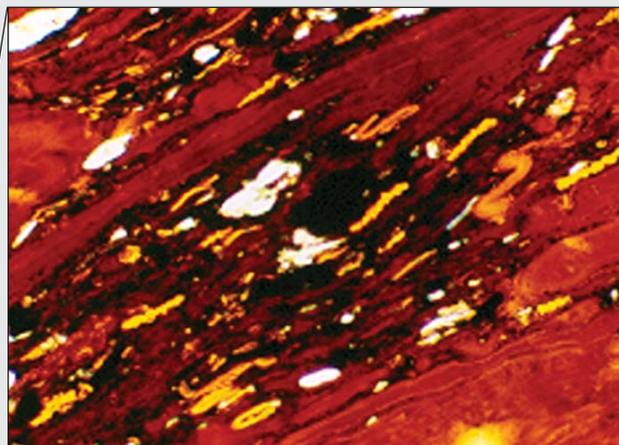
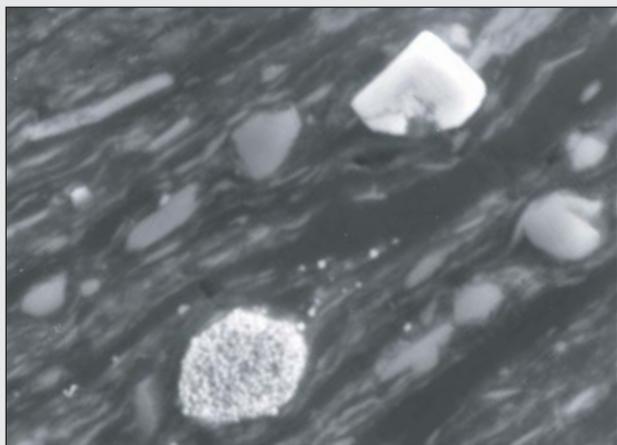


U.S. Department of the Interior
U.S. Geological Survey

Coal—A Complex Natural Resource

An overview of factors affecting coal quality and use in the United States
With a contribution on coal quality and public health



U.S. GEOLOGICAL SURVEY CIRCULAR 1143

Cover: Chunk of Texas subbituminous coal in the field. Pen for scale. Note the very thin, light-colored laminations that indicate bedding. Top-left enlargement is an example of a scanning photomicrograph showing minerals in coal. The bright-white, oval-shaped fragment is a pyrite framboid; the bright-white triangular fragment is zircon; each fragment is about 10 microns wide. The light-colored, equant blebs are quartz grains. They are set in a light-gray matrix consisting of coal macerals and a variety of clay minerals. Top-right enlargement is an example of a transmitted-light photomicrograph showing various coal macerals (organic components) such as vitrinite (dark reddish orange); liptinite (yellow and light orange); and fusinite, inertinite, and minerals (black). View is about 200 micrometers wide.

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By Stanley P. Schweinfurth

With a contribution on coal quality and public health by Robert B. Finkelman

U.S. GEOLOGICAL SURVEY CIRCULAR 1143

A primer on the origins and quality of coal with a brief examination of how quality affects coal use, and a separate section on coal and public health

**U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary**

**U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director**

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FOREWORD

During the 20th century, dramatic shifts took place in the types and sources of energy consumed in the United States. The future energy mix and the technologies used in fuel combustion will be critical in determining the economic and environmental health of the Nation as we move ahead in the 21st century. Coal was a major primary energy source within the United States for all of the last century, and, currently, coal is used to generate more than 50 percent of the Nation's electric energy. Coal supplies are adequate within the United States for this century and coal is the least expensive of the fossil fuels, making it a reliable and economical source of energy. Recent studies, however, suggest that an increased use of coal may contribute to the degradation of the environment and to global warming. A thorough understanding of coal quality will lead to the development of methods to better control the harmful effects of coal use on the environment and human health.

The U.S. Geological Survey (USGS) is actively involved in research on the quality and abundance of coal, as well as on the complex geological and geochemical factors that govern coal quality. In addition, the U.S. Geological Survey gathers information on the location, size, and nature of coal deposits, which also contributes to a basic understanding of the Nation's energy resources. This research is pertinent to discussions of future energy resources, global warming, and the dependence of the Nation on imported fossil fuels—all of which are concerns that are being faced daily at local, State, and National levels. Understanding the nature of coal quality is important for two critical issues facing our Nation—the economy and the environment.

The wise use of our Nation's resources and the careful stewardship of our public lands depend on the dissemination of accurate and timely earth science information. The U.S. Geological Survey is proud to present this report on one of the major issues to be addressed in the future use of coal.

Charles G. Groat
Director

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Coal—A Complex Natural Resource

An overview of of factors affecting coal quality and use in the United States

By Stanley P. Schweinfurth

INTRODUCTION

Coal is abundant in the U.S., is relatively inexpensive, and is an excellent source of energy and byproduct raw materials. Because of these factors, domestic coal is the primary source of fuel for electric power plants in the U.S., and will continue to be well into the 21st century. In addition, other U.S. industries continue to use coal for fuel and coke production and there is a large overseas market for high-quality American coal.

Because humans have used coal for centuries, much is known about it. The usefulness of coal as a heat source and the myriad of byproducts that can be produced from coal are well understood. The continued and increasingly large-scale use of coal in the United States and in many other industrialized and developing nations has resulted in known and anticipated hazards to environmental quality and human health. As a result, there is still much to be learned about the harmful attributes of coal and how they may be removed, modified, or avoided to make coal use less harmful to humans and nature. These issues of coal quality have not been examined carefully until recently.

Some of the problems that accompany the mining and use of coal are well known. Acid mine drainage results when coal beds and surrounding strata containing medium to high amounts of sulfur, in the form of compounds known as sulfides, are disrupted by mining, thereby exposing the sulfides to air and water. Atmospheric sulfur oxides (SO_x) and subsequent acid deposition (such as acid rain) result from the burning of medium- to high-sulfur coal. The quality of surface and ground water may be affected adversely by the disposal of the ash and sludge that result from the burning of coal and cleaning of flue gases. These are some of the serious problems requiring either improved or new remedies. Other environmental problems are associated with emissions of carbon dioxide (CO_2) and nitrogen oxides (NO_x), two of the so-called “greenhouse gases.” These emissions are often attributed to coal use only; however, they also result from the burning of any fossil or biomass fuel, such as wood, natural gas, gasoline, and heating oil. The greenhouse gas problem requires a broader solution than just reducing the use of coal. Research currently is

being conducted in the U.S. and several other countries into the reduction and disposal of CO_2 from coal combustion. An excellent review of the results of this research and the prospects for coal can be found in a publication of IEA Coal Research (1999).

Fluidized-bed combustion (FBC) of coal, which is a new method for controlling sulfur emissions, is gaining wide acceptance. In this system, finely ground coal is mixed with finely ground limestone. Both are fed together into a furnace in a constant stream onto a horizontally moving grate. Air is forced up through the grate and the entire mass is ignited at relatively low temperatures. The forced air causes the ground coal and limestone to be mixed with the hot gases of combustion, which in turn promotes the conversion of any SO_x to gypsum as the burning mass moves along on the grate. According to the U.S. Department of Energy (2000), high-sulfur coal may be burned in this way while simultaneously capturing up to 95 percent of the SO_x and most of the NO_x emitted.

Reduction and disposal of CO_2 emissions is the subject of current research in the U.S. and several other countries.

The Clean Air Act Amendments of 1990 (Public Law 101-549) required the U.S. Environmental Protection Agency (EPA) to conduct studies of 15 trace elements released by the burning of coal to determine if they present health hazards. These 15 elements (antimony, arsenic, beryllium, cadmium, chlorine, chromium, cobalt, lead, manganese, mercury, nickel, potassium, selenium, thorium, and uranium), along with many other potentially hazardous substances released into the air by other industries, are termed “hazardous air pollutants” (HAPs).

On the basis of epidemiological studies, the EPA concluded that, with the possible exception of mercury, there is no compelling evidence to indicate that trace-element emissions from coal-burning power plants cause human health problems (U.S. Environmental Protection Agency, 1996). In December 2000, after extensive study, the EPA announced a

finding that regulation of mercury emissions from coal-fired power plants is necessary and appropriate because coal-fired power plants are the largest unregulated source of manmade emissions of mercury in the U.S. (U.S. Environmental Protection Agency, 2000).

EPA will propose regulations to limit mercury emissions in 2003 and will issue final emissions rules by 2004. Meanwhile, arsenic is still under study, not as an emissions problem from coal combustion, but for its potential role as a hazard in ground water if it is leached from coal-mining waste or from fly ash in disposal sites. Additional coal-quality research on both mercury and arsenic is being conducted at the U.S. Geological Survey (USGS) and elsewhere in order to (1) help identify their sources in coal, and (2) help resolve any remaining potential hazards issues with regard to these two elements.

In 1996, the EPA said that, of the potential HAPs from coal combustion, only mercury and arsenic needed additional study. In 2000, EPA determined that mercury emissions require regulation.

Other problems that may arise from the use of coal are not necessarily harmful to the environment or human health, but affect the use and efficiency of coal-burning equipment. For example, certain constituents in coal may cause severe erosion and corrosion of, or the buildup of mineral deposits on, furnace and boiler parts. These effects greatly reduce the efficiency and life expectancy of furnaces or boilers; as a result, costly repairs are often required.

Thus far, coal has been discussed as if it were a single homogeneous material, but this is done only for convenience in this report. In fact, a wide variety of coal types exists, depending on differing proportions and combinations of organic and inorganic (mineral) components, sulfur, and ash. For example, sulfur content may range from low (less than 1 percent), through medium (1 to 3 percent), to high (greater than 3 percent), and ash yields may range from a low of about 3 percent to a high of 49 percent (if ash yields are 50 percent or greater, the substance is no longer called coal). Coal may produce high or low amounts of energy, or contain high or low amounts of the substances that produce organic chemicals and synthetic fuels, or contain higher or lower amounts of the elements that are considered to be hazardous air pollutants (HAPs). This range in properties results from coal's diverse origins, including the long and complex geologic histories of coal deposits.

The purpose of this report is to acquaint students, non-coal scientists, and the general public with some basic information on (1) the subject of coal quality and the reasons

why it is so complex, (2) methods for determining coal quality, and (3) the need for continuing studies of this complex subject. A discussion on the origins of coal is included in order to provide a framework for understanding coal's complex nature. See the section on "Further Reading" for a bibliography on coal quality and other topics (such as coal mining, uses for coal, or health effects of coal use).

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COAL IN THE UNITED STATES

A discussion of coal use in the U.S. and of the beneficial things that come from coal is necessary in order to provide the reader with a better understanding of the importance of coal quality and the need for continuing research on coal quality.

COAL PRODUCTION AND CONSUMPTION

Coal use in the U.S. began around two thousand years ago. Early inhabitants of this continent probably gathered coal from outcroppings, beaches, and streambeds. Coal

mining by European-Americans began in the Richmond basin of Virginia between 1720 and 1750. The Richmond area is known to have furnished coal during the American Revolution. Between 1750 and 1800, coal was discovered in many parts of the northern and southern Appalachian basin. As the population moved westward after the American Revolution, coal deposits were discovered, progressively, in the midcontinent (including Texas), the Rocky Mountains region, the Colorado Plateau, and the northern Great Plains. The first coal in the West was found along the Missouri River in 1804 by the explorers Meriwether Lewis and George Rogers Clark (Collier's Encyclopedia, 1960).

In the U.S., coal is used to produce approximately 56 percent of the annual electricity requirement; 90 percent of the coal produced is used for this purpose.

After 1830, with the beginning of the railroads, the real growth of the coal industry began. The railroads not only used coal, they also provided the means to transport coal, which encouraged the growth of energy-intensive industries. The growth of the railroads also encouraged the expansion of the iron and steel industry, which, by the

1860s, had abandoned charcoal in favor of coke for the reduction of iron ore to pig iron. In the 1880s, after the invention of electric turbines, coal soon became the principle energy source for steam-generated electricity. For a much more detailed account of the early days of coal discovery and use in the U.S., see Eavenson (1942).

By 1918, industry in the U.S. depended almost entirely on coal. During World War II, demand for coal drove coal production to record highs, but shortly thereafter, petroleum replaced coal as our chief source of energy. For about a decade following World War II, most of the decline in coal use was due to the replacement of coal-burning railroad engines with diesel engines. In the 1960s, coal production and consumption began to rise due to an increasing demand for electricity, and has risen ever since. In 1961, the U.S. produced 420.4 million tons (1 ton=2000 pounds) and used 390.4 million tons for domestic purposes; in 1998, production was 1,118.7 million tons and domestic use in 1999 was 1,045.2 million tons (figs. 1, 2) (Energy Information Administration, 2000).

The difference between the amounts of coal produced and used in the U.S. is accounted for mainly by exports. Revenue from coal exports helps reduce the deficit in the balance of payments the U.S. makes to its foreign suppliers of consumer goods. In 1998, coal exports of 78 million tons earned approximately \$2.9 billion (Energy Information Administration, 1999b).

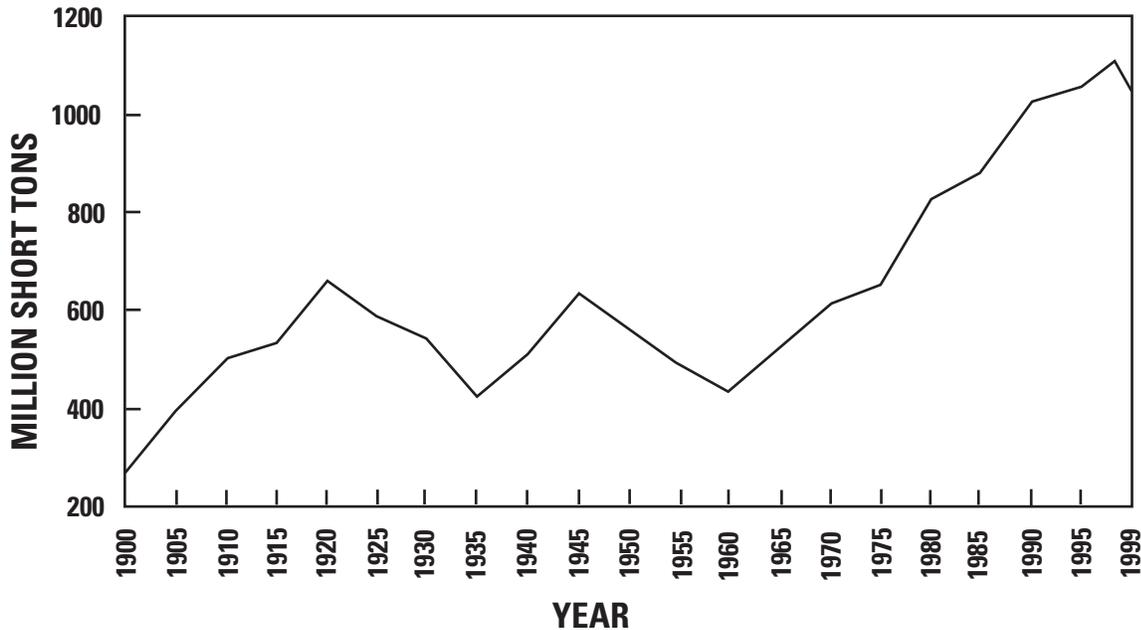


Figure 1. Graph showing trends in U.S. coal production from 1900 to 1999. The rapid growth in production after 1960 is attributed to (1) abundant reserves, (2) high productivity resulting in favorable prices for coal, and (3) the large increase in demand for electricity. Data from Energy Information Administration (2000).

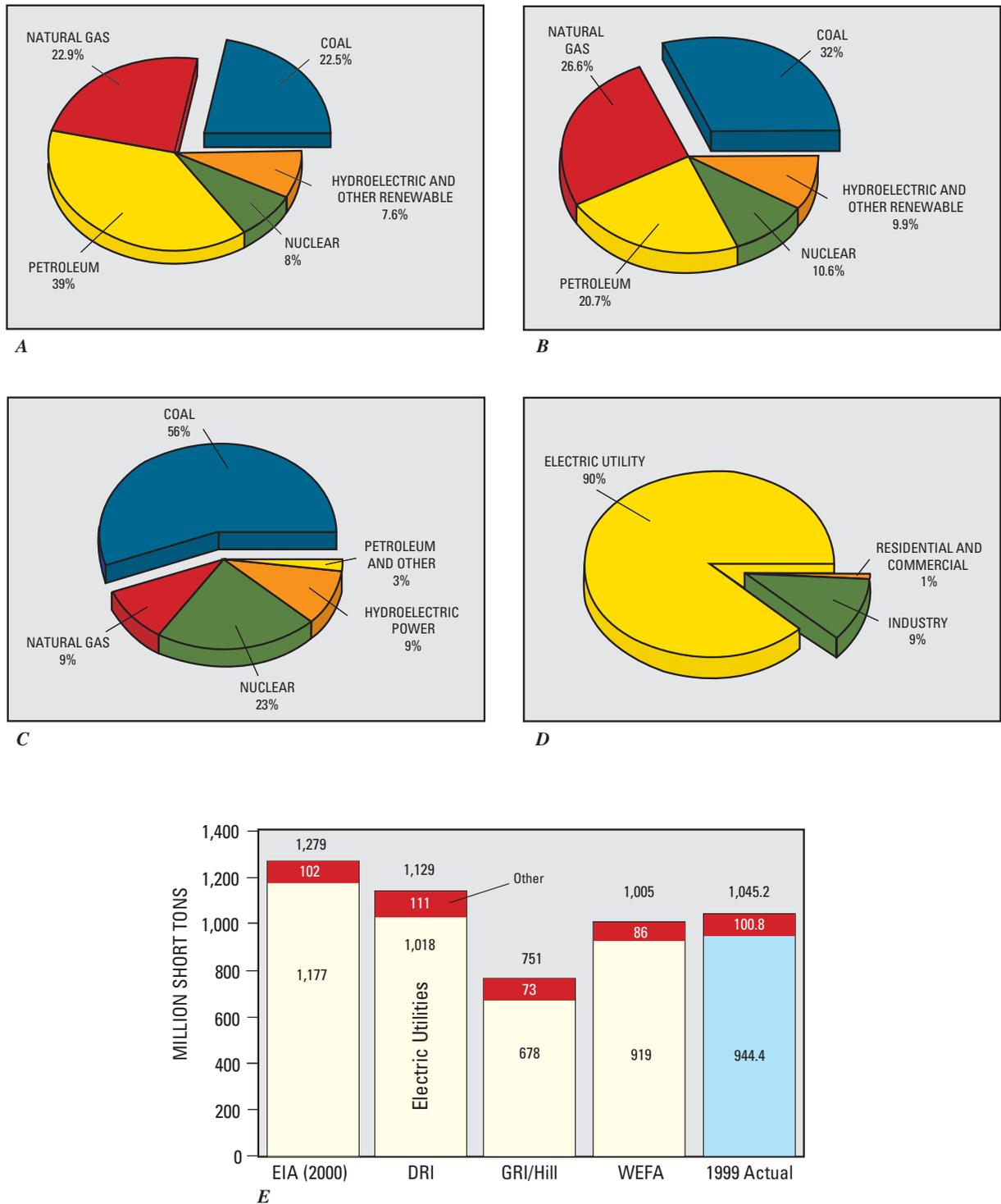


Figure 2. Diagrams showing energy consumption and production in the U.S. *A*, Energy consumption in 1999. Of the various commodities consumed, approximately 54 percent of the oil and 16 percent of the natural gas are imported; the coal and other commodities are almost entirely domestic. *B*, Energy production in 1999. *C*, Electricity generated in 1999, by all commodities. *D*, Coal consumption in 1999 by the economic sectors shown. *E*, Forecasted coal consumption for 2020 by electric utilities (yellow)

and other uses (red). The basis for comparison of commodities in diagrams *A*, *B*, and *C* is quadrillion Btu, or “quads.” Total quads produced and consumed in 1999, were, respectively, 72.5 and 96.6. The basis for diagrams *D* and *E* is million short tons. EIA, Energy Information Administration; DRI, Standard & Poor’s Data Resources Inc.; GRI/Hill, Gas Research Institute; WEFA, The WEFA Group. Data from Energy Information Administration (1999a, 2000).



