THE CHEMICAL AND PHYSICAL CHARACTERISTICS OF COAL

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In this chapter, an introductory overview of coal is presented, which includes a description of coal along with discussions of how it is formed, coal resources, and recoverable reserves in the world, with an emphasis on the United States' coals and coalfields, the types and characteristics of coal, and coal classification systems relevant to commercial coal use. The purpose of this chapter is to provide the reader with basic coal information as a prelude to the subsequent chapters.

1.1 DEFINITION OF COAL

Van Krevelen (1993) offers an encompassing definition of coal:

> Coal is a rock, a sediment, a conglomerate, a biological fossil, a complex colloidal system, an enigma in solid-state physics and an intriguing object for chemical and physical analyses.

In short, coal is a chemically and physically heterogeneous, "combustible," sedimentary rock consisting of both organic and inorganic material. Organically, coal consists primarily of carbon, hydrogen, and oxygen, with lesser amounts of sulfur and nitrogen. Inorganically, coal consists of a diverse range of ash-forming compounds distributed throughout the coal. The inorganic constituents of coal can vary in concentration, from several percentage points down to parts per billion.

1.2 ORIGIN OF COAL

Coal is found in deposits called seams that originated through the accumulation of vegetation that has undergone physical and chemical changes. These changes include decaying of the vegetation, deposition and burying by sedimentation, compaction, and transformation of the plant remains into the organic rock found today. Coals differ throughout the world in terms of the kinds of plant materials deposited (type of coal), the degree of metamorphism or coalification (rank of coal), and the range of impurities included (grade of coal).

There are two main theories about the accumulation of the vegetal matter that creates coal seams (Moore, 1922). The first theory, and the one that is most accepted because it explains the origin of most coals, is that the coal formed in situ—that is, where the vegetation grew and fell—and such a deposit is said to be autochthonous in origin. Most coal deposits began with thick peat bogs where the water was nearly stagnant and plant debris accumulated. Vegetation tended to grow for many

Clean Coal Engineering Technology. http://dx.doi.org/10.1016/B978-0-12-811365-3.00001-6

generations, with plant material settling on the swamp bottom and converted into peat by microbiological action. After some time, the swamps became submerged and were covered by sedimentary deposits, and a future coal seam was formed. When this cycle was repeated over hundreds of thousands of years, additional coal seams were formed. These cycles of accumulation and deposition were followed by diagenetic (i.e., biological) and tectonic (i.e., geological) actions. Ultimately, depending upon the extent of temperature, time, and forces exerted, the different ranks of coal that are currently observed were formed.

While the formation of most coals can be explained by the autochthonous process, some deposits are not easily explained by this model. Some coals appear to have been formed through the accumulation of vegetal matter that has been transported by water. According to this theory (i.e., allochthonous origin) the fragments of plants were carried by streams and deposited on the bottom of the sea or lakes, which later became compressed into solid rock.

Major coal deposits formed in nearly every geological period since the Upper Carboniferous Period, 350–270 million years ago, with the main coal-forming periods shown in Fig. 1.1 (Walker, 2000). Fig. 1.1 shows the relative ages of the world's major coal deposits. The considerable diversity of various coals is due to the differing climatic and botanical conditions that existed during the main coal-forming periods, along with subsequent geophysical actions.

The most significant events of coal formation occurred during Carboniferous times. In what is now southern and northern Europe, the continents of Africa, South America, and North America shifted together, forming a single land mass (Pangea) and creating a zone of mountain-building

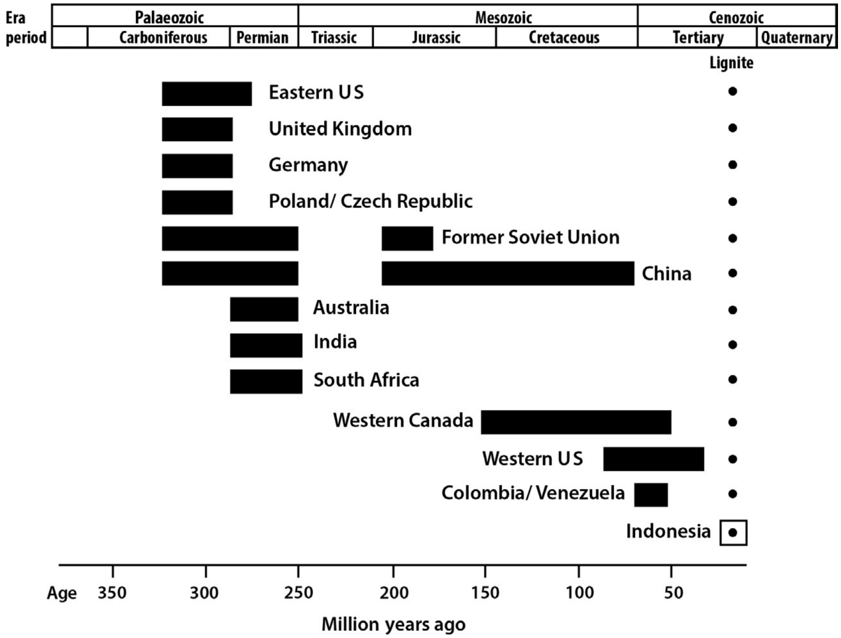
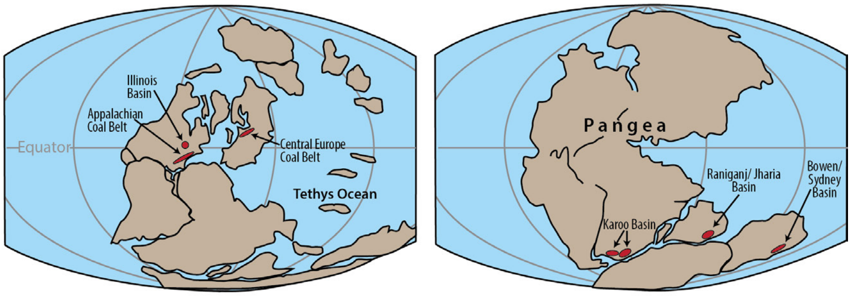


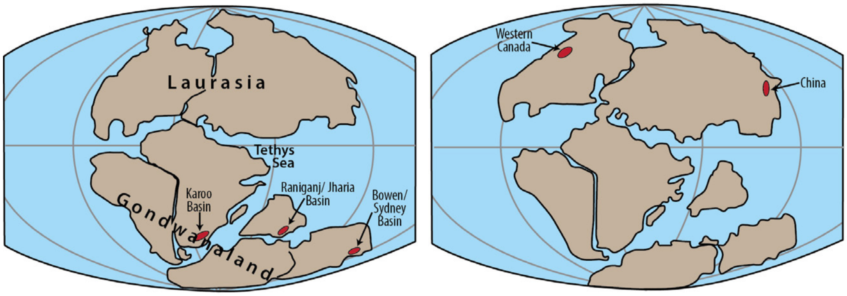
FIG. 1.1

Comparison of the geological ages of the world's hard coal and lignite deposits.



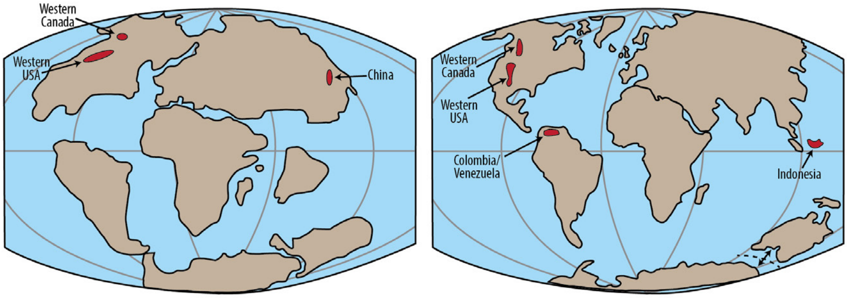
Late Carboniferous
300 million years ago

Permian
270 million years ago



Triassic
225 million years ago

Jurassic
175 million years ago



Cretaceous
145 million years ago

Tertiary
65 million years ago

FIG. 1.2

Continental reconstruction and coal basin formation.

Modified from Walker, S., 2000. Major Coalfields of the World. IEA Coal Research, London; University of Southern California, 2007. Earth guide online classroom. http://earthguide.ucsd.edu/eoc/teachers/t_tectonics/t_tectonics.html.

(Walker, 2000; Berkowitz, 1979). Fig. 1.2 shows the various periods of continental reconstruction with some of the coal basins formed during that period identified. As the Tethys Sea began its slow retreat toward the present-day limits of the Mediterranean Sea during the Lower Carboniferous times (i.e., Mississippian period), coal began to deposit in Pennsylvania and Virginia, New Brunswick and Nova Scotia, Scotland, Northumberland (Britain), and Maine, Brittany and Basse-Loire (France) (Berkowitz, 1979).

At the time the major Carboniferous coal basins were being formed in the Northern Hemisphere, the southern part of the Pangea continent (Gondwana) was centered over the South Pole. This landmass drifted northward with the approach of the Permian period and transformed from a subarctic to a cool temperate climatic zone. During the Permian period, major coal deposits formed in Australia, South Africa, India, and South America (Walker, 2000; Berkowitz, 1979).

In Jurassic times, North America and Africa drifted apart. Coal deposits formed during the Triassic and Jurassic periods in what are now Australia and China. During the Cretaceous period, Africa drifted from South America, and the Pacific Philippine Plate began to separate from the Asian continental plate. India moved toward Asia, and major deformation occurred in response to collision and subduction along the cordillera of North and South America (Walker, 2000). These movements created the conditions for the development of the final main phase of coal formation, which extended from the Cretaceous to Tertiary times.

The differences between coals of different geologic ages can be related to their various modes of formation (Walker, 2000; Berkowitz, 1979). The Northern Hemisphere (Laurasian) Carboniferous coals are rich in the vitrinite group of macerals (these are discussed later in the chapter) that are characteristic of deposition in quickly subsiding conditions. Such deposits often contain numerous well-defined seams. Many of the Southern Hemisphere (Gondwanan) Permian coals were deposited on more stable shelf areas, sometimes forming thick seams that grade into carbonaceous shale. The vitrinite content is variable. Gondwanan coals also tend to have a higher mineral matter content than Laurasian coals, in the form of finely dispersed grains of clay and quartz that are difficult to remove during beneficiation. The sulfur content of Laurasian coals is generally higher than those of Gondwanan origin. This appears to relate to the higher frequency of marine roof rocks associated with Laurasian coals, whereas Gondwana coals are often overlain by freshwater sediments.

1.3 COALIFICATION

The geochemical process that transforms plant material into coal is called coalification and is often expressed as

$$\text{Peat} \rightarrow \text{lignite} \rightarrow \text{subbituminous coal} \rightarrow \text{bituminous coal} \rightarrow \text{anthracite}$$

This is a simplistic classification, and more elaborate systems have evolved and are discussed later in this chapter. Coalification can be described geochemically as consisting of three processes: the microbiological degradation of the cellulose of the initial plant material, the conversion of the lignin of the plants into humic substances, and the condensation of these humic substances into larger coal molecules (Tatsch, 1980). The kind of decaying vegetation, conditions of decay, depositional environment, and the movements of the earth's crust are important factors in determining the nature, quality, and relative position of the coal seams (Van Krevelen, 1993). Of these, the physical forces exerted upon the deposits play the largest role in the coalification process. Variations in the chemical composition of the original plant material contributed to the variability in coal composition (Van Krevelen, 1993; Schobert, 1987). The vegetation of various geologic periods differed biologically and chemically, and the conditions under which the vegetation decayed are important. The depth, temperature, degree of acidity, and the natural movement of water in the original swamp are important factors in the formation of the coal (Van Krevelen, 1993; Mitchell, 1997).

The geochemical phase of the coalification process is the application of temperature and pressure over millions of years, and it is the most important factor of the coalification process. While there is some disagreement as to which is more important in promoting the chemical and physical changes—the high pressures exerted by massive overburdening strata or time-temperature factors—the changes are characterized physically by decreasing porosity and increasing gelification and vitrification (Elliott, 1981).

The process of coalification involves several sequential reactions from the base material, the plant life that forms the basis for coal. Highly reactive matter (e.g., some extractives and hemicelluloses) can undergo low-grade oxidation or volatilization processes in the presence of heat and pressure. This material can "leave" the fuel matrix. The lignins, which are the "glues" that hold the biomass material together, remain in the fuel matrix and contain aromatic structures as single units. Under pressure and temperature, lignins and other remaining biomass matter undergo condensation to form peat and then the various coals. The condensation processes produce coals with fused aromatic rings ranging in number from two to six depending upon coal rank.

Coalification also involves changes in functional groups attached to the fused aromatic structures, or coal backbones. As rank increases, the number and type of functional groups decreases. For example, methoxy ($-O_{COOH_3}$) functional groups are commonly found in significant concentrations in lignites and some subbituminous coals. As rank increases, the concentration of such functionalities decreases; bituminous coals do not contain such functional groups. The characteristics of oxygen, which Van Krevelen and Schuyer (1957) identified, are important considerations in understanding the chemical changes in coal as a function of rank (i.e., increasing coalification). In Table 1.1, note the higher total concentration of oxygen in the lower-rank coals and also the presence of oxygen in highly reactive functional groups (O_{COOH}, O_{COOH_3} , and O_{OH}). As rank increases (which is indicated by increasing carbon content), the concentration of oxygen in the coal decreases, and the presence of oxygen in the most reactive functionalities decreases to nearly zero.

As rank increases, chemically there is a decrease in moisture and volatile matter (i.e., methane and carbon dioxide) content, as well as an increase in the percentage of carbon, a gradual decrease in the percentage of oxygen, and ultimately, as the anthracitic stage is approached, a marked decrease in the content of hydrogen (Schobert, 1987; Elliott, 1981). For example, carbon content (on a dry, mineral-matter-free basis) increases from ~50% in herbaceous plants and wood to 60% in peat, 70% in lignite, 75% in

Table 1.1 Oxygen Content by Functional Group

Carbon Content (%)	Oxygen Content by Functional Group (Wt.%)				
	O_{COOH}	O_{COOH_3}	O_{OH}	$O_{C=O}$	O_{NR}
65.5	8.0	1.1	7.2	1.9	9.6
70.5	5.1	0.4	7.8	1.1	8.2
75.5	0.6	0.3	7.5	1.4	6.4
81.5	0.3	0.0	6.1	0.5	4.2
85.5	0.05	0.0	5.6	0.5	1.75
87.0	0.0	0.0	3.2	0.6	1.3
88.6	0.0	0.0	1.9	0.25	0.85
90.3	0.0	0.0	0.5	0.2	2.2

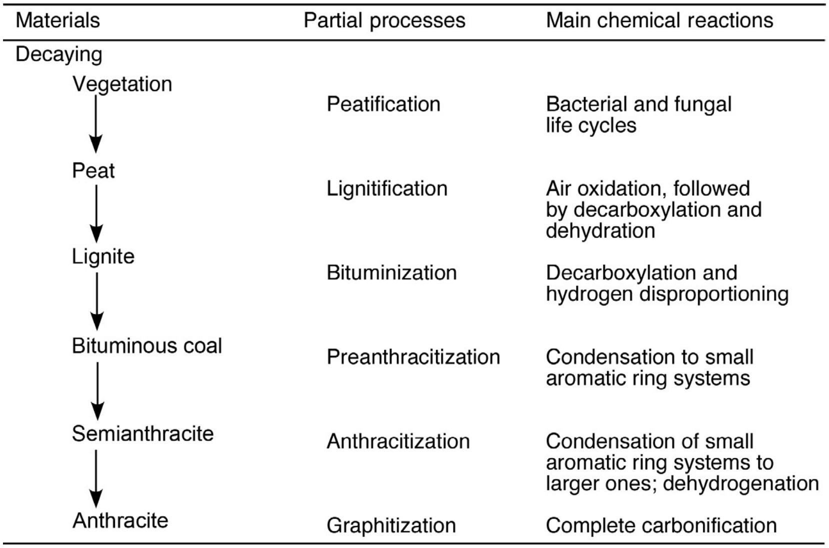


FIG. 1.3

The coalification process.

subbituminous coal, 80–90% in bituminous coal, and >90% in anthracite (Berkowitz, 1979; Schobert, 1987; Singer, 1981; Miller et al., 2003). This change in carbon content is known as carbonification. The coalification/carbonization process is shown in Fig. 1.3, where some of the main chemical reactions that occur during coalification are listed (Van Krevelen, 1993).

