CHAPTER 1

Introduction to Applied Coal Petrology

Colin R. Ward
Isabel Suárez-Ruiz

1.1 Fundamental Concepts

Coal is a combustible sedimentary rock, composed essentially of lithified plant debris. The plant debris was originally deposited in a swampy depositional environment to form a soft, spongy sediment called *peat*. However, physical and chemical processes brought about by compaction and elevated temperatures with prolonged burial at depths of up to several kilometers and over periods of up to several hundred million years then changed the peat into coal through a process referred to as *coalification* or *rank advance*.

The properties of a given coal can be related to three independent geological parameters, each of which is determined by some aspect of the coal's origin. As discussed more fully by authors such as Ward (1984), Diessel (1992a), Taylor et al. (1998), and Thomas (2002), these parameters are briefly defined as follows:

- *Rank*. Coal rank reflects the degree of metamorphism (or coalification) to which the original mass of plant debris (peat) has been subjected during its burial history. This depends in turn on the maximum temperature to which it has been exposed and the time it has been held at that temperature and for most coals reflects the depth of burial and geothermal gradient prevailing at the time of coalification in the basin concerned. Heat flow from nearby igneous intrusions, however, may also play a part.
- *Type*. Coal type reflects the nature of the plant debris from which the original peat was derived, including the mixture of plant components (wood, leaves, algae, etc.) involved and the degree of degradation to which they were exposed before burial.

The individual plant components occurring in coal, and in some cases fragments or other materials derived from them, are referred to as *macerals* (see Chapter 2); these form the fundamental starting point for many different coal petrology studies.

- *Grade.* The grade of a coal reflects the extent to which the accumulation of plant debris has been kept free of contamination by inorganic material (mineral matter), including the periods before burial (i.e., during peat accumulation), after burial, and during rank advance. A high-grade coal is therefore a coal, regardless of its rank or type, with a low overall proportion of mineral matter, and hence a high organic matter content.

Although organic matter derived from marine algae occurs in very old (Precambrian) sedimentary rocks, land plants capable of forming coal did not appear until the Silurian and Devonian periods. Major coal deposits occur in the Carboniferous strata (354–290 My) of Europe and North America, and in the Permian (290–248 My) sequences of Australia, India, South America, and the other land masses that made up the former continent of Gondwanaland. Coals of Carboniferous and Permian age also occur in China. Mesozoic coal occurs in a number of areas, notably the Jurassic (205–142 My) of Australia and China and the Cretaceous (142–65 My) of North America. There are also significant resources of Palaeogene and Neogene age (65–1.8 My) in various continents, including Europe, North America, Asia, and Australia.

1.2 Coal Resources, Mining, and Utilization

Coal is a versatile fossil fuel that has long been used for a variety of domestic and industrial purposes. It currently provides around 25% of the world's total primary energy (International Energy Agency, 2007) and, although subject to some possible variation with different policy developments, is expected to provide a similar share in future years (e.g., 23–26% in 2030; International Energy Agency, 2007).

Most of the world's coal is used for the production of electric power (see Chapter 4). The other main use is for production of coke as a reducing agent in the iron and steel industry (see Chapter 7). Coal is also used as fuel for a range of manufacturing processes, such as the production of heat in cement kilns and other industrial plants, gasification and petrochemical production (see Chapter 5), and heating domestic and commercial buildings. In addition, it is used as a raw material in a range of nonenergy applications (see Chapter 8), such as the production of carbon electrodes for the aluminum industry or as a precursor for a number of other carbon-based industrial materials.

The availability of coal resources has been a major contributor to the economic growth of many countries, either directly through their own resources or indirectly through access to the international coal trade. In the late 19th and early 20th centuries, coal was mainly used as a transport fuel (such as for ships and railway locomotives) or as a source of heat and power for industrial and domestic applications. In the middle of the 20th century the use of coal decreased in some areas because of low oil prices, but the oil supply crisis of the 1970s reversed this trend and led to an increase in coal consumption. Another consequence of the oil supply crisis was a significant increase in coal liquefaction research and development (see Chapter 6), although much of this work was subsequently put on hold when oil prices stabilized.