Figure 3. Photograph of the Navajo power plant, which is a coal-fired, electric-power-generation plant near Page, Ariz. Photograph by J.C. Willett (U.S. Geological Survey).

According to the Energy Information Administration (2000), approximately 1,099.1 million tons of coal were produced in 1999 (slightly less than in 1998) and 1,045.2 million tons were used domestically (slightly more than in 1998). The differences in production and consumption between 1998 and 1999 were due to a reduction in exports of 20 million tons in 1999. Of the total coal used domestically in 1999, 90 percent (944.4 million tons) was used to fuel electric power plants (fig. 3), which produced 56 percent of the electricity in the U.S. The other 10 percent was used in industrial (coke and heating), residential, and commercial applications (fig. 2).

COAL PRICES

Steady improvements in the efficiency of coal mining in the U.S. have kept coal prices low. In 1998, the average price of a ton of coal at the mine was \$17.67; the average price of a ton of coal delivered to electric utilities was

\$25.64 (Energy Information Administration, 2000). Prices in 1986 of \$23.99 and \$33.30 per ton, respectively, demonstrate this trend. Furthermore, over the last decade, coal has been the least expensive of the three main fuel sources—coal, natural gas, and petroleum—in the U.S. On the basis of a common unit of heat (million Btu) over the ten-year period, coal prices averaged about \$0.91 at the mine; natural gas averaged \$1.72 at the wellhead; and crude oil averaged \$2.70 at the domestic first point of purchase (Energy Information Administration, 2000). Lower prices probably encourage continued high and (probably) increasing levels of coal use in the U.S.

In 1999, the Energy Information Administration (EIA) forecasted that, by the year 2020, average coal prices would decrease further to approximately \$20.01 per ton delivered to electric power plants (in 1998 dollars). Coal production is forecast by the EIA (fig. 2) to grow to approximately 1,300 million tons by 2020, of which domestic use will account for 1,279 million tons; of that amount, 1,177 million tons will be used by electric power plants. These figures indicate a rate of growth of approximately one percent per year for both coal production and power plant use. Other domestic uses of coal are forecast by the EIA to remain about the same by 2020 (Energy Information Administration, 2000).

COAL SUPPLY

Although coal deposits are widely distributed throughout the U.S., the bulk of coal mining and consumption remained, until recently, in the eastern part of the country, mostly in the Appalachian basin. This was due to the concentration of population and industry in the East. Coal production recently has been moving to the Western States because the bulk of the remaining resources of low-sulfur coal are located in the Rocky Mountains and northern Great Plains regions. The demand for low-sulfur coal is based on the Clean Air Act Amendments of 1990, which began implementation in 2000. The new regulations limit SO_x emissions from coal-fired power plants to 1.2 lbs per million Btu. Power-plant managers are finding that converting their coal supplies from medium- and high-sulfur coal to low-sulfur coal, rather than installing flue-gas desulfurization (FGD) systems, generally is the least expensive option for achieving the required level of SO_x emissions (U.S. Geological Survey, 2000). There are reserves of low-sulfur coal remaining in the Appalachian basin, but most of the remaining reserves occur at depths requiring costlier underground mining methods to recover them.

Whether or not substantially more coal is used in the future than presently, coal is abundant enough in the U.S. to supply anticipated requirements for much of the 21st century. In 1999, the National Mining Association (NMA) reported that 30 of the largest coal companies in the U.S. have

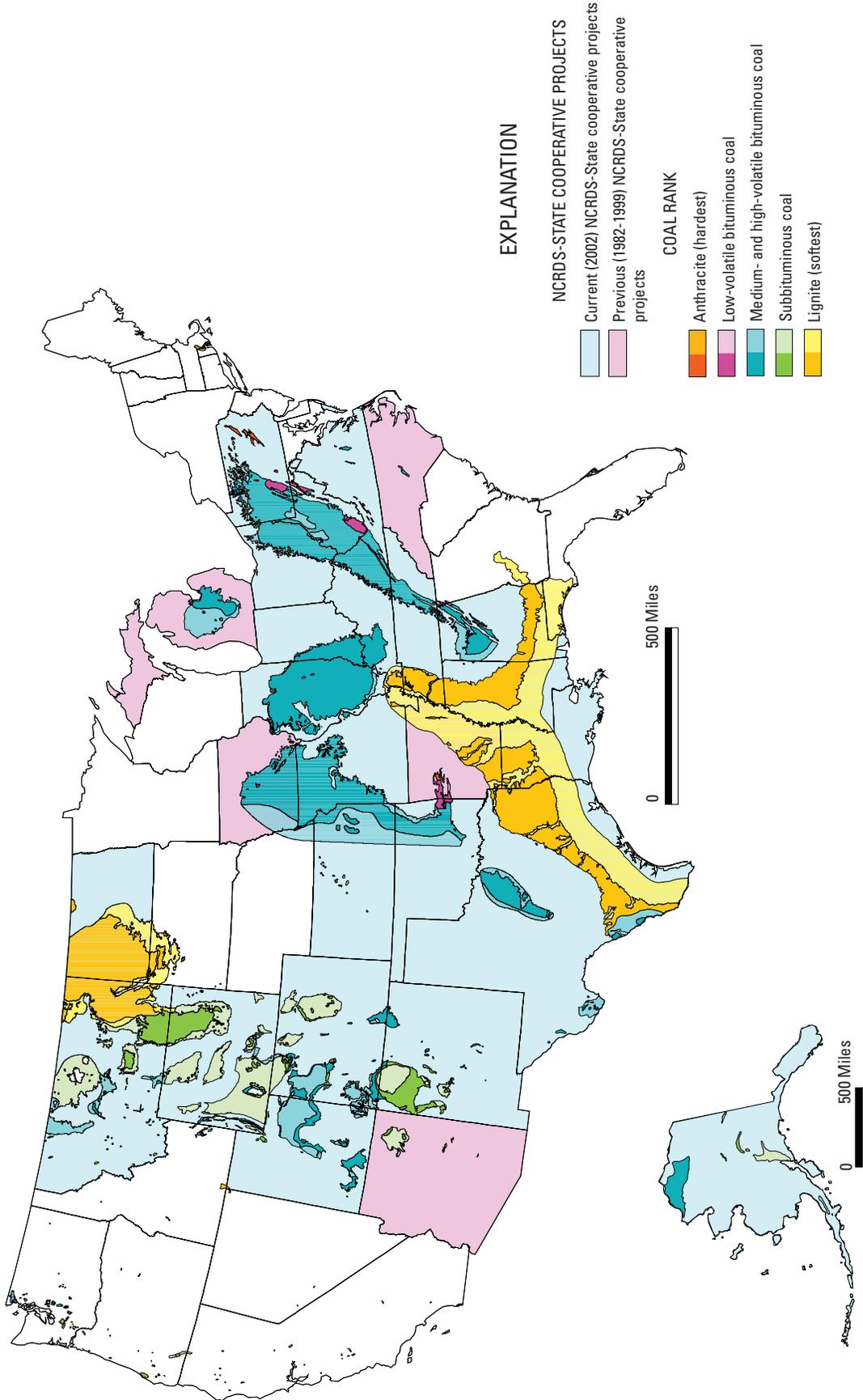


Figure 4. Map showing coal fields of the U.S. classified by coal rank and areas of cooperative study of coal resources and quality. For each category of coal rank, darker color indicates area of coal outcroppings and lighter color indicates area of subsurface coal. Also shown are States with long-term, current (light blue) or previous (light pink) cooperative relationships with the U.S. Geological Survey in the National Coal Resources Data System (NCRDS) for the long-term study of coal resources and quality. Modified from Tully (1996) and M.D. Carter (U.S. Geological Survey, written commun., 2002). (Some States contain coal fields that are too small to show rank colors.)

approximately 68 billion tons of coal in reserve (National Mining Association, 1999). In addition, numerous small coal-mining companies have reserves that are not included in the NMA's report, and there are additional coal deposits that could be mined, when and if needed.

In order to estimate the abundance of coal in beds and zones that will provide the largest percentage of the Nation's domestic energy production for the next 50 years, the USGS, in cooperation with the geological surveys of the major coal-producing States (Arizona, Colorado, Illinois, Indiana, Kentucky, Maryland, Missouri, Montana, New Mexico, North Dakota, Ohio, Pennsylvania, Tennessee, Texas, Utah, Virginia, West Virginia, and Wyoming) is in the midst of a basinwide reassessment of the coal resources of the U.S. (U.S. Geological Survey, 1996, 2000). Figure 4 shows the general distribution of coal deposits in the U.S. Results of the assessment for the Northern Rocky Mountains and Great Plains region, which includes selected coal beds of the Greater Green River, Hanna-Carbon, Powder River, and Williston basins; the Colorado Plateau; and the northern and central Appalachian Basin coal regions are available in CD-ROM format (Fort Union Coal Assessment Team, 1999; Kirschbaum and others, 2000; Northern and Central Appalachian Basin Coal Regions Assessment Team, 2001).

The USGS also is leading a cooperative program with some of the same States to assess the actual availability and recoverability of coal in areas smaller than basins. This study takes into account the many restrictions on mining imposed by environmental and land-use regulations and by the physical constraints based on geology and mining practices (Eggleston and others, 1990). For additional information on coal resources, please see the "Coal Resources" subsection of the "Further Reading" section.

COAL BYPRODUCTS

Coal—that black, dusty rock that evokes punishment of bad children at holiday times—is actually a very remarkable and rewarding material. In addition to providing heat to generate electricity (which is currently the primary use of coal), a myriad of other beneficial substances are derived from coal. Perhaps the best known of these substances is coke, which is used in the steel industry to separate iron from its ore. Coal is used in the production of other, perhaps unexpected products such as pharmaceuticals, textile dyes, food and wood preservatives, and other simple or highly complex chemicals (see centerfold). These chemicals typically are produced during the production of coke by a process called destructive distillation. In this process, coal is packed into a closed, oxygen-restricted container (retort, or coke oven) and then heated to a high temperature. This process drives off the volatile matter in the coal. The

volatile matter contains the parent compounds that are used to produce the products shown in the centerfold. The lack of oxygen in the retort prevents the chemicals from completely burning.

In the past, large quantities of an impure gas containing methane and carbon monoxide (called town gas or water gas) were derived from coal in the U.S. and elsewhere. Water gas was used for heating and cooking, but has been replaced largely by natural gas in the U.S. since the 1940s. In other parts of the world, notably in Germany during World War II and in South Africa today, gasoline and heating oil have been derived from coal. Currently, research is being conducted in the U.S. to improve the techniques and economics of producing both gas and oil (called "synfuels") from coal. This work is sponsored by the U.S. Department of Energy and involves numerous private, industrial, and academic organizations (U.S. Department of Energy, 2000).

*Coal is more than just a fuel source;
it contains complex tars, oils, and
gases that can be broken down into
many useful products such as dyes,*

Coal combustion products (CCPs), consisting of fly ash, bottom ash, boiler slag, and flue-gas-desulfurization (FGD) material, also have become important in the economy. As coal burns, it emits sulfur in the form of sulfur oxide. FGD is the process by which a chemical, such as calcium carbonate (CaCO_3), is injected into the flue-gas stream to trap the sulfur by combining with it to produce gypsum (CaSO_4). Gypsum is heavy and falls to the bottom of the FGD unit as sludge in a wet process, or as a powder in a dry process.

According to the USGS (Kalyoncu, 1999), approximately 57.2 million tons of fly ash, 15.2 million tons of bottom ash, 2.7 million tons of boiler slag, and 22.7 million tons of FGD material were produced in 1998. The amounts of each CCP that were used in 1998 were (in percent) 33.6, 31.3, 80.1, and 10, respectively; the rest was disposed of in landfills, settling ponds, or by other means. Coal fly ash is used mainly as an additive in concrete; fly ash may also be used as structural fill, as road base material, in waste stabilization, or in mining applications. Bottom ash is used mainly as road base and structural fill material as well as in concrete and as grit for snow and ice control. Boiler slag is used mostly in blasting grit and roofing granules. FGD gypsum is used mainly in wall-board, with small amounts being used in concrete and agricultural applications. Figure 5 shows photographs of examples of some uses for fly ash and FGD gypsum.

There are other, perhaps less well known products that can be derived from coal. For example, sulfur oxides can be captured from flue gas and used to make sulfuric acid,

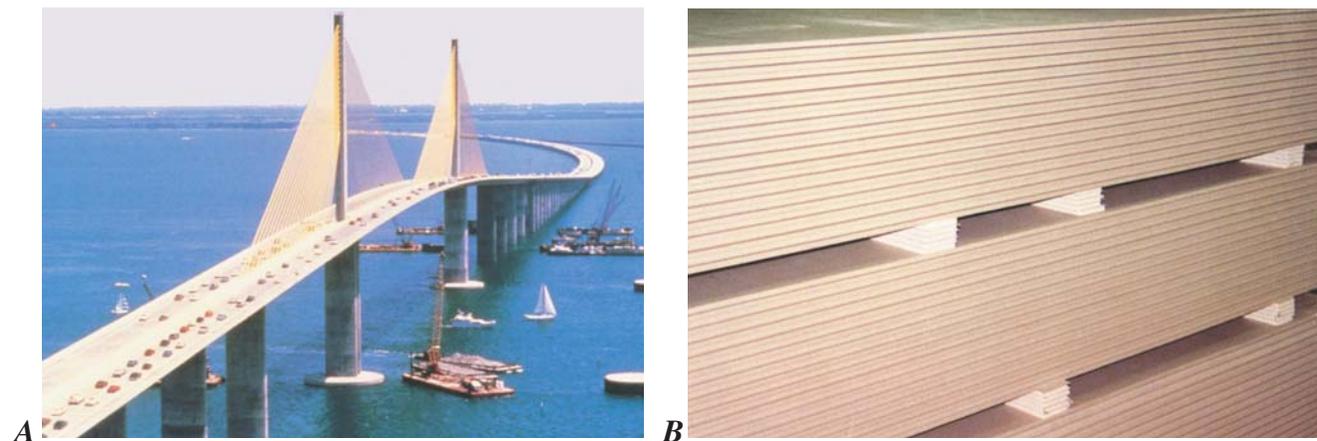


Figure 5. Photographs showing examples of the uses for coal combustion byproducts. *A*, Fly-ash concrete was used in the decking and piers of the Sunshine Skyway bridge over Tampa Bay in

Florida. *B*, The gypsum produced by wet scrubbers was used in the manufacture of high-quality wallboard. Photographs from American Coal Ash Association (1998), used with permission.



Figure 6. Photograph of the Okefenokee Swamp, Ga., which is a modern peat-forming swamp. Modern swamps are studied as possible analogs of ancient environments in which coal beds formed. The tall trees are mostly bald cypress with some bay and black gum, the foreground is mostly sedge and reed-like plants,

and the open-water areas contain water lilies. Common characteristics that modern swamps share with ancient swamps include low topography, fresh water, and varying climate. Photograph by W.H. Orem (U.S. Geological Survey).

which is an important industrial raw material. Other valuable elements, such as mercury and chlorine, also can be recovered from flue gas (Finkelman and Brown, 1991).

WHAT IS COAL?

ORIGINS

Coal begins as peat, which consists of loosely consolidated layers of various mixtures of plant and mineral matter. Peat accumulates in wetlands called “peat swamps,” “bogs,”

or “mires.” In this report, the term “peat swamp” is used to indicate a peat-forming wetland. Figure 6 is a photograph of the Okefenokee Swamp, which is a modern swamp where peat is forming. Peat swamps are wetlands that have the appropriate conditions for peat accumulation, such as abundant moisture, a stable to slowly sinking land surface, and protection from rapidly eroding forces such as rivers and ocean waves.

Over millions of years, burial, compression by overlying inorganic sediments, and the effects of heat (from depth in the earth or proximity to volcanic sources) cause peat to change to coal (fig. 7). The resultant coal is an extremely complex, mostly organic, generally well bedded sedimenta-

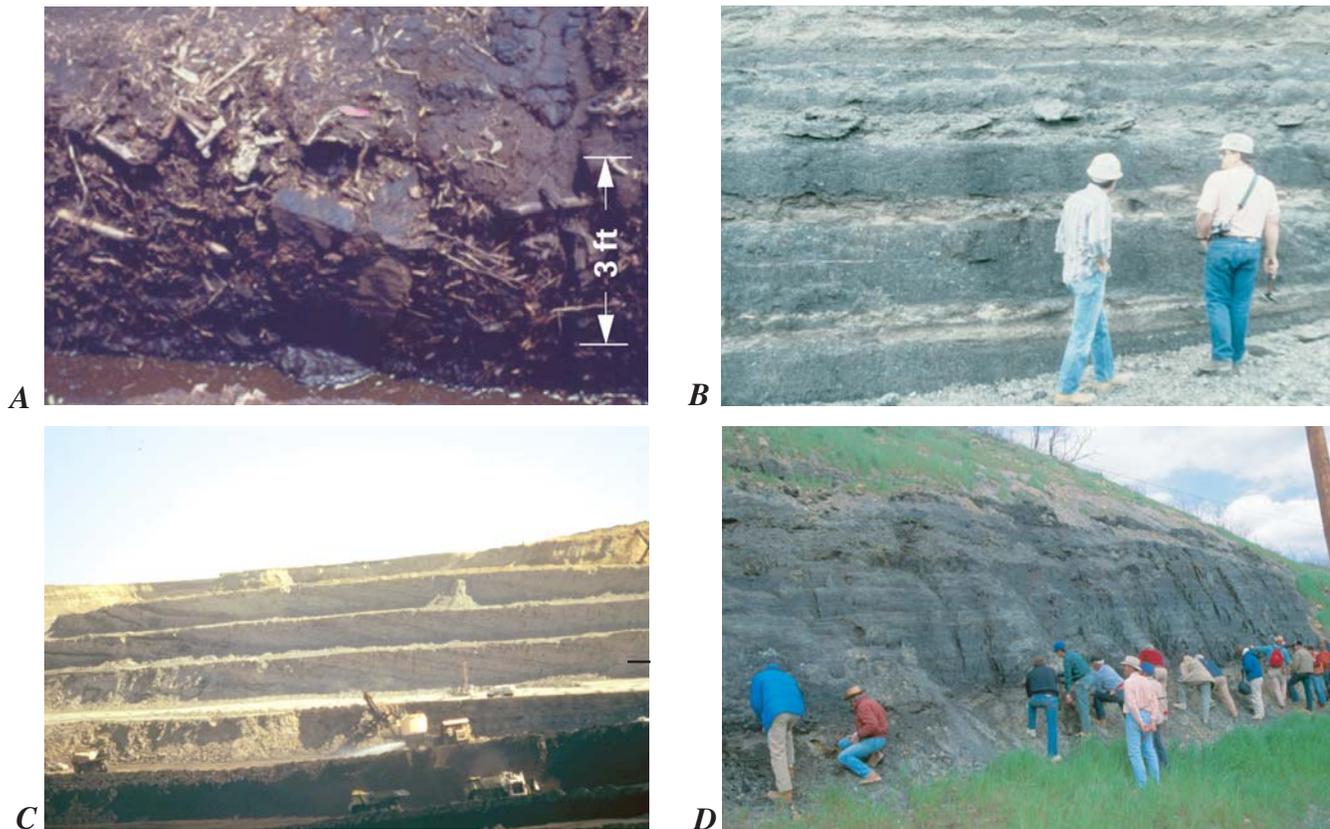


Figure 7. Photographs showing examples of peat and coal beds. *A*, Peat bed in Indonesia. The face is approximately 3 ft high. Note heterogeneous plant material in a finer groundmass of peat. At this location, the peat bed is approximately 20 ft thick and 5,000 yrs old at the base. Photograph by S.G. Neuzil (U.S. Geological Survey). *B*, San Miguel lignite beds of Eocene age in a coal strip mine in Texas. The individual beds of lignite (dark) are interspersed with beds of volcanic ash (lighter). The original peat has been compressed into a relatively homogeneous, evenly bedded material, but it still has a dull luster. Photograph by P.D. Warwick

(U.S. Geological Survey). *C*, Subbituminous coal strip mine in the Paleocene Anderson-Wyodak coal zone, Powder River basin, Wyoming. This bed is approximately 100 ft thick at this location, and is divided into two 50-ft-thick sections by the light-colored sedimentary rock parting above the power shovel. Photograph by P.D. Warwick (U.S. Geological Survey). *D*, Roadcut exposing the bituminous Pennsylvanian Pittsburgh coal bed, near Morgantown, W. Va. The normal lustrous, black appearance of this coal has been dulled by exposure to the weather. Photograph by C.B. Cecil (U.S. Geological Survey).

ry rock. To be classified as coal, the rock must contain less than 50 percent ash-forming mineral matter. If it contains between 30 and 50 percent mineral matter, it is classified as impure coal.