1.4 THE CLASSIFICATION OF COAL

Efforts to classify coals began over 185 years ago and were prompted by the need to establish some order in the confusion in identifying different coals. Two types of classification systems arose: one to aid scientific studies and one to assist coal producers and users. The scientific systems of classification are concerned with the origin, composition, and fundamental properties of coals, while the commercial systems address trade and market issues, utilization, technological properties, and suitability for certain end uses. It is the latter classification systems that will be discussed here. Excellent discussions on scientific classifications are given elsewhere (Van Krevelen, 1993; Berkowitz, 1979).

1.4.1 BASIC COAL ANALYSIS

Before discussing the rank, type, grade, and classification systems of coal, there is a discussion of basic coal analyses, on which the classification schemes are based. These analyses do not yield any information on coal structure but do provide important information on coal behavior and are used in the marketing of coals.

Three analyses are used in classifying coal: two chemical analyses and one calorific determination. The chemical analyses include proximate and ultimate analysis. The proximate analysis gives the relative amounts of moisture, volatile matter, ash (i.e., inorganic material left after all the combustible matter has been burned off), and, indirectly, the fixed carbon content of the coal. The ultimate analysis gives the amounts of carbon, hydrogen, nitrogen, sulfur, and oxygen comprising the coal. Oxygen is typically determined by difference, i.e., subtracting the total percentages of carbon, hydrogen, nitrogen, and sulfur from 100, because of the complexity in determining oxygen directly. However, this technique accumulates all the errors in determining the other elements into the calculated value for oxygen. The third important analysis, the calorific value (also known as heating value), is a measure of the amount of energy that a given quantity of coal will produce when burned.

Since moisture and mineral matter (or ash) are extraneous to the coal substance, analytical data can be expressed on several different bases to reflect the composition of as received, air-dried, or fully water-saturated coal or the composition of dry, ash-free (daf) or dry, mineral-matter free (dmmf) coal. The most commonly used bases in the various classification schemes are shown in Fig. 1.4 (Ward, 1984). Descriptions of the most commonly used bases are as follows (Van Krevelen, 1993):

- As received—data are expressed as percentages of the coal with the moisture. This is also sometimes referred to as as-fired and is commonly used by the combustion engineer to monitor operations and for performing calculations since it is the whole coal that is being utilized.
- Dry basis (db)—data are expressed as percentages of the coal after the moisture has been removed.

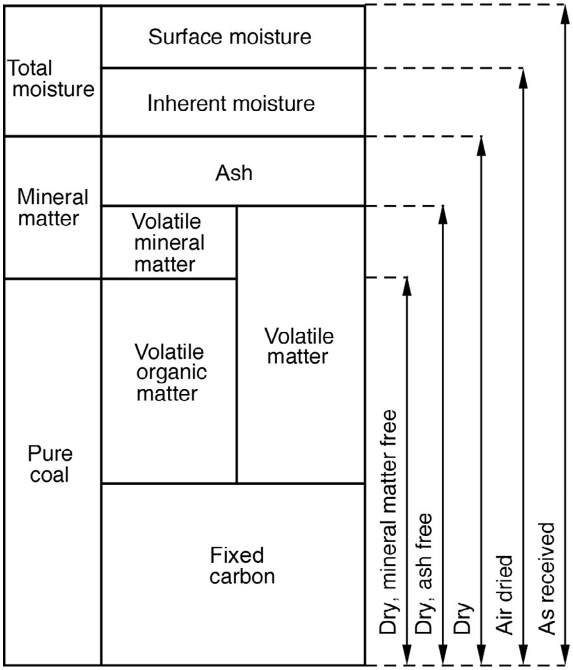


FIG. 1.4

Relationship of different analytical bases to coal components.

- Dry, ash-free (daf) basis—data are expressed as percentages of the coal with the moisture and ash removed.
- Dry, mineral-matter-free (dmmf) basis—the coal is assumed to be free of both moisture and mineral matter and the data are a measure of only the organic portion of the coal.
- Moist, ash-free (maf) basis—the coal is assumed to be free of ash but still contains moisture.
- Moist, mineral-matter-free (mmmf) basis—the coal is assumed to be free of mineral matter but still contains moisture.

1.4.2 THE RANKS OF COAL

The degree of coal maturation is known as the rank of coal and is an indication of the extent of metamorphism the coal has undergone. Because vitrinite precursors (see Section 1.4.3 for a discussion on maceral types), such as humates and humic acids, were the major constituents in peat, the extent of metamorphism is often determined by noting the changes in the properties of vitrinite (Elliott, 1981). Some of the more important properties of vitrinite that did change with metamorphism are listed in Table 1.2 (Elliott, 1981). Metamorphism did affect the other macerals, but the relationship between the severity of metamorphism and the magnitude of change are different from those of vitrinite.

Several useful rank-defining properties are elemental carbon content, volatile matter content, moisture-holding capacity, heating value, and microscopic reflectance of vitrinite (Elliott, 1981).

Table 1.2 Properties of Vitrinite Affected Progressively by Metamorphism

Increase with increasing rank
Reflectance (microscopic) and optical anisotropy Carbon content Aromaticity, $f_a = C_{aromatic}/C_{total}$ Condensed-ring fusion Parallelization of molecular moieties Heating value (a slight decrease at very high rank)
Decrease with increasing rank
Volatile matter (especially oxygenated compounds) Oxygen content (especially as functional groups) Oxidizability Solubility (especially in aqueous alkalis and polar hydrocarbons)
Increase initially to a maximum, then decrease
Hardness (minor increase at very high rank) Plastic properties Hydrogen content
Decrease initially to a minimum, then increase
Surface area Porosity (and moisture holding capacity) Density (in helium)

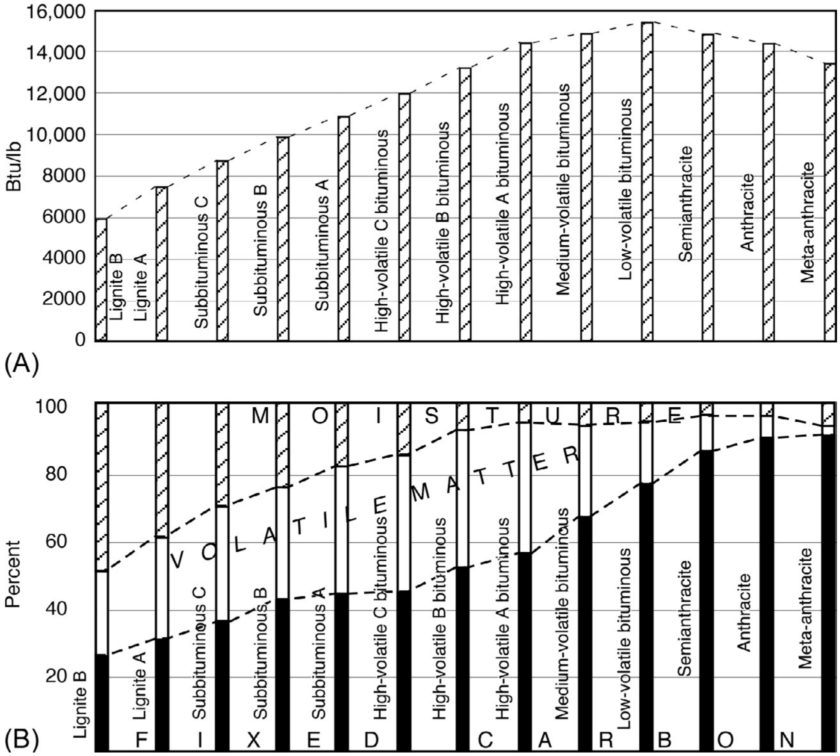


FIG. 1.5

Comparison of heating values (on a moist, mineral matter-free basis) (A) and proximate analyses (B) of coals of different ranks.

Fig. 1.5 illustrates the relationship between rank and fixed carbon content (Averitt, 1975), the one chemical property most used to express coal rank. In the United States, lignites and subbituminous coals are referred to as being low in rank while bituminous coals and anthracites are classified as high-rank coals. In Europe, low-rank coals are referred to as brown coal or lignite, and hard coals are anthracite and bituminous coals; in some cases, subbituminous coals are included as well. Fig. 1.5 illustrates this relationship between rank and fixed carbon content (Averitt, 1975). Fixed carbon content in Fig. 1.5 is calculated on a dmmf basis. Fig. 1.5 also shows the comparison between heating value and rank with the heating value calculated on an mmmf basis. Note that the heating value increases with increasing rank but begins to decrease with semianthracitic and higher rank coals. This decrease in heating value is due to the significant decrease in volatile matter, which is shown in Fig. 1.5 (Averitt, 1975). The relationship between heating value (and fixed carbon content) and coal rank in the United States is also shown in Fig. 1.6 (Schwienfurth, 2009).

Another example of the coal composition/rank relationship is shown in Fig. 1.7, which is a type of coalification diagram; this figure is based on an analysis of the U.S. Geological Survey coal database (U.S. Geological Survey, 2006). In general, as coal rank increases, there is a decrease in O/C and H/C atomic ratios.

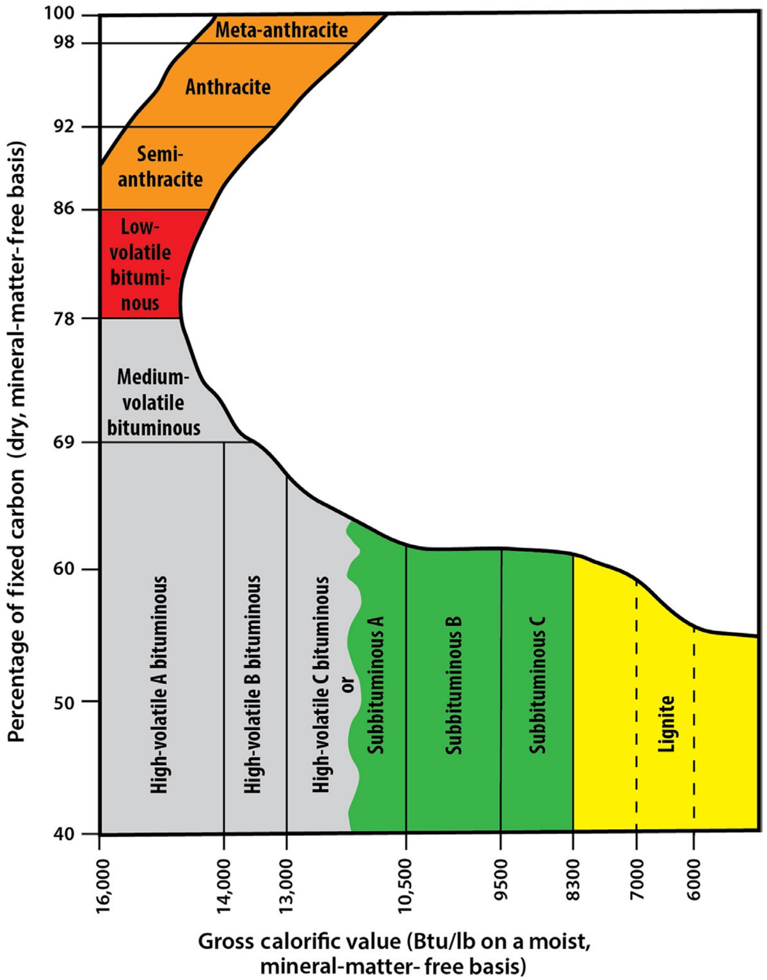


FIG. 1.6

Diagram showing classification of coals by rank in the United States.

The hydrogen content of the humic coals tends to be fairly constant at 5.5 ± 0.5%, despite a wide variation of carbon content over the range of coal ranks (Schobert, 1987). The variation of hydrogen content as a function of carbon content is represented as the Seyler coal band shown in Fig. 1.8.

Porosity decreases with an increasing level of metamorphism, thereby reducing the moisture-holding capacity of the coal. Moisture-holding capacity is also affected by the functional group characteristics, and in coals where cationic elements replace protons on acid functional groups, moisture-holding capacity is reduced (Elliott, 1981).

Vitrinite reflectance is another import rank-measuring parameter. The advantage of this technique is that it measures a rank-sensitive property on only one petrographic constituent; therefore, it is applicable

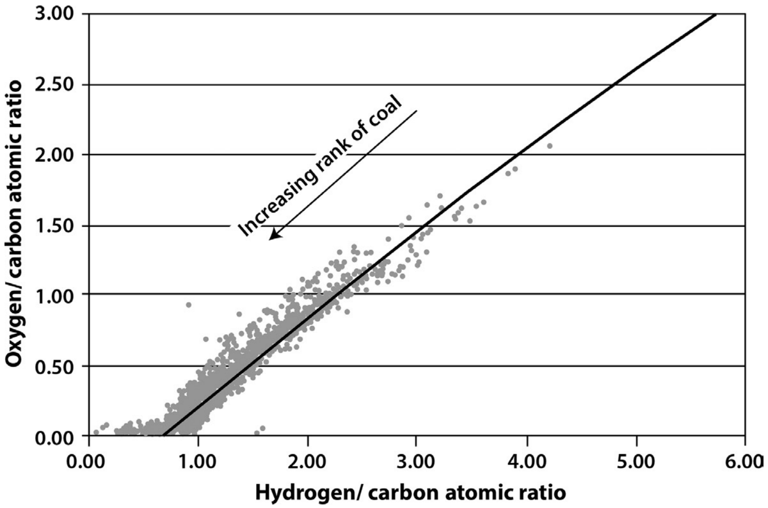


FIG. 1.7

Coal rank as a function of hydrogen/carbon and oxygen/carbon atomic ratios.

even where the coal type is atypical (Elliott, 1981). This is illustrated in Fig. 1.9, which shows the relationship of vitrinite reflectance, as well as several other parameters, as a function of coal rank.

1.4.3 THE TYPES OF COAL

As mentioned previously, coal is composed of macerals, discrete minerals, inorganic elements held molecularly by the organic matter, and water and gases contained in submicroscopic pores. Macerals are organic substances derived from plant tissues that have been incorporated into the sedimentary strata, subjected to decay, compacted, and chemically altered by geological processes. This organic matter is extremely heterogeneous and a classification system has been developed to characterize it (Elliott, 1981; Taylor et al., 1998; Bustin et al., 1983). Coal classification, known as petrography, was primarily used to characterize and correlate coal seams and resolve questions about coal diagenesis and metamorphism, but it is now an important tool in assessing coals for industrial applications (Suárez-Ruiz and Crelling, 2008; Miller and Tillman, 2005).

All macerals are classified into three maceral groups—vitrinite, liptinite (sometimes also referred to as exinite), and intertinite—and they are characterized by their appearance, chemical composition, and optical properties. Each maceral group includes a number of macerals and other subcategories, but only the three preceding maceral groups are introduced here; more extensive discussions of petrography can be found elsewhere (Berkowitz, 1979; Elliott, 1981; Taylor et al., 1998; Bustin et al., 1983).

In most cases, the constituents in the coal can be traced back to specific components of the plant debris from which the coal formed (Berkowitz, 1979; Elliott, 1981; Taylor et al., 1998; Bustin et al., 1983). Fig. 1.10 is a simplified overview of these various substances that accumulated as peat deposited and the components they represent in coal. Adding to the complexity of the source materials were inorganic substances (also shown in Fig. 1.10) that entered the environment as mineral grains and dissolved

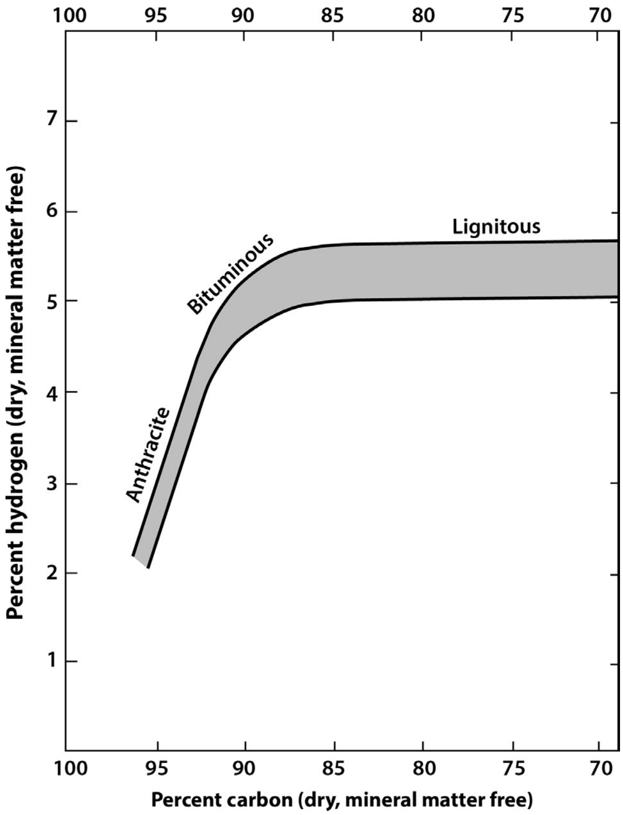


FIG. 1.8

The Seyler coal band. Most of the humic coals in the world have carbon and hydrogen contents that lie in the shaded region of the band.

