CHAPTER 6

Coal

> *... plants are a significant geological force of nature – a critical missing feedback linking biology, chemistry, and physics that has shaped our planet's history ...*
>
> David Beerling 2007

Synopsis

For industrial nations, abundant energy in the form of coal was the fundamental precondition for development (Freese 2003). Considering examples such as China and India, this is not different today. Development requires bounteous and low-cost energy, which involves sacrificing the pre-industrial farming society with its perceived peaceful and sustainable life. For liberating the inherent energy, coal must be combusted, resulting in various hazardous emissions that have to be controlled. Coal's most widely discussed emission is carbon dioxide because of its influence on global climate. This feeds a lively debate about the future of coal.

This chapter starts with a concise introduction to coal utilization, production and resources, including information on possible carbon dioxide mitigation strategies. To lay the base, the ensuing sections discuss the substance of coal, its formation from peat deposited in ancient wetlands and the processes that make coal from peat. We then look at weathering of coal, which often involves self-ignition and natural coal seam fires. Practical aspects of coal science, such as its application in exploration, reserve estimation, mining and environmental mitigation, conclude the chapter.

At present, the major utilization of coal is electricity production. China, for example, derives ~80% of its electricity from coal and the United States 50%. Cokes produced from certain hard coals, and anthracite, are ideal reductants for processing oxide metal ores and are also used in many other industrial processes (e.g. soda ash and carbide manufacture, cement-making, hydrogen production by steam reforming). Domestic heating is a minor sector of coal use. In the near future, the production of liquid fuels from coal and lignite, based on the Fischer-Tropsch synthesis and similar processes ("coal-to-liquids technology"), is expected to expand considerably. This is due to increasing economic viability, as prices of petroleum and natural gas rise. South Africa has a long tradition of providing its liquid fuel needs by this technology. Today, many more countries, which have limited natural hydrocarbon but large coal reserves, plan to take this route (e.g. Australia,

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Economic Geology Principles and Practice
Metals, Minerals, Coal and Hydrocarbons – Introduction to Formation and Sustainable Exploitation of Mineral Deposits, Walter L. Pohl

China, India, New Zealand, USA). Gasification is emerging as an improved technology for electricity production from coal, resulting in lower sulphur dioxide, nitrogen oxide, mercury and particulate emissions, compared to a conventional pulverized coal power plant. The IGCC (integrated gasification combined cycle) process also uses less water and can be more economically retrofitted for carbon capture.

This scenario implies that in the future, production and use of coal will continue to grow. Is this supported by sufficient coal resources? Today's deposits that can be exploited under existing economic and operating conditions ("proven reserves") contain ~ 826,000 Mt. Of this total, one half comprises black coal and anthracite, the remainder brown coal and lignite (*BP Statistical Review of World Energy* 2010). World production of coal and lignite in 2009 was ~7023 Mt (equal to 3409 Mt of oil equivalent). The largest producers of hard coal are China (45.6%), USA, India, Australia, Russia and South Africa. Germany is the leading lignite producer, followed by USA, Greece and Australia.

Dividing reserves by annual production (R/P) gives the so-called "static period of availability" of coal reserves at ~120 years (Figure 6.1). Of course, the ratio does not define the end of coal, because additional giant resources are available. It illustrates only the difference between coal and other raw materials, concerning the rules for defining coal reserves and the long-term nature of planning. At face value, coal reserves are assured for a much longer time than petroleum (at the end of 2009 ~46.7 years, the Canadian oil sands not included) and natural gas reserves (~63 years). As explained in Chapter 7, oil and gas production will continue far beyond this period. Additional giant energy resources are available if today's uneconomic coal occurrences can be made useful, for example by new extraction technology or *in-situ* gasification.

More than 60% of world coal reserves occur in the USA, Russia and China. With nearly 30%, the USA hosts the largest reserves of all countries. Black coal (anthracite and bituminous coal) reserves occur in USA, China, India, Russia, Australia and South Africa. Significant brown coal (sub-bituminous coal and lignite) reserves occur in USA, Russia, China, Australia, Ukraine, Colombia and Canada.

Carbon capture and storage must result in a higher price of electricity and requires giant investments. Economists are divided on the best mitigation path to take. Should the huge sums needed for a reduction of anthropogenic CO_2

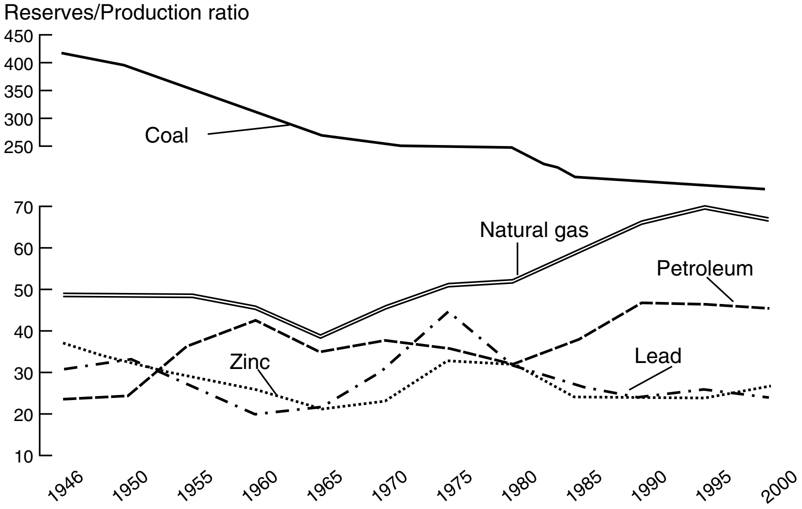


Figure 6.1 Evolution of the reserves to production ratio R/P (also called "life-index" or "R/C ratio") of energy raw materials coal, petroleum and natural gas, compared to lead and zinc, from 1945 to 2000 (adapted from Wellmer 2008). With permission from www.schweizerbart.de. The rapid fall of the R/P ratio of coal is not due to depletion, but to gradual world-wide acceptance of stricter rules for declaring reserves (cf. Chapter 5.3.2 "Ore Reserve Estimation and Determination of Grade"). In 2010, R/P ratios were 47 years for oil, 63 for gas and 120 for coal (BP 2010).

BOX 6.1 Coal and carbon dioxide

Worldwide, there are ~2100 coal-fired power plants. Burning coal implies the generation of waste gases, including CO_2, SO_2 and NO_X. The two latter can be reduced to low levels by better combustion and flue gas cleaning technologies. Reduction of greenhouse gas (GHG) carbon dioxide emissions progresses only gradually, however, mainly by more efficient combustion and by saving energy. The energy yield was improved from ~33% in the past to 55% in modern coal-fired power plants. Even so, coal-burning accounts for roughly one-third of the CO_2 generated by human activity (a total of 7 Gt per year, Normile 2009). One tonne of black coal containing 80% C generates nearly 3 t CO_2. Today, the public, governments and industry are prepared to take more radical counter measures against CO_2 (and other) emissions into the atmosphere. This is certainly desirable, even if a leading role of CO_2 as a control on climate is not undisputed and the climate's sensitivity to a doubling of CO_2 may be commonly overestimated (Plimer 2009, Kirkby 2008, Royer *et al.* 2007). About 75% of the greenhouse effect is due to clouds and water vapour and 20% to CO_2 but without CO_2 and minor GHGs, Earth would rapidly fall into icehouse state (Lacis *et al.* 2010). Present data are insufficient to decide if climate change increases or decreases evaporation (Dolman & de Jeu 2010) which is a significant factor of the Earth's surface energy balance. Stratospheric water vapour is unexpectedly revealed as an important climate driver (Solomon *et al.* 2010). For the last five years, the energy balance of the Earth defies climate modellers (Trenberth & Fasullo 2010).

Apart from reducing fossil fuel use, two mitigation strategies against the increase of atmospheric CO_2 concentration are mainly pursued (Lackner 2003): i) Net carbon storage in forestry and agriculture, including soil improvement by adding biomass or char; and ii) carbon-capture and storage systems (CCS) that include underground sequestration in mature oil and gas fields, in deep coal beds and in deep saline aquifers. The last has been practised for many years in the Norwegian offshore gas field Sleipner (Bickle *et al.* 2007, Figure/Plate 6.2). Worldwide available pore space is thought to be very large (Figure 6.3). Less credible, CO_2 might be disposed of as a liquid in deep oceans, in zeolites, and in magnesite made from serpentinite and dunite. CO_2 capture technologies, more than sequestration, are costly. Two technologies of capturing CO_2 are currently favoured: The first binds CO_2 on monoethanolamine (MEA) or ammonium carbonate in order to separate it from nitrogen in the flue gas, whereas the second burns the coal with pure oxygen.

Figure 6.2 (Plate 6.2) Sleipner platform in the North Sea off Norway is the world's first large-scale geological CO_2 sequestration operation. On the platform, carbon dioxide is separated from natural gas and pumped into a sub-seafloor aquifer. © Øyvind Hagen, Statoil.

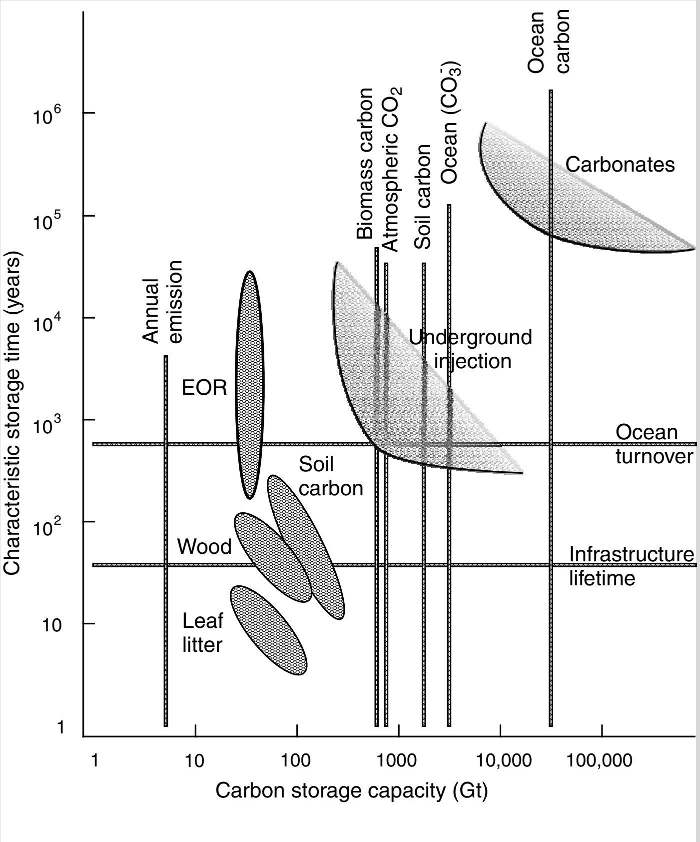


Figure 6.3 Comparison of several significant variants of CO_2 sequestration, their estimated storage capacity and time of immobilization (modified from Lackner 2003). Reprinted with permission from AAAS. Carbonates guarantee the maximum of isolation time, whereas biomass is short-lived. Advisable seem to be EOR (enhanced oil recovery) and deep injection with its large capacity.

At ambient pressure and temperature, carbon dioxide is a gas (density 1.98 g/cm^3) that is 1.53 times heavier than air. At moderately low temperatures (31.1 to −56 °C) and a pressure from 5–73 bar, CO_2 is a liquid heavier than water. Above its critical point at 31.1 °C and ca. 73 bar, carbon dioxide transforms into a low-viscosity supercritical fluid. This is the state of concentrated CO_2 in geological reservoirs at depths below ~500–1000 m. With a density of 0.5–0.7 g/cm^3, supercritical CO_2 is less dense than brine or petroleum but more dense than methane. Within the reservoir, injected CO_2 is gradually dissolved in formation water and commonly occurs as ionic HCO_3^- (eq. 1.14). In time, it may be immobilized by precipitation of carbonates such as calcite. Leakage from CO_2 repositories to the surface must be minimized, not only because escape defies the purpose of storage, but also in order to prevent hazards to human and animal life. Carbon dioxide gas is an inert asphyxiant and because of its density, collects in calm depressions and basements. Humans react to CO_2 concentrations of 4–5% in air by accelerated breathing and discomfort, at 7–10% persisting for several minutes by fainting (Weinstein & Cook 2004). Maximum work exposure is set to 0.5%. Because of the perceived hazard, offshore sites such as Sleipner are probably more acceptable than onshore storage in densely populated regions (Schrag 2009). Haszeldine (2009) presented a map of CO_2 emission sites in Northwest Europe and a draft of possible pipelines and storage fields in the North Sea.

Once captured, CO_2 is liquefied, dried and pumped down into geological reservoirs. This technology is well-known in the oil and gas industry because for many years, supercritical carbon dioxide has been used to displace hydrocarbons from reservoir pore space in order to enhance oil recovery. One example is the almost pure magmatic CO_2 from Bravo Dome gas field in New Mexico, which is used for carbon dioxide injection to maximize oil recovery in western Texas. The comparable but less practised CO_2-enhanced methane recovery (ECBM) from deep unexploitable coal seams may offer another path of CO_2 geosequestration (Ozdemir 2009). In the Rangely Oil Field, Colorado, loss of injected carbon dioxide by micro-seepage to the atmosphere is a fraction of natural methane seepage (Klusmann 2003). The safety case for geological CO_2 storage is gaining strength (Houston *et al.* 2007) and in a North Sea oil field CO_2 pool, seal performance for >70 million years has been demonstrated (Lu *et al.* 2009). For prospective storage sites, the main questions that must be answered concern: i) the pressure management; and ii) the fate of the displaced pore fluid (Schrag 2009). Although large-scale capture and geological sequestration of CO_2 still present technological challenges, CCS may soon be widely employed, provided that clear regulations assure companies of a long-term business perspective (Haszeldine 2009). Overall it is expected that in a few decades, CO_2 emissions from coal, oil and gas power stations will be reduced to unproblematic levels similar to the successful mitigation of SO_2 and NO_x. On that base, fossil fuels can yet provide long-term sustainable energy for the world's industry and humans (Haszeldine 2009, Jaccard 2006).

emissions be provided now because of ethical considerations (Stern & Taylor 2007), or "ramp up" slowly as conventional economic analysis (Nordhaus 2007) indicates? For the second more realistic case, a strategy might be prepared to arrest a possible "run-away" warming of the Earth's climate, when the upper limit of the IPCC (UN Intergovernmental Panel on Climate Change) temperature rise is near. This includes various techniques of *climate engineering* (Wigley 2006). Injecting aerosols or aerosol precursors (i.e. SO_2) into the stratosphere can provide a negative forcing of the temperature and offset part of the positive forcing due to increased greenhouse gas concentrations. Volcanic eruptions provide natural examples of this effect. In June 1991, Mt Pinatubo blew ~10 Mt sulphur into the stratosphere and caused detectable cooling without disruption of the climate system. Another method might be fertilizing the upper oceans with iron in order to amplify biomass production, enhancing carbon storage by burial of organic matter in ocean floor sediments (Boyd 2007). Such actions could slow warming and provide time for the huge investments needed to reduce human CO_2 emissions.

6.1 THE SUBSTANCE OF COAL

6.1.1 Coal types

Coals are solid, combustible, fossil sedimentary rocks that formed from land plants (*Embryophyta*) profusely growing in ancient wetlands. After deposition, the peat was covered by sediments, usually clay and sand. Diagenetic processes acting on the material caused an overall enrichment of carbon (coalification). The difference between coal, peat and coal shale is important because in many countries the state controls coal mining, whereas peat and coal shale belong to the land owner.

Peat, the soft sediment in mires and fens, is the precursor of coal, which is a hard rock. Low-grade lignites (bog coal) are intermediate between mature peat and mature lignite. The limit between peat and lignite is rather a matter of convention. In some countries peat may be an important source of energy.

Coal shale and bituminous shale can be valuable raw materials, for example in cement production (cf. Chapter 3 "Carbonate Rocks"). These rocks are remarkable because they self-ignite and burn slowly when dumped on waste rock tips without special precautions. Generally, the limit between coal and coal shale may be set at 50 wt. % combustible substance (dry basis). However, coal with more than 30 wt. % of non-combustible matter is rarely used as a fuel. Coals with higher content of mineral matter (e.g. clay, silt, sand, carbonates, sulphides), but not exceeding 50%, are called "impure coals". If feasible, mine-site processing is often employed to upgrade the coal content of low-grade impure material.

The distinction between brown coal and black coal originated in Europe, because there is such an obvious difference between Tertiary low-rank brown and Carboniferous high-rank black coal, with rare intermediate quality deposits. The first has a low calorific power and its use is restricted to energy and heat production, whereas the second is a prime fuel and a valuable industrial reductant (e.g. for iron melting). The terms brown coal and lignite are widely considered as synonymous. The terms "black" or "hard coal" are little used

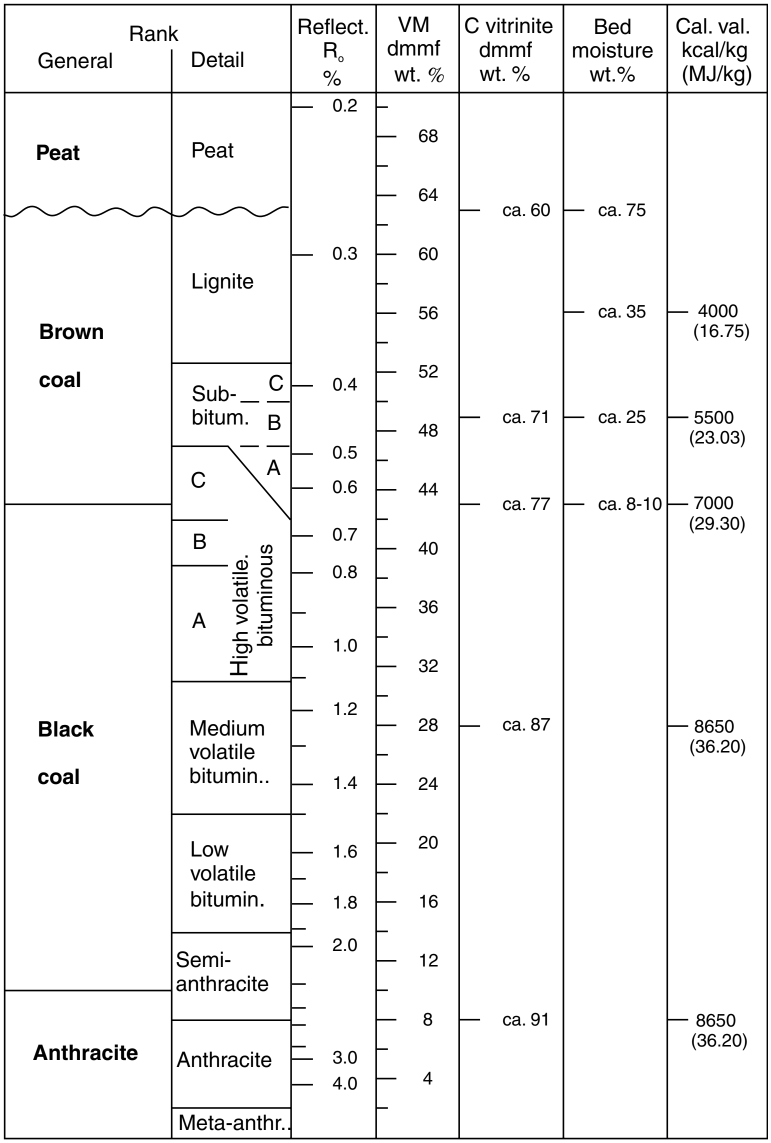


Figure 6.4 Classification of coal according to rank with reference to important properties (modified from Taylor *et al.* 1998). With permission from www.schweizerbart.de. The international unit for calorific value in the SI-System is *Joules*. Conversion: 1 kcal = 4.1868 kJ [d.m.m.f. = calculated to dry and mineral matter free, i.e. pure coal substance].

in English; the common terms are "bituminous coal" and "anthracite" (Ward 1984, Thomas 2002).

Low rank coals (lignite and sub-bituminous coal, Figure 6.4) are subdivided according to water content. Bituminous coals are mainly classified by % volatiles liberated at high temperature in the absence of oxygen. This underlines that at differing rank, suitable parameters for coal classification vary. Some observations on macroscopic characterization of coal types include the following:

Lignites

Lignites are yellow or brown coals that can be cut with a knife. Lowest rank soft, earthy or crumbly lignite is called "bog coal"; it occurs in thick banded seams that are not jointed. In certain horizons, upright tree stumps or fallen logs are numerous. Exposed bog coal crumbles quickly because of drying and shrinkage. Seams occur at little depth below the surface and country rocks are unconsolidated sediments. "Lumpy" lignites are harder and more consolidated and on extraction break into large fragments. This type is made up of brown tree stumps, logs and branches. The seams are banded, either by thin layers of clastic sediment, detrital coal, or by charcoal and charred woody debris (fire horizons). Lumpy lignite occurs at a depth to a few hundred metres below moderately consolidated sediments. Today, lignites are exclusively used for large electricity production units.

Sub-bituminous coal

Sub-bituminous coal ("black lignite") is markedly brittle. With increasing rank (from C to A, Figure 6.4) its colour varies from dull brown to lustrous bright black. Fossilized wood can still be recognized. The seams are closely jointed and banded. On drying, dull coal disintegrates into small cubic lumps, whereas lustrous sub-bituminous coal with lower water content changes little. Sub-bituminous coal occurs at a depth of several hundred metres below medium-consolidated sediments.

Bituminous coal

Bituminous coal occurs in well-consolidated sediments (e.g. sandstone, shale) and both coal and host rocks are jointed. From low to high rank, the main varieties are:

- high volatile bituminous (gas coal);
- medium volatile bituminous (coking coal); and
- low volatile bituminous coal (steam coal).

There is little macroscopic difference between the three; all bituminous coals are brittle and composed of thin dull and bright bands. As volatile substance content decreases, banding and layering of coal wanes and disappears when the anthracite rank is attained. Natural coking coals and commercial blends that provide good coke are most valuable. Non-coking bituminous coals are burned in power plants and general industry; gas coal is especially suitable for the production of liquid fuels.

Anthracite

Anthracites are black, and display a metallic lustre and a conchoidal fracture. Due to the very low content of volatile matter, anthracites burn with little smoke and with short flames. They are preferred for steam and heat generation. Meta-anthracite is transitional to graphite. In fact, a sizeable part of traded "graphite" is meta-anthracite.

The coal varieties described so far are *humic coals*. They originate from land plants and peat, and represent the majority of all coal extracted. Many deposits of humic coal contain a minor part of less common coal varieties. These include *sapropelic* (boghead and cannel coal, schungite) and *liptobiolite* coals. Sapropelic coal is formed as a bottom sediment in stagnant anoxic water from small particles of plant residues, spores and foundered mats of floating algae. The sediment is putrefied rather than peatified. Liptobiolites consist of plant material that resists oxidation on the peat surface (e.g. spores, pollen, wax, resin, amber) and accumulates in situ or after transport by wind and flowing water.

