive energy through the production of methane (methanogens) or the oxidation of methane (methanotrophs). The production of methane from organic matter associated with coal beds is a mixture of biogenic and thermogenic gas (Smith and Pallasser, 1996; Scott et al., 1994) and involves a combination of acetate fermentation and CO_2 reduction (Schoell, 1988; Whiticar et al., 1986) as well as thermocatalytic degradation of organic matter. Earlier studies of the Fruitland Formation assumed that the transport of microbes into the basin to metabolize organic compounds and produce methane would require regional and continuous flow of groundwater (Scott et al., 1994). We now know, however, that autotrophic *Archaea* capable of producing methane from organic substrates are ubiquitous, both in marine sediments (D'Hondt et al., 2002) and in subsurface terrestrial environments often hundreds of meters deep (Kotelnikova, 2002). The presence of microorganisms appears to be limited only by high temperatures, rather than the throughflow of water, since the microbial communities have been adapting to their physical conditions, possibly since initial deposition and burial. In the case of the Fruitland Formation, the metabolic activity in the deep overpressured portions of the basin may be enhanced by the moderate heating that is necessary to break down organic matter, forming the precursors for biogenic methanogenesis (Wellsbury et al., 2003). This may explain why the stable isotopic composition of the methane, as well as ratios of methane to the heavier hydrocarbons in the Fruitland Formation, does not indicate a pure "biogenic" or "thermogenic" end-member in the traditional sense (e.g., Scott et al.,1994; Whiticar et al., 1986) in that the two processes do not occur independently.

Where methane is derived from the reduction of carbon dioxide in coal seams, the CO_2 may be derived from an external source (Smith and Pallasser, 1996) or from the local oxidation of organic matter. In either case, the microbial pathways involved in the biogenic reduction of CO_2 must ultimately derive the hydrogen to produce methane from the formation waters. This results in deuterium-depleted methane and residual waters that are enriched in deuterium. The observation that deuterium excesses in portions of the basin are also accompanied by $^{87}Sr/^{86}Sr$ ratios that are much higher than seawater values (Fig. 7) implies that the original connate waters have at some point received an influx of waters from another source that was in contact with basement rocks.

Coalbed methane systems are analogous to marine sediments in that the oxidation of methane is also controlled by microbial activity. In marine systems, the predominant form of methane degradation is through sulfate reduction, and the depth at which this occurs is both a function of the upward flux of methane and the downward flux of seawater sulfate (D'Hondt et al., 2002; Dickens, 2001; Boetius et al., 2000). Similarly, in basins hosting coalbed methane systems, methane in anoxic and suboxic groundwaters is also oxidized by sulfate-reducing microorganisms in the following reactions (e.g., Schumacher, 1996):

$$2CH_4 + SO_4^{2-} \rightarrow 2HCO_3^- + H_2S \quad (2)$$

$$2CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O + CO_2 \quad (3)$$

The predominant source of sulfate in the hydrological systems associated with coal beds is the weathering of pyrite and marcasite by surface waters and oxic shallow groundwater (Van Voast, 2003). More recently, microbial oxidation of sulfide associated with hydrocarbon seeps has also been noted as a source of sulfate (Senko et al., 2004). Because the sulfate involved in this reaction is rapidly depleted through the oxidation of methane, these reactions are necessarily limited to areas near the coal outcrops and along areas of seepage, and do not occur deep within the basin. These bacterially mediated reactions also serve to limit the amount of methane that actually reaches the surface during seepage. As has been observed in marine systems (Boetius et al., 2000), the biogeochemical processes near coal outcrops are likely moderated by microbial consortia that both produce methane through CO_2 reduction and then oxidize the methane through sulfate reduction. Kotelnikova (2002) estimated that sulfate reduction at the margins of hydrocarbon bearing basins, coupled with the direct degradation of methane by aerobic methanotrophs in shallow groundwater, is responsible for the net removal of as much as 25% of the total diffusive flux of methane before it reaches the surface. In the Fruitland Formation waters, sulfate concentrations are generally below detection limits and contrast sharply with sulfate concentrations in the surface waters (Fig. 13). Even the shallow monitoring wells show nearly complete removal of sulfate through microbial processes.

Methane oxidation and sulfate reduction therefore have a direct impact on water chemistry. Bicarbonate-rich waters result, and alkalinity increases dramatically, promoting the precipitation of calcite along coal cleats and fractures. Waters recovered from the shallow monitoring wells near outcrop often show significant loss of calcium due to this process (Fig. 14) relative to both surface waters and the sodium-rich formation waters. In addition, the reduced sulfur species produced through methane oxidation results in localized precipitation of pyrite.

The reducing conditions caused by the oxidation of methane also indirectly affect dissolution of barite ($BaSO_4$), which becomes undersaturated in sulfate-depleted waters. It is likely that the dissolved barium that is present in the production well waters originated from barite in marine sediments (Torres

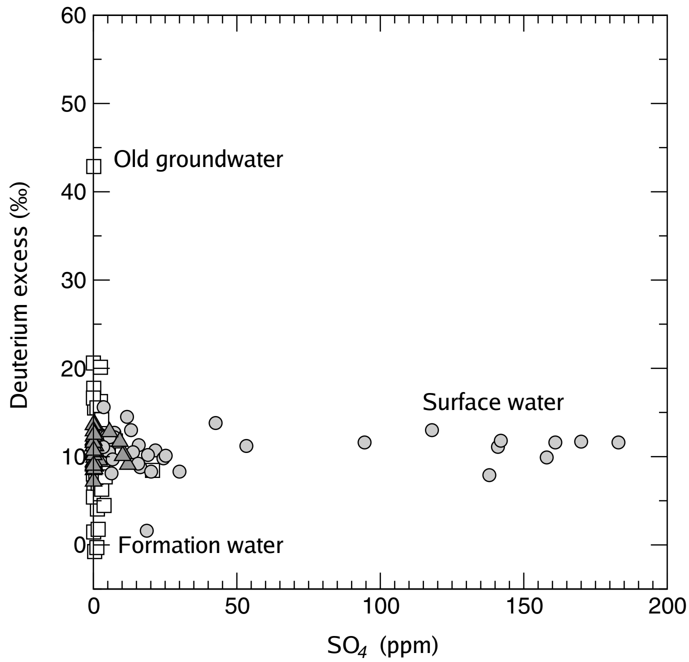

Figure 13. Sulfate is found in surface waters due to the weathering of pyrite. In both the production wells and the test wells, all of the sulfate has been removed through anaerobic oxidation of methane. White squares—production wells; light gray circles—streams and rivers; dark gray triangles—shallow monitoring wells.

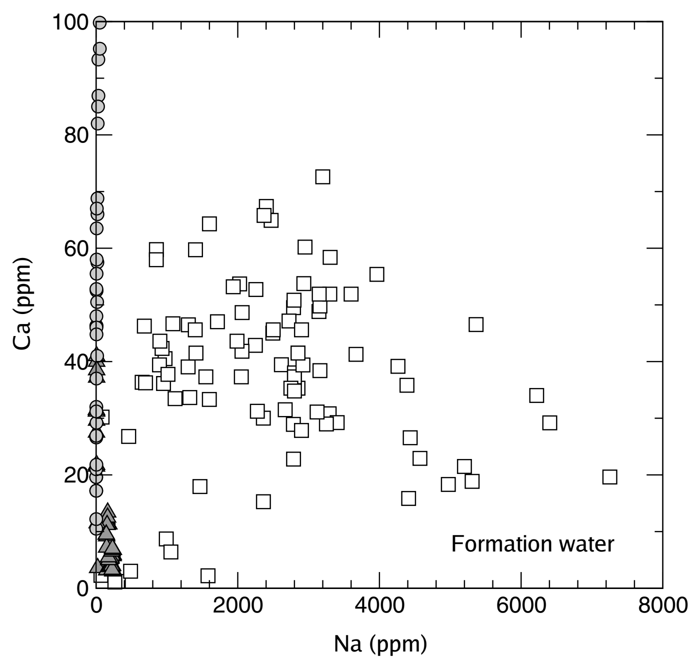

Figure 14. Production wells tend to be sodium-rich and calcium-poor due to the presence of original seawater and the precipitation of calcite in the coals as a result of the anaerobic oxidation of methane (AOM). Because AOM is associated with sulfate reduction near the margins of the basin, the shallow test wells show even greater removal of calcium than the production wells. White squares—production wells; light gray circles—streams and rivers; dark gray triangles—shallow monitoring wells.

et al., 1996; Dickens 2001) and was released during anaerobic oxidation of methane. Significant amounts of barium (>5 ppm) are found only in the Fruitland Formation production wells, where sulfate is essentially absent (Fig. 15). Where barium comes into contact with sulfate-rich surface waters, it is reprecipitated as authigenic barite (Senko et al., 2004). Both deuterium-enriched and deuterium-depleted production well waters show high barium concentrations (Fig. 16). Thus, any sulfate initially present in old groundwater has already been reduced to sulfide and has no net effect on the dissolved barium concentration.

Three spring and seep samples were collected in the South Fork of Texas Creek (Plate 1L; Tables 4 and A2), just 5 km west of the Pine River, in order to determine whether the water is sourced from local meteoric recharge or is issuing from deeper, perhaps connate, sources. This drainage occupies a strike valley in the Fruitland Formation coals. Two of the samples (Texas Creek seep and Tributary seep) were collected from springs associated with active gas seeps, while the third (New Texas Creek seep) was collected from the creek itself, near another prominent gas seep. All of the seep samples had excess deuterium values consistent with surface waters. Sulfate concentrations (3.4–19.0 ppm) also indicate oxic waters, while the calcium concentrations for the seeps (41–67 ppm) are all greater than those observed in the Pine River monitoring wells. Of the three, the Tributary seep sample showed unusually low strontium isotopic ratios ($^{87}Sr/^{86}Sr$ = 0.707511), possibly indicative of weathering of authigenic carbonates during the recent infiltration of meteoric water along a nearby north-south fracture zone. Given the concurrent presence of methane and sulfate, the admixture of gas and local groundwater must be localized and intermittent along areas of outcrop, as is consistent with interpretations by Oldaker (1999).

Influence of Seasonal Surface Water Fluctuations on Groundwater Chemistry

Samples were collected on a bimonthly basis during 2001 and 2002 from five groundwater monitoring wells in the Pine River drainage, which are either above or within 100 m of the Fruitland Formation coal subcrops, under the Quaternary river gravels (Table A2). Three of the wells (Killian Deep-Kfr, James1-Kfr, and Salmon3-Kfr) are completed in the Fruitland coals (Kfr); one is completed in the transitional clastics located just above the coals (Kfrt) in the upper reaches of the formation (Salmon3-Kfrt), and one is completed in the Quaternary alluvial river gravels (Qal) (James2-Qal). In addition, the Florida and Animas rivers were sampled during the course of the investigation (Table A2). All of these samples were collected in order to examine the relationships between surface waters and formation waters and the potential for recharge or discharge of fluids from the Fruitland Formation coal outcrops.

Since snowmelt during the summer months affects the chemistry of runoff, it should have direct bearing on the chemistry and isotopic composition of the shallow monitoring wells if recharge effectively migrates through the coals in which the wells are completed. Conversely, should the formation waters

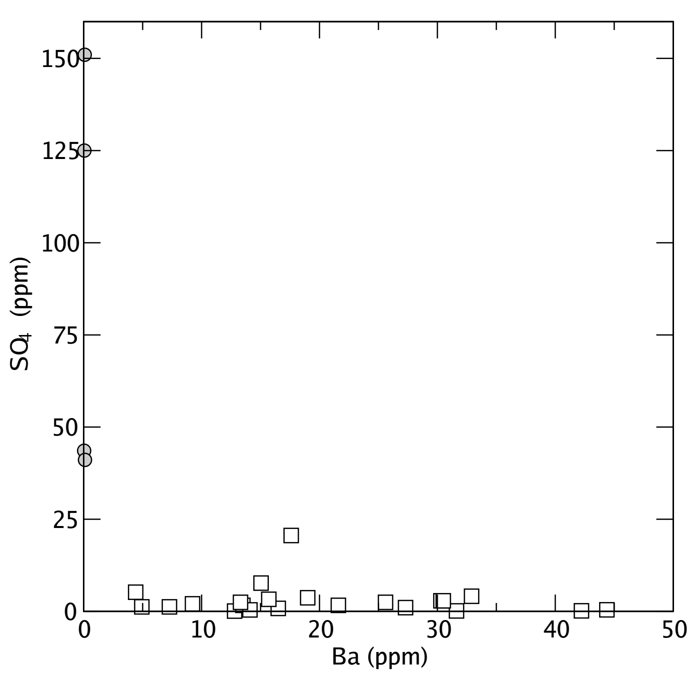

Figure 15. Formation waters have high barium contents. Surface waters fall outside the zone of sulfate reduction and have high sulfate concentrations. White squares—production wells; light gray circles—streams and rivers.