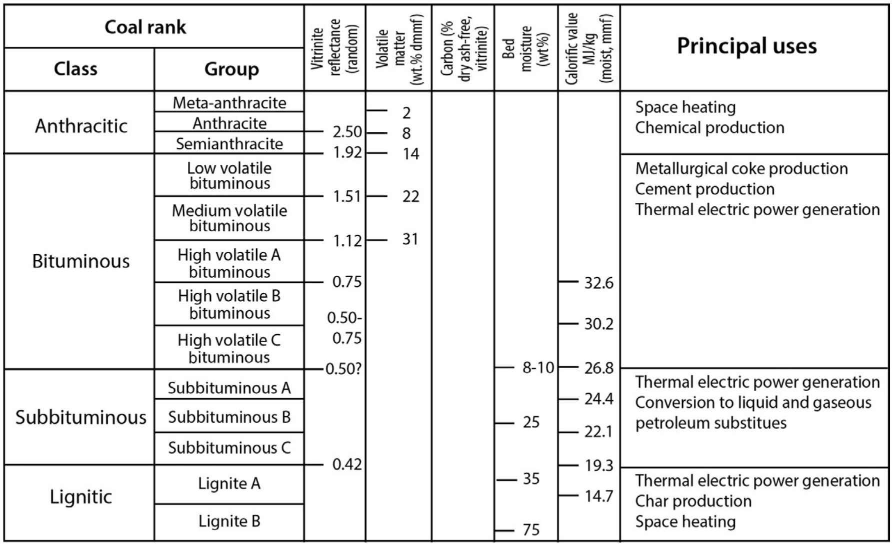
Modified from Schobert, H.H., 1987. Coal: The Energy Source of the Past and Future. American Chemical Society, Washington, DC.

ions. Many of the dissolved ions either combined with the organic fraction or were precipitated in place to form discrete mineral grains (Elliott, 1981).

Vitrinite group macerals are derived from the humification of woody tissues and can either possess remnant cell structures or be structureless (Mitchell, 1997). Vitrinite contains more oxygen than the other macerals at any given rank level, and they are characterized by a higher aromatic fraction.

Liptinite group macerals are not derived from humifiable materials but rather from relatively hydrogen-rich plant remains such as resins, spores, cuticles, waxes, fats, and algal remains, which are fairly resistant to bacterial and fungal decay (Berkowitz, 1979; Suárez-Ruiz and Crelling, 2008). Liptinites are distinguishable by a higher aliphatic (i.e., paraffin) fraction and a correspondingly higher hydrogen content, especially at lower ranks (Taylor et al., 1998).

The inertinite group macerals were derived mostly from woody tissues, plant degradation products, or fungal remains. While they were derived from the same original plant substances as vitrinite and liptinite, they have experienced a different primary transformation (Taylor et al., 1998). Inertinite group



Coal rank: Class	Coal rank: Group	Vitrinite reflectance (random)	Volatile matter (wt.% dmmf)	Carbon (% dry ash-free, vitrinite)	Bed moisture (wt%)	Calorific value MJ/kg (moist, mmf)	Principal uses
Anthracitic	Meta-anthracite		2				Space heating Chemical production
	Anthracite	2.50	8				
	Semianthracite	1.92	14				
Bituminous	Low volatile bituminous	1.51	22				Metallurgical coke production Cement production Thermal electric power generation
	Medium volatile bituminous	1.12	31				
	High volatile A bituminous	0.75				32.6	
	High volatile B bituminous	0.50- 0.75				30.2	
	High volatile C bituminous	0.50?			8-10	26.8	
Subbituminous	Subbituminous A					24.4	Thermal electric power generation Conversion to liquid and gaseous petroleum substitues
	Subbituminous B				25	22.1	
	Subbituminous C	0.42				19.3	
Lignitic	Lignite A				35	14.7	Thermal electric power generation Char production Space heating
	Lignite B				75		

FIG. 1.9

Classification of coals by rank and indices of organic maturity (Note: To convert from MJ/kg to Btu/lb, multiply by 429.923).

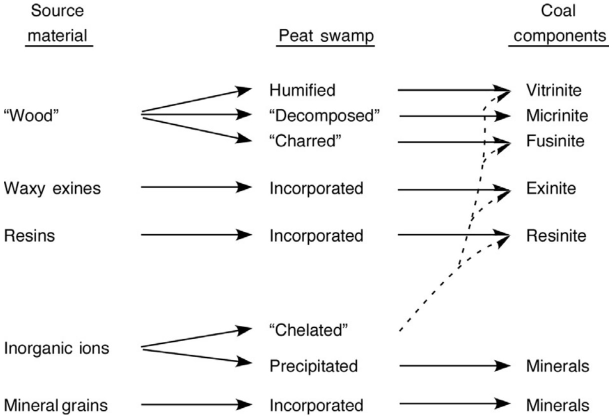


FIG. 1.10

Plant materials that accumulated along with inorganic materials in the peat swamp retain their identity as distinctive macerals in the coal.

Modified from Elliott, M.A. (Ed.), 1981. Chemistry of Coal Utilization: Second Supplementary Volume. John Wiley & Sons, New York, NY.

macerals are characterized by a high carbon content that resulted from thermal or biological oxidation, as well as low hydrogen content and an increased level of aromatization (Van Krevelen and Schuyer, 1957; Taylor et al., 1998).

Although petrographic analysis has many uses, it was initially used to primarily characterize and correlate seams and resolve questions about coal diagenesis and metamorphism. Later, it influenced developments in coal preparation (i.e., crushing, grinding, and removal of mineral constituents) and conversion technologies (Berkowitz, 1979). Industrially, petrographic analysis can provide insight into the hardness of a coal (i.e., its mechanical strength) as well as a coal's thermoplastic properties, which is of significant importance in the coking industry.

1.4.4 THE GRADES OF COAL

The grades of coal refer to the amount of mineral matter that is present in the coal and are a measure of coal quality. Sulfur content, ash fusion temperatures (i.e., the measure of the behavior of ash at high temperatures), and quantity of trace elements in coal are also used to grade coal. Formal classification systems have not been developed for the grades of coal, but grade is still important to the coal user.

Mineral matter may be finely dispersed throughout the coal or occur in discrete partings in the coal. Some of the inorganic matter and trace elements are derived from the original vegetation, but the majority is introduced during coalification by wind or water to the peat swamp or through movement of solutions in cracks, fissures, and cavities (Mackowsky, 1968). Coal mineralogy can affect the ability to remove minerals during coal preparation/cleaning, coal combustion and conversion (i.e., production of liquid fuels or chemicals) characteristics, and metallurgical coke properties.

1.4.5 CLASSIFICATION SYSTEMS

An excellent discussion of the many classification systems, scientific as well as commercial, is provided by van Krevelen (Van Krevelen, 1993). The commercial systems that are discussed here consist of two primary systems: the ASTM (American Society of Testing Materials) system used in the United States/North America and an international ECE (Economic Commission for Europe) Codification system developed in Europe. It is interesting to note that in all countries, the classification systems used commercially are primarily based on the content of volatile matter (Van Krevelen, 1993). In some countries, a second parameter is also used, and in the United States, for example, this is the heating value (see Fig. 1.5). In many European countries, this parameter is either the caking or the coking properties. Caking coals are coals that pass through a plastic state upon heating in which they soften, swell, and resolidify into a coherent carbonaceous matrix. Noncaking coals, on the other hand, do not become plastic when heated and produce a weakly coherent char residue. Coking coals are strongly caking coals that exhibit characteristics that make them suitable for conversion into metallurgical and other industrial cokes (Berkowitz, 1979).

The ASTM classification system

The ASTM classification system (ASTM D388) distinguishes between four coal classes, each of which is subdivided into several groups and is shown in Table 1.3 (Berkowitz, 1979). As previously mentioned, high-rank coals (i.e., medium volatile bituminous coals or those of higher rank) are classified based on their fixed carbon and volatile matter contents (expressed on a dmmf basis), while low-rank coals are classified in terms of their heating value (expressed on an mmmf basis).

Table 1.3 ASTM Coal Classification by Rank

Class/Group	Fixed Carbon[a] (%)	Volatile Matter[b] (%)	Heating Value[b] (Btu/lb)
Anthracitic			
Metaanthracite	>98	<2	
Anthracite	92–98	2–8	
Semianthracite	86–92	8–14	
Bituminous			
Low volatile	78–86	14–22	
Medium volatile	69–78	22–31	
High volatile A	<69	>31	>14,000
High volatile B			13,000–14,000
High volatile C			10,500–13,000[c]
Subbituminous			
Subbituminous A			10,500–11,500[c]
Subbituminous B			9500–10,500
Subbituminous C			8300–9500
Lignitic			
Lignite A			6300–8300
Lignite B			<6300

[a] *Calculated on dry, mineral matter-free coal; correction from ash to mineral matter is made by means of the Parr formula: mineral matter = 1.08[percent ash + 0.55(percent sulfur)]. Ash and sulfur are on a dry basis.*

[b] *Calculated on mineral-matter-free coal with bed moisture content.*

[c] *Coals with heating values between 10,500 and 11,500 Btu/lb are classified as high-volatile C bituminous if they possess caking properties; they are classified as subbituminous A if they do not possess caking properties.*

This classification system was developed for commercial applications but has proved to be satisfactory for certain scientific uses as well (Elliott, 1981). For example, if a given coal is described as being a certain rank, then an estimate of some properties can be made, and if the coal is classified as subbituminous/lignitic or anthracitic, then it would not be considered for certain applications such as coke production.

International classification/codification systems

Because of the increasing amount of coal trade worldwide, the ECE Coal Committee developed a new classification system in 1988 for higher rank coals (Van Krevelen, 1993). The original international system had deficiencies in that it was primarily developed for trading Northern Hemisphere coals, which have had distinctly different characteristics than those from the Southern Hemisphere (e.g., Australia and South Africa). As trade of Southern Hemisphere coals increased, it became apparent that a new classification system was needed. This new system, which in reality is a system of codes, is better known as a codification system. The codification system for hard coals, combined with the ISO (International Organization for Standardization) codification of brown coals and lignites (which was established in 1974), provides a complete codification for coals in the international trade.

Table 1.4 Codification of Brown Coals and Lignites

Parameter	Total Moisture Content (Run-of-Mine Coal)		Tar Yield (Dry, Ash Free)	
Digit:	**1**		**2**	
Coding:	**Code**	**Wt.%**	**Code**	**Wt.%**
	1	≤20	0	≤10
	2	>20 to 30	1	>10 to 15
	3	>30 to 40		
	4	>40 to 50	2	>15 to 20
	5	>50 to 60	3	>20 to 25
	6	>60	4	>25

The ISO codification of brown coals and lignites is given in Table 1.4 (Van Krevelen, 1993). Total moisture content of run-of-mine coal and tar yield (i.e., determination of the yields of tar, water, gas, and coke residue by low-temperature distillation) are the two parameters coded.

The ECE international codification of higher-rank coals is much more complicated and is listed in Table 1.5 (Van Krevelen, 1993). Eight basic parameters define the main properties of the coal, which are represented by a 14-digit code number. The codification, which is for medium- and high-rank coals, blends and single coals, raw and washed coals, and all end-use applications, is commercial and includes petrographic, rank, grade, and environmental information (Van Krevelen, 1993). The major drawback of this system is that it is very complicated.

1.4.6 GENERAL COAL CHARACTERISTICS

As mentioned previously, coal is composed of complex mixtures of organic and inorganic compounds. The organic compounds, originating from the plants that live and die in the swamps/bogs, number in the millions. The more than 100 inorganic compounds in coal either were introduced into the swamps from water-borne or wind-borne sediment or were derived from elements in the original vegetation (Schwienfurth, 2009).

Coals may contain as many as 76 of the 90 naturally occurring elements of the periodic table, as shown in Fig. 1.11; however, most of those elements are present in only trace amounts on the order of parts per million. The organic compounds in coal are composed of the elements carbon, hydrogen, nitrogen, sulfur, oxygen, and trace amounts of many other elements. The mode of occurrence of the trace elements in coal affects the quality of the coal. If trace elements are organically bound, it is difficult to remove them from the coal by cleaning processes and they are released mainly during utilization such as upon combustion. In contrast, trace elements associated with clays or pyrite may be removed through coal cleaning processes prior to utilization.

Examples of US and international coal analyses are provided to illustrate the differences in coal composition as a function of rank and geographical location. Coal analyses exhibit variability both within and between coal seams, but the following tables show some of the major differences between the ranks of coal and geographical location for some of the major coal producers in the world. These

Table 1.5 International Codification of Higher-Rank Coals[a]

Parameter	Vitrinite Reflectance (Mean Random)		Characteristics of Reflectogram[b]				Maceral Group Composition (mmf)				
							Inertinite[c]		Liptinite		
Digit:	1, 2		3				4		5		
Coding:	Code	R_{random}%	Code	Standard Deviation		Type	Code	Vol.%	Code	Vol.%	Petrographic Tests
	02	0.2–0.29	0	≤1	No gap	Seam coal	0	0 to <10	1	0 to <5	
	03	0.3–0.39	1	>0.1 to ≤0.2	No gap	Simple blend	1	10 to <20	2	5 to <10	
	04	0.4–0.49	2	>0.2	No gap	Complex blend	2	20 to <30	3	10 to <15	
	–	–	3		1 gap	Blend with 1 gap	–	–	–	–	
	48	4.8–4.89	4		2 gaps	Blend with 2 gaps	7	70 to <80	7	30 to <35	
	49	4.9–4.99	5		>2 gaps	Blend with >2 gaps	8	80 to <90	8	35 to <40	
	50	≥5.0				9	≥90	9	≥40		

Parameter	Crucible Swelling No.		Volatile Matter[d], daf		Ash, Dry		Total Sulfur, Dry		Gross Calorific Value, daf		
Digit:	6		7, 8		9, 10		11, 12		13, 14		
Coding:	Code	Number	Code	Wt.%	Code	Wt.%	Code	Wt.%	Code	MJ/kg	Technological Tests
	0	0–0.5	48	≥48	00	0 to <1	00	0 to <0.1	21	<22	
	1	1–1.5	46	46 to <48	01	1 to <2	01	0.1 to <0.2	22	22 to <23	
	2	2–2.5	44	44 to <46	02	2 to <3	02	0.2 to <0.3	23	23 to <24	

Continued

Table 1.5 International Codification of Higher-Rank Coals[a]—cont'd

Parameter	Crucible Swelling No.		Volatile Matter[d], daf		Ash, Dry		Total Sulfur, Dry		Gross Calorific Value, daf		
Digit:	**6**		**7, 8**		**9, 10**		**11, 12**		**13, 14**		
Coding:	**Code**	**Number**	**Code**	**Wt.%**	**Code**	**Wt.%**	**Code**	**Wt.%**	**Code**	**MJ/kg**	**Technological Tests**
	–	–	–	–	–	–	–	–	–	–	
	7	7–7.5	12	12 to <14	20	20 to <21	29	2.9 to <3.0	37	37 to <38	
	8	8–8.5	10	10 to <12	–	–	30	3.0 to <3.1	38	38 to <39	
	9	9–9.5	09	9 to <10			–	–	39	≥39	
			–	–							
			02	2 to <3							
			01	1 to <2							

[a] *Higher-rank coals are coals with gross calorific value (maf) ≥24 MJ/kg and those with gross calorific value (maf) <24 MJ/kg provided mean random vitrinitic reflectance ≥0.6%. To convert from MJ/kg to Btu/lb, multiply by 429.23.*

[b] *A reflectogram as characterized by code number 2 can also result from a high-rank seam coal.*

[c] *It should be noted that some of the intertinite may be reactive.*

[d] *Where the ash content of the coal is more than 10%, it must be reduced, before analysis, to below 10% by dense medium separation. In these cases, the cutting density and resulting ash content should be noted.*

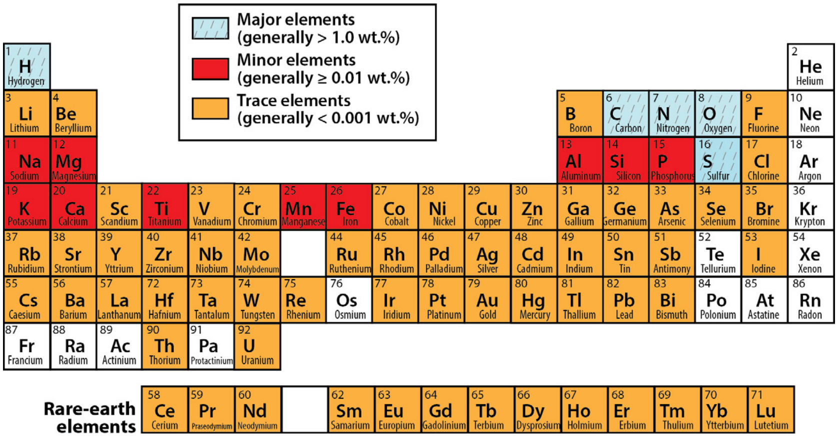


FIG. 1.11

Periodic table of the elements (minus those artificially prepared), showing those found in coal.