In the U.S., individual coal beds may be as thin as a few inches or (rarely) as thick as 200 ft and may cover areas as small as a few square yards or as large as several counties or even States; for example, the Pittsburgh coal bed extends over all or parts of 25 counties in the area where Ohio, Pennsylvania, and West Virginia join (see fig. 4). Figure 8 shows two examples from the Powder River basin in Wyoming of peat deposits in relation to laterally and vertically bounding sediments deposited by rivers. The deposits were subsequently buried and converted to lignite and coal.

COMPOSITION

Coal is composed of complex mixtures of organic and inorganic compounds. The organic compounds, inherited from the plants that live and die in the swamps, number in the millions. The approximately more than 120 inorganic compounds in coal either were introduced into the swamp from waterborne or windborne sediment, or were derived from elements in the original vegetation; for instance, inorganic compounds containing such elements as iron and zinc are needed by plants for healthy growth. After the plants decompose, the inorganic compounds remain in the resulting peat. Some of those elements combine to form discrete

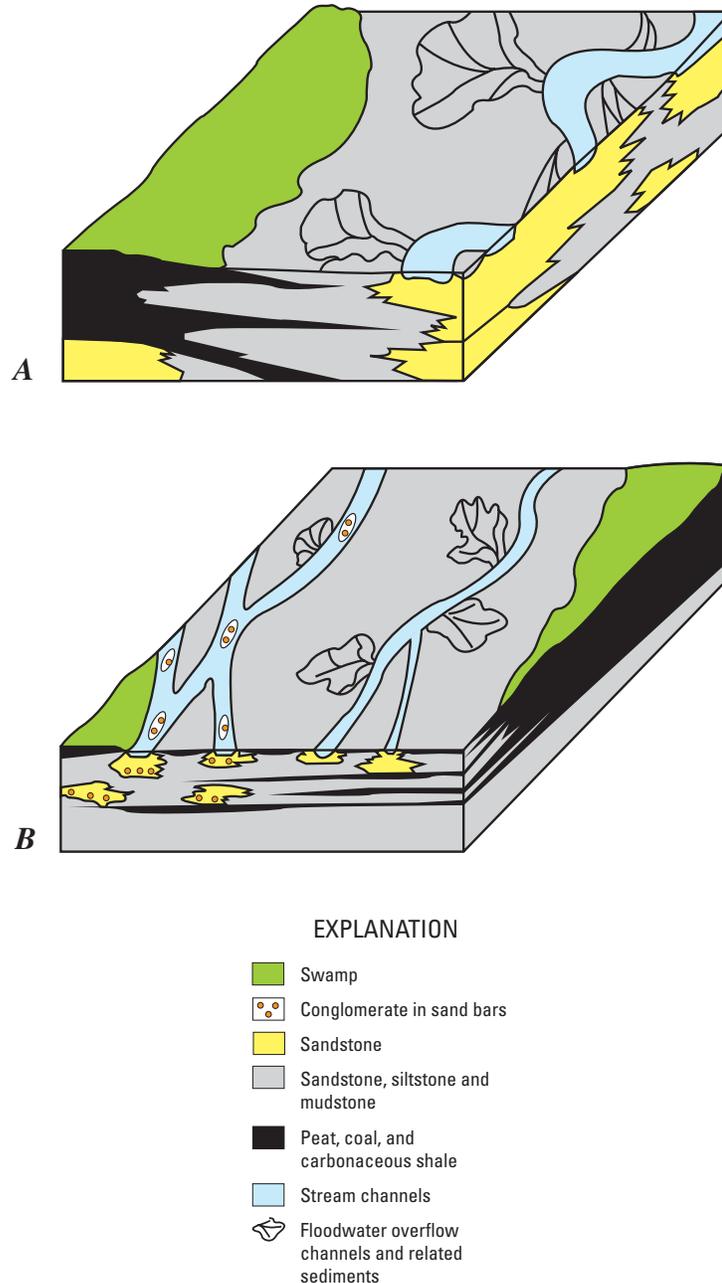


Figure 8. Block-diagram models illustrating some of the peat-sediment-climate relationships possible in the process of peat development and burial. These models explain the environments of deposition for two large coal deposits of Paleocene age in the Powder River basin of Wyoming. No specific scale implied, but the blocks represent general areas of approximately 9 to 25 mi², and depths of approximately 50 to 100 ft. **A**, Decker-Tongue River area. This peat deposit developed continuously in the same place because low areas, formed by faulting or compaction of underlying sediments, may have restricted the location of a meandering stream to the edge of the peat deposit. Also, the river system may have had a somewhat restricted sediment supply, or the river system may not have been vigorous enough to invade the peat swamp except at the margin. The climate probably was wet most of the year because the peat surface in the model is shown to be higher than the sur-

face of the stream valley. A wet climate promotes vigorous plant growth on top of the peat, which holds water like a sponge, allowing the peat to pile up above the surrounding area. The result is a large, thick, clean, coal deposit. **B**, Kaycee-Linch area. In this case, the river system apparently had a coarser and more abundant sediment supply and was more vigorous than in part **A**, as shown by the conglomerate bars in some of the stream channels, which are a sign of stronger current flow. This river system was able to move back and forth across the peat swamps, limiting the resulting deposits, in part, to thin, discontinuous beds. This environment appears also to have been wet, but a better supply of sediment and stronger stream flows limited peat preservation. Modified from Flores and others (1989), used with permission of the American Geophysical Union.

Table 1. Common minerals found in coal and their elemental compositions.

[Although more than 120 different minerals have been identified in coal samples, only about 33 of these occur in most coal samples; of these, only about 8 generally are abundant enough to be considered as major constituents. Data from R.B. Finkelman (U.S. Geological Survey, written commun., 2000).]

Mineral name	Chemical composition	Remarks
Major Mineral Constituents (In general order of abundance)		
Quartz	SiO ₂	
Clay Minerals:		
Kaolinite	Al ₂ Si ₂ O ₅ (OH) ₄	
Illite	KAl ₄ (AlSi ₇ O ₂₀)(OH) ₄	
Montmorillonite	($\frac{1}{2}$ Ca,Na) _{0.7} (Al,Mg,Fe) ₄ [(Si,Al) ₄ O ₁₀] ₂ (OH) ₄ ·nH ₂ O	
Chlorite	(Mg,Al,Fe) ₁₂ [(Si,Al) ₈ O ₂₀](OH) ₁₆	May have Mn. (Clays may also contain Be, Cr, Ni, and other trace elements.)
Pyrite	FeS ₂	May contain As, Cd, Co, Hg, Ni, Sb, and Se.
Calcite	CaCO ₃	
Siderite	FeCO ₃	May contain Mn.
Minor Mineral Constituents		
Analcime	NaAlSi ₂ O ₆ ·H ₂ O	
Apatite	Ca ₅ (PO ₄) ₃ (OH,F,Cl)	
Barite	BaSO ₄	
Chalcopyrite	CuFeS ₂	
Clausthalite	PbSe	
Crandallite Group		
Crandallite	CaAl ₃ (PO ₄) ₂ (OH) ₅ ·H ₂ O	
Florencite	CeAl ₃ (PO ₄) ₂ (OH) ₆	
Gorceixite	BaAl ₃ (PO ₄) ₂ (OH) ₅ ·H ₂ O	
Goyazite	SrAl ₃ (PO ₄) ₂ (OH) ₅ ·H ₂ O	
Dolomite	CaMg(CO ₃) ₂	
Feldspars	(Ca,K,Na)AlSi ₃ O ₈	
Galena	PbS	
Marcasite	FeS ₂	May contain same elements as pyrite.
Monazite	(Ce,La,Y,Th,Nd)PO ₄	
Rutile/Anatase	TiO ₂	
Sphalerite	ZnS	May contain Cd.
Xenotime	YPO ₄	
Zircon	Zr[SiO ₄]	
Trace Mineral Constituents		
Chromite	FeCr ₂ O ₄	
Gibbsite	Al(OH) ₃	
Gold	Au	
Gypsum	CaSO ₄ ·2H ₂ O	
Halite	NaCl	
Magnetite	Fe ₃ O ₄	
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(OH) ₂	

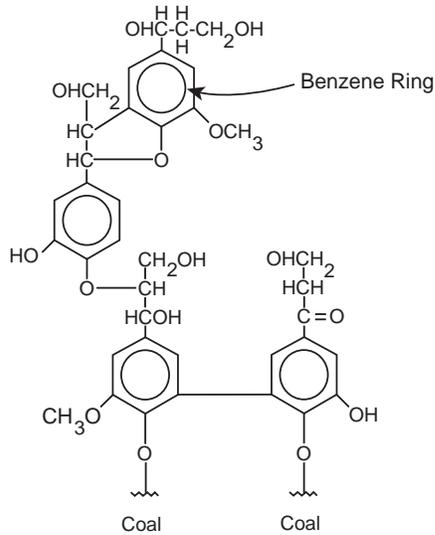


Figure 10. Diagram showing hypothetical structure of a lignin-derived organic molecule in a brown coal (lignite). This structure is based on studies using carbon-13 nuclear-magnetic-resonance (^{13}C NMR) spectroscopy and other organic-geochemical methods such as those described in table 2. Lignin is one of the constituents of woody tissue found in all vascular plants, such as trees and shrubs (W.H. Orem, U.S. Geological Survey, written commun., 1997). Studying organic matter helps provide information about the plant sources of coal and, subsequently, coal quality. See figure 9 for chemical elements.

minerals, such as pyrite. Other sources of inorganic compounds used by the plants may be either the mud that coats the bottom of the swamp, sediments introduced by drainage runoff, dissolved elements in the swamp water, windborne sand, ash, or dust.

Coals may contain as many as 76 of the 92 naturally occurring elements of the periodic table (fig. 9); however, most of those elements usually are present in only trace amounts on the order of parts per million. Occasionally, some trace elements may be concentrated in a specific coal bed, which may make that bed a valuable resource for those elements (such as silver, zinc, or germanium) (Finkelman and Brown, 1991). Some elements, however, have the potential to be hazardous (for example, cadmium or selenium), particularly if they are concentrated in more than trace amounts. Although as many as 120 different minerals have been identified in coal, only about 33 of them commonly are found in coal, and of these, only about 8 (quartz, kaolinite, illite, montmorillonite, chlorite, pyrite, calcite, and siderite) are abundant enough to be considered major constituents (table 1).

The organic compounds in coal are composed of the elements carbon, hydrogen, oxygen, nitrogen, sulfur, and trace amounts of a variety of other elements. Although only a few elements compose the organic compounds found in coal, these compounds are extremely complex and, as a

result, they are not well understood; for example, an attempt to define the structure of just one organic compound in a brown coal (lignite) is shown in figure 10, but even this relatively simple structure is based on scientific conjecture. The organic compounds in coal produce heat when coal is burned; they also may be converted to synthetic fuels, or may be used to produce the organic chemicals shown in the centerfold illustration.

The affinities of trace elements for either the organic compounds or the minerals in coal affect the quality of the coal. If trace elements are organically bound, then it is difficult to remove them from the coal by cleaning processes, such as crushing and washing, which remove mineral matter from coal before it is burned. Organically bound trace elements may be released only by burning, or by deep chemical leaching, which is both very difficult and uneconomical. In contrast, trace elements associated with clays or pyrite may be largely removed from the coal by cleaning processes. The trace elements then may be disposed of in an environmentally safe manner or recovered and put to some other use. To date, however, the recovered mineral matter from coal has not been used for very many purposes, with a few major exceptions such as gypsum, the various forms of ash, and a small amount of germanium (used in semiconductors).

Coal may contain as many as 76 of the 92 naturally occurring elements of the periodic table.

MINERALS IN COAL

The most common minerals in coal (for example, illite clay, pyrite, quartz, and calcite) are made up of these most common elements (in rough order of decreasing abundance): oxygen, aluminum, silicon, iron, sulfur, and calcium. These minerals and other less common minerals usually contain the bulk of the trace elements present in coal (table 1). Minerals in coal commonly occur as single crystals or clusters of crystals that are intermixed with organic matter or that fill void spaces in the coal; sizes of mineral grains range from submicroscopic to a few inches. Some clusters of mineral grains, however, such as fracture fillings (fig. 11) or coal balls (fig. 12), may reach sizes that range from fractions of an inch up to several feet across. Coal balls result when mineral matter (such as calcite, pyrite, or siderite) infuses peat before it is compressed. Mineral grains in coal also often occur as discrete particles, such as the blebs of pyrite (framboids), which may be identified in the photomicrographs of coal in figure 13. The more finely divided the mineral grains, the higher the magnification needed to identify them (figs. 13, 14).

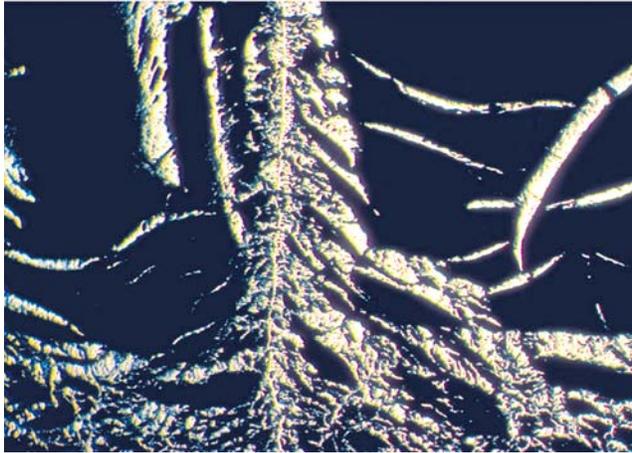


Figure 11. Photomicrograph of pyrite (yellow) filling fractures in the Upper Freeport coal bed in Pennsylvania. Magnification approximately $\times 4000$. From Atlas of Coal Geology, American Association of Petroleum Geologists (AAPG) Studies in Geology No. 45 (Papp and others, 1998); AAPG copyright 1998, reprinted by permission of the AAPG, whose permission is required for further use.

Although much is known about the minerals in coal, much remains to be learned about their occurrence, abundance, origin, and composition. For example, the type of clay mineral in a coal, whether montmorillonite or illite, determines how a coal will react when burned. Montmorillonite (table 1) may or may not break down (dissociate) into its constituent parts when coal is burned; if it does dissociate, then, upon cooling, it may recombine with other elements or minerals to form mineral deposits on the inside surfaces of furnaces and boilers (fig. 15). This process (called “slagging” or “fouling”) produces barriers to heat exchange in the affected equipment, which can substantially reduce its efficiency and require costly repairs. Illite (table 1), however, with its simpler composition, does not cause such problems under normal furnace operating conditions. Where these two clay minerals and others occur, their relative abundances, relationships to

The mineral content of coal determines what kind of ash will be produced, which in turn determines the design of a furnace or boiler.

other minerals, and exact compositions are subjects for continued research in coal quality.

When coal is burned, most of the mineral matter and trace elements generally form ash; however, some minerals break down into gaseous compounds which go out the furnace’s flue. Pyrite, for example, breaks down into the indi-

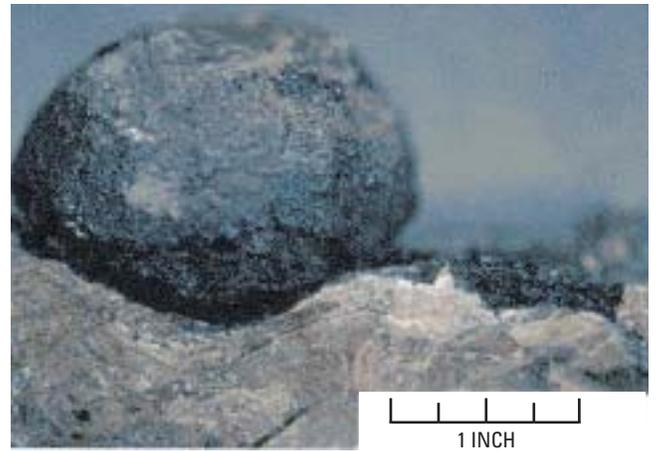


Figure 12. Photograph of small coal ball specimen from the Carbondale Formation, Illinois basin. Coal balls are concretions that occur within coal beds and are composed largely of carbonate minerals and occasionally of pyrite. Modified from a photograph by James Humphrey (Curragh Queensland Mining Ltd., Australia) in Atlas of Coal Geology, American Association of Petroleum Geologists (AAPG) Studies in Geology No. 45 (Papp and others, 1998); AAPG copyright 1998, reprinted by permission of the AAPG, whose permission is required for further use.

vidual elements iron and sulfur. Each element then combines with oxygen to become, respectively, iron oxide and SO_x . Iron oxide, a heavy solid, becomes part of the ash and SO_x , a gas, is emitted as part of the flue gas. Some trace elements also dissociate from their organic or mineral hosts when coal is burned and follow separate paths. Most become part of the ash, but a few of the more volatile elements, such as mercury and selenium, may be emitted in the flue gas.

The mineral content of coal determines what kind of ash will be produced when it is burned. The fusion temperature (melting point) of the ash dictates the design of furnaces and boilers. In general, if the fusion temperature is relatively low, then the molten ash is collected at the bottom of the furnace as bottom ash, requiring one design; however, if the fusion temperature is relatively high, then the part of the ash that doesn’t melt easily, called “fly ash,” is blown through the furnace or boiler with the flue gas and is collected in giant filter bags, or electrostatic precipitators, at the bottom of the flue stack, requiring a different design. Coals that are relatively rich in iron-bearing minerals (such as pyrite or siderite) have low fusion temperatures while coals relatively rich in aluminum-bearing minerals (such as kaolinite or illite) tend to have high fusion temperatures. If an electric generating or heating plant is designed to burn one type of coal, then it must continue to be supplied with a similar coal or undergo an extensive and costly redesign in order to adapt to a different type of coal. Similarly, furnaces designed to use coal that produces high amounts of heat will suffer severe losses in efficiency if they must accept coal that burns with substantially less heat.