Boghead coal

Boghead coal (torbanite) is composed of characteristic algal colonies (e.g. *Pila, Reinschia*). Boghead is of blackish-brown or greenish-black colour and gives a brown streak. Similar to cannel coal, it is very fine-grained and homogeneous, and presents a conchoidal fracture. Boghead occurs with humic coals or forms independent seams that may grade into oil shale and petroleum source rock as mineral matter content increases. Volatile matter content of boghead is very high, so that the material is preferably used for "synthetic oil" production. On heating in a retort, up to 800 litres of oil per tonne may be recovered (cf. 7.7 "Oil Shale").

Cannel coal

Cannel coal burns like a candle when ignited, explaining its name given by miners. It is black with a greasy dull lustre and has a black streak. Often found in the upper part of humic coal seams, it forms thick slab-like beds. Constituents are mainly derived from vascular plants and comprise uniformly fine-grained particles such as spores, resins, plant debris, black carbon and algae (Hutton & Hower 1999). Siderite lenses and bands are frequent in cannel coal and beds may pass into massive siderite. Cannel coal occurs in all major coal fields of the world. *Jet (gagatite)* is similar to cannel coal and both can be worked into black jewellry and ornamental articles. However, jet originates from tree logs that were embedded in bituminous shale (e.g. in the Jurassic beds of Yorkshire). *Schungites* are Palaeoproterozoic equivalents of sapropelic coal, formed from mats of Cyanobacteria and of exuded bitumen (Medwedev *et al*. 2001, Melezhik *et al*. 2004).

Liptobiolites

Liptobiolites are concentrations of plant constituents that resist aerobic weathering. In Eocene lignite seams in Germany, bands of yellow, light brown or pink *pyropissite* are common. Pyropissite is essentially composed of pollen, wax, resin and leaf cuticles in variable ratios. Often, the strata are more prevalent near margins of coal basins, yet formed as aquatic sediments. Pyropissite can be ignited similar to cannel coal. *Amber* is re-sedimented fossil resin, occurring in large lumps that the plants produced to seal and protect wounds and to discourage herbivores. Earliest amber dates from the Carboniferous (Grimaldi 2009). In the Palaeocene-Eocene, major amber deposits were formed in deltas and shallow water along the southeastern shore of the Baltic Sea (Kharin *et al*. 2004). Baltic amber was already highly valued by Neolithic people ~13,000 years ago and traded throughout Europe. Amber is used for the production of ornaments, special lacquers and chemicals.

Saline coals

Saline coals contain elevated gypsum, NaCl and KCl, because of contact with brines (Yudovich & Ketris 2006a). In Northern Germany, chloride-sulphate brines are common in the vicinity of subcropping Permian salt formations (Figure/Plate 5.18). Where brines infiltrate lignite and sub-bituminous coal, severe problems arise for boiler operations, because alkalis, silica and iron tend to combine in fouling surfaces of steam generators in power plants. Leaching of salt deposits is also the reason for the salinity of underground water pumped from black coal mines near Cracow, Poland; coal quality, however, is hardly affected because the small porosity of bituminous coal inhibits absorption of salt. Saline mine waters can also be a result of aridity, as in Australia (Côte *et al*. 2007).

This overview shows that coals are described according to the three parameters:

1 rank (grade of diagenesis);
2 type of organic precursor; and
3 content of inorganic substance.

Traded coal is often a mixture from different seams and deposits. Its characterization is based on technological and commercial parameters (calorific power, water content, volatile content, coking properties, etc.) that are translated into numeric codes (Gayer & Pesek 1997, Thomas 2002). These codes are shorthand descriptions of quality and possible use.

6.1.2 Petrography of coal

Most coals are very heterogeneous, both macroscopically and under the microscope. This is aggravated by the fact that organic constituents exhibit a continuously changing chemical composition as rank increases, very different from the stable properties of minerals. Because of these impediments, it took more than 100 years to develop an internationally recognized system of coal petrography. Its base is the Stopes-Heerlen System, which was first presented by Marie C. Stopes at Heerlen, Netherlands in 1935.

A full description of the composition of a "coal rock" can only be carried out with a microscope (Taylor *et al*. 1998). Yet, macroscopic features are useful for a preliminary approach, similar to the field description of ordinary rocks. In this way, mine exposures or drill cores of coal are examined and the occurring coal varieties ("lithotypes") and interbedded non-coal rocks are recorded in a ply-by-ply manner. Under the microscope with a 25- to 50-fold magnification, the organic constituents of coal ("macerals") are determined. The microscopic quantification of different macerals making up coal layers ("microlithotypes") provides a precise characterization of coal.

Lithotypes

Lithotypes are layers in coal that can be macroscopically distinguished. Bituminous coal always consists of thin bright and dull layers that trace sedimentary bedding. Bright layers are *vitrain*, dull ones *durain*. Vitrain is more brittle than durain and narrowly jointed by cleats. Thick vitrain displays conchoidal fractures. Parting planes of coal are often covered with numerous soft and friable fragments of coal with a silky lustre, resembling charcoal. This is *fusain*. *Clarain* consists of alternating thin laminae of vitrain and durain.

These four coal lithotypes form pure coal; many seams, however, contain mineral matter as thin strata of clastic sediment, in mixed coal/mineral material, and as concretions or joint-fillings. Clay and silt are the most common diluting materials; with increasing content, impure coal (<20 vol. % clay, $D < 1.5$), carbonaceous shale (20–60 vol. % clay, $D = 1.5$–2.0) and coaly shale (>60 vol. % clay, $D > 2.0$) are distinguished.

Lignite lithotypes cannot be described in the same terms as bands of bituminous coal. Visible wood remains ("xylite") are often present and these sections of a seam are called *xylite-rich coal*. Stratified or unstratified detrital humic groundmass is *matrix coal*. Charcoal horizons consist of *charcoal-rich coal*, and coal containing clastic minerals, carbonates and sulphides is *mineral-rich coal*. Colour and degree of gelification can be used for a subdivision into lithotype varieties (e.g. black gelified matrix coal). Charcoal (fusain) is very common in Tertiary coals, possibly because oxygen content in the atmosphere was higher (23% in the Eocene) favouring the incidence of peat fires. Remember that by photosynthesis (eq. 6.1), vigorous plant growth causes increasing oxygen concentration in the air parallel to depletion of CO_2. When reduced carbon is buried, as in coal, surplus oxygen remains in the atmosphere (Garrels *et al.* 1976, Falkowski & Isozaki 2008).

Documentation of macropetrographical analysis is commonly presented in the form of seam sections that are valuable tools for investigating lateral facies variations. Brightness logs (ply-by-ply % of vitrain) are used in exploration to characterize the coking potential of individual seams.

Macerals

Microscopic investigations of coal started with thin sections. The introduction of polished sections and microscopy under incident light (Stach 1935), later completed by the techniques of oil immersion, luminescence and fluorescence microscopy, was the foundation of modern coal petrology (Taylor *et al.* 1998, Sykorova *et al.* 2005). Macerals are organic coal constituents visible at magnifications between 25 and 50 times and have differing optical properties, hardness and shape (Stopes 1935). The term was deliberately chosen for its similarity to the word "minerals". Macerals may be recognizable parts of plants or products of their degradation. Organic macerals are not crystalline substances. In bituminous coal, three groups of macerals are distinguished: i) vitrinite group; ii) liptinite group; and iii) inertinite group:

> *Vitrinite group* macerals are mainly derived from wood. Vitrinite is very bright and is either cellular (Figure 6.5, *telinite*) or homogeneous (Figure 6.6, *collinite*). Vitrinite is the purest and most constant constituent of coal. This is the reason for its use as a sensitive and precise means of coal rank determination. *Huminites* (Figure/Plate 6.7, Figure 6.8) are those macerals of lignites and sub-bituminous coals that would form vitrinite at higher rank.
>
> *Liptinites* (earlier called exinite) comprise macerals that originate from plant matter, which resists humification, including spores, pollen, resins, waxes and fats. Liptinite is common in dull coal bands. It is rich in hydrogen and, together with hydrogen-rich ("perhydrous") vitrinite, is the main source of volatile matter (and of natural gas and petroleum: Wilkins & George 2002). Illuminated with UV or blue light, liptinite demonstrates fluorescence. Cannel and boghead coal are predominantly liptinitic. During

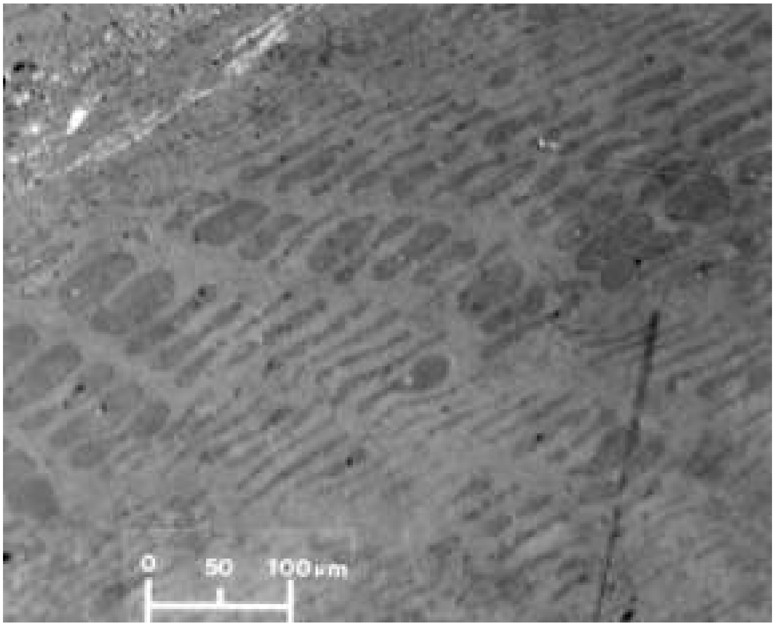


Figure 6.5 Microphotograph of the coal maceral telinite (a vitrinite; clearly recognizable cell walls of more or less intact but humified plant tissue) in Pennsylvanian bituminous coal, USA. Reflected light, oil immersion. Courtesy of Maria Mastalerz and Indiana Geological Survey.

coalification, beyond coking coal, liptinites produce much methane. The concurrent loss of hydrogen leads to an appearance that approaches vitrinite. Liptinite group macerals derived from plants include *sporinite* (Figure 6.9), *cutinite* (epidermis of leaves), *resinite* and *alginite*. Fluorescence distinguishes the macerals *fluorinite* (derived from fats and oils), *bituminite* (decomposed algae, bacteria, proteins) and *exudatinite* (diagenetically mobilized bitumen). Liptinites are indicators of wet conditions or even open water in mires, so that elevated clay content of liptinite-rich coal is not unusual.

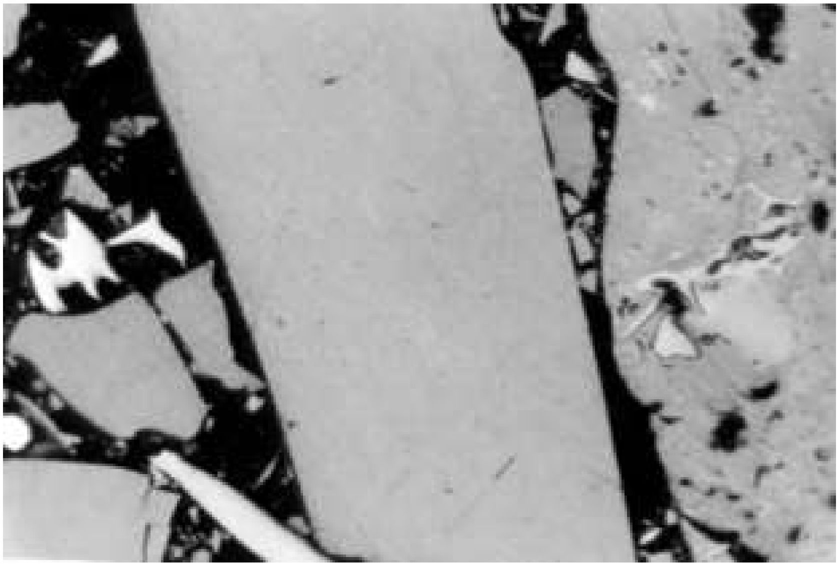


Figure 6.6 Microphotograph of the coal maceral collotelinite (vitrinite, more or less homogenized) in Pennsylvanian bituminous coal, USA. Reflected light, oil immersion; long side of image 0.5 mm. Courtesy of Maria Mastalerz and Indiana Geological Survey.

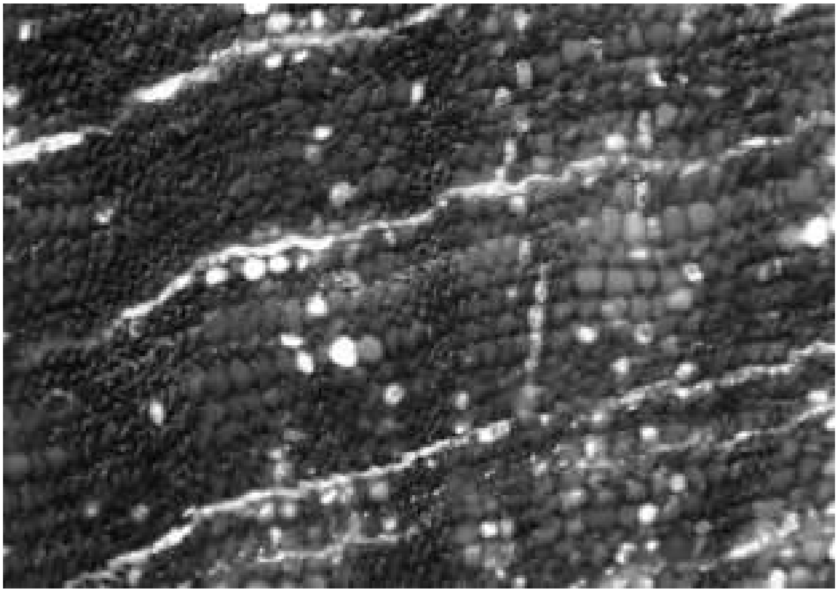


Figure 6.7 (Plate 6.7) Microphotograph of the coal maceral textinite (a huminite; ungelified woody tissue with intact botanical cell structures) in Tertiary lignite, Poland. Reflected light, oil immersion; long side of image 0.5 mm. Courtesy of Maria Mastalerz and Indiana Geological Survey.

Inertinites are coal constituents whose chemical composition changes little as rank increases and that do not melt during coking. All inertinites have high carbon and low hydrogen content and reflect strongly under incident light. Many inertinites originate from precursors of vitrinite group macerals. Their notable properties are due to partial oxidation during early stages of coal formation (Moore *et al.* 1996). The most

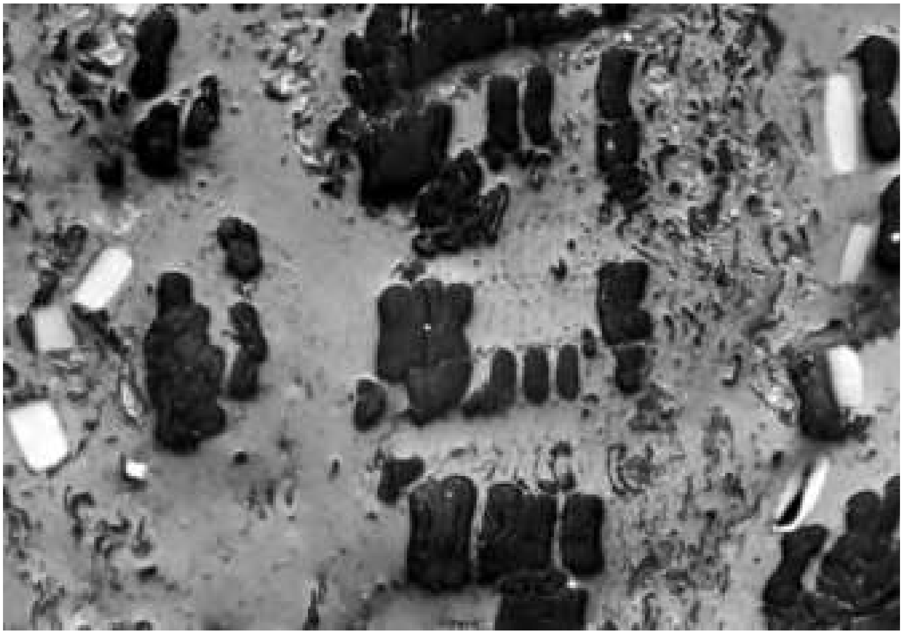


Figure 6.8 (**Plate 6.8)** Microphotograph of the coal maceral ulminite (a huminite; more or less gelified woody tissue) in Tertiary lignite, Poland. Reflected light, oil immersion; long side of image 0.5 mm. Courtesy of Maria Mastalerz and Indiana Geological Survey.

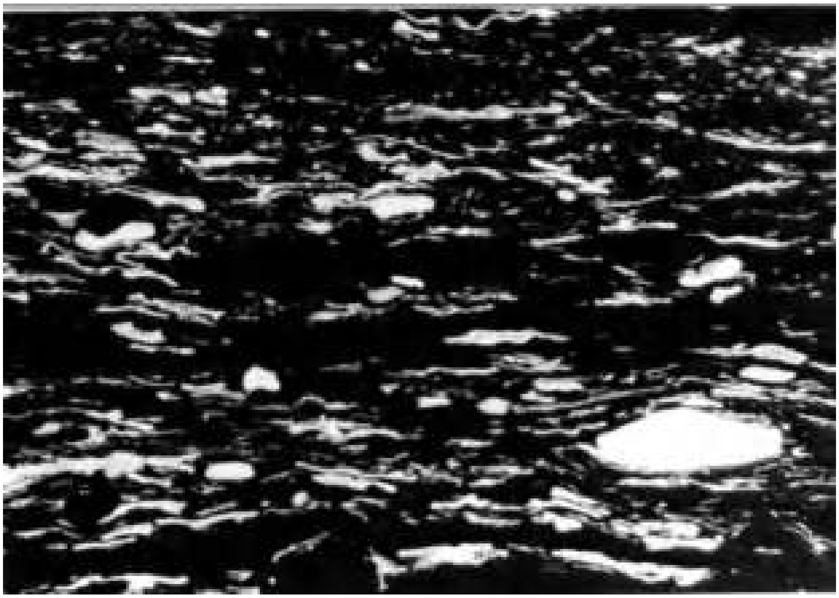


Figure 6.9 (Plate 6.9) Microphotograph of the coal maceral sporinite (liptinite; wax-coated fossil spores and pollen) in Pennsylvanian bituminous coal, USA. Fluorescent light; long side of image 1.0 mm. Courtesy of Maria Mastalerz and Indiana Geological Survey.

frequent inertinitic component of coal is *fusinite* (Figure 6.10). Under the microscope fusinite exhibits the cellular structure of wood and its anatomic details. Former cell lumina may be filled with humic gel or mineral substance (clay, carbonate, pyrite, etc.). *Semifusinite* is intermediate between fusinite and vitrinite. Most fusinite is fossil charcoal produced by forest fires that were ignited by lightning (Guo & Bustin 1998). The degree of carbonization correlates with temperature, as illustrated by tree logs that were externally carbonized but preserve a core of ordinary vitrinite. Small rounded particles of inertinite are called *macrinite*. *Micrinite* particles are very tiny and originated probably as airborne soot or carbon black. In Tertiary brown coals, a very common inertinite, besides fusinite, is *sclerotinite* that consists of round

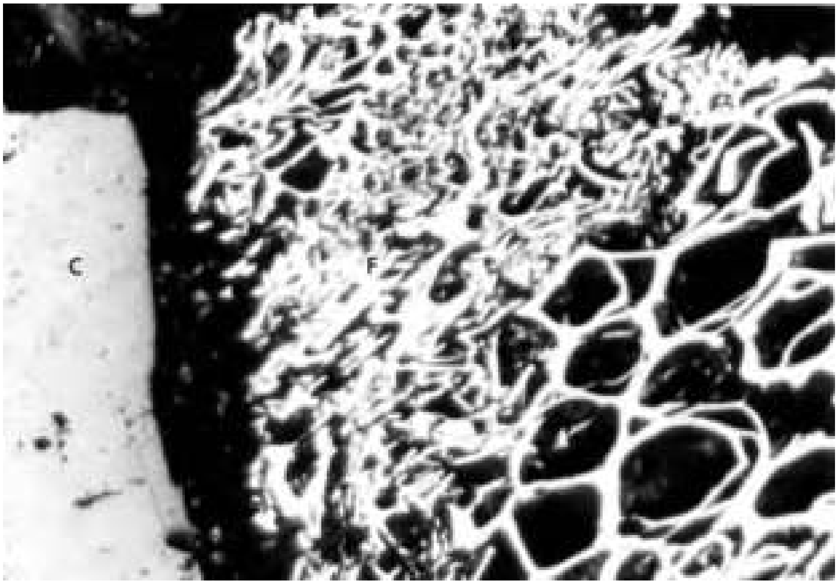


Figure 6.10 Microphotograph of the coal maceral fusinite (an inertinite; highly reflecting, well-preserved cellular structure inherited from ligno-cellulosic cell walls) in Pennsylvanian bituminous coal, USA. F-fusinite, C-collinite. Reflected light, oil immersion; long side of image 0.5 mm. Courtesy of Maria Mastalerz and Indiana Geological Survey.

or oval, brightly reflecting particles with one or several cavities. Sclerotia are remains of mycelia, spores and other fungal tissues.

Microlithotypes

Microlithotypes are defined by common associations of macerals. They can be mono-, bi- and trimaceralic, for example *vitrite, vitrinertite* and *vitrinertoliptite* (Taylor *et al.* 1998). Microlithotypes are determined with the microscope and recorded in seam sections. They are useful for an interpretation of conditions in the former swamp. Diessel (1986) proposed that the degree of decomposition of plant tissue (TPI = tissue preservation index measured by the ratio humotelinite/humodetrinite) and the relative water level vs. peat oxidation (GI = groundwater index, the huminite/inertinite ratio) can be used for the determination of facies and plant communities. Controls using peat of known depositional facies showed that pH and the microbial decomposition of peat are additional obligatory parameters of facies interpretations (Dehmer 1995). Coal petrography alone is probably not sufficient for identification of swamp type and facies (Moore & Shearer 2003).

6.1.3 The chemical composition of coal

Coals are extremely heterogeneous mixtures of various organic substances and of inorganic material, including water, inorganic colloids and minerals. The chemistry of the organic matter depends on the fraction of different macerals (the coal type) and the degree of diagenetic changes (rank, or maturity of coal). Full chemical analysis of coal is little used in practice but its complex organic compounds are determined for scientific elucidation (Bustin *et al.* 1997; Hatcher & Clifford 1997). In chemical terms, coal consists of aromatic nuclei, cross-linking bridges and adhering functional groups containing oxygen, sulphur and nitrogen.