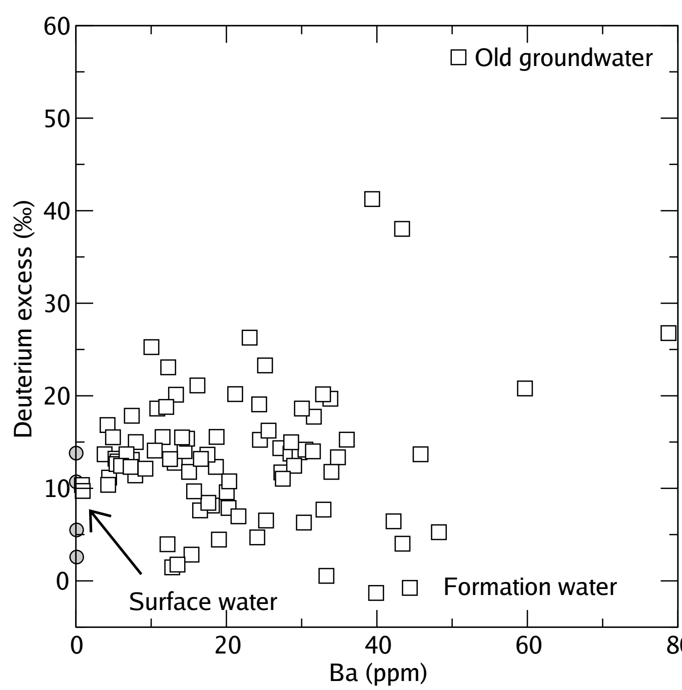

Figure 16. Barium-rich waters show a bimodal distribution between deuterium depleted and deuterium enriched samples. White squares—production wells; light gray circles—streams and rivers.

TABLE 4. ANALYSES OF SURFACE WATERS FROM THE TEXAS CREEK AREA

Location:	Texas Creek seep	Tributary seep	New Texas Creek seep
Sample no.			
$\delta^{18}O$ (‰)	–12.61	–12.61	–12.36
δD (‰)	–91.2	–90.7	–87.8
Sr (ppm)	0.5	0.34	0.44
$^{87/86}Sr$	0.709516	0.707511	0.709077
δsw	35.5	–165.0	–8.4
Si	1.8	7.5	12.0
Fe	0.1	0.21	8.0
Mn	0.63	0.02	1.35
Mg	21.0	6.4	12.4
Ca	67.0	41.0	50.5
Na	10.5	15.0	15.2
K	4.4	1.0	3.4
CO_3	0	0	0
HCO_3	343.2	163.6	272.2
F	0.25	0.36	0.15
Cl	3.4	1.9	1.2
Br	0.2	0	0
SO_4	6.7	19.0	3.4
NO_3	2.5	3.3	0.7
PO_4	0	0	0
pH	7.96	7.17	7.59
Alk as $CaCO_3$	281	134	223
TDS	288	176	242

Note: Units in mg/l unless otherwise noted.

discharge into the alluvium beneath which the coal subcrops, the alluvium and/or the Pine River might show a relatively greater input from seeps during the winter months when input from snowmelt is at a minimum. Previous work in the same study area (Oldaker, 1999) supports the latter of the two scenarios, since the potentiometric surface measured in the monitoring wells in the Pine River drainage is higher than the head provided by the river at the same locations.

Chloride concentrations are consistently lower in the Pine River than in the shallow monitoring wells (Fig. 17). However, the chloride concentration in all three settings—the river, the alluvium and the monitoring wells—increases steadily from late autumn until runoff commences in succeeding years, at which time the chloride in both the river and the alluvium is quickly diluted. The chloride in the shallow monitoring wells is also diluted, although somewhat more slowly. This dilution of the monitoring well waters may be caused by either recharge in the river floodplain or by limited infiltration and recharge at points topographically above and adjacent to the river valley, followed by hydrodynamic dispersion of formation water chloride along fractures (Park and Bethke, 2002). Because there is no apparent surface source for chloride, the winter increase in chloride concentrations reflects migration of waters from the Fruitland Formation or from deeper sources along the north-south fracture system on which the Pine River drainage is developed. In the case of the monitoring wells that sampled intervals within the Fruitland coals and overlying clastic material, the fluctuations are more attenuated.

Values of δD for the river water and monitoring wells show a similar pattern (Fig. 18). Concentration increases in winter are followed by dilution during the months of June and July, when there is a sharp drop in deuterium due to the upstream melting of isotopically depleted snow. In 2001, this abrupt drop is offset in the James2-Qal well, but nearly coincided with the drop observed in early July of 2002. The other monitoring wells that sample the shallow Fruitland Formation waters show much-attenuated offsets of this same pattern. Year-to-year variances may be due to seasonal differences in temperature. In any case, the well waters sampling the Fruitland maintain a ~10‰ deuterium depletion relative to the Pine River throughout the year, again reflecting localized infiltration from high in the surrounding hills and confirming an absence of substantive effective recharge.

As with chloride, strontium concentrations in the river water are much lower than in the formation waters, and this dif-

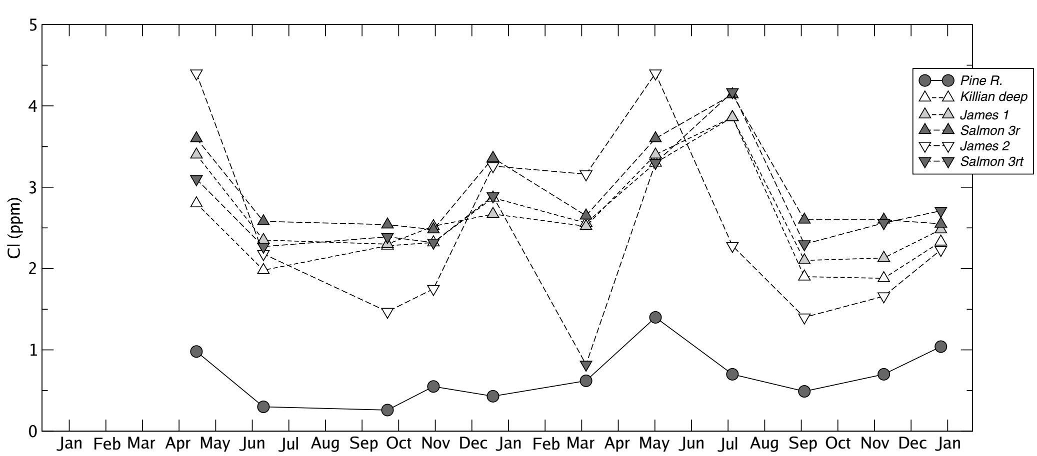

Figure 17. Time series for chloride concentrations in the Pine River (shaded circles and solid lines) and test wells (upright and inverted triangles, dashed lines) from 2001 to 2002.

ference is maintained throughout the year (Fig. 19). Strontium concentrations decrease early in the spring due to snowmelt and continue decreasing from March to June in the Pine River. They then increase and level off from September through March, perhaps due to an increase in weathering of secondary carbonates, or marine-derived carbonates in shales, during cold weather. Again, waters in the Quaternary alluvium (James2-Qal) show a similar response to seasonal changes. The monitoring wells in the Fruitland Formation have strontium concentrations up to an order of magnitude greater than the Pine River and variations that do not correlate with the chloride patterns described above. This indicates that other processes are mediating the availability of strontium in near-surface environments.

These seasonal variations in the source, concentration, and potential mediation of strontium also have a significant impact on the $^{87}Sr/^{86}Sr$ ratios of the Pine River waters (Fig. 20). These ratios are anticorrelated with strontium concentrations in the river waters, but positively correlate with concentrations in the monitoring well formation waters. The strontium ratios at the monitoring wells do not change appreciably, however, due to the high strontium concentrations and low $^{87}Sr/^{86}Sr$ ratios imparted by the original connate waters. Even waters in the James2-Qal, which has a similar strontium concentration to the Pine River, show no appreciable seasonal change in $^{87}Sr/^{86}Sr$ ratios.

The calcium concentrations in the Pine River (Fig. 21) correlate with strontium concentrations and are anticorrelated with the seasonal fluctuations of $^{87}Sr/^{86}Sr$ ratios (Fig. 20), as would be expected from the release of strontium by marine-derived carbonates during weathering in the winter months. Water samples from the alluvial deposits (James2-Qal) show the same general pattern, although offset by a month or two, with even higher calcium concentrations due to shallow water-rock interactions. In contrast, the Fruitland Formation monitoring well waters nearby show very little annual fluctuations. As discussed with Figure 14, if limited infiltration of calcium did occur near the coal outcrops, it has been removed as a result of precipitation of authigenic carbonates. Subsurface methane oxidation in the alluvium is limited, insomuch as bicarbonate concentrations never reach saturation with respect to calcite, despite the high Ca concentrations. In addition, the James2-Qal well shows an

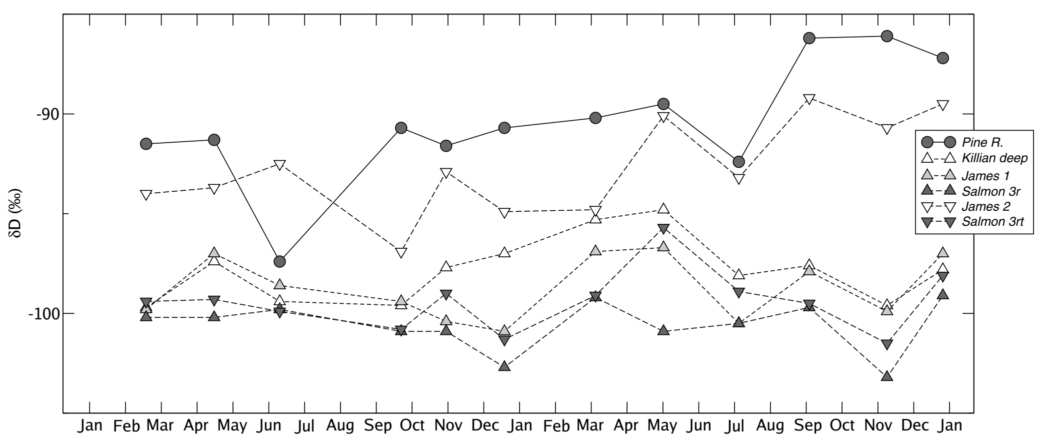

Figure 18. Time series for δD values during 2001–2002. Symbols as in Figure 17.

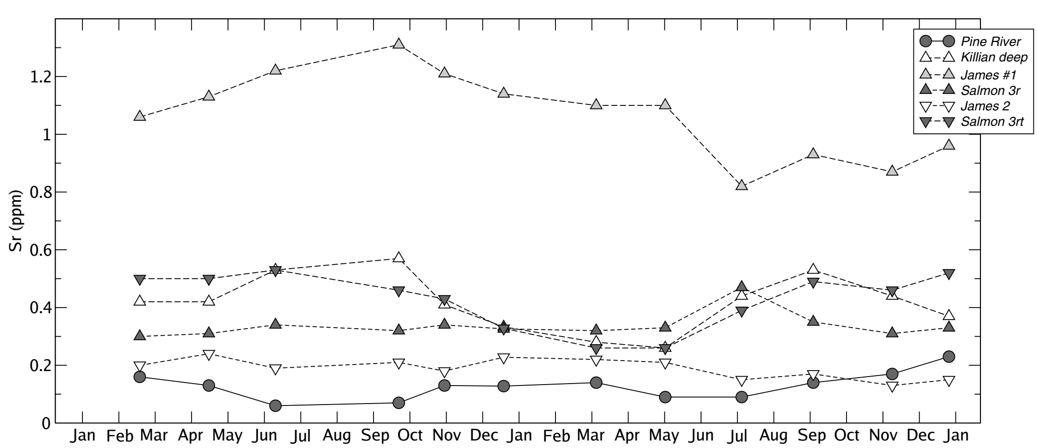

Figure 19. Time series showing seasonal variations in Sr concentrations.

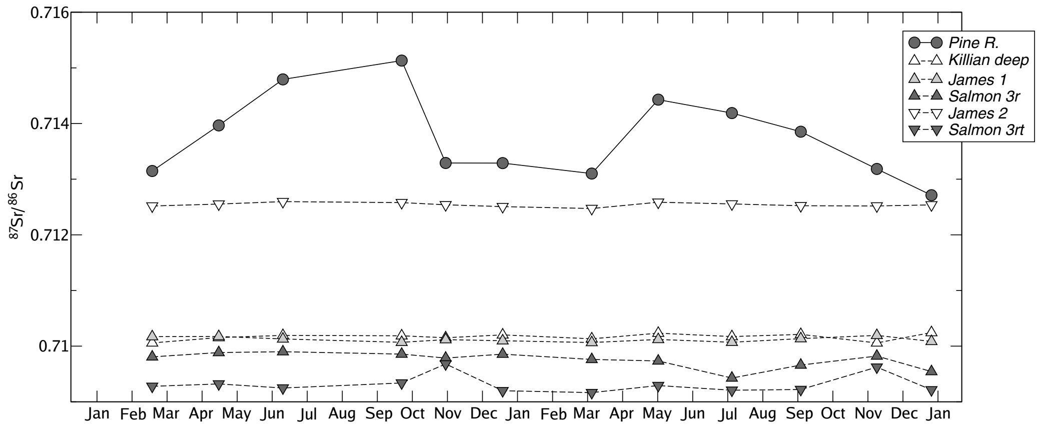

Figure 20. Time series plot for $^{87}Sr/^{86}Sr$ during the two-year study period. Note that high ratios in the Pine River correspond to seasonally low total Sr concentrations in the previous figure.