Though coal usage has continued to increase, environmental concerns and changes in the political climate have again begun to give coal an unfavorable public image. Increasing concerns about coal utilization as a contributor to greenhouse gas emissions, particularly CO_2, have led to more intense questioning of the role of coal and a renewed search for alternative energy sources. According to International Energy Agency data (International Energy Agency, 2007), coal became the world's principal source of anthropogenic CO_2 emissions in 2004, moving ahead of emissions derived from oil and natural gas sources. This has led to another change in the focus of coal research, with the emphasis shifting toward increasing the efficiency of coal utilization and to integrating coal utilization with CO_2 sequestration/storage processes.

1.2.1 Coal Resources and Production

According to data reported by the World Energy Council (2007), the total proven recoverable reserves of coal worldwide (all ranks) are currently estimated at 847 Mt, made up of 431 Mt of bituminous coal and anthracite, 267 Mt of subbituminous coal, and 150 Mt of lignite. The reserves are located on every continent and in over 70 countries, with major proportions identified in the United States, the Russian Federation, China, India, Australia, South Africa, Ukraine, and Kazakhstan.

World coal production in 2006 was 6,284 Mt (International Energy Agency, 2007), represented by 5,370 Mt of hard coal (bituminous coal and anthracite) and 914 Mt of subbituminous coal and lignite (brown coal; Table 1.1). This continues the trend previously reported by the World Coal Institute (2005), indicating an overall increase of about 40% in coal production during the past 20 years. China is now the largest single producer, with 2,841 Mt of hard coal in 2006. Other major producers, especially of hard coal, include the United States, India, Australia, South Africa, Russia, and Indonesia.

TABLE 1.1
Coal production, exports, and imports by country, 2006 (Data compiled from International Energy Agency, 2007.)

Coal Production	*Hard Coal (Mt)*	*Brown Coal (Mt)*	*Coal Exports*	*Hard Coal (Mt)*	*Coal Imports*	*Hard Coal (Mt)*
People's Republic of China	2,481	(a)	Australia	231	Japan	178
United States of America	990	76	Indonesia	129	Korea	80
India	427	30	Russia	92	Taiwan	64
Australia	309	71	South Africa	69	United Kingdom	51
South Africa	244	0	People's Republic of China	63	Germany	41
Russia	233	76	Colombia	60	India	41
Indonesia	169	0	United States of America	45	People's Republic of China	37
Poland	95	61	Canada	27	United States of America	33
Kazakhstan	92	5	Kazakhstan	26	Russia	26
Colombia	64	0	Vietnam	22	Italy	25
Rest of world	266	595	Rest of world	51	Rest of world	243
Total	**5,370**	**914**	**Total**	**815**	**Total**	**819**

(a) Included with hard coal production.

The size and extent of the world's coal reserves suggest that there is enough available to meet demands for the next 150–190 years at current production rates. The life of the reserves could be extended still further through discovery of new reserves and through upgrading less well-known deposits as a result of further exploration activities. Reserves may also be effectively increased by advances in mining technology that would allow previously inaccessible resources to be reached. On the other hand, limitations on coal mining and use due to higher costs, increased regulatory restrictions, carbon penalties, and land-use conflicts may reduce the recoverable reserves below levels that would otherwise be available for economic use.

The great magnitude, widespread distribution and relatively long projected life of the world's coal resources, compared to those of oil and gas, and the fact that many economies still depend on coal for a significant part of their energy needs (Thomas, 2002; Mills, 2004) mean that coal is expected to continue as a major energy resource for the next few decades at least. This does not, however, remove the need to establish new technologies or to improve those already in existence, to control and where possible reduce the emissions from coal utilization so that they are in accord with emerging environmental regulations and trading agreements.

1.2.2 Coal Mining and Utilization

Coal is mined via two basic methods, surface and underground mining, with the choice being mainly determined by the geology of the deposits involved. Coal seams close to the ground surface, where the overlying strata as well as the coal itself can be safely and economically removed, may be won by *open-cut mining* techniques (see Figure 1.1). Although such operations may have a more significant environmental impact than coal extraction by underground methods, a higher proportion of the *in situ* coal (usually more than 90%) is recovered for use, including in many cases seams that are either too thin or too thick for effective recovery in underground operations. With some possible exceptions, open-cut methods usually provide coal at a lower overall cost than underground mines; they also avoid some of the safety hazards, such as roof falls, gas outbursts, and coal-dust explosions, that can occur in the underground mining environment.