In practice, large numbers of coal samples are analysed by standard procedures that include proximate and ultimate analysis. This is sufficient to control the quality from underground grade control to the final shipping product. Fewer samples will be analysed for data, such as potential atmospheric pollutants in the coal, the chemical composition of ash, the grain size distribution and coking properties. Proximate analysis includes the determination of moisture, volatile matter (fixed carbon), ash content and calorific value (heat energy per unit mass). Ultimate analysis serves to reveal the content of the major elements C, O, H, N and S in coal. Online X-ray fluorescence analysis of lignite and coal destined for power plants targets mainly elements that contribute to slagging and fouling of boilers (Si, Ca, Fe, K, Al, S, Na). The data are used for overall coal quality management, blending and automatic alarms, if critical parameters are exceeded.

Organic precursors and chemical compounds of coal

Cellulose $(C_6H_{10}O_5)_n$ is the major component of higher plants. By means of the chlorophyll, plants synthesize carbohydrates such as cellulose from carbon dioxide in the air plus water (eq. 6.1). In wood and bark, cellulose is reinforced by *lignin.* Lignins are a group of complex organic polymers containing aromatic nuclei with side chains. Molecular weight of lignin macromolecules surpasses 10,000 units. They are more resistant against microbial attack compared to cellulose. Different plants and even parts of plants have diverse lignin types and concentrations (5–45% in dry substance). Plants use wax, cutine (leaf surfaces) and suberine (bark) as a protection of the surface of vegetative organs. Sugars (glucose $C_6H_{12}O_6$), starch (polysaccharide carbohydrates) and proteins are rapidly decomposed by microbes in the peat. Much of the nitrogen in coal is inherited from protein in plants and microbes.

Simplified formula of cellulose production by photosynthesis – The fundamental reaction of life:

$$6CO_2 + 5H_2O \rightarrow C_6H_{10}O_5 + 6O_2 \qquad (6.1)$$

Lignin and cellulose are precursors of huminite and vitrinite. Cellulose and lignin are detectable in xylite and humotelinite of lignites but not in subbituminous coal. They are transformed by humification into humic substances (Kögel-Knabner 1993) that form the bulk of coal. Humic substances are heterogeneous mixtures of organic compounds that are divided into fulvic acid, humic acid and humins. They are colloidal dark-coloured complex substances, with a high molecular weight built from the elements carbon, oxygen, hydrogen and nitrogen. All contain an aromatic nucleus and various functional groups. When fulvic acid transforms into humic acid, both oxygen content and solubility in KOH decrease; humins are insoluble:

> Yellow to red-brown hydrophilic *fulvic acids* occur in soil, peat and wetland water. They have a molecular weight of 400–1500 and dissolve in both acidic and alkaline water. *Humic acids* are brown to black, hydrophobic and have a higher molecular weight. Soluble in alkaline water, they flocculate under acidic conditions. Both organic acids form salts (fulvates, humates) with cations including Na, Ca, Mg, Fe and Al. Black humins are the product of ageing of humic acids and their salts. Among the humates, *dopplerite* (the calcium salt of humic acid) is relatively common. It is a gel-like substance filling cavities in lignite seams. It shrinks and cracks on drying, and turns into a brilliant black material with conchoidal fracture. Generally, the early transformation of peat by *humification* is followed by a stage of more or less pervasive *biochemical gelification*.

Spores, pollen, resins, waxes and fats are *lipids* formed by higher plants. Lipids change little during humification and biochemical gelification. Severe alteration begins only with the onset of maturation to bituminous coal. In brown coal, part of the lipids can be determined under the microscope, but much remains undetected and is only revealed by organic solvent extraction (e.g. wax by benzene). *Chlorophyll* is normally destroyed before peatification. Macroscopically visible chlorophyll in lignites is very rare; one famous locality was Geiselthal in Germany (Figure/Plate 5.19).

Humins evolve during coalification by increasing *aromatization*. As functional groups, bridges and side-chains of nuclei are broken down, and islands of well-ordered structural elements ("crystallites") grow larger. During coal maturation, aromatic clusters are increasingly arranged into flat sheets that resemble the graphite lattice.

Volatile matter, fixed carbon and chemical composition

Run-of-mine coal contains water and minerals (ash). Data on moisture and ash content allow the calculation of the fraction of pure coal (dry, ash-free = d.a.f., or more precisely, dry, mineral matter-free = d.m.m.f.) in a sample. Data on coal's chemical composition and yield of volatile matter are of both practical and scientific use.

Heating a water-free coal sample under exclusion of air induces processes of pyrolysis and carbonization. This results in release of flammable gas ("town gas" as opposed to natural gas), liquids and vapours that condense to tar. Because high temperatures are attained, liberation of volatiles from minerals (e.g. water from clay, CO_2 from carbonate) must be accounted for. The term "volatile matter" (VM) describes the mass loss of the sample due to abstraction of organic and other volatiles. Volatile matter content of coal decrease with increasing rank (Figure 6.4), whereas the share of non-volatile (or "fixed") carbon increases. Fixed carbon is therefore as useful as volatile matter for measuring coal rank.

The elements making up coal are predominantly inherited from the peat-forming plants. Main elements are carbon, hydrogen and oxygen, with nitrogen and sulphur as minor components. Pure coal of high-volatile bituminous A-rank with 84% C has an average chemical composition that can be expressed by the "formula" $C_{10}H_7O$.

The continuous enrichment of carbon and the decrease of hydrogen (and oxygen) with increasing rank have been known for a long time (Figure 6.11). During lower rank coalification, oxygen diminishes rapidly, because of the loss of CO_2 and H_2O. A strong decrease of hydrogen occurs between high-volatile bituminous A-rank coal and anthracite. During this stage of coalification, a large volume of methane (CH_4) is released. The resulting bend in the coal band is sometimes termed a "jump of coalification". In parallel with chemical changes, several physical alterations are also observed, such as an increase of reflection and a decrease of liptinite fluorescence.

Sulphur occurs in many forms in coal, including massive, coarse, or very finely disseminated

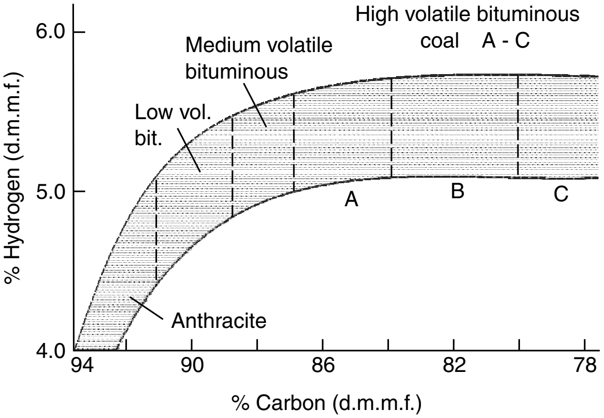


Figure 6.11 An updated rendering of Seyler's (1933) illustration of coal chemistry in carbon-hydrogen space. The diagram displays the typical composition of humic coals (the coal band), the increase of carbon with higher rank, and the rapid drop of hydrogen content at about the rank of coking (medium volatile) coal (d.m.m.f. = dry mineral matter free).

pyrite, soluble sulphate, acid-volatile sulphides (AVS) and organic sulphur. Only a small part of organically-bound sulphur is inherited from plants, which host the element in the form of aminoacids (C-S-form) or as ester-sulphate (C-OSO_3; e.g. in polysaccharides, phenol, etc.). In coals that are S-rich, most sulphur is derived from bacterially reduced sulphate. Pyritized bacterial colonies in coal have been demonstrated (Southam *et al.* 2001). Sulphate is commonly imported: i) by flooding of the peat mire with seawater; and ii) by sulphate-carrying groundwater that seeps into the peat from the surroundings, either during or after formation of the peat. In the first case, sulphur is concentrated in the upper part of the seam, whereas in the second, sulphate infiltrates from the footwall.

Sulphur content can be exceptionally high in coal seams with carbonate-rich host rocks. This setting induces alkaline conditions in the mire (e.g. in the Everglades, Florida, USA, up to pH 8.6). Seawater flooding has a similar effect. Higher pH favours sulphate-reducing microbial activity and the resulting H_2S will combine with iron or with organic substances in the peat. Alkaline swamps may even conserve calcareous fossils and skeletons of vertebrates (Geiseltal is famous for its Eocene fauna; Figure/Plate 5.19). In the Schöningen lignite pit (Figure/Plate 5.18), numerous boulder-like calcite concretions occurred in the seam where its footwall was formed by karstified Triassic limestone. Extraction of the lignite was severely impeded. This problem had not been recognized when mining reserves were defined by drilling.

Seams that were inundated with seawater are characterized by elevated sulphur, ash and nitrogen content. Coals that are derived from unusually acidic peat (with a pH as low as 3.3 compared with average peat of pH 4.8–6.5) contain little sulphur. Acidic swamps may be indicated by kaolinized footwall rocks of coal seams. Exceptionally low sulphur content of 0.06% (air-dried) has been reported for the high-volatile bituminous B-coal from the Tanjung mine in Borneo. The product is sold under the trade name of "Envirocoal"; resources are estimated at >1000 Mt:

> Sulphur in coal is undesirable because in boilers it is oxidized to SO_2 and enters the flue gas. Likewise, sulphur in coking coal diminishes product quality. Mitigation of inorganic sulphur is possible by mine-site coal processing (e.g. removal of pyrite) but is not feasible for organically-bound sulphur. Several technical solutions for withholding sulphur from the atmosphere are applied in power stations, although not without repercussions on the price of electricity.

Nitrogen is foremost inherited from proteins in the peat. During coalification, it enters the coal macromolecules. Coking or gasification of coal generates ammonia that can be a valuable by-product. For burning, however, low-nitrogen coal is preferred, because elimination technologies such as reduction of NO_x to N^0 or NH_4 are costly.

Nitrogen is a biogenic element of coal. Plants contain a number of trace elements, including Ca, N, K, P, S, Mg and Fe, but also Na, Si, Al, Mn, B, Ba, Sr, Zn and Cu. Several of these elements are selectively enriched in biomass and the resulting coal. The enrichment may be quantified by the biological accumulation coefficient (eq. 6.2).

Biological accumulation coefficient B_s as a measure of preferential enrichment of elements in organic substance:

$$B_s = \frac{\%\text{ in ash of organic substance}}{\%\text{ Clarke crustal average}} \qquad (6.2)$$

B_s-values >10 are commonly determined for P, S, Se, Cl, Br and I, values between 1 and 10 for Ca, Na, K, Mg, Sr, Zn and B, whereas most other elements are comparatively depleted ($B_s < 1$). World average chlorine content of coal amounts to 340 ± 40 (hard coal) and 120 ± 20 ppm (brown coal: Yudovich & Ketris 2006a). The world average for ash is 1435 ppm Cl compared to a Clarke of 126 ppm. The selenium average is 1.6 ± 0.1 ppm and 1.0 ± 0.15 ppm, respectively for hard and brown coal, compared with a Clarke value of 0.05 ppm (Yudovich & Ketris 2006b). Note that the enrichment is not literally "biological" but represents accumulation from the live plants ("inherent elements") to late diagenesis (Swaine 1990). Furthermore, comparison with average shale should be more relevant than with Clarke values, which include basalts (Reimann & de Caritat 1998). Of course, the geogenic background of the watershed must be considered in the interpretations.

Accessory metal content in coal has little economic significance, mainly because of low and fluctuating in-seam content. In power stations, however, some metals may be enriched in the ash to extractable grades (both bottom and fly ash). Metals that were occasionally produced from coal ash include vanadium, germanium and uranium. Coals with anomalous germanium content occur in America, Australia, China and Russia (Seredin *et al*. 2006). Metalliferous (Seredin & Finkelman 2008) and especially uraniferous coals are ubiquitous. In coal, uranium is adsorbed on organic matter. This may be due to: i) syngenetic enrichment from waters draining the former hinterland of the peat swamps; or ii) later, epigenetic input. The first has an equivalent in today's uraniferous mires in Sweden, whereas the second is typically due to the later passage of uranium-bearing groundwater (e.g. Wackersdorf, Figure 2.43). REE are enriched to 300–1000 ppm in giant coal deposits of the Russian Far East, possibly sourced from nearby volcanic rocks (Seredin 1996).

Trace elements in coal are determined by sedimentary and diagenetic conditions. Their distribution is usually irregular, so they are rarely useful for identifying specific seams in multi-seam deposits. An exception may be the ratio Al/La-Sc (Chyi & Medlin 1996). Several trace elements are harmful, either for power station operation (Na, Cl, etc.) or for the environment (e.g. arsenic, mercury, radioactive elements). Therefore, a thorough geochemical investigation of all coal deposits is mandatory. This must include the determination of the preferred carrier (mineral or maceral) of significant elements and of speciation. In many cases, ecologically sensitive elements are concentrated in pyrite, kaolinite and illite, in which case removal by coal processing may be feasible (Palmer & Lyons 1997). The fate of hazardous trace elements in power stations and especially the level of stack emissions must be monitored (Huggins & Goodarzi 2009). Anticipatory mitigation is required.

Clearly, peat and coals are extremely efficient *geochemical barriers*, due to processes that include biochemical accumulation, reduction, sorption and ion exchange. Import of elements into swamps may occur by surface water, seawater and groundwater. Seawater influence is indicated by higher content of B, Sr, Mg and, of course, Cl, Na, SO_4, Ca, K and Br. Groundwater may contribute U, V, Mo and in case of contact with saline brines or evaporite rocks, Na, K, Ca, Mg, Cl, B, Sr, Br and SO_4. Hydrothermal epigenetic metal enrichment in lignites is rare (Seredin *et al.* 2006), whereas most hard coals exhibit traces of mineralization by the passage of diagenetic (basinal) fluids.

Isotopic investigations of coal are mainly based on the elements C, O, H and N. Isotopic composition is a function of coal age, geographical latitude, mean annual temperature (reflected in the D/H ratio), dominant plants (carbon isotopes), isotopic character of precipitation including seasonal variations (Jahren & Sternberg 2008) and coal maturity and degassing history (Whiticar 1997). Carbon in coal is clearly enriched in ^{12}C relative to the source (atmospheric and mantle) carbon, because photosynthesis strongly discriminates against $^{13}CO_2$. The Middle Miocene Yallourn seam lignites (Latrobe Valley, Australia), for example, have $\delta^{13}C$ (PDB) values from −25.3 to −27.3‰ (Holdgate *et al.* 2007). Cyclicity correlates well with the deep-sea $\delta^{13}C$ marine organic record. Contrary to earlier assumptions, the oxygen isotope ratio ($\delta^{18}O$) of cellulose is not a reliable proxy of ambient temperature and relative humidity (Helliker & Richter 2008). The source of nitrogen may be discerned, because little fractionation takes place when plants or microbes assimilate nitrogen from air ($\delta\ ^{15}N_{Plants}$ from −3.1 to −0.4‰), whereas uptake of nitrates enriches heavy nitrogen. The release of methane during coalification initially mobilizes light carbon and hydrogen. Theoretically, this should translate into an enrichment of heavy isotopes in coal. However, depletion of ^{12}C during coalification cannot be measured, because the seams are a giant reservoir of carbon. Deuterium, however, is slightly enriched (Schoell 1983). Rhenium-osmium ages of pyrite may be used to investigate the diagenetic evolution of coal deposits.

Water in coal

Water is an essential component of brown coal. Lignites contain between 30 and 75 wt. % water (Figure 6.4). This figure reveals why power stations burning these low-grade "wet" coals are built near the mines. The water content of bituminous coal and anthracite is low (from 9–2.5%) and this explains why they are shipped across the world's oceans.

Coal contains water in four possible forms:

1 surface, or adventitious moisture;
2 hygroscopic moisture in capillaries;
3 adsorbed water; and
4 mineral moisture.

Drying higher rank coal in air removes surface water. Hygroscopic and adsorbed water are termed "inherent moisture" and are determined by heating to 105°C. Mineral moisture is mainly a component of clay in coal. Surface water content reflects conditions of sampling, for example rain or drought. Yet coal samples are always hermetically sealed on site, because adventitious moisture influences mass calculations and processing of coal. Compared with inherent moisture, lignites have little surface moisture. However, on drying in air, lignite looses even hygroscopic and adsorbed water and may crumble into low-value coal dust.

Gas in coal

Methane is the most common gas occluded or adsorbed in coal seams. It may be accompanied by minor fractions of ethane and propane, and by traces of hydrogen and helium. Some coal seams contain large amounts of carbon dioxide. Whereas the source of CO_2 is usually external to the coal measures, for example volcanogenic, methane is produced during coalification within the seam. Abiotic methane production from liptinites begins with the coalification jump from sub-bituminous coal B to A rank. Medium volatile bituminous (coking) coals have the highest content (10–30 m^3 gas per tonne of coal). Methane mixed with 5–14% air is highly explosive ("fire damp"). The largest mass of gas is formed from humic substances during continuing maturation to anthracite. It is estimated that 1 kg of coal produces ~200 litres methane during maturation from high volatile bituminous coal B to anthracite. Because country rocks of higher-grade bituminous coals are increasingly permeable as jointing intensifies, 90–95% of methane produced migrates away from the seams. This is one reason why the actual gas content of coal *in situ* cannot be predicted (Bustin & Clarkson 1999). Only the ash-content correlates (negatively) with gas in coal, because gas is almost exclusively hosted by organic material. If the migrating gas encounters a trap capped by impermeable rocks (in northern Germany, usually Zechstein salt rock, cf. Chapter 4), important and even giant gas deposits can form (e.g. Groningen, Netherlands). Most lignites and sub-bituminous (C and B) coals are methane-free. Yet, underground extraction of brown coals is not without its own dangerous gases – poisonous CO and asphyxiant CO_2 can form by slow oxidation in parts of the mine with stagnant air. CO_2 collects in hollows, as it is

1.53 times heavier than air. Increasingly, methane gas released from coal mines is used for heating, power generation, as a vehicle fuel, or for chemical manufacturing. Mine methane that cannot be used should be flared off, as conversion to CO_2 lowers the greenhouse effect (Gayer & Harris 1996).

Only a fraction of the carbon dioxide adsorbed in coal seams is derived from coalification. If high content is encountered, the source is usually igneous or otherwise endogenous. Faults and permeable sandstones have been identified as conductors. In the past, several mines suffered catastrophic carbon dioxide blow-outs, filling the mine openings not only with the asphyxiating gas but also with coal dust. The precondition for gas-driven coal outbursts are high *in-situ* gas pressures in the coal. *Coal outbursts* are violent and spontaneous ejections of powdered coal and gas from the working coal face (Guan *et al.* 2009). Coal dust in air is by itself explosive and very destructive but methane is often involved. Seams with a clayey hanging wall are prone to trap gas and to impede natural degassing. In that case, a slow advance of extraction, deliberate fracturing and loosening of the rock mass, and drainage boreholes may decrease gas pressures. Ordinary degassing of CH_4 and CO_2 is not dramatic. Gas blowers occur along joints, or gas bubbles rise in water channels along mine tunnels. Coal mines and oil or gas fields tend to be well separated, but in a few cases, a near neighbourhood did cause accidents (Nottinghamshire, UK, Stevenson 1999).

Ash and minerals in coal

It is important to understand the difference between ash and minerals in coal (Ward 2002). Ash represents incombustible matter in coal measured by controlled oxidation (burning) of a sample at 700–850 °C ("high-T ash"). This causes loss of CO_2 from carbonate, SO_2 from sulphides and H_2O from clay. The mass of ash is less than the original mass of minerals in coal. Because coal ash consists essentially of oxides, its chemical composition is investigated with analytical methods used for silicate rock analysis. Calculation of norm percentages of minerals in coal from high-T ash data is very imprecise. It is recommended to determine minerals directly by appropriate methods after careful drying and oxidation at low temperature (150 °C: "low-T ash").

Ash of run-of-mine coal has various sources:

- wall rocks extracted with coal;
- minerals that were transported into the swamp, diluting the organic material (e.g. clastic or volcanic sediments);
- diagenetic minerals introduced after sedimentation;
- salts dissolved in pore water; and
- the inherent biogenic mineral matter content of plants (e.g. silica of *equisetum*). Matrix coal (of lignite) or dull, bituminous coal contains more ash than bright coal:

> Ash content and calorific value of coals are negatively correlated. Generally, high ash coal is economically less desirable and is a bigger environmental burden. If possible, ash content of run-of-mine coal is reduced by one of three technologies: i) Processing in a dense liquid medium washing plant; ii) in heavy media cyclones; or iii) in jigs (separating particles of different density by pulsations immersed in water). All methods rely on the increase of coal density as a function of ash content. Because of the increasing need to manage scarce water resources (e.g. in Australia), novel dry processing methods for upgrading coal are employed wherever possible.

Minerals in bituminous coal include silicates, carbonates, sulphides, sulphates, phosphates and others. Apart from minerals, immature lignites may contain amorphous and semi-ordered substances, such as allophane instead of kaolinite.

Quartz is very common in coal, mostly of detrital origin, but also as a chemical precipitate such as silicified tree logs, which occur in many lignites. Kaolinite is the most frequent clay mineral in coal, both as clastic sediment and as an authigenic and diagenetic mineral. Other clay minerals that are not rare in coal include montmorillonite, illite and mixed-layer clays. Illites in anthracite are remarkable because of high content (45–80 mole %) of NH_4 instead of K, due to pronounced liberation of nitrogen in this coalification stage (Daniels *et al.* 1994). Coal seams formed in volcanic surroundings may have high zeolite content (e.g. Beypasari, Anatolia: Querol *et al.* 1997). Pyrite (and other sulphides including sphalerite, marcasite, and galena) can be found filling cell lumina, or as framboids, idiomorphic crystals, small bedding-parallel lenses, thin coating of joints and in cross-cutting veins. All this indicates that sulphide formation starts with early diagenetic microbial sulphate reduction (Southam *et al.* 2001) and continues into late diagenetic stages with inflow of basinal hydrothermal fluids. Carbonates in coal comprise siderite, ankerite, calcite and dolomite. Siderite and dolomite form syngenetic layers or concretionary horizons in coal seams. The preservation of uncompressed cells in concretions is due to very early lithification. Carbonates in cleats (joints) of coal must have been introduced during late diagenesis. Sulphates in coal are products of natural pyrite oxidation by meteoric waters. Some may form by exposure to humid mine air. Exceptions are sulphates in saline coal that are derived from invading brines. Authigenic apatite and Sr, Ba and Ca aluminophosphates are trace minerals in all coals (Ward *et al.* 1996).

Minerals in coal influence the feasibility of exploiting the coal (Ward 2002). Some minerals may cause geotechnical problems, for example montmorillonite clay in opencut mining in a high-precipitation landscape. Processing, transport, storage, combustion, coking and coal liquefaction can all be affected. Pyrite is critical, because its oxidation induces acidity from the mine through processing to coal and waste rock tips. Also, pyrite is a common carrier of undesirable trace elements such as As, Hg and Sb. In the boiler, the fusion temperature of the ash is very important. Most combustion chambers cannot deal with low-melting ash due to higher content of montmorillonite, chlorite, carbonates, sulphates and pyrite. As a radical solution of the problems caused by unfavourable minerals in coal, acid-alkaline leaching has been proposed. Its product is nearly pure organic matter (UCC = ultra clean coal). Note that fly ash and slag from large-scale burning of coal can be useful by-products that find application in producing cement, concrete and ceramics, as a source of alkalinity in environmental technology, as a road construction material and as a self-hardening fill in underground mines.