Modified from Schwienfurth, S.P., 2009. An Introduction to Coal Quality. U.S. Geological Survey Professional Paper 1625-F.

tables show the variability in various constituents that can lead to emissions such as sulfur, nitrogen, and mineral matter, i.e., fly ash and bottom ash. Also, where available, chlorine and mercury concentrations in the coal are also provided.

There is a very mature worldwide market for steaming coal. Until recently, the main coal exporting countries have been Australia, South Africa, Colombia, Poland, and the United States. More recently, the export markets in Russia, China, and Indonesia have been developed. The main importers of traded coals are developed countries with limited or no indigenous coal, i.e., countries in Western Europe and the Far East (Japan, Korea, and Taiwan). It should be noted that nearly all of this market is for relatively high-quality bituminous coal, as it is not economical to transport lower-rank coals large distances. The main exception is Indonesian coal that is mainly subbituminous in nature, although some high-volatile content bituminous coals are produced. These coals are mainly exported to countries in the Pacific Rim but have occasionally been purchased by European utilities.

The common feature of nearly all of these coals is the low sulfur content—0.3–0.8% for bituminous coals. Although the United States has been a significant coal exporter in the past, this exporting currently tends to be restricted to the higher sulfur content (>1%) coals. Because of SO_2 emission legislation in the United States, the low-sulfur indigenous coals generally command a higher price in the US market. For the same reason, there is increasing interest in importing low-sulfur world-traded coals into the United States. Because of the geographical proximity, the obvious source is South America (mainly Colombia, but also Venezuela), but even subbituminous Indonesian coal has been purchased by US utilities. The commercial attractiveness of importing coal into the United States will be heavily dependent on freight rates, which fluctuate considerably. However, it is conceivable that, in addition to South American coals, South African or even Russian coal could be attractive to East Coast utilities; similarly, Australian coals could be attractive on the West Coast.

Properties of selected anthracites, bituminous coals, and low-rank coals in the United States are given in Table 1.6 (Penn State Coal Sample Bank, n.d.), Table 1.7 (Tillman et al., 2004), and Table 1.8 (Miller, 2005), respectively. Tables 1.9 through 1.11 contain characteristic coal analyses for selected international anthracites, lignite/brown coals, and bituminous coals, respectively.

Table 1.6 Properties of Selected Anthracites in the United States

Rank	**Anthracite**	**Anthracite**	**Anthracite**	**Semianthracite**	**Semianthracite**	**Semianthracite**
Sample description	Mammoth Seam, PA	Buck Mtn. Seam, PA	#8 Leader Seam, PA	#8 Seam, PA	Gunnison Co., CO	L. Spadra Seam, AR
Proximate analysis (%, as-received)						
Moisture	3.1	2.5	1.3	1.0	1.1	0.8
Ash	23.4	13.6	8.2	25.1	7.0	6.3
Volatile matter	3.9	5.6	7.0	8.2	10.2	12.1
Fixed carbon	69.6	78.3	83.5	65.7	81.7	80.8
Ultimate analysis (%, dry, ash free)						
Carbon	93.5	90.8	91.3	89.6	91.5	92.2
Hydrogen	1.9	2.6	3.9	3.8	3.4	3.9
Nitrogen	1.2	0.8	0.6	1.4	1.6	2.1
Sulfur	1.0	0.6	1.2	1.6	0.8	0.8
Oxygen	2.4	5.2	3.0	3.6	2.7	1.0
HHV[a] **(Btu/lb)**	10,860	12,603	14,125	11,194	14,098	14,372
Maceral group anal. (vol.% min. free[b]**)**						
Vitrinite	89.5	96.3	97.5	70.8	92.4	87.7
Inertinite	10.5	3.7	2.5	29.2	7.6	12.3
Liptinite	0.0	0.0	0.0	0.0	0.0	0.0
Vitrinite reflectance (mean-maximum % in oil)	5.72	4.17	2.82	2.15	3.10	2.47
Ash fusion temperatures (reducing conditions, °F)						
Initial deform.	2700+	–[c]	–	–	–	2150
Softening	2700+	–	–	–	–	2250
Hemispherical	2700+	–	–	–	–	2485
Fluid	2700+	–	–	–	–	2560

Ash composition (%)						
SiO_2	56.5	54.9	56.7	58.8	37.4	34.4
Al_2O_3	28.4	32.4	32.5	32.3	25.3	26.2
TiO_2	1.77	3.82	1.81	1.27	0.80	1.01
Fe_2O_3	6.10	3.29	4.55	4.18	12.8	13.8
MgO	1.32	1.09	0.41	0.64	2.02	4.96
CaO	0.84	1.53	0.58	0.29	10.8	7.19
Na_2O	0.29	0.12	0.16	0.28	1.25	1.80
K_2O	2.70	1.22	2.30	2.99	1.20	1.50
P_2O_5	0.25	0.06	0.09	0.06	1.69	0.66
SO_3	0.70	2.10	0.20	0.10	7.69	9.00
Trace elements (ppm whole coal, dry)						
Chlorine	1300	100	100	400	100	100
Chromium	41	44	27	71	4	16
Mercury	–	0.05	0.08	–	–	0.03
Nickel	21	27	15	53	4	29
Lead	–	11	<3	19	–	10
Strontium	82	17	11	5	178	116
Vanadium	58	24	22	76	11	20

[a] *Higher heating value.*
[b] *White light.*
[c] *Not available.*

Table 1.7 Properties of Selected Bituminous Coals of the United States

Rank	**Low Vol.**	**Low Vol.**	**Med Vol.**	**Med. Vol.**	**Med. Vol.**	**High Vol. A**
Sample description	L. Kittanning Seam, PA	Elk Lick Seam, WV	U. Freeport Seam, PA	Dutch Creek Seam, CO	Sewell Seam, WV	Pittsburgh #8, PA
Proximate analysis (%, as-received)						
Moisture	2.0	1.3	6.1	1.1	1.5	2.4
Ash	10.1	18.3	10.1	5.3	4.2	10.0
Volatile matter	17.4	16.0	22.9	26.9	24.6	35.2
Fixed carbon	70.5	64.4	60.9	66.7	69.7	52.4
Ultimate analysis (%, dry, ash free)						
Carbon	88.8	87.2	87.0	87.4	88.2	83.3
Hydrogen	4.7	4.7	5.5	5.9	5.0	5.7
Nitrogen	1.6	1.5	1.7	1.7	1.5	1.4
Sulfur	1.6	3.3	2.9	0.7	0.7	1.3
Oxygen	3.2	3.3	2.9	4.3	4.6	8.3
HHV[a] **(Btu/lb)**	14,025	12,535	14,006	14,889	14,871	13,532
Maceral group anal. (vol.% min. free[b]**)**						
Vitrinite	90.0	92.7	88.5	94.4	77.2	83.0
Inertinite	9.9	7.3	11.5	5.6	18.0	8.9
Liptinite	0.1	0.0	0.0	0.0	4.8	8.1
Vitrinite reflectance (mean-maximum % in oil)	1.73	1.63	1.24	1.28	1.35	0.87
Ash fusion temperatures (reducing conditions, °F)						
Initial deform.	2700+	2530	–	2020	2750	2225
Softening	2700+	2550	–	2130	2800+	2330
Hemispherical	2700+	2600	–	2200	2800+	2390
Fluid	2700+	2670	–	2250	2800+	2445

Ash composition (%)						
SiO_2	42.7	50.8	39.2	24.8	52.8	55.8
Al_2O_3	39.0	27.5	27.5	22.7	33.3	25.8
TiO_2	1.86	1.55	1.05	0.82	1.02	1.21
Fe_2O_3	10.7	14.5	18.7	10.8	4.59	6.37
MgO	0.57	0.80	0.34	3.52	0.97	0.91
CaO	1.71	1.15	4.06	9.40	1.78	3.20
Na_2O	0.43	0.49	0.11	2.84	0.70	0.49
K_2O	1.61	2.40	0.91	0.33	2.29	2.19
P_2O_5	0.94	0.39	0.84	0.90	1.16	0.56
SO_3	0.40	0.82	5.00	13.7	0.20	2.10
Trace elements (ppm whole coal, dry)						
Chlorine	1300	700	100	700	2600	2300
Chromium	26	32	19	3	11	21
Mercury	–[c]	–	0.16	–	–	–
Nickel	10	15	20	<1	11	11
Lead	–	8	13	–	–	–
Strontium	203	152	172	200	104	111
Vanadium	37	38	26	6	11	7
Rank	**High Vol A**	**High Vol A**	**High Vol A**	**High Vol A**	**High Vol B**	**High Vol B**
Sample description	L. Kittanning Seam, WV	U. Kittanning Seam, WV	Blind Canyon Seam, UT	L. Elkhorn Seam, KY	Hazard #5 Seam, KY	Hiawatha Seam, UT
Proximate analysis (%, as-received)						
Moisture	1.8	1.5	4.7	1.3	3.8	4.9
Ash	11.8	10.4	5.6	9.7	9.1	7.1
Volatile matter	33.6	32.1	42.4	30.9	34.6	39.5
Fixed carbon	52.8	56.0	47.3	58.1	52.5	48.5

Continued

Table 1.7 Properties of Selected Bituminous Coals of the United States—cont'd

Rank	**High Vol A**	**High Vol A**	**High Vol A**	**High Vol A**	**High Vol B**	**High Vol B**
Ultimate analysis (%, dry, ash free)						
Carbon	84.5	85.2	81.3	86.5	82.8	80.6
Hydrogen	5.6	5.5	6.2	5.5	5.5	5.7
Nitrogen	1.4	1.5	1.6	1.4	1.6	1.4
Sulfur	1.0	2.0	0.4	0.6	0.8	0.9
Oxygen	7.5	5.8	10.5	6.0	9.3	11.4
HHV[a] **(Btu/lb)**	13,272	13,678	13,923	13,897	13,369	13,264
Maceral group anal. (vol.% min. free[b]**)**						
Vitrinite	52.5	89.0	69.1	71.2	60.3	89.2
Inertinite	30.3	7.6	13.6	16.8	21.1	9.6
Liptinite	17.2	3.4	17.3	11.9	18.7	1.2
Vitrinite reflectance (mean-maximum % in oil)	0.91	1.07	0.66	1.03	0.80	0.58
Ash fusion temperatures (reducing conditions, °F)						
Initial deform.	2700+	2310	1900	2700+	2700+	2110
Softening	2700+	2400	2020	2700+	2700+	2210
Hemispherical	2700+	2460	2090	2700+	2700+	2260
Fluid	2700+	2510	2240	2700+	2700+	2360
Ash composition (%)						
SiO_2	53.0	46.1	50.3	58.2	54.1	49.5
Al_2O_3	34.9	29.5	15.3	28.3	31.1	21.2
TiO_2	2.28	1.28	0.96	1.58	1.81	1.12
Fe_2O_3	5.49	15.0	6.88	3.37	3.86	4.19
MgO	0.70	0.82	1.26	1.10	0.83	0.97
CaO	0.89	2.59	12.0	0.69	2.09	8.09
Na_2O	0.16	0.24	6.91	0.56	0.32	4.91
K_2O	2.14	1.87	0.59	3.74	2.08	0.21

P_2O_5	0.08	0.21	0.38	0.08	0.42	0.88
SO_3	1.00	1.30	4.80	0.50	1.20	8.00
Trace elements (ppm whole coal, dry)						
Chlorine	600	3700	1200	900	1100	300
Chromium	31	18	6	21	31	19
Mercury	–[c]	–	–	0.08	–	–
Nickel	18	6	<0.4	15	24	24
Lead	–	–	–	7	10	8
Strontium	39	62	85	73	297	262
Vanadium	28	7	9	25	34	8

Rank	**High Vol B**	**High Vol B**	**High Vol C**	**High Vol C**	**High Vol C**
Sample description	Kentucky #9 Seam, KY	Illinois #9 Seam, IL	Wadge Seam, CO	Illinois #5 Seam, IL	Indiana #6 Seam, IN
Proximate analysis (%, as-received)					
Moisture	6.8	5.3	9.5	9.5	11.5
Ash	11.4	10.3	6.4	9.5	13.5
Volatile matter	38.4	37.0	38.0	36.4	33.5
Fixed carbon	43.4	47.4	46.1	44.6	41.5
Ultimate analysis (%, dry, ash free)					
Carbon	79.1	79.9	77.5	78.4	79.7
Hydrogen	5.8	5.6	5.5	5.2	4.9
Nitrogen	1.4	1.6	1.8	1.4	1.6
Sulfur	4.8	4.6	0.6	4.9	3.4
Oxygen	8.9	8.3	14.6	10.1	10.4
HHV[a] (Btu/lb)	12,687	12,633	12,762	12,722	12,292
Maceral group anal. (vol.% min. free[b])					
Vitrinite	85.7	87.9	89.2	87.5	89.0
Inertinite	6.6	12.1	8.7	10.6	8.7

Continued

Table 1.7 Properties of Selected Bituminous Coals of the United States—cont'd

Rank	**High Vol B**	**High Vol B**	**High Vol C**	**High Vol C**	**High Vol C**
Liptinite	7.7	0.0	2.1	1.9	2.3
Vitrinite reflectance (mean-maximum % in oil)	0.56	0.33	0.60	0.62	0.43
Ash fusion temperatures (reducing conditions, °F)					
Initial deform.	1755	2090	2700+	1945	2035
Softening	1900	2125	2700+	2065	2080
Hemispherical	2000	2185	2700+	2160	2365
Fluid	2040	2285	2700+	2245	2425
Ash composition (%)					
SiO_2	41.2	–	48.7	43.1	50.1
Al_2O_3	15.6	–	31.1	16.0	18.8
TiO_2	0.75	–	0.92	0.78	0.89
Fe_2O_3	22.0	–	3.60	24.2	20.2
MgO	0.70	–	1.47	0.81	0.86
CaO	8.08	–	6.22	5.66	2.16
Na_2O	0.66	–	0.92	0.45	0.57
K_2O	1.89	–	0.84	1.76	2.57
P_2O_5	0.04	–	1.03	0.10	0.15
SO_3	9.40	–	3.90	6.10	2.30
Trace elements (ppm whole coal, dry)					
Chlorine	1600	–	100	800	500
Chromium	23	–	4	10	14
Mercury	–[c]	–	–	–	–
Nickel	8	–	<2	13	6
Lead	–	–	–	–	–
Strontium	21	–	175	17	24
Vanadium	19	–	7	14	19

[a] *Higher heating value.*
[b] *White light.*
[c] *Not available.*

Table 1.8 Properties of Selected Low-Rank Coals in the United States

Rank	Subbit. B	Subbit. B	Subbit. B	Subbit. B	Lignite A	Lignite
Sample description	Wyodak Seam, WY	Rosebud Seam, MT	Black Thunder, WY	Antelope WY	Beulah Seam, ND	L. Wilcox Seam, TX
Proximate analysis (%, as-received)						
Moisture	26.3	19.8	26.3	11.0	33.4	28.5
Ash	5.6	7.3	5.6	5.6	6.4	15.3
Volatile matter	33.1	32.3	33.1	38.4	37.4	44.2
Fixed carbon	35.0	41.6	35.0	45.0	22.8	12.0
Ultimate analysis (%, dry, ash free)						
Carbon	75.5	75.3	75.5	75.1	73.1	72.3
Hydrogen	6.1	5.1	6.2	5.2	4.5	5.2
Nitrogen	1.0	1.1	1.0	0.9	1.0	1.4
Sulfur	0.5	0.9	0.4	0.3	0.8	0.9
Oxygen	16.9	17.6	16.9	18.5	20.6	20.2
HHV[a] **(Btu/lb)**	12,145	11,684	12,220	11,758	11,062	9882
Maceral group anal. (vol.% min. free[b]**)**						
Huminite	85.7	79.8	–	–	73.8	90.0
Inertinite	9.7	18.8	–	–	19.5	6.9
Liptinite	4.6	1.4	–	–	6.7	3.1
Huminite reflectance (mean-maximum % in oil)	0.29	0.51	–	–	0.35	0.44
Ash fusion temperatures (reducing conditions, °F)						
Initial deform.	2100	2145	–	–	2000	2310
Softening	2130	2170	–	–	2070	2360
Hemispherical	2160	2205	–	–	2100	2500
Fluid	2185	2310	–	–	2140	2540

