

CHAPTER 1

Coal Formation and the Origin of Coal Fires

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Evidence for an underground coal-mine fire in Renton, Pennsylvania includes this sinkhole and the anomalous snow melt, smoke, and fumes. As pillars of coal that support the roof of an underground mine burn, the roof collapses, forming a sinkhole visible at the surface. *Photo: US Bureau of Mines, 1985.*

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1.1. The Formation of Coal

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Coal seam (photo center) exposed in the New River Gorge, West Virginia.

Photo: National Park Service, <http://nps.gov/neri/NatureScience/geologicformations.htm>

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Introduction

p0030

Coal formation has been described as “an inefficiency in the carbon cycle,” (Barghoorn, 1952) when carbon from plants remains in terrestrial sediments and is not recycled to the atmosphere (Figure 1.1.1). Coal is, by definition, a readily combustible rock containing more than 50% by weight and 70% by volume of carbonaceous material (Schopf, 1966). Another definition describes coal as a combustible solid, usually stratified, which originated from the accumulation, burial, and compaction of partially decomposed vegetation in previous geologic ages (Hendricks, 1945).

p0040

Coal has been used for over 3000 years, in China, in Bronze Age Europe, and by Plains Indians in America (Cassidy, 1973). During the Middle Ages, coal use became more common, for forges, kilns, and breweries, as well as domestic heating (EIA, 2002). In 1306, King Edward issued a royal decree banning the use of coal in London, but the ban was ineffective because charcoal made from wood was in short supply. The development of brick chimneys 100 years later alleviated the problem to some extent (Hessley et al., 1986). In the United States, wood was the primary fuel used by the colonists. It was abundant and relatively easy to obtain. In 1850, coal was used to fuel the steam engine and became the principal source of energy until 1950 when it was surpassed by petroleum for use in automobiles and by natural gas for home heating (Figure 1.1.2). Since 1984, coal has produced about one third of the energy consumed in the United States (EIA, 2002). And 92% of the coal mined in the United States is used to produce over 50% of our electricity (EIA, 2006). Projections by the US Department of Energy indicate that coal consumption will continue to increase as demand for electricity increases (EIA, 2008).

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As of 2005, world coal consumption was 5883 million mt (metric tons) of which China consumed 2339 million mt, the United States—1086 million mt, and India—493 million mt (EIA, 2008). World coal consumption is projected to grow by 2.5% per year to 9583 million mt (EIA, 2006). In spite of the environmental problems associated with coal mining and coal use (acid mine drainage, coal fires, greenhouse gas emission, air pollution, etc.), it seems that coal will continue to be a major source of energy for the foreseeable future.

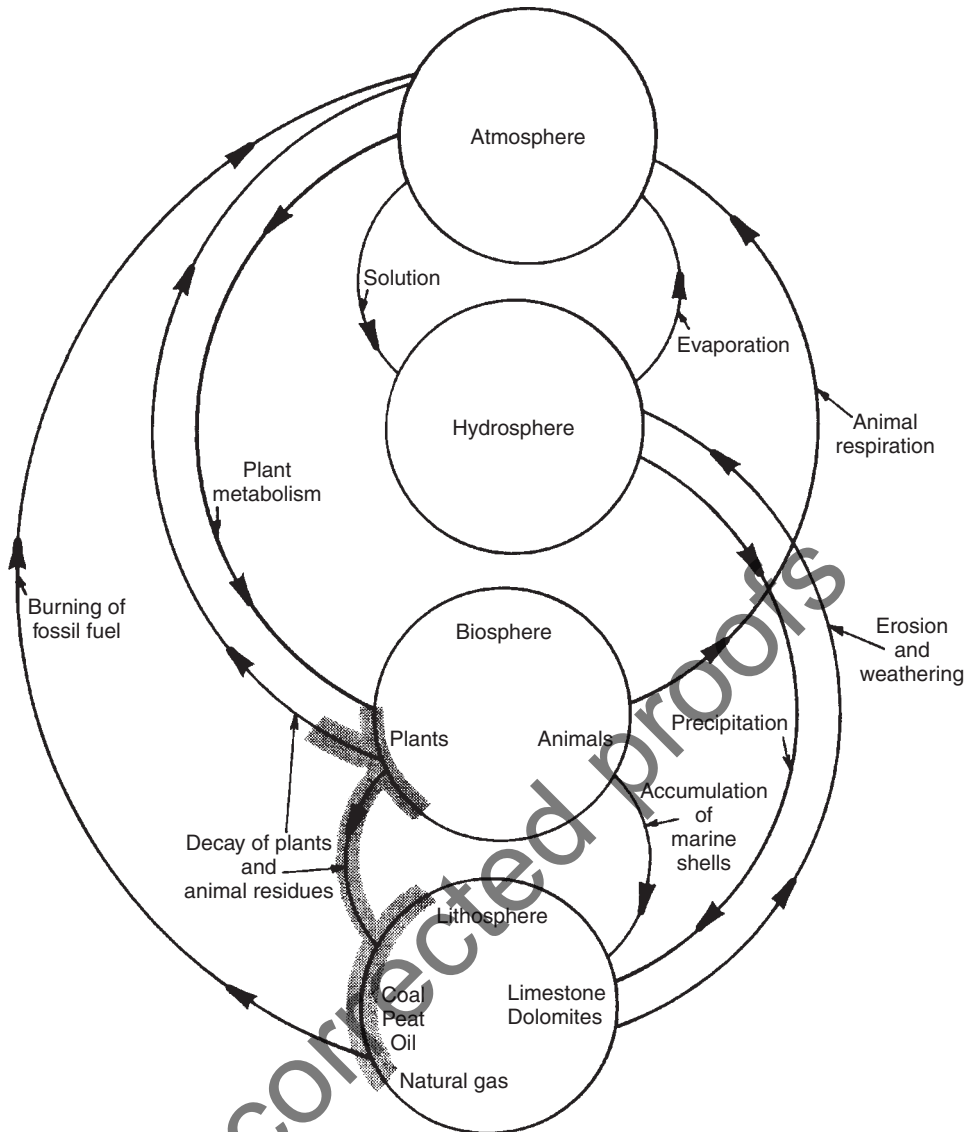


Figure 1.1.1. The carbon cycle. From Kim and Kissell 1988, p. 18.

Geologic Distribution of Coal Seams

Although coal deposits are known to have formed in every geologic period, the development of land plants in the Silurian and Devonian provided source material for peat and coal. The periods of greatest coal formation were the Carboniferous and the Cretaceous/Tertiary (Cooper and Murchison, 1969; van Krevelen, 1963).

Carboniferous Coals

The formation of coal deposits required abundant plant material, a suitable climate, areas for accumulating peat and means of preserving the carbonaceous sediment. These conditions were prevalent over large areas during the Carboniferous (Pennsylvanian in the United States) period. During this period, large areas of what is now the Eastern USA, Europe, Asia, and Australia were located near the equator and had a climate that was tropical to subtropical with mild temperatures, high humidity and heavy rainfall, without cold winters, or extended dry periods (White, 1925).