Most of the world's coal resources, however, occur at depths where only underground mining is likely to be possible. Underground mining currently accounts for about 60% of world coal production (World Coal Institute, 2005), and open-cut mining the remaining 40%.

The coal extracted from an open-cut or underground mine, referred to as *run-of-mine* (ROM) coal, often contains impurities such as rock from the roof and floor or layers of noncoal material occurring

FIGURE 1.1. Aerial view of open-cut coal mine, Queensland, Australia, showing overburden removal to expose the coal seam. (Photo: C.R. Ward.)

within the seam. A coal preparation process (see Chapter 3) is commonly used to reduce the proportion of this material, ensuring a consistent standard of coal quality and enhancing the suitability of the mine product for specific end uses.

Coal currently supplies fuel for 39% of the world's electricity generation, a proportion that is expected to remain at a similar level for at least the next 30 years (International Energy Agency, 2007). The demand for coal in the iron and steel industry is expected to increase by almost 1% per year over the same period of time. The biggest market for coal, particularly for steam-raising (power generation) and coking purposes, is found in the developing Asian countries, which account for 54% of total coal consumption. China is one of the most significant coal users, and the United States, India, Japan, and Russia are large coal consumers. Coal is also traded all over the world. Australia is the world's largest coal exporter (Table 1.1), with almost 75% of the country's coal exports going to the Asian market. Other major exporters include Indonesia, Russia, South Africa, China, and Colombia.

Certain characteristics of coal ensure its place as an efficient and competitive energy source and that it contributes to stabilizing energy prices. As reported by the World Coal Institute (2005), key factors include (1) the very large reserves without associated geopolitical or safety issues, (2) the availability of coal from a wide variety of sources, (3) the facility with which coal can be stored in normal conditions, and (4) the nonspecial and relatively inexpensive protection required for the main coal supply routes.

1.3 Environmental Issues and Options

Both coal mining and coal consumption have a significant impact on the natural environment. Thus, although coal is an important contributor to the economic and social development of many countries, there is a strong need to minimize and where possible reduce the negative impacts associated with its mining and use. Some of these impacts and their implications, especially to human health, are further discussed in Chapter 10.

1.3.1 Impacts Associated with Coal Mining

Coal mining, particularly in the case of open-cut mines, requires that large areas of land are temporarily disturbed, and perhaps withdrawn from other productive uses such as agriculture, while the process of coal extraction is under way. The land may, however, be returned to productive use after mining or even while mining in other parts of the area is still in progress (Figure 1.2). With underground operations, subsidence may result in a lowering of the ground surface above and around the mined-out coal bed. Other environmental risks associated with coal mining may include increased generation of noise and dust around the mine installations, soil erosion, water pollution (including in some cases acid mine drainage), and potential impacts on local biodiversity (wildlife and vegetation).

An associated problem may be the release of methane (referred to as *coal mine methane,* or CMM), which, as well as being potentially explosive, is also a significant greenhouse gas. If present in the subsurface coal seam, the methane has to be drained before underground

FIGURE 1.2. A golf course developed on rehabilitated overburden dumps at an open-cut coal mine in northern Thailand. (Photo: C.R. Ward.)

mining operations, to maintain safe working conditions. Ideally, however, the methane should be used rather than simply released into the atmosphere, even though, if mixed with the ventilation exhausts from underground mines, it may only be at very low concentrations. Methane accounts for 18% of the overall global-warming effect associated with human activities (World Coal Institute, 2005), although methane from coal accounts for only 8% of the world's major methane emissions. Utilization of methane produced during coal mining would clearly reduce the environmental impact its release might otherwise generate and could also have a commercial benefit through uses such as additional power generation.

Before a coal mine is allowed to commence operations, thorough studies must be carried out to identify all the potential risks to the surrounding environment and to minimize any negative impacts. Such a study, especially for an open-cut mine, should include a final land rehabilitation plan aimed at returning the land to other acceptable uses once the mining operations are completed.

1.3.2 Impacts of Coal Combustion

Coal consumption for power generation and heat production is of growing environmental concern, due mainly to emissions of CO_2 associated with the combustion process. The release of CO_2 into the atmosphere as a consequence of human activities, especially those related to fossil fuel combustion, has been reported to be linked to increased global warming and associated climate change. According to the World Coal Institute (2005), CO_2 emissions from all sources, including coal, account for around 50% of the overall global-warming effect associated with human activities. Although coal is only one of many sources represented by this anthropogenic CO_2, the coal industry is searching for and developing technological options to mitigate its contribution to the problem.