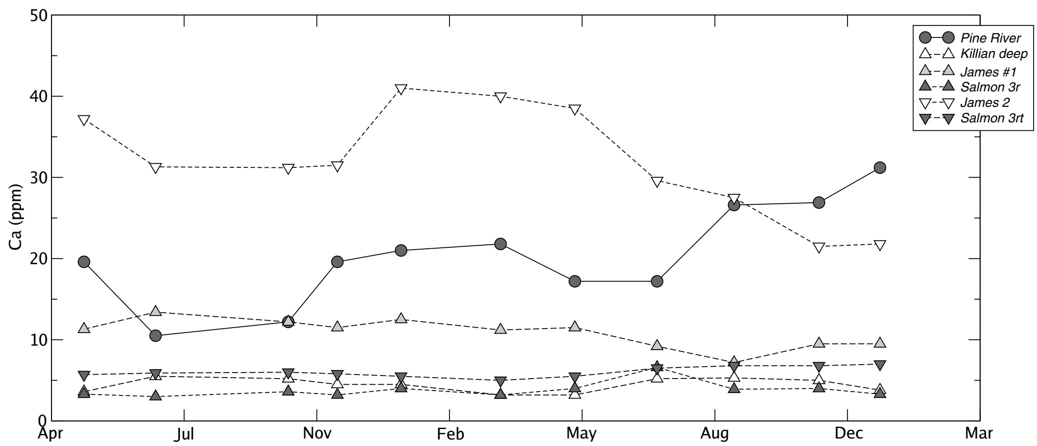

Figure 21. Time series plot for calcium concentrations.

influx of sulfate from the weathering of pyrite that is greater than the removal of sulfate, either through the interaction with barium from formation waters or the oxidation of methane migrating to the surface.

In general, the James2-Qal samples more closely resemble the Texas Creek seeps—which also have high calcium concentrations, measurable sulfate, and low $^{87}Sr/^{86}Sr$ ratios—rather than the monitoring wells that are completed in the Fruitland Formation intervals. Although we see seasonal fluctuations in the monitoring wells in the Fruitland Formation, the amount of water infiltrating the coals is small, and the flux is slow enough that microbial processes can quantitatively remove all of the sulfate and a good deal of the calcium from the water. The striking difference between these shallow monitoring wells and both the overlying alluvial sediments and the nearby river suggests that the effective recharge to the coals from local river alluvial plains is negligible. This is not surprising, given that discontinuities in the coals are well documented (Fassett, 1985, 2000), and numerous hydrological barriers impede throughflow within the Fruitland Formation, even at the uplifted margins of the San Juan Basin. The relationship between regional structural features and the distribution of geochemical signatures within the basin will be discussed further.

Geobotanical Mapping

Geobotanical anomalies are sensitive indicators of naturally occurring hydrocarbon microseeps, which can be studied over large areas through Landsat satellite imagery (Warner, 1997). Trees are particularly sensitive to gas seeps, due to a combination of factors related to methane-induced anoxia. The oxidation of methane in the near surface generally releases reduced metal species into the water that may be directly toxic to vegetation or that may be toxic to microrhizal fungi, which promote root growth in trees. In addition to releasing phytotoxic elements, the oxidation of methane in the micro-seep environment may inhibit the uptake of alkaline soil elements such as calcium, strontium, and barium (Schumacher, 1996).

These effects have particular relevance to the San Juan Basin area, since the subcrop of the Fruitland Formation under the Pine River alluvium leaks methane. This seepage has probably been going on for many decades (Baldwin and Oldaker, 1997), but has been quite conspicuous since ca. 1993: gas has appeared in domestic water wells, and trees have died, apparent victims of methane-induced anoxia in the root zones. Seeps in the South Fork of Texas Creek have been conspicuously active for a similar period of time. Pasture grass-kills and deaths of higher-order vascular vegetation in recent years are attributed to methane-induced anoxia here as well. Aerial photographs from the Department of Agriculture reveal the continuous presence of several seep-related grass-kills as far back as the late 1950s.

Botanical mapping was undertaken in an effort to develop quantitative documentation of the onset of stress in the vegetation. Although anecdotal evidence is available, the quantification of seep timing can shed light on the hydrocarbon system being investigated. Stress onsets that are unique and singular events and that coincide with increased industry withdrawal of methane from the down-dip reaches of the formation might indicate reservoir and aquifer continuity to the outcrop and thereby lend credence to the currently accepted hydrocarbon system models. Alternatively, demonstration that seepage has been persistent through time—either continuously or episodically—could lead to other conclusions regarding reservoir mechanics.

This work was started along the South Fork of Texas Creek because the Pine River area has been substantially impacted by cultural activities. The Pine River area is prone to severe seasonal flooding, which can also cause stress to the vegetation. Working in a less disturbed area allowed for fewer ambiguities in the interpretation of the vegetation patterns and stresses observed, and establishing an analog there would facilitate interpretation of the more complex Pine River area. Arp (2002) demonstrated that seepage has been ongoing for at least as long as 100 years, the ages of the oldest trees for which ring structures and crown morphologies could be examined. Geomorphic mapping, which was performed concomitantly, suggests an even longer history of landscape evolution that is influenced by the activity of seeps in the area.

The seeps were found to be episodic in their activity, metaphorically similar to the escape of steam from a pipe organ—first in one place, then another, then in several more—with intensities varying similarly. The timing of several specific, more pronounced events was determined by sectioning several large trees. The timing of these events was then tested at Pine River, where stress events are also found to be present. Crown deaths and pronounced changes in ring structures are documented to have occurred at both locations at the same time. More complete understanding of the outcrop expression of the hydrocarbon system at Texas Creek also allowed the identification of more subtle anomalies at Pine River which had not been previously identified. Examination of precipitation records confirmed that these events were not related to either drought or flood events (Oldaker, 2000), and the transcendence of stress-event timing across species boundaries confirmed that insect and disease pathogens were similarly unlikely causes (Arp, 2003).

This portion of the work concluded that the beds of Fruitland Formation coal that outcrop in the South Fork of Texas Creek and in the Pine River area are not connected to the deeper-in-the-basin beds. The time transgressive nature of Fruitland–Pictured Cliffs sedimentation suggests that this down-dip lithostratigraphic discontinuity should exist, and this discontinuity has been previously interpreted by other workers (Fassett, 1985).

The work of Arp (2002, 2003) and Oldaker (2000) clearly demonstrates that significant seep activity has substantially predated industry activity—the withdrawal of methane from the Fruitland Formation coals has neither diminished nor increased the seepage of methane from the outcrop. The withdrawal of water and diminishment of formation pressures that accompany methane production have not stopped the flow of connate-water springs at the outcrop. The deep-basin reaches of the Fruitland Formation are therefore not in lithostratigraphic or gas-migration–path continuity with the outcrop.

ADDITIONAL CONSIDERATIONS

As the foregoing data are synthesized and a picture for the Fruitland coal hydrocarbon system is developed, there are several additional observations and data that should be considered and must be amenable to explanation within the context of that hydrocarbon system. Those are briefly described here.

Formation Hydrostatic Pressures and Heads

The Fruitland Formation coals have historically been considered to constitute a regionally interconnected hydrologic unit (Thomson, 2000). This interpretation is based on the observation that the potentiometric heads are highest in the wettest and topographically highest part of the San Juan Basin and decline with distance into the basin and toward the San Juan River, the topographically lowest Fruitland Formation outcrop. This apparent pattern of regional flow from high elevation recharge areas to low elevation discharge areas is common and consistent with commonly held views of the hydrologic cycle (Thomson, 2000). However, this interpretation of a through-flowing system is clearly in conflict with much of the data already presented. A simple explanation, which recognizes the lithologic discontinuities of the coal intervals, is that the presence of a continuous water phase, even at irreducible levels, is sufficient to develop a potentiometric surface such as is seen in the Fruitland Formation coals. Overpressure in the basin center also indicates the presence of a permeability barrier and precludes throughflow.

Methane Flux at the Outcrop

Soil gas monitoring probes, 160 in all, are in place along lines that traverse the Fruitland Formation coal outcrop. These probes are monitored by the Bureau of Land Management (BLM), who report that statistically significant increasing flux trends are present in the data that these probes provide (M. Janowiak, 2002, personal commun.). From this they conclude that the coals at the outcrop are part of an aquifer system linked to downdip methane-producing wells (M. Janowiak, 2002, personal commun.).

The same data were examined by other workers. They too concluded that some locations appear to exhibit an increasing trend in methane concentrations in the soil gas but also point out that other locations appear to have decreasing trends. More than 80% of the data exhibit no trend at all. All three patterns are often seen at the same site.

The areal photographs that were examined as part of the botanical mapping demonstrate that seeps wax and wane through time at specific points. Previously active seeps are now found to be inactive (Arp, 2003), and new seeps appear from time to time. These observations demonstrate that changes in the rate of methane flux at outcrop cannot be interpreted as indicative of connection to gas production activities in the deeper basin.

Other Thermogenic Gasses in the Formation

Thermogenic gasses that are thought to have been sourced by deeper formations are also present in the coals. Gas chromatograms of both coal extracts and oil produced from the coals show bimodal distributions of n-alkanes that can be interpreted to be due to a combination of thermal degradation and migration fractionation (Clayton et al., 1991; Scott et al., 1994). Although no consensus has been reached regarding which process is dominant, or even if the n-alkanes are coal-sourced, a new hydrocarbon system model may constrain these interpretations.

Reservoir Performance

We have already noted that coalbed methane wells are unusual because they often flow water during early production tests. They do this because most of the gas contained in a CBM reservoir is held sorbed to surfaces within the coal and is not released until the hydrostatic pressure is reduced through the removal of water from the reservoir. Nevertheless, it is also common that recently completed wells produce gas at relatively high rates immediately after completion. This “flush” gas production usually diminishes rapidly, yielding to increasing water rates that only subside after sorbed gas begins to be released. These changes in the flow behavior of CBM wells carry important information about the reservoirs that is often not considered in the context of hydrocarbon systems or basinwide hydrology (Kaiser et al., 1994; Thomson, 2000). Specifically, this behavior indicates that the cleat systems are not fully water-saturated.

Relative Permeability to Water

The relative permeability of a formation to water is a function of water saturation (Mavor, 1996). If water saturation is reduced, the relative permeability of the formation to water diminishes, and if water saturation is diminished to irreducible levels, the permeability will approach zero. A coal bed with cleats that are gas charged would be expected to have negligible relative permeability to water (Morris et al., 1999).

Pressures of Continuous Phases

The dominant source of pressure in a gas reservoir is the buoyancy force exerted by a continuous column of gas. This buoyancy pressure is contained by the opposing forces of water saturation and capillary pressure in the overlying cap rock and by the hydrodynamic (i.e., gravitational) forces that supplement them. If a reservoir is severely stratified, as the coals are, gas columns sufficient to overcome these confining pressures cannot develop, and gas cannot migrate.

The potentiometric surface of water in the Fruitland Formation coals exhibits a very abrupt, steepening change in gradient along the southern boundary of the high-gas-rate production Fairway. Pressure differentials of several hundred pounds are measured in wells only a few hundred feet apart where they straddle this apparent pressure boundary. Interpreted in the context of continuous phases, these pressure differentials indicate that either phase continuity is lost across this boundary or that a flow boundary of some sort is present.

Noble Gas Dating of Formation Waters

The decay of uranium and thorium in the subsurface contributes radiogenic isotopes of the noble gasses to formation waters over time. Helium-4 age dating therefore provides a check of ages derived from ^{129}I or ^{36}Cl (Bethke et al., 2000). Within the formation waters of the Fruitland, ^{4}He ages generally coincide with ^{129}I ages (Sorek et al., 2001; Sorek, 2003). If iodine were released diagenetically from the coals into young water (Fabryka-Martin et al., 1991), then the water would show anomalously old iodine ages accompanied by young helium ages. The fact that both the helium and iodine systems in the Fruitland are essentially coupled indicates the lack of any substantial throughflow in the system over millions of years and confirms the ^{129}I ages.

DISCUSSION

Synthesis of all the data presented here, in context with the additional information already present in the scientific literature, leads to the conclusion that the prevailing hydrologic models for the Fruitland Formation coal hydrocarbon system are incorrect. The Fruitland Formation coals cannot be a through-flowing system because the member and bed-level architectures of the formation are too discontinuous, and because the radiogenic isotope data that have become available in recent years indicate that the formation waters in the center of the basin are connate. The stable isotope signatures for the deep basin waters lead to similar conclusions because they do not resemble present-day meteoric waters. Similarly, the anion and cation analyses of produced waters indicate that multiple discrete water populations are present in the basin, and this could not be the case if a through-flowing aquifer system is operative.

The methane seeping from the outcrop is not due to industry production activities. The botanical and geomorphic data indicate that the seeps have been emitting methane for many decades at least and probably since the coals were brought to outcrop. The waters that appear to accompany this seeping methane do not clearly resemble either the Fruitland Formation waters or the surface waters in these drainages due to extensive microbial and water-rock interaction.

Effective recharge of the Fruitland Formation coals is not taking place at the outcrop. Localized recharge at outcrop, which might travel as far as the nearest river or creek before emerging, should reemerge as springs at breaks-in-slope where valley floors meet hillsides, but no such springs are found.