Continued

Table 1.8 Properties of Selected Low-Rank Coals in the United States—cont'd

Rank	Subbit. B	Subbit. B	Subbit. B	Subbit. B	Lignite A	Lignite
Ash composition (%)						
SiO_2	31.7	31.3	31.4	35.5	11.5	47.9
Al_2O_3	16.1	16.8	14.0	17.1	11.1	22.2
TiO_2	1.27	0.79	1.6	1.02	0.57	1.75
Fe_2O_3	4.84	4.78	6.4	5.41	9.29	3.51
MgO	4.64	5.21	4.5	4.45	9.94	2.79
CaO	23.5	17.1	21.2	18.1	27.4	14.0
Na_2O	1.80	0.20	1.0	1.39	9.39	0.37
K_2O	0.40	0.10	0.5	0.40	0.59	0.55
P_2O_5	0.89	0.24	1.2	2.22	0.49	0.11
SO_3	12.7	19.3	18.2	9.8	18.2	7.00
Trace elements (ppm whole coal, dry)						
Arsenic	1	–	–	–	–	–
Cadmium	<0.2	–	–	–	–	–
Chlorine	–[c]	200	–	–	800	1100
Chromium	3	7	–	–	5	17
Mercury	0.12	–	–	–	–	–
Nickel	2	7	–	–	<0.4	5
Lead	5	5	–	–	–	–
Selenium	2	–	–	–	–	–
Strontium	164	225	–	–	772	158
Vanadium	11	5	–	–	14	34

[a] *Higher heating value.*
[b] *White light.*
[c] *Not available.*

Table 1.9 Properties of Selected International Samples of Anthracite

	Germany	Spain	Russia	Russia	China	China	Korea
Rank	Anthracite	Anthracite	Anthracite	Semianthracite	Anthracite	Anthracite	Anthracite
Proximate analysis (%, as-received)							
Ash	4.0	31.9	11.3	13.4	15.0	9.9	31.5
Moisture	3.0	3.1	2.0	4.0	2.3	1.1	3.4
Volatile matter	7.2	7.1	3.0	9.9	7.6	8.5	4.8
Fixed carbon	85.8	57.9	83.7	72.7	75.1	80.5	60.3
Ultimate analysis (%, moisture, ash free)							
Carbon	91.8	87.2	94.6	90.0	–	–	
Hydrogen	3.6	2.5	1.8	4.2	–	–	
Oxygen	2.6	8.0	1.8	2.1	–	–	
Nitrogen	1.4	0.9	1.0	1.5	–	–	
Sulfur	0.7	1.4	0.8	2.2	–	–	
Higher heating value (Btu/lb)	15,440	14,090	14,590	15,380	15,360	14,790	12,980
Ash fusion temperatures (reducing conditions, °F)							
Initial deformation	–[a]	2160	–	–	–	–	–
Softening	–	2420	–	–	–	–	2220
Hemispherical	–	N/A	–	–	–	–	–
Fluid	–	2640	–	–	–	–	–
Ash composition (%)							
SiO_2	–	59.0	–	–	–	–	65.0
Al_2O_3	–	20.5	–	–	–	–	20.1
Fe_2O_3	–	7.5	–	–	–	–	5.3
CaO	–	3.5	–	–	–	–	1.0
MgO	–	1.9	–	–	–	–	1.0
Na_2O	–	0.9	–	–	–	–	0.5
K_2O	–	4.0	–	–	–	–	5.0
TiO_2	–	1.3	–	–	–	–	0.9
P_2O_5	–	N/A	–	–	–	–	N/A
SO_3	–	2.0	–	–	–	–	N/A
Hardgrove Grindability Index	–	54	–	–	–	–	59

[a] *Not available.*

Modified from Singer, J.G. (Ed.), 1981. Combustion: Fossil Power Systems. Combustion Engineering, Inc., Windsor, CT.

Table 1.10 Properties of Selected International Samples of Lignite/Brown Coal

	Germany	**Germany**	**Greece**	**F.Y.**[a]	**Turkey**	**Poland**	**Russia**
Rank	Brown	Lignite	Lignite	Brown	Brown	Lignite	Lignite
Proximate analysis (%, as-received)							
Ash	14.0	16.0	15.0	17.8	16.0	7.3	6.9
Moisture	56.0	10.0	62.0	49.7	55.0	53.9	37.0
Volatile matter	16.5	38.5	14.3	16.9	19.4	23.6	24.5
Fixed carbon	13.5	35.5	8.7	15.6	9.6	15.2	31.6
Ultimate analysis (%, moisture, ash free)							
Carbon	68.3	74.0	60.5	61.9	61.4	71.4	72.2
Hydrogen	5.0	5.5	6.2	4.3	5.1	5.8	4.3
Oxygen	27.5	14.5	30.6	29.8	29.6	20.2	22.1
Nitrogen	0.5	1.4	1.3	0.9	0.8	0.6	1.1
Sulfur	0.5	4.6	1.4	3.1	5.1	2.0	0.3
Higher heating value (Btu/lb)	11,340	12,780	10,510	9450	10,190	12,510	11,190
Ash fusion temperatures (reducing conditions, °F)							
Initial deformation	–[b]	–	–	2700+	–	–	–
Softening	–	–	–	2700+	–	–	–
Hemispherical	–	–	–	N/A	–	–	–
Fluid	–	–	–	2700+	–	–	–

Ash composition (%)							
SiO_2	–	–	–	21.6	–	–	–
Al_2O_3	–	–	–	3.1	–	–	–
Fe_2O_3	–	–	–	6.0	–	–	–
CaO	–	–	–	45.6	–	–	–
MgO	–	–	–	2.5	–	–	–
Na_2O	–	–	–	0.4	–	–	–
K_2O	–	–	–	0.2	–	–	–
TiO_2	–	–	–	0.1	–	–	–
P_2O_5	–	–	–	0.4	–	–	–
SO_3	–	–	–	15.1	–	–	–
Hardgrove Grindability Index	–	–	–	58[c]	–	–	–

[a] *Former Yugoslavia.*
[b] *Not available.*
[c] *At 36% moisture.*
Modified from Singer, J.G. (Ed.), 1981. Combustion: Fossil Power Systems. Combustion Engineering, Inc., Windsor, CT.

Table 1.11 Properties of Selected International Samples of Bituminous Coal

	Poland	**Russia**	**Russia**	**Russia**	**Russia**	**China**	**China**
Rank	hvA	Low vol.	hvA	hvB	hvC	Low vol.	Med. vol
Proximate analysis (%, as-received)							
Ash	11.5	16.0	19.0	14.7	19.8	13.2	12.7
Moisture	8.8	3.0	5.0	8.0	12.0	1.2	0.9
Volatile matter	29.6	13.0	24.3	30.2	30.0	18.4	26.7
Fixed carbon	50.1	68.0	54.7	47.1	38.2	67.2	59.7
Ultimate analysis (%, moisture, ash free)							
Carbon	82.9	88.0	83.0	82.0	77.0	–	–
Hydrogen	5.2	4.5	5.1	5.5	5.6	–	–
Oxygen	9.9	2.9	5.6	8.5	12.3	–	–
Nitrogen	1.0	1.5	1.5	1.5	1.6	–	–
Sulfur	1.0	3.1	4.8	2.5	3.5	–	–
Higher heating value (Btu/lb)	14,550	15,400	15,140	14,600	13,900	15,940	15,530
Ash fusion temperatures (reducing conditions, °F)							
Initial deformation	2160	–	–	–	–	–	–
Softening	2210	–	–	–	–	–	–
Hemispherical	–[a]	–	–	–	–	–	–
Fluid	2460	–	–	–	–	–	–
Ash composition (%)							
SiO_2	46.8	–	–	–	–	–	–
Al_2O_3	21.8	–	–	–	–	–	–
Fe_2O_3	9.6	–	–	–	–	–	–
CaO	5.8	–	–	–	–	–	–
MgO	3.5	–	–	–	–	–	–
Na_2O	0.8	–	–	–	–	–	–
K_2O	3.1	–	–	–	–	–	–

TiO_2	0.7	–	–	–	–	–	–
P_2O_5	0.3	–	–	–	–	–	–
SO_3	6.6	–	–	–	–	–	–
Hardgrove Grindability Index	49	–	–	–	–	–	–

	China	**China**	**India**	**India**	**S. Africa**	**Australia**	**Australia**
Rank	hvA	hvB	Med vol.	hvB	Med vol.	hvA	hvB
Proximate analysis (%, as-received)							
Ash	16.6	10.2	38.9	31.6	13.9	16.5	26.0
Moisture	1.2	3.1	1.1	6.9	2.9	4.1	7.3
Volatile matter	36.3	41.2	15.2	22.9	28.1	35.5	31.0
Fixed carbon	45.9	45.5	44.8	38.6	55.1	43.9	35.7
Ultimate analysis (%, moisture, ash free)							
Carbon	–[a]	–	83.6	–	84.6	81.2	77.4
Hydrogen	–	–	4.5	–	4.9	6.1	5.5
Oxygen	–	–	9.9	–	7.2	11.0	15.3
Nitrogen	–	–	1.3	–	2.2	1.1	1.2
Sulfur	–	–	0.7	1.8	1.1	0.6	0.6
Higher heating value (Btu/lb)	15,530	13,610	14,635	13,500	14,070	14,630	13,490
Ash fusion temperatures (reducing conditions, °F)							
Initial deformation	–	–	2250	2600	2410	2280	2280
Softening	–	–	2670	2700+	2430	2500	2480
Hemispherical	–	–	–	–	–	–	–
Fluid	–	–	2700+	2700+	2700	2700+	2700+
Ash composition (%)							
SiO_2	–	–	65.9	60.8	41.5	56.1	54.5
Al_2O_3	–	–	23.7	24.8	30.8	25.9	24.0

Continued

Table 1.11 Properties of Selected International Samples of Bituminous Coal—cont'd

	China	China	India	India	S. Africa	Australia	Australia
Fe_2O_3	–	–	6.0	6.8	4.8	3.8	6.7
CaO	–	–	1.1	2.1	8.7	5.0	3.7
MgO	–	–	0.6	0.5	2.2	2.1	2.3
Na_2O	–	–	0.1	0.1	0.2	0.6	0.3
K_2O	–	–	1.4	1.0	0.3	0.7	1.0
TiO_2	–	–	2.2	–	1.0	1.1	1.8
P_2O_5	–	–	–	–	1.0	0.5	0.2
SO_3	–	–	0.3	1.7	7.6	3.2	3.3
Hardgrove Grindability Index	–	–	63	60	46	48	45

[a] *Not available.*

Modified from Singer, J.G. (Ed.), 1981. Combustion: Fossil Power Systems. Combustion Engineering, Inc., Windsor, CT.

1.5 COAL DISTRIBUTION AND RESOURCES

Coal deposits are broadly categorized into resources and reserves. Resources refer to the quantity of coal that may be present in a deposit or coalfield but may not take into account the feasibility of mining the coal economically. Reserves generally tend to be classified as proven or measured and probable or indicated, depending on the level of exploration of the coalfield. The basis for computing resources and reserves vary between countries, which makes it difficult for direct comparisons. In addition, the techniques are constantly being refined, thereby resulting in variability from year to year. Walker (2000) discusses some of the various measurement criteria used by the major coal producing countries in the world in detail. Similarly, the Energy Information Administration (EIA) discusses measurement criteria as well (EIA, 2013).

Fig. 1.12 illustrates the relationship between coal resources and reserves in the United States (as of Jan. 1, 2014) (EIA, 2015). The United States has a total of more than 3900 billion short tons of coal resources with ~20 billion short tons classified as recoverable reserves at active mines, out of 257 billion short tons that are economically recoverable and a demonstrated reserve base of 480 billion short tons.

The definitions to interpret Fig. 1.12 are as follows:

- Total resources—coal that can currently, or potentially may, be extracted economically;
- Measured resources—quantity of coal that has been determined to a high degree of geologic assurance;

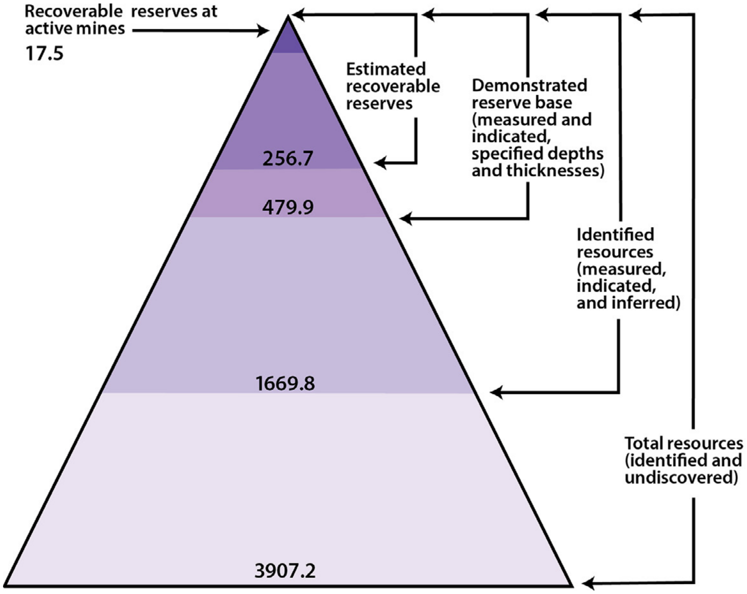


FIG. 1.12

United States coal resources and reserves in billion short tons.

- Indicated resources—quantity of coal that has been determined to a moderate degree of geological assurance;
- Inferred resources—quantity of coal that has been determined with a low degree of geologic assurance; and
- Recoverable reserves—coal that can be recovered economically with technology currently available or in the foreseeable future.

Terminology also varies among countries and can contribute to confusion when comparing coal resources and reserves. For discussion purposes in this chapter, recoverable coal reserves will primarily be used when comparing world coal deposits to lessen confusion.

1.5.1 COAL RESERVES IN THE WORLD

Coal is the most abundant fossil fuel in the world (EIA, 2015; BP, 2014). The world's proved coal reserves are sufficient to meet 113 years of global production—by far the largest reserve-to-production (R/P) ratio for any fossil fuel (BP, 2014). In comparison, proved world oil and natural gas reserves have R/P ratios of 53 and 55, respectively, which is approximately half that of world coal reserves. Coal reserves are also more widely distributed throughout the world, as shown in Fig. 1.13. All major regions of the world contain appreciable quantities of coal except for the Middle East, which on the other hand,

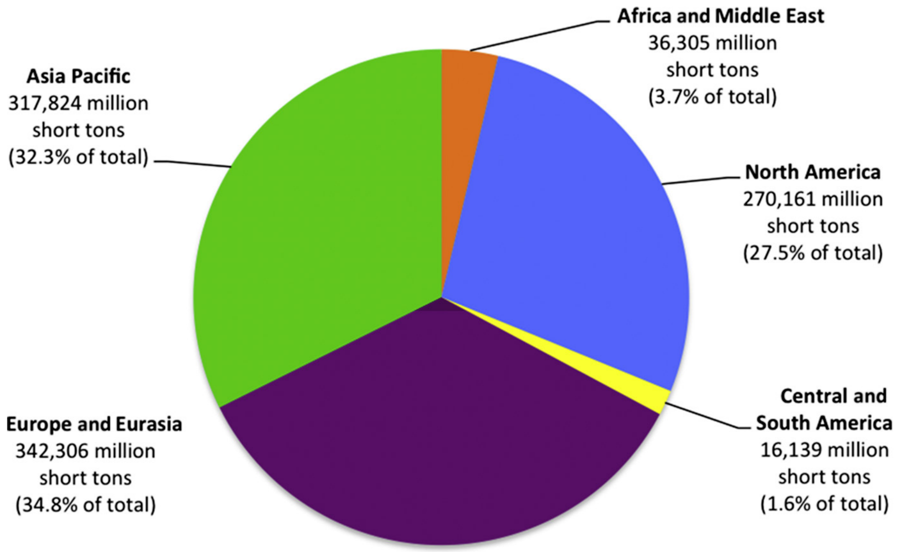


FIG. 1.13

Distribution of proved coal reserves in the world (world total is 982,735 million short tons).

Modified from BP, 2014. BP Statistical Review of World Energy, 63rd ed. BP, London, June.

contains nearly 50% of the world oil reserves and over 40% of the world natural gas reserves; however, these totals are on the decline as there is an increase in the production of unconventional natural gas and oil due to the implementation of new technologies (i.e., hydraulic fracturing), especially in the United States.