As part of this process, new technologies and improvements to existing technologies have been developed to increase the efficiency of combustion and power generation and reduce the CO_2 and other emissions per unit of electrical energy produced. As well as CO_2, the emissions released during coal combustion (described more fully in Chapters 4 and 10) may include oxides of sulphur and nitrogen (SOx and NOx), fine solid particulates, and possibly a range of trace elements, among which mercury is of special interest in some areas (U.S. Environmental Protection Agency, 2005a; Commission of the European Communities, 2005).

Clean coal technologies offer a series of technological options for improving the environmental performance of coal, reducing emissions and at the same time increasing the amount of useable energy derived from each ton of coal. These can include more efficient coal preparation (see Chapter 3), which serves not only to increase the heating value of the coal and therefore the efficiency of the combustion process but may also reduce the levels of sulphur and ash-forming mineral matter. This may in turn help to reduce the amount of waste as well as, perhaps, SOx and potentially harmful trace elements associated with the combustion process.

Sulphur and nitrogen oxides released into the atmosphere from coal combustion (as well as from other noncoal sources) may chemically react with water vapor and other substances to form acids that are finally deposited as acid rain. Use of feed coals with a low sulphur content is in many cases the most economical way of reducing SOx emissions. An alternative, however, is the incorporation of flue gas desulphurization (FGD) systems in power plants (see Chapter 4), which can remove as much as 99% of the SOx emissions otherwise released and therefore help considerably in the prevention of acid rain problems. The technologies developed to reduce SOx emissions from coal combustion in power plants are also effective in some cases for reducing emissions of sulphur-related trace elements such as mercury.

Emissions of nitrogen oxides contribute not only to the formation of acid rain but also to the development of photochemical smog. In the case of coal combustion these emissions may be controlled by the use of improved burner designs (low NOx burners) and possibly by using selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) technologies to treat the flue gas stream. Although such an approach may reduce NOx emissions by up to 80–90% (World Coal Institute, 2005), there may be a trade-off due to less efficient combustion of the coal, resulting in higher levels of unburnt carbon in the ash from the power plant. This may in turn impact the usefulness of the ash for processes such as cement and concrete manufacture. Another alternative is to use fluidized-bed combustion (FBC), an advanced, high-efficiency technology that may reduce both nitrogen and sulphur oxide emissions by 90% or more (World Coal Institute, 2005).

The release into the atmosphere of fine particulates from coal combustion can be reduced, if not totally eliminated, by incorporation of electrostatic precipitators (ESP) or baghouses with fabric filters (FF) in the combustion stream. These may recover the suspended coal ash (fly ash) and other fine particulates with an efficiency of up to at least 99.5%.

1.3.3 Amelioration of Combustion Impacts

Because of CO_2's association with global warming, the reduction of CO_2 emissions from coal utilization is one of the biggest present-day challenges faced by the world coal industry. In the case of coal combustion a significant step has been taken with the development of supercritical and ultra-supercritical steam cycle technologies, which can achieve thermal efficiency levels of 43–45% (supercritical) to 50% in the case of ultra-supercritical power plants (World Coal Institute, 2005). Integrated gasification combined cycle (IGCC) technology (see Chapters 4 and 5) is another possible option, producing gas from coal for use in a gas turbine rather than using direct coal combustion. IGCC-based power plants may reach high efficiency levels (50%) and can also be designed to capture CO_2 emissions more effectively for input to subsurface storage systems.

Carbon capture and storage technologies are perhaps the most promising options for substantially reducing CO_2 emissions from coal utilization, and a great deal of research is being carried out in this field (see Chapter 9). This research is directed toward both the procedure for CO_2 capture from the gases produced in different utilization plants and the identification of appropriate geological environments and sites where CO_2 can be permanently stored in a way that prevents its escape back into the atmosphere. Although there are other sources of CO_2 emissions from coal, such as the iron and steel industry, cement plants, and domestic usage, and there are also numerous sources of CO_2 unrelated to coal utilization (e.g., motor vehicles, air transport, and charcoal production), the initial focus of such activities is mainly on coal combustion in power plants. This is partly because they represent large but stationary sources of CO_2 and partly because the organizations involved in their operation might be expected to have a capacity for implementing any remediation measures that may be developed.