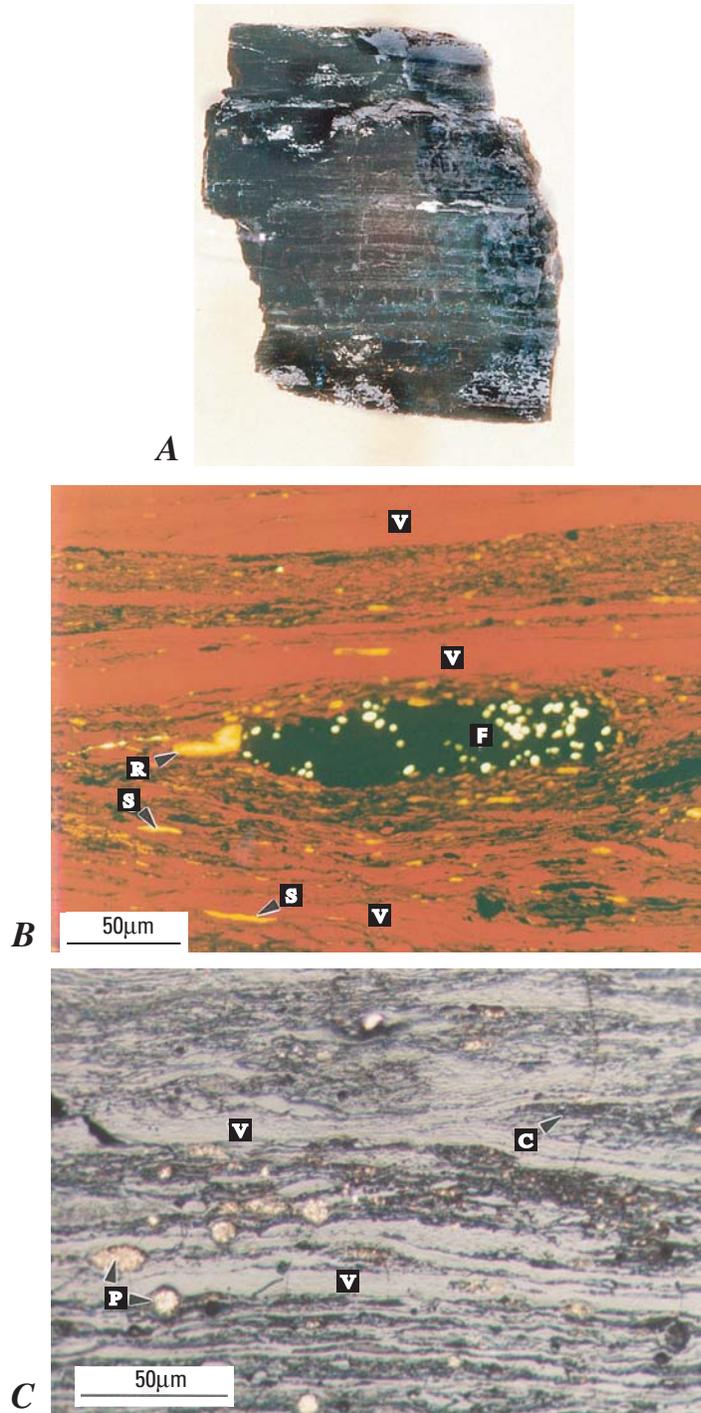


Figure 13. Photograph and photomicrographs of Pennsylvanian bituminous coal. *A*, Photograph of a lump of bituminous coal from Pennsylvania showing typical banding caused by layering of a variety of preserved plant types as they accumulated in an ancestral peat swamp. Magnification $\times 0.55$. *B*, Photomicrograph of a thin section of a small piece of bituminous coal from Illinois photographed in transmitted light. Magnification approximately $\times 330$. *C*, Photomicrograph of a polished surface of a small piece of bituminous coal from Pennsylvania photographed in reflected light. Magnification approximately $\times 250$. Parts *B* and *C* show some typical constituents—macerals (plant remains) and minerals—found

in bituminous coals. Macerals are abbreviated as follows: V, vitrinite; F, fusinite; S, sporinite; and R, resinite. Minerals are abbreviated as follows: P, pyrite; and C, clay-sized minerals. The scale bar on parts *B* and *C* is 50 micrometers, which is equivalent to about 0.002 inch. The lump of bituminous coal is included to provide a comparison between what can be seen in a lump of coal and the wealth of detail in coal that can be seen with high magnification. The lump of coal is approximately 260 times larger than the chips of coal represented by either of the photomicrographs. Photographs and photomicrographs by R.W. Stanton (U.S. Geological Survey).

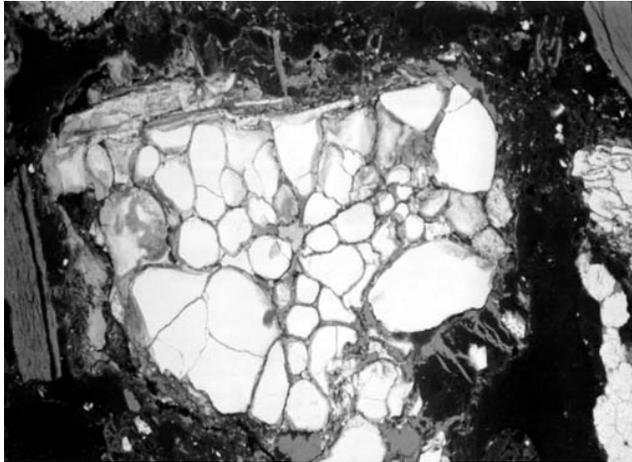
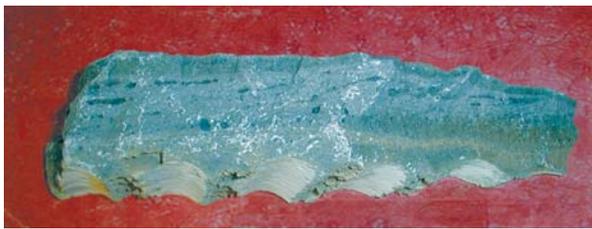


Figure 14. Scanning-electron microscope photomicrograph of a fragment of pyrite infilling plant cells in coal. Bright areas are pyrite, gray areas are organic cell walls, and black area is epoxy mounting media. Sample is from a bituminous coal from Pennsylvania. Magnification approximately $\times 1000$. Modified from a photomicrograph by L.F. Ruppert (U.S. Geological Survey).



A



B

Figure 15. Photographs of mineral deposits (“slagging and fouling”) on boiler pipes. **A**, Slag deposits forming on tubes in platen area of a coal-fired boiler at Alliant Energy WP&L, Columbia Energy Center Unit 1, Portage, Wisc. Tubes are about 1.75 inches in diameter. **B**, Ash deposit removed from steam tubes in a coal-fired boiler at an AmerenUE plant using subbituminous coal from the Powder River Basin, Wyoming. The plant was originally designed to use bituminous coal. Ash fragment is approximately 12 inches long by 5 inches wide by 3 inches tall at its tallest point. This deposit was removed by explosive cleaning. Photographs by C.J. Zygarlicke (University of North Dakota Energy and Environmental Research Center, Grand Forks, N.D.); used with permission of Alliant Energy, Portage, Wisc. (A), and AmerenUE, St. Louis, Mo. (B).

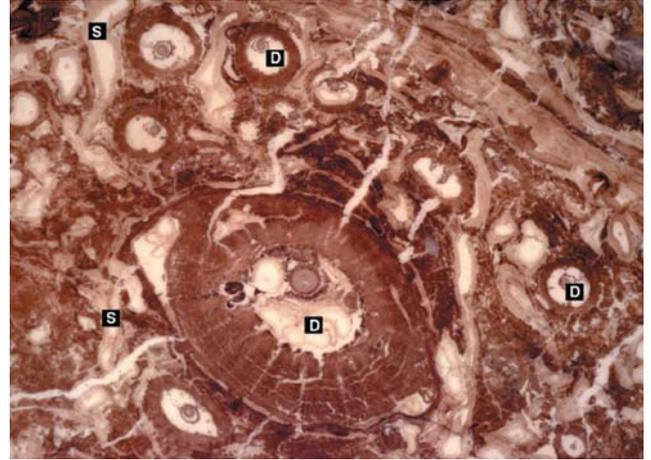


Figure 16. Photograph of a cross section of a calcareous coal ball from the Middle Pennsylvanian Murphysboro coal bed equivalent, Indiana. The coal ball contains permineralized plant material that enables scientists to identify the individual plants and the plant communities (flora) that contributed to the peat, which later became a coal bed. The coal ball contains some identifiable remains of branches and twigs of lycosid trees (*Diaphorodendron vasculare*), labeled D on the photograph. The structures, labeled S, are sections of lycosid rootlets, called stigmata. Compare these structures with the shapes of the macerals in the photomicrographs of coal (fig. 13). Modified from a photograph by W.A. DiMichele (National Museum of Natural History, Smithsonian Institution, Washington, D.C.).

MACERALS

The particles of organic matter in coal, inherited from the remains of plant parts, are called “macerals.” Many different types of macerals occur in coal; a few of the more common macerals are identified in the photomicrographs of a bituminous coal from Illinois (fig. 13). The identification of the original plant and its parts (such as bark, roots, spores, or seeds) that produced an individual coal maceral is helpful in determining coal quality. These connections usually are difficult to make because the original plant material has been compressed or altered beyond recognition. Coal balls (fig. 12) result when mineral matter (such as calcite, pyrite, or siderite) infuses peat before it is compressed. Coal balls often contain permineralized plant materials that have maintained their original structures because the mineral matter has prevented compression and degradation of the plants (fig. 16). Coal balls, therefore, can be used as an aid in connecting the degraded, compressed plant matter of a coal bed to the original plants.

Macerals are grouped into three main types: (1) vitrinite, (2) liptinite, and (3) inertinite. Liptinite and inertinite each contain additional maceral subtypes (American Association of Petroleum Geologists, 1998); however, in

this report, just the principal maceral types will be discussed with brief referral to some of the subtypes for illustrative purposes. Vitrinite, which is the most common maceral, results from the coalification of amorphous humic plant material (structureless plant remains). Vitrinite, sometimes called pure coal, is sensitive to heat and becomes denser, tougher, and more vitreous as it is subjected to higher heat levels, either with depth in the earth, or by proximity to an external heat source, such as a volcano. An index of vitrinite reflectance is used by coal scientists to determine the level of heat, or maturity, to which coals and other organic matter, such as petroleum, have been subjected.

Liptinite develops from waxy or oily plant parts such as spores, algae, and resin; the liptinite group contains several subgroups based on these original plant parts—sporinite, alginite, and resinite, respectively. Liptinite macerals are more enriched in hydrogen than either vitrinite or fusinite; liptinite-rich coals produce larger amounts and higher grades of liquid fuel when subjected to destructive distillation than either vitrinite- or fusinite-rich coals. Some coals, called “bog-head” or “cannel” coals consist almost entirely of oil-rich algal and plant spore material. These coals tend to yield large amounts of coal oil (kerosene) when subjected to destructive distillation because the macerals are rich in oily material. However, both cannel and bog-head coals are relatively rare.

Inertinite incorporates a group of common macerals that forms from partially oxidized or burned plant cell walls. Fusinite, or mineral charcoal, is a prominent representative of this group. Mineral charcoal is produced when, occasionally and sometimes seasonally, the surface layers of a peat swamp dry out and some surface peat either slowly oxidizes or catches fire, or some growing plants are partially charred. (The common and naturally occurring fires of the Florida Everglades are modern examples of this process.)

Coals can range in maceral composition from mostly vitrinite to mostly fusinite, depending on the original plant matter and the degree of preservation. Vitrinite-rich coals are shiny black, clean, fractured conchoidally, and often exhibit iridescence (called “peacock coal”) on fresh surfaces. Fusinite-rich coals, in contrast, are similar to charcoal and are dull, black, friable, and dusty. For more information on macerals and vitrinite reflectance see the subsection on “Coal Quality” in the “Further Readings” section.

COAL RANK

A major factor in determining coal quality is coal rank. Rank refers to steps in a slow, natural process called “coalification,” during which buried plant matter changes into an ever denser, drier, more carbon rich, and harder material. The major coal ranks, from lowest to highest, are lignite (also called “brown coal” in some parts of the world),

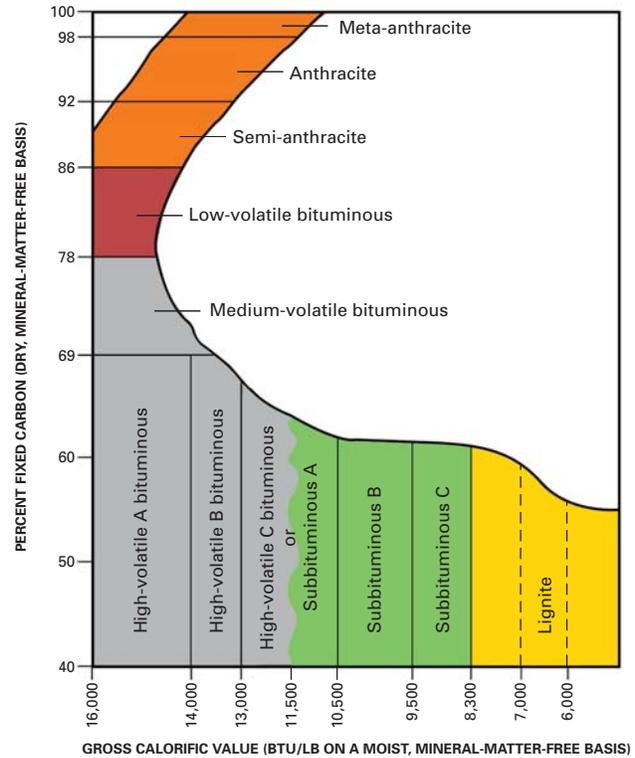


Figure 17. Diagram showing classification of coals by rank in the U.S. Rank is a measure of the progressive alteration in the series from lignite to anthracite. Higher rank coals are generally harder, contain less moisture and volatile matter, and have higher calorific values. Modified from Trumbull (1960). For a more detailed explanation of coal rank determination, see ASTM International (2002).

subbituminous coal, bituminous coal, and anthracite. Each rank may be further subdivided, as shown in figure 17. The rank of coal is determined by the percentage of fixed carbon, moisture (water), volatile matter, and calorific value in British thermal units (Btu) after the sulfur and mineral-matter content have been subtracted. Fixed carbon is solid, combustible matter left in coal after the lighter, volatile, hydrogen-rich compounds are driven off during coalification. Volatile matter is slowly removed from coal during coalification, but may be rapidly removed during destructive distillation. Volatile matter contains the raw materials from which the organic chemicals are obtained. In the U.S., the tests to determine the amounts of the above-mentioned substances and the rank of the coal are performed using standards published by ASTM International (2002).

In general, the higher the rank of a coal, the more deeply it was buried, and, therefore, the higher the temperature it was subjected to during and after burial. Older coals tend to be of higher rank because they are more likely to have been buried more deeply for longer periods of time than younger coals. To give a sense of the effects of increasing rank, the following comparison may be used: lignite is

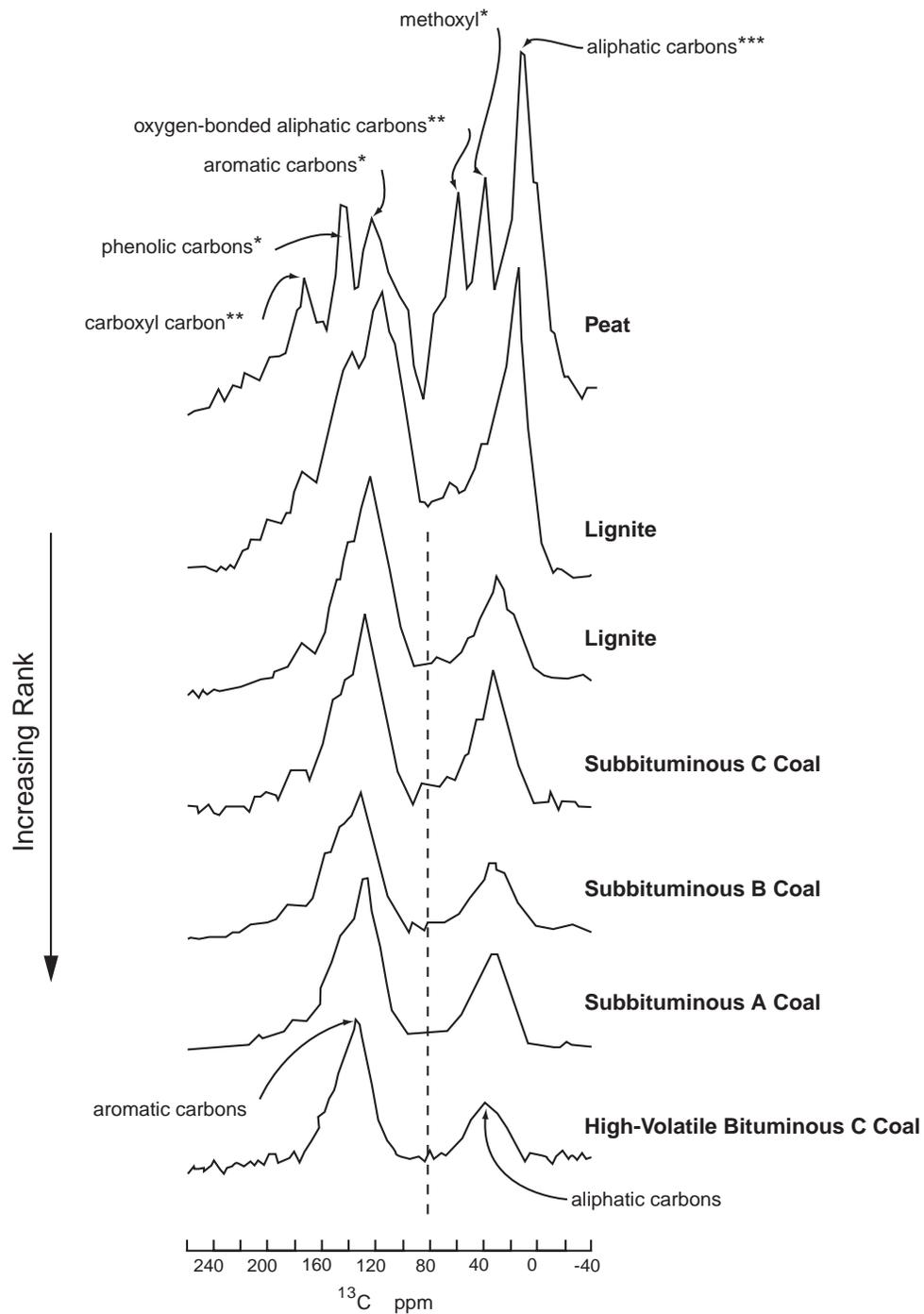


Figure 18. Carbon-13 nuclear-magnetic-resonance (^{13}C NMR) spectra of coals of increasing rank (see figure 17); ^{13}C is a stable isotope of carbon. Diagram shows changes in certain organic compounds brought about by increased coalification. The peaks represent varieties of organic compounds. As rank increases, the variety of compounds decreases and the remaining compounds become structurally tighter and denser. The compounds lost are those that are high in hydrogen and oxygen. Peaks marked with a single asterisk are lignin (woody tissue) indicators; those marked with a double asterisk represent carbohydrates (sugars); and those

marked with a triple asterisk represent aliphatic substances (such as waxes and resins). The diagram shows that the carbohydrates are eliminated early in the coalification process, whereas the lignins, waxes, and resins persist to become the principal constituents of higher ranked coals. The scale at the bottom of the figure is a standard ^{13}C NMR scale in ppm (parts per million) representing distance, in frequency units, from a standard, which is assigned a position of zero on the scale. The position of peaks is used to interpret the chemical structure of the substance being analyzed, in this case coal. Data from W.H. Orem (U.S. Geological Survey).

Centerfold. Coal byproducts in tree form showing basic chemicals as branches and derivative substances as twigs and leaves. The basic chemicals may be obtained from coal through heating in a closed container (destructive distillation); the derivatives require additional processing of those basic materials. One ton of bituminous coal roasted in an airtight oven (destructive distillation) produces approximately 1,300 to 1,500 pounds of coke, 8 to 10 gallons of coal tar, 3 gallons of light oil, 5 to 6 pounds of ammonia, and 9,500 to 11,000 cubic feet of gas. Modified from an undated public domain illustration provided by the Virginia Surface Mining and Reclamation Association, Inc. Norton, Va.

Schweinfurth, S.P., 2003, Coal—A complex natural resource; an overview of factors affecting coal quality and use in the United States: U.S. Geological Survey Circular 1143, 43 p.

Eon	Era	Period	Epoch	Millions of Years Ago
Phanerozoic	Cenozoic	Quaternary	Holocene Pleistocene	1.6
		Tertiary	Pliocene Miocene Oligocene Eocene Paleocene	
	Mesozoic	Cretaceous	Late Early	66
		Jurassic	Late Middle Early	138
		Triassic	Late Middle Early	205
	Paleozoic	Permian	Late Early	240
		Pennsylvanian	Late Middle Early	290
		Mississippian	Late Early	330
		Devonian	Late Middle Early	360
		Silurian	Late Middle Early	410
		Ordovician	Late Middle Early	435
		Cambrian	Late Middle Early	500
	Proterozoic	Late Proterozoic Middle Proterozoic Early Proterozoic		570
	Archean	Late Archean Middle Archean Early Archean		2,500
	pre-Archean			

Figure 19. Chart showing divisions of geologic time (ages are approximate). Since the Mississippian Period, major coal deposits have formed some place in the world except during the most recent period (Quaternary); however, major peat deposits formed (and

are still forming) during the Quaternary and it is possible that there may be Quaternary lignite deposits as well. Periods of major coal deposits in the U.S. are shaded.