Coal is available in almost every country worldwide, with recoverable reserves in around 70 countries. Total recoverable reserves of coal around the world are estimated at over 982 billion short tons (BP, 2014). According to BP (2014) and EIA (2013), this is enough coal to last ~115–150 years at current consumption levels. However, this could be extended further by the discovery of new reserves through ongoing and improved exploration activities, and by advances in mining techniques, which will allow previously inaccessible reserves to be reached.

Historically, estimates of world recoverable coal reserves, although relatively stable, have declined gradually from 1145 billion short tons in 1993, to 1085 billion short tons in 2003, to 983 billion short tons in 2013 (BP, 2014). It should be noted, however, that the assessments are constantly changing. For example, Germany had a major reassessment around 2005 when their lignite deposits experienced a significant downward adjustment from about 73 billion short tons of recoverable coal reserves to 7 billion short tons (EIA, 2006). However, in 2009, Germany's lignite reserves estimate increased by 37 billion short tons, reflecting a new assessment (EIA, 2013). Other countries have also been applying more restrictive criteria for various parameters in their coal reserve assessments.

A detailed breakdown of the estimated recoverable world coal reserves of 983 billion short tons is provided in Table 1.12. Table 1.12 classifies the recoverable coal reserves in two major categories—recoverable anthracite and bituminous coal (i.e., hard coal) and recoverable lignite and subbituminous coal—for the major regions and countries of the world.

Although coal deposits are widely distributed, 77% of the world's recoverable reserves are located in six countries: the United States (≈27%; ≈262 billion short tons), Russia (≈18%; ≈173 billion short tons), China (≈13%; ≈126 billion short tons), Australia (≈9%; ≈84 billion short tons), India (≈7%; ≈67 billion short tons), and Germany (≈5%; ≈45 billion short tons). Fig. 1.14 shows the ten countries with the largest recoverable coal reserves. Approximately 70 countries contain recoverable coal; however, the 10 shown in Fig. 1.14 contain more than 895 billion short tons or more than 91% of the world's total.

Table 1.13 lists the major coal producing countries/regions and their reserves-to-production (R/P) ratios in years. These data are based on recoverable reserves and production from EIA (2013), which are the most recent as of 2009, and they differ slightly from BP data (BP, 2014) (e.g., BP reports a world R/P ratio of 113 years, and IEA reports a world R/P ratio of 119 years). The EIA data are reported here because they provide a clearer breakdown of coal rank (i.e., subdividing subbituminous coal and lignite), whereas BP combines the two lower-rank coals into one category. The data are comparable between the two data sets, but what is especially worth noting is that the R/P ratio varies from 50 to 100 years for some countries/regions with heavy usage and/or low reserves to more than 500 years for countries with little or no production. Most major coal-producing countries are in the ≈100- to 250-year range except for China. Note that China, which is a country with the third largest recoverable reserves in the world, has an R/P ratio of <40 years. This is low compared to countries such as the United States (230–270 years) or Russia (450–480 years), which are the two leading countries with recoverable reserves.

Table 1.12 World's Estimated Recoverable Coal Reserves (million short tons)

Region/Country	Anthracite and Bituminous Coal	Subbituminous Coal and Lignite	Total	Percent of World Total (%)	R/P Ratio
North America					
Canada	3829	3426	7255	0.7	95
Mexico	948	387	1335	0.1	73
United States	119,601	141,970	261,571	26.6	266
Total	124,378	145,783	270,161	27.5	250
Central and South America					
Brazil	–	7308	7308	0.7	>500
Columbia	7436	–	7436	0.8	79
Venezuela	528	–	528	0.1	206
Other	63	804	867	0.1	278
Total	8027	8112	16,139	1.6	149
Europe and Eurasia					
Bulgaria	2	2606	2608	0.3	83
Czech Republic	200	960	1160	0.1	21
Germany	53	44,643	44,696	4.5	213
Greece	–	3329	3329	0.3	56
Hungary	14	1815	1829	0.2	174
Kazakhstan	23,699	13,338	37,037	3.8	293
Poland	4605	1419	6024	0.6	38
Romania	11	310	321	<0.05	12
Russian Federation	54,109	118,962	173,071	17.6	452
Spain	220	364	584	0.1	120
Turkey	355	9237	9592	1.0	141
Ukraine	16,921	20,417	37,338	3.8	384
United Kingdom	251	–	251	<0.05	18
Other	1583	22,880	24,463	2.5	236
Total	102,026	240,280	342,306	34.8	254

Africa and Middle East					
South Africa	33,241	–	33,241	3.4	117
Zimbabwe	553	–	553	0.1	315
Other Africa	1038	236	1274	0.1	466
Middle East	1237	–	1237	0.1	>500
Total	36,069	236	36,305	3.7	126
Asia Pacific					
Australia	40,895	43,321	84,216	8.6	160
China	68,563	57,650	126,213	12.8	31
India	61,839	4960	66,799	6.8	100
Indonesia	–	30,883	30,883	3.1	67
Japan	371	11	382	<0.05	288
New Zealand	36	593	629	0.1	126
North Korea	331	331	661	0.1	15
Pakistan	–	2282	2282	0.2	>500
South Korea	–	139	139	<0.05	69
Thailand	–	1366	1366	0.1	69
Vietnam	165	–	165	<0.05	4
Other	1745	2342	4087	0.4	87
Total	173,946	143,878	317,824	32.3	54
Total World[a]	444,442	538,288	982,735	100.0	113
OECD	171,401	252,781	424,182	43.2	191
Non-OECD	273,045	285,508	558,553	56.8	86
European Union	5382	56,437	61,819	6.3	103
Former Soviet Union	95,597	155,765	251,362	25.6	396

[a] *Appendix A contains a listing of the countries that are in the OECD (Organization for Economic Cooperation and Development), non-OECD (Non-Organization for Economic Cooperation and Development), and European Union.*

Modified from BP, 2014. BP Statistical Review of World Energy, 63rd ed., June.

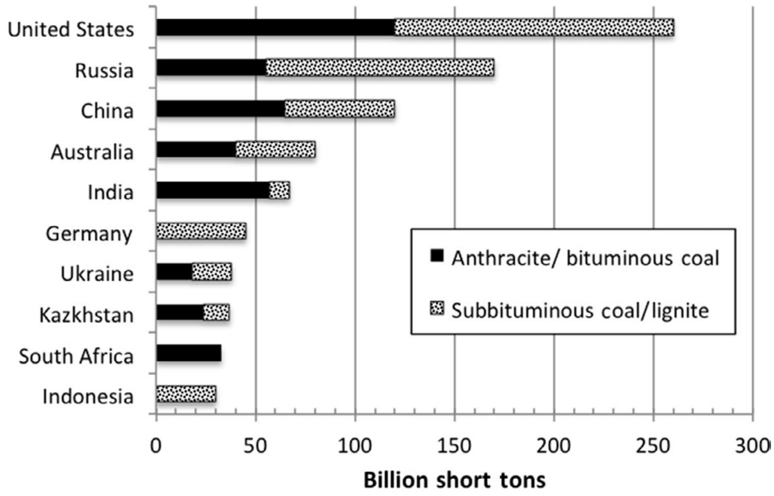


FIG. 1.14

Countries with the largest recoverable coal reserves.

Table 1.13 World Recoverable Coal Reserves (Billion Short Tons) and Reserves-to-Production Ratio (Years)

	2009 Recoverable Reserves by Coal Rank					
	Bituminous Coal and Anthracite	Subbituminous Coal	Lignite	Total	2010 Production	R/P Ratio (Years)
World Total	*445.0*	*285.9*	*215.2*	*930.4*	*8.0*	*119*
United States[a]	118.4	107.2	33.1	*258.6*	1.1	238
Russia	54.1	107.4	11.5	*173.1*	0.4	482
China	68.6	37.1	20.5	*126.2*	3.5	36
Other Non-OECD Europe and Eurasia	42.2	18.9	39.9	*100.9*	0.3	311
Australia and New Zealand	40.9	2.5	41.4	*84.8*	0.5	179
India	61.8	0.0	5.0	*66.8*	0.6	109
OECD Europe	6.2	0.9	54.5	*61.6*	0.6	99
Africa	34.7	0.2	0.0	*34.9*	0.3	122
Other Non-OECD Asia	3.9	3.9	6.8	*14.7*	0.5	29
Other Central and South America	7.6	1.0	0.0	*8.6*	<0.1	101
Canada	3.8	1.0	2.5	*7.3*	<0.1	97
Brazil	0.0	5.0	0.0	*5.0*	<0.1	842
Other[b]	2.6	0.8	0.1	*3.6*	<0.1	233

[a] *Data for the U.S. represent recoverable coal estimates as of Jan. 1, 2012.*
[b] *Includes Mexico, Chile, Middle East, Japan, South Korea, and Greenland.*

1.6 MAJOR COAL PRODUCING REGIONS IN THE WORLD

Coal is found on all inhabited continents of the world. It is very likely that coal is also on Antarctica, particularly when one looks at the coal forming periods in history and the corresponding locations of the present day continents. A review of the major coal producing countries in the world is provided and summarized by coal-producing region.

1.6.1 NORTH AMERICA

The recoverable coal reserves of North America are the third largest in the world with more than 270,000 million short tons identified, or more than 27% of the world's total reserves (see Table 1.12). Coal is found in the United States, Canada, Mexico, and, to a much lesser extent, Greenland.

United States

The coal reserves of the United States are the largest of any country in the world, with more than 261,000 million short tons (BP, 2014). Recoverable coal reserves are found in 32 of the states, with the major coalfields shown in Fig. 1.15 (Averitt, 1975). The 11 states with the largest recoverable coal reserves are listed in Table 1.14 and they contain ~92% of the total coal in the United States (EIA, 2015). The top five states contain more than 70% of the total recoverable coal reserves in the United States.

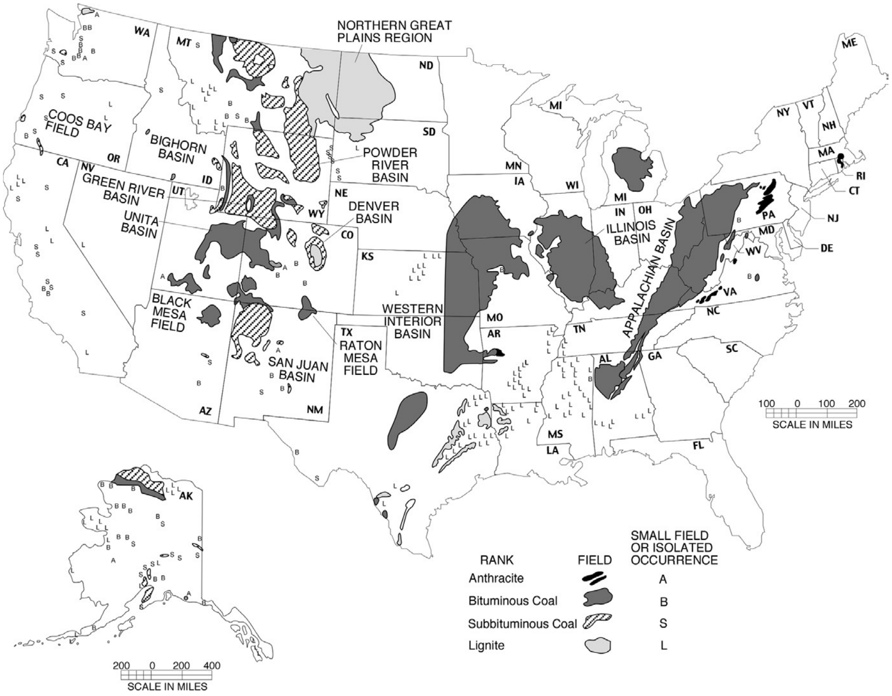


FIG. 1.15

Major coal-bearing areas of the United States.

Table 1.14 Top Eleven States With the Largest Recoverable Coal Reserves (Million Short Tons), 2007

	Recoverable Coal Reserves (Million Short Tons)		
State	**Underground Mineable Coal**	**Surface Mineable Coal**	**Total**
Montana	35,897	38,704	74,600
Illinois	27,762	10,039	37,802
Wyoming	22,922	14,090	37,011
West Virginia	14,865	2037	16,902
Kentucky	6895	7247	14,143
Pennsylvania	10,289	979	11,267
Ohio	7598	3711	11,309
Colorado	5788	3743	9531
Texas	–	9211	9211
New Mexico	2758	4060	6818
North Dakota	–	6685	6685
Total	134,774	100,506	235,280
Percentage of U.S. total	91.4	92.0	91.7

After New Mexico and North Dakota, which each have recoverable reserves of 6700–6800 million short tons, the states with the next largest reserve totals are Indiana and Missouri, with ≈3800 million short tons each. After that, recoverable reserve totals for the other states are <3000 million short tons per state.

Carboniferous coal deposits in the Eastern United States occur in a band of coal-bearing sediments that encompass the Illinois and Appalachian Basins (Walker, 2000). By contrast, coal deposits in the Western United States range from Upper Jurassic to Tertiary in age.

Of the four ranks of coal in the United States—anthracite, bituminous, subbituminous, and lignite—bituminous coal accounts for ≈44% of recoverable reserves. Bituminous coal is concentrated primarily east of the Mississippi River with the greatest amounts in Illinois, West Virginia, Kentucky, Pennsylvania, and Ohio (see Table 1.14). All subbituminous coal, which accounts for ≈41% of the demonstrated reserve base, is located west of the Mississippi River and is concentrated in Montana and Wyoming. Lignite accounts ≈12% of the demonstrated reserve base and is found mostly in Montana, Texas, and North Dakota. Anthracite only accounts for ≈3% of the demonstrated reserve base, and it is found only in Pennsylvania.

The United States Geological Survey has divided the reserves into seven provinces: (1) Eastern Province, (2) Interior Province, (3) Gulf Province, (4) Northern Great Plains Province, (5) Rocky Mountain Province, (6) Pacific Coast Province, and (7) Alaskan Province. The provinces are further subdivided into regions, fields, and districts. Carboniferous coal deposits in the eastern United States occur in a band of coal-bearing sediments that include the Appalachian and Illinois basins. Coal deposits in the western United States range from Upper Jurassic to Tertiary in age.

The Eastern Province includes the anthracite regions of Pennsylvania and Rhode Island, the Atlantic Coast region of middle Virginia and North Carolina, the vast Appalachian basin, which extends from Pennsylvania through eastern Ohio, western Kentucky, West Virginia, western Virginia, Tennessee, and into Alabama. The Eastern Province is about 900 miles long and 200 miles wide at is broadest point (Schobert, 1987). This province also contains the greatest reserves of anthracite in the United States with ~760 million short tons in eastern Pennsylvania.

The Appalachian basin contains the largest deposits of bituminous coal in the United States. In the northern region of the Appalachian basin the coal rank ranges from high-volatile bituminous in the west to low-volatile bituminous in the east. In the central region, the coal includes low- to high-volatile bituminous rank. In the southern region, the coals are mainly of high-volatile bituminous rank with some medium- and low-volatile bituminous coals (Walker, 2000). Coals are used for steam production, electricity generation, and metallurgical coke production. These coals have high heating values, low- to medium-ash contents (up to 20%), and variable sulfur contents with much of the coal containing sulfur in the 2–4% range.

The Interior Province is subdivided into three regions: the Northern region consisting of Michigan; the Eastern region or Illinois basin consisting of Illinois, southern Indiana, and western Kentucky; and the Western region consisting of Iowa, Missouri, Nebraska, Kansas, Oklahoma, Arkansas, and western Texas. The Eastern region is the most important region of this province, with vast reserves contained in Illinois (i.e., nearly 38,000 million short tons) and western Kentucky (nearly 9000 million short tons of the more than 14,000 million short tons, listed in Table 1.14). The coal in the Interior Province is mainly bituminous in rank and tends to be lower in rank and higher in sulfur than the Eastern Province bituminous coals. Coals are used for steam production, electricity generation, and metallurgical coke production. Coal composition in this province is quite variable with coals from the Illinois basin noted for having high-sulfur content (3–7%). The ash content is variable.

The Gulf Province consists of the Mississippi region in the east and the Texas region in the west. The coals in this province, which extends from Alabama and through Mississippi, Louisiana, and Texas, are lignitic in rank and are the lowest ranked coals in the United States, with moisture contents up to 40%.

The Northern Great Plains Province contains the large lignite deposits of North and South Dakota and eastern Montana, along with the subbituminous fields of northern and eastern Montana and northern Wyoming. These lignite deposits are contained in the Fort Union Region and are the largest lignite deposits in the world (Schobert, 1987). The coals are used primarily as power station fuels. The lignite contains high moisture (38%), low ash (6%), medium sulfur (<1%) contents, and a heating value of ~6800 Btu/lb.