1.4 The Role of Applied Coal Petrology

For as long as coal has been used in industry it has been important to assess the quality of the coal and determine the chemical and physical properties that influence its suitability for the purpose in question. Some coals can be sold and used in the as-mined state (i.e., as ROM coal), whereas others may require quality improvement through coal preparation processes. Coals from different sources can also be blended to obtain a product that has particular quality characteristics.

Although some of the tests and analyses applied to coal have changed in response to new technological developments and improvements in analytical techniques, coal science still has a strongly traditional basis. Many of the tests that are used in coal characterization, such as proximate and ultimate analysis and heating value determination (see Chapter 2), are little changed from those applied to coal testing over 100 years ago.

1.4.1 History and Scope of Coal Petrology

Coal petrology is also a branch of coal science that dates back to the beginning of the 20th century, and it was in 1913 that White and Thiessen laid down some of the fundamentals that underpin coal petrology today. The titles of Thiessen's works in the 1920s, *Under the Microscope Coal Has Already Lost Some of Its Former Mystery*, reflected new discoveries in this emerging field (Thiessen, 1920a–c, 1921, 1926). However, the thin-section techniques Thiessen used and the resulting nomenclature developed at the U.S. Bureau of Mines (the Thiessen–Bureau of Mines system) are not used in modern coal characterization.

At about the same time, Stach (1935) was developing the discipline in Europe, in this case using reflected-light microscopy techniques. These techniques are still used in modern coal petrography. Stopes (1919, 1935), who was also interested in the nature of coal, coined the term *maceral* and established the concept of lithotypes that is also used today (see Chapter 2). Cady (1939) introduced the lithotype concept to the North American coal community, although the concept of macerals was not adopted until later.

The widespread use of coal petrology in the steel industry and the founding of the International Committee for Coal Petrology (now the International Committee for Coal and Organic Petrology, ICCP) in 1953 and later the North American Coal Petrographers group (succeeded by The Society for Organic Petrology, TSOP, in 1984) served to emphasize the use of reflected-light techniques in the study of coal, to unify maceral nomenclature, and to establish a classification of the coal components that can be identified using microscopic techniques. The currently accepted classification of coal components is a result of the work of the ICCP, expressed through the production of a number of editions of the *International Handbook of Coal Petrology* (ICCP, 1963, 1971, 1975, 1993). These have been replaced in part by more recent publications (ICCP, 1998, 2001; Sýkorová et al., 2005), detailing revised and expanded nomenclature and a new reclassification.

Because coal is a complex rock, coal petrology is a broader subject than merely the simple study of its organic constituents, the macerals. In the present work, coal petrology is broken down into three fundamental components: (1) organic petrology, (2) inorganic petrology and geochemistry, and (3) coal rank, or the metamorphic transformation of the macerals and minerals in coal.

Investigating a coal for the purpose of utilization involves knowing something about all these characteristics, none of which should be separated from the others. Coal quality is a function of these factors and their interactions, and coal petrology is the fundamental discipline that contributes to the knowledge of coal quality. The petrology of a coal may be expressed by a number of fundamental parameters, including (1) the nature of the organic constituents in terms of macerals or maceral groups (an indicator of coal type), (2) the mineral matter, including the major elements in the coal or oxides in the ash, the minerals in the coal, the forms of sulfur, and the trace elements that may also be present (indicators of coal grade), and (3) the vitrinite reflectance (which is usually taken as an indicator of coal rank).

These parameters reflect the composition and rank of the coal and are the primary factors that contribute to the coal's specific physical and chemical properties. The physical and chemical properties in turn determine the overall quality of the coal and its suitability for specific purposes. The analytical procedures used to determine the petrographic, physical, and chemical properties have been standardized in a number of international norms (ISO, ASTM, etc.) and additional discussion is given in compilations such as those of Peters et al. (1962), Karr (1978a,b; 1979), Ward (1984), van Krevelen (1993), and Thomas (2002).