Physical properties

The density of coal increases with both rank and ash content. Lignites have a density of ~1.2 (range 1.1–1.25), bituminous coals 1.35 (1.2–1.5) and anthracites 1.5 (1.34–1.8) g/cm^3. As a rule, coals are less dense than clastic country rocks at the same level of diagenesis (lignite-associated sand 1.8 and silty clay 2.0; sandstone hosting bituminous coal 2.0–2.4, shale 2.0–2.5 g/cm^3). The density of coal of a specific rank correlates positively with ash content. The density difference between low-ash and impure coal is the base for coal processing methods that strive to reduce the percentage of pyrite, country rock material and impure coal.

The hardness of brown coals increases with lower water content. Bituminous coals are hard but brittle and this may cause excessive comminution by handling. Generally, markets prefer lumpy coal to fines. Grindability of vitrain is higher than that of durain, so that vitrinitic coals are more susceptible to fining.

Optical translucence of coal decreases with higher rank, whereas reflectance and anisotropy increase. This is caused by more pervasive ordering of aromatic rings and clusters. Reflectance is determined quantitatively under the microscope using polished mounts of coal (Taylor *et al.* 1998). The degree of reflectance [R] is determined as a percentage of the incident light. Because reflectance correlates closely with coal rank and chemistry, its determination provides a very precise measure of coalification (Figure 6.4). The same technology is used to determine the maturation level of dispersed organic particles in sediments and due to its predictive capabilities, this method has a central role in petroleum and natural gas exploration.

Under the microscope, coals are birefringent. With crossed Nicols, extinction positions are normally parallel and at right-angles to bedding planes. The same anisotropy is exhibited by reflectance. The maximal reflectance [R_{max}] is found parallel to bedding, and R_{min} at 90° to sedimentary stratification. This is caused by the anisotropic molecular structure of coal, which is imprinted by vertical lithostatic stress σ_V and associated strain. Coal seams that were deformed in an orogenic stress field with horizontal stress σ_H larger than σ_V, display oblique extinction angles (Petrascheck 1954).

The inherent heat energy is one of the first parameters for assessing coal. It is expressed as specific energy, or calorific value of coal, which is the amount of heat available per unit mass [kJ/kg]. The calorific value increases during coalification to the stage of medium volatile (coking) coal; further maturation causes no little change (Figure 6.4). Water and ash reduce the available energy. The first because of the energy needed to heat and evaporate the moisture, the second because of several endothermic reactions, but foremost the reduced amount of pure coal mass. Because of these relations, coal for power production is not traded per mass unit but for its inherent energy yield.

Cokeability

Coke is the vesicular and fused solid residue that forms when coking coal is heated in the absence of air to a temperature of several hundred to 1000 °C. If non-coking coals are treated in the same way, the residue is not coke but char (less porous or unfused solid). Coke is a highly valued energy carrier and reducing agent of the iron and steel industry. Important properties of coke include lumpiness, mechanical strength and durability. Apart from coke, saleable by-products of the process of carbonization are coal, or town gas (hydrogen, methane, other hydrocarbon gases, carbon monoxide), crude benzole, coal tar and ammoniacal liquor (Ward 1984).

Cokeability depends on the coincidence of coal becoming plastic ("fluid") when heated coinciding with volatile release forming gas bubbles. The result is swelled and porous coke. The coking process can be adapted to different coals by technological parameters, but rank and the ratio of macerals control the feasibility. Coke is often compared to concrete; inert components (the pebbles) are bound by a reactive matrix (cement). Liptinite is an excellent swelling agent, vitrinite a moderate one. Inertinite and most minerals remain unchanged. Vitrinite determines plasticity and gas release, because liptinite content is rarely above 5% of the total coal mass. In the case of high inertinite content, it is preferred to have it mixed with vitrinite, because this will stiffen the pore walls of the coke. Generally, vitrinite content (brightness) and its maturity are the main controls on cokeability.

Lignites and anthracites are not cokeable. However, many ingenious ways of making coke from non-coking coal have been developed. One example is the blending of reactive material such as coking coal or bitumen with inert additives (anthracite, carbon black). The mass is then formed into high-pressure briquettes. After coking, the briquettes are a valuable smokeless fuel.

Synfuels (coal-to-liquids technology)

With rising petroleum prices, worldwide production of liquid fuels from coal is rapidly expanding. One of the largest plants is still the facility at Secunda, South Africa, that was built to cope with an apartheid era fuel embargo. Unfortunately, underground storage of the waste product CO_2 was not planned and today the plant is the Earth's single largest point source of carbon dioxide emissions (20 Mt/y).

> Synfuels production is carried out by several industrial processes, basically variations of the Fischer-Tropsch synthesis. The principle is gasification of coal in the presence of steam and some oxygen at high temperature and pressure. Two separate gas streams are produced, "synthetic gas" with the composition $CO + H_2$, and waste CO_2. The synthetic gas (or syngas) is then converted by hydrogenation in the presence of catalysts into products such as gasoline, diesel fuel, jet fuel or chemical feedstocks. Combined with underground CO_2 sequestration, synfuels have a smaller carbon footprint than petroleum-based fuels.

New developments in underground and *in-situ* gasification of coal support hopes that this technology may finally reach profitability. Underground production of syngas eliminates all costs of mining and transport. Syngas can be directly burned to produce electricity, or converted to synfuels and to pure hydrogen by removal of CO_2. Since nearly 50 years, the world's only commercial plant of underground gasification of coal (UGC) combined with electricity generation operates in Uzbekistan. In the Surat Basin, Australia, a demonstration plant produces diesel fuel from UGC syngas. In Britain, *in-situ* gasification of deep coal below the Firth of Forth, combined with carbon dioxide capture and sequestration, was licensed in 2009. It is claimed that the UGC process can be applied to deep, high ash, conventionally unexploitable coal, which would immensely widen the resource base of coal.

6.2 PEAT FORMATION AND COAL DEPOSITS

Even though coal is chemically and petrographically very different from other sediments, it is an integral constituent of many sedimentary sequences. Peat deposition occurs in diverse terrestrial, limnic and coastal settings. Sufficient understanding of a coal deposit, including very practical aspects, can only be acquired by a comprehensive study covering all aspects of the evolution of a coal basin.

6.2.1 Types and dimensions of coal seams

Coal occurs in beds (strata) that are called seams. Many coal seams have a tabular shape characterized by a large areal extension but low thickness. Very thin strata that cannot be economically extracted are referred to as coal bands, or stringers. Two main types of coal seams can be discerned, which impose quite different approaches, from exploration to extraction:

- Concordant seams occur over large areas intercalated among strata of host sediments of the same age; lateral changes in seam thickness and facies are very gradual.
- Discordant seams typically occur above a stratigraphical unconformity and constitute the base of transgressive sediments; discordant seams display considerable and rapid lateral changes.

Discordant seams originate by:

- regional subsidence of previously formed landscapes with depressions, which are semi-closed and support a high groundwater table such as karst and broad valleys;
- local subsidence of the surface on the downthrow side of normal (tensional) faults; or
- above salt rock bodies undergoing subrosion.

The thickness of coal seams typically amounts to a few metres (black coal) or a few tens of metres (lignite). Exceptions include the Tertiary (Eocene-Miocene) brown coal seams in the Latrobe Valley, Victoria, Australia, which are supposedly the thickest on Earth, with a maximum of 320 m of coal (Holdgate *et al.* 2007, Barton *et al.* 1993; Figure 6.12). The district's youngest (Middle Miocene Yallourn) seam alone is 100 m thick and covers a stratigraphical record of 1.3 My. A black coal seam at Fushun in China reaches 200 m (Figure 6.13). However, extremely thick coal strata are very rare (Volkov 2003).

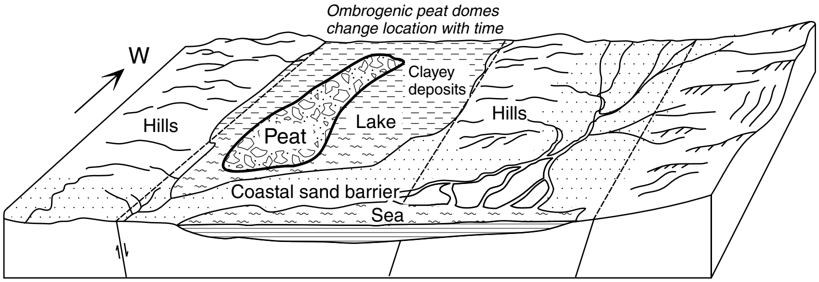


Figure 6.12 Schematic reconstruction of the palaeogeographic setting of Miocene peat formation in the Latrobe Valley, Victoria, Australia, in a wide tectonic graben (Holmes 1993). Ponding of water favourable for peat growth was caused by a coastal sand barrier and high global sea levels. Recoverable resources of the District are estimated at 37,000 Mt of earthy lignite with low ash contents and calorific value, and 60–70% moisture.

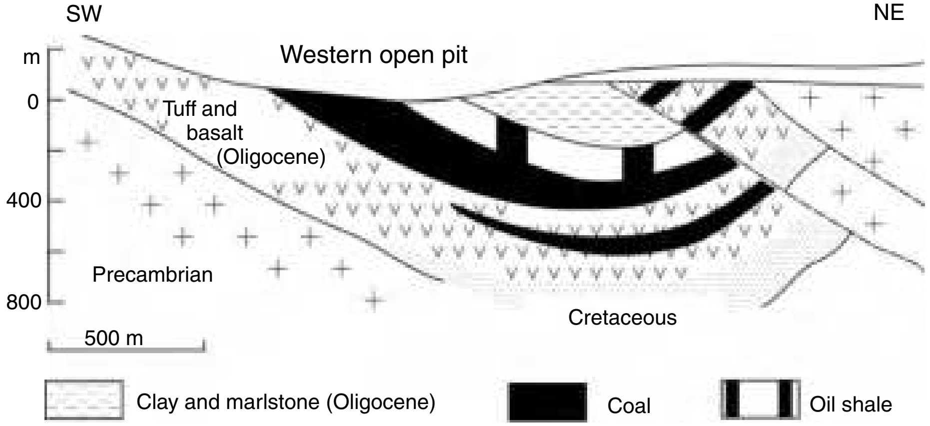


Figure 6.13 Geological section of the Palaeogene bituminous coal and oil shale deposit Fushun in Liaoning, China, illustrating the extraordinary thickness of the seam (Volkov 2003). With permission from Springer Science + Business Media.

Compaction of peat

Like all sedimentary rocks, peat, lignite and coal are compacted when covered by overburden rocks. In engineering geology, the *consolidation theory* explains and describes mathematically the increasing density and decreasing porosity, permeability, water content and thickness during compaction (Terzaghi *et al.* 1996). The same phenomena affect peat but at shorter time-scales. In addition, a part of peat consolidation is a function of synsedimentary biological activity. Therefore, most geological methods that aim to determine the original thickness of peat transformed into a coal seam target the (total) peat thickness at the time of deposition of the first overburden rocks (Widera *et al.* 2007). Consolidation during peat formation ("self-consolidation") is generally disregarded. Nadon (1998) vividly argued that self-consolidation of peat explains most of the total compaction and that this takes place in the few uppermost metres of the peat profile. Deep, mature peat is assumed to have compacted to 0.2–0.3 m, compared to near-surface material 1 m thick. The main means of measuring consolidation in buried peat or coal are lenses of clastic sediments of the same age, either on top of the down-warped coal surface or interbedded with it (Widera *et al.* 2007, Nadon 1998). Of course, for a precise determination of the coefficient of coal consolidation, the compaction of the clastic sediments should also be determined. Because it is much smaller than that of organic substance, it is often disregarded. If measurements are impossible, the traditional rule of thumb may be helpful: Six metres of peat consolidate to 3 m of lignite and to 1 m of black coal.

The areal extension of coal seams is typically quite small for local discordant seams (a few km^2), whereas concordant seams reach very large dimensions. The Pennsylvanian (Late Carboniferous) Pitsburgh seam in the Appalachian foreland basin (Virginia) occurs discontinuously over an area of ~30,000 km^2. It is historically one of the most important sources of coal in the United States, with an exploitable area of 5600 km^2 (Cross 1993). The spread of the Katharina seam in northern Germany (210 × 50 km) is comparable. In the Tertiary lignite district of Saxony and Thuringia (Germany), the main seam is developed over 750 km^2.

6.2.2 Concordant and discordant clastic sediments in coal seams

Thin strata of clastic or volcanogenic sediments in coal seams (dirt bands, partings, tonstein) are quite frequent. They divide the seam into several coal sub-layers that are called plies. Non-coal bands display a thickness from 1 to more than 50 cm.

Dirt bands are an economic disadvantage, because the material dilutes run-of-mine coal. Fine-grained clay and silt predominate, whereas bands of sand, carbonates and volcanic tuff are less frequent. In black coal, sideritic ironstones and even siderite oolites have been reported. In many cases, certain bands form recognizable key horizons that assist coal seam correlation. In that respect, tonstein bands (kaolinized pyroclastic tuffs) can be useful marker beds, because they often possess specific properties (e.g. crystals, glass shards, pumice), which designate particular beds. In addition, they contain trace minerals such as zircon and sanidine that allow precise radiometric dating. Thick kaolinitic partings may be a source of valuable fire clay. Bentonitic bands are rare in coal seams, because of the generally acidic environment of peat-forming wetlands.

The lateral evolution of coal thickness, number of plies and partings is depicted by seam sections, which are positioned on mine maps (Figure 16.6). The resulting seam facies maps reveal genetic and practical information, such as estimates of the likely dilution of coal in reserve blocks. Partings may be very useful when thick seams are to be exploited in benches (slices), if they can be utilized to delimit roof and floor of the slice. Dirt bands may laterally thicken to the extent that a seam is split in two or more unexploitable coal stringers.

Clastic strata in coal implicate shallow lakes and inflow of sediment-laden water into the swamp. Thick coal seams form when subsidence is such that profuse plant growth is maintained. For optimum conditions, groundwater levels should oscillate little about a mean, just covering the peat surface. In the case of higher subsidence, the swamp surface and with it the plants drown in open water. Clastic sediment deposition is the consequence, especially towards basin centres where seams tend to split by increasing thickness of dirt bands (Figure 6.14 and Figure 6.15). Mineral matter content of the coal (ash) rises in parallel

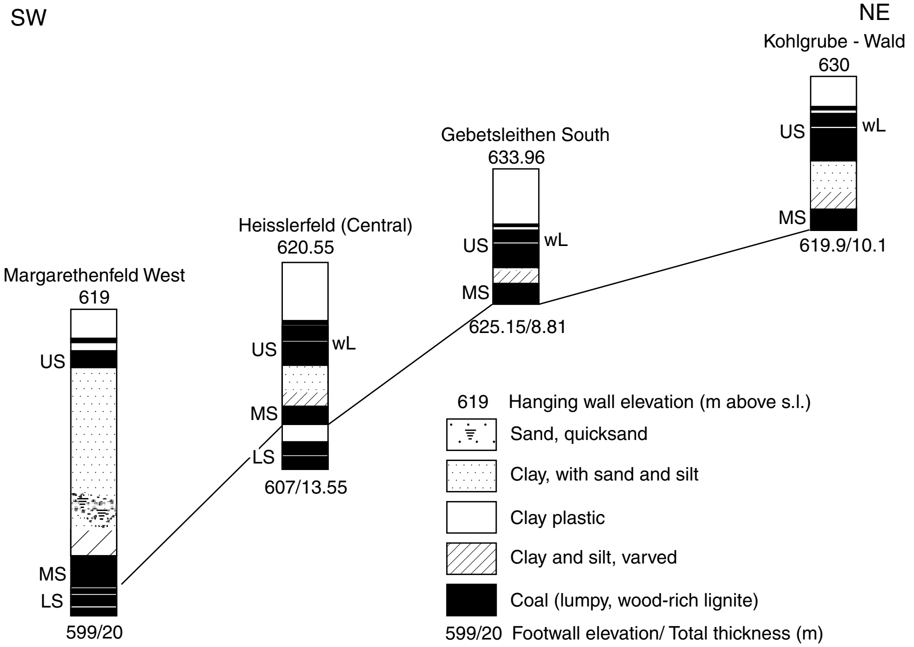


Figure 6.14 Part of the seam facies map of a lignite basin. The sections indicate a more limnic centre in the southwest and dryer conditions in the northeast (Hausruck, Austria; Pohl 1968). Thickness of seams (LS = Lower, MS = Middle and US = Upper Seam) and facies of clastic sediments are clearly a function of the relative altitude. wL is a thin kaolinitic marker bed in the Upper Seam (volcanic tuff).

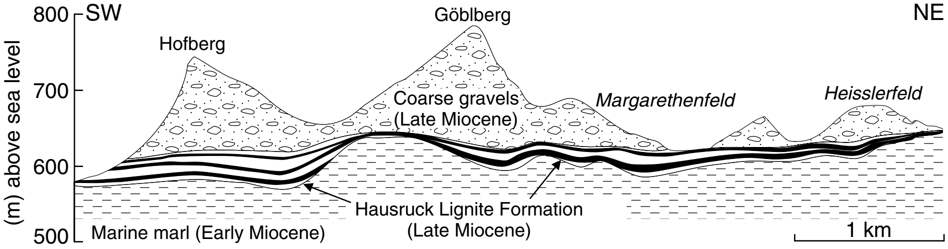


Figure 6.15 Geological section of the southwestern part of the Hausruck lignite district, Austria (Pohl 1968). The drawing uses different vertical and horizontal scales in order to single out the thin Hausruck Lignite Formation (seams in black). Observe that its thickness is greater in basin centres than at higher elevations.

until content surpasses acceptable levels. Dry swamp areas (deep groundwater levels) and basin-marginal positions of the swamp display increasing oxidation and microbial destruction of plant matter, which thins the coal seam to a band resembling forest floor litter. Swamp margins may be associated with clastic fans built up by creeks, which reach out into the seam in the form of sand and gravel beds.

The different facies zones of a coal swamp are more profoundly distinguished by the inclusion of petrographical, chemical and palaeobotanical methods. Two papers by Teichmüller 1958, 1991) about the Lower Rhine Valley lignites in Germany stimulated research and discussion of swamp facies. In this broad graben basin, Oligocene and Early Miocene sediments pass from a southern freshwater swamp to a northwestern marine bay of the North Sea (similar to the setting of the Latrobe Valley, Figure 6.12, Schäfer *et al.* 2005). Swamps occupied a broad tectonically subsiding embayment, which was surrounded on three sides by land. Teichmüller postulated three main wetland facies zones: (1) a marginal broad zone of forest swamp which graded into (2) wide reed expanses and (3) shallow water with deposition of humic sapropels. Alternating dark and light bands of woody lignite and assumed reed coal make up most of the seam. Like other sedimentary facies changes, this was considered as the vertical expression of a horizontal oscillation of facies zones (1) and (2). Moosbrugger *et al.* (1994) described in great detail one of the forest bands, which is mainly composed of conifers of the *Taxodiaceae* and *Cupressaceae* families with a few interspersed palm trees. Teichmüller based her interpretation on a comparison with the cypress swamps of the southeastern coastal USA. Meanwhile, supposedly better equivalents were discovered in the swamp forests of Southeast Asia. Tropical swamps in Indonesia consist of woody dark layers, which are the base for ombrogenic peat domes made of pale, earthy and oxidized material (Esterle & Ferm 1994). The same interpretation is used to explain colour-banding in the giant Morwell lignite deposit (part of the Latrobe district, Figure 6.12), which is interpreted to reflect orbitally forced climate oscillations (Large *et al.* 2004).

In the Hausruck lignites, nearly all coal is characterized by a preponderance of *Sequoia* wood, including giant tree trunks and numerous forest fire horizons (Pohl 1968). Near the basin margin in the northeast, the lignite seam is quite thin and displays high ash content. Towards the south, coal thickness increases until it reaches a maximum of 7 m. The Hausruck Lignite Formation attains a total thickness of 30 m in the southwestern depocentre and the seams contain increasing mineral matter, both as ash and in dirt bands, until the impure coal is not marketable. A peculiar varved limnic clay above the Middle Seam is a useful marker (Figure 6.14). Taken together, these observations imply a high and relatively dry setting in the northeast that grades into a lower and mostly limnic basin in the southwest. Geochemical methods confirm this model (Bechtel *et al.* 2003).

Some bodies of clastic sediments are drastically different from the thin clastic strata in coal seams, by exhibiting a short lenticular shape (in cross-section) but a great length in map view. The sediments include clay, sand and coal fragments. Cross-sections of these clastic bodies in coal can be very complex, because their compaction is small compared to peat. Contacts are often slickensided and fractured. These structures are infilled channels of meandering creeks and rivers in the swamp. Actually, vegetation is the clue for stabilization of river banks and of meandering single-thread channels (Tal & Paola 2007). In the Pennsylvanian coal fields of Illinois, USA, a giant swamp river is known with a width of 3–8 km and a length of 275 km.

It is important to distinguish clastic inclusions formed during peat formation from clastic infill deposited by streams, which cut into the seam from a base in the hanging wall (incised channels, or washouts*)*. In Illinois, Middle Pennsylvanian channels in coal measures were incised when a glacial climate period induced low sea-levels and seasonally dry climate (Falcon-Lang *et al.* 2009). Very deep incisions were made by rivers flowing beneath inland ice shields, which covered northern Europe in the Pleistocene. The subglacial erosion was well exposed in open pits exploiting Miocene lignites in the Lausitz District (Germany). Fluviatile washouts are identified by sharp erosive contacts instead of the transitional character between peat (coal) and synsedimentary channels. In the Hausruck District, washouts take the form of round potholes (scours) of 30 m diameter and 10 m depth, which are filled with alluvial gravel and sand resembling the overlying coarse sediments of the large Late Miocene alluvial fan of a large river originating in the Alps (Figure 6.15).

Some seams are cross-cut by clastic dykes, which usually originate in a bed of sand or mud that is present in the hanging wall. Arguably this is an effect of synsedimentary earthquakes. Dykes, swamp channel fill bodies and washouts are always serious and costly challenges to mechanical coal extraction.

6.2.3 Peat formation environments

Coals originated in former wetlands of coastal and inland settings (Greb & DiMichele 2006). The formation of peat deposits requires that:

- a profuse growth of higher plants is possible;
- dead plant material is covered by water so that oxidation and microbial decomposition is restricted; and
- that only a minimum of clastic sediment enters the peatland.

Most important is a suitable water level; if the water is too deep, higher plants cannot survive. If the swamp falls dry, peat and plant matter will be rapidly decomposed. Also, a water level that is favourable for the growth of higher plants will indirectly limit introduction of clastic sediment.

Both transgression and regression of the sea may promote the formation of peatlands. In the first case, the rising sea dams up coastal freshwater so that swamps form. As the waterline slowly migrates landwards, the swamps drown and peat beds are covered by marine sediment (e.g. coastal sand or shallow water carbonate mud). Many Palaeozoic coal seams in Northern Europe and in Eastern Australia (Herbert 1997), but also Tertiary lignite deposits in the Mediterranean realm attest to this course of events. Regression causes peat formation when the retreating sea exposes wide coastal flats where swamp forests thrive (e.g. the giant Miocene lignite deposits of Lausitz, Eastern Germany: Standke *et al.* 1993). In this case, marine sediments are found below the seam that is covered by terrestrial deposits.