The Northern Great Plains Province also contains extensive subbituminous coal reserves from the Powder River basin. Wyoming and Montana are the states with the largest recoverable low-rank coal reserves in the United States. Wyoming's coal reserves are split between the Northern Great Plains Province and the Rocky Mountain Province. The Powder River basin coals are used primarily as power station fuels and average about 1% sulfur with generally low ash content (3–10%).

The Rocky Mountain Province includes the coalfields of the mountainous districts of Montana, Wyoming, Utah, Colorado, and New Mexico. The coals range in rank from lignite through anthracite in this province. The most important Rocky Mountain Province coals are the coals from Wyoming, primarily those from the Green River, Hanna, and Hanna Fork coalfields. These coals are subbituminous in rank, typically contain low sulfur, and are used in power generation stations.

The Pacific Coast Province is limited to small deposits in Washington, Oregon, and California. The coals range in rank from lignite to anthracite. The fields are small and scattered and are not being utilized to any great extent.

The Alaskan Province contains coal in several regions (Singer, 1981). These coals vary in rank from lignite to bituminous with a small amount of anthracite. The total reserves are estimated to be 15% bituminous coal and 85% subbituminous coal and lignite. However, extensive mining is not performed due to the low population density and pristine wilderness environment. Only fields close to main lines of transportation have been developed. The coals are used primarily for steam generation and as power station fuels.

Canada

Canada has about 7300 million short tons of recoverable coal ranging in rank from anthracite to lignite, as shown in Fig. 1.16. The coal deposits formed in late Jurassic, Cretaceous, and early Tertiary times. Most of the recoverable reserves are in British Columbia, Alberta, and Saskatchewan, which is an extension of the Great Plains province coals from the United States. Coals from western Canada tend to be low in sulfur and, with those from Alberta and Saskatchewan, are used as power station fuels, while British Columbia metallurgical coal is exported to East Asia.

Coals from eastern Canada, primarily the Cape Breton Island coalfield in Nova Scotia, are the most important in the Atlantic region. The coals are of high-volatile bituminous rank and vary from medium to high sulfur. Coal production in Nova Scotia is a small percentage of the national output and continues to decline further.

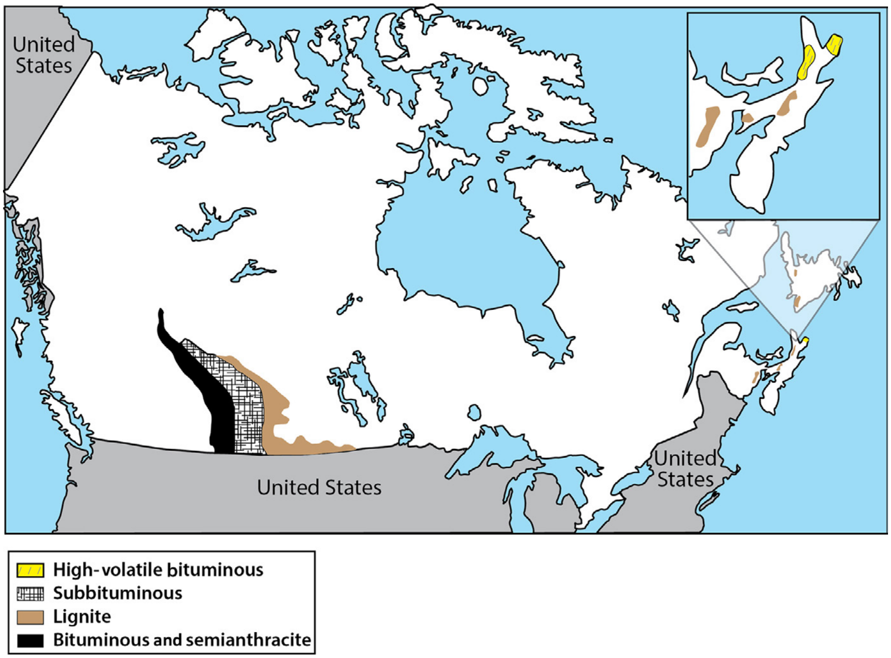


FIG. 1.16

Distribution of coal in Canada.

Modified from Walker, S., 2000. Major Coalfields of the World. IEA Coal Research, London; Singer, J.G. (Ed.), 1981. Combustion: Fossil Power Systems. Combustion Engineering, Inc., Windsor, CT.

1.6.2 EUROPE AND EURASIA

Europe and Eurasia contain extensive recoverable coal reserves totaling over 342,000 million short tons or nearly 35% of the world's total reserves. Six countries contain 90% of the recoverable reserves for this region: Russia, Germany, Ukraine, Kazakhstan, Turkey, and Poland.

Russia

Russia has extensive coal reserves, more than 173,000 million short tons (≈18% of the world total), of which nearly 119,000 million short tons are subbituminous and lignitic in rank. The coal resources in eastern Siberia and the Russian Far East remain largely unused because of their remoteness and lack of infrastructure (Walker, 2000).

Russia's main coal basins contain coals ranging from Carboniferous to Jurassic in age. Most hard coal reserves are in numerous coalfields in European and central Asian Russia, particularly in the Kuznetsk and Pechora basins and the Russian sector of the Dontesk basin. The Kansk-Achinsk basin, in eastern Siberia, is the country's main source of subbituminous coal. The Moscow basin contains significant lignite reserves, but production has virtually stopped (Walker, 2000). Fig. 1.17 shows selected coal basins in Russia, with an emphasis on the major coal basins.

The Kuznetsk basin, which is located to the east of Novosibirsk, contains coals exhibiting a wide range in quality and rank from brown coal to semianthracite. The ash content of the coal is variable and the sulfur content is generally low. High-quality coals with low moisture, ash, and sulfur contents are used for coking and steam coal production. This basin is now the largest single producer in Russia providing coking and steam coal.

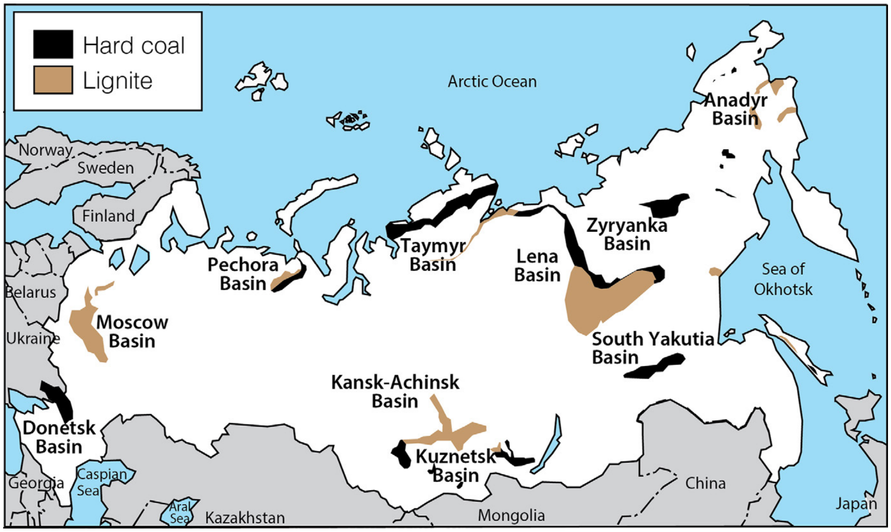


FIG. 1.17

Coal map of Russia.

Modified from Walker, S., 2000. Major Coalfields of the World. IEA Coal Research, London.

The Pechora basin is located in the extreme northeast of European Russia. The coal rank in the basin increases from brown coal in the west to bituminous coal and anthracite in the east. Ash content varies considerably from 9% to 43%, while sulfur content, for the most part, does not exceed 1.5%. This basin is the principal supplier of coking coal.

The Dontesk basin is located in eastern Russia and western Ukraine and contains the whole range of coal rank from brown coal to anthracite, which increases towards its central and eastern sections. These coals tend to have ash contents of 15–20% and sulfur contents of 2–4% and are used as coking and steam coals.

The Kansk-Achinsk basin, located adjacent to the east side of the Kuznetsk basin, contains brown coals that are described as lignites or subbituminous coals; however, their heating value is higher than that of most lignites. These coals have low to medium ash contents (6–20%) and low sulfur contents (<1%), which make them attractive for power station fuel.

Germany

For decades, Germany has been a major European coal producer and consumer. Germany's total recoverable coal reserves are nearly 45,000 million short tons, of which about 50 million short tons are hard coal (anthracite and bituminous coal) with the rest being brown coal (lignite), as shown in Table 1.12. Germany's three main areas of lignite resources consist of the Rhineland, Lusatian, and Central German (Mitteldeutschland) basins, which are of Tertiary age. In addition, Germany has hard coal capacity, which is of Carboniferous age, located in the Ruhr and Saar basins. Fig. 1.18 shows the distribution of hard coal and lignite in Germany.

Of the three main lignite basins, the Rhineland deposits are now the most important and are located between the River Rhine and the German/Dutch/Belgian border. The Central German and Lusatian basins are located in eastern Germany. The lignites have heating values of 3350–5400 Btu/lb and moisture contents that vary from 40% to 60%. Ash and sulfur contents vary from 1.5% to 8.5% and 0.2% to 2.1%, respectively, with Rhineland basin lignite containing sulfur contents <0.5%. These coals are used for producing electricity in generating stations.

The Ruhr coalfield primarily consists of bituminous coal, much of which is coking coal. There are two small areas of anthracite in the basin. The ash and sulfur contents of the coals in this basin are 4–9% and <1%, respectively. The coals are used primarily for electricity generation, along with some industrial applications.

Ukraine

The Ukraine has significant coal reserves totaling over 37,000 million short tons, which is nearly evenly split between hard coal (bituminous and anthracite) and brown coal, as shown in Table 1.12. Most of the coal resources are found in two coal basins—the Donetsk and Dnieper basins—and they are shown in Fig. 1.19.

The Donetsk basin, which is Carboniferous in age, is located in the east (and crosses over into Russia) and contains most of the country's hard coal resources. These coals contain medium ash (15–20%) and medium to high sulfur (2–4%) contents. These coals are used for steam production, power station fuels, and metallurgical applications.

The Dnieper basin is adjacent to the eastern edge of the Donetsk basin and stretches across much of central Ukraine. This basin contains Ukraine's brown coal reserves and currently is of relatively minor importance (Walker, 2000).

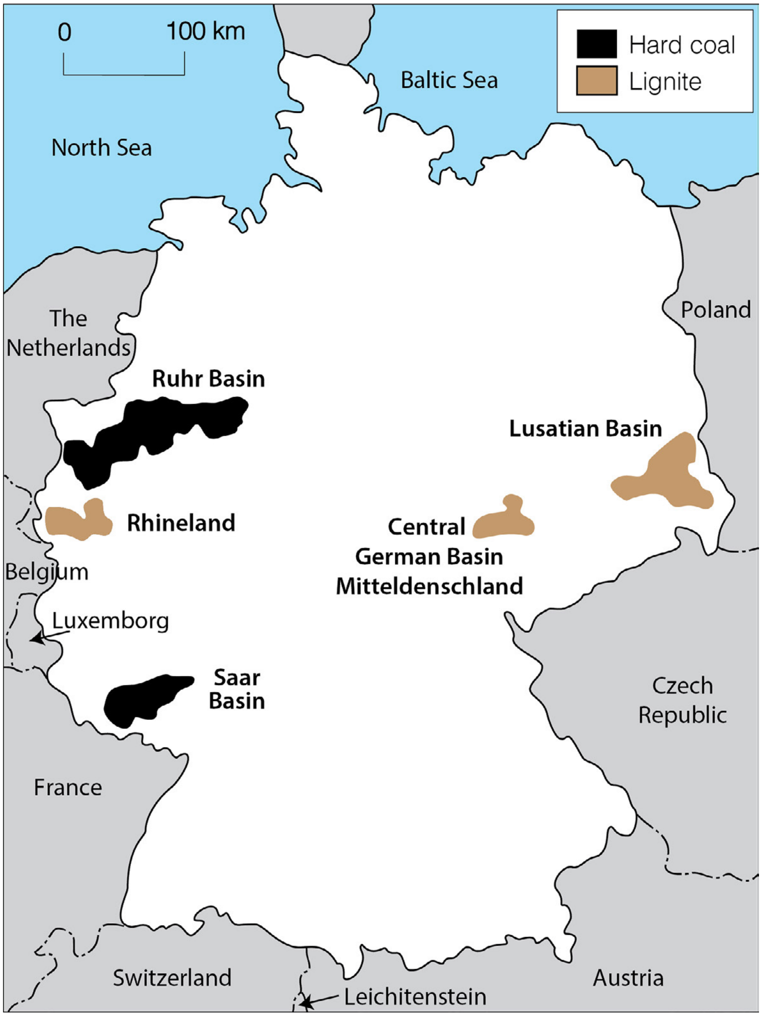


FIG. 1.18

Distribution of coal in Germany.

Modified from Walker, S., 2000. Major Coalfields of the World. IEA Coal Research, London; EUROACOAL (European Association for Coal and Lignite AISBL), 2013. Coal Industry Across Europe, 5th ed. EUROACOAL, Brussels, November.

Kazakhstan

Kazakhstan contains similar total recoverable coal reserves as the Ukraine, with ~37,000 million short tons. Unlike the Ukraine, however, most of Kazakhstan's reserves are hard coals that total nearly 24,000 million short tons. The coal deposits are late Carboniferous and Jurassic in age and are located mainly in the Karaganda and Ekibastuz basins, which produce hard coal. The coal deposits of these basins lie along the southern edge of the Siberian platform (Walker, 2000). In the Karaganda basin, coking and steam coals are produced that have sulfur contents ranging from 1.5% to 2.5% and high ash content

FIG. 1.19

Location of coal basins in the Ukraine.

Modified from Walker, S., 2000. Major Coalfields of the World. IEA Coal Research, London; EUROACOAL (European Association for Coal and Lignite AISBL), 2013. Coal Industry Across Europe, 5th ed. EUROACOAL, Brussels, November.

(20–35%). Coals from the Ekibastuz basin typically have high ash (39% on average) and low sulfur (<1%) contents and are predominately used for thermal power generation.

Turkey

Turkey has considerable reserves of Carboniferous hard coal and Tertiary brown coal. As shown in Table 1.12, Turkish coal reserves total nearly 9600 million short tons, with all but ~360 million short tons being lignite. The principal hard coal deposit is in the Zonguldak basin, between Eregli and Amasra on the Black Sea cost in northwestern Turkey (EUROACOAL, 2013). The coal is bituminous in rank with low ash and sulfur content and is suitable for use as a coking coal. Tertiary lignite basins are present across west and central Turkey. In general, lignites of Eocene age are found in the north of the country, and Miocene lignites occur in western Turkey, while deposits in the northwest are Oligocene (Walker, 2000). The most important lignite deposits are located in the Afsin-Elbistan lignite basin of southeastern Anatolia, near the city of Maras (EUROACOAL, 2013). The Soma basin is the second largest lignite deposit in Turkey. Other important deposits are located in the Tunçbilek, Seyitömer, Bursa, Çan, Mugla, Beypazan, Sivas, and Konya Karapinar basins. The lignite quality is highly variable. Heating values range between 2040 and 8000 Btu/lb, ash contents range between 20% and 53%, and sulfur contents vary between 1% and 5% (Walker, 2000).

Poland

Poland contains recoverable coal reserves of more than 6000 million short tons, and 4600 million short tons are hard coal. The hard coal deposits are found in three main basins located in the southern half of the country—the Upper Silesian, Lower Silesian, and Lublin basins. Fig. 1.20 shows the hard coal

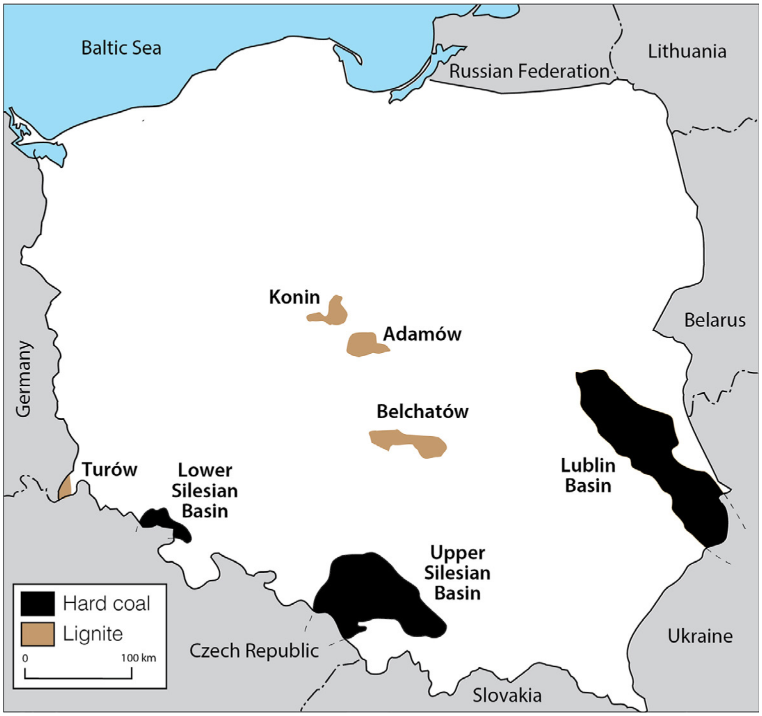


FIG. 1.20

Coal deposits in Poland.