1.4.2 Coal Characteristics for Utilization

The basic chemical parameters of a coal are determined by proximate analysis (moisture, ash, volatile matter, and fixed carbon percentages) and ultimate analysis (carbon, hydrogen, nitrogen, sulphur, and oxygen contents). Other analyses that may be carried out include determining the forms of sulphur in the coal (pyritic, sulphate, organic) and the carbon (or CO_2) content derived from the carbonate mineral fraction. The chlorine content, which is mainly associated with inorganic salts (relatively high proportions of chlorine may give rise to corrosion in coal utilization), and the phosphorous content (an undesirable element in coals to be used in the steel industry) may also be determined. The ash of the coal may be analyzed to determine the major and minor metal oxides (these influence coal and ash behavior during usage), and the proportions of a number of different trace elements, some of which could be potentially hazardous, may also be evaluated.

In addition to the chemical properties, effective use of coal also requires knowledge of particular physical properties, such as the coal's density (which is dependent on a combination of rank and mineral matter content), hardness, and grindability (both related to coal composition and rank). Other properties include the coal's abrasion index (derived mainly from coarse-grained quartz) and the particle size distribution. Float-sink testing may also be integrated with the analysis process, separating the (crushed) coal into different density fractions as a basis for assessing its response to coal preparation processes. Float-sink techniques may also be used to provide a coal sample that represents the expected product of a preparation plant, to assess the quality of the coal that will actually be sold or used rather than the *in situ* or run-of-mine material represented by an untreated (raw) coal sample.

As well as proximate and ultimate analysis data, the coal quality parameters that need to be taken into account in coal combustion, such as in coal-fired power plants, include information from a number of specific tests, such as:

- *The Hardgrove grindability index (HGI).* This indicates the ease with which the coal can be ground to fine powder and is important for gauging the coal's compatibility with the pre-combustion pulverization system of the plant concerned. This HGI is most directly related to the maceral and maceral group composition (see Chapter 3) but is also dependent on rank and mineral content.
- *The heating value, calorific value, or specific energy.* This indicates the amount of heat liberated per unit of mass of combusted coal and is of fundamental importance in setting the price of particular coals for combustion applications. Although generally regarded as a rank-related parameter, the calorific value is also dependent on the macerals in the coal and the mineral composition.
- *The total sulfur content.* This may be derived from a combination of the organic constituents and the mineral matter. As well as the overall percentage, it may be expressed in some cases as the sulfur dioxide emissions expected in relation to the heating (or calorific) value—for example, as kg SO_2/GJ.
- *The ash fusion temperatures.* These indicate the behavior of the ash residues from the coal at high temperatures and are mainly related to the chemical composition of the ash and the nature of the coal's mineral matter (see Chapter 4). They are used to indicate whether the ash will remain as a fine powder within the furnace system after the coal is burned or whether it might partly melt and form a slag on the boiler's heat exchange surfaces.

Other tests that provide information about the potential behavior of coals during carbonization and coking processes (see Chapter 7) include:

- *The free-swelling index (FSI) or crucible swelling number (CSN).* This is a measure of the increase in volume of the coal when it is heated in a small crucible in the absence of air. This test is also used to characterize coals for combustion, especially where the coal is burned in beds of coarse-crushed material in stoker-based systems.

- *The Roga index.* This test provides information on the caking properties of the coal, in a similar way to the free-swelling index. The index itself is derived from the strength or cohesion of the coke produced in the crucible, as evaluated by a subsequent tumbler test.
- *The Gray-King and Fischer assays.* These determine the proportions of coke or char (carbonaceous solids), tar (organic liquids), liquor (ammonia-rich solutions), and gas produced when the coal is carbonized (heated in the absence of air) under particular laboratory conditions and hence provide a basis for estimating the yields of coke and coke byproducts obtained from the coal in an industrial coke oven or oil-shale processing plant.
- *Giseler plastometer and Audibert-Arnu dilatomer tests.* These monitor how the coal behaves as the different macerals melt, devolatilize, and resolidify at different temperatures during the carbonization process (see Chapter 7). The Gieseler plastometer evaluates the coal's behavior by measuring the fluidity of a packed coal powder as it is heated, whereas the Audibert-Arnu dilatometer measures the contraction and expansion of a powdered sample pressed into a cylindrical coal "pencil." Such properties are significant when different coals are blended for coke production, to ensure compatibility of the different blend components. Indeed, coal-blending strategies for coke production are generally decided from a combination of rheologic and petrographic parameters for individual coal samples, which are used to select coals to make up a blend with specific coking properties.