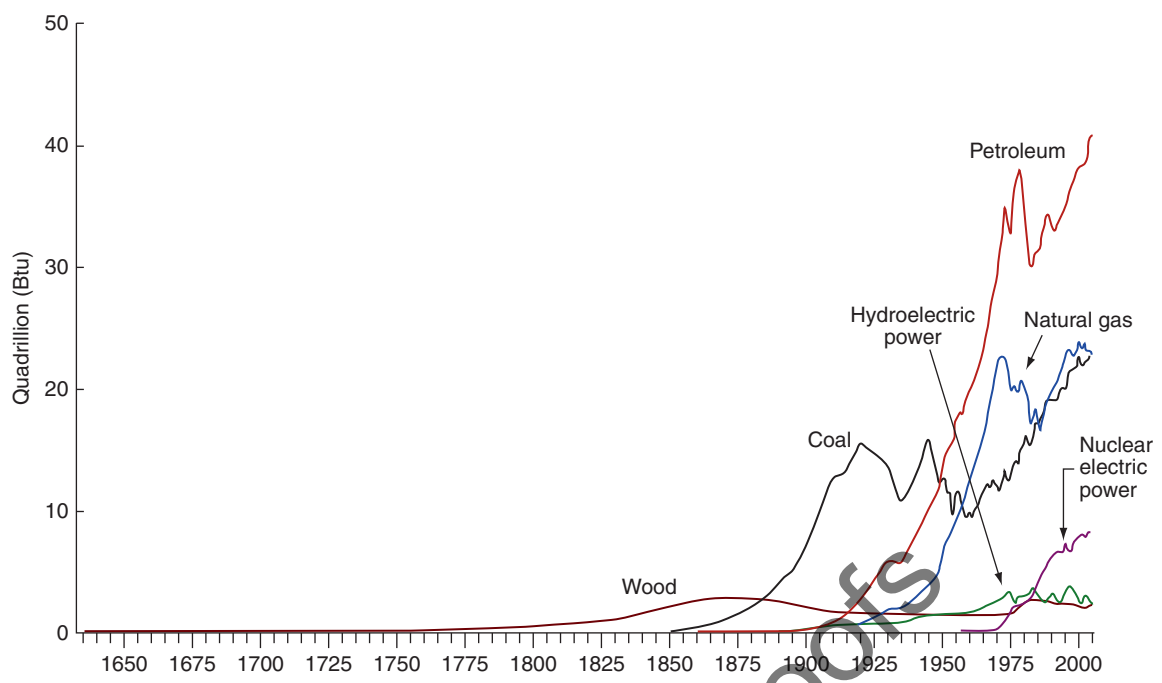


Figure 1.1.2. Energy consumption from 1635 to 2006. From EIA 2006, Figure 5.

In the early Carboniferous, coal swamps were found primarily in the low-latitude areas. In the later Carboniferous, a belt of coal swamps extended from the mid-western United States through Europe to Africa. Another coal belt extended from the Donets Basin of Russia to Morocco. In China and Mongolia, coals and interbedded marine sediments are related to the mid-Carboniferous transgression and regression of a broad seaway (Tatsch, 1980).

Terrestrial plants had been developing for 100 million years, and by the Carboniferous, plants adapted to semiaquatic or marshy areas were abundant. The majority of coal-forming plants were fern-like pteridophytes, such as the calamites (Figure 1.1.3), smaller plants, 4.5–12 m high that formed dense jungles, similar to canebrakes. The lycopodia or club mosses, lepidodendra and sigillaria, grew to over 30 m and had diameters in excess of 1.2 m. Spermatophytes of the period included cordaites, a tall slender tree that may have been an upland plant whose leaves were carried by streams into the peat swamp (Edmunds, 2002; Janssen, 1939; Kummel, 1961).

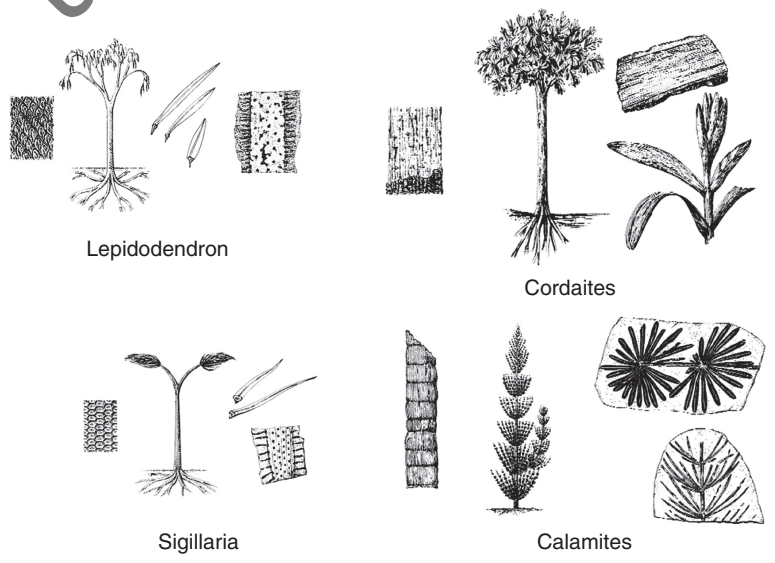


Figure 1.1.3. Carboniferous coal-forming plants. From Edmunds 2002, with permission.

s0050 Cretaceous/Tertiary Coals

p0100 Extensive deposits of Cretaceous and Tertiary coals are found in the western North America, Northeastern Russia and Siberia. They are also found in Europe, Japan, Africa, China, New Zealand, Australia, and South America. In the Western United States, a seaway extended periodically from the Arctic Ocean to the Gulf of Mexico. A seaway also connected the Barents Sea with the Tethys Ocean. In the late Cretaceous, the Tethys Seaway was also connected to the South Atlantic through the Niger Trough. An interior sea existed in central Australia in the mid-Cretaceous (McCabe and Parrish, 1992).

p0110 Cretaceous coals developed in areas where the annual precipitation exceeded evaporation. In tropical areas, rainfall was high and the humid climate preserved sediments. In higher mid-latitudes, evaporation was constrained by the cooler climate (McCabe and Parrish, 1992). In the Western United States, which has the largest volume of Cretaceous coal, wetlands developed along the margin of the retreating sea. The rising Rocky Mountains created intermontane valley swamps. A warm humid climate and isolation from the Cretaceous sea produced extremely thick, low-sulfur coals (Smith et al., 1994; WSGS, 2001).

p0120 During the early Cretaceous, conifer forests with ferns, gingophytes, and Czekanowskiales were the prevalent in the coal-forming swamps. In the middle Cretaceous, although forests remained dominated by conifers, **angiosperms** diversified and became an important component of the vegetation. In the late Cretaceous, conifers continued to dominate the coal-forming swamps, but angiosperm trees and shrubs were also important (Saward, 1992).

s0060 Coal Swamps

p0130 A site in which carbonaceous sediments could accumulate was created by erosion and the retreat of shallow seas. Broad level areas at or very near sea level, such as coastal plains, deltas, or a partially filled basins, could readily develop the marshy conditions needed for the growth of a carbonaceous swamp or mire. The consistent gradual rise in sea level or continuous slow land subsidence was required for between 1000 and 100 000 years in order to form a 10 m peat deposit which would be converted to a 1.5 m coal seam (Ashley, 1928). **Eustatic** rise in sea level, due to the melting of glaciers in the southern hemisphere, or **epeirogenic** sinking of the land would facilitate continual deposition of plant residues (Bennett, 1963; Kay and Colbert, 1965; Wanless et al., 1969).

p0140 Marshy conditions fostered the formation of peat and the preservation of the organic sediment. Under aerobic conditions, plants are rapidly decomposed to cell carbon, carbon dioxide (CO₂), and water (H₂O). In a marshy area, the movement of fresh H₂O is inhibited, and an anaerobic environment develops, slowing the rate of microbial decay and allowing carbonaceous sediments to accumulate. Toxic products also accumulate in the slow moving H₂O, decreasing microbial activity and preserving the sediments from further alteration. A rapid rise in sea level or increase in the rate of subsidence would flood the swamp, halting growth, and burying the peat under inorganic sediment.

p0150 In contrast to the slow deposition of peat, the deposition of inorganic sediments was relatively rapid, turbulent, and variable. The rocks associated with coal seams are usually fine grained clastics, particularly shales, mudstones, and siltstones. Black shales overlying many coal seams represent a gradational change as more sediment was carried into the peat swamp. Sandstones immediately above a coal seam may be related to erosion and subsequent deposition within an existing seam. Channel sands can be seen as stream erosion of an existing coal or peat deposit and deposition of sediments within the stream channel (McCullogh et al., 1975). The rate of sediment deposition within or immediately above the peat would affect the concentration of **syngenetic** minerals, while sandstones deposited above a coal seam could increase the concentration of **eigenetic** minerals.

s0070 Cyclothems

p0160 A cyclothem is a series of repeating sediments representing the transgression and regression of H₂O or the submergence and emergence of land. In coal-bearing strata, changes in depositional environment produced a cyclic repetition of beds. The cyclothem is defined as a series of beds deposited during a single sedimentary cycle.