Modified from Walker, S., 2000. Major Coalfields of the World. IEA Coal Research, London; EUROACOAL (European Association for Coal and Lignite AISBL), 2013. Coal Industry Across Europe, 5th ed. EUROACOAL, Brussels, November.

and lignite basins in Poland. These basins are of Carboniferous age. Poland uses its hard coal in world export markets.

Poland's lignite deposits are found in a number of Tertiary basins across the central and southwestern parts of the country. Poland ranks fourth in world lignite production and is the second largest European producer after Germany (World Coal Association, 2014). The lignite is used as a fuel for electricity generation. Polish lignite has variable ash contents (4–25%) and low to medium sulfur contents (0.2–1.7%).

1.6.3 ASIA PACIFIC

This region contains significant recoverable coal reserves totaling nearly 318,000 million short tons, or ~32% of the world total. China, Australia, India, and Indonesia comprise most of this total, with more than 126,000, 84,000, 66,000, and 30,000 million short tons, respectively.

China

China contains more than 126,000 million short tons of recoverable coal reserves in the world, third behind the United States and Russia (BP, 2014). These recoverable reserves are nearly equally divided

FIG. 1.21

Coal deposits in China.

Modified from Walker, S., 2000. Major Coalfields of the World. IEA Coal Research, London; Library of Congress Geography and Map Division, 1992. Coal deposits: China.

between hard coal and lignite deposits (i.e., 68,600 and 57,700 million short tons, respectively), with the hard coals being of Carboniferous, Permian, and Jurassic age and the lignite being Tertiary in age. Coalfields are scattered throughout China, with the largest deposits in western China stretching from north to south, with most of the reserves in the northern part, specifically in the Inner Mongolia, Shanxi, and Shaanxi Provinces. These are shown in Fig. 1.21. Significant anthracite deposits are found in the Shanxi and Guizhou Provinces. Bituminous coal deposits occur in the Heilongjiang, Shanxi, Jiangxi, Shandong, Henan, Anhui, and Guizhou Provinces (Walker, 2000).

China is the world's largest coal producer, with most of the coal being used internally for industry and electricity generation. Hard coal rank appears to increase slightly northwards from the Yangtze River; locally, seam quality is very variable (Walker, 2000).

Australia

Australian recoverable coal reserves total over 84,000 million short tons, which is nearly equally divided between hard coal and lignite deposits (i.e., 41,000 and 43,000 million short tons, respectively) with the hard coals being of Carboniferous and Permian age and the lignite being Tertiary in age. The coal deposits in Australia are shown in Fig. 1.22.

Coal is mined in all of the states except for the Northern Territory. New South Wales and Queensland produce both steam and metallurgical coal for export, while production in Victoria, South Australia, and Western Australia is for thermal electricity generation (Walker, 2000). Hard coal is mined in New

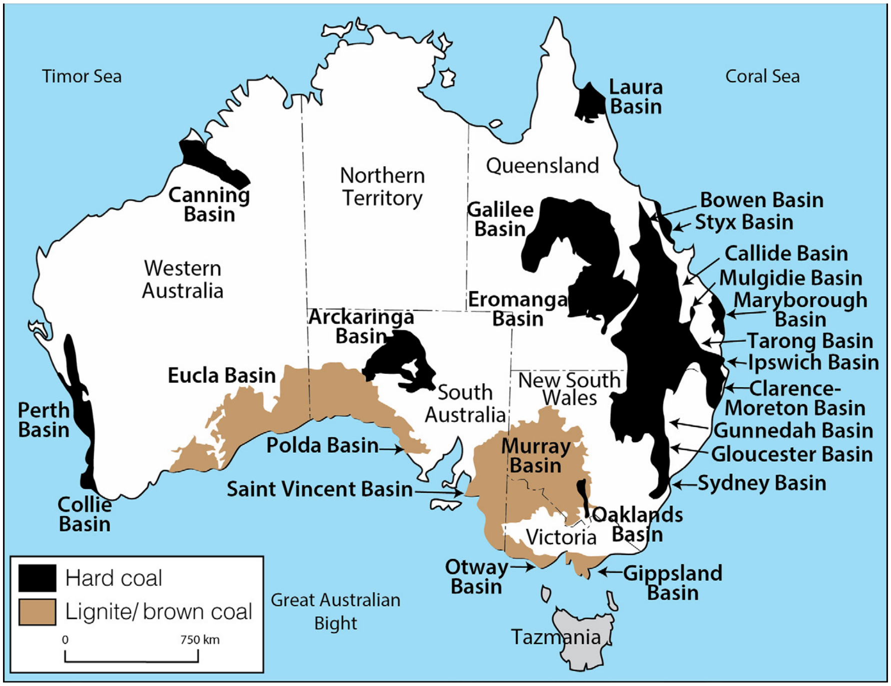


FIG. 1.22

Coal deposits in Australia.

Modified from Australian Government, Geosciences Australia, 2014. Major Coal Basins with In Situ Resources. Australian Government, Geosciences Australia, Canberra.

South Wales, Queensland, and Western Australia, while subbituminous and brown coal is mined in South Australia and Victoria. The major coal reserves are found in eastern Australia with the Bowen, Sydney, and Gippsland basins being the most important.

The Bowen basin is located in Queensland and was developed during early Permian times. The rank varies in this basin increasing from west to east, with the higher-rank coals ranging from low-volatile bituminous coal in the west to semianthracites and anthracites in the east. The coals have low sulfur content (typically 0.3–0.8%) and ash contents of 8–10% and 8–16% for coking and thermal coals, respectively.

The Sydney basin is located in New South Wales, is of Permian age, and consists of several coalfields. In general, the Sydney basin coals are medium- to high-volatile bituminous coal, with the highest rank contained in the northern portion of the basin. The coals in this basin have low sulfur content (<1%) and ash contents typically ranging from 6% to 24%, with one coalfield exceeding 40% ash.

The brown coal resources found in the Gippsland basin that lie within the Latrobe Valley in Victoria and are of Tertiary age. This area is noted for its thick coal seams—ranging from 330 to 460 ft in thickness. The brown coals have low heating values (3400–5200 Btu/lb) due to high and very variable moisture contents, which range from 49% to 70%. Ash contents, on the other hand, are low and range from 0.5% to 2%.

India

India's recoverable coal reserves rank fifth in the world, with more than 66,000 million short tons. These reserves vary in rank from lignites to bituminous coal, with most of it being hard coal (i.e., nearly 62,000 million short tons), although coal quality is generally poor. India's coalfields are located mainly in the east in the states of Assam, Bihar, Uttar Pradesh, Madhya Pradesh, Andhra Pradesh, Orissa, and West Bengal (Walker, 2000). India's coalfields are shown in Fig. 1.23. India's coals are principally of Permian age, with some being of Tertiary age.

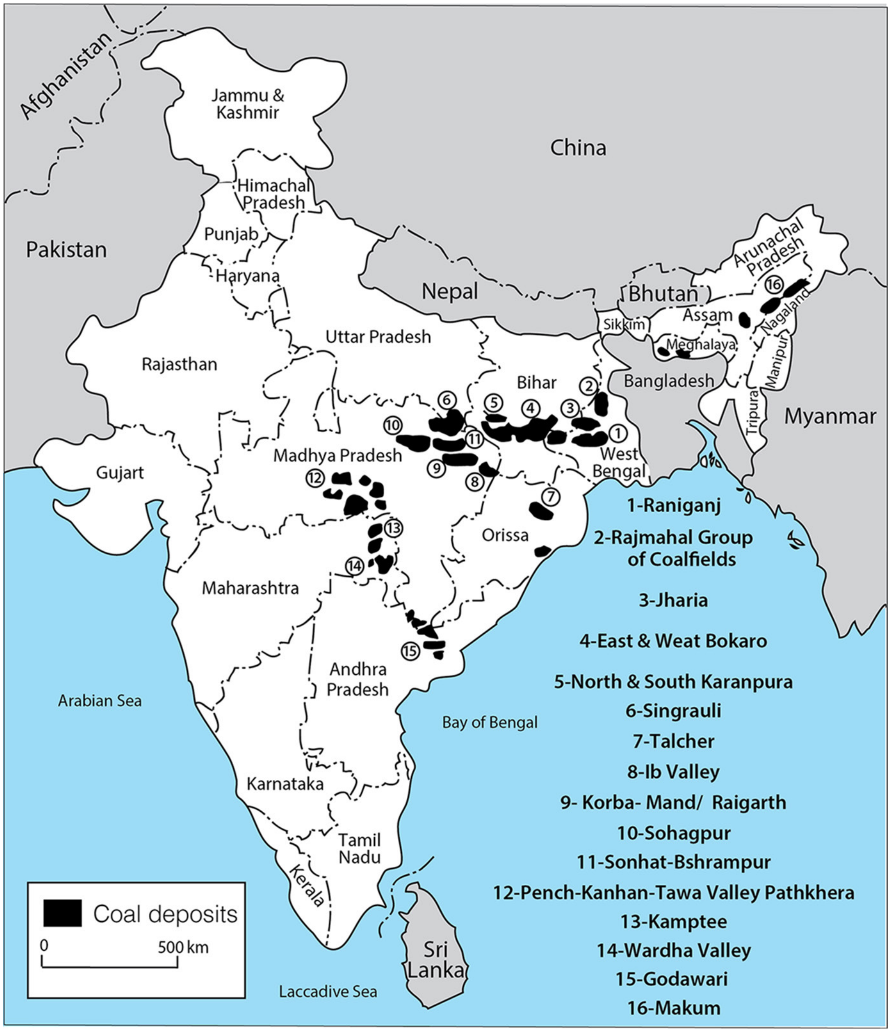


FIG. 1.23

Coal deposits in India.

Modified from Walker, S., 2000. Major Coalfields of the World. IEA Coal Research, London; Kelafant, J., 1998. Coalbed methane could cut India's energy deficit. Oil Gas J. 96 (21), 42–50.

The most significant deposits are in the Raniganj and Jharia basins of northeast India. In the Raniganj basin, the rank increases from noncaking bituminous coal in the east to medium coking coal in the west. Ash content is variable though, varying from 15% to 35%. Sulfur content is low (<1%).

The Jharia coalfield is India's major source of prime coking coal, although it also contains significant noncoking coal as well. As with Raniganj basin coals, ash content varies from 15% to 35%, with low sulfur contents in the Jharia basin.

Most of India's lignite mining occurs in southern India in the Neyveli coalfield, although other areas contain larger resources. The lignite contains low ash (2–12%) and low sulfur (<1%) contents; however, the moisture content is high, varying between 45% and 55%.

India's coal is used primarily for power production. Although India has substantial recoverable resources, coal imports are steadily rising to meet demands for coking coal, as well as for steam coal as new power plants begin operation (Walker, 2000).

Indonesia

Indonesian coals are predominately Tertiary (Miocene) in age (Walker, 2000). Some coals found in west Sumatra and southeast Kalimantan are somewhat older and are of Eocene age. Indonesian coal ranges in rank from lignite to anthracite. Lignite is found predominately in southern Sumatra, while Kalimantan's coals are mainly subbituminous and higher-rank coals. Fig. 1.24 shows the locations of Indonesian coalfields.

Coal quality varies significantly. Coals of all ranks typically exhibit a high moisture content, although better-quality coals often have low ash and sulfur contents and high volatile matter content. Coals from Kalimantan are marketed as prime blending coals for thermal generation. These coals have moisture contents that typically range from 10% to 20%, volatile matter contents range from 35% to 45%, ash contents range from 1% to 12%, and sulfur contents are below 1%.

FIG. 1.24

Indonesian coalfields.

Modified from Belkin, H.E., Tewalt, S.J., 2007. Geochemistry of Selected Coal Samples from Sumatra, Kalimantan, Sulawesi, and Papua, Indonesia. USGS (United States Geological Survey), Reston, VA.

1.6.4 AFRICA AND THE MIDDLE EAST

Coal deposits in Africa and the Middle East total over 36,000 million short tons, or ~4% of the world's total, with South Africa's reserves dominating this region at more than 33,000 million short tons (BP, 2014).

Africa contains more than 35,000 million short tons of recoverable coal, with ~33,000 million short tons of those reserves in South Africa. Thirteen other countries contain the balance, with only one of those countries, Zimbabwe, containing ≈550 million short tons; the rest contain a total of ≈1300 million short tons (see Table 1.12).

South Africa

South Africa's recoverable coal reserves of 33,000 million short tons consist entirely of hard coal. These coals are of Carboniferous and Permian age with significant deposits in the Great Karoo basin. This basin extends about 300 miles from west to east across the northern Free State Province, south and east Mpumalanga, and about 700 miles from southern Mpumalanga in the north to the center of Kwazulu-Natal in the south (Walker, 2000). Although the Great Karoo basin is the largest, there are several other basins and a total of 19 coalfields located throughout South Africa. Fig. 1.25 shows the coal deposits in South Africa.

The hard coal consists of bituminous coals, anthracite, and semianthracite. The ash content ranges from 7% for some anthracites to over 30% for bituminous coals. Sulfur contents range from <1% to nearly 3%. Domestically, the coal is used for electricity generation and conversion into synthetic liquid fuels and chemical feedstocks. South Africa exports significant quantities of steam coal with minor amounts of coking coal and anthracite.

1.6.5 CENTRAL AND SOUTH AMERICA

Central and South America contain ~16,000 million short tons of recoverable coal reserves, or 1.6% of the world's total. Coal is found in several countries including Argentina, Bolivia, Brazil, Chile, Columbia, Ecuador, Peru, and Venezuela; however, two of the countries contain the majority of these reserves—Colombia with more than 7400 million short tons and Brazil with 7300 million short tons (BP, 2014). Fig. 1.26 shows the coal deposits in South America, specifically those in Colombia and Brazil.

Brazil's coals are subbituminous and lignitic in rank while Colombia's coals are primarily high-volatile bituminous with a small amount of subbituminous coals. These coals formed during late Cretaceous to Tertiary times.

Colombia

South America formed part of Gondwana until continental fragmentation took place in Cretaceous times (Walker, 2000). In late Cretaceous to Tertiary times, conditions for the development of coal-forming deposits existed. Coal deposits are widespread throughout northern and eastern Colombia and the Cerrejón and La Loma basins are the principal centers for coal export. Cerrejón coals range from high-volatile A to high-volatile C bituminous rank. These coals generally have low ash (5–11.5%) and sulfur (0.4–0.8%) content. Average quality parameters at La Loma (Mina Pribbenow) are 11,800 Btu/lb, 4.5% ash, and 0.65% sulfur.

FIG. 1.25

Coal deposits in Africa and South Africa.

Modified from Walker, S., 2000. Major Coalfields of the World. IEA Coal Research, London; Singer, J.G. (Ed.), 1981. Combustion: Fossil Power Systems. Combustion Engineering, Inc., Windsor, CT.

FIG. 1.26

South American (Colombia and Brazil) coal deposits.

Modified from Walker, S., 2000. Major Coalfields of the World. IEA Coal Research, London; Singer, J.G. (Ed.), 1981. Combustion: Fossil Power Systems. Combustion Engineering, Inc., Windsor, CT; Trewalt, S.J., Findelman, R.B., Torres, I.E., Simon, F., 2006. World Coal Quality Inventory: Colombia. USGS (United States Geological Survey), Reston, VA (Chapter 5); Willett, J.C., Finkelman, R.B., Kalkrueth, W., Karlsen, A.W., 2006. World Coal Quality Inventory: Brazil. USGS (United States Geological Survey), Reston, VA (Chapter 3).

Brazil

All of Brazil's economically recovered coal deposits are in the Rio Bonito Formation of the Paraná basin located in the southernmost region of Brazil (Willett et al., 2006). There are eight large coal deposits located in this basin. The ash content of these coals is high, typically >35%. Most of the coal produced in Brazil is used for power generation.

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