Figure 20. Photograph of an in-situ fossilized tree base and root system in the roof of an underground coal mine. The coal bed being mined is in the Cretaceous Blackhawk Formation, Wasatch Plateau coal field near Huntington, Utah. Note the radiating root network. Photograph by Alex Papp (ARCO Coal Company, Denver, Colo.) in Atlas of Coal Geology, American Association of Petroleum Geologists (AAPG) Studies in Geology No. 45 (Papp and others, 1998); AAPG copyright 1998, reprinted by permission of the AAPG, whose permission is required for further use.

soft, dusty, and can ignite spontaneously under the appropriate conditions, whereas anthracite is quite hard, clean to the touch, and must reach a temperature of about 925° F before it will ignite. Furthermore, anthracite contains about twice the calorific value of lignite (about 15,000 Btu/lb and 7,000 Btu/lb, respectively) because lignite contains more moisture and oxygen and less fixed carbon than anthracite. Subbituminous and high-volatile bituminous C coals have oxygen and moisture content and calorific values that range between those of lignite and anthracite. Bituminous coals of higher rank have calorific values that may exceed those of anthracite (fig. 17). Figure 18 shows nuclear-magnetic-resonance (^{13}C NMR) spectra of coals of increasing rank, illustrating the changes in the organic structures as coal progresses through stages of increasing rank.

WHY IS COAL SO COMPLEX?

Coal is complex because of the wide variety of factors that determine the quality of coal. These factors include the following: (1) the plants, plant remains, and other organisms (such as bacteria) in the peat swamp; (2) biological and chemical processes, and the degree of preservation of the plant matter; (3) the geometry and location of the swamp; (4) the mineral matter that accumulated with the plant material, or was introduced at some later stage; and (5) coalification. Geologic age and history will be a recurring theme

throughout this discussion. Figure 19 shows the times in geologic history when coal beds formed.

THE PLANTS

Coal begins as peat, which forms in swamps having favorable conditions as explained in a previous section entitled “Origins.” These swamps, which are generally filled with standing or slowly moving water, are ideal places for prolific plant growth. When plants fall into the swamp, water covers them and slows or prevents rapid decomposition. Slow decomposition and a quiet environment allow plant matter to accumulate and form peat. The organic matter composing the peat may accumulate in place or, less commonly, may be carried by flowing water to accumulate elsewhere, but generally nearby. Most coal beds were formed from plant material that accumulated in place (fig. 20).

Coal is a complex material formed by a mix of substances and processes. The substances are plant remains and mineral matter. The processes aren't completely understood, but involve chemical and biological reactions, heat, burial, and time.

Plant communities (flora) in peat swamps may consist of many plant types, or of only a few. Swamp flora have changed substantially through geologic time because of evolution. For instance, lycopsids and tree ferns (fig. 21) are found in older coal beds; more modern forms, such as rushes, water lilies, mangrove, and bald cypress trees (shown in figure 6) may be found in younger coal beds. Flora of the Cretaceous Period (fig. 22) included abundant species that contained relatively more resinous substances than those of the much earlier Pennsylvanian Period. Tertiary plants generally were woodier than those of either the Pennsylvanian or the Cretaceous Periods. In addition, floral communities varied from location to location even within the same time period. These changes in plant species resulted in small changes in nutrient requirements. The result is that geologically younger coals may have different mineral matter compositions than older coals.

BIOLOGICAL AND CHEMICAL PROCESSES

Once plant debris has been deposited in a peat swamp, it is subjected to degradation and decomposition by micro-

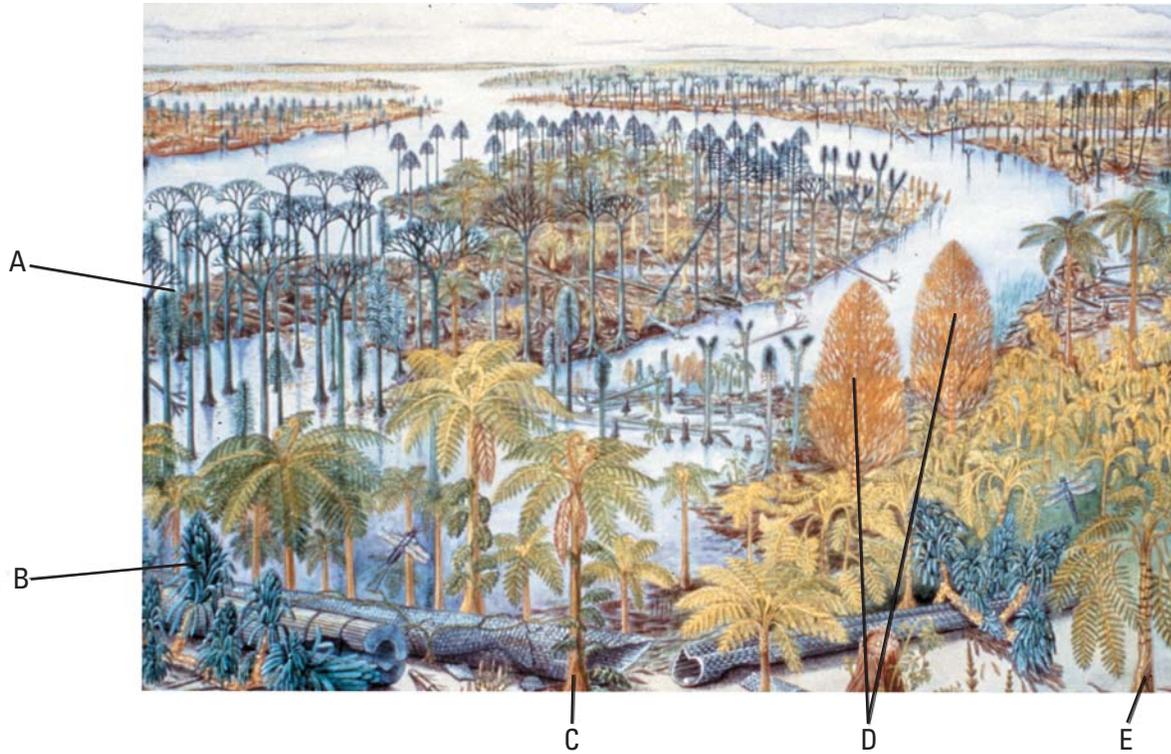


Figure 21. Reconstruction of a tropical peat swamp of Middle Pennsylvanian age (about 300 million years ago). The taller plants (A) were tree lycopsids (*Lepidophloios*), some of which grew to heights of 80 to 100 ft. Today, the lycopsids are represented by lowly club mosses. Other plants include cordaites (B), which were seed plants with strap-shaped leaves that are now extinct; tree ferns (C), which still live in warm, damp areas; calamites (D), which is a tree-size scouring rush; and pteridosperms (E), which

were seed plants with fernlike leaves that are now extinct. The tree-like scouring rushes, which reached heights of 30 to 50 ft, are represented today by plants that grow in damp, but not necessarily warm, areas usually to only a few feet in height. From an illustration by Alice Prickett in *GSA Today* (Gastaldo and others, 1996, fig. 1); Geological Society of America (GSA), copyright 1996, reproduced with permission of the GSA (Boulder, Colo.), whose permission is required for further use.

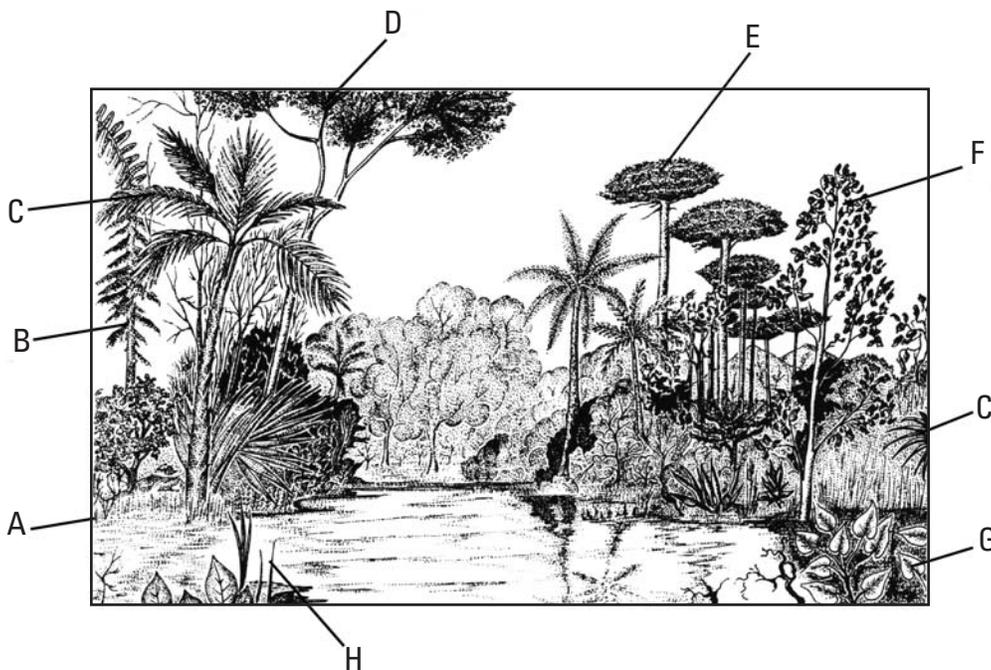
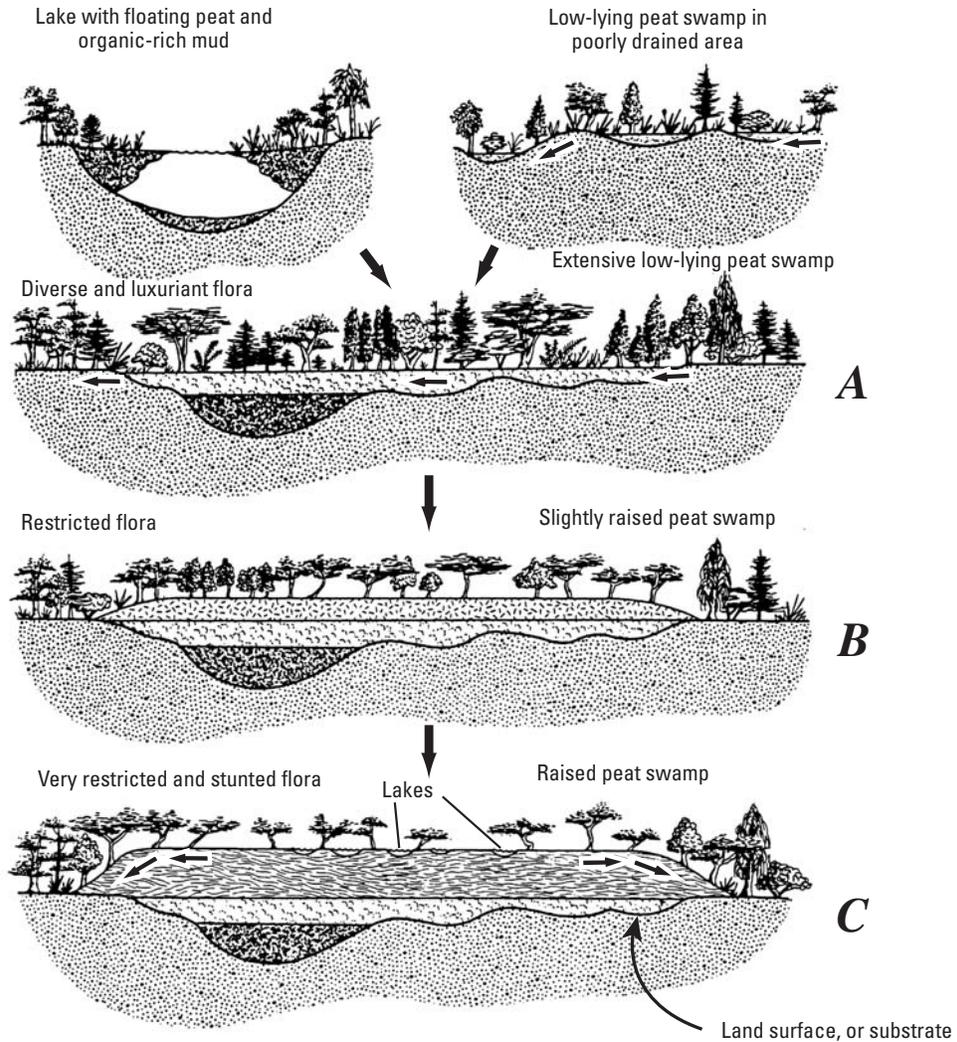


Figure 22. Reconstruction of a peat-forming, fluvial coal swamp and peripheral, bottom-land vegetation of Late Cretaceous age (about 70 million years ago) in what is now eastern Utah. Representative plants are as follows: A, horse-tail rush; B, sequoia; C, palm; D, *Rhamnites*, now extinct; E, *Araucaria*, now extinct; F, sycamore; G, fig; and H, cattail. Plants were growing on the banks of the swamp. Modified from Tidwell (1998, figure 37), used with permission of the author.



EXPLANATION

-  Earth material
-  Organic-rich mud
-  Planar (topogenous) peat
-  Domed (ombrogenous) peat
-  Water flow

Figure 23. Sketches illustrating a possible evolution from a planar (topogenous) peat deposit to a domed (ombrogenous) peat deposit. **A**, planar; **B**, transitional, slightly domed; and **C**, domed. A planar deposit may evolve into a transitional or domed deposit if climatic conditions change; the two types of peat deposits also may occur independently. No scale implied, but the horizontal dimension could be many miles and the ver-

tical dimension could be 500 to 1,000 ft. Individual plant types were not identified in the source for this figure, but a typical flora might include cypress, magnolia, and willow trees; sassafras, sumac, and witch hazel shrubs; and ferns, reeds, and lilies as low-growing and water plants. Modified from McCabe (1987), used with permission of The Geological Society (London).

bial action, oxidation, and biogeochemical processes. These processes are pervasive and, to a large extent, determine the character of any resultant coal. The processes, which operate on microbiological and microchemical levels, are constantly changing and, therefore, are difficult to characterize. What is known is that (1) the degradation processes are carried out by oxygen from the atmosphere and various microorganisms, such as bacteria and fungi; and (2) the processes are moderated by the acidity or alkalinity of the available water. When the oxygen in the peat has been depleted, anaerobic bacteria (such as those responsible for fermentation) continue the process of degradation. Although pervasive, the process of plant decomposition is also selective in that different plant parts degrade at different rates. The most resistant parts, such as bark, cuticle, spores, lignin-rich wood, and charcoal (fusinized peat), are the parts most often retained in coal as macerals.

When standing water covers fallen plant matter, atmospheric oxidation is halted; soon thereafter, biochemical change slows to a virtual halt. Once plant matter is converted to peat and is buried, further substantial changes depend more on increases in temperature and pressure than on oxidation and biochemical processes. The acidity or alkalinity of peat swamp water may also control the rate and amount of change that takes place. Usually, the more acidic the water, the more plant matter is preserved because bacterial activity is reduced. If their work is carried to completion, bacteria and fungi produce CO₂, water, and ash; in effect, it is a slow-burning process.

SWAMP GEOMETRY, LOCATION, AND CLIMATE

From the late Paleozoic to the present, two principal types of peat swamps have existed: planar (topogenous) and domed (ombrogenous) (fig. 23). Each has unique floral characteristics that affect the quality of the resulting coal.

The planar peat swamp generally develops in areas of seasonal rainfall, mainly in low-lying areas, and depends on a high ground-water table for its continued existence. The resulting peat deposit often has an undulating bottom and a flat top. Because it forms in low-lying areas, the planar swamp is subject to periodic flooding, which results in the introduction of extraneous mineral matter such as clay, silt, and sand. This sediment brings in nutrients, but may also add impurities to any resulting coal; in extreme cases, the sediment may bury the swamp, which results in the termination of peat formation.

The domed peat swamp develops in areas that receive substantial rainfall during most of the year. In this environment, new plants grow above fallen plants, which decay very slowly because the swamp, like a sponge, remains saturated with water. This process gradually allows the top of the swamp to rise above the surrounding topography. The result is a peat deposit that has a raised, or domed, surface.



Figure 24. Photograph of a coal strip-mine highwall exposure of a thick lens-shaped parting, possibly a floodwater overflow (see fig. 9) in the Upper Freeport coal bed, central Appalachian basin. Photograph by Mark Scanlon (Canyon Fuel Co., LLC, Price, Utah) in Atlas of Coal Geology, American Association of Petroleum Geologists (AAPG) Studies in Geology No. 45 (Papp and others, 1998); AAPG copyright 1998, reprinted by permission of the AAPG, whose permission is required for further use.

The dome prevents or limits the extent of flooding of the swamp and thereby prevents the introduction of mud, silt, and sand, except around the fringes. New plants depend on dead ones for their nutrients, thus depleting the earlier deposited peat of mineral matter. The flora become stunted and restricted to plants that can survive in a mineral-poor, acidic soil. As a result, domed peat tends to contain much less mineral matter than planar peat and the resulting coals are purer.

A peat deposit may have originated as either the planar or the domed type and then, due to a change in the climate or topography or both, may transform into the other type and even back again (fig. 23). The resulting coal beds may be composites of the two types. These conditions make determining the quality of the composite coal beds difficult.

The geographic location and climate of the precursor peat swamp also affect coal quality. At present, swamps are located in tropical, temperate, and cool climates, near coastlines and inland, beside rivers and within river deltas, and in upland areas. This wide variety of geographic locations and climates in which swamps develop was most likely the case at least as far back as the Devonian Period (fig. 19).

Peat swamps located close to rivers or within river deltas suffer the possibility of periodic flooding and the introduction of large amounts of mineral matter. Swamps along coastlines, while not as easily subjected to river flooding, may be affected by offshore or coastal storms that wash sediment over offshore bars and beaches into the swamps behind them. The added mineral matter may be disseminated in the peat, may occur as layers in the peat, or may cause peat formation to stop. Discrete layers of mineral matter in coal beds are called “partings” (fig. 24).

Climate, which to some extent depends on geography, affects the growing season and the amount of rainfall that a swamp receives and, therefore, helps determine the kind of peat that will eventually form. Thick, extensive coal beds generally are thought to have originated as large peat swamps in warm, humid, and tropical to subtropical regions (Cecil, 1990). For example, extensive, thick (some up to 50 ft) peat deposits have been accumulating on the coastal areas of the islands of Indonesia (principally Sumatra; fig. 7A) and Borneo, as well as others (Neuzil and others, 1993). Those areas are in warm, ever-wet, climatic zones.

Extensive peat deposits currently are forming in the Florida Everglades, but the climate there is much more variable than that of Borneo. Southern Florida has periodic rainfall and extended dry periods that allow the surface peat to dry out and oxidize, or even burn off, resulting in a relatively thin deposit.

Other modern peat deposits form in a wide variety of climatic conditions; two additional examples are provided. The Vajugankojev swamp in Siberian Russia, which is a notoriously cold region, is described by Cameron and others (1989) as, at an area of approximately 21,000 mi², the largest “peatland” in the world; however, even though the region is cold, the location of the swamp is low, flat, and wet, and part of the year is conducive to adequate plant growth while the coldness of the rest of the year serves to protect much of the plant matter from decay. No thickness of peat in this swamp was reported.