1.4.3 Petrological Controls on Coal Characteristics

Although various combinations of these tests are used to evaluate the suitability of particular coals for a variety of industrial processes, the properties determined by the various tests are ultimately related to the coal composition (organic and inorganic components) and the coal rank (degree of metamorphism). Organic petrology therefore plays a fundamental role in determining coal behavior, and evaluation of petrographic properties (e.g., maceral percentages, vitrinite reflectance, mineral matter composition) should be an essential part of any coal analysis and testing program.

Another factor that must be taken into account in determining coal quality is the degree of coal oxidation. Coal oxidation may result from exposure to weathering processes during handling and transport or when the coal is stockpiled under different environmental conditions.

Oxidation may affect both the organic and inorganic components and can give rise to deterioration in the coal properties, especially those relevant to coking applications (see Chapter 7). Petrographic examination may help to identify coals that have been oxidized and perhaps explain any anomalous behavior associated with the oxidation process.

A different consequence of coal oxidation is the development of spontaneous combustion (see Chapters 10 and 11), when the heat generated by in-situ oxidation causes the coal to smolder and ultimately burn without any external heat source. The liability to oxidation is mainly determined by the coal's rank, in conjunction perhaps with the maceral and mineral (e.g., pyrite) content (see Chapters 3 and 11). Low-rank coals are particularly prone to spontaneous combustion; other factors, such as access of air to coal stockpiles, may need to be controlled to reduce spontaneous combustion risk.

Role of Organic Constituents

The organic constituents of coal, including both the maceral groups (liptinite, inertinite, and huminite/vitrinite) and the individual macerals in those groups (see Chapter 2), are, singly and in combination (as natural associations or microlithotypes), fundamental to many coal properties. Vitrinite is the most common maceral group in many coals, especially the Carboniferous coals of the Northern Hemisphere, and it is the properties of the vitrinite in such coals, together with the variations in those properties with rank, that to a large extent determine the properties of the coal concerned.

There are, however, major exceptions to this principle, such as with the Permian Gondwana coals of India, Australia, Southern Africa, South America, and Antarctica. These coals are commonly rich in inertinite-group macerals, with vitrinite in some cases forming only a relatively minor component. The different maceral assemblage reflects deposition in a cooler and drier climate and a more terrestrial environment than the Carboniferous coals of Europe or North America. The Gondwana coals are also more variable, and vitrinite-rich and inertinite-rich coals may occur in close proximity, and even as different parts of the same coal seam.

Environmentally Significant Inorganic Components

The inorganic constituents of coal are often expressed on the basis of simple parameters such as ash yield and sulfur content. It is, however, often convenient to express an inorganic constituent relative to another parameter, such as the expression of sulfur in terms of SO_2 emissions per unit energy, with the latter being derived from the heating value.

Knowledge of the inorganic constituents in coal may take on a more complex role if emissions of the so-called hazardous air pollutants (abbreviated as HAPs) are regulated. HAPs generally include Sb, As, Be, Cd, Ni, Pb, Se, Hg, Co, Cr, and Mn, with Cl and the radionuclides, Th and U, also included in some assessments. In the United States, the focus has been on Hg, with the U.S. Environmental Protection Agency (2005a) mandating a reduction in Hg emissions to 15 short tons/year by 2018 (from early 21st-century levels of about 45 short tons/year). The European Union is also taking measures on this matter, as described in Chapter 4.

Many of the elements that may be of concern are trapped with the fly ash after coal combustion (discussed in Chapter 4) and, in the case of power plants using flue-gas desulphurization (FGD) systems, with the FGD (or scrubber) byproducts. Coal beneficiation processes prior to utilization may also serve as a means of reducing the levels of at least some trace elements (e.g., Hower et al., 1998). Elements of concern that occur at significant levels in the processing or utilization residues may give rise to waste disposal or control problems that are different from air pollution, through processes such as leaching into the natural environment following ground or surface water infiltration (e.g., Jankowski et al., 2006) and the potential for such issues may also need to be investigated.