Several “ideal” cyclothems have been defined (Kosanke et al., 1960; Weller, 1931), but, in a top-down sequence, they basically consist of shale, limestone, shale, coal, underclay, limestone, shale, and sandstone. The ideal cyclothem is typically associated unstable shelf or interior basin conditions. It represents maximum alteration of marine and nonmarine conditions, typical of western Illinois. The Southern Appalachian or Piedmont-type cyclothem is characterized by dominant continental clastic sediments, well-developed coals, and few marine beds. Alternating limestone and shale are representative of marine cyclothems, with thin sandstones and subordinate underclays and coals (Krumbein and Sloss, 1963).

Several mechanisms have been proposed for the formation of cyclothems. Diastrophic theories attribute them to sinking basins and rising source areas. Climatic theories propose that glaciations produced sea level oscillations, rainfall cycles, and variable erosion. Sedimentation theories attribute the formation of cyclothems to differential deposition related to depth of H_2O , strength of currents, distance from a river’s mouth, and compaction of sediments. It is unlikely that a single mechanism operating on a limited time span can adequately explain the development of multiple types of sedimentary cycle (Weller, 1931, 1964). In the Appalachian area, the sedimentary rocks are similar to deltaic deposits. Coal, ironstones and limestones are the chemical deposits formed in nonmarine, brackish, or marine environments. Episodes of detrital or clastic sedimentation interrupted the development of chemical deposits. The detrital rocks have a finite horizontal limit and grade laterally into chemical sediments (Ferm and Cavaroc, 1969).

Coalification

Peat formation is considered the biochemical stage of coal formation, during which plant residues are partially decomposed. The geochemical stage of **coalification** is a continuous and irreversible process that produces a rock from the organic sediment. In the long term, coalification produces progressively higher **rank** coals (ASTM, 2005) from lignite through subbituminous, high-volatile bituminous, medium-volatile bituminous, low-volatile bituminous to anthracite. Heat and pressure are the primary agents of coal metamorphism, rather than time (Figure 1.1.4). Temperature and pressure increase as a function of depth; high temperature is also related to folding and faulting and to the presence of igneous intrusions.

The first step in coalification is the removal of H_2O due to the weight of overlying sediments (Figure 1.1.5). An increase in the carbon concentration and a decrease in the hydrogen and oxygen concentrations are noted in higher rank coals (Hessley et al., 1986).

Coal macromolecules are formed from altered biopolymers in plants (Hatcher and Clifford, 1997). **Dehydroxylation**, **ether cleavage**, and **demethylation** are proposed mechanisms by which brown coal and lignite are produced from **lignin**. The removal of alkyl side chains and condensation reactions are assumed to account for increasing aromatic character. Coalification to the bituminous rank involves the reduction in oxygen content through

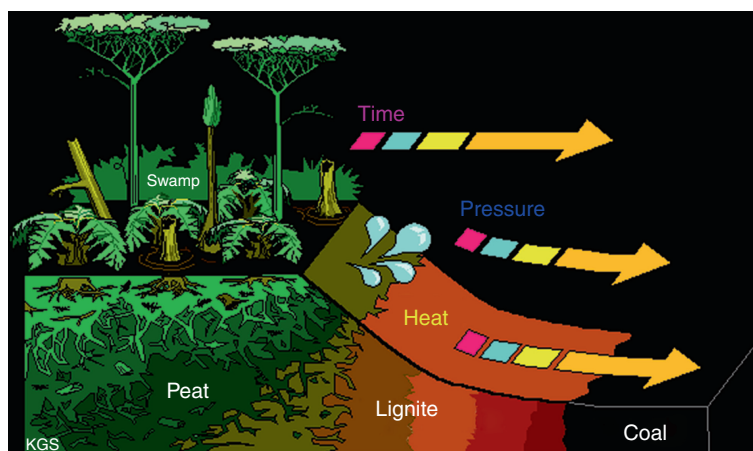


Figure 1.1.4. The transition from peat to hard coal, due primarily to heat at elevated pressures and extended periods of time. From Kentucky Geological Survey, University of Kentucky, <http://www.uky.edu/KGS/coal/>, with permission.

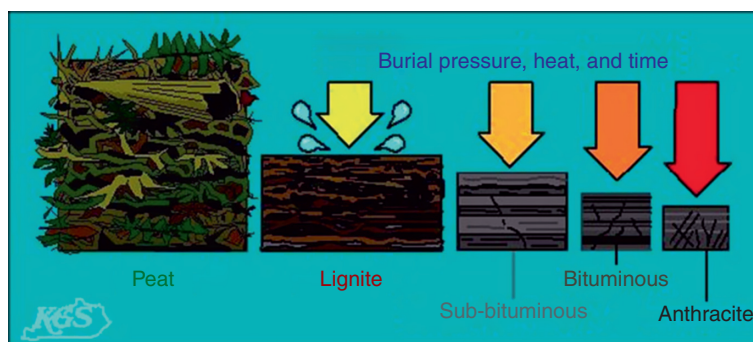


Figure 1.1.5. Increasing rank of coal due to pressure, heat, and time. From Kentucky Geological Survey, University of Kentucky, <http://www.uky.edu/KGS/coal/>, with permission.

pyrolytic condensation to form polycyclic aromatic ring structures with the loss of side chain carbons. During geochemical coalification, there is an increase in carbon content, and a decrease in the concentration of oxygen and hydrogen. Humic structures become more aromatic, and alkyl chains are split off to form CO_2 and CH_4 (Teichmuller and Teichmuller, 1967).

The increase in coal rank with increasing depth (**Hilt's Rule**) was assumed to be a function of increasing overburden pressure. Also, folding was assumed to accelerate coalification by tangential pressure. However, experimental evidence suggests that static pressure actually inhibits the chemical processes of coalification. The increase of rank with depth is as readily explained by increasing rock temperature. Increases in rank along thrust planes can be related to the frictional heating during tectonic movements. Magmatic contacts also produce local increases in rank. The maximum depth of burial and the maximum temperature to which the coal was exposed for long periods of time determine the rank of the coal. An estimate of the maximum temperature required to produce different coal ranks is given in Table 1.1.1. Coalification is a function of time only if the temperature is sufficiently high. Coals of the same rank can be produced either by short intense heating or by heating at lower temperatures for longer periods of time.

It is relatively well established that age is not a primary determinant of coal rank and that tectonic events increase the rank of coal beds. Most Pennsylvanian age coals in the Appalachian Basin and in the Interior Basin are bituminous in rank (Figure 1.1.6). The folded and faulted coals affected by the Alleghenian orogeny are anthracites. The Cretaceous coals of the Powder River Basin (PRB) in the Western United States are primarily subbituminous, while the younger Paleogene and Neogene coals affected by the formation of the Alps are bituminous to anthracite.

Table 1.1.1

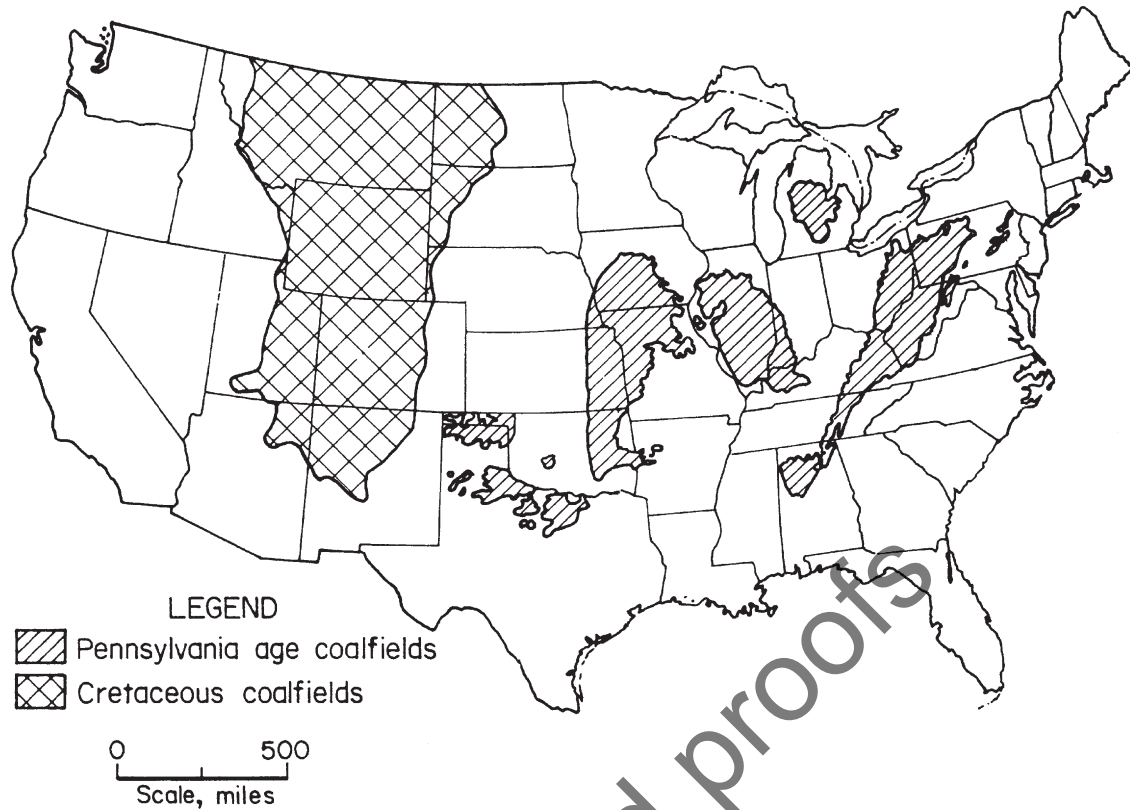
Estimated temperature, depth of burial, and time required for metamorphism in normal coal series.