A swamp on Great Cranberry Island, Maine, also described by Cameron and others (1989), is another example of a swamp located in a cool temperate climate. This swamp formed during the recent past as sea level rose and built up a beach ridge approximately 11 to 12 ft high. A lake, which was formed behind the rising beach ridge, slowly filled with peat as the beach rose. The resultant peat deposit is relatively small (less than 250 acres) but it reaches thicknesses of as much as 27 ft. Whether either of these modern peat deposits will ever become a coal bed cannot now be determined; however, research on modern peat deposits, wherever they are located and under whatever climatic conditions they are deposited, may help in finding additional high-quality coal deposits in older rocks.

MINERAL MATTER

The living plants in a peat swamp absorb mineral matter from (1) the soil they grow in, (2) dissolved mineral matter in the water of the swamp, and (3) introduced mineral matter, such as waterborne or windborne sediment, or volcanic ash. Some of the dust and ash may be dissolved in the swamp water and serve to support plant growth, as described in the discussion of domed peat deposits, or they may occur as disseminated grains in the peat or as discrete layers called

partings (fig. 24). Partings may be paper thin or they may be several feet thick. In the case of the planar swamp, dust or ash will further dilute the organic matter composing the peat, thus raising the mineral-matter content or creating partings. In the case of the domed swamp, however, these sediments may add enough new nutrients to the swamp to prolong its life and produce a thicker peat and ultimately a thicker coal bed. Volcanic ash and some types of dust are rich in the nutrients required for vigorous plant growth.

Throughout geologic time, the peat swamps that were not destroyed by erosion or oxidation were buried by sediments, which, depending on their source, affected the mineral-matter content of the resultant coal in different ways. In general, riverborne sediments tend to be richer in some elements, such as iron, whereas oceanborne sediments tend to be richer in other elements, such as sulfur.

In many coals, some of the mineral matter was introduced by epigenetic (low temperature) mineralization after the bed was formed (fig. 11). In this process, the minerals were introduced into fractures (called “cleat;” see below under “Coalification”) and along bedding planes in the coal bed as ions in moving water and were deposited when the water lost its ability to maintain the mineral-forming ions in solution. This could occur when the ion-bearing water entered a different temperature and (or) chemical environment.

Epigenetic minerals commonly include pyrite, calcite, siderite, and kaolinite, and in rare cases, sphalerite and galena (see table 1 for compositions of these minerals). Epigenetic mineralization, estimated to have been introduced during the Permian Period into coal beds of older Pennsylvanian age (see fig. 19), is particularly notable in coals of the midcontinent region of the U.S. (Cobb, 1979; Brannon and others, 1997).

COALIFICATION

From the time the peat is buried, it goes through a series of chemical and physical changes called “coalification,” which is the process that produces coals of increasing rank (fig. 17). Coalification is a continuing process involving increases in both temperature and pressure resulting from burial in the earth. Burial is a process that may happen very slowly or relatively rapidly depending on the speed and magnitude of the geologic forces operating on the region. Increasing temperature is considered more important than increasing pressure in promoting coalification. Higher temperatures eliminate moisture and volatile elements and, therefore, help produce coals of higher rank and higher heat (calorific) value. Higher temperatures are generally associated with deeper burial in the earth, although proximity to an unusual source of heat, such as a volcano, could produce similar effects.



Figure 25. Photograph of part of an exposed coal bed showing well-developed face cleat and poorly developed butt cleat. The coal bed is in the Cretaceous Fruitland Formation in the San Juan basin, near Durango, Colo. The compass is 2.75 in. wide. Photograph by Walter Ayers (S.A. Holditch Assoc., Inc., College Station, Tex.) in Atlas of Coal Geology, American Association of Petroleum Geologists (AAPG) Studies in Geology No 45 (Papp and others, 1998); AAPG copyright 1998, reprinted by permission of the AAPG, whose permission is required for further use.

When increases in depth of burial or temperature no longer occur, coalification slows and then ceases (unless another source of higher heat affects the coal). Thereafter, the coal will remain at the same rank even if it is raised up again (either by tectonic uplift or erosion of overlying sediments, or both) into a region of much lower temperature or pressure. Once the coal is exposed to weathering (oxidation), however, it is slowly reduced to ash.

Coalification is a baking process in the earth, under pressure. As it proceeds, it produces coal of increasing hardness and calorific value and results in a reduction of tar, oil and gas.

Coalification affects not only the organic matter in coal, but the mineral matter as well. As coalification proceeds, organic matter, which is relatively rich in water, oxygen, and hydrogen, gradually loses those constituents and becomes relatively enriched in fixed carbon. Some of the hydrogen and carbon are converted to methane gas (CH_4) in the process. Changes that occur to the mineral matter during coalification are less well understood. During coalification, clay minerals may become more refractory

(that is, less affected by heat and chemicals), and the elements in other minerals may become rearranged, making them more crystalline. Although deeper burial, and therefore higher temperatures, implies greater age, coals of approximately the same geologic age may exhibit a wide range in rank depending on their geologic histories. For example, Pennsylvanian coals in the eastern U.S. (figs. 4, 19) range in rank from anthracite in easternmost Pennsylvania to high-volatile C bituminous coal in western Illinois and Iowa. Coals beds in what is now eastern Pennsylvania were subjected to strong mountain-building forces during the late Paleozoic, when the Appalachian Mountains were formed. During this time, the beds were forced deep into the earth into zones of high heat, and then were compressed into tight folds. In contrast, the coals to the west, in what are now the States including western Pennsylvania, Ohio, Indiana, Illinois and Iowa, were subjected to lesser depths of burial and little or no mountain-building forces.

During the process of coalification, sets of roughly parallel, closely spaced fractures (cleat) form in the coal. Cleat tend to form in two sets at right angles to one another; one set, the face cleat, is dominant, while the other set, the butt cleat, may be only poorly developed (fig. 25). Cleat are generally well developed in bituminous coals; lignites and sub-bituminous coals, both less well coalified, generally exhibit only incipient cleat. Anthracite in eastern Pennsylvania generally does not exhibit cleat because strong mountain-building forces welded the coal back together into solid massive beds. (For a thorough discussion, see Damberger, 1991.)

DETERMINING THE QUALITY OF COAL

By now, it should be clear why coal is such a complex and heterogeneous material. The interplay of the many factors that affect the peat and the resulting coal affects its composition, but the composition is never quite static because it is subject to continuing change. In the past, coal was simply dug up and burned or turned into coke with little concern for its quality as long as it made a hot fire, did not have too much ash or sulfur, and would ship long distances without turning to dust. Now we know that a complete understanding of coal quality is important in order to address environmental or industrial concerns such as (1) SO_x and hazardous air pollutants (elements such as mercury and selenium in hot flue gases); (2) boiler slagging and fouling; (3) the high costs of flue-gas desulfurization; (4) the disposal of scrubber sludge, ash, and CO_2 ; (5) the development of clean-coal technologies; and (6) the promotion of coal as a source for synthetic oil and gas.

Many techniques currently exist for studying coal quality. Some analytical techniques (such as the ones used to determine coal rank, moisture, ash yield, sulfur content, and

Table 2. Procedures and purposes of American Society for Testing and Materials (ASTM) methods for testing coal.

Procedure	Purpose
Classification of coal by rank	Classify coal into categories indicating ranges of physical and chemical characteristics that are useful in making broad estimates of the behavior of coal in mining, preparation, and use.
Coal ash	Determine amount of ash at a given temperature.
Equilibrium moisture	Determine moisture-holding capacity of coal.
Forms of sulfur	Determine whether sulfur is in pyrite, organically bound, or in sulfates.
Free-swelling index	Determine how well a coal will form coke.
Fusibility of ash	Predict whether the coal ash will perform properly in the process for which it was chosen.
Gross calorific value	Determine potential for energy production, in kilocalories per kilogram. ¹
Hardgrove grindability	Determine resistance to grinding.
Major and minor elements	Identify major and minor elements.
Proximate analysis	Determine amount of ash, fixed carbon, moisture, and volatile matter.
Reflectance of organic matter	Determine rank and how well a coal will form coke.
Total moisture	Determine inherent water and any other water present.
Trace elements	Identify trace elements.
Ultimate analysis	Determine amount of ash, carbon, hydrogen, nitrogen, oxygen, and sulfur.
Volatile matter	Identify products given off as gases or vapors.
Maceral analysis	Determine kinds and amounts of macerals in coal.

¹ One kilocalorie per kilogram = 1.798 British thermal units (Btu) per pound.

volatile matter) are highly standardized. Coal mines, electric utilities, the coke industry, and commercial analytical labs commonly employ these tests. Many of the standards for these techniques, as well as the standards for precision in their use, are published by ASTM International (2002) and are widely followed by the coal industry in the U.S. Research scientists studying coal quality use not only the results of ASTM-based analyses in their work, but also other generally accepted techniques that have not been standardized by the ASTM; however, once research shows that a new technique is useful and accepted by the coal industry, standards may be developed for its application.

Research is currently underway to improve the existing techniques used by coal scientists for analyzing coal, to adapt some techniques used in the analysis of other materials, and to develop new analytical techniques. Procedures approved by the ASTM and their purposes are given in table 2. A list of analytical techniques currently used in coal-quality research at the USGS and their purposes is given in table 3. The two suites of analyses serve different purposes. The results of the ASTM suite of analyses allow coal-using industries to directly compare coals of differing qualities,

which enables them to select a coal that is best suited to their needs. These results also allow coal research scientists to study the geologic history of a coal bed through levels of rank, and ash, sulfur, and moisture contents. The suite of analyses used by the USGS was developed to (1) aide in the search for valuable mineral byproducts, (2) develop methods to aide in determining the origins and correlations of individual coal beds, and (3) analyze for the locations, amounts, and affinities of elements that are known to, or might, pose a hazard to health. The results of both sets of analyses performed on a sample of bituminous coal from Alabama are provided in table 4 (the results of ASTM analyses are given first; the results of USGS analyses follow). The ASTM analyses were performed by the U.S. Department of Energy at the Pittsburgh, Pa., laboratory; the USGS analyses were performed at USGS laboratories at Reston, Va., and Denver, Colo.

The USGS has developed a large file of data on coal quality including the results of both ASTM and USGS procedures (Bragg and others, 1997). These data result from analyses performed on coal samples collected by USGS scientists or by cooperating agencies, such as

Table 3. Analytical methods and individual techniques used in research on coal quality and their purposes.

Method	Purpose
1. Analytical chemistry. Wet chemistry. Inductively coupled plasma mass spectroscopy (ICP-MS). Inductively coupled plasma atomic emission spectroscopy (ICP-AES). Neutron activation (NA). Atomic absorption spectroscopy (AAS). Molecular absorption spectroscopy (MAS). Optical emission spectroscopy (OES). Stable-isotope mass spectrometry (SINS).	Determine inorganic elements and compounds.
2. X-ray fluorescence.	Determine elemental composition.
3. X-ray diffraction.	Determine mineral structure.
4. Optical microscopy.	Determine distribution of coal particles and minerals and content of macerals, pollen, and spores.
5. Accelerated particle. Scanning-electron microscope (SEM) with energy dispersive X-ray analyzer (EDAX). Transmission-electron microscope (TEM). Electron microprobe (EMP). Proton induced X-ray excitation (PIXE) Laser microprobe-mass analyzer (LAMMA). Ion microprobe (IM).	Determine shapes, sizes, and distribution of mineral grains at very high magnification and semiquantitative determination of some elements. Similar to SEM. Also used for mineral identification. Determine structure and elemental composition of individual mineral and maceral grains. Similar to EMP, but more sensitive. Determine trace-element presence in coal macerals. Determine trace element presence in coal macerals.
6. Nuclear magnetic resonance (NMR).	Determine structures and structural changes of organic compounds.
7. Gas chromatography/mass spectrometry (GC/MS).	Determine organic compounds.
8. Thermoluminescence (TD) and cathodoluminescence (CD) detectors.	Infer the origin of specific minerals, whether from an igneous or sedimentary source.
9. Fourier transform infrared analysis (FTIR).	Quantitatively determine clay mineralogy and organic compounds.

Table 4. Results of standard ASTM International (ASTM) analyses and U.S. Geological Survey (USGS) research analyses of a sample (USGS 212277) of Pennsylvanian bituminous C coal from the Mary Lee coal bed, Walker County, Ala.

[Data from Bragg and others (1988). Btu, British thermal units; na, not available]

ASTM Standard Analyses		MnO	0.02	Gd	1.7	
Proximate (in percent)		Na ₂ O	0.38	Ge	0.98	
Moisture	2.6	K ₂ O	2.5	Hf	1.0	
Volatile matter	32.2	Fe ₂ O ₃	7.0	Hg	0.22	
Free carbon	50.1	TiO ₂	1.2	Ho	0.76	
Ash	15.1 ¹	P ₂ O ₅	1.3	In	0.76	
Ultimate (in percent, unless otherwise noted)		SO ₃	2.3	Ir	1.7	
Hydrogen	5.0	Minor elements (whole-coal basis, in parts per million (ppm))			La	13.0
Carbon	67.6	Si	37,000	Li	40.0	
Nitrogen	1.5	Al	22,000	Lu	0.15	
Oxygen	9.6	Ca	38,000	Mn	35.0	
Sulfur	1.2	Mg	270	Mo	0.19	
Calorific value (Btu/lb)	12,060	Na	450	Nb	2.1	
Air-dried loss	0.3	K	3,400	Nd	8.5	
Forms of sulfur		Fe	7,800	Ni	9.4	
Sulfate	0.01	Ti	1,100	Os	2.5	
Pyritic	0.66	S	1,500	P	900.0	
Organic	0.55	Trace elements (whole-coal basis, in parts per million (ppm))			Pb	4.8
Free swelling index	2.5	Ag	0.011	Pd	0.11	
Ash fusion temperature (in °F)		As	7.6	Pr	7.6	
Initial	2,300	Au	1.1	Pt	0.52	
Softening	2,430	B	66.0	Rb	32.0	
Fluid	2,520	Ba	150.0	Re	1.1	
Hardgrove grindability index	na	Be	0.99	Rh	0.25	
Equilibrium moisture (in percent)	na	Bi	1.1	Ru	0.25	
USGS Research Analyses		Br	11.0	Sb	0.7	
USGS Ash (in percent)	16.0 ¹	Cd	0.058	Sc	5.1	
Oxides (in weight percent of ash)		Ce	24.0	Se	1.5	
SiO ₂	50.0	Cl	540.0	Sm	1.9	
Al ₂ O ₃	26.0	Co	3.9	Sn	0.34	
CaO	3.4	Cr	22.0	Sr	340.0	
MgO	0.28	Cs	2.3	Ta	0.36	
		Cu	12.0	Tb	0.33	
		Dy	2.5	Th	3.9	
		Er	1.1	Tl	0.52	
		Eu	0.47	Tm	0.52	
		F	140.0	U	1.0	
		Ga	5.3	V	24.0	
				W	0.6	
				Y	5.9	
				Yb	1.1	
				Zn	11.0	
				Zr	24.0	

¹USGS ash slightly different from ASTM ash because of different temperatures used in ashing furnaces.

State geological surveys and universities. ASTM analyses were performed by the former U.S. Bureau of Mines (USBM) and by independent testing laboratories; analyses for oxides and trace elements were performed at USGS laboratories based on USGS-developed standards.

SAMPLING TECHNIQUES

Most analyses of coal, for both standard and research purposes, are conducted on carefully collected samples of whole coal. Coal samples are taken from a variety of places—individual coal beds in place, coal-mine conveyor systems, trucks, train cars, or stockpiles—depending on the needs of the sampling and analytical programs. The goal of this process is to collect a sample that will be as representative as possible of the coal bed or other source from which it is taken. In order to produce reliable results from testing programs, sampling must be done very carefully. Samples must be taken without contamination from extraneous material, and location and orientation must be documented.

There are also a few techniques for analyzing coal beds in place. Geophysical logging is conducted in drill holes during exploration and mine planning programs. This technique measures electrical resistivity, transmissivity of sound, inherent electrical properties (such as self-potential), and the reaction of coal to bombardment by atomic particles (such as neutrons) (Wood and others, 1983). These methods accurately identify coal beds and their boundaries, and help determine whether a coal bed merits additional exploration and mining; however, they are only good for an approximate analysis of coal quality.

Channel and drill-hole-core samples are two of the most common types of samples used for characterizing a coal bed. A channel sample is taken from a freshly exposed coal bed (usually in an underground or surface coal mine) by cutting a 2- to 4-in channel into the bed from top to bottom and collecting all the coal from the channel (fig. 26). Drill-hole core samples (fig. 27) are taken from subsurface coal beds where the coring bit does the cutting. If the coal bed is divided horizontally into benches (individual beds of coal separated by mineral partings), or if the bed is layered by distinct types of coal, then the benches or beds may be sampled separately, which allows for a more detailed characterization of the individual parts. The ASTM recently has published standards for the collection of channel and core coal samples (ASTM International, 2002).

The number of channel or core samples taken depends on how well the coal bed needs to be characterized. If any two samples of the same bed show considerable variation in quality between them, then more samples may be taken from the area between the two initial samples; however, cost may be a factor in the decision to collect more samples.



Figure 26. Photograph of a coal bed “face” in an underground coal mine showing personnel collecting a channel sample of fresh coal. The collecting team is standing on a floor that has been excavated below the base of the coal bed to facilitate mining. The white color in the background is limestone dust sprayed on the coal face to control coal dust. The coal sample is collected on a clean plastic sheet to minimize contamination from the floor of the mine. This sample is from the Lower Freeport coal bed, Indiana County, Pa., where the bed is about 56 in thick. Photograph by R.W. Stanton (U.S. Geological Survey).

The purpose of the analysis often determines the type of sample that is collected. If the purpose is to characterize a stock of already mined coal, then gross samples may be taken at regularly or randomly spaced intervals from the stockpile, coal car, or conveyor belt. If the purpose is to examine some specific property of a coal bed, then a sample of only a small part of the bed may be taken. If the purpose of the sample is to study some directionally controlled characteristic, such as the orientation of mineral grains, the sample must be labeled to show top and bottom and, in some cases, compass directions. For some types of analyses (for example, by either petrographic or scanning-electron microscope, figs. 11, 13B, 13C, 14), small blocks of coal are cut out of larger samples and one side is polished and examined. This technique is used when it is necessary to see the microscopic details of the types, distributions, and arrangements of the macerals and minerals in a coal sample.

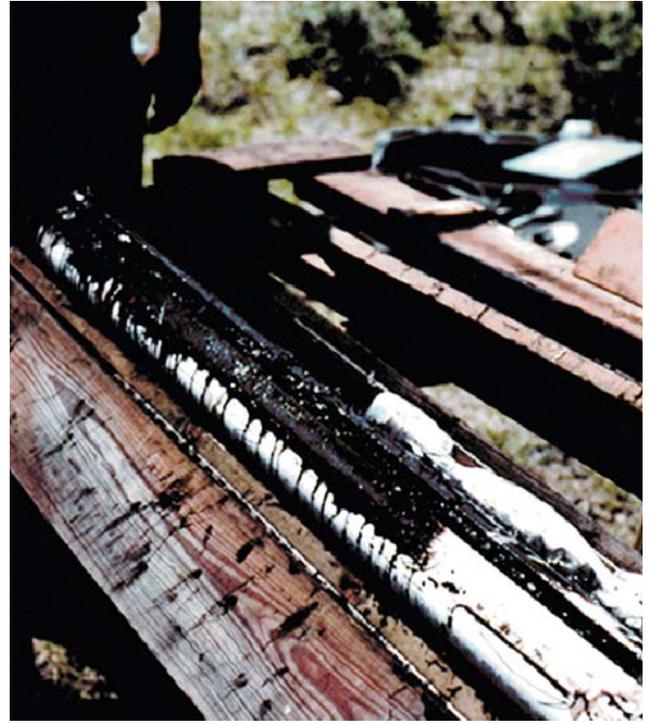
When a coal sample arrives at the lab, it is crushed (unless it is to be examined in block form) and its particles are thoroughly mixed to ensure that the sample is homogeneous. The crushed sample then is divided into appropriately sized subsamples for each analytical technique to be used.