The lower heating value of lower-rank coals means that more coal must be burned to produce one unit of electricity compared to higher-rank (e.g., bituminous) coals. Just as the amount of sulfur in a coal can be translated into kg of SO_2 per GJ of energy produced, on the basis of the heating value, the abundance of HAPs and similar elements may also need to be expressed in energy terms.

Evaluation and Significance of Coal Rank

Coal rank is commonly expressed in terms of vitrinite reflectance (see Chapter 2). Because it is measured by optical microscopy and takes into account only one coal component, this parameter has the capacity to provide an indicator that is independent of other factors (e.g., coal type or grade). Unlike other indicators, such as total (organic) carbon, volatile matter, or calorific value, it is not dependent on the overall coal composition (e.g., relative proportions of different macerals); the only requirement for the determination is that vitrinite is present in the coal.

Although vitrinite reflectance is widely used as a measure of coal rank, it is not always a truly independent rank indicator. As discussed further in Chapter 2, some vitrinites may have anomalously low reflectance (due, for example, to the original depositional environment), a phenomenon known as *reflectance suppression* (Barker, 1991), which may give misleading results if other indicators are not taken into account. Despite the advantages and simplicity of vitrinite reflectance, it is very difficult to find an indicator of coal rank that is totally independent of the organic and inorganic composition or of other influencing factors such as the depositional environment of the original peat deposit.

Despite the difficulties in identifying a robust rank indicator, a number of coal properties progressively change with rank advance (Figure 1.3), and the rank of a coal is thus a major factor influencing its potential usage. For example, the heating value determines how much coal is required to produce a given amount of steam and hence to generate a given amount of electricity, and the rank thus represents the fundamental basis for assessing the values of coals, per tonne, on the steaming coal market.

The free-swelling index (FSI), which is important for both metallurgical and steaming coals, is also at least in part a rank-dependent parameter, increasing with rank through the high-volatile bituminous range but decreasing again above the medium volatile bituminous range. The free-swelling index also depends on the maceral composition of the coal, with the vitrinite maceral group being the main contributor to swelling properties. Some of the inertinite group macerals,

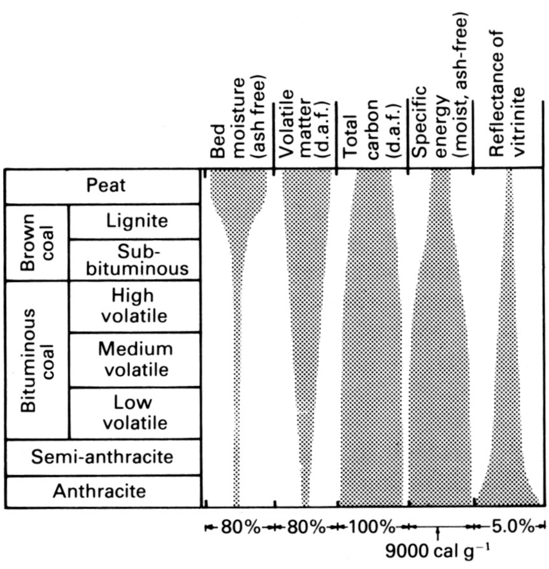

FIGURE 1.3. Variation in some key coal properties with rank advance. (Source: *Coal Geology and Coal Technology,* by C. R. Ward (Ed.), "Blackwell Scientific Publications, Melbourne," 345 pp., copyright 1984, with permission from Blackwell.)

and also the mineral matter, act as diluents, reducing the swelling properties that would otherwise apply to vitrinite-rich coals at the relevant rank level.

1.4.4 Integration of Coal Petrology in the Evaluation Process

This book considers coal as the sum of all its components, organic and inorganic, together with the metamorphic changes they have undergone through the rank advance process. It is the integration of these fundamental factors that is important, rather than the features or percentages of any individual component. The interplay of coal characteristics and coal utilization has been important as long as coal has been used and will continue to be important (as discussed in Chapters 8 and 9) until coal is no longer a viable economic resource.

Since the beginnings of the science, coal petrology has been found to be a powerful tool in the characterization of coals for both geological and industrial applications. This book focuses on the applications of coal petrology to coal mining, preparation, and (especially) utilization as well as to other related areas, such as archaeological studies (see Chapter 11). Each of these subjects is a major topic in itself, and the book is able to present only a brief review of each. Bibliographic references are provided, however, for additional information on specific aspects and applications.