| Coal rank | Temperature ($^{\circ}\text{C}$) | | Depth of burial (m) | | | Time (10^6 years/transition)* |
|---------------|------------------------------------|----------------------|---------------------|----------------------|----------------------|----------------------------------|
| | Range* | Maximum [†] | Maximum* | Maximum [‡] | Maximum [†] | |
| Peat | 10–20 | 15 | | | | 67 |
| Lignite | 20–40 | 45 | <1000 | 1500 | 1750 | 28 |
| Subbituminous | 40–50 | 80 | | 2300 | 2400 | 4 |
| Bituminous | 50–100 | 175 | <2100 | 6100 | >6000 | 6 |
| Anthracite | 100 to >150 | 205 | >2700 | 7600 | | 1.7 |

* Francis (1961).

[†] White (2002).

[‡] Smith et al. (1994).



r0060 **Figure 1.1.6.** Location of Pennsylvanian and Cretaceous/Tertiary coalfields in the United States. Based on Kim and Chaiken (1993, p.3)

s0090 **Possible Mechanisms for Increasing Coal Rank**

p0230 The increased temperature necessary to increase rank is assumed to be related to depth of burial (Francis, 1961). The increased pressure and deformation during tectonic activity are presumed to have little effect on coal rank (Teichmuller and Teichmuller, 1982). The hydrothermal brines expelled from tectonic belts are currently postulated as a mechanism of anomalous heat transfer (Copard et al., 2000).

p0240 A number of authors have described increases in the maturation of coal-bearing rocks as related to a particular mechanism, i.e., depth of burial, magmatic intrusion, tectonic activity, and more recently, hydrothermal fluids. The following examples demonstrate the variety of plausible mechanisms and are not intended to be a comprehensive catalog of such studies.

s0100 p0250 **Depth of Burial** Paleo heat flow values and the thickness of eroded sediments in the Saar basin were evaluated with one-dimensional thermal models based on **vitrinite reflectance** and temperature data (Hertle and Littke, 2000). The thermal maturity of the sediments is explained by deep burial and moderate heat flow. The calculated heat flows imply a maximum burial of 30–40 km. The effect of volcanism on heat distribution was considered to be much less than the effect of deep burial.

p0260 In the southern part of the Lower Saxony Basin, areas of high thermal maturation had previously been attributed to magmatic intrusions (Petmucky et al., 1999). Based on numerical modeling, only deep burial and relatively low heat flow produced a satisfactory fit between measured and calculated data. The low gradient in vitrinite reflectance with depth and sedimentation rates of 170 m/m.y. support depth of burial rather than magmatic intrusion as the coalification mechanism.

p0270 Although coalification patterns in the Upper Silesian Coal Basin generally followed Hilt's Rule, deviations from it were also observed (Sivek et al., 2002). Most of the localized variations can be explained by igneous intrusions and tectonic deformation. Heat flow effects related to hydrothermal fluid migration are rare.

p0280 In a study of four widely separated coal basins, Hower and Gayer (2002) determined that coal metamorphism is generally controlled by increased temperature related to depth of burial. However, there are sufficient exceptions to this to attribute some increases in coal rank to other causes, such as igneous and tectonic activity, and to the movement of hydrothermal fluids.

s0110 p0290 **Igneous Activity and Tectonism** In the Illinois basin, Damberger et al. (1999) correlated the rank of most of the coal seams with maximum depth of burial. A rank increase in the coal seams of SE Illinois that exceeds the expected increase was attributed to a heating event related to a paleo-geothermal anomaly.

p0300 In Indonesia, Paleogene coals are generally bituminous in rank, while Neogene coals are subbituminous (Daulay and Cook, 2000). However, in some areas Neogene coals in geologically young basins are bituminous. In this area, increased rank is attributed to uplift and igneous intrusions.

p0310 Tectonic displacement of coal seams in China has resulted in comminution of coal in the footwall (Cao et al., 2000). Only slight differences in reflectance and other chemical properties were observed in bituminous and anthracite samples collected from undisturbed and from deformed layers. However, lower molecular weight hydrocarbon fragments were concentrated in the deformed samples, indicating that there was some modification of chemical structure due to exposure to tectonic pressure.

p0320 Isotopic ratios of authigenic clay minerals indicated that two episodic, short-lived thermal events were responsible for increases in the rank of coals in the Bowen Basin of Australia (Uysal et al., 2001). Rather than gradual temperature increase due to progressive burial, the increased maturity of the coals is related to igneous activity associated with the breakup of Gondwana.

s0120 p0330 **Hydrothermal Fluids** Anomalous variations in rank unrelated to depth of burial or igneous heat flow have been attributed to the transient geothermal gradients due to the migration of hydrothermal fluids (Hower and Gayer, 2002). This model suggests that coal maturation is due to long term (>10 my) burial and to short lived (1–2 my) regional high-temperature fluid flow. However, a simple causal relationship between coal metamorphism and fluid flow has not yet been demonstrated; rather a variety of parameters have been cited to support the increase in coal rank by hydrothermal fluids.

p0340 Numeric heat flow models of a transition zone between the Alps and the Pannonian Basin were used to evaluate heat flow in Paleogene and Neogene sediments (Sachsenhofer et al., 2001). Oligocene vulcanism was the main heat source for the Paleogene sediments, and magmatic activity was partially responsible for Miocene heat flow. But igneous rocks were absent in at least one area of very high heat flow, and local increases in the rank of coals may be due to migrating fluids expelled from sediments beneath the Alpine front (Sachsenhofer and Rantitsch, 1999).

p0350 Pyrite from 14 samples of lower Pennsylvanian coals of northwestern Alabama was examined by ion microprobe/SEM (Kolker et al., 1999). Epigenetic pyrite was found to be enriched with arsenic. Arsenic-rich coals are prevalent in fault zones, implying that hydrothermal fluids were limited to fault zones and that the hydrothermal activity was post coalification.

p0360 The vertical distribution of coal rank in the South Wales coalfield was found to deviate from the relationship of Hilt's Law (Fowler and Gayer, 1999). Variations in vitrinite reflectance were correlated with the intensity of tectonic deformation. The complexity of a detailed model of faults necessary to explain the vertical rank profile by post coalification faulting renders this model improbable. Shear stress, frictional heating, and localized fluid flow are considered more probable mechanisms for this vertical rank profile.