ANALYSIS

The primary reason for analyzing coal is to determine whether it will meet the needs of a specific application, or to characterize the general quality of the coal for future ref-

**A**

Figure 27. Photographs of a core-drilling rig and a collected core. **A**, A truck-mounted, mobile, core-drilling rig on location in the process of collecting core of the Upper Freeport coal bed in western Pennsylvania. Photograph by R.W. Stanton (U.S. Geological Survey). **B**, Coal core, 3 inches in diameter, from a coal bed in the

**B**

Powder River basin, Wyoming. The white material beneath the core is plastic tubing used to collect the core and prevent it from falling apart. The upper half of the tubing has been removed to provide access to the coal. Photograph by P.D. Warwick (U.S. Geological Survey).

erence. For instance, coal may be analyzed to determine how much sulfur (or other element) is present, its form, and how it is distributed. If the sulfur is present in discrete pyrite grains, then much of it may be cleaned out of the coal; but, if it is organically bound, then the sulfur may be released only by burning, by using a solvent, or by employing a bacteriologic technique (although the latter two techniques are still largely experimental). If the coal has a high organic sulfur content, then it may have to be mixed or blended with a coal of lower sulfur content in order to meet sulfur emissions standards, or the sulfur may have to be cleaned out of the flue gas by flue-gas desulfurization (FGD), which is an expensive procedure. Similarly, analysis may determine whether a trace element, such as arsenic, may be eliminated from a coal by washing or whether it must be trapped in the flue gas. Finally, in extreme cases, analysis may determine that the coal cannot be used.

In general, the coal-mining and coal-consuming industries determine coal quality for immediate or near-term use, whereas Federal and State governments analyze coal to (1) characterize large areas of unmined coal (resources) for

future reference, (2) to support policy decisions related to future coal use, and (3) to supply Federal and State regulatory agencies with information about the quality or special characteristics of future coal supplies, such as the presence, amounts, and modes of occurrence of sulfur and potentially toxic trace elements. Figure 28 shows a coal scientist at work identifying coal macerals and coal rank in a polished sample of coal using a high-powered, reflected-light microscope.

Coal samples may be received at the laboratory in a variety of conditions. Accordingly, analytical results may be reported in a variety of ways, depending on the condition of the samples when received and the use of the analysis. Some samples arrive in a fresh condition, not long after sampling; these may be analyzed without further processing, except grinding and mixing. The analytical results for these samples are reported on an “as-received” basis. Some samples arrive dried out due to long storage, transportation over long distances, or mishandling. The results of analyses on dried-out samples are reported on a “dry” basis. The opposite conditions may also occur if the sample arrives

wet because of excess moisture in the sample that may or may not be present in the coal bed; in this case the analyses may be reported on a "moist" basis.

Analyses also may be reported on a "mineral-matter-free" or "dry, mineral-matter-free" basis for use in calculating coal rank because rank is a function only of the maturity of the organic matter. "Mineral-matter-free" means that the amount of mineral matter in the sample has been subtracted from the total analytical results to provide only the amount that is organic. "Dry, mineral-matter-free" means that the sample was received in a dry or nearly dry state, or was dried out before an analysis was made.

An analysis on a mineral-matter-free basis also may be used for comparison with the results of an as-received analysis of "run-of-mine" coal (as it comes from the mine) if there is to be further processing, such as coal cleaning. Run-of-mine coal frequently contains (1) large amounts of mineral matter from partings in the coal bed, (2) rocks from above and below the coal bed that are mined along with the coal, (3) minerals that fill veins in the coal bed, and (4) mineral matter dispersed in the coal (such as pyrite grains). Mineral matter in run-of-mine coal may cause the coal to exceed the ash and sulfur limits set by contract requirements and environmental regulations. A mineral-matter-free analysis may indicate whether or not it will be worthwhile to clean the coal; however, the need for cleaning depends on the intended use of the coal and normal cleaning practices may not bring a coal to a completely mineral-free condition.

Most chemical analyses require the destruction of the coal sample in order to determine calorific value, volatile matter, and mineral-matter content. Destruction is achieved by burning the coal sample in a high-temperature furnace. Although that procedure is fine for determining the calorific value of coal, it is not suitable for retention of some of its volatile inorganic elements, such as mercury. Subjecting the sample to a process called "low temperature ashing," in which the sample is exposed to high-frequency radiation in a high-oxygen atmosphere, permits the organic matter to be driven off while preserving most of the mineral matter. Nevertheless, some of the very volatile inorganic elements (such as chlorine, mercury, or selenium) may be lost in this process and are best measured in whole-coal samples by X-ray fluorescence or other techniques. Most microscopic and microprobe techniques require whole-coal samples because the objective is to determine the interrelations between the constituent parts of the coal.

ORGANIC GEOCHEMISTRY

Because coal is principally an organic substance, organic geochemistry is an important factor in the study of the origin, structure, quality, and utilization of coal.



Figure 28. Photograph of a coal scientist at work identifying coal macerals and rank in a polished sample of coal using a high-powered, reflected-light microscope. Photograph by R.W. Stanton (U.S. Geological Survey).

Determining the organic matter in coal is necessary for studying (1) the organic structure and the organic sulfur compounds in coal, (2) modern peat-forming swamps as analogues of ancient peat-forming swamps, (3) the potential for coal gasification and liquefaction, and (4) the effects of coal mining and coal use on surface water, ground water, and air quality.

Recent advances in analytical instrumentation have greatly aided organic geochemical studies of coal. Most coals consist of a mechanical mixture of two principal organic components: (1) resin-like (aliphatic) organic matter of uncertain origin (that is, the specific plant structures have been destroyed during the coalification process), and (2) benzene-like (aromatic) organic matter derived from wood tissues (lignin). Using solid-state, ^{13}C nuclear-magnetic-resonance (NMR) spectroscopy, coals now are routinely classified based on their aromatic content.

Organic geochemical studies of modern peat attempt to relate processes occurring in modern environments to those that occurred in ancient peat swamps.

Other commonly used analytical techniques such as gas chromatography/mass spectrometry, the electron microscope, and the scanning electron microscope are used to study the organic sulfur concentration and distribution in coals. So far, these studies seem to indicate that most of the sulfur in organic compounds in coal is present at the edges of the organic molecules. This finding may aid the development of effective desulfurization procedures for coal containing large amounts of organically bound sulfur.

The energy produced and the reactivity of coal during burning is determined by its chemical and physical struc-

ture. Through computer-assisted molecular design, scientists can now construct two- and three-dimensional models of organic compounds in coal and determine the arrangements of the elements in various model structures.

Organic geochemical studies of modern peat deposits attempt to relate processes occurring in modern environments to those that occurred in ancient peat swamps. Such studies serve as a mechanism for a better understanding of and an ability to predict coal quality by providing insight into the early stages of coal formation; for example, a geochemical analysis of an ombrogenous peat, which is easy to sample, greatly enables the ability to predict the quality of other coal deposits that originated as ombrogenous peat deposits but that are much more difficult and costly to sample.

MINERAL-MATTER CHEMISTRY

Studies of mineral matter in coal are performed by a variety of analytical techniques. The principal techniques are analytical chemistry, X-ray spectroscopy, scanning-electron microscopy, petrography, and mineralogical studies (table 2). Two newer techniques, (1) inductively coupled plasma, atomic-emission spectrometry (ICP-AES); and (2) inductively coupled plasma, mass spectrometry (ICP-MS), have been applied to coal analysis with excellent results and are worth a brief description. Using these techniques, a sample of coal ash is first decomposed with various acids and put into solution. The solution is then aspirated into a flame (plasma), which energizes the atoms of the different elements present in the solution to generate characteristic wavelengths of radiation. The spectrum produced by the radiation is then measured in a spectrometer. The data from the spectrometer are fed into a computer where the results are compared to standard samples and the concentration of each element in the sample is calculated. The two ICP techniques simultaneously and quantitatively analyze about 50 different inorganic elements, which is a large increase in the efficiency of coal analysis. The ASTM recently has adopted ICP-AES and ICP-MS techniques as industry standard methods for analyzing coals for inorganic elements (ASTM International, 2002).

Microscopic studies of coal petrography are used to identify the constituents in coal and how they are arranged and to provide knowledge of the maceral composition and distribution. Coal petrographers may assess the rank of a coal by measuring the intensity of light reflected from the vitrinite macerals in a polished surface of a coal sample; the higher the reflectivity, the higher the rank. In some instances, however, petrographic study is not adequate to characterize all of the coal constituents. For example, if mineral matter, such as pyrite, exists as extremely small discrete grains, or if it is located inside plant cells (which are

also extremely small), then identification becomes difficult with an optical microscope. In these cases, a scanning-electron microscope is used to study minute particles of mineral material. Figure 14 is a photomicrograph taken with a scanning-electron microscope of plant cells in coal containing minute grains of pyrite. In this case, chemical and mineralogic analyses had already determined the presence of pyrite, but the photomicrograph allows the pyrite to be studied in greater detail. This information could be used to determine whether the coal must be ground into a powder that is fine enough to liberate such fine-grained pyrite (an expensive process).

CONCLUSIONS

Although much is known about coal quality, much also remains to be learned. To this end, research on coal quality is being conducted in both the public and private sectors. Current studies encompass all aspects of the origin, burial history, and composition of coal in order to understand the various factors involved in determining coal quality, such as how and where to find the right coal for a specific use and how to clean coal to make its use more environmentally and industrially acceptable.

In the past, the only consideration given to coal quality was whether coal lumps held together during shipping burned easily to produce a hot fire and didn't produce too much ash. Today, however, concerns about human health, the environment, energy demands, and the supply of certain raw materials have broadened our concept of coal quality and our need to know much more about the origins, nature, and effects of coal quality. An extensive evaluation of coal quality must be central to coal use. Whatever coal is used for, whether for the direct production of energy, chemicals, synthetic fuels, or the recovery of useful minerals, and whatever problems and solutions accompany that use depend on the quality of the coal. Additional, sophisticated, multidisciplinary research on coal quality is required for the future. The results will help make it possible for society to continue to benefit from the good qualities of coal and to make progress in avoiding the undesirable affects of coal use.

In the near term, the most immediate advancements related to coal-quality research appear to be improvements in the efficiency of coal use (including more efficient production of synthetic fuels) and the development of methods to best understand, and thus control, the less desirable components in coal that have the potential to contribute to environmental degradation and adverse health effects. In the longer term, the recovery of useful substances from coal (such as iron, silver, sulfur, and zinc, as well as organic chemicals, gypsum, and ash) should be an exciting area for research related to coal quality.

COAL QUALITY AND PUBLIC HEALTH

By Robert B. Finkelman

Prior to the widespread adoption of selective mining procedures and pollution-control technology, human health had been affected by sulfur and particulates emitted from coal combustion. This section describes several examples of how organic compounds and trace elements are still affecting the health of people in Europe, Asia, and America.

The inorganic (and in some cases, organic) constituents in coal may have profound effects on the health of those people burning coal in their homes or living near coal deposits, coal mines, or coal-burning power plants. Trace elements, such as arsenic (As), emitted from coal-burning power plants in Europe and Asia have been shown to cause severe health problems. Water leaching of organic compounds from lignites may be the cause of a kidney disease that has taken the lives of more than 100,000 people in the Balkans. Widespread health problems may be caused by domestic coal combustion in developing countries. Millions of people suffer from fluorosis, thousands from arsenism. In the southwestern U.S., many members of the Navajo Nation are dependent on coal as their primary source of energy. Many Navajo suffer from chronic respiratory problems that are attributed to emissions from the burning of coal in their hogans.

A better knowledge of coal-quality parameters may help to minimize some of these health problems. Information on the concentrations and distributions of potentially toxic elements in coal may help us to avoid those parts of a coal deposit having undesirably high concentrations of these elements.

Information on the modes of occurrence of these elements and the textural relations of the minerals and macerals in which they occur may help us to anticipate the behavior of the potentially toxic components during coal cleaning, combustion, weathering, and leaching. Coal quality characterization, therefore, offers coal scientists opportunities to contribute to important societal needs such as improved public health.

POLYCYCLIC AROMATIC HYDROCARBONS (PAHS)

BALKAN ENDEMIC NEPHROPATHY

Balkan endemic nephropathy (BEN) is a potentially fatal degenerative kidney disease common in parts of former Yugoslavia, Bulgaria, and Romania. An article in a popular science magazine attributed more than 100,000 deaths to BEN since it was recognized as a distinct disease in 1956 (Zimmerman, 1983). Intensive medical research had failed

to identify the cause of BEN or to explain why it occurs in clusters of villages along river valleys.

In the early 1990s, U.S. Geological Survey (USGS) researchers identified a link between the occurrence of BEN and the distribution of Pliocene lignites, which are the youngest, most chemically reactive coals in the Balkans region (Feder and others, 1991). They suggested that BEN is attributable to ingestion of organic compounds from well water that had been in contact with Pliocene lignites. Ground water in the endemic villages was found to be highly concentrated in organic chemicals such as PAHs. They also suggested that the hydrocarbons, some of which were known carcinogens, were the cause of BEN. Further evidence was found from laboratory experiments. Using distilled water to leach samples of Pliocene lignites from Yugoslavia, USGS researchers extracted a suite of PAHs similar to that found in the well water of the endemic villages (Orem and others, 1999).

BEN also may exist in Turkey and other countries. Turkey has extensive near-surface deposits of Pliocene lignites and many Turkish villagers rely solely on well water for their drinking needs. If these wells are drilled into the Pliocene lignite aquifers or into aquifers in contact with the lignites, BEN could result from drinking the water.

Information on the concentrations and distributions of potentially toxic elements in coal may help us to avoid those parts of a coal deposit that have undesirably high concentrations of those elements.

LUNG CANCER

PAHs released during unvented coal combustion in homes in Xuan Wei County, China, have been cited as the primary cause for the highly elevated incidence of lung cancer there. The PAH levels in the homes burning "smokey" coal are at industrial levels resulting in a lung cancer mortality rate five times the national average of China (Mumford and others, 1987).

TRACE ELEMENTS

Concerns have been expressed in the United States and elsewhere over the release of As, Be, Cd, Cl, Co, Cr, F, Hg, Mn, Ni, Pb, Sb, Se, and U during the burning of coal. Recent data from the U.S. Environmental Protection Agency (EPA) (1996) indicate that trace-element emissions

from coal-burning power plants that use coal with relatively low to moderate trace-element concentrations, or that have efficient pollution control devices may not present a significant health risk. Their data indicate that the risk of cancer from trace elements inhaled by humans who live or work near power plants is less than 1 in 1 million.

Elsewhere in the world, trace elements emitted from coal-burning power plants have been shown to cause severe health problems. In Czechoslovakia, children living in the vicinity of a power plant that burned high-arsenic lignite (about 1,000 parts per million (ppm) on a dry basis) suffered significant hearing loss that was attributed to arsenic poisoning from the power-plant emissions (Bencko and Symon, 1977). Perhaps the most widespread health problems are caused by domestic coal combustion in developing countries. Millions of people suffer from fluorosis and thousands suffer from arsenosis caused by coal combustion in China. Selenium and mercury poisoning also have been attributed to domestic coal combustion in China. Adsorption of fluorine by corn dried over high-fluorine (>200 ppm) coal fires is the probable cause of extensive dental and skeletal fluorosis in southwest China. The problem is compounded by the use of clay as a binder for making briquettes; that clay typically is a high-fluorine (about 900 ppm) residue from the intense leaching of the limestone substrate.

In Guizhou Province, China, the practice of drying chili peppers over high-arsenic coal fires has led to thousands of cases of arsenic poisoning (Finkelman and others, 1999). The contaminated chili peppers commonly are used for cooking and thus become the principal source of arsenic poisoning. One coal sample from this region analyzed at the U.S. Geological Survey laboratory contained 35,000 ppm arsenic on an as-received basis! Chili peppers dried over the high-arsenic coal fires contain more than 500 ppm arsenic (fresh chili peppers contain less than 1 ppm arsenic). Arsenosis, which results from ingestion of the chili peppers tainted with arsenic from the mineralized coal, also has led to severe skin cancers in the affected population (Finkelman and others, 1999).

Nearly 500 cases of human selenosis in southwest China have been attributed to the use of selenium-rich, carbonaceous shales known locally as "stone coal" (Zheng, 1992). The stone coals contain as much as 8,390 ppm selenium. The selenosis is attributed to the practice of using the combustion ash as a soil amendment. This introduces large amounts of selenium to the soil and results in selenium uptake by the crops.

Coal combustion is considered to be the largest man-made source of mercury in the environment. Although there are no confirmed reports that mercury from emissions directly impacts human health, mercury may contribute to health problems through bioaccumulation in the food chain. Mercury, a portion of which is derived from coal combustion, is deposited in lakes and rivers and can be converted to toxic methylmercury, which then accumulates and

becomes enriched in fish and birds. Cases of mercury poisoning have been documented in people who eat contaminated fish for prolonged periods, both in the United States and abroad. Pregnant women and subsistence fishermen are particularly vulnerable.

A rare occurrence of chronic thallium poisoning was reported from Guizhou Province, China (Zhou and Liu, 1985). The source of the thallium poisoning appears to be from vegetables grown in soil developed over a mercury-thallium-rich mining slag. Most symptoms, such as hair loss, are typical of thallium poisoning; however, loss of vision in several patients was considered to be unique. Mineralogical analysis of coal used in the homes of the patients with visual impairment revealed abundant mercury minerals. Chemical analysis of a sample of coal being used in Guizhou Province, China, indicated the mercury concentration to be 55 ppm (Finkelman, 1999), about 200 times the average mercury concentration found in U.S. coals.

SUMMARY

Coal scientists and technologists are ideally positioned to help minimize health problems due to coal combustion by providing information on coal quality. Information on the concentrations and distributions of potentially toxic elements in coal may assist people dependent on local coal sources to avoid those areas of a coal deposit having undesirably high concentrations of toxic compounds. Information on the modes of occurrence of potentially toxic elements and the textural relations of the minerals and macerals in which they occur may help us to anticipate the behavior of the potentially toxic components during coal cleaning, combustion, weathering, and leaching.