The Fruitland Formation, where it is present in broad alluvial river valleys, is being seasonally recharged to a very limited depth. This limited recharge is seen in the seasonal variances already discussed, but the recharging water is displaced from the formation regolith during the winter. Seasonal variations in alluvial water chemistries require that the formation waters discharge to the alluvium and mix with surface water.

The early "flush" methane production, which many wells deliver from virgin reservoirs, is evidence that the cleat systems in the coals were gas-filled prior to the initiation of production activities. As such, the formation's relative permeability to water is vanishingly low to negligible.

This is not to say that the cleats have always been gas-filled. The CT, XRD, and electron microprobe data all indicate that mildly oxidizing waters have moved through the formation at some point in the geologic past. Their signatures are found in the mineral zoning patterns, in the etched cleat faces, and in the statistical population analyses of the low-Cl, low-TDS waters that are present in the coals closer to outcrop, up-dip of the deep-basin waters.

PROPOSED HYDROCARBON SYSTEM MODEL

It is widely accepted that the methane endowment of the Fruitland Formation coals is largely the product of in situ methane-generative processes: the coals are their own source rocks. The coals were deposited shoreward of Pictured Cliffs Sandstone beaches and between the coastal-plain channels that fed sediment to those beaches. All of this took place during Late Cretaceous time, between 73 and 75 Ma. They were subsequently buried under several thousand feet of additional sediment as the basin continued to subside. Except for a brief episode of uplift in latest Cretaceous time, subsidence persisted through the closing phases of the Laramide orogeny, which ended ca. 30 Ma. Maturation of the coals continued through this time.

The San Juan Basin began to take its present form ca. 40 Ma when both its margins and center were uplifted during the closing phases of the Laramide orogeny. Erosion had already begun during the Laramide, and the basin margins were exposed quite early. Radiogenic isotope dating indicates that infiltration of meteoric waters at the outcrop of the coal allowed recharge to move several miles to tens of miles into the basin prior to ca. 35 Ma. Diminished formation pressures brought about by uplift and accelerated erosion allowed gas to desorb from the coals. This desorbing gas, plus gas that may have migrated from deeper formations, filled much of the cleat porosity and caused relative permeability to water to become so low that further recharge and throughflow were precluded. The fresh water recharge plumes and entrained bacteria were therefore introduced to the coals prior to 35 Ma. Any additional precipitation and recharge would have been unable to flow through the reservoir and would have immediately rejoined surface waters: The "bottle" of the formation was full and any additions simply spilled out. Continuity of an irreducible water phase from the outcrop to the basin center preserved, and preserves, the hydraulic head and the picture of a dynamic system that it appears to portray.

Erosion of coal at the basin margin continually exposes new coal laminae or biosomes. As determined from pressure build-up tests and pressure transient analysis, each reservoir unit is 10–150 ha (25–375 acres) in areal extent and millimeters to centimeters in thickness. They retain pressure and gas charge until the protective rocks that encase them are breached. This allows pressure to drop and gas to desorb, gas that then slowly builds column and buoyancy pressure until it is able to migrate to the outcrop and escape. Significant increases in outcrop discharge may thus result from either the recent breaching of a fully charged reservoir unit or the concomitant breaching of several when topography allows.

Individual biosomes will slowly discharge their gas charges when breached by erosion until they reach equilibrium with the prevailing pressures. Areas with low effective porosity will lose gas much more slowly and will require more extensive weathering (oxidation) in order to release their methane endowment. This is part of the reason that some seeps persist for years or decades and others are short-lived.

A second reason for variance in apparent seep activity is the amount of precipitation available for infiltration and near-surface recharge (Oldaker, 2000). During periods of drought, the water table may subside by one to several meters (3 ft or tens of feet). This will diminish the weathering efficiency very close to the surface and effectively move the seep source to greater depth. With a thicker unsaturated zone to migrate through, the released methane becomes diffused and is not noticed at the surface. As precipitation increases and the water table rises, released methane is pushed to the surface. At the same time, the zone of more efficient weathering is again brought closer to the surface; this diminishes subsurface diffusion, and the methane that escapes is limited to a much narrower area. This results in local increases in soil-gas methane concentrations.

Although Fruitland Formation coal beds are stagnant aquifers at this time, fluids continue to traverse the formation via fractures and faults. The waters that come to the surface in the South Fork of Texas Creek area reach the surface where the Fruitland Formation coals outcrop but have chemical signatures that are unlike any Fruitland Formation coal waters. Neither do they resemble present-day meteoric waters. They must be coming from other, deeper sources and are reaching the surface by traveling along fractures and faults that have also influenced the topography and helped produce the tributary subsequent stream valleys in which the springs and seeps are found.

Fractures also provide conduits for vertical migration of fluids in the deeper reaches of the basin and along the basin axis. Stable isotopic signatures are unique in that area, and the radiogenic isotope data indicate that the fluids have had long residence times in formations with high uranium concentrations—significantly higher than the concentrations generally found in the Fruitland Formation coals. Fluids migrating up fractures from the Jurassic Morrison Formation, a formation noted for its uranium deposits, might account for these signatures (Riese and Brookins, 1984). It is tempting to speculate whether fluid migration from deeper, higher pressure environments may also have contributed to the overpressures that exist in the Fruitland, to the abrupt potentiometric surface gradient changes that are observed, and to the unique levels of methane endowment and productivity that the Fruitland Formation coals exhibit.

Relationship between Production Well Chemistry and Regional Structural Features

The northwest-southeast–striking fractures and fracture systems that allowed migration of geochemically distinct waters into the Fruitland coals from deeper formations also influence reservoir performance. These fracture systems provide additional surfaces from which gas can desorb and permeability pathways along which gas can migrate to a wellbore.

The north-south–striking fractures and fracture systems induced by formation of the Rio Grande rift also contribute to improved reservoir performance. These fractures also provide gas migration pathways and appear to be allowing gas and water migration today. Fractures in this set are partially responsible for the previously described seep activity and for the geochemical signatures found in the monitoring wells. We interpret that the waters that migrate to the surface along these fractures are from deeper formations: their geochemical signatures are unlike the signatures of connate Fruitland waters, and the seeps they cause occur at locations that are stratigraphically above and below the Fruitland coal outcrop. The areal distribution of these seeps is also locally influenced by the dip of bedding at the surface: gas migration appears to be up dip and away from the mapped trace of fractures—a topographic manifestation that would be unlikely if the seep is emanating along bedding.

CONCLUSIONS

The Fruitland Formation coal hydrocarbon system appears to be unique. Its origins stem from the serendipitous convergence of many necessary and contributing factors: a unique tectonic framework, collection of depositional environments, and structural and landscape evolution were all necessary ingredients in the development of this resource.

Our work finds that the Fruitland coal hydrocarbon system is more complex than previously recognized. Previous workers have concluded that the coals are their own methane source and that some thermogenic gas has also migrated into the system. The presence of biogenic gas in the formation is also widely recognized and has been interpreted to indicate contemporary meteoric recharge of the formation. We conclude that this may be taking place in the regolith but that biogenic methane across the producing area is probably sourced by microbes introduced 35–40 Ma.

Our work also finds that the Fruitland coal hydrology is considerably more complex than previously recognized. Previous discussions of the hydrology have focused on connate waters and meteoric waters thought to be recharging the coals today. By contrast, our work indicates that at least four distinct waters are present and variably mixed in the coals. Connate waters fill the formation in the center of the basin, at the center of our study area. Meteoric recharge is restricted to coal and regolith no more than a few kilometers from the outcrop. Meteoric water found further down-dip than a few kilometers is fossil meteoric water and reflects recharge between 35 and 40 Ma. Waters from deeper formations also traverse and locally recharge fractures in the coals. These more deeply sourced waters migrate vertically along fractures, have been identified by others, and are geochemically characterized by our work.

The Fruitland Formation coal reservoirs are extraordinarily heterogeneous collections of biosomes. These biosome facies changes reflect subtle differences in depositional environments and in the botanical assemblages present in them. Each of these biosomes exhibits unique reservoir performance characteristics. Vitrinite yields the most gas and possesses the best cleat permeability. Wells that penetrate more vitrinite therefore produce at higher rates.

Recharge of Fruitland Formation coals took place prior to 35–40 Ma, particularly the high vitrinite–content coals. This recharge brought oxygenated waters through the cleats and oxidized the coals that they contacted. This oxidation further enhanced permeability and the ultimate methane yield of the coals because it expanded existing cleats and opened new ones, thus increasing effective porosity and permeability.

The Paleozoic architecture of the basin continues to influence fluid flow in the coals. Basement faults and fractures have propagated through the overlying stratigraphic section and have allowed vertical migration of both hydrocarbons and water. Fractures or faults in the coals may be contributory to the high permeability found in the Fairway and to its abrupt southern boundary. The Cenozoic Rio Grande rift event imposed a second fracture set on the basement and overlying sediments. Differential weathering on prominent fractures determined the locations for the north-south drainages that dominate the northern San Juan Basin and provides the locus for many of the methane seeps documented there.

Methane seeps at the coal outcrop have been active for decades, probably since the coals were first exposed at the edge of the basin. The presence of these seeps is due to continued weathering and breaching of biosome-scale reservoir compartments. Weathering and erosion is more rapid where coal outcrops are intersected by fracture systems and helps explain why the seeps are most active, or conspicuous, in valleys that cross the outcrop.

Reservoir performance predictions require that an array of wells has already been drilled across the producing area. If the authigenic mineral constituents in the coals penetrated by these wells are analyzed and identified, it may be possible to identify areas that have experienced oxidizing hydrodynamic flow at some point in the past. If cores are collected, the character of cleat surfaces can be studied for evidence of oxidation. The maceral compositions of the penetrated intervals can also be examined more effectively using core than by using wireline techniques alone. Each of these methods may be useful in differentiating potentially good reservoir areas from potentially poor ones.

The lithologic heterogeneity of the reservoirs and the areal extent of the individual biosomes that compose it will continue to be obstacles to reservoir performance prediction. Although it is possible to attempt the prediction of production rate, it is not possible to precisely predict the volume of reservoir that will be efficiently drained by a well until after it is drilled, completed, and has some production history. All available engineering data indicate that methane production wells do not drain the reservoir areas they were intended to drain and often do not drain some of the completed coals.

The hydrocarbon systems analysis described here leads to a new and comprehensive interpretation of the Fruitland coalbed methane system. The data we have provided should be used to constrain future attempts to digitally model the hydrology of the Fruitland coals. Other basins, other aquifers, and other hydrocarbon systems may also benefit from reexamination in the context of complete hydrocarbon system analysis.

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TABLE A1. ANALYSES OF PRODUCED WATERS

API #	Lat °N	Long °W	TDS mg/l	Na mg/l	Cl mg/l	Sr mg/l	$(CO_3)^{-2}$ mg/l
Part 1							
30045278500000	36.89548	108.06984	26026	5200	6035	2	1.45
30045269750000	36.94714	107.54215	21423	3290	299	23	90.1
30045275970000	36.93008	107.84932	638	68.57	49	2	0.028
30045279000000	36.98888	107.84595	30108	4973	891	34	23.59
30045284100000	36.95845	107.77862	28515	4572	639	23	37.16
30045276220000	36.89273	107.63277	30164	5309	1591	32	42.9
30045283260000	36.94189	107.69322	25068	4434	1605	29	62.68
30045289340000	36.95503	108.14198	38557	7253	3066	28	32.42
30045272520000	36.98745	107.97099	10190	1466	49	5	23.9
30045270960000	36.9964	107.69026	20541	3403	712	22	28.12
30045269820000	36.95604	107.47896	12735	2785	647	19	34.32
05067078260000	37.08015	108.03328	16356	2362	68	9	40.76
30045271390000	36.97584	107.54285	18455	2787	360	17	18.19
30045287500000	36.96884	107.89204	25475	4412	1482	20	14.08
30045274900000	36.92924	108.04388	14720	4389	5628	13	1.32
05067063680000	37.14527	107.93319	9315	1303	29.39	2	6.13
05067076070000	37.15731	107.96933	16383	2403	140	6	8.32
05067081710000	37.151865	107.960381	4969	650	41	1	5.63
30045287220000	36.94081	107.64145	19008	3252	1369	13	4.92
30045283600000	36.92802	107.59039	17999	2787	417	11	15.21
30045287770000	36.96298	107.59514	17464	2794	695	11	7.65
30045279220000	36.96086	107.70345	25809	3964	711	14	23.98
05007061370000	37.14527	107.37366	12029	2361	1746	14	12.12
05007061220000	37.14263	107.36547	11678	2026	1027	11	5.66
05067075190000	37.02742	107.61772	15735	2495	394	9	7.01
05067066060000	37.08543	107.96005	6848	851	22.61	3	4.66
05067078790000	37.11414	107.71663	14993	3146	3050	10	9
30045277430000	36.98123	107.94695	34507	6220	2417	13	21.89
05067075980000	37.00648	107.93485	20625	3670	1526	10	25.89
05067066510000	37.20101	107.82601	6575	974	32.32	2	5.43
05067075460000	37.22771	107.74623	5095	698	60.5	1	1.91
05067065290000	37.16478	107.58947	6452	952	165	2	3.46
05067068500000	37.16517	107.80114	7593	1115	141	1	5.19
05067078540000	37.20465	107.64558	9402	1300	50.63	3	4.34
05067070060000	37.10837	107.82623	13277	2276	668	4	5.45
05067072290000	37.143	107.74437	7653	1085	139	2	4.23
05067076320000	37.03502	107.49959	19172	2899	296	9	17.76
05067070370000	37.05710	107.59155	13533	2062	358	6	16.95
05067067980000	37.08601	107.60947	13076	1936	276	8	13.33
05067068750000	37.14361	107.64312	8842	1322	233	2	14.64
05067071210000	37.02827	108.03439	36843	5365	579	14	38.82
05067071410000	37.25394	107.61757	6011	895	49.78	1	2.46
05067076780000	37.06268	108.0694	15633	2471	38.76	5	21.54
05067077390000	37.00302	108.08865	40440	6405	1096	15	61.06
05067072210000	37.04797	107.91438	10043	1403	169	4	2.67
05067079020000	37.07182	107.66393	17815	2932	1194	11	8.41
05067078130000	37.14985	107.90806	5569	681	14.2	1	7.82