p0370 Daniels et al. (1990) collected 15 coal samples from the anthracite fields of Pennsylvania and analyzed minerals from three distinct locations with the coal: in the coal matrix, in the systematic cleat, and in a poorly mineralized nonsystematic joint set. Mineral assemblages in the three were significantly different; the differences are attributed to differences in the composition of fluids during late stage diagenesis. Enrichment in Mg and Na suggests that the minerals were derived from migrating hydrothermal fluids in the higher permeability systematic joint sets of the coal seams which acted as regional aquifers. The authors suggest that the hydrothermal fluids at temperatures between 250 and 300°C caused the increase in coal rank. Depth of burial is discounted as the primary mechanism due to the necessity of assuming that the coal was covered by 6 km of overburden, an unusually large value. Since igneous activity is absent in this region, the heat flow necessary to produce anthracite would have to have come from another source.

s0130 **Experimental Studies of Coalification**

p0380 **Vitrinite reflectance** ($R_{v \max}$ %, R_o %) is the percentage of light reflected from the surface of polished vitrinite. It is a standard measurement used to classify organic rocks, and standard values are associated with various ranks of coal (Table 1.1.2).

p0390 According to Cooper (1996), the time–temperature index (TTI method), based on both laboratory studies and observations of reflectance and temperature in drill holes, assumes that vitrinite reflectance doubles for every 10°C increase in temperature. The reflectance of vitrinite is affected by the chemical reorganization of aromatic groups associated with the liberation of reactants (namely, O and H). From these experiments, Burnham and Sweeney (1989) have derived the following equation relating changes in vitrinite reflectance to changes in major element concentration:

$$R_o\% = 12 \exp \left[-3.3 \left(\frac{H}{C} \right) \right] - \left(\frac{O}{C} \right).$$

p0400 In artificial maturation experiments on one humic coal, samples were heated isothermally for 24 h at temperatures between 200 and 800°C (Han et al., 2001). Based on vitrinite reflectance, the sample maturity increased from high-volatile bituminous ($R_{v \max} = 0.77\%$) to anthracite ($R_{v \max} = 5.02\%$). The process is characterized by two fast reaction phases and two slow reaction phases. The first fast phase occurs at 0.9% vitrinite reflectance and is associated with the removal of attached fragments from aromatic rings. The second fast phase coincides with the late anthracite increase in reflectance. The increase in maturity was attributed to the temperature dependent breakage of C–C bonds and the generation of gaseous hydrocarbons.

p0410 In another laboratory experiment, the change in vitrinite reflectance was determined over a pressure range of 0.5–20.0 kbar at temperatures between 200 and 350°C (Dalla Torre et al., 1997). The results indicated that applied pressure suppressed increases in vitrinite reflectance.

s0140  **Coal Composition**

p0420 The composition of coal can be described by its components, by the elemental concentrations, and by macroscopic and microscopic composition.

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Table 1.1.2
Coals by rank and vitrinite reflectance (% R_o).

| Coal rank | | Range * | Random † | Maximum † | Minimum ‡ |
|---------------|-----------------|-----------|----------|-----------|-----------|
| Class | Group | | | | |
| Anthracite | Meta-anthracite | | | | |
| | Anthracite | | 6.55 | 7.00 | 2.50 |
| | Semianthracite | | 2.65 | 2.83 | 1.92 |
| Bituminous | Low volatile | | 1.85 | 1.97 | 1.51 |
| | Medium volatile | 1.00–1.40 | 1.49 | 1.58 | 1.12 |
| | High volatile | 0.3–1.00 | | | 0.5 |
| Subbituminous | | <0.40–0.6 | 0.60 | 0.63 | 0.42 |
| Lignite | | | 0.40 | 0.42 | |

* Pearson Coal Petrography.

† White. (2002).

‡ Smith et al. (1994).

s0150 **Proximate Composition**

p0430 On a **proximate** basis, coal is composed of moisture, mineral matter, volatile matter, and fixed carbon (Table 1.1.3) (ASTM, 2007; Hessley et al., 1986). Although one of the first effects of coalification is removal of H₂O, some physically and chemically bound H₂O remains in coal. Volatile matter includes gases that are released by thermal decomposition (pyrolysis) of coal, such as hydrogen, carbon monoxide (CO), methane, and other hydrocarbons, tar vapors, ammonia, CO₂, and H₂O vapor other than residual moisture. The fixed carbon is the solid combustible material in coal, the nonvolatile organic portion. It is estimated by difference, subtracting the percentages of moisture, ash, and volatile matter from 100. The heating value and rank of the coal increase with increased fixed carbon content (Figure 1.1.7). On a practical basis, coals are usually compared on a moisture and mineral matter-free (mmmf) or dry ash-free (daf) basis.

10030 **Table 1.1.3**
Examples of variation in proximate composition (wt.%) and calorific value (MJ/kg) of coal by rank.

| Coal rank | Moisture* | Ash* | Volatile Matter | Fixed Carbon | Calorific value [†] |
|----------------------------|------------------|-------------------|-------------------|-------------------|------------------------------|
| Lignite [‡] | 35.43 | 8.06 | 29.86* | 26.5* | 23.0 |
| Subbituminous [‡] | 14.74 | 10.97 | 36.42* | 37.8* | 33.5 |
| Bituminous [‡] | 6.97 | 7.87 | 43.14* | 41.0* | 36.0 |
| High-volatile bituminous | 6.9 [§] | 5.1 | >31 | <69 | 35.6 |
| Medium volatile bituminous | 1.5 [§] | 0.2 [§] | 31 | 69 | 36.0 |
| Low-volatile bituminous | 0.8 [§] | 1.2 [§] | 22 | 78 | 36.4 |
| Semianthracite | 0.6 [§] | 8.32 [§] | 14 | 86 | 36.0 |
| Anthracite | 1.4 [§] | 1.6 [§] | 8 | 92 | 35.2 |
| Meta-anthracite | | | <2 | >98 | |

Note: The data should not be considered representative.

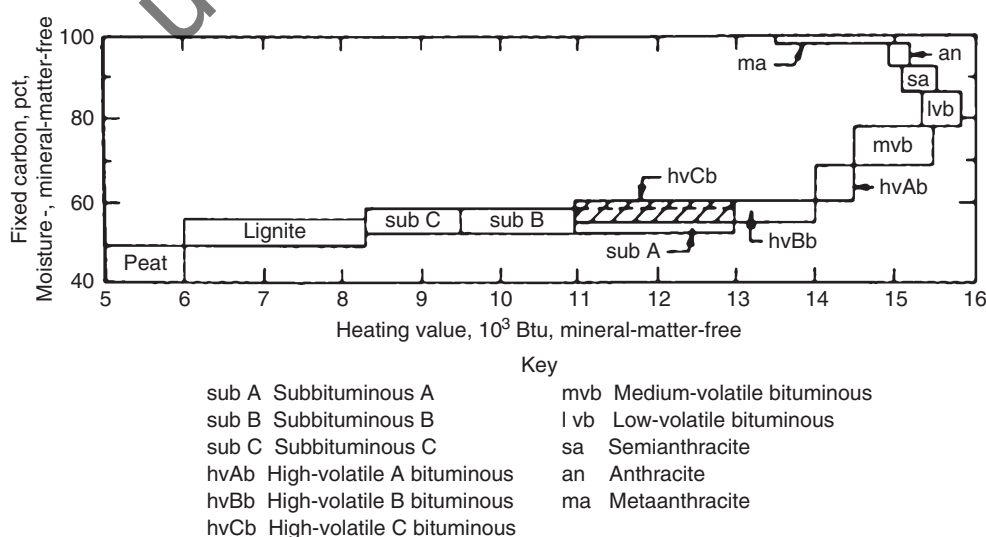
* As received.

[†] White (2002).

[‡] White and Theisen (1913).

[§] Kosanke (1952).

^{||} ASTM (2005).