Low-lying swamps (fens) develop in depressions or vales of the land, such as alluvial interchannel areas, moraine hills, constricted river bends, volcanic craters and in drowning karst dolines. Even in such terrestrial surroundings, the water table rise may be caused by eustatic increase of the sea level. Shallow lakes first develop a stage of floating peat that accretes on the lake margin. Next, a luxuriant and diverse flora expands across the former lake. Such low-lying swamps promote minerotrophic and eutrophic conditions with a high rate of organic production, but result in coal with high ash and elevated sulphur content. In contrast to ombrogenic bogs, fens are important sources of CH_4 and contribute to CH_4 and CO_2 fluctuations in the atmosphere. As greenhouse gases, both are factors of climate variations.

Ombrogenic, oligotrophic **raised swamps (bogs)** occur in regions of high precipitation. Raised bogs

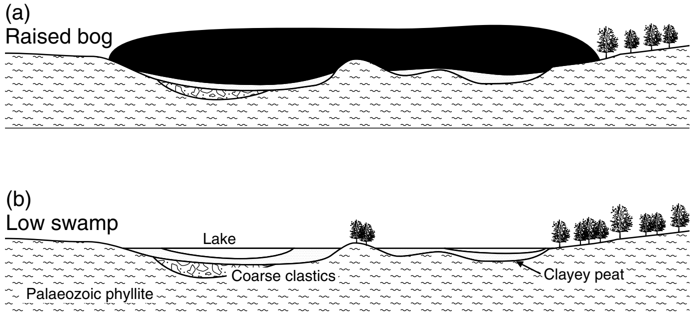


Figure 6.16 Simplified evolution of peat formation in the Miocene coal basin at Leoben, Austria, from an early, rather unproductive stage of a low-lying swamp (a) depositing high-ash peat to (b) a highly productive raised bog (modified after Gruber & Sachsenhofer 2001). Copyright (2001) with permission from Elsevier.

are independent of morphology and may even grow on mountains, although with a small chance of preservation. The transition from an original low-lying swamp into a raised bog is often observed ("domed peat deposit", Figure 6.16). The domes reach impressive dimensions. On the coastal plains of Sarawak Island, Pleistocene-Holocene peat domes attain 20 m thickness and a surface of 1000 km^2 (Staub & Esterle 1994). Raised bog peat differs from low-lying swamp peat by low ash and sulphur concentrations, acidic pH and less decomposition. However, low concentration of limiting nutrients (Ca, P, K, N) may severely curb productivity. Remember that six major elements – H, C, N, O, S and P – are required to build all biological macromolecules (Falkowski *et al.* 2008). Coastal raised swamps of the Indonesian islands are most probably the modern equivalents of ancient low-sulphur and low-ash coal (Cobb & Cecil 1993). In the Northern Hemisphere, lignin-free *sphagnum* (a moss) is at present the most important peat-producer of raised bogs.

The majority of coals are autochtonous, derived from plants that grew at, or near their present location in the seam. The opposite, allochthonous formation of coal from transported plants or peat is quite rare. Upright trees, tree stumps and seat rocks (root horizons in footwall sand or clay) are indicators for autochthonous coal. Stump horizons in German lignites are ubiquitous (Moosbrugger *et al.* 1994), and some stumps display over 1500 annual growth rings (Kurths *et al.* 1993). This implies coal formation periods with very stable conditions and little incremental peat deposition. Allochthonous seams are characterized by a high siliciclastic fraction, high ash, rounded coal fragments, non-oriented driftwood masses, rapidly varying seam thickness, discordant boundaries and cross-bedding within the coal. Allochthonous origin is relatively more common in Gondwana coal (Begossi & Della Favera 2002, Glasspool 2003). Of course, much plant matter in all swamps is transported for short distances and may be called "parautochthonous". This is especially obvious for the char fragments of fire horizons, which form continuous laminae of the lithotype fusain (Lamberson 1996).

The formation of swamps and extensive peat deposits, and the preservation of peat and its transformation into coal, require a set of favourable factors including climate, tectonics and palaeogeography.

Climate is an essential control on peat-forming plant communities. Sufficient precipitation is the basic precondition. It should not fall below 40 mm/month, even in dry seasons. Monthly average temperatures should remain above 10 °C, because this is the minimum that supports lush plant growth. Tropical, warm and humid forest swamps are optimal for a high production rate of plant substance, where trees grow within 7 to 9 years to heights of 30 m. Growth in cooler climates is much slower, with an estimated peat increment of 0.5–1 mm/a compared to 1–4 mm/a in the tropics (Falcon-Lang *et al.* 2009). Although many major coal deposits originated in tropical climate zones, significant coal resources formed in temperate and even cool climates. The Late Carboniferous (Pennsylvanian) coals of Europe, North America and China were deposited in swamp forests of *Sigillaria* and *Lepidodendron* at tropical latitudes (Ziegler *et al.* 1997). These rain forests were ecologically quite heterogeneous (DiMichele *et al.* 2007). Glacial climate cycles, however, induced long phases of dry tropical vegetation, which are poorly represented in the fossil record (Falcon-Lang *et al.* 2009). The giant Permian coal deposits of the Southern Hemisphere, with their boreal *Gangamopteris-Glossopteris* flora, formed during the same Permo-Carboniferous glaciation in a cool and humid climate, although possibly with tropical summer temperatures (Rayner 1996). Burial of peat depressed atmospheric CO_2 to very low concentrations. Waxing and waning of the ice sheets controlled climate and eustatic sea levels.

> The typical Permian flora of southern continents was one of the main arguments when Suess (1885) recognized the former land connection between Africa, Madagascar and India, and called this landmass "Gondwana". Today we know that Australia, Antarctica and much of South America were also part of Gondwana. Gondwana and Laurasia finally collided at ~300 Ma, resulting in the formation of Supercontinent Pangaea (Torsvik & Cocks 2004), which was the stage for Permo-Carboniferous glaciation and peat formation.

Coal seams are terrestrial climate archives, just like recent peat deposits (Large *et al.* 2003). The density of stomata on fossil cuticles allows an estimate of atmospheric CO_2 concentrations back into the Palaeozoic (Retallack 2001). A coal formation in northeastern Greenland just straddles the end-Triassic extinction and displays a ^{12}C spike that is attributed to sudden release of methane from gas hydrates on the ocean floor (Beerling 2007). At the same time, foundering and rifting of Pangaea started with the outpouring of basalts in the Central Atlantic Magmatic Province (Marzoli *et al.* 1999). Exceptionally fusinite-rich (40–60%) Mid-Cretaceous seams in British Columbia, Canada, testify to unusually frequent swamp fires, which were probably caused by dry climate periods (Lamberson *et al.* 1996). The iridium anomaly and botanical extinction caused by the Chixculub impact at the Cretaceous/Tertiary boundary were confirmed in a coal seam of New Zealand (Vajda & McLoughlin 2004).

Wetlands are significant factors of climate regulation, by preserving large masses of carbon in the form of peat and coal (Beerling 2007). Today's wetlands cover a surface of 250–500 Mha and contain 110–450 Gt C_{org}. In comparison, the mass of $C(CO_2)$ in the atmosphere is ~780 Gt. Clearly, an important function of peat and coal sedimentation is abstraction of CO_2 from the atmosphere and concurrent cooling of climate. At the same time, burial of organic matter is the cause of a net oxidation of the atmosphere via photosynthesis (Falkowski & Isozaki 2008). When CO_2 concentration in the atmosphere decreased to very low levels in the Late Palaeozoic (Figure 6.17), the Earth's climate fell into glacial mode. The

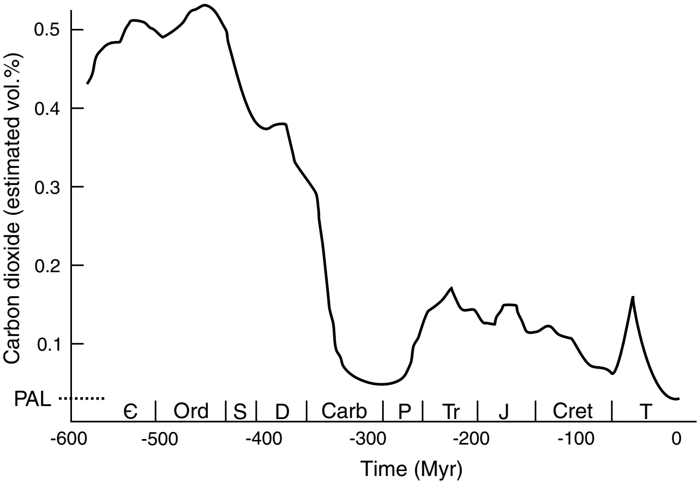


Figure 6.17 Reconstruction of CO_2-levels in the Earth's atmosphere from the Cambrian until today (cf. Normile 2009) based on geochemical models (Berner & Kothavala 2001) and various proxy data (Retallack 2001). Adapted by permission from Macmillan Publishers Ltd: *Nature* copyright (2001). Error margins are not shown. PAL is the present atmospheric level at ~0.039 volume % CO_2 in air. At about 635 Ma in the Neoproterozoic Marinoan Snowball Earth glaciation, pCO_2 had been as high as 1.25–8% (Bao *et al.* 2009).

resulting Gondwanan continental glaciation lasted from 326 to 267 Ma (Horton & Poulsen 2009). At the end of the Permian period, the eruption of the giant Siberian trap basalt province (Kamo *et al.* 2003) terminated the period of low CO_2 concentration in the atmosphere, although the long-term draw-down was only interrupted. The reverse – warming of the climate – is a consequence of swamps falling dry and oxidation of peat and coal, including burning it in power stations (releasing CO_2). Warming is also caused by methane released into the atmosphere through the activity of microbial methanogens in wetlands. However, the Earth's carbon cycling remains incompletely understood (Normile 2009). Our planet encloses other reservoirs of carbon and carbon dioxide, which share in the control of atmospheric carbon dioxide, and climate is influenced by a plethora of processes apart from the CO_2 cycle (Plimer 2009, Solomon *et al.* 2010). During the last ice age and its numerous glacial/interglacial periods, carbon dioxide varied from ~180–300 ppm, but the variations were not the cause but the consequence of temperature amplitudes between -9 and $+3\,^{\circ}$C (Shackleton 2000).

Tectonic processes provide the slow subsidence that enhances peat thickness by balancing swamp growth. This includes all scales of tectonics, from wide epeirogenic flexure of intracratonic basins and platforms to the formation of orogenic foredeeps and local rift valleys (Figure 6.12). Post-orogenic intramontane basins are formed by tensional or shear strain of thickened orogenic crust. Embryonic folding of a basin during peat sedimentation may cause thinned seams over future anticlines and thickened coal in the depressions (e.g. Sydney District, Australia; Wise *et al.* 1991). Rim synclines of salt diapirs and walls (Figure/Plate 5.18) may collect large volumes of peat.

Palaeogeographical reconstructions of important coal basins of the Earth lead to an enhanced understanding of the conditions that support the formation of large coal deposits (Rowley *et al.* 1985). Palaeogeographical reconstructions at the scale of coal-forming wetland landscapes are useful for exploration and exploiting coal. A problem of such reconstructions for the geological past is the absence of recent examples of giant wetlands, because in the Holocene, continents are in a state of emergence and general dryness. Today, there is no wetland resembling the Westphalian coal belt in Europe with an East-West extension of ~3000 km, and a North-South width of 800 km (Ziegler 1982). Coal "giants" were typically deposited in periods of marine ingression into continents, at relatively higher sea levels than today. Therefore, instead of relying on the rules of actualism, facies analysis of the sediments associated with coal seams is the basis for modelling the sedimentary environment. Work in the foreland of the Appalachian Mountains resulted in the establishment of the Allegheny model that gained worldwide acceptance.

The Allegheny model is based on the observation that thick coal formations consist of disconformity-bounded stratigraphical repetitive sequences of sediments that have been termed "cyclothems" (Figure 6.18). Cyclothems were originally defined as "designating a series of beds deposited during a single sedimentary cycle of the type that prevailed during the Pennsylvanian period" (Wanless & Weller 1932). The concept and its significance are still discussed today (Horton & Poulsen 2009, Weibel 2004, Wilkinson *et al.* 2003). Sediments making up cyclothems can be related to several depositional environments, which are the key to the recognition of favourable peat-forming areas (Thomas 2002, Ward 1984):

- *Marine shelf* Fossiliferous shale, sandstone and carbonates, rarely dark phosphatic shale, all deposited in relatively deep water and far from the shoreline; no coal;
- *Delta front, coastal barriers and brackish lagoons* Mainly quartzites that are interbedded either with shale and carbonates (seawards) or with dark shale and thin coal beds (landwards); the shoreline may be marked by the occurrence of flint;
- *Lower delta plain* Lagoonal or deltaic shales that are overlain by silt and sandstone, incised by sandy alluvial channels; thin coal beds are ubiquitous, either in abandoned channels or in wide coastal swamps between active flow channels;
- *Upper delta plain and broad alluvial plains* Terrestrial clastic rocks and thick coal seams; peat formed in wide swamps covering inundation

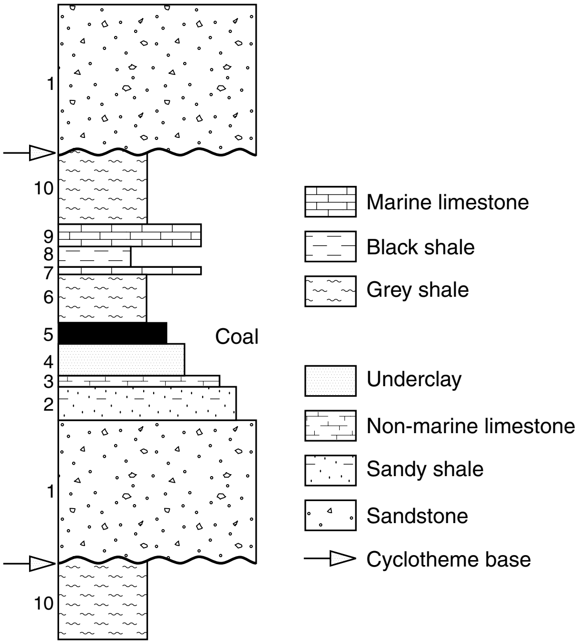


Figure 6.18 The "ideal" cyclothem (modified from Wanless & Weller 1932 and Wilkinson *et al.* 2003). Wilkinson *et al.* argue, however, that the apparently regular succession of sediments in cyclothems is accidental. The variable width of the column emphasizes different lithologies and grain size.

plains, lakes and abandoned channels; coal seams contain clastic interbeds; generally, fining-upward sediments are characteristic.

The formation of Pennsylvanian cyclothems may have been controlled by: i) eustatic glacial forcing of sea levels; or ii) tectonic impulses. The first can be caused by orbital control of sea levels and climate oscillations related to the Milankovitch theory (Heckel 1986), or by greenhouse gas control. There is little doubt that most cyclothems reflect global change of sea levels due to waxing and waning of continental ice sheets. Estimates of the glacial-eustactic amplitudes during the Pennsylvanian vary around ~100 m, similar to the Pleistocene. Glacial-eustatic cyclothems are separated by lowstand terrestrial units or by exposure surfaces. Orbital insolation changes are controlled by the Earth's precession, obliquity and eccentricity, with recurrence sinusoidal periods of ~20, 40 and 100 kyr, 400 kyr and 2.5 Myr. The short cycles provide a possible time-scale to single cyclothems. In the Pleistocene, a combination of orbital control and consequent greenhouse gas decrease to less than 280 ppm CO_2 equivalent, is thought to have caused growth of ice sheets and fall of sea levels by 120 m. Simulations of Late Palaeozoic orbital cycles, glaciation and sea levels at different pCO_2 (Horton & Poulsen 2009) suggest that orbital cycles alone only account for ~10 m sea level change; greenhouse gas forcing must be induced to replicate observations.

Global extent of glacial eustasy caused by Late Palaeozoic glaciation of Gondwana translates into the probability that single cyclothems should be datable events worldwide (Miall 1997). The origin of specific cyclothems is still discussed. The Carboniferous coal measures of northern Germany, for example, were deposited in coastal swamps of the Variscan foredeep (Figure 6.19) and display many cycles of marine transgression and regression. Resulting cyclothems are considered eustatic-tectonic by Süss *et al.* (2000) and glacial-eustatic by Hampson *et al.* (1999).

6.2.4 Host rocks of coal

A siliciclastic nature of rocks hosting coal is the norm (Figure/Plate 6.20). Exceptional cases include Late Permian coal seams in southern China, which rest on marine platform carbonates.

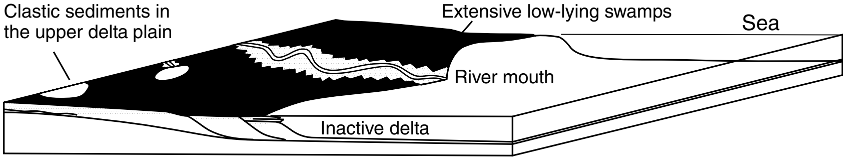


Figure 6.19 The largest expansion of Late Carboniferous paralic swamps in northern Germany occurred at times of beginning transgression of the sea. In sequence stratigraphic terms, this is an "early transgressive systems tract" (Hampson *et al.* 1999). Black – peat areas.

This coal contains marine fossils and is enriched in organic S, Na, Mg and Ca. A setting similar to recent coastal mangrove swamps is assumed (Shao *et al.* 1998).

An appropriate study of host rocks is a vital part of scientific and practical investigations of coal deposits. Sedimentological data are needed for palaeogeographical models and for resource estimation, physical properties determine mining methods and costs. Note that rocks associated with coal always display grey colouring; red (haematitic) sediments are free of coal. The grey colour of host rocks is, of course, simply a result of the reducing sedimentary-diagenetic environment and is caused by fine-grained organic substances and pyrite. In rare cases, the connection between former swamps and nearby hills is exposed and lateritic (red) soil is observed. An example is the paralic (coastal) Late Carboniferous seams of the Sydney basin on Canada's Atlantic seaboard,

Figure 6.20 (Plate 6.20) Outcrop of Permian Great Northern coal seam below fluvial conglomerate on the Pacific shore, Sydney basin, New South Wales, Australia. Note vertical joints and subdivision of seam into plies. Courtesy of Keith Bartlett, Minarco-Mineconsult, Tuggerah, NSW.

which are interbedded with transported red soil and calcrete nodules (Tandon & Gibling 1997). Autochthonous calcic vertisols are attributed to glacial dry climate spells in the Mid-Carboniferous of Illinois (Falcon-Lang *et al.* 2009).

Floor (footwall) of coal seams

Coal seams may be in direct contact with older basement (Figure 6.16), but are more commonly underlain by clastic sediments of the same age. Plant roots and their symbiotic fungal associates secrete organic acids that dissolve mineral particles in the soil to liberate nutrients needed for growth. This enhances the rates at which continental silicate rocks undergo abiotic chemical weathering (Berner *et al.* 2003, Berner 1997). Organic acids dissolved in seepage water from the mires act as reductants and break down soil minerals. In the case of good drainage, iron and alkalis are removed, resulting in bleaching, kaolinization and the upgrading of quartz sands. In consequence, valuable kaolin, illitic fireclay and high-grade sand or quartzite deposits in coal districts are not rare. Also, the downward seepage of water removes large quantities of CO_2 from the atmosphere, for example by calcite formation in deeper parts of the aquifers. At the same time, dissolved matter entering the sea favoured proliferation of marine carbonate-forming life. The combined effect is the steady drop of atmospheric CO_2 during the Palaeozoic (Figure 6.17), while land plants emerged and colonized the Earth's terrestrial surface and as a side-effect, lowered ambient temperatures.

A characteristic footwall rock of seams is *seat earth,* or *underclay,* which is the soil that supported the peat-forming vegetation. The material is typically fine-grained (clay and silt) but may be sandy. Coalified remains of roots are abundant and reach a depth of 10 m below coal seams. Siderite concretions mark many of these horizons as former gley and semi-gley soil.

Roof (hanging wall) of coal seams

Thinly stratified carbonaceous shale with numerous leaf fossils, cannel coal and bituminous shale are characteristic roof rocks of Late Palaeozoic coal seams in the Northern Hemisphere. These rocks indicate deglaciation, rising oceanic and local water levels, and drowning of the swamp. In contact with air, as for example on waste dumps, these rocks are prone to self-ignition. Sand as a roof rock of seams in orogenic foreland basins may have originated by subduction earthquakes and consequent tsunamis. Also possible is a genetic equivalence with the mud deposited by Hurricane Katrina over wide wetland areas of Louisiana, USA (Turner *et al.* 2006). Coals with marine hanging wall rocks contain relatively more ash, sulphur and nitrogen, and more volatile matter than is expected from the rank of nearby freshwater coal. The elevated bitumen concentrations shift coking behaviour. These negative consequences of seawater inundation require a considerable time; peat in Panama, which was submerged by an earthquake below sea level in 1991, displayed little alteration three years later (Phillips *et al.* 1994). A relatively thin roof of freshwater clay and silt provides sufficient sealing to prevent negative consequences of marine transgression on coal quality (Eble & Greb 1997).

6.2.5 Marker beds in coal formations

At scales of less than 10,000 years and 10 km distance, coal seams must be considered as diachronous beds, except if the opposite can be proved, for example by a tuff marker bed. At larger time spans and distances, seams may be used as time markers. They are, however, a rather poor basis for chronostratigraphy but serve very well in lithostratigraphical work. In mining applications such as seam correlation, the latter has proved its high worth.

Lithostratigraphical orientation is most important in coal districts with numerous seams, which are deformed by folds, faults and overthrusting. Lithological marker horizons, fossil-rich bands, characteristic host rocks, palaeosoils and recognizable dirt bands in single seams, such as tuff and fire horizons, all serve to build a lithostratigraphical division, and to match an unknown seam into the system, for example after driving a tunnel through a fault with uncertain throw.

Marine marker horizons are the product of transgression of the sea over coastal peat swamps or freshwater mud flats. In the Ruhr District, Germany, 40 exploitable seams and 18 marine marker horizons are distinguished. These marine flooding events are traceable throughout Europe and already long ago served to establish international stratigraphical boundaries. Typical rocks are dark banded shales with a rich fauna, in part open marine pelagic, whereas others display a fauna of a few species in brackish settings.

Volcanic tuff horizons are very useful correlation markers, because ash falls mark actual time horizons. When a tuff band cuts through a seam at an oblique angle, the seam is diachronous. In European and North American, Carboniferous coal seams, tonstein (German for "claystone") horizons are relatively frequent. They represent kaolinized rhyolitic tuff with recognizable characteristic rhyolite quartz, former glass shards, sanidine, zircon and ilmenite. With a thickness of <10 cm, many tonstein bands are known over thousands of square kilometres. Kaolin originated in the acidic swamp; later diagenesis transformed much kaolin into illite (e.g. Sabero, Spain: Knight *et al.* 2000).