(*continued*)

TABLE A1. ANALYSES OF PRODUCED WATERS *(continued)*

API #	Lat	Long	TDS	Na	Cl	Sr	$(CO_3)^{-2}$
	°N	°W	mg/l	mg/l	mg/l	mg/l	mg/l
05067067780000	37.26137	107.55438	10093	1713	176	3	13.68
05007061250000	37.02023	107.40839	14082	2723	2224	15	16.9
05067071360000	37.24715	107.68172	6753	931	92.42	2	13.06
05067068990000	37.21771	107.54688	18553	2616	305	6	22.83
05067069050000	37.07909	107.52606	20735	4262	2580	11	25.51
05067062850000	37.17952	107.52854	13329	2249	1211	6	29.33
05067071440000	37.10051	107.57224	15894	2256	332	7	9.88
05067076940000	37.18697	107.72045	8115	1015	53.99	2	49.25
05067074900000	37.09352	107.92456	14352	2060	143	7	25.3
05067071490000	37.14396	107.86538	17328	2371	259	11	3.76
05067064130000	37.11417	107.94214	6955	850	12.4	2	7.63
05067080600000	37.07933	107.72585	16755	3304	2816	11	12.38
05067075530000	37.11746	107.77219	10639	1599	424	3	11.06
05067076680000	37.18612	107.88096	3546	460	71.55	0	8.52
05067072410000	37.06467	107.79813	19471	3160	898	11	19
05067075130000	37.23061	107.8539	2865	991.4	66.3	1.1	493
05067074730000	37.24835	107.80997	3316	1056	323	1.6	493
05067075340000	37.27763	107.77377	816	314.5	0	0.2	99
05067082470000	37.26144	107.73763	1546	486.4	73.2	0.4	118
05067078140000	37.30545	107.69162	605	84.1	4.36	3.8	0
05067071590000	37.29952	107.63571	745	265.5	8.72	0.1	0
05067068110000	37.01392	107.80713	7730	2800	1040	N.D.	0
05067068110000	37.01392	107.80713	N.D.	N.D.	N.D.	N.D.	N.D.
05067070890000	37.04977	107.67523	9842.31	2670	962	N.D.	0
05067070890000	37.04977	107.67523	N.D.	N.D.	N.D.	N.D.	N.D.
05067070890000	37.04977	107.67523	N.D.	N.D.	N.D.	N.D.	N.D.
05067071050000	37.01997	107.66165	11482.26	2850	817	N.D.	0
05067071050000	37.01997	107.66165	N.D.	N.D.	N.D.	N.D.	N.D.
05067071690000	37.00255	107.81117	9300	3160	1890	N.D.	0
05067071690000	37.00255	107.81117	N.D.	N.D.	N.D.	N.D.	N.D.
05067073130000	37.04179	107.85167	N.D.	N.D.	N.D.	N.D.	N.D.
05067073480000	37.0166	107.74425	10864.21	2850	1210	N.D.	0
05067073480000	37.0166	107.74425	N.D.	N.D.	N.D.	N.D.	N.D.
05067076960000	37.06932	107.97461	N.D.	1580	40	N.D.	500
05067077340000	37.07785	107.89183	N.D.	N.D.	N.D.	N.D.	N.D.
05067070220000	37.05786	107.74576	8922.95	2500	1190	N.D.	0
05067076520000	37.02651	107.79233	N.D.	N.D.	N.D.	N.D.	N.D.
05067077680000	37.06535	107.85005	5940	2050	407	N.D.	0
05067071180000	37.02196	107.89714	8380	2950	892	N.D.	0
05067071180000	37.02196	107.89714	N.D.	N.D.	N.D.	N.D.	N.D.
05067071110000	37.04121	107.94251	8090	3120	215	N.D.	0
05067073680000	37.05606	107.95503	5400	1990	122	N.D.	0
05067073680000	37.05606	107.95503	N.D.	N.D.	N.D.	N.D.	N.D.
05067073620000	37.09261	107.9785	4510	1550	35	N.D.	0
05067075910000	37.08531	107.95303	2580	900	70	N.D.	0
05067074890000	37.09943	107.93129	3380	1410	55	N.D.	0
05067074890000	37.09943	107.93129	N.D.	N.D.	N.D.	N.D.	N.D.
05067074900000	37.09352	107.92456	3690	1400	60	N.D.	0
05067073630000	37.08482	107.91649	4660	1600	95	N.D.	0
05067071170000	37.01437	107.90801	8430	3200	560	N.D.	0
05067073250000	37.02237	107.86112	8800	3300	682	N.D.	0

(*continued*)

TABLE A1. ANALYSES OF PRODUCED WATERS *(continued)*

API #	Lat	Long	TDS	Na	Cl	Sr	$(CO_3)^{-2}$
	°N	°W	mg/l	mg/l	mg/l	mg/l	mg/l
05067070990000	37.00777	107.7728	8350	3150	690	N.D.	0
05067071020000	37.02168	107.64618	11550.2	2850	542.3	N.D.	0
05067073230000	37.01167	107.85538	N.D.	N.D.	N.D.	N.D.	N.D.
05067072900000	37.00629	107.69251	10842.28	2900	1440	N.D.	0
05067072900000	37.00629	107.69251	N.D.	N.D.	N.D.	N.D.	N.D.
05067071060000	37.01183	107.67207	10260.92	2800	1110	N.D.	421
05067071690000	37.00255	107.81117	10400	3600	1940	N.D.	0
05067082850000	37.194	107.73645	2302	729.4	18.6	N.D.	<2
30039244170000	36.9456	107.30116	12085	4100	4910	1.1	<2
05067082610000	37.15035	107.7756	3076	1004	390	16.5	<2
30039243360000	36.98663	107.26426	16112	5992	5760	0.2	<2
30039244470000	36.97081	107.33871	9489	2906	2710	<.1	<2
30039244610000	36.992249	107.353073	8437	2821	1690	0.3	<2
30039246960000	36.968094	107.219498	309	11	1.69	5.9	<2
30039245550000	36.98468	107.32428	6407	1745	1780	<.1	<2
30039241690000	36.938919	107.35405	11765	4065	3560	26.3	<2
05067082130000	37.20879	107.71863	1883	569.5	6.78	17.6	<2
Pine River	N.D.	N.D.	136	13.6	<1	0.5	<2
Florida River	N.D.	N.D.	210	23.2	3.39	<.1	<2
05067079640000	37.301666	107.605179	738	220.2	1.69	<.1	<2
05067080570000	37.303024	107.606995	331	193	1.69	<.1	<2
Animas River	N.D.	N.D.	331	28.5	20.3	15.9	<2
05067080180000	37.299408	107.606995	2960	220.7	2.54	0.4	160
05067082070000	37.12883	107.80722	5730	1906	1310	9.1	<2
05067082080000	37.20749	107.59924	10058	3694	3810	3.3	<2

Note: Analyses of surface and monitoring well waters included for benchmarking. N.A.—not applicable; N.D.—no data; bd—below detection limit; A—age not determinable.

TABLE A1. ANALYSES OF PRODUCED WATERS

API #	I	δ¹⁸O	δD	$^{87/86}$Sr	^{129}I/I	I age	^{36}Cl/Cl	Cl age
	mg/l	‰	‰		10^{-15}	Ma	10^{-15}	Ma
Part 2								
30045278500000	1.458	–30.61	–127.6	0.708197	790.0	15.0	N.D.	N.D.
30045269750000	0.193	–7.62	–59.5	0.709274	1718.0	A	N.D.	N.D.
30045275970000	0.142	–5.93	–72.6	0.706620	3933.0	A	N.D.	N.D.
30045279000000	0.091	–4.62	–31.7	0.709493	10400.0	A	N.D.	N.D.
30045284100000	0.141	–5.37	–29.6	0.710933	3651.0	A	N.D.	N.D.
30045276220000	2.979	–4.83	–32.2	0.711392	346.0	33.0	N.D.	N.D.
30045283260000	3.672	–6.98	–38.1	0.710499	283.0	38.0	N.D.	N.D.
30045289340000	1.180	–5.38	–43.8	0.709480	487.0	26.0	N.D.	N.D.
30045272520000	0.063	–7.22	–14.9	0.709913	10346.0	A	N.D.	N.D.
30045270960000	0.065	–5.21	–32.1	0.709976	13527.0	A	6	1.9
30045269820000	0.067	–5.83	–38.5	0.709218	2770.0	A	N.D.	N.D.
05067078260000	0.059	–12.45	–88.2	0.711234	3503.0	A	N.D.	N.D.
30045271390000	0.119	–7.91	–55.4	0.710172	4524.0	A	N.D.	N.D.
30045287500000	2.563	–6.41	–28.0	0.710233	296.0	37.0	N.D.	N.D.
30045274900000	1.195	–6.03	–45.4	0.709397	2090.0	A	N.D.	N.D.
05067063680000	0.027	–13.54	–87.2	0.712923	7610.0	A	55.0	1.0
05067076070000	0.271	–11.91	–72.2	0.710702	158000.0	A	12	1.6
05067081710000	0.005	–13.97	–100.6	0.710725	66832.0	A	N.D.	N.D.
30045287220000	1.050	–7.48	–45.5	0.710158	1855.0	A	8	1.8
30045283600000	0.233	–9.31	–55.4	0.709392	660.0	19.0	N.D.	N.D.
30045287770000	0.659	–8.86	–51.2	0.710166	285.0	38.0	N.D.	N.D.
30045279220000	0.216	–6.5	–31.2	0.710983	1211.0	5.0	N.D.	N.D.
05007061370000	0.131	–7.36	–38.7	0.709235	5706.0	A	N.D.	N.D.
05007061220000	0.102	–9.14	–54.5	0.709347	9578.0	A	N.D.	N.D.
05067075190000	1.370	–10.27	–68.4	0.711500	131.0	55.0	N.D.	N.D.
05067066060000	0.027	–14.82	–93.3	0.710085	14882.0	A	280	0.3
05067078790000	8.981	–5.78	–45.7	0.711826	124.0	57.0	2	2.4
30045277430000	1.211	–6.57	–11.3	0.710315	452.0	27.0	N.D.	N.D.
05067075980000	0.295	–7.26	–1.5	0.710307	1740.0	A	N.D.	N.D.
05067066510000	0.207	–14.1	–97.8	0.711600	2738.0	A	N.D.	N.D.
05067075460000	0.389	–14.06	–98.8	0.712025	322.0	35.0	N.D.	N.D.
05067065290000	1.280	–13.9	–98	0.711601	145.0	53.0	N.D.	N.D.
05067068500000	0.841	–13.9	–98.3	0.712062	188.0	47.0	N.D.	N.D.
05067078540000	0.292	–13.83	–95.1	0.710665	344.0	33.0	N.D.	N.D.
05067070060000	4.226	–11.34	–78.4	0.711943	138.0	52.0	N.D.	N.D.
05067072290000	0.972	–13.91	–97.2	0.710602	187.0	47.0	16	1.5
05067076320000	0.111	–6.8	–40.5	0.709120	4982.0	A	N.D.	N.D.
05067070370000	2.262	–11.46	–78	0.710972	133.0	55.0	0	bd
05067067980000	1.142	–11.28	–75	0.710504	168.0	50.0	N.D.	N.D.
05067068750000	1.455	–12.52	–87.4	0.711803	194.0	46.0	N.A.	N.A.
05067071210000	1.213	–8.23	–27.8	0.710598	366.0	32.0	N.A.	N.A.
05067071410000	0.254	–14.46	–102.6	0.711519	385.0	31.0	39	1.1
05067076780000	0.081	–13.69	–95.5	0.709926	7992.0	A	N.D.	N.D.
05067077390000	0.176	–7.26	–31.3	0.710107	4943.0	A	N.A.	N.A.
05067072210000	0.571	–13.82	–95.2	0.711322	450.0	27.0	N.A.	N.A.
05067079020000	3.894	–6.79	–47.8	0.710942	174.0	49.0	N.A.	N.A.
05067078130000	0.003	–14.09	–100.1	0.710551	72278.0	A	230	0.3

(continued)