10070 **Figure 1.1.7.** Progressive increase in fixed carbon and heating value for ranks of coal from peat to anthracite. From Kim and Kissell 1988, p. 19.

p0440 The mineral matter in coal, determined by low-temperature ashing or by dissolution in HF, is emplaced during or after coal formation. Minerals that are an integral part of the organic matrix are considered included minerals, while those in the cleats and fractures are termed excluded minerals. Although some of the inorganic compounds originate in the plant material, most are deposited during (**syngenetic**) or after (**epigenetic**) coalification. Syngenetic minerals can be formed by precipitation in an anoxic, aqueous medium during the biochemical stage of coalification, or they may be detrital clastics transported into the peat swamp by wind or H₂O. Epigenetic minerals are deposited within the coal seam, in cracks, fractures, and bedding planes, by migrating fluids. They may also be produced from syngenetic minerals by increased temperature and pressure. Mackowsky (1968) indicated that most of the silicates, quartz, and phosphates had been transported into the peat swamp. Carbonates, sulfides, and chalcedony from the weathering of feldspar and mica, were formed within the swamp. These minerals tended to be intimately intergrown with the organic matrix, as included minerals. Some carbonates, sulfides, and oxides were deposited in cleats and fractures; these excluded minerals are independent of the organic portion.

p0450 The quartz in 40 samples of a PRB coal was primarily detrital, but trace amounts of β -form quartz, with apatite and zircon, were attributed to air-fall and reworked volcanic ash deposited in the peat swamp (Brownfield et al., 1999). In a study of Gulf Coast lignites, enrichment of some elements was attributed to proximity to igneous rocks or to deposition of volcanic ash (Warwick et al., 1997).

p0460 Coal–mineral matter includes a variety of minor or trace elements. The concentration of these elements in coal may be greater than their average concentration in the earth's crust (Table 1.1.4). The distribution of trace elements varies too widely to be described by a general statement. Coals from different areas may show distinctive trace element characteristics (Table 1.1.5), and within a single coal seam, the trace element distribution may not be consistent. This suggests that no single process has been responsible for the accumulation of trace elements in coal. When compared to the overlying **carbonaceous shale**, the concentration of trace elements is lower in coal, reflecting the influx of detrital inorganic sediments that eventually terminated the formation of the peat swamp (Kim, 2002).

s0160 **Ultimate Composition**

p0470 **Ultimate** analysis of coal is the determination of the carbon, hydrogen, sulfur, nitrogen, and oxygen (Table 1.1.6) (ASTM, 2002; Hessley et al., 1986). Carbon includes organic and any mineral carbonate. Hydrogen is present in the organic portion of the coal and as H₂O. Nitrogen is assumed to be part of the organic matter, and sulfur may be

10040 **Table 1.1.4**
Distribution of trace elements in coal ash compared to the average concentration in the earth's crust and shales (mg/kg).

| Element | Crust | Shale | Coal | Coal ash, minimum | Coal ash, maximum |
|---------|-------|-------|-------|-------------------|-------------------|
| Ag | 0.7 | .07 | <0.05 | 1 | 10 |
| As | 1.8 | 13 | <100 | 100 | 900 |
| B | 10 | 100 | 58 | 86 | 5800 |
| Ba | 425 | 580 | 92 | 300 | 3500 |
| Be | 2.8 | 3 | 1 | 1 | 30 |
| Co | 25 | 19 | 9 | 30 | 300 |
| Cr | 100 | 90 | 20 | 50 | 400 |
| Cu | 55 | 45 | 12 | 20 | 500 |
| Mn | 950 | 830 | 85 | 200 | 1000 |
| Mo | 1.5 | 2.6 | 3 | 10 | 200 |
| Ni | 75 | 68 | 22 | 50 | 800 |
| Pb | 12.5 | 20 | 40 | 5 | 700 |
| Sr | 375 | 300 | 110 | 80 | 3500 |
| V | 135 | | 5 | 100 | 1000 |
| Zn | 70 | 95 | 34 | 100 | 1000 |

Source: Based on Nicholls (1968).

t0050

Table 1.1.5
Minerals identified in coal.

| Sample | Bituminous | PRB |
|-----------------|------------|---------|
| Units | wt.% mm* | wt.% mm |
| No. of Samples | 3 | 1 |
| Quartz | 12 | 27 |
| Kaolinite | 13 | 19 |
| Illite | 13 | 8 |
| Montmorillonite | <1 | 2 |
| Feldspar | <1 | 2 |
| Silicates | 27 | 29 |
| Pyrite | 16 | 1 |
| Sulfides | <1 | 1 |
| Siderite | <1 | <1 |
| Calcite | 3 | – |
| Carbonates | 2 | <1 |
| Rutile/anatase | <1 | 3 |
| Phosphates | <1 | 6 |

Source: After Senior et al. (2000).

PRB, Powder River Basin.

*wt.% mm = weight % of mineral matter.

t0060

Table 1.1.6
An estimate of the average ultimate composition of coal by rank (wt.%).

| Coal rank | C | H | N | O |
|------------|----|-----|-----|-----|
| Peat | 56 | 5.8 | 1.4 | 36 |
| Lignite | 69 | 4.6 | 1.2 | 25 |
| Bituminous | 86 | 5.4 | 1.6 | 7.5 |
| Anthracite | 94 | 2.5 | 1.0 | 2.3 |

Source: After Tatsch (1980) and Mott (1942).

organically bound, in pyrites and in inorganic sulfates. Oxygen, which can be in the organic and inorganic portions of the coal, is determined by difference. The ultimate composition of coal on a moisture and mineral matter-free (mmmf) basis is the hypothetical pure coal substance.

s0170

Macroscopic and Microscopic

p0480

On a macroscopic scale, most large coal deposits are described as banded, exhibiting layers which represent variations in the plant material or its degree of biochemical alteration. These coals are termed **autochthonous** and were formed in situ. **Allochthonous** or drift coals are those in which plant material was carried into the area of deposition. Two types of drift coals are cannel coal formed from plant spores and boghead coal formed from the remains of algae. **Drift coals** tend to be smaller deposits and have a higher concentration of mineral matter (>10%). (Hessley et al., 1986)

p0490

Stopes (1919) described banded coals by what he called **lithotypes**. Vitrain was a bright glassy band, formed from wood or bark. Clarain was a smooth interlaminated band of bright and dull coal; no specific origin was postulated. Durain was a dull black band and was very hard. In contrast, fusain was a charcoal-like band, porous, friable, and frequently containing mineral matter.

p0500 On a microscopic scale, three **macerals**, the organic equivalent of minerals (Stopes, 1935), were identified: vitrinite, exinite, and inertinite. Vitrinite, typically shiny and glassy, is the coalified remains of cell walls, woody tissue of stems, branches, leaves and roots of plants, and the precipitated gels from these materials. In white light, vitrinite is a pale-gray to white. It is the predominant maceral in coal, and is the only important component of vitrain. It has a relatively high concentration of oxygen and a moderate amount of hydrogen and volatile matter. Exinite was formed from waxy resinous debris, and is divided into sporinite, alginite, resinite, and cutinite. It is rich in hydrogen and is primarily aliphatic. Inertinite, the third maceral, is formed from oxidized wood or bark. It is aromatic and has low-volatile matter content. The relatively unreactive inertinite which forms fusain is made up of macrinite and micrinite, massive or granular residues of protoplasm. Also, fusinite is oxidized woody tissue in which the cell structure is still visible, semifusinite is less oxidized, and sclerotinite is formed from fungal remains (Petraakis and Grandy, 1980).

p0510 The preceding information on coal, how it is formed and its composition, is intended as a general overview. For more detailed information, consult the listed references.

Uncorrected proofs

s0180



1.2. Origin of Coal Fires

Sinkholes such as this one due to an underground mine fire in Renton, Pennsylvania may develop without warning, resulting in injury or death.

Photo: US Bureau of Mines, 1985.

s0190

Introduction

p0530

Coal fires in abandoned mines, in waste banks, and in unmined outcrops constitute serious safety and environmental hazards. Subsidence, the emission of toxic fumes, and deterioration in air quality create an unsafe and unpleasant atmosphere that can consume resources and depress property values for affected land and for adjacent areas. Fires in abandoned mines and waste banks often affect people who had no connection with the original mining.

p0540

Coal fires occur in almost every coal-bearing area and have been a problem for hundreds of years. In 1765, a fire was started in the Pittsburgh seam in Pennsylvania. This fire was active until at least 1846 (Eavenson, 1938, 1942). In the Western United States, coal-outcrop fires were a natural feature of the landscape. In 1805, Lewis and Clark, in their exploration of the Missouri River, reported that coal seams were plainly visible in the bluffs along the river and that some of the veins were burning, ignited by spontaneous combustion or by grass fires (Lavender, 1988, pp. 190, 196). In southeastern Montana, an outcrop fire in a 6 m (~20 ft) thick seam has propagated ~1524 m (5000 ft) along a small drainage basin. The fire has affected a total area of 500 acres and has been burning for an estimated 400–600 years (Shellenberger and Donner, 1979). Hundreds of natural coal-bed fires are burning in the PRB. The age of zircons in associated clinker indicates that such fires have been occurring in this area for thousands of years (Heffren et al., 2007). Coal fires associated with the abandoned or inactive coal mines are reported from mining areas around the world (Prakash and Gupta, 1999; Stracher and Taylor, 2004). Surface expressions of underground coal fires observable in the field include baked rocks, areas of dead vegetation, land subsidence, and gas vents and fissures with encrusted minerals (Gupta and Prakash, 1998; Stracher, 2007).