REFERENCES CITED

- ASTM International, 2002, Coal and coke, *in* Annual book of ASTM standards, section 5, Petroleum products, lubricants, and fossil fuels, v. 05.06, Gaseous Fuels; Coal and Coke: Philadelphia, Pa., ASTM International, p. 163–626.
- Bencko, V., and Symon, K., 1977, Health aspects of burning coal with a high arsenic content: *Environmental Research*, v. 13, p. 386–395.
- Bragg, L.J., Oman, J.K., Tewalt, S.J., Oman, C.L., Rega, N.H., Washington, P.M., and Finkelman, R.B., 1998, U.S. Geological Survey coal quality (COALQUAL) database; version 2.0: U.S. Geological Survey Open-File Report 97–134, 1 CD-ROM (also available on the web at <http://energy.er.usgs.gov/products/databases/coalqual/intro.htm>. Accessed February 7, 2002).
- Brannon, J.C., Podosek, F.A., and Cole, S.C., 1997, Radiometric dating of Mississippi Valley-type ore deposits, *in* Sangster, D.F., ed., Carbonate-hosted lead-zinc deposits: Society of

- Economic Geologists Special Publication 4, p. 536–545.
- Cecil, C.B., 1990, Paleoclimate controls on stratigraphic repetition of chemical and siliciclastic rocks: *Geology*, v. 18, no. 6, p. 533–536.
- Cobb, J.C., 1979, Timing and development of mineralized veins during diagenesis in coal beds, *in* Cross, A.T., ed., Proceedings, Ninth International Congress on Stratigraphy and Geology of the Carboniferous, Champaign-Urbana, Ill., May 17–26, 1979: *Compte Rendu-Congres International de Stratigraphie et de Geologie du Carbonifere*, v. 9, no. 4, p. 371–376.
- Collier's Encyclopedia, 1960, Coal—Development in the United States: New York, P.F. Collier and Son Corp., v. 5, p. 206.
- Cross, A.T., and Phillips, T.L., 1990, Coal-forming plants through time in North America, *in* Lyons, P.C., Callcott, T.G., and Alpern, B., eds., Peat and coal—Origin, facies, and coalification: *International Journal of Coal Geology*, v. 16, no. 1–3, p. 1–46.
- Damberger, H.H., 1991, Coalification in North American coal fields, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., Economic geology, U.S.: Denver, Colo., Geological Society of America, The Geology of North America, v. P-2, p. 503–522.
- Dienhart, G.J., Stewart, B.R., and Tyson, S.S., eds., 1998, Coal ash—Innovative applications of coal combustion products (CCP's): Alexandria, Va., American Coal Ash Association, 99 p.
- Eggleston, J.R., Carter, M.D., and Cobb, J.C., 1990, Coal resources available for development—A methodology and pilot study: U.S. Geological Survey Circular 1055, 15 p.
- Energy Information Administration, 1999a, Annual energy outlook 2000, with projections to 2020: Energy Information Administration Report DOE/EIA-0383(2000), 249 p. (also available on the web at <http://www.eia.doe.gov/oiaf/archive/aeo00/>. Accessed February 10, 2003).
- 1999b, Coal industry annual 1998: Energy Information Administration Report DOE/EIA-0584(98), 308 p. (also available on the web at <http://tonto.eia.doe.gov/FTP/ROOT/coal/058498.pdf/>. Accessed February 10, 2003).
- 2000, Annual energy review 1999: Energy Information Administration Report DOE/EIA-0384(99), 374 p. (also available on the web at <http://tonto.eia.doe.gov/FTP/ROOT/multifuel/038499.pdf/>. Accessed February 10, 2003).
- Eavenson, H.N., 1942, The first century and a quarter of American coal industry: Pittsburgh, Pa., [privately printed], 701 p.
- Feder, G.L., Radovanovic, Z., and Finkelman, R.B., 1991, Relationship between weathered coal deposits and the etiology of Balkan endemic nephropathy: *Kidney International* 40 (Suppl. 34), p. S9–S11.
- Finkelman, R.B., 1999, Health impacts of domestic coal combustion, *in* Proceedings, Twenty-Fourth International Technical Conference on Coal Utilization and Fuel Systems, Clearwater, Fla., March 8–12, 1999: Washington, D.C., Coal and Slurry Technology Association, p. 14–18.
- Finkelman, R.B., Belkin, H.E., and Zheng, B., 1999, Health impacts of domestic coal use in China: [U.S.] National Academy of Science Proceedings, v. 96, p. 3,427–3,431.
- Finkelman, R.B., and Brown, R.D., Jr., 1991, Coal as a host and as an indicator of mineral resources, *in* Peters, D.C., ed., *Geology in coal resource utilization*: Fairfax, Va., Tech Books, p. 471–481.
- Finkelman, R.B., Feder, G.L., Orem, W.H., and Radovanovic, Z., 1991, Relation between low-rank coal deposits and Balkan endemic nephropathy: Association of Geoscientists for International Development Newsletter, v. 5, p. 23.
- Flores, R.M., Warwick, P.D., and Moore T., 1989, Tertiary and Cretaceous coals of the Rocky Mountains region: Washington, D.C., American Geophysical Union, Twenty-eighth International Geological Congress Field Trip Guidebook T132, 60 p.
- Fort Union Coal Assessment Team, 1999, 1999 Resource assessment of selected Tertiary coal beds and zones in the Northern Rocky Mountains and Great Plains region: U.S. Geological Survey Professional Paper 1625–A, version 1.1, 2 CD-ROMs (also available on the web at <http://greenwood.cr.usgs.gov/energy/coal/PP1625B/>. Accessed February 10, 2003).
- Gastaldo, R.A., DiMichele, W.A., and Pfefferkorn, H.W., 1996, Out of the icehouse into the greenhouse; a late Paleozoic analog for modern global vegetational change: *GSA Today*, v. 6, no. 10, p. 1–7.
- IEA Coal Research, 1999, CO₂ reduction—Prospects for coal: London, IEA Coal Research, 84 p.
- Kalyoncu, Rustu, 1999, Coal combustion products: U.S. Geological Survey, Mineral Industry Surveys, 1998 Annual Review, 19 p.
- Kirschbaum, M.A., Roberts, L.N.R., and Biewick, L.R.H., eds., 2000, Geologic assessment of coal in the Colorado Plateau—Arizona, New Mexico, and Utah: U.S. Geological Survey Professional Paper 1625–B, version 1.0, 2 CD-ROMs (also available on the web at <http://greenwood.cr.usgs.gov/energy/coal/PP1625A/>. Accessed February 11, 2003).
- McCabe, P.J., 1987, Facies studies of coal and coal-bearing strata, *in* Scott, A.C., ed., Coal and coal-bearing strata; recent advances: Geological Society [London] Special Publication 32, p. 51–66.
- Mumford, J.L., He, X.Z., Chapman, R.S., Cao, S.R., Harris, D.B., Li, X.M., Xian, W.Z., Jiang, C.W., Xu, J.C., Wilson, W.E., and Cooke, M., 1987, Lung cancer and indoor air pollution in Xuan Wei, China: *Science*, v. 235, p. 217–220.
- National Mining Association, 1999, Facts about coal 1997–98: Washington, D.C., National Mining Association, 84 p.
- Neuzil, S.G., Supardi, Cecil, C.B., Kane, J.S., Soedjono, K., 1993, Inorganic geochemistry of domed peat in Indonesia and its implication for the origin of mineral matter in coal, *in* Cobb, J.C., and Cecil, C.B., eds., Modern and ancient coal-forming environments: Geological Society of America Special Paper 286, p. 23–44.
- Northern and Central Appalachian Basin Coal Regions Assessment Team, 2001, 2000 Resource assessment of selected coal beds and zones in the northern and central Appalachian Basin coal regions: U.S. Geological Survey Professional Paper 1625–C, version 1.0, 2 CD-ROMs (also

- available on the web at <http://pubs.usgs.gov/prof/p1625c/>. Accessed February 12, 2003).
- Orem, W.H., Feder, G.L., and Finkelman, R.B., 1999, A possible link between Balkan endemic nephropathy and the leaching of toxic organic compounds from Pliocene lignite by groundwater; preliminary investigation: *International Journal of Coal Geology*, v. 40, no. 2–3, p. 237–252.
- Papp, A.R., Hower, J.C., and Peters, D.C., 1998, Atlas of coal geology: AAPG Studies in Geology No. 45, 1 CD-ROM.
- Sargent-Welch Scientific Company, 1979, Periodic table of the elements: Buffalo Grove, Ill., Sargent-Welch Scientific Company, 1 p.
- Tidwell, W.D., 1998, Common fossil plants of western North America: Washington, D.C., Smithsonian Institution Press, 299 p.
- Trumbull, James, 1960, Coal fields of the United States, exclusive of Alaska—Sheet 1: Washington, D.C., U.S. Geological Survey Map, scale 1:5,000,000.
- Tully, John, 1996, Coal fields of the conterminous United States: U.S. Geological Survey Open-File Report 96–92, scale 1:5,000,000 (available on the web at <http://energy.er.usgs.gov/products/openfile/OF96–92/>. Accessed February 11, 2003).
- U.S. Department of Energy, 2000, Clean coal technology; Clean coal technology demonstration program, program update as of September 1999: U.S. Department of Energy Report DOE/FE–0415, 304 p.
- U.S. Environmental Protection Agency, 1996, Study of hazardous air pollutant emissions from electric utility steam generating units—Interim final report: U.S. Environmental Protection Agency Report EPA–453/R–96–013a, 812 p.
- 2000, EPA decides mercury emissions from power plants must be reduced: U.S. Environmental Protection Agency Press Release, December 14, 2000 (also available on the web at <http://www.epa.gov/ttnatw01/comburst/utiltox/pr121400.htm/>. Accessed February 11, 2003).
- U.S. Geological Survey, 1996, Assessing the coal resources of the United States: U.S. Geological Survey Fact Sheet FS–157–96, 8 p.
- 1999, Coal resource assessments in the northern and central Appalachian basin: U.S. Geological Survey Fact Sheet FS–115–99, 4 p. (also available on the web at <http://pubs.usgs.gov/factsheet/fs115-99/>. Accessed February 10, 2003).
- 2000 [2001], Forces shaping future U.S. coal production and use [revised]: U.S. Geological Survey Fact Sheet FS–158–00, 2 p. (also available on the web at <http://pubs.usgs.gov/factsheet/fs158-00/>. Accessed February 10, 2003).
- Virginia Surface Mining and Reclamation Association, Inc., [undated], Coal tree byproducts: Norton, Va., Virginia Surface Mining and Reclamation Association, Inc., 1 p.
- Wood, G.H., Jr., Kehn, T.M., Carter, M.D., and Culbertson, W.C., 1983, Coal resource classification system of the U.S. Geological Survey: U.S. Geological Survey Circular 891, 65 p. (also available on the web at <http://energy.er.usgs.gov/products/papers/C891/index.htm/>. Accessed February 10, 2003).
- Zheng, B., Hong, Y., Zhao, W., Zhou, H., Xia, W., Su, H., Mao, D., Yan, L., and Thornton, I., 1992, The Se-rich carbonaceous siliceous rock and endemic selenosis in southwest Hubei, China: *Chinese Science Bulletin*, v. 37, no. 20, p. 1,725–1,729.
- Zhou, D., and Liu, D., 1985, Chronic thallium poisoning in a rural area of Guizhou Province, China: *Journal of Environmental Health*, v. 48, no. 1, p. 14–18.
- Zimmerman, D.R., 1983, Death along the Danube: *Science*, v. 4, no. 4, p. 58–65.

FURTHER READING

GENERAL BACKGROUND

- Cameron, C.C., Esterle, J.S., and Palmer, C.A., 1989, The geology, botany and chemistry of selected peat-forming environments from temperate and tropical latitudes: *International Journal of Coal Geology*, v. 12, p. 105–156.
- Lindbergh, Kristina, and Provorose, Barry, 1980, Coal; a contemporary energy story: Seattle, Wash., Scribe Publishing Corp., 207 p.
- Scott, A.C., ed., 1987, Coal and coal-bearing strata; recent advances: Geological Society [London] Special Publication 32, 332 p.
- U.S. Geological Survey, 1988, Coal resources, *in* National energy resource issues; geologic perspective and the role of geologic information: U.S. Geological Survey Bulletin 1850, p. 29–49.

COAL QUALITY

- Bohor, B.F., and Triplehorn, D.M., 1993, Tonsteins—Altered volcanic-ash layers in coal-bearing sequences: Geological Society of America Special Paper 285, 44 p.
- Cohen, A.D., and Andrejko, M.J., 1983, Use of models on modern peat deposits to predict the distribution of mineral matter in coals, *in* Raymond, R., Jr., and Andrejko, M.J., eds., Proceedings, Mineral matter in peat; its occurrence, form, and distribution, Los Alamos, N.M., September 26–30, 1983: Los Alamos National Laboratory Report LA–9907–OBES, p. 77–85.
- Dutcher, R.R., ed., 1978, Field description of coal: Philadelphia, Pa., American Society for Testing and Materials Special Technical Publication, 71 p.
- Garbini, Susan, and Schweinfurth, S.P., eds., 1986, A national agenda for coal quality research; symposium proceedings: U.S. Geological Survey Circular 979, 334 p.
- Gluskoter, H.J., 1975, Mineral matter and trace elements in coal [reprinted from Trace elements in fuel, no. 141 of *Advances in Chemistry Series*]: Washington, D.C., American Chemical Society, 22 p.
- Golightly, D.W., and Simon, F.O., eds., 1989, Methods for sampling and inorganic analysis of coal: U.S. Geological Survey Bulletin 1823, 72 p.
- McCabe, P.J., 1991, Geology of coal; environments of deposition, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., Economic geology, U.S.: Denver, Colo., Geological Society

of America, *The Geology of North America*, v. P-2, p. 469–482.

Phillips, T.L., and Cross, A.T., 1991, Paleobotany and paleoecology of coal, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., *Economic geology*, U.S.: Denver, Colo., Geological Society of America, *The Geology of North America*, v. P-2, p. 483–502.

Stach, E., Taylor, G.H., Mackowsky, M.T.H., Chandra, D., Teichmuller, M., and Teichmuller, R., 1975, *Coal petrology*, second edition: Berlin, Gebruder Borntraeger, 428 p.

COAL RESOURCES

Andrews, R.E., Weisenfluh, G.A., Hiatt, J.K., and Sergeant, R.E., 1994, Available coal resources of the Salyersville South 7.5-minute quadrangle, Magoffin County, Kentucky: Kentucky Geological Survey Information Circular 47, 44 p.

Averitt, Paul, 1975, Coal resources of the United States, January 1, 1974: U.S. Geological Survey Bulletin 1412, 131 p.

Axon, A.G., 1996, Available coal resources of the Bethesda 7.5-minute quadrangle, Belmont County, Ohio: Ohio Division of Geological Survey Report of Investigations 145, 27 p.

Breyer, J.A., 1991, Tertiary coals of the Gulf Coast, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., *Economic geology*, U.S.: Denver, Colo., Geological Society of America, *The Geology of North America*, v. P-2, p. 573–582.

Cross, A.T., 1991, Coals of far-Western United States, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., *Economic geology*, U.S.: Denver, Colo., Geological Society of America, *The Geology of North America*, v. P-2, p. 583–590.

Donaldson, A.C., and Eble, C.F., 1991, Pennsylvanian coals of central and eastern United States, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., *Economic geology*, U.S.: Denver, Colo., Geological Society of America, *The Geology of North America*, v. P-2, p. 523–546.

Flores, R.M., and Cross, A.T., 1991, Cretaceous and Tertiary coals of the Rocky Mountains and Great Plains regions, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., *Economic geology*, U.S.: Denver, Colo., Geological Society of America, *The Geology of North America* v. P-2, p. 547–571.

Flores, R.M., Ochs, A.M., Stricker, G.D., Roberts, S.B., Ellis, M.S., Keighin, C.W., Murphy, E.C., Cavaroc, V.V., Jr., Johnson, R.C., and Wilde, E.M., 1999, National coal resources assessment non-proprietary data; location, stratigraphy, and coal quality of selected Tertiary coals in the Northern Rocky Mountains and Great Plains region: U.S. Geological Survey Open-File Report 99-376, 1 CD-ROM.

Osmonson, L.M., Rohrbacher, T.J., Molnia, C.L., and Sullivan, G.L., 2000, Coal recoverability in the Hilight quadrangle, Powder River Basin, Wyoming; a prototype study in a western coal field: U.S. Geological Survey Open-File Report 00-103, 23 p.

Rohrbacher, T.J., Teeters, D.D., Sullivan, G.L., and Osmonson, L.M., 1993, Coal resource recoverability; a methodology: U.S. Bureau of Mines Information Circular 9368, 48 p.

Schultz, J.E., and Eakins, Wynn, 2000, Availability of coal resources in Colorado; Somerset coal field, west-central

Colorado: Colorado Geological Survey Resource Series 38, 84 p.

Tabet, D.E., Quick, J.C., Hucka, B.P., and Hanson, J.A., 1999, The available coal resources for nine 7.5-minute quadrangles in the northern Wasatch Plateau coalfield, Carbon and Emery Counties, Utah: Utah Geological Survey Circular 100, 46 p.

Treworgy, C.G., Korose, C.P., Chenoweth, C.A., and North, D.L., 1999, Availability of the Springfield coal for mining in Illinois: *Illinois Minerals* 118, 43 p.

U.S. Geological Survey, 1996, Assessing the coal resources of the United States: U.S. Geological Survey Fact Sheet FS-157-96, available on the web at <http://energy.usgs.gov/factsheets/nca/nca.html>. (Accessed February 11, 2003).

———2000, Federally owned coal and Federal lands in the Northern Rocky Mountains and Great Plains region: U.S. Geological Survey Fact Sheet FS-011-00, 6 p. (also available on the web at <http://pubs.usgs.gov/fs/fs-0011-00/>. Accessed February 11, 2003).

Wood, G.H., Jr., and Bour, W.V., III, 1988, Coal map of North America: Reston, Va., U.S. Geological Survey Special Map, scale 1:5,000,000.

UTILIZATION

American Coal Ash Association, 1995, Fly ash facts for highway engineers: American Coal Ash Association Report FHWA-SA-94-081, 70 p.

Attanasi, Emil, 2000, Forces shaping future U.S. coal production and use: U.S. Geological Survey Fact Sheet FS-158-00.

Damberger, H.H., Harvey, R.D., Ruch, R.R., and Thomas, Josephus, Jr., 1984, Coal characterization, *in* Cooper, B.R., and Ellingson, W.A., eds., *The science and technology of coal and coal utilization*: New York, Plenum Press, p. 7–45.

Elliott, M.A., ed., 1981, *Chemistry of coal utilization*, second supplementary volume: New York, Wiley-Interscience, 2,374 p.

National Mining Association, 1998, *International coal, 1998 edition (1996–1997 Data)*: Washington, D.C., National Mining Association and Coal Exporters Association of the United States, 114 p.

Stricker, G.A., 1991, Economic Alaskan coal deposits, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., *Economic geology*, U.S.: Denver, Colo., Geological Society of America, *The Geology of North America*, v. P-2, p. 591–602.

HEALTH EFFECTS

Chu, P., and Porcella, D.B., 1995, Mercury stack emissions from U.S. electric utility power plants, *in* Arcella, D.B., Huckabee, J.W., and Wheatly, Brian, eds., *Mercury as a global pollutant: Water, Air, and Soil Pollution*, v. 80, no. 1–4, p. 135–144.

Swaine, D.J., and Goodarzi, F., 1995, Environmental aspects of trace elements in coal: Dordrecht, The Netherlands, Kluwer, 312 p.

Wilson, R., Colome, S.D., Spengler, J.D., and Wilson, D.G., 1980, *Health effects of fossil fuel burning*: Cambridge, Mass., Ballinger Publishing Co., 392 p.

APPENDIX 1

FEDERAL AGENCIES WITH REGULATORY OR RESEARCH RESPONSIBILITIES FOR COAL AND COAL QUALITY

U.S. Department of the Interior

1849 C Street, NW.
Washington, DC 20240
Telephone: (202) 208-3100
Internet: <http://www.doi.gov/>

U.S. Geological Survey

12201 Sunrise Valley Drive
Reston, VA 20192
Telephone: (703) 648-4000
Internet: <http://www.usgs.gov/>

U.S. Bureau of Land Management

1849 C Street, NW.
Washington, DC 20240
Telephone: (202) 452-5125
Internet: <http://www.blm.gov/>

Office of Surface Mining

1951 Constitution Avenue, NW.
Washington, DC 20240
Telephone: (202) 208-2719
Internet: <http://www.osmre.gov/>

U.S. Department of Energy

1000 Independence Avenue, SW.
Washington, DC 20585
Telephone: (202) 586-5000
Internet: <http://www.doe.gov/>

Energy Information Administration

1000 Independence Avenue, SW.
Washington, DC 20585
Telephone: (202) 586-8800
Internet: <http://www.eia.doe.gov/>

Office of Fossil Energy

1000 Independence Avenue, SW.
Washington, DC 20585
Telephone: (202) 586-6503

Internet: <http://www.fe.doe.gov/>

Argonne National Laboratory

9700 South Cass Avenue
Argonne, IL 60439
Telephone: (630) 252-2000
Internet: <http://www.anl.gov/>

U.S. Department of Agriculture

Washington, DC 20250
Telephone: (202) 720-2791
Internet: <http://www.usda.gov/>

U.S. Forest Service

Washington, DC 20250
Telephone: (202) 720-2791
Internet: <http://www.fs.fed.us/>

U.S. Environmental Protection Agency

1200 Pennsylvania Avenue, NW.
Washington, DC 20460
Telephone: (202) 260-2090
Internet: <http://www.epa.gov/>

U.S. Senate

Committee on Energy and Natural Resources
364 Dirksen Building
Washington, DC 20510
Telephone: (202) 224-4971
Internet: <http://energy.senate.gov/>

U.S. House of Representatives

Committee on Resources
1324 Longworth House Office Building
Washington, DC 20515
Telephone: (202) 225-2761
Internet: <http://resourcescomm.house.gov/>