TABLE A1. ANALYSES OF PRODUCED WATERS *(continued)*

API #	I	$\delta^{18}O$	δD	$^{87/86}Sr$	$^{129}I/I$	I age	$^{36}Cl/Cl$	Cl age
	mg/l	‰	‰		10^{-15}	Ma	10^{-15}	Ma
05067067780000	0.542	–13.13	–91.4	0.711503	231.0	42.0	N.D.	N.D.
05007061250000	2.854	–4.85	–34.1	0.710046	236.0	42.0	N.A.	N.A.
05067071360000	0.646	–13.88	–93.2	0.710701	308.0	36.0	N.A.	N.A.
05067068990000	1.033	–10.19	–62.9	0.711634	179.0	48.0	N.A.	N.A.
05067069050000	13.840	–4.64	–33.1	0.711490	143.0	53.0	N.A.	N.A.
05067062850000	2.882	–5.72	–41.8	0.711490	167.0	50.0	N.A.	N.A.
05067071440000	1.901	–10.97	–77.0	0.710964	138.0	54.0	N.A.	N.A.
05067076940000	0.109	–12.96	–90.0	0.711901	5696.0	A	N.A.	N.A.
05067074900000	0.032	–14.46	–89.4	0.710735	1158.0	6.0	32	1.2
05067071490000	0.522	–13.47	–87.6	0.710139	245.0	41.0	18	1.4
05067064130000	0.037	–14.18	–101.0	0.710324	23170.0	A	N.D.	N.D.
05067080600000	6.326	–4.55	–37.7	0.711797	153.0	52.0	N.A.	N.A.
05067075530000	2.986	–12.26	–86.3	0.711824	126.0	56.0	N.A.	N.A.
05067076680000	0.508	–13.61	–98.5	0.711554	214.0	44.0	N.A.	N.A.
05067072410000	0.924	–9.16	–61.5	0.710296	437.0	28.0	N.A.	N.A.
05067075130000	N.D.	–13.92	–101.0	0.712941	350.0	33.0	N.A.	N.A.
05067074730000	N.D.	–13.84	–101.0	0.712551	155.0	51.0	N.A.	N.A.
05067075340000	N.D.	–13.42	–103.3	0.712172	7673.0	A	40	1.1
05067082470000	N.D.	–12.95	–103.9	0.711823	408.0	30.0	N.D.	N.D.
05067078140000	N.D.	–13.99	–101.2	0.709946	51350.0	A	250	0.3
05067071590000	N.D.	–13.63	–98.9	0.710838	5308.0	A	340	0.2
05067068110000	N.D.	–8.49	–56.2	N.D.	N.D.	N.D.	N.D.	N.D.
05067068110000	N.D.	N.D.	N.D.	N.D.	1030.0	9.0	43	1.1
05067070890000	N.D.	–5.92	–45.6	N.D.	N.D.	N.D.	N.D.	N.D.
05067070890000	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
05067070890000	N.D.	–6.04	–42.9	0.710474	420.0	29.0	N.D.	N.D.
05067071050000	N.D.	–8.26	–59.1	N.D.	N.D.	N.D.	N.D.	N.D.
05067071050000	N.D.	N.A.	N.A.	N.D.	670.0	18.0	N.D.	N.D.
05067071690000	N.D.	–6.2	–43.3	N.D.	N.D.	N.D.	N.D.	N.D.
05067071690000	N.D.	N.A.	N.A.	N.D.	1060.0	8.0	9	1.7
05067073130000	N.D.	–7.73	–53.8	N.D.	600.0	21.0	N.D.	N.D.
05067073480000	N.D.	–6.52	–47.7	N.D.	N.D.	N.D.	N.D.	N.D.
05067073480000	N.D.	N.A.	N.A.	N.D.	216.0	44.0	N.D.	N.D.
05067076960000	N.D.	–14.68	–100.6	N.D.	2579.0	A	38	1.1
05067077340000	N.D.	–12.58	–84.0	0.713119	900.0	12.0	N.D.	N.D.
05067070220000	N.D.	–9.44	–67.9	N.D.	N.D.	N.D.	N.D.	N.D.
05067076520000	N.D.	–9.85	–58.2	0.710665	3080.0	A	N.D.	N.D.
05067077680000	N.D.	–10.11	–67.7	N.D.	N.D.	N.D.	N.D.	N.D.
05067071180000	N.D.	–7.83	–51.6	N.D.	N.D.	N.D.	N.D.	N.D.
05067071180000	N.D.	N.A.	N.A.	N.D.	420.0	29.0	N.D.	N.D.
05067071110000	N.D.	–12.59	–80.6	N.D.	N.D.	N.D.	N.D.	N.D.
05067073680000	N.D.	–14.37	–99.4	N.D.	N.D.	N.D.	N.D.	N.D.
05067073680000	N.D.	N.A.	N.A.	N.D.	N.D.	N.D.	N.D.	N.D.
05067073620000	N.D.	–14.85	–100.0	N.D.	N.D.	N.D.	N.D.	N.D.
05067075910000	N.D.	–14.64	–101.6	N.D.	N.D.	N.D.	N.D.	N.D.
05067074890000	N.D.	–14.44	–103.2	N.D.	N.D.	N.D.	N.D.	N.D.
05067074890000	N.D.	–14.59	–99.5	0.710429	589.0	21.0	0	bd
05067074900000	N.D.	–14.59	–104.6	N.D.	N.D.	N.D.	N.D.	N.D.
05067073630000	N.D.	–14.47	–102.6	N.D.	N.D.	N.D.	N.D.	N.D.
05067071170000	N.D.	–7.71	–47.5	N.D.	N.D.	N.D.	N.D.	N.D.
05067073250000	N.D.	–7.05	–42.4	N.D.	N.D.	N.D.	N.D.	N.D.

(*continued*)

TABLE A1. ANALYSES OF PRODUCED WATERS *(continued)*

API #	I	$\delta^{18}O$	δD	$^{87/86}Sr$	$^{129}I/I$	I age	$^{36}Cl/Cl$	Cl age
	mg/l	‰	‰		10^{-15}	Ma	10^{-15}	Ma
05067070990000	N.D.	–7.36	–43.9	N.D.	N.D.	N.D.	N.D.	N.D.
05067071020000	N.D.	–8.95	–63.9	N.D.	N.D.	N.D.	N.D.	N.D.
05067073230000	N.D.	–5.98	–30.2	0.710672	3840.0	A	N.D.	N.D.
05067072900000	N.D.	–7.33	–50.2	N.D.	N.D.	N.D.	N.D.	N.D.
05067072900000	N.D.	N.D.	N.D.	N.D.	192.0	47.0	N.D.	N.D.
05067071060000	N.D.	–7.41	–49.6	N.D.	N.D.	N.D.	N.D.	N.D.
05067071690000	N.D.	–7.92	–48.1	N.D.	N.D.	N.D.	N.D.	N.D.
05067082850000	0.0876	–14.57	–103.1	0.711394	5002.0	A	48	1.0
30039244170000	4.36	–6.81	–48.9	0.709609	412.0	29.0	0.0	bd
05067082610000	2.63	–13.34	–96.8	0.712536	201.0	46.0	N.D.	N.D.
30039243360000	10.6	–6.33	–38.2	0.710390	253.0	40.0	7.3	1.8
30039244470000	4.37	–5.59	–40.4	0.710409	276.0	38.0	7.4	1.8
30039244610000	4.84	–4.96	–40	0.710571	289.0	37.0	9.0	1.7
30039246960000	0.0023	–6.99	–60.2	N.D.	85073.0	A	35.0	1.2
30039245550000	2.62	–4.49	–45.4	0.711617	424.0	29.0	N.D.	N.D.
30039241690000	12.63	–4.14	–39.6	0.710237	214.0	44.0	14.0	1.6
05067082130000	0.0435	–14.72	–105.2	0.711374	13032.0	A	N.D.	N.D.
Pine River	0.0012	–13.62	–96.5	N.D.	1308059.0	A	N.D.	N.D.
Florida River	0.1723	–12.67	–90.5	0.708596	3873.0	A	N.D.	N.D.
05067079640000	0.0283	–13.92	–99.1	0.710030	53909.0	A	N.D.	N.D.
05067080570000	0.0014	–13.05	–92.7	0.712619	436155.0	A	1540.0	A
Animas River	0.0014	–14.36	–102.1	0.709752	631330.0	A	N.D.	N.D.
05067080180000	0.0114	–13.7	–99.7	0.709286	84671.0	A	N.D.	N.D.
05067082070000	3.7	–12.41	–87.7	0.712100	201.0	46.0	N.D.	N.D.
05067082080000	12.24	–11.17	–80.7	0.710922	202.0	45.0	0.0	bd

Note: Analyses of surface and monitoring well waters included for benchmarking. N.A.—not applicable; N.D.—no data; bd—below detection limit; A—age not determinable.

TABLE A2. ANALYSES OF SURFACE WATERS AND WATERS FROM NEAR-OUTCROP MONITORING WELLS

Part 1: 2001 data

Animas River

Sample date	2/28/2001	4/25/2001	6/18/2001	9/26/2001	11/2/2001	12/20/2001
Sample number	01W0017	01W0032	01W0035	01W0048	01W0056	01W0064
$\delta^{18}O$ (‰)	–13.92	–13.82	–15.30	–13.79	–13.91	–13.86
δD (‰)	–100.6	–99.4	–108.6	–99.2	–99.7	–103
Sr (ppm)	0.87	0.48	0.31	1.02	1.11	0.122
$^{87/86}Sr$	0.709639	0.709831	0.709514	0.710056	0.70975	0.709636
δsw	46.6	65.8	34.1	88.3	57.7	46.3
Si	N.D.	1.6	2.5	5.5	4.4	4.6
Fe	N.D.	0.11	0.061	0.053	0.03	<0.01
Mn	N.D.	0.013	<0.005	0.025	0.01	0.01
Mg	N.D.	7.4	3.75	13.8	15.6	12.4
Ca	N.D.	46.3	29.2	86.9	93.3	82
Na	N.D.	6.5	6.1	33	31.7	23
K	N.D.	1.07	0.92	4.8	4.69	3.69
CO_3	N.D.	1.97	0	0	0	0
HCO_3	N.D.	122.4	64.2	192	177	158
F	N.D.	0.23	0.2	0.43	0.42	0.37
Cl	N.D.	6.3	4.21	32.8	31	26.4
Br	N.D.	<0.05	0.028	0.038	<0.05	0
SO_4	N.D.	53.3	42.6	141	161	138
NO_3	N.D.	0.61	0.66	0.32	0.15	3
PO_4	N.D.	<0.25	<0.02	0.085	<0.02	0
pH	N.D.	8.47	7.26	5.95	5.88	5.28
Alk as $CaCO_3$	N.D.	103.6	51.4	158	145	130
TDS	N.D.	247.8	154.4	413	429.5	371

Florida River

Sample date	2/28/2001	4/25/2001	6/18/2001	9/26/2001	11/2/2001	12/20/2001
Sample number	01W0018	01W0031	01W0034	01W0047	01W0055	01W0063
$\delta^{18}O$ (‰)	–12.96	–13.26	–13.86	–12.74	–12.49	–12.65
δD (‰)	–91.6	–94.7	–96.4	–88.9	–89.4	–92.4
Sr (ppm)	0.43	0.5	0.25	0.33	0.35	0.314
$^{87/86}Sr$	0.711029	0.711698	0.710811	0.710741	0.711057	0.711117
δsw	185.5	252.5	163.8	156.8	188.4	194.4
Si	N.D.	1.5	2.1	2.6	2.3	2.1
Fe	N.D.	0.16	0.011	0.095	<0.01	<0.01
Mn	N.D.	0.01	<0.005	0.019	0.015	<0.01
Mg	N.D.	6.4	5.12	6.78	7.75	7.2
Ca	N.D.	46.3	32	37	48	46
Na	N.D.	3.9	3.2	4	4.3	4
K	N.D.	0.98	0.92	1.2	0.91	0.95
CO_3	N.D.	7.87	0	0	0	0
HCO_3	N.D.	163.2	117	141	175	164
F	N.D.	0.06	0.12	0.17	0.125	0.14
Cl	N.D.	1.9	0.68	0.52	1.15	1.18
Br	N.D.	<0.05	0.036	0	<0.05	0
SO_4	N.D.	15.8	11.7	13.1	13.8	16.3
NO_3	N.D.	0.18	0.34	0	<0.02	2.3
PO_4	N.D.	<0.25	0.25	0	0.036	0
pH	N.D.	8.8	7.8	6.7	6.06	5.02
Alk as $CaCO_3$	N.D.	146.9	93.8	115	144	135
TDS	N.D.	248.3	173.6	135	164.6	161

(*continued*)

TABLE A2. ANALYSES OF SURFACE WATERS AND WATERS FROM NEAR-OUTCROP MONITORING WELLS (*continued*)