6.2.6 Coal formation in geological space and time

A large number of coal basins were formed in coastal swamps and are called *paralic* (Greek for "by the sea"). Marine marker horizons clearly indicate the proximity of the sea and its occasional invasion. Limnic coal basins formed in intracontinental and often intramontane swamps and display freshwater-dominated rocks. The term "limnic" is not fully satisfactory because little coal originated in lakes. The majority was deposited in a "telmatic" (wetland) or terrestrial (raised bog) environment. Of course, host rocks of "limnic" coal are mainly of limnic and fluviatile facies, with occasional volcanic and marine influence.

The geodynamic nature of coal basin settings suggests a classification along the following lines:

1 *Foreland and molasse basins* are caused by downflexure of the lithosphere, due to subduction and the advancement of an orogenic front. Sediment fill is very thick (up to 8000 m in the North European Carboniferous) and of continental derivation, but mainly deposited in the sea. Paralic seams are numerous, although thin (1–2 m) and cover a large surface. The sedimentary package is folded and faulted, with a decrease of strain from the orogenic front towards the foreland. Examples are giant coal deposits in the Appalachian foreland (Cross 1993), the North-Variscan foredeep of Europe (Drozdzewski 1993), the Bowen Basin west of the Tasman orogenic belt in Australia and the Karoo Basin north of the Cape belt in South Africa (Cadle *et al.* 1993).

2 *Intramontane and intermontane basins* are the result of late-orogenic distension and collapse of mountain belts, and of large transform or shear structures, which create transtensional, transpressional and simple pull-apart basins. Sediments are predominantly limnic and alluvial with marine intercalations. The base of the infill may be a discordant seam. The number of seams is rarely more than 10, but the thickness of individual seams may surpass 100 m. The total thickness of coal formations is rather limited. Tectonic strain varies widely. This type is well illustrated by the Early Tertiary Raton and Powder River basins in North America, although the two originated during the Laramide orogenesis as isolated fragments of a former Cretaceous foreland basin.

3 *Intracontinental and platform basins* Coal-bearing sediment sequences display a thickness of a few hundred metres only. Few seams are developed but some may reach great thicknesses. The seams are constant and attain large areal extensions to several 10,000 km^2. Bedding is nearly horizontal to moderately inclined. This type of coal basins is the result of slow, wide-ranging epeirogenic subsidence of stable cratonic regions. Examples include Gondwana coal basins north of the *sensu stricto* Karoo Basin in South Africa and India, the Tunguska Basin in Central Siberia and the lignites of Eastern Germany.

Times of peat (coal) formation

Earliest rocks resembling coal are known from the Archaean Witwatersrand gold placers (cf. Chapter 2 "Gold"); the so-called carbon leaders are graphitic pyrobitumen seams, which may be derived from algae. Plants first invaded the land

~470 million years ago (in the Silurian). In the geologically short time since, they have diversified and profoundly moulded the Earth's climate and the evolutionary trajectory of life (Beerling 2007). Humic coal became only a possibility with this conquest. The earliest known vascular plant is fragile and leafless *Cooksonia* (425 Ma). In the early Devonian, the first tiny leaves are found (*Eophytophyllon bellum*). Later during the Devonian, terrestrial vascular plants became so widespread that atmospheric CO_2 concentration fell rapidly, caused by intensified weathering (Figure 6.17, Berner 1997). At the same time, the oxygen concentration in air started to rise, reaching a peak of ~35% in the Permian (compared with the present atmospheric level of 21%).

The oldest coal deposits date from the Late Devonian of Arctic regions (Asia, northern Europe, Canada), with fossils of genus *Archaeopteris* as the earliest tall trees. Well-developed seat rocks are known in Quebec (Elick *et al.* 1998). Since then, coal was formed in all geological stages. Two main periods of coal formation, however, stand out because of the sheer mass of coal contained: The Late Carboniferous-Permian and the Late Cretaceous-Tertiary, which contain ~55 and 26%, respectively, of world resources. Both are related to late orogenic dynamics of continental collision (the Variscan and Alpidic cycles, respectively). Late Palaeozoic coals of the northern hemisphere (China, Europe, North America) formed in a relatively short time span of ~30 Ma in the Late Carboniferous. During this time, the region passed the tropical rain forest zone while Pangaea drifted northwards. Most of the coals of the Gondwanan part of Pangaea (Australia, Africa, Antarctica, India, South America) were deposited later, in the Early and Mid-Permian. Coal formation in both hemispheres is intimately controlled by continental glaciation lasting from 326 to 267 Ma (Horton & Poulsen 2009).

6.3 THE COALIFICATION PROCESS

The natural process system, which transforms plant material into coal, is called coalification, as proposed by Gümbel (1883). Gümbel coined the term in order to stress the contrast with carbonization that is provoked by anoxic heating of wood in a charcoal pile. Coalification can be considered to consist of a first stage that takes place in the swamp during peat formation, and a second stage that begins with deposition of cover rocks above the peat. The first is also called "peatification" and is primarily a biochemical process. The second, geochemical coalification is essentially abiotic, driven mainly by increasing temperature and pressure. The domain of coalification is largely equivalent to that of diagenesis, the term applied to inorganic sediments (cf. Chapter 1.4 "Diagenetic Ore Formation Systems"), and to "maturation", which is used in the hydrocarbon industry to describe changes of dispersed organic matter in sediments related to oil and gas generation.

6.3.1 Biochemical peatification

Most peat-forming wetlands have an oxidized near-surface layer but at little depth, reducing conditions prevail. A fully developed vertical redox-stratification may include oxic, suboxic, sulphidic and methane zones with increasing depth. The aerobic oxic zone is defined by the presence of dissolved oxygen in pore waters and is generally very shallow. The suboxic zone is identified by accumulation of dissolved Fe(II) and Mn(II) in the pore waters and is anaerobic. Due to sulphate reduction, dissolved H_2S builds up in the sulphidic zone. Organic matter degradation by anaerobic methanogenesis sets in when sulphate is depleted to levels that do not support microbial respiration. Lateral variation of the zonation is considerable (Koretsky *et al.* 2007).

Dead plant matter in the swamp is decomposed by bacteria, archaea, actinomycetes and fungi. Synthesis of humic macromolecules occurs by microorganisms proliferating on organic residues (Kögel-Knabner 1993). Different products are due to the respective redox environment and the fate of various building materials of the plant. Sugars, starch, pectine and protein are rapidly metabolized, as is cellulose, which is not protected by lignin. Lignin is preferentially attacked by fungi; the effect is transformation into solid humic substances under preservation of shape (Hatcher & Clifford 1997).

Cork (suberine) and tannine-impregnated tissues are only in part microbially decomposed. Wax and resins remain unaffected. Lipids such as pollen, spores and cuticles preserve both shape and material composition. Some peats display enrichment of carbon to 60% (d.m.m.f.) already near the surface; the increase of carbon towards depth is slow and in rare cases attains a maximum of ~64% C. Clearly, carbon is not a useful parameter for the determination of peat maturity.

Only abiotic changes such as condensation, polymerization and reduction take place below ~10 m under the surface. Most conspicuous are decreasing porosity and water content of the peat as a function of increasing consolidation. Some observations suggest that water content is reduced by 1% for every 10 m; such experimental data collected from a specific deposit may serve well for studying the maturity distribution. The transition from peat to bog coal and lignite is a matter of convention, with no natural limiting mark. Water, free cellulose and carbon content, or the ease of cutting may be parameters taken into account (Figure 6.4, Taylor *et al.* 1998).

The most significant process of peatification as a precursor of coal formation is humification, which is a limited oxidation of lignin, cellulose and proteins. Humification may be followed by biogenic gelification. Microbiota are the key to more intense decomposition. Preconditions for high microbial activity include: i) a rather basic pH of the swamp: ii) the availability of sufficient nutrients (Ca, P, K, N): iii) elevated temperature; and iv) free oxygen in surface water. Therefore, high biogenic gelification is one of the indicators of swamp facies. In some cases, clearly variable gelification of different plies in one coal seam has been observed.

Burial of the peat by alluvial, limnic or marine sediments terminates the biochemical peatification process, and geochemical coalification takes over.

6.3.2 Geochemical coalification

Petrographical, chemical and physical properties of coal change with increasing rank. Peat and bog coal are little different, but already in sub-bituminous coal organic constituents are markedly changed. This observation provoked remarks that coalification may be better considered as a kind of metamorphism and not of diagenesis (Hower & Gayer 2002). Taking into account, however, that host rocks of coal experience diagenesis while coal rank increases, using the term metamorphism appears highly impractical.

Humins evolve during coalification by increasing aromatization, condensation and clustering (Hatcher & Clifford 1997). As functional groups, bridges and side-chains of nuclei are broken down, islands of well-ordered structural elements ("crystallites") grow larger. During coal maturation, aromatic clusters are increasingly arranged into flat sheets that resemble the graphite lattice.

During coalification, elemental ratios of H/C and O/C change, and decomposition reactions liberate water, CH_4 and CO_2 or CO (Kopp *et al.* 2000). Note that in certain districts, $C_{2\text{-}4}$ hydrocarbon gas may occur apart from methane. In the Ruhr District, Germany, this "wet gas fraction" attains 70%. In addition, all humic coals exude a little bitumen similar to crude oil. Coal as a source rock for oil deposits, however, is uncommon (Wilkins & George 2002).

6.3.3 Measuring the degree of coalification

Quantitative determination of coal rank relies on chemical and physical changes during coalification. Because these changes are not equally distinct over the whole rank scale, certain methods are preferred in specific rank regions.

In lignites and sub-bituminous coals, moisture decreases rapidly with increasing rank (Figure 6.4), which makes its determination a useful parameter of maturity. In Australian (Holdgate 2005; Figure 6.12) and Lower Rhine bog coal, water content decreases 3–5% per 100 m depth increment, and in the sub-bituminous coal of Borneo at 1% per 100 m. This loss of water is caused by a reduction of the pore volume, but also chemical loss of hydroxyl (-OH) and other organic groups. Factors that influence gradual loss of water include burial depth, time, seawater contact, lithotype and tectonic strain (e.g. folding). Moisture of bituminous coal changes little and is of no use for rank determination.

In mining practice, the rank of black coal is measured by volatile matter yields. Because macerals display different content of volatiles, bright lithotype layers (vitrain) are preferably used for precise rank measurements. The reverse, i.e. fixed carbon (% C = 100 − % V.M.) may also serve to express rank. Increasing coal rank reduces volatile matter and increases fixed carbon content. Already in 1873, Hilt had reported that the rank of black coal in a shaft increases with depth (Hilt's law). The gradient is locally different but the average decrease of V.M. is ~1.4% per 100 m. Sivek *et al.* (2008) show that in the Upper Silesian coal basin, deviations from the average are due to elevated pressure in tectonically deformed areas, to thermal influence from igneous intrusions and even to palaeoweathering.

The standard method of rank measurement, however, is the determination of vitrinite reflectance (Taylor *et al.* 1998). This is carried out with a photometer mounted on a microscope, by illuminating a polished surface of coal with non-polarized light under oil immersion and measuring the reflected fraction of the incident light. In routine work, particle mounts are prepared and reflectance is measured. Statistical evaluation reveals the mean of random reflectance (R_r or in oil immersion $R_{r,o}$, often written R_o), which correlates closely with coal rank. Reflectance determined with polarized light on oriented coal samples reveals an anisotropy of high (R_{max}), intermediate and low (R_{min}) values. In little deformed coal seams, R_{max} is oriented parallel to bedding and R_{min} across it at a right-angle. This is due to the gravity-induced natural stress field, which causes growth or adjustment of structural lamellae into near-horizontal bedding planes. Deviations from this ordinary spatial arrangement may occur in folded seams and are important keys for resolving the relative timing of coalification and deformation, and for reconstruction of the palaeo-stress field. Average reflectance increases from ~0.3% (of incident light) for lignite to ~4% for anthracite. The increase is much steeper in high-rank compared to lower rank coals (Figure 6.4).

Changes of macerals of the liptinite group can also be employed for studies of coal rank (Taylor *et al.* 1998). Illuminated with blue or long-wave UV light under the microscope, liptinites exhibit fluorescence (Figure/Plate 6.9). The intensity of fluorescence is highest in peat and lignite and decreases with higher rank. Quantitative measurement of rank is possible up to the so-called coalification break at ~29% V.M. (high volatile bituminous coal). At higher rank, in medium volatile bituminous coal, liptinites approach vitrinite in chemical and optical properties and the two cannot be distinguished. Precursors of liptinites are mainly paraffinic (aliphatic) waxes and lipids of plants, which are very stable during peatification. In the sub-bituminous stage, liptinites exude bitumen, just like petroleum source rocks. Subsequently, methane is released until liptinites loose their petrographical identity.

Physico-chemical investigations of structural change during coalification, such as aromatization, condensation and clustering, also reveal much about the coalification process (Hatcher & Clifford 1997). This is, however, hardly ever applied in practice, in contrast to the methods presented above. Visualization of coalification data in relation to geological features is provided by maps and sections, which display rank by contours of equal water and V.M. content, or reflectance.

6.3.4 Causes of coalification

Many observations in coal mines provide arguments concerning the agents of coalification, including:

- time, because older coal is commonly of higher rank;
- temperature, because coal in proximity of igneous rocks is upgraded and deeper coal is subject to higher heat flow;
- pressure, which also rises with depth;
- tectonic strain, as in the same basin undeformed coal tends to display lower rank compared to folded seams; and
- swamp facies, which partly controls volatile matter content.

Currently, a dominating role of temperature is generally accepted, but the influence of other factors is not negated (Sivek *et al.* 2008, Hower & Gayer 2002).

Thermal metamorphism of coal

Thermal metamorphism of coal in contact with magmas continues to provide a deeper understanding of coalification (Mastalerz *et al.* 2009). Of course, quantification of the temperatures that acted on coal excites much interest. Estimates are made by comparison with results from laboratory experiments, or are derived from the assumed liquid and solidus temperature of the magma and the heat conductivity of host rocks and coal. Actually, with a high heat capacity and one of the lowest heat conductivity coefficients of geological materials (0.016–0.148 W/[m.K], Bychev *et al.* 2004), coal is an excellent insulator. To give one example, coal intruded and covered by Permo-Triassic trap basalt in the Tungus Coal Basin, Siberia, was heated to a maximum of 650–700 °C (Pavlov *et al.* 2005).

Generally, coal affected by the heat aureole of magmas displays reduced moisture and volatile matter content (higher rank), whereas ash yield increases. Black coal is visibly altered above ~300 °C and, above 500 °C, obtains an appearance that resembles industrial coke. Natural coke and graphite often occur as a thin fringe with hexagonal jointing along the contact. Natural coke can be formed from coal that is not cokeable, because of too high V.M.; this observation indicates that confining pressure had an influence. The coke fringe is followed by thermally altered coal, which is dense, hard and dull, and may be hexagonally jointed. Vitrinites in the intermediate zone exhibit incipient melting, loss of volatile matter and exudation of tar. Softening induces viscous plastic flow of coal that destroys sedimentary bedding. Fluid coal may be injected into host rocks resembling a dyke. Haematite may replace pyrite and abundant CO_2 causes deposition of much carbonate, both in coal and in the igneous rock body, which is itself heavily altered. This raises the ash content of coal. Water vapour or supercritical fluid may form at the igneous contact, impeding vitrinite alteration (Barker *et al.* 1998).

Lignites are strongly dehydrated near the contact, which induces cracks and joints. Coke formation is less frequent but confirmed. Anthracites hardly melt and, without exhibiting visible alteration, are upgraded to meta-anthracites, which are commercially extracted and marketed as graphite (cf. Chapter 3, "Graphite"):

> The West Siberian Tungus Coal Basin extends over $\sim$1.2 M km^2 and hosts a thick Permo-Carboniferous coal-bearing series with many important coal seams. Total coal resources are estimated to reach 40,000 Mt (Pavlov *et al.* 2005). Trap basalts covered and intruded the coal sequence at the Permo-Triassic boundary. This induced a short pulse of thermal metamorphism that upgraded previous lignites and sub-bituminous brown coal to coking coal rank, anthracite, and even graphite. At the same time, the process must have released enormous volumes of CO_2, methane, water vapour and hydrogen sulphide that contributed to the near-extinction of life on Earth. In the northern part of the Tungus Basin, the coal series is covered by low-permeability rocks and Pavlov *et al.* (2005) speculate that giant resources of coal-bed methane may be trapped in this area.

Deep igneous intrusions may impose a wide halo of regional thermal coalification, with a peak in the anthracite stage (e.g. in the western Lower Saxony Basin of northern Germany: Kus *et al.* 2005). Rapid rise and denudation of metamorphic massifs may also impose a regional coalification gradient (Sachsenhofer 2000). In the Eastern Alps, Tertiary coal occurs in many intramontane basins (Figure 6.16). Over a distance of ~100 km from east to west, rank increases from lignitic to high volatile bituminous B. The highest rank occurs proximal to the Tauern Window, a tectonic unit that was metamorphosed in the Eocene and unroofed in the Miocene (Neubauer *et al.* 2000).

Geothermal coalification by subsidence

In contrast to spatially circumscribed heat sources, the geothermal field of the Earth provides ubiquitous heat energy. Heat flow from depth provokes a temperature rise with increasing depth, which is called the *geothermal gradient*, with an average of ~25–30 °C/km. However, the geothermal gradient varies with lithology; it may be as low as 14 °C/km for highly conductive salt and 47 °C/km for insulating coaly shale. Other variations are due to the tectonic setting. Subsidence of a coal basin shifts coal into higher temperature conditions, which intensify coalification. The depth arrangement of rank reflects the wide or narrow spacing and the shape of isotherms (contours of equal T). Coalification isolines may be used to reconstruct the geothermal gradient responsible for coalification.

The coalification gradient is a function of geothermal gradient and lithologies at a specific location. Based on quantitative estimates of overburden and heat flow at the time of coalification, calculation of coalification temperatures is possible. If time is not a limiting kinetic factor (see below), typical coalification temperatures are ~50–200 °C (sub-bituminous and bituminous coal). Anthracite is formed at 200–300 °C, which is the reason why this rank is relatively rare. Often, anthracitization is clearly related to magmatic heat sources, but there are other genetic possibilities. In the Appalachians, hot tectonic brines, which are expulsed from the westward moving nappe pile, are considered to have been the agents of heating (Figure 1.74, Daniels *et al.* 1994). Anthracite occurring on the northern margin of the South Wales Basin (UK) was formed by the passage of hot basinal fluids, which were displaced by cool water due to a topographic gradient (Gayer *et al.* 1998). Another hypothesis suggests that the commonly moderate extension of anthracite fields might be explained by an early synclinal downwarp, which is now concealed by later strong deformation such as folding and inversion (Lyons 1991).

The coalification temperature can be calculated from vitrinite reflectance data (e.g. from a drillhole profile) and an estimate of palaeoheat flow derived from specific geological constraints. One of several models was proposed by Sweeny & Burnham (1990). The model is based on chemical kinetics (eq. 6.3). Calculations based on this model demonstrate that coalification represented by reflectance (% R_o) is mainly controlled by temperature, whereas the reaction time exerts a much smaller influence (Figure 6.21).

ARRHENIUS-equation describing the kinetics of an endothermic chemical reaction (here coalification):

$$k = A \cdot e^{-E/RT} \qquad (6.3)$$

k = reaction rate (1/m.y.), A = specific reaction constant (frequency factor, 1/m.y.), E = activation energy (kJ/mol), R = universal gas constant ($J.K^{-1} \cdot mol^{-1}$) and T = temperature in Kelvin (°C + 273).

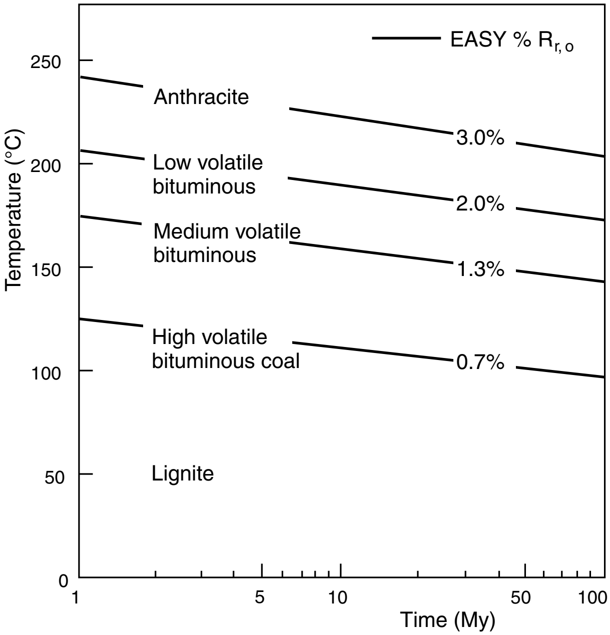


Figure 6.21 Vitrinite reflectance in a temperature-time diagram as calculated with the numeric coalification model EASY % from Sweeny & Burnham (1990). Comparison with coal rank is only indicative. AAPG [1990] reprinted by permission of the AAPG whose permission is required for further use.

Duration of coalification

Many investigations of coalification in geologically young sedimentary basins constrain the main parameters temperature, heat flow and duration of heating to narrow confidence limits. Results show that duration of coalification varies widely. For magmatic heating, coalification time is normally very short (<1 Ma). Long duration (25–35 Ma) was reported for anthracitization in eastern Pennsylvania (Daniels *et al.* 1994). The reaction rate of coalification is still not fully known, so that the effective heating time needed to reach equilibrium at a certain temperature cannot be predicted. The reverse is clearly displayed by observations: Rank once reached is hardly altered by lower temperatures, even if they act for a very long geological time. In this case, activation energy is the limiting factor. An example is the Ruhr District coals in Germany, where coalification patterns were imprinted during the Latest Carboniferous/Earliest Permian before the rocks were folded. In spite of elevated rock temperatures of >50 °C for the last 250 Ma, coal rank was not changed (Figure 6.22).

The role of lithostatic stress and fluid pressure

Considering the increase of coalification as a function of depth, lithostatic stress might play a role. This is certainly the case for lignite, which matures by compaction and dewatering. Bituminous coals attain higher rank mainly by chemical processes, but also by physical compaction such as decreasing porosity and this may be favoured by higher stress. High confining (fluid) pressure, however, may inhibit maturation (Carr 1999) by impeding expulsion of coalification by-products, such as H_2O, CO_2, CH_4, higher hydrocarbons and N.

Tectonic stress and strain

Many observations prove that folding of coal seams does not cause coalification (Figure 6.22). In fact, this was already documented by Petrascheck (1954) when he defined pre-, syn- and post-tectonic coalification based on microscopic investigations of the optical anisotropy of different folded coal seams (Figure 6.23). In the southern Ruhr District, where seams are most intensely folded, coalification is even lower than in less deformed regions (Nöth *et al.* 2001). Nevertheless, tectonic strain that favours permeability, such as pervasive shearing, advances maturation of bituminous coals and of anthracite, and graphitization (Ross & Bustin 1997). With shearing, graphite formation seems to be possible at temperatures little over 300 °C (Bustin *et al.* 1995). M. & R. Teichmüller (1966) observed a sharp coalification increase proximal to an overthrust fault in the Ruhr District. They suggested that friction heat may have been the agent. Heating by circulating hot hydrothermal fluids could be an alternative explanation (Golytsin *et al.* 1997).