80200 Incidence of Coal Fires

p0550 **R**ecent studies have indicated that uncontrolled coal fires are a global problem. In addition to the inherent health and safety problems, such fires are believed to contribute to greenhouse gas emissions. Over 1% of the global emission of CO₂ from fossil fuels is believed to be generated by coal fires in China (Rosema et al., 1999; Stracher and Taylor, 2004; Voigt et al., 2004).

p0560 In the United States, fires in abandoned mines and in outcrops, termed wasted coal fires, have occurred during the past 200 years. Since 1950, there have been over 600 coal-related fires in the United States (Johnson and Miller, 1979). As of 2005, 141 fire-control projects on abandoned mine lands (AMLs) were listed on the Office of Surface Mining Reclamation and Enforcement's Inventory (OSMRE, 2005). This is an underestimate of the actual number of fires because many that occur are not associated with coal mining. In the United States, most underground mine fires are in the eastern coal-producing states. The characteristics of eastern fires vary depending upon whether they are in bituminous or anthracite seams. Waste bank fires occur in the eastern and central states where the majority of coal-preparation plants were located. Outcrop fires in inactive or unmined deposits are more prevalent in the Western United States.

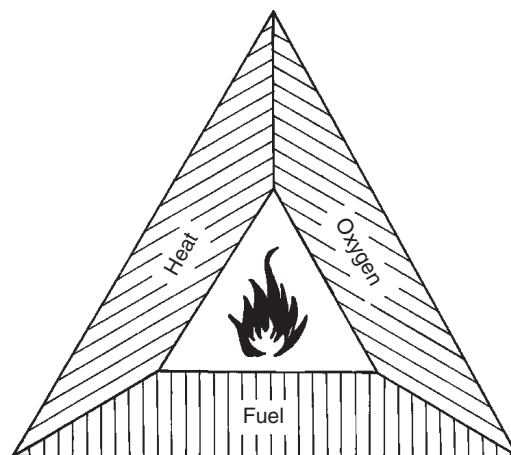
p0570 Currently, coal fires are a serious problem in the Jharia coalfield of India and the Wuda coalfield in Inner Mongolia. Fires are also a problem in Indonesia, New Zealand, South Africa, Australia, Siberia, and other parts of the world (Masalehdani et al., 2007; Michalski, 2004; Sokol and Volkova, 2007; Stracher, 2007; Whitehouse and Mulyana, 2004). In addition to the loss of energy resources, coal fires are a source of CO₂ and other air pollutants. They may cause subsidence, ignite forest fires, and can create a health hazard due to airborne dust, acid gases, and potentially toxic trace elements and organic compounds (Finkelman, 2004). Uncontrolled burning of coal can create problems from an unpleasant atmosphere to the destruction of property to the devastation of ecosystems.

80210 Ignition and Propagation of Coal Fires

p0580 **A**s with any fire, coal fires require three elements: fuel, oxygen, and an ignition source (Figure 1.2.1). In coal combustion, the fuel is the carbon in the coal. If combustion is considered the **exothermic** reaction of carbon and oxygen to form CO₂, written as



the amount of heat liberated is 93.7 kcal/mol.



f0080 **Figure 1.2.1.** Fire triangle showing the three essential elements for any fire: fuel, oxygen, ignition source. From Kim and Chaiken 1993, p. 6.

p0590 However, coal is not composed of elemental carbon. On a dry, mineral matter free basis, coal contains between 60 and 90% carbon. The rest of the coal “molecule” is composed of hydrogen, oxygen, nitrogen, and sulfur. For example, the stoichiometric combustion of coal can be written as (Chaiken, 1977):



p0600 This reaction produces 138.4 kcal/mol. Combustion reactions are exothermic. Depending on the rank of the coal, combustion produces from 5 to 10 kcal/g of coal or between 6 and 16 000 Btu/lb.

p0610 The oxidation of coal occurs constantly. The temperature of the coal is a function of the rate of heat generation versus the rate of heat loss. Since the rate of heat generation is an exponential function of temperature and the rate of heat loss is a linear function of temperature, as the temperature increases, the reaction rate increases faster than the heat loss (Kanury, 1975). Ignition is a function of the amount of energy released by a reaction and the rate at which it is released, as well as the rate at which energy is transferred from the reacting mass to the surroundings. The reaction rate is a function of the concentration of reactants, carbon and oxygen, the surface area, particle size, temperature, and activation energy.

s0220 Sources of Ignition

p0620 There are two types of ignition: forced and spontaneous. Forced ignition sources include lightning, brush and forest fires, improperly controlled man-made fires and spontaneous combustion in adjacent materials like trash. Spontaneous combustion in coal or coal refuse is related to the oxidation of the coal to form CO₂, CO, and H₂O (Kim, 1977). Spontaneous combustion may be the initial cause of a fire which is then spread by conduction or convection to other areas of a mine (Banerjee, 1985; CMRS, 1991).

p0630 The oxidation of pyrite and the adsorption of H₂O on the coal surface also are exothermic reactions that increase the probability of spontaneous combustion. Thermophilic bacteria may also contribute to raising the temperature of the coal (Chaiken et al., 1983).

s0250 Factors Favoring Propagation of Coal Fires

p0640 An abandoned mine or waste bank is a physical environment that favors the accumulation of heat. In bituminous-coalfields, the depth of overburden, the degree of fracturing, and the nature of the overlying strata are the primary geologic factors (Dalverny and Chaiken, 1991).

p0650 In underground mines that used a **room-and-pillar mining system**, a relatively large proportion (30–50%) of the coal is left in place. The **roof coals** and carbonaceous shales are also left in the mine. The tonnage of combustible material remaining in the mine may exceed that extracted during mining. Older mines had several entries at the outcrop for drainage, ventilation, and access. Fires usually started at the outcrop and propagated along the outcrop or through interconnected workings. Heat could move by convection through the mine or by conduction into the overburden. The overburden served as an insulator, preventing the transfer of heat away from the combustible material. As the overburden became warmer or as the coal pillars failed, the overburden subsided, creating a system of cracks and fractures through which smoke and fumes left the mine and fresh air entered the mine (Figure 1.2.2). Under these conditions, most abandoned mine fires exhibit smoldering combustion, involving relatively small amounts of coal at any given time, with little visible flame. They can continue to burn in an atmosphere with as little as 2% oxygen (Scott, 1944). Such fires can burn for extended periods of time (10–80 years) and are difficult to extinguish (Dalverny and Chaiken, 1991; Kim et al., 1992; Leitch, 1940).

p0660 In abandoned surface mines, the coal outcrop may be left exposed when stripping operations are terminated, or coal refuse may be left in contact with the outcrop. In either case, fires are not unusual. If a stripping operation involved the **barrier pillar** of an abandoned mine, it is possible for a fire to propagate into the mine (Kim and Chaiken, 1993).