Part 1: 2001 data, continued

Pine River

Sample date	2/28/2001	4/25/2001	6/18/2001	9/26/2001	11/2/2001	12/20/2001
Sample number	01W0019	01W0027	01W0033	01W0044	01W0049	01W0062
$\delta^{18}O$ (‰)	–12.92	–13	–14.12	–12.79	–12.76	–12.77
δD (‰)	–91.5	–91.3	–97.4	–90.7	–91.6	–90.7
Sr (ppm)	0.16	0.13	0.06	0.07	0.13	0.128
$^{87/86}Sr$	0.713147	0.713966	0.714793	0.715131	0.713291	0.713289
δsw	397.4	479.3	562	595.8	411.8	411.6
Si	N.D.	1	3.5	2.3	1.8	3.4
Fe	N.D.	0.05	0.022	0.028	0.02	<0.01
Mn	N.D.	<0.01	<0.005	0.019	0.008	<0.01
Mg	N.D.	2.8	1.57	1.92	2.4	2.65
Ca	N.D.	19.6	10.5	12.2	19.6	21
Na	N.D.	2.4	2	2	1.7	2.8
K	N.D.	0.56	0.65	0.8	0.8	0.9
CO_3	N.D.	4.72	0	0	0	0
HCO_3	N.D.	66.4	42	30.4	75.8	72.6
F	N.D.	0.15	0.11	0.2	0.16	0.18
Cl	N.D.	0.98	0.3	0.26	0.55	0.43
Br	N.D.	<0.05	<0.02	0	<0.05	0
SO_4	N.D.	7.3	3.58	3.63	<0.01	5
NO_3	N.D.	0.37	0.13	0.047	0.14	2.9
PO_4	N.D.	<0.25	0.063	0.052	0.18	0
pH	N.D.	8.5	7.85	4.85	6.8	4.57
Alk as $CaCO_3$	N.D.	62.32	33.6	24.9	62.2	59.5
TDS	N.D.	106.3	64.46	38.5	64.7	75

Killian Deep (Kfr)

Sample date	2/28/2001	4/25/2001	6/18/2001	9/26/2001	11/2/2001	12/20/2001
Sample number	01W0020	01W0030	01W0040	01W0041	01W0054	01W0057
$\delta^{18}O$ (‰)	–13.83	–13.68	–13.91	–13.76	–13.61	–13.56
δD (‰)	–99.7	–97.4	–99.4	–99.6	–97.7	–97
Sr (ppm)	0.42	0.42	0.53	0.57	0.41	0.333
$^{87/86}Sr$	0.710058	0.710154	0.710193	0.710186	0.710151	0.710202
δsw	88.5	98.1	102	101.3	97.8	102.9
Si	N.D.	6.2	7.2	5.8	5.2	6.6
Fe	N.D.	0.31	0.087	0.26	0.1	0.17
Mn	N.D.	<0.01	<0.005	<0.01	<.005	<0.01
Mg	N.D.	1.3	1.42	1.22	1.14	1
Ca	N.D.	3.6	5.5	5.2	4.5	4.5
Na	N.D.	188	208	186	192	181
K	N.D.	0.93	1.35	1.4	1.24	1.26
CO_3	N.D.	19.3	0	0	0	0
HCO_3	N.D.	490	587	510	509	483
F	N.D.	1.2	1.8	1.68	1.57	1.46
Cl	N.D.	2.8	1.98	2.28	2.32	2.87
Br	N.D.	<0.05	0.043	0.049	<0.05	0.04
SO_4	N.D.	<1.2	0.012	0	<0.01	0
NO_3	N.D.	0.23	<0.01	0	<0.02	2.6
PO_4	N.D.	<0.25	<0.02	0	<0.02	0
pH	N.D.	8.8	8.03	5.92	6.62	8.02
Alk as $CaCO_3$	N.D.	433.9	470	418	417	396
TDS	N.D.	713.9	814.4	455	458.8	440

(*continued*)

TABLE A2. ANALYSES OF SURFACE WATERS AND WATERS FROM NEAR-OUTCROP MONITORING WELLS (*continued*)

Part 1: 2001 data, continued

James #1 (Kfr)

Sample date	2/28/2001	4/25/2001	6/18/2001	9/26/2001	11/2/2001	12/20/2001
Sample number	01W0021	01W0026	01W0037	01W0042	01W0052	01W0059
$\delta^{18}O$ (‰)	–14.01	–13.79	–13.74	–13.74	–13.73	–13.74
δD (‰)	–99.8	–97	–98.6	–99.4	–100.4	–100.9
Sr (ppm)	1.06	1.13	1.22	1.31	1.21	1.14
$^{87/86}Sr$	0.710171	0.710174	0.710129	0.710069	0.710117	0.710097
δsw	99.8	100.1	95.6	89.6	94.4	92.4
Si	N.D.	5.8	6	7	6	6.1
Fe	N.D.	0.01	0.022	0.17	1.86	0.3
Mn	N.D.	<0.01	0.039	0.053	0.061	0.04
Mg	N.D.	3.7	4.29	4.4	4.1	4.35
Ca	N.D.	11.3	13.4	12.2	11.5	12.5
Na	N.D.	181	163	153	163	162
K	N.D.	1.85	2.15	2.3	2.19	2.35
CO_3	N.D.	9.05	0	0	0	0
HCO_3	N.D.	517.2	504	472	474	485
F	N.D.	0.46	0.52	0.55	0.54	0.66
Cl	N.D.	3.4	2.35	2.3	2.52	2.67
Br	N.D.	<0.05	0.055	0.035	<0.05	0.05
SO_4	N.D.	<0.2	0.15	0	0.015	0
NO_3	N.D.	0.25	<0.01	0	<0.02	3.4
PO_4	N.D.	<0.25	<0.02	0	<0.02	0
pH	N.D.	8.4	7.87	6.2	5.9	5.1
Alk as $CaCO_3$	N.D.	439.2	403	387	389	397
TDS	N.D.	734	696	414	425.3	433

Salmon #3 (Kfr)

Sample date	2/28/2001	4/25/2001	6/18/2001	9/26/2001	11/2/2001	12/20/2001
Sample number	01W0022	01W0029	01W0039	01W0046	01W0051	01W0061
$\delta^{18}O$ (‰)	–13.97	–13.76	–13.76	–13.78	–13.77	–13.74
δD (‰)	–100.2	–100.2	–99.8	–100.9	–100.9	–102.7
Sr (ppm)	0.30	0.31	0.34	0.32	0.34	0.326
$^{87/86}Sr$	0.709807	0.709885	0.7099	0.709857	0.709786	0.709856
δsw	63.4	71.2	72.7	68.4	61.3	68.3
Si	N.D.	1.4	3.1	2.6	1.6	1.6
Fe	N.D.	0.03	0.017	0.01	<0.01	<0.01
Mn	N.D.	<0.01	<0.005	<0.01	<0.005	<0.01
Mg	N.D.	0.6	0.63	0.68	0.56	0.53
Ca	N.D.	3.3	3	3.6	3.2	4
Na	N.D.	237	235	220	240	231
K	N.D.	1	1.44	1.4	1.19	1.45
CO_3	N.D.	61.8	37	15.7	0	0
HCO_3	N.D.	512.8	556	594	597	621
F	N.D.	0.91	1.13	1.2	1.19	1.28
Cl	N.D.	3.6	2.58	2.54	2.48	3.36
Br	N.D.	<0.05	0.018	0.04	<0.05	0.04
SO_4	N.D.	0.26	0.17	0	0.072	0.05
NO_3	N.D.	0.1	<0.01	0	<0.02	3.6
PO_4	N.D.	<0.25	0.025	0.016	<0.02	0
pH	N.D.	9.53	9.01	8.74	7.9	7.88
Alk as $CaCO_3$	N.D.	523.5	505	513	490	509
TDS	N.D.	822.8	840.1	541	544.4	553

(*continued*)

TABLE A2. ANALYSES OF SURFACE WATERS AND WATERS FROM NEAR-OUTCROP MONITORING WELLS (*continued*)

Part 1: 2001 data, continued

James #2 (Qal)						
Sample date	2/28/2001	4/25/2001	6/18/2001	9/26/2001	11/2/2001	12/20/2001
Sample number	01W0023	01W0025	01W0036	01W0043	01W0053	01W0058
$\delta^{18}O$ (‰)	–13.14	–12.85	–13.26	–13.23	–13.01	–13.15
δD (‰)	–94.0	–93.7	–92.5	–96.9	–92.9	–94.9
Sr (ppm)	0.2	0.24	0.19	0.21	0.18	0.228
$^{87/86}Sr$	0.712518	0.712553	0.712597	0.712579	0.71254	0.712507
δsw	334.4	338	342.4	340.6	336.7	334.4
Si	N.D.	2.3	3	4.6	4	4.1
Fe	N.D.	0.21	1.29	4.8	2.38	0.5
Mn	N.D.	0.21	0.2	0.16	0.15	0.19
Mg	N.D.	7.8	6.3	5.67	5.5	7.7
Ca	N.D.	37.2	31.3	31.2	31.5	41
Na	N.D.	8.3	7.1	5.5	4.9	7
K	N.D.	1.24	1.27	2	1.2	1.45
CO_3	N.D.	0	0	0	0	0
HCO_3	N.D.	164	146.4	125	131	161
F	N.D.	0.14	0.19	0.19	0.2	0.16
Cl	N.D.	4.4	2.18	1.47	1.75	3.26
Br	N.D.	<0.05	<0.02	0	<0.05	0
SO_4	N.D.	12	0.52	0.64	0.71	10.6
NO_3	N.D.	0.051	<0.01	0	<0.02	3.6
PO_4	N.D.	<0.25	<0.02	0	<0.02	0
pH	N.D.	8.18	7.1	5.25	5.78	5.4
Alk as $CaCO_3$	N.D.	134.5	117	102	107	132
TDS	N.D.	237.8	199.8	118	116.8	159

Salmon #3 (Kfrt)						
Sample date	2/28/2001	4/25/2001	6/18/2001	9/26/2001	11/2/2001	12/20/2001
Sample number	01W0024	01W0028	01W0038	01W0045	01W0050	01W0060
$\delta^{18}O$ (‰)	–13.92	–13.44	–13.77	–13.59	–13.59	–13.55
δD (‰)	–99.4	–99.3	–99.9	–100.8	–99	–101.3
Sr (ppm)	0.50	0.5	0.53	0.46	0.43	0.328
$^{87/86}Sr$	0.709278	0.709321	0.709248	0.709338	0.70968	0.709199
δsw	10.4	14.8	7.5	16.5	50.7	2.6
Si	N.D.	4.6	4	5.9	5	3.2
Fe	N.D.	0.02	0.033	0.051	0.09	0.025
Mn	N.D.	0.014	<0.005	<0.01	<0.005	0.01
Mg	N.D.	1.2	1.16	1.05	0.78	0.5
Ca	N.D.	5.7	5.9	6	5.8	5.5
Na	N.D.	240	242	222	225	198
K	N.D.	1.07	1.3	1.3	1.2	1.1
CO_3	N.D.	43.3	21.2	0	0	0
HCO_3	N.D.	570	626	604	590	531
F	N.D.	0.92	1.18	1.3	1.32	1.5
Cl	N.D.	3.1	2.27	2.39	2.32	2.89
Br	N.D.	<0.05	0.029	0	<0.05	0
SO_4	N.D.	<0.2	0.012	0	<0.01	0
NO_3	N.D.	0.15	<0.01	0	0.029	2.75
PO_4	N.D.	<0.25	0.06	0	<0.02	0
pH	N.D.	9.17	8.62	7.81	7.01	8.01
Alk as $CaCO_3$	N.D.	539.6	535	495	484	435
TDS	N.D.	870.1	905.1	538	532.1	477

Note: Units in mg/l unless otherwise noted. Kfr—Cretaceous Fruitland Formation; Qal—Quaternary alluvium; Kfrt—Cretaceous Fruitland Formation upper classics; N.D.—not determined.

TABLE A2. ANALYSES OF SURFACE WATERS AND WATERS FROM NEAR-OUTCROP MONITORING WELLS (*continued*)

Part 2: 2002 data

Animas River

Sample date	3/5/2002	4/30/2002	7/1/2002	8/28/2002	10/31/2002	12/16/2002
Sample number	02W0008	02W0016	02W0027	02W0038	02W0039	02W0054
$\delta^{18}O$ (‰)	–13.74	–14.43	–14.11	–13.95	–13.87	–12.87
δD (‰)	–98.2	–102.4	–103	–100	–99.2	–91.4
Sr (ppm)	1.01	0.71	1.17	1.45	0.82	0.63
$^{87/86}Sr$	0.709614	0.709738	0.7102894	0.710355	0.709586	0.709434
δsw	44.1	57.7	112.3	119.4	42.5	27.3
Si	5.25	2.2	6.3	5.3	2.1	2.5
Fe	0.015	<0.05	<0.1	<0..05	0.026	0.05
Mn	0.009	0.04	<0.005	<0.01	<0.005	0.025
Mg	13.6	10.2	17.9	20.8	10.5	35.2
Ca	85	66	95.2	99.8	68.8	57.5
Na	27	19.8	52.5	52	19.2	18.8
K	4.15	3.3	6.5	6.8	3.4	5.2
CO_3	0	0	0	0	0	0
HCO_3	171	134.6	235.8	240.6	119.8	97.4
F	0.41	0.46	0.47	0.42	0.39	0.26
Cl	30	18.6	53.5	58.7	20.3	134.3
Br	0.05	0	0.17	0.08	0.07	0.89
SO_4	170	118	158	183	142	94.5
NO_3	2.84	3.1	0.32	2.2	3.5	3.71
PO_4	0	0	0	0	0.035	0.027
pH	5.3	8.29	7.74	7.7	8.15	7.16
Alk as $CaCO_3$	140	110	193.4	197.3	98.2	79.9
TDS	422	308	507	548	329	401