Swamp facies

Seams that display marine influence on peat are of higher rank than close-by freshwater seams. This

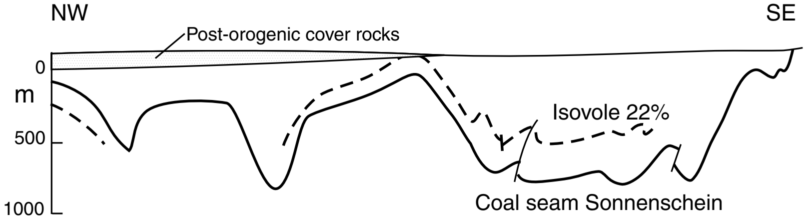
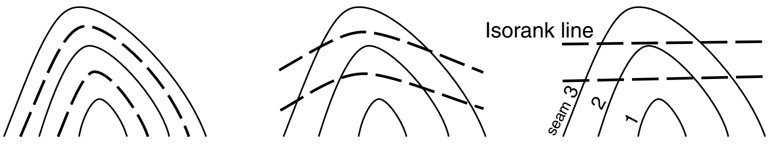


Figure 6.22 The parallel pattern of folded seam Sonnenschein in the Bochum synclinorium (Northern Germany) and the isovole 22% V.M. proves that coalification took place before deformation. Modified from M. & R. Teichmüller (1966, 1981) in Taylor *et al.* (1998). With permission from www.schweizerbart.de.



(a) Pre-orogenic coalification

(b) Syn-orogenic (or combined pre-/post-orogenic)

(c) Post-orogenic coalification

Figure 6.23 Pre-, syn- and post-tectonic relations between folded seams and the position of lines of equal coal rank (isovoles or isoreflectance limits). Modified from M. & R. Teichmüller (1966) and W.E. Petrascheck (1954) in Taylor *et al.* (1998). With permission from www.schweizerbart.de.

observation of coal miners was often verified, for example in the Netherlands, where Carboniferous coal rank decreases from deltaic to alluvial floodplain coal (Veld *et al.* 1996).

6.3.5 Coal maturity and diagenesis of country rocks

Studies of thermal evolution and burial history of sedimentary basins are not only based on vitrinite reflectance of coal and the maturation stage of dispersed kerogen in sediments. Detailed mineralogical investigations of pore cements, pore fluids and of pelitic rocks add another component. The field experience of the relations between coal rank and lithification grade of host rocks, such as lignite occurring in plastic clay and loose sand, black coal in hard shale and sandstone, and graphite in phyllite and quartzite, is resolved in numerous intricate details of diagenesis. Only one aspect is the chemical change and increasing crystallinity of clay minerals, from amorphous "clay" colloids and kaolin in the peat mire, to illite, chlorite and sericite near the transition to metamorphism (Bucher & Frey 2002).

Yet, the determination of coal rank and kerogen maturity provide a tool for highly accurate and high-resolution investigations of the thermal evolution of a basin and of the diagenetic grade of its components. Very low grade metamorphism begins approximately with the formation of meta-anthracite at $R_{max} > 4\%$, and the greenschist facies at $R_{max} > 5\%$ with semi-graphite and graphite.

Reflectance studies of disseminated coal particles and of kerogen in sediments are an important tool of petroleum and natural gas exploration. Already White (1935) had recognized that oil formation occurs mainly within a specific stage of diagenesis (the "oil window") that relates to coal rank. The oil window is confined between approximately 44 and 24% of volatile matter in coal, and 0.6 to 1.4% reflectance of vitrinite (Figure 6.4). Coal of higher rank is related to natural gas deposits (cf. Chapter 7.2 "The Origin of Petroleum and Natural Gas").

6.4 POST-DEPOSITIONAL CHANGES OF COAL SEAMS

After burial underneath siliciclastic sediments, peat is submitted to endogenetic alterations, foremost those of coalification. Meteoric and diagenetic fluids affect coal by epigenetic deposition of minerals in pores, joints (called cleats) and faults, raising ash content. Tectonic deformation of seams leaves structures that influence product quality and mining conditions. Exhumation and erosion expose coal to exogenetic alterations that reduce coal quality.

6.4.1 Tectonic deformation

Under tectonic strain, coal exhibits a more ductile response than its common siliciclastic host rocks. However, even peat and low-rank lignite may develop extensional fissures, which are intruded by liquefied mud and sand forming clastic dykes, probably caused by earthquakes. At higher rank, the ductility of coal promotes thinning and thickening of seams similar to marble bands in metamorphic rocks, and the injection of coal dykes into host rocks (Thomas 2002).

Brittle deformation of black coal at low temperature results in brecciation and mylonitization, yielding a fractured and powdery material. Shearing at elevated temperature causes structural adjustment, such as changes of the orientation of optical axes and locally increased coalification (Taylor *et al.* 1998).

Dense jointing (joints in coal are called *cleats*) is characteristic for black coal. Most lignites display no joints at all, just like their host rocks. In artifical outcrops (e.g. open pit walls), some intensely gelified lignites develop polygonal fractures soon after exposure, which are not tectonic but an effect of dehydration and shrinkage. Cleat systems of black coal form in response to tectonic stress. This is easily verified by the spatial and genetic relations to joints in host shales and sandstones. Spacing of joints depends on bed thickness and mechanical properties of rocks. The same is observed in coal, with a higher cleat density (lower spacing) in bright coal (vitrain) compared to dull coal (durain). Joints in siliceous wall rocks occur at even larger intervals. The orientation of cleats is skilfully exploited by miners for easier, that is less energy-consuming, extraction of the coal. Cleats (and many bedding planes in seams) are planes of mechanical separation. This is the reason why aperture and density of cleats (e.g. number per m) and the degree of penetration, or in other terms, their frequency, persistence and connectivity control properties such as gas flow, porosity, coal rock strength and grain size distribution of run-of-mine coal (Laubach *et al.* 1998). The careful documentation of cleat data is an important aspect of coal geological practice.

6.4.2 Epigenetic mineralization of coal seams

Coal cleats and other fractures may be coated by minerals such as carbonate, barite, clay, markasite, pyrite, galena, sphalerite (in the Illinois District), uraninite (in the western US) and quartz. This raises the ash content of coal. Rarely, exploitable veins were encountered. In the Ruhr District, Germany, veins with zinc and lead sulphides were commercially exploited until 1962. The base metal veins were hosted by faults cutting anticlines at right-angles, clearly indicating a late syntectonic (probably diagenetic) origin. Generally, hydrothermal ore deposits in coal are hardly ever of economic interest, although many mineralized coals are reported (Laznicka 1985). To the scientist, hydrothermal minerals in coal reveal properties of fluids, which migrated through the rock body, their relative and absolute timing, and the conditions of mineral precipitation (Daniels *et al.* 1994).

In contrast to black coal, peat and lignites are porous and reactive rocks that act as physicochemical traps for trace elements, which are transported with surface or groundwater. Potentially economic concentrations of vanadium, uranium and germanium were mentioned earlier. Laznicka (1985) reports coals anomalous in copper, gallium, molybdenum and nickel.

6.4.3 Exogenetic alteration of coal

Near-surface oxidation may induce self-ignition of seams and is the most common agent of reducing coal quality.

At the surface, sub-bituminous and bituminous coals alter to black, soot-like soft soil. Apart from solid residues of oxidation, reaction products include CO_2 and soluble organic matter (DOC – dissolved organic carbon: Chang & Berner 1999), which enters the groundwater. Lignites, however, rot and turn into humic soil constituents. The original thickness of the seam cannot be deduced from observations in the surface zone. In most settings, destructive weathering (supergene alteration zone I) only affects coal to a depth about equal to the saprolite zone of the regolith profile.

Below the first, a second zone of alteration leaves coal macroscopically intact. The seam displays its full thickness, and the coal is physically fresh. Only disseminated, or fracture-coating gypsum and other sulphates may be visible indicators of oxidation, but these often extend beyond degradation. The severe reduction of coal quality in this zone is only recognized by determination of calorific value and cokeability. Easily soluble sulphates are a nuisance for extraction and processing, and seepage water activates swelling clays in the seam, which cause additional problems. The vertical thickness of supergene alteration zone II is commonly several tens of metres.

Micropetrographical methods are not suited to map the extension of zone II, because vitrinite reflectance remains unchanged. Possible keys such as microfractures with higher reflecting rims occur only above an oxidation temperature of 150 °C (Taylor *et al.* 1998).

Meteoric seepage may reach hundreds of metres below the surface, as jointed seams behave as aquifers. This can be beneficial because infiltration initiates secondary microbial methanogenesis, enhancing gas production from Coal Bed Methane operations (c.f. Chapter 7.5 "Exploitation of Petroleum and Natural Gas Deposits").

Natural coal seam fires

Natural coal seam fires cause destruction of large panels of near-surface coal seams. In fact, the "fires" are rather smouldering sections with an activity that changes from hardly visible to quite dramatic. Ash and cinder are remains of burnt coal. Footwall rocks may be baked, but hanging wall shales are usually fired and sintered (cf. Chapter 3 "Clay and Clay Rocks"), and display attractive colours ranging from purple-violet through brick-red, orange, yellow to white. Very dense varieties are called *porcellanite* or *porcelain jasper*. Others resemble volcanic scoria. The fired clay rocks resist weathering and erosion so that long chains of hills mark the former presence of coal seams (Alberta, Colorado, North Dakota). Reduction of iron (by reaction with heated coal or with CO) causes widespread formation of magnetite (and some native iron), which facilitates aeromagnetic mapping of former seams, even under young cover.

Oxidation and self-ignition of coal is an exothermal process. The oxidation of pyrite produces 1546 kJ/mol and of coking coal 5176 kJ/mol (assuming a composition of $\sim C_{10}H_7O$), which results in heating. Coals rich in vitrinite and fusinite are especially vulnerable. Mylonitization multiplies the hazard, because a high internal surface favours reaction with oxygen. The thermal conductivity of coal is the smallest among all rocks (<0.50 [W/(m.K)] compared to 1.98 (shale) and 3.12 (sandstone) supporting heat accumulation. Usually, temperatures rise to 30–80 °C, but then drop off slowly, which may be due to: i) complete oxidation of all accessible surfaces; or ii) consumption of all available oxygen. Oxidizing coals with a high internal surface in contact with ample oxygen display continuing heating until self-ignition occurs at ~120–250 °C.

6.5 APPLICATIONS OF COAL GEOLOGY

> *An engineer, who has built a bridge, can strike you nearly dead with professional facts; the captain of a Ganges river steamer can, in one hour, tell legends sufficient to fill half a book, but a couple of days spent on, above and in a coal mine yields more mixed information than two engineers and three captains*
>
> Rudyard Kipling 1888

Practicians in the earth sciences serve the coal industry in the full cycle from exploration to extraction, environmental mitigation and mine closure, similar to other sectors of mining. However, some aspects of working in coal are specific, which is the motivation for this section.

6.5.1 Exploration

Exploration for buried coal seams is based on geological hypotheses that rely mainly on palaeogeography and facies distribution in space and time. Geophysical detection of coal at depth is only indirectly possible, for example by delineating bedding and structures utilizing methods such as seismic, gravity and magnetic surveys. At moderate depth, the low conductivity of coal may permit mapping by electrical methods. Oxidation of coal in the near-surface raises ground temperatures, allowing helicopter-mounted thermal (radiometric) mapping of coal seam outcrops. Soil gas analyses are a rarely used geochemical component of prospect exploration. Combined with geological outcrop mapping, facies models and geophysical data justify the design of a reconnaissance drilling grid. From the early planning stages through detailed exploration to coal extraction, geological, engineering and environmental perspectives must be equally considered (Bartlett *et al.* 2009).

Geological and geophysical indications allow no more than estimates of prognostic resources. Definition of identified resources requires quantitative data such as depth, thickness, structures and quality of coal. Defining measured resources implies drilling (Figure 6.24), supplemented by physical exposure and sampling of coal in deep trenches or underground exploration drifts. The distance between drilling sites may be based on geostatistics of nearby mining fields. If such data are unavailable, a relatively wide grid is initially chosen, which is filled in as the need arises. In the Latrobe Valley brown coal, initial drillholes were spaced at 1 to 2 km distance; mining reserves are defined by a 400 m drilling grid (Waghorne 2001). Continuous geostatistical control assures that an optimal solution is found as soon as possible (Figure 5.16; Saikia & Sarkar 2006).

In black coal regions with simple large-scale structure, such as the western margin of the Late Palaeozoic Bowen Basin, Queensland, Australia, drillhole spacings of 1 to 2 km are sufficient for the first phase of exploring underground mining resources. Reserve drilling at the Burton Downs Mine was initially laid out in the form of profiles

Figure 6.24 Truck-mounted drill rig, here employed in coal exploration in the Sydney basin, New South Wales, Australia. Courtesy of Keith Bartlett, Minarco-Mineconsult, Tuggerah, NSW.

across the strike of the seam at a 100 m distance, with intervals along the profiles of 50 m. Geostatistical variography soon demonstrated that the lateral homogeneity of the deposit allows a separation between profiles of 400 m. Considerable reduction of costs was the consequence. Note, however, that actual extraction of the coal at Burton (and elsewhere) is increasingly assisted by detailed three-dimensional seismic imaging of faults, unstable roof conditions and gas accumulations in advance of longwalls (Walton *et al*. 2000).

Core drilling (commonly using slimline 63.5 mm diameter) is advisable in all reconnaissance work, because the wealth of data that can be extracted from the core, such as lithology, stratigraphy, facies, spatial orientation, tectonic deformation, hydrogeological and geotechnical properties, justifies the higher costs (Figure 6.25). Subsequent infill drilling may employ down-the-hole hammers (DTH) or other percussion technologies through overburden, but should change to coring near the seam. A near 100% recovery of core in coal must be aspired. Because friable parts of the seam are easily lost during coring, triple-tube core barrels may be needed. Aluminium or plastic liners protect the samples from damages during removal from the barrel and later handling. After logging, e.g. brightness and inorganic partings, the containers are sealed in order to guard the coal from oxidation and desiccation, but allow X-ray radiography of the core samples with no additional manipulation. X-ray radiography is preferable to photographs, because it provides clear images of the distribution of minerals (ash) in the coal.

Geophysical borehole logging is commonly applied in order to provide *in-situ* control of seam boundaries and depth information reported by the drilling team, and data such as water and ash content. Frequently, radiometric, density and electrical methods are employed (Figure 5.8). Infill percussion (DTH) holes are routinely surveyed by geophysical borehole logs (Fullagar 2000). Recently, acoustic scanning technology emerged as an important wireline tool for investigating the orientation of joints, fractures and borehole breakout, which is a proxy revealing the horizontal stress direction (Bartlett & Edwards 2009). In mechanized underground mining and coal seam gas projects, for example, this is vital information.

Samples of coal, especially of lignite and brown coal are prone to desiccation and must be protected. Cool storage of low rank coals prevents the growth of fungi and bacterial attack. However, the only guarantee of long-term preservation of initial properties is coal sample storage under argon immersion. For petrographical and technological sampling, cores are split or sawed in half

Figure 6.25 Slimline (HQ) drill core section of Permian Wallarah-Great Northern coal seam in the Sydney basin, New South Wales, Australia. Courtesy of Keith Bartlett, Minarco-Mineconsult, Tuggerah, NSW. Light shales in the footwall (foreground right) grade into bedded coal which is overlain by matrix-supported roof conglomerate (back, left). Figures marked in white on core denote brightness.

parallel to the core axis. One half is archived for eventual later requirements. Samples of the seam's immediate wall rocks are often needed for geomechanical investigations and must be as carefully preserved as the coal. In all cases, the needs of the hydrogeologist and the geotechnical engineer for data must be accounted for (cf. 5.2 "Trenching and Drilling").

Worldwide, **exploration for coal bed methane** (CBM), also called coal seam gas (CSG), is a rapidly growing field in the quest for energy. In principle, data on geology and volume of seams, and the properties of coal are required for an estimate of potential gas *in situ*. Rank, macerals, lithotype and moisture content are main controls on the methane adsorption capacity of coal and must be determined. In bituminous coals of the Pennsylvanian Weibei Coalfield, Ordos Basin, China, for example, the adsorption capacity (on a dry and ash-free basis) varies from 14 to 30 m^3/t but gas *in situ* is $<15\ m^3/t$ (Yanbin Yao *et al.* 2009). The permeability of these coals is between 0.1 and 10 mD and the porosity ranges from 2 to 7%. The authors combine regional data on seam thickness, gas content, coal rank, methane concentration, permeability, porosity, burial depth and deformation pattern to define targets for detailed investigations.

6.5.2 Reserve estimation

Geological coal resources and exploitable reserves are estimated and classified with the same methods that are stipulated for other solid minerals (e.g. JORC-Code: AusIMM 2004, cf. Chapter 5.3.2 "Ore Reserve Estimation and Determination of Grade"). Geological certainty and economic viability are the most important parameters.

The economic viability of a coal deposit is a function of: i) the geological situation; ii) coal quality; and iii) technical and economic conditions (the "modifying factors"). Geological situation and coal quality are objective determinants and independent of time. They include the geometry of the deposit, as well as geomechanical, hydrogeological, geochemical and geothermal parameters. The modifying factors are time-dependent and prone to change, for example by new technologies in mining, processing and utilization, and by new factors in economy, markets, law, environmental regulations, society and politics (Kininmonth & Baafi 2009, Waghorne 2001). Reserve estimates only conform to international standards if the modifying factors are accounted for. This is the main reason why coal reserves decrease consistently (Figure 6.1), whereas those of other minerals hardly change, as ever more coal producers adopt international bankable reporting standards.

Coal reserve estimation incorporates several distinct features. Unlike black coal, low rank coal (lignite and brown coal), for example, is hardly ever traded. Low energy (6–16 MJ/kg) and high water content (>30%) of run-of-mine coal preclude transport to any distance from the mine. Mines are usually linked to adjacent captive power stations, which are specifically designed for each deposit (Figure 5.18). In addition, low rank coal is hardly ever upgraded by processing. The consequence is that the feasibility of mining combined with electricity production must be demonstrated for a reserve. Utmost diligence must be used to determine the *in-situ* density, moisture and ash content, because this defines coal delivered to the power plant. Even then, small deviations are still to be expected: In the Latrobe Valley (Figure 6.12), run-of-mine coal is typically 1% higher in ash and 1% lower in moisture than indicated by drilling (Waghorne 2001). Certain variations of the coal quality, due to lateral or vertical facies change of the seam, may be unacceptable for the power station. If this cannot be mitigated by blending from different faces, such coal is not included in reserves. The overall economy of a lignite mine cannot be established by reference to a market. The only available economic measure is the price of electricity and its competitiveness. Resources and reserves need to be extensive, because amortization of power plants is measured in decades.

Higher-rank bituminous coal resource estimates are based on determination of the volume and *in-situ* bulk density at *in-situ* moisture of the coal (Lipton 2001). Large-diameter (100–200 mm) drilling provides advance samples for determination of additional important properties, such as washability and coal fragmentation (Figure 6.26). As soon as possible, semi-industrial scale bulk

Figure 6.26 Large diameter core (200 mm diameter) is drilled for quantifying technological parameters of coal such as fragmentation and washability. Courtesy of Keith Bartlett, Minarco-Mineconsult, Tuggerah, NSW.

samples are acquired by trial box cuts and underground work. Oxidized parts must be outlined and clearly separated from unaltered coal. High-rank coal seams occur typically at an inclination to the horizontal. Therefore, the volume is best calculated from true thickness and true area of the seam. High ash plies or partings can be included or excluded, but consistency is vital. Dilution during mining (e.g. from hanging wall, footwall, partings, longwall edges) increases the tonnage, but mining losses decrease it. Black coal is typically crushed and washed, or submitted to density separation in order to lower ash content. Certain grain fractions of traded coal command higher prices. An optimum grain size distribution of the saleable product demands care from extraction and through processing. These are only some of the points that have to be considered when estimating *in-situ* tonnages and marketable products.

Present mining technologies pose a lower limit to the extractable thickness of black coal seams. Cut-off thickness may be ~50 cm in an opencast mine, and 100 cm for underground mining. Also, costs preclude coal mining at great depth. Northern Germany's indicated coal resources at <1500 m depth comprise ~25,000 Mt; extraction to this depth is technically feasible, although not economically competitive. Very deep coal (>1500 m) in Northern Germany is estimated to total ~350,000 Mt. Similar relations are known from many regions of the world.

Motivated by this situation, the potentially elegant method of ***in-situ* coal gasification** was examined by numerous research projects in the past, although with moderate success. The principle is to drill holes into a coal seam, pump in air and steam, ignite the coal so that gasification starts and extract the gas produced ("syngas"). Today, directional drilling is envisaged in order to divide a seam into panels (600 × 30 m) that allow better control of the process. The recovery of the energy inherent in coal is estimated as between 50 and 80%. Trial runs in the Surat Basin, Australia (2008), support hopes that this technology may finally reach profitability. Giant tonnages of deep, currently unmineable coal might be converted into profitable resources.

6.5.3 Coal mining geology

All available geological information is collected in a database, which is the foundation for a three-dimensional geological deposit model. Basic datasets include spatial information, coal rank, *in-situ* heat, moisture, ash and methane content, bulk density and the spatial orientation of cleats. Maps displaying contour lines of seam floors and isolines of seam thickness, and sections illustrating spatial geometry of stratigraphy, bedding planes and structures, assist in communicating the model. Hydrogeological and geomechanical information is integrated. Much of this work can be done in Geographic Information System (GIS) space, but dedicated specialized programmes allow integrated mine planning and scheduling. Note that the geological model must be validated by a competent person (cf. Chapter 5.3 "Ore Reserve Estimation and Determination of Grade").

In multi-seam deposits, the correlation of individual seams is crucial for the accuracy of the geological model. Only a correct correlation truly supports reserve estimates and mine planning. Modern underground mining technology and future automated mining methods require reasonably constant conditions. Severe production loss is hardly avoidable if longwall faces run unprepared into faults, erosion channels or magmatic dykes. Supporting geology, high-resolution seismic and tomographic methods are routinely employed to investigate and image the seam in front of the advancing face.

Methane and CO_2 content in coal and host rocks of a deposit are spatially varied. The gas distribution must be documented in order to assist mine planning. Gas is, of course, a security risk (Hargraves 1997), but also a major cost factor, because the necessary precautions such as higher air flow and gas drainage drillholes make extraction more expensive. Methane in mine return air should always be used, by burning in a power station or in a fuel cell unit. Apart from methane gas explosions, instantaneous coal outbursts are a deadly danger in many deep black coal mines. *Coal outbursts* are violent and spontaneous ejections of powdered coal and gas from the working coal face (Guan *et al.* 2009). They may be followed by methane explosions. The mechanism of coal outbursts is similar to other gas-driven solid eruptions (e.g. of magma, salt and other rocks) insofar as high internal gas pressure is released into expansion and fragmentation when external confining pressure is suddenly removed (Guan *et al.* 2009).