Florida River

Sample date	3/5/2002	4/30/2002	7/1/2002	8/28/2002	10/31/2002	12/16/2002
Sample number	02W0007	02W0015	02W0026	02W0037	02W0040	02W0053
$\delta^{18}O$ (‰)	–12.64	–11.88	–12.04	–9.98	–11.74	–11.86
δD (‰)	–90.4	–86.7	–88	–78.2	–84.2	–84.8
Sr (ppm)	0.35	0.42	0.31	0.48	0.4	0.42
$^{87/86}Sr$	0.710885	0.710581	0.71088	0.710747	0.710731	0.71103
δsw	171.2	142	171.9	158.6	157	186.9
Si	1.58	0.75	2.2	1.1	2.4	4.2
Fe	<0.01	<0.05	<0.1	<0.05	0.02	0.02
Mn	0.004	<0.02	<0.005	<0.01	<0.005	0.02
Mg	9.4	10.8	8.8	11.6	9.4	9.9
Ca	52.5	58	44.8	63.5	52.8	55.5
Na	7.4	7.5	5.7	7.6	4.95	7.4
K	0.95	1.5	1.5	2.25	1.4	1.4
CO_3	0	0.98	3.93	0	1.57	1.97
HCO_3	206	209.8	158.2	230.6	125.8	201.2
F	0.12	0.27	0.19	0.19	0.19	0.13
Cl	2.52	3.6	2.43	1.6	1.43	3.02
Br	<0.03	0	0	0.03	0	0
SO_4	21.6	30	20.1	18.6	24.4	25.2
NO_3	2.74	2.6	0	1.6	2.9	1.9
PO_4	0	0	0	0.13	0.042	0
pH	5.4	8.38	8.52	8.08	8.41	8.37
Alk as $CaCO_3$	169	173	136.3	189.1	106	168.3
TDS	200	219	168	222	164	210

(*continued*)

TABLE A2. ANALYSES OF SURFACE WATERS AND WATERS FROM NEAR-OUTCROP MONITORING WELLS (*continued*)

Part 2: 2002 data, continued

Pine River

Sample date	3/5/2002	4/30/2002	7/1/2002	8/28/2002	10/31/2002	12/16/2002
Sample number	02W0003	02W0009	02W0020	02W0036	02W0046	02W0055
$\delta^{18}O$ (‰)	–12.81	–12.71	–12.56	–11.93	–12.07	–12.42
δD (‰)	–90.2	–89.5	–92.4	–86.2	–86.1	–87.2
Sr (ppm)	0.14	0.09	0.09	0.14	0.17	0.23
$^{87/86}Sr$	0.713101	0.714429	0.714188	0.713853	0.709822	0.712712
δsw	392.8	526.8	502.7	469.2	66.1	355.1
Si	2.68	<0.75	1.6	2.4	3.2	4.2
Fe	0.02	<0.05	<0.1	0.077	<0.01	<0.02
Mn	0.008	0.03	<0.005	<0.01	<0.005	<0.02
Mg	3	2.5	2.67	3.7	3.4	3.94
Ca	21.8	17.2	17.2	26.6	26.9	31.2
Na	5	2.1	2.6	2.6	2.6	3.7
K	0.82	0.89	0.8	1.4	1.1	1.3
CO_3	0	0	0	0	3.34	0
HCO_3	90.4	60.2	67	90.4	96.6	101.6
F	0.16	0.28	0.22	0.18	0.18	0.18
Cl	0.62	1.4	0.7	0.49	0.7	1.04
Br	<0.03	0	0	0	0.02	0.017
SO_4	4.58	7.2	6.3	15.6	5.4	5.66
NO_3	3.76	2.4	0	1.1	2.3	1.81
PO_4	0	0	0.04	0.29	0.02	0.026
pH	6.4	7.92	7.88	7.68	8.6	8.12
Alk as $CaCO_3$	74.1	49.4	54.9	74.1	84.8	83.3
TDS	87	63.6	65.1	99.1	96.9	103

Killian Deep (Kfr)

Sample date	3/5/2002	4/30/2002	7/1/2002	8/28/2002	10/31/2002	12/16/2002
Sample number	02W0006	02W0014	02W0025	02W0033	02W0041	02W0052
$\delta^{18}O$ (‰)	–13.38	–13.4	–13.74	–13.9	–13.85	–13.63
δD (‰)	–95.3	–94.8	–98.1	–97.6	–99.6	–97.8
Sr (ppm)	0.28	0.26	0.44	0.53	0.44	0.37
$^{87/86}Sr$	0.710132	0.710233	0.710172	0.710211	0.710058	0.710244
δsw	95.9	107.2	101.1	105	89.7	108.3
Si	6.65	4.5	6.7	6.5	8	5.3
Fe	0.19	0.19	0.12	<0.05	0.047	0.16
Mn	0.009	<0.02	0.008	<0.01	<0.005	<0.02
Mg	0.85	808	1.4	1.7	1.2	1.03
Ca	3.2	3.2	5.2	5.3	5	3.8
Na	156	150	203	210	192	192
K	1.05	1.2	1.5	1.47	1.3	1.3
CO_3	0	0	0	0	0	0
HCO_3	408	402.2	562.4	579.4	544.6	482.8
F	1.08	1.1	2.46	1.9	1.73	1.55
Cl	2.56	3.3	3.86	1.9	1.88	2.33
Br	<0.03	0	0.03	0	0.021	0
SO_4	0	0	0.1	0.006	0.01	0.036
NO_3	3.82	3.2	0	1.3	4	2.31
PO_4	0	0	0	0.018	0.053	0
pH	5.8	7.98	8.16	7.94	7.88	8.1
Alk as $CaCO_3$	335	330	461.2	475.1	446	448
TDS	376	505	501	516	483	395.9

(*continued*)

TABLE A2. ANALYSES OF SURFACE WATERS AND WATERS FROM NEAR-OUTCROP MONITORING WELLS (*continued*)

Part 2: 2002 data, continued

James #1 (Kfr)

Sample date	3/5/2002	4/30/2002	7/1/2002	8/28/2002	10/31/2002	12/16/2002
Sample number	02W0004	02W0012	02W0023	02W0035	02W0043	02W0050
$\delta^{18}O$ (‰)	–13.72	–13.69	–13.68	–13.77	–13.76	–13.69
δD (‰)	–96.9	–96.7	–100.5	–97.9	–99.9	–97
Sr (ppm)	1.1	1.1	0.82	0.93	0.87	0.96
$^{87/86}Sr$	0.710065	0.71012	0.71007	0.710135	0.710193	0.710085
δsw	89.2	95.9	90.9	97.4	103.2	92.4
Si	6.75	3.8	8	4.9	6.9	5.3
Fe	0.15	<0.05	<0.1	0.23	0.26	0.18
Mn	0.037	<0.02	0.052	0.046	0.043	0.06
Mg	4.2	4.2	3.7	3.8	3.7	3.84
Ca	11.2	11.5	9.2	7.2	9.5	9.5
Na	155	150	150	148	143	144
K	2.3	2.2	2.3	2	2.2	2.3
CO_3	0	0	0	0	0	0
HCO_3	455	455.8	436.8	451.4	451.4	439.4
F	0.54	0.61	0.69	0.61	0.62	0.66
Cl	2.52	3.4	3.86	2.1	2.13	2.48
Br	0.03	0.11	0	0.02	0.017	0
SO_4	0.04	0	0.09	0.042	0.01	0
NO_3	4.18	2.2	0	1.5	3.3	2.95
PO_4	0	0	0	0	0	0.037
pH	5.7	7.7	7.79	7.87	7.7	7.82
Alk as $CaCO_3$	373	374	358.2	370.1	370	360.3
TDS	411	402	393	844	394	388

Salmon #3 (Kfr)

Sample date	3/5/2002	4/30/2002	7/1/2002	8/28/2002	10/31/2002	12/16/2002
Sample number	02W0002	02W0011	02W0022	02W0032	02W0045	02W0049
$\delta^{18}O$ (‰)	–13.82	–13.73	–13.7	–13.91	–13.96	–13.84
δD (‰)	–99.2	–100.9	–100.5	–99.7	–103.2	–99.1
Sr (ppm)	0.32	0.33	0.47	0.35	0.31	0.33
$^{87/86}Sr$	0.709761	0.709734	0.709427	0.70966	0.713184	0.709543
δsw	58.8	57.3	26.6	49.9	402.3	38.2
Si	1.91	1.5	4.5	6.7	3.7	4
Fe	<0.01	<0.05	<0.1	<0.05	0.023	<0.02
Mn	<0.002	<0.02	<0.005	0.015	<0.005	<0.02
Mg	0.65	0.7	1.12	0.7	0.4	0.58
Ca	3.2	4	6.6	3.9	4	3.3
Na	235	231	228	226	220	225
K	1.3	1.3	1.4	1.25	1.2	1.4
CO_3	16.5	75	14.75	13.37	4.1	19.9
HCO_3	580	581.8	594.6	589.2	605.8	570.6
F	1.19	1.3	1.48	1.2	1.2	1.15
Cl	2.65	3.6	4.14	2.6	2.6	2.55
Br	0.03	0	0	0.12	0	0
SO_4	0	0	0.09	0.037	0.034	0.008
NO_3	3.33	1.7	0	2.3	3	1.32
PO_4	0	0	0	0	0	0
pH	8.72	9.19	8.72	8.67	8.43	8.84
Alk as $CaCO_3$	475	508	512.2	504.4	504	501
TDS	552	607	555	548	538	540

(*continued*)

TABLE A2. ANALYSES OF SURFACE WATERS AND WATERS FROM NEAR-OUTCROP MONITORING WELLS (*continued*)

Part 2: 2002 data, continued

James #2 (Qal)						
Sample date	3/5/2002	4/30/2002	7/1/2002	8/28/2002	10/31/2002	12/16/2002
Sample number	02W0005	02W0013	02W0024	02W0034	02W0042	02W0051
$\delta^{18}O$ (‰)	–13.11	–12.72	–12.72	–12.71	–12.65	–12.39
δD (‰)	–94.8	–90.1	–93.2	–89.2	–90.7	–89.5
Sr (ppm)	0.22	0.21	0.15	0.17	0.13	0.15
$^{87/86}Sr$	0.712473	0.712586	0.712555	0.712523	0.712519	0.712538
δsw	330	342.5	339.4	336.2	335.8	337.7
Si	4.05	2.6	4	3.9	2.1	3.2
Fe	0.15	0.09	<0.1	<0.05	0.052	0.26
Mn	0.177	0.19	0.155	0.13	0.047	0.09
Mg	7.5	8.2	6.08	5.7	5.3	5.45
Ca	40	38.5	29.6	27.5	21.5	21.8
Na	7.5	8	6.3	6	5.3	7
K	1.32	1.6	1.7	1.4	1.1	1.6
CO_3	0	0	0	0	0	0
HCO_3	161	170.2	134.6	127.8	107.8	112
F	0.15	0.28	0.21	0.21	0.23	0.14
Cl	3.16	4.4	2.28	1.4	1.66	2.23
Br	<0.03	0	0	0	0.017	0.014
SO_4	10.2	9.2	0.4	0.34	0.22	2
NO_3	4.1	3	0	1.6	2.6	2.38
PO_4	0	0	0	0.018	0.11	0.029
pH	4.9	7.38	7.47	7.32	8.09	8.04
Alk as $CaCO_3$	132	140	110.4	104.8	88.4	91.8
TDS	158	160	117	111	93.2	101

Salmon #3 (Kfrt)						
Sample date	3/5/2002	4/30/2002	7/1/2002	8/28/2002	10/31/2002	12/16/2002
Sample number	02W0001	02W0010	02W0021	02W0031	02W0044	02W0056
$\delta^{18}O$ (‰)	–13.56	–13.56	–13.64	–13.77	–13.81	–13.65
δD (‰)	–99.1	–95.7	–98.9	–99.5	–101.5	–98.1
Sr (ppm)	0.26	0.26	0.39	0.49	0.46	0.52
$^{87/86}Sr$	0.709165	0.709292	0.709208	0.709221	0.709623	0.709215
δsw	–0.8	13.1	4.7	6	46.2	5.4
Si	5.25	3	6.4	5.8	5.9	1.7
Fe	0.034	<0.05	<0.1	0.05	0.014	<0.02
Mn	0.012	<0.02	<0.005	<0.01	<0.005	<0.02
Mg	0.5	0.4	0.96	1.3	1	1.07
Ca	5	5.5	6.5	6.8	6.8	7
Na	178	175	220	243	236	232
K	0.81	0.95	1.3	1.48	1.4	1.5
CO_3	0	0	14.48	23.21	9.64	36.6
HCO_3	499	467.4	572.4	617.8	635	605.6
F	1.42	1.6	1.5	1.3	1.38	1.61
Cl	0.82	3.3	4.17	2.3	2.56	2.71
Br	<0.03	0	0	0	0	0
SO_4	0.23	5.6	0.1	0.056	0	0.021
NO_3	3.24	2.5	0	1.2	3.2	2.87
PO_4	0	0	0	0.11	0	0.077
pH	8	8.21	8.7	8.85	8.56	8.84
Alk as $CaCO_3$	409	383	493.3	545.3	537	540.9
TDS	441	428	537	591	581	575

Note: Units in mg/l unless otherwise noted. Kfr—Cretaceous Fruitland Formation; Qal—Quaternary alluvium; Kfrt—Cretaceous Fruitland Formation upper classics.

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