In most lignite and coal mining districts, **hydrogeological modelling** is an absolutely essential component of investigations, from prefeasibility studies to mine closure. Commonly, host rocks of coal include aquifers that enforce dewatering in order to avoid water inrushes and unstable ground conditions. Appropriate dewatering studies are highly critical (Brown 2010). Drawdown cones may be very wide and affect whole basins, with the consequence that regional water management is required (Kumar *et al.* 2010).

Geotechnical investigations of coal and host rocks (Hoek & Brown 2003, Terzaghi *et al.* 1996) are needed to design mine openings sufficiently safe but at lowest cost. In opencasts, this is mainly a question of pit slope angles. In underground mining, sections of rock mass quality below average must be identified in order to minimize the hazard for personnel, as well as costs. Often, seepage water raises fluid pressure (u) and reduces shear resistance (Figure 1.39; Brady & Brown 2004). Underground longwall operations should be oriented in a way as to minimize the hazard of spalling caused by joints, fractures and horizontal stress (Bartlett & Edwards 2009).

Underground extraction of coal causes subsidence that may induce lowering of the surface, open fractures and damage to buildings and infrastructure. Earth falls or slope instability can be triggered. Often, the pre-mining surface water regime is fundamentally changed. Abstraction of coal causes various reactions to the newly opened void (Figure 6.26). In the immediate hanging wall of the extracted coal, the rocks fracture and a loosened destressed zone develops to a certain height above the seam. Broken roof strata loosely fill the goaf (Zone 1). At a higher level, subsidence is enacted rather by bending than fracturing, and the rock mass is little disturbed (Zone 2). On the surface, extensional fracturing and faulting may occur. As the extraction front passes underneath buildings or infrastructure, induced strain is initially tensile followed by compressive deformation (Zone 3). For a stringent geomechanical analysis, refer to Brady & Brown (2004).

The total subsidence of the surface may reach 80% of the coal thickness extracted, mainly as a function of nature and thickness of the overburden. Duration of subsidence and surface extent of mining influence are controlled by several factors. which include the geomechanical properties of the overburden rock mass. The limits can be defined by an experimental angle α drawn from the edge of the underground void (Figure 6.27). Thick competent sandstones in the hanging wall above the seam may inhibit loosening and caving in zone (1). A possible consequence is the accumulation of stresses over a wider area, which are suddenly released when the strength of the rock mass is exceeded. The resulting shockwaves may cause damage in the surroundings (e.g. an earthquake of magnitude 4 in the Saar Province, Germany, in 2007). In mining practice, preventive counter measures such as filling the goaf with tailings are taken in order to minimize subsidence, hazard and damages.

6.5.4 Environmental aspects of coal mining

Black coal, green future...

Materials World 2003

Already during reconnaissance exploration, the influence of future mining on landscape, water and humans should be considered in order to avoid investing in sensitive areas. When entering the phase of detailed exploration, a preliminary environmental impact study should be done in order to design and install all required monitoring systems, such as groundwater wells and surface water discharge weirs. Studies of rare species are advisable. For the definition of reserves, large datasets must be acquired, including coal chemistry.

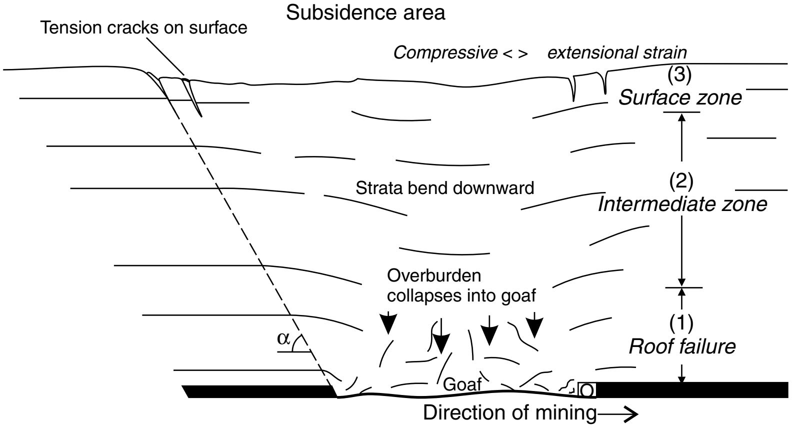


Figure 6.27 Underground longwall extraction of a coal seam panel causes surface subsidence (adapted from Ward 1984). Three affected depth zones are distinguished: (1) Loosened and destressed rock mass falls into the goaf, (2) zone of intermediate ductile deformation and (3) zone of surficial fracturing and damage by the "strain wave" passing from tension to compression. Angle α describes the width of mining influence. The square with the inscribed O is the longwall opening.

Standard coal quality is described by proximate analyses (ash, moisture, volatile matter and fixed carbon by difference), ultimate analyses (C, H, N, S, ash and O by difference), calorific values and sulphur forms. This allows estimating the potential atmospheric emissions of sulphur, carbon and nitrogen, and the potential contribution of these elements to environmental problems and global climate change. For environmental impact studies, properties including major, minor and trace element concentrations, modes of occurrence of environmentally sensitive elements, cleanability, mineralogy, organic chemistry, petrography and leachability, should be determined (Finkelman & Gross 1999). Trace element analyses of coal are the base for mitigation measures in the power station where the coal is combusted (Finkelman *et al.* 2002). Critical elements specified as hazardous air pollutants (HAPs) by the US Clean Air Act (1990) are As, Be, Cd, Cl, Cr, Co, F, Hg, Mn, Ni, Pb, Sb, Se and U. One example is mercury emissions from coal-fired power plants in the United States, which in 2004 amounted to 48 tonnes. Novel scrubber technologies similar to those used for SO_2 control are installed to alleviate this problem.

Operating coal mines

Lowering water tables by pumping, both in underground mines and in open pits (Figure 6.28), enforces discharge of large amounts of water into nearby streams. This may induce unwanted degradation of water quality (e.g. pH, total dissolved solids, iron, manganese, sulphate and trace metals such as Se). Treatment of the lifted groundwater is commonly required. Undisturbed coal seams normally act as weakly permeable aquitards; the permeability of host rocks depends on their nature, degree of consolidation and the characteristics of joint systems. Coal mine water is typically characterized by low pH and high content of Fe(II) or Fe(III), suspended particles, SO_4^{2-} (from pyrite oxidation), Cl^- (from formation or geothermal waters) and in the absence of sulphate, elevated content of Ba, Sr and Ra. When such water is mixed with common surface water, "radiobarite" is

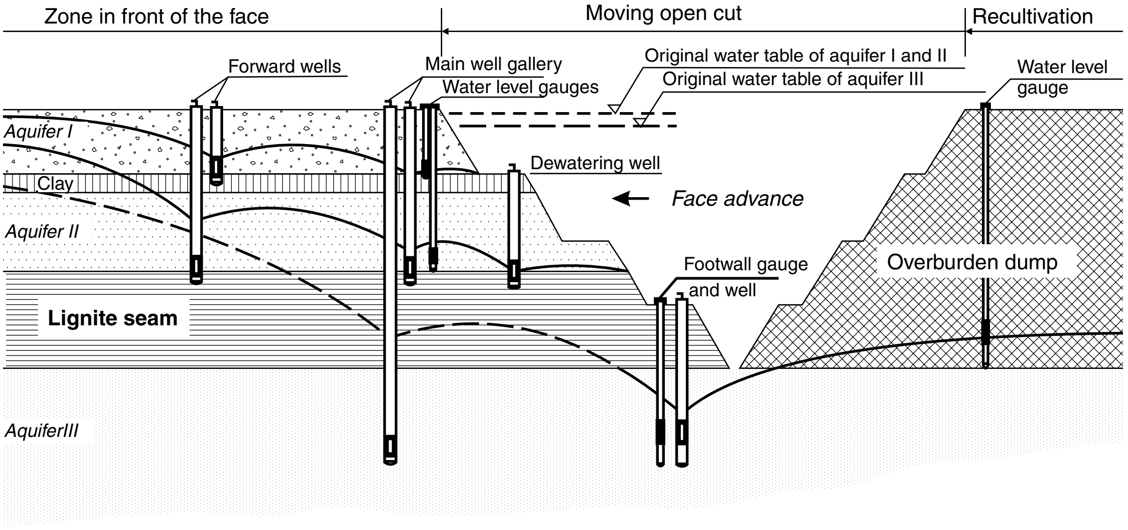


Figure 6.28 Schematic illustration of water management in a lignite open pit (not to scale). Aquifers I to III consist of poorly consolidated sand and gravels. In front of the advancing open cut, water tables are lowered by well screens, in order to minimize inflow into the pit and to stabilize pit slopes. Below the bottom of the pit, water pressure is reduced to avoid inrush of water or of liquefied sand. Water level gauges are for control, and alert in the case of rapid rise.

precipitated, which may be an environmental problem (Schmid & Wiegand 2003). In Silesia, Poland, radium concentrations reach a maximum of 390 kBq/m^3, but Ra is precipitated underground by reaction with phosphogypsum before the water is evacuated. The acid formation potential of waste rock and overburden destined for surface disposal must be investigated (Verburg *et al.* 2009). Any hazardous material is covered with standing water or with clay in order to prevent contact with oxygen.

As a greenhouse gas in the atmosphere, methane is 21 to 70 times more potent than CO_2 (depending on how the comparison is made). Conventionally, methane mixed with return ventilation air (VAM) was released into the atmosphere. In the recent past, VAM represented ~10% of all anthropogenic emissions of methane and 60 to 70% of all greenhouse gas emissions from underground mines. After agriculture, black coal mining was the largest human source of CH_4, followed by household refuse dumps. Today, the small concentrations of methane in ventilation air (0.2–1.2%) are combusted in mine-site power stations, for example in Australia, together with coal shale or with impure coal. Gasification of VAM with coal processing waste offers the greatest efficiency of energy production and the lowest environmental footprint (Clarke 2010). Mine methane that cannot be used must be burnt, because conversion to CO_2 lowers the greenhouse effect.

Nearly all coal mines move large masses (Figure 6.29) that must be transported, temporarily stored or ultimately disposed of, including coal, overburden, waste rock and processing sludges. This offers numerous possibilities to raise environmental compatibility, not least by well-planned recultivation (Richards *et al.* 1993). Landscaping and recultivation must be carried out as far as possible during mining when large earth-moving machinery is available. Of course, renaturation of artificial ponds, streams and barren land should also be considered, because spontaneous invasion of species often provides much higher ecological value.

The burning of coal produces a considerable mass of combustion residues, including fly-ash, boiler bottom ash and slag, and flue-gas desulphurization sludge including gypsum. Disposal of these materials requires well-planned strategies. Their possible environmental impact has to be carefully considered, not least because they concentrate potentially hazardous trace elements of the coal (Huggins & Goodarzi 2009). As far as feasible, the residues should be utilized, for example as cement raw materials and construction aggregates in the building industry (in America currently ~37% of the total coal mining waste). This preserves limited resources of sand and gravel, and saves energy. Combustion residues that cannot be marketed are buried in exhausted opencast mines and surface impoundments (58%), and only 5% are backfilled in underground coal mines. The latter procedure improves the stability of mine openings (Michalski & Gray 2001), reduces surface subsidence (Brady & Brown 2003) and is an important option in mine reclamation. Because coal ash is highly alkaline, it is

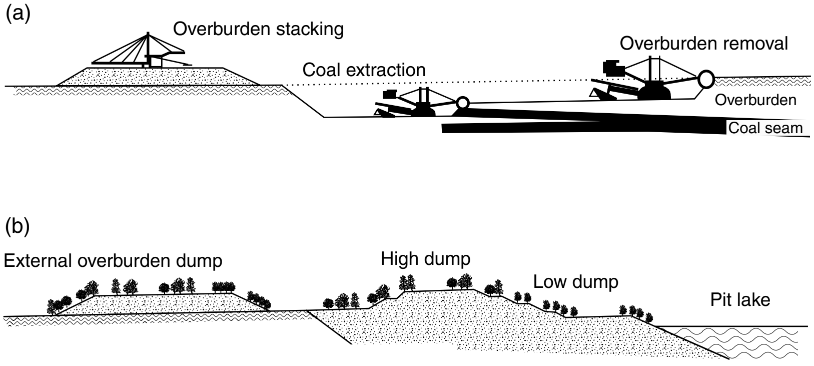


Figure 6.29 Lignite open pit in operation (upper section) and after landscaping, recultivation and rebound of groundwater levels (lower section).

Figure 6.30 (Plate 6.30) Post-mining lignite open pit lakes in the Lausitz region, Germany, in the last stages of filling and rehabilitation. Courtesy of P. Radke, © LMBV, Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH.

suitable for treatment or prevention of acid mine water generation (Canty & Everett 2006).

Closure of coal mines and remediation

Considerable investments are needed in order to avoid post-mining environmental damage. Main hazards include chemically (pyrite, markasite) or mechanically unstable overburden tips and processing sludge dams, coal fires in dumps or residual coal *in situ*, rising groundwater levels, outflow of methane and carbon dioxide, and of acid mine water with a high iron concentration (Younger 2002, Bell 1998). Best practices and technologies related to sulphide mineral oxidation, acid mine drainage and metal leaching are described in the online *GARD Guide* (Verburg *et al.* 2009). The severe reduction of coal mining in Europe within the last decades left many exemplarily remediated sites, but unfortunately, also a large number of brown fields, which still await action.

Underground openings of historic shallow mining can be prone to sudden collapse. Where maps are insufficient, ground geophysics or airborne remote sensing methods are used for localization. LIDAR (Light Detection And Ranging) is employed to create high-resolution digital elevation models (DEM), which illuminate slight depressions that develop above voids.

Rising groundwater levels after cessation of pumping might be considered a blessing, but in some coal mining districts surface subsidence accumulated to an extent that large areas were flooded, if nature would be allowed to take over. Although the resulting wetlands might be an ecologist's dream, densely populated countries cannot afford the loss of land and settlements. Water management by pumping may be the only long-term solution. Another potentially damaging effect of rising groundwater is uplift of land, which is mainly due to buoyancy forces (Terzaghi *et al.* 1996, Brady & Brown 2004).

Spoil heaps that have been built in the past from tailings of less efficient coal washing plants can today be a source of revenue by "tip washing" (i.e. recovery of remaining coal). Because this type of land cannot be developed before the coal is cleaned out (considering the threat of self-ignition) and the surface is levelled, tip washing by modern plants is an important step towards restoration.

Coal mine fires

Outcropping coal seams burned naturally in the geological past (e.g. in the Pliocene of the Powder River basin, USA: Heffern & Coates 2004). Today, thousands of coal mine fires are burning on abandoned mine lands throughout the world (Stracher 2004, 2007). They threaten the health and safety of local populations, destroy property values and consume a non-renewable resource. In abandoned mines, fires started by self-ignition or by human action may be unnoticed for many years, until fumes and collapse holes become a threat to nearby residents. In the Permian coal fields of Bihar in India, $\sim$2000 km^2 of land and one million people are endangered by underground fires (Michalski & Gray 2001). Some of the fires have been burning since 1916. Remediation would be possible, but the costs are prohibitive. Burning coal can only be extinguished by airtight sealing, whether in a mine, on coal dumps or in natural outcrops. Mitigation technologies include total excavation, trenching, flooding and quenching, bulk filling of mine workings, saturation grouting, surface seals, inert gas injection and chemical foams. Fubao Zhou *et al*. (2006) report successful extinction of a mine fire by borehole injection of a foam made of water, clay and nitrogen. Quenching with water alone is not possible.

Opencast lakes (Figure 6.29, Figure/Plate 6.30)

Closure involves cleaning up and shaping the interior of the pit, foremost the slopes. The stability safety margin acceptable for a mining operation is commonly not sufficient for post-mining use. In fact, the changing hydraulic regime may bring about large landslides. Many pits fill by natural groundwater inflow, which in others is supplemented with water from nearby streams. The latter is chosen in order to avoid a long period of slope weathering and acid formation, and to top up water quickly with inflow of an acceptable quality. Additional technical measures may be necessary, for example neutralization of low-pH lake water by coal ash (Loop *et al*. 2003). Well-planned pit lakes are often an enrichment of the landscape and provide refuges for nature as well as benefits to the people. Very instructive examples can be studied in all German lignite mining districts.

Post-closure uses

Recultivated land is assigned to forestry and agriculture. Brown fields may be valuable sites for other industries. Closed deep coal mines can be utilized for the storage of natural gas. Moderately toxic waste, such as fly and bottom ash from coal-fired power stations, is very suitable as a stabilizing fill of underground mine openings (Wendland & Himmelsbach 2002). CO_2 sequestration in deep coal mines is considered. Deep water-filled workings of former coal mines may provide abundant cheap geothermal energy (see below).

Gas seepage

(CH_4, CO_2) from closed coal mines is not rare, especially during the period of flooding after closure. The main hazard is accumulation of gas in buildings. Falling barometric air pressure causes expansion of gas in the mine, which can result in overflow. Mitigation methods include filling of near-surface mine openings and sealing by injections, if needed. Methane should never be released into the atmosphere but must be used. A pilot plant in Ohio, USA, demonstrates burning methane from a closed mine in a fuel cell for electricity production. Note that methane seepage (containing traces of ethane and propane) from the ground is a widespread natural process; with 42–64 Tg/year, geological sources such as petroleum and coal basins are second only after wetlands (Etiope & Ciccioli 2009).

Geothermal use of mine water

This is an economically alluring option for heating and cooling buildings based on heat pump systems (Watzlaf & Ackman 2006). Flooded coal mines are particularly suitable because of their broad-based accessibility. Coal seams are commonly mined over large areas, so that the warm water filling mine tunnels, collapsed longwall voids and loosened rock can be pumped from wide-spaced boreholes. The large contact surface between water and rocks increases the sustainability of heat exchange. Various designs of heat extraction are possible, for example closed loop systems (cycling a refrigerant fluid contained in thin-walled pipes through a water-filled shaft) and open-loop systems (pumping water from the mine and re-injecting it through a second well). Flooded parts of the Pittsburgh coal seam in the northern Appalachian coal basin of the United States might potentially heat and cool hundreds of thousands of homes (Watzlaf & Ackman 2006).

6.6 SUMMARY AND FURTHER READING

Coal supplies a third of the world's primary energy consumption, especially base load electricity, and is an important fuel and reductant in many industries. It is the foundation of the present rapid development of China, India and other nations. In that role it is a blessing, yet coal is highly controversial because most mines are very large and profoundly alter the land and adjacent communities. Burning coal contributes to anthropogenic carbon dioxide emissions (Box 6.1). Coal resources and reserves are very large and can support humanity for hundreds of years. Acceptance of continuing coal mining and combustion, however, depends on minimizing emissions and negative environmental effects. Progress is already made but critics expect faster action. Several elegant solutions are investigated, ranging from carbon dioxide capture and geological sequestration to *in-situ* gasification.

Coals are solid, combustible, fossil sedimentary rocks formed from land plants profusely growing in ancient wetlands. Early (biochemical) and late diagenetic (geochemical) processes enriched carbon and produced the coalification array, which reflects a continuous evolution of properties such as colour, transparency, reflectance, molecular structure, specific density, calorific value, organic chemistry, elemental composition, moisture content and many other parameters. Coal rank increases from lignite to bituminous coal and anthracite; the transition to graphite marks the boundary to metamorphism.

The chemical composition of coal is determined by its derivation from plants and comprises carbon, hydrogen and oxygen, with nitrogen and sulphur as minor components. Low-rank bituminous coal can be characterized by the "formula" $C_{10}H_7O$. During diagenesis, carbon increases from ~60 to 90% C, whereas hydrogen decreases from 5.5 to <3%. This is due to the release of a large volume of methane (CH_4). Part of the methane remains absorbed in the coal, where it is a bane for underground miners as "fire damp", but a favourable resource for gas producers as coal bed methane (CBM). Most gas migrates towards the surface, acting as a powerful greenhouse gas in the atmosphere. A small part is trapped in the crust and forms many of the world's giant natural gas deposits.

Climate is an essential control on peat-forming plant communities and consequently, coal seams are terrestrial climate archives. At the same time, however, wetlands are prime factors of climate regulation by the fixation of carbon in peat and coal. The characteristic alternating dark and light bands of many lignites, and the repetitive sequences of host sediments that have been called "cyclothems" in black coal districts might be controlled by: i) eustatic forcing of sea levels; or ii) tectonic impulses. The first is probably the general background to occasional interference of the second. Presently, eustatic glacial forcing is attributed to orbital control of sea levels and climate, modulated by greenhouse gas control. With a better understanding of palaeoclimate, the influence of other climate-forcing processes will certainly be revealed.

At geological time-scales, coal formation is restricted to the last 10% of earth history. Earliest exploitable coal deposits date from the Late Devonian (ca. 370 Ma) of the Arctic realm, with fossils of genus *Archaeopteris* representing the first tall trees. In the Late Carboniferous (Pennsylvanian) of the Northern Hemisphere, coal was formed in extensive tropical coastal swamp forests of *Sigillaria* and *Lepidodendron*. The giant Permian coal deposits of the Southern Hemisphere with their boreal *Gangamopteris-Glossopteris* flora originated at high latitudes in a cool and humid climate. In both hemispheres, coal formation is intimately controlled by continental glaciation lasting from 326 to 267 Ma.

Coalification is preceded by humification of peat, which is a limited oxidation of lignin, cellulose and proteins by microbiota feeding on plant matter. Humins evolve during diagenetic coalification by increasing aromatization, condensation and clustering. Rank of lignites and sub-bituminous coals is measured by water content. Volatile matter yield differentiates between higher grade black coals. The standard method of precise rank determination is reflectance. Temperature, heat flow and duration of heating are controls of coalification. The process can be modelled applying the Arrhenius equation, which describes the kinetics of an endothermic chemical reaction. Results indicate that typical coalification temperatures are $\sim$50–200 °C (sub-bituminous and bituminous coal). Anthracite is formed at 200–300 °C.

Technologies in applied coal geology, coal mining and environmental mitigation are in a phase of revolutionary change. Because of the size of the industry, the impact of coal extraction and use affects large regions. Pioneers in the industry already approach the ideals of green mining but the bulk trails behind. Let us not forget that investments in green mining raise costs that have to be recovered from the electricity market. Clear national and international regulations are the precondition for industry to broadly invest in carbon capture and sequestration (Box 6.1), calling for governments to agree on actions. Let them act in such a way, however, as not to block human inventiveness in overcoming obstacles.

For a synopsis of the geological diversity of 13 world-scale coal mining districts, I recommend the volume edited by Cross (1993). As an insight into the present state of industrial practice, the book by Kininmonth & Baafi (2009) is singularly valuable. Beerling (2007), a climate scientist, recounts in a lively scientific style *How Plants Changed Earth's History*. Freese's (2003) *Coal, a Human History* is a very readable historical account of the significance of coal for economic development by fuelling the Industrial Revolution, which started in 18th-century England, its social impact and further fate until today's preoccupation with carbon dioxide.