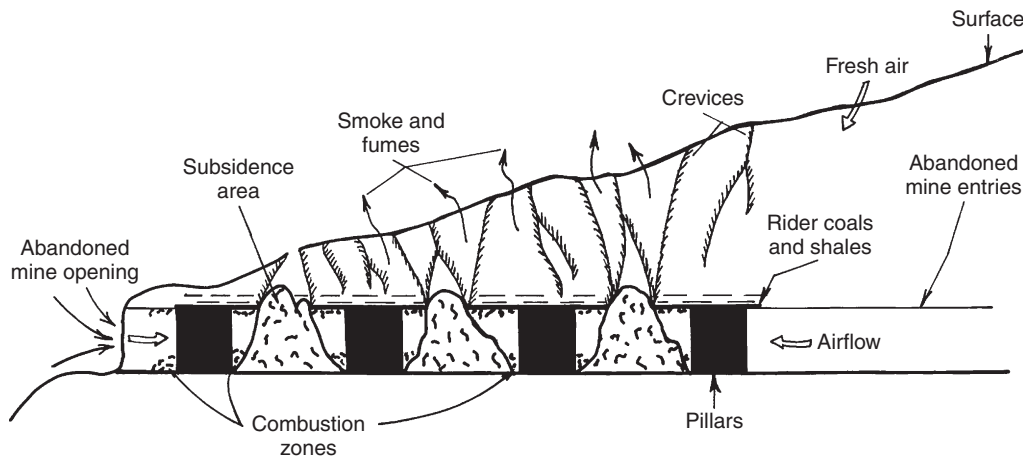


Figure 1.2.2. Wasted-coal fire in an abandoned mine showing emission of smoke and fumes through cracks and fractures and intake of fresh air through openings and overburden. From Kim and Chaiken 1993, p. 3.

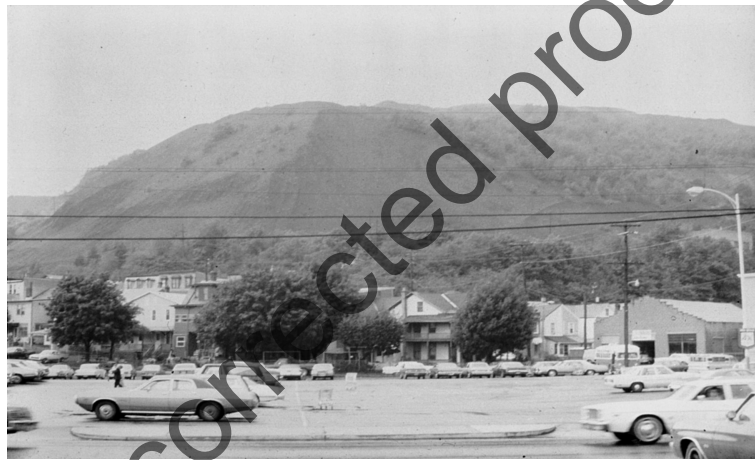


Figure 1.2.3. Glenburn anthracite waste bank at Shamokin, Pennsylvania. From Kim and Chaiken 1993, p. 5.

Surface disposal of coal waste, from mines, and from preparation plants, is also a source of wasted-coal fires (McNay, 1971). Approximately 25% of the coal removed from the mine in the United States was rejected and disposed of on the surface (Doyle, 1976). Over the past 200 years, over three billion tons of refuse has accumulated in 3000–5000 active and abandoned waste piles and impoundments in the eastern coalfields alone. It has been estimated that a billion m^3 of anthracite waste has been disposed of in surface piles in the anthracite region (Figure 1.2.3). The refuse consists of waste coal, slate, carbonaceous shales, pyritic shales, and clay associated with the coal seam. The combustible content of this material averages between 2000 and 6000 Btu/lb. Material with a combustible content above 1500 Btu/lb will support combustion (Chaiken, 1980; Kim, 1995).

In anthracite mines and in some western mines, the **dip** or **pitch** of the beds also influences the propagation of fires. On steep pitches, differences in temperature and elevation are sufficient to control the circulation of air and fumes. The movement of hot gases can transfer heat to other areas of a mine. The distance between coal beds and their connection by fractures or tunnels determines the transfer of heat between beds and the possibility of propagation of a fire from the source bed to adjacent beds (White, 1973).

The rank of a coal is also a factor in the incidence of coal fires. Generally, lower rank coals tend to be more susceptible to spontaneous combustion. Although lignites and subbituminous coals are more prone to spontaneous

combustion, spontaneous combustion in higher rank coals can be supposed from the number of fires in which no other cause is suggested (Kim and Chaiken, 1993).

p0700 Natural barriers to subsurface fire propagation include faults where vertical displacement disrupts the continuity of the coal bed. Boundary pillars are considered natural barriers to fire propagation because solid coal seams do not burn readily. The H₂O table serves as a barrier by limiting the amount of oxygen and by absorbing energy released by the fire. In the absence of these natural barriers, a subsurface fire can, in an extended time period, burn from outcrop to outcrop (Kim and Chaiken, 1993).

s0240 Hazards

p0710 The primary hazards of coal fires are toxic fumes and subsidence. These fires also can affect the conservation of coal resources, ignite surface fires, and affect the value of adjacent property. Fumes from a fire zone frequently contain coal distillates, mercaptans carbonyl sulfides, which create noxious and unpleasant odors in addition to CO₂ and CO. Subsidence occurs when a fire consumes a portion of the coal, removing support from the overlying strata. The surface expression of the subsurface fire may be a small vent, a fracture line, a slight depression or a relatively large sinkhole. At least 60 deaths have been attributed to accidents at burning-coal refuse piles (McNay, 1971).

p0720 The potentially most serious problem associated with coal fires is the migration of toxic fumes from the fire through overlying strata into homes or other enclosed surface structures. A fire produces CO, CO₂, H₂O, and consumes oxygen. CO is the most serious hazard. This colorless, odorless gas readily combines with the hemoglobin of the blood, which normally transports oxygen; it replaces oxygen and forms carboxyhemoglobin. The effect of CO exposure increases with duration of exposure, higher humidity, and lower barometric pressure. The rate of effect also increases with increased physical exertion. Other factors in individual response to CO exposure are age (very old and very young), pregnancy, heart disease, poor circulation, anemia, asthma, lung impairment, or the presence of drugs/alcohol in the blood (Plunkett, 1976).

p0730 The hazards of mine fires are insidious. They are not like hurricanes, tornados, earthquakes, or floods, in which a single catastrophic event affects a large number of people. Fires in abandoned mines and waste banks are protracted events; they can have a moderate effect on people for 20 years or more. The most widespread effect is the environmental degradation caused by noxious odors and fumes. A more serious, but less prevalent, effect is subsidence and/or fume migration into surface structures (Kim and Chaiken, 1993).

s0250 Control of Coal Fires

p0740 In order to to extinguish a fire, one of the three elements, fuel, oxygen, or energy, must be removed. Fuel is removed when it is consumed or when it is physically separated from the burning mass. Oxygen removal depends on either the introduction of an inert atmosphere or on the isolation of the fire zone from sources of fresh air. Heat removal can be accomplished by moving a heat-absorbing agent (usually an inert gas or H₂O) through the mine. To prevent reignition of the fire, all coal and heated rock must be cooled below the reignition temperature. Even very small isolated areas where the coal is oxidizing at a high rate can serve as reignition points if the control measure fails and oxygen becomes available. It is generally assumed that if the temperature is below 100° C, the chance of reignition is small (Kim and Chaiken, 1993).

s0260 Conventional Methods of Extinguishing Subsurface Fires

p0750 Excavation (loading out, daylighting, dig and quench, stripping) is a fuel-removal method that is the most successful of the AML fire-control techniques (Chaiken, 1984). It involves physically removing the burning material and cooling it to extinguish the fire. The hot material is cooled either by spraying it with H₂O or by spreading it out on the ground and allowing it to cool in air. H₂O is preferred as the heat removal medium. It is also used to protect equipment from high temperatures and to suppress dust. If properly applied, excavation is the surest method of extinguishing wasted-coal fires. However, exposure of smoldering coal to an unlimited supply of oxygen can produce a sudden increase in fire activity (Figure 1.2.4). Excavation also involves exposure of men and equipment to a hazardous environment (Figure 1.2.5) The recurrence of excavated fires is usually due the failure to



Figure 1.2.4. Combustion enhanced by excavating hot coal in the presence of an unlimited supply of oxygen. Photo courtesy of the West Virginia Department of Natural Resources.



Figure 1.2.5. Excavation involves the hazards of working in hot material and toxic fumes. US Bureau of Mines photo 1982, Calamity Hollow Burnout Control Project.

completely excavate the fire or to the failure to lower the temperature of backfilled material beyond the reignition point (Kim and Chaiken, 1993).

Inundation methods of extinguishing wasted-coal fires involve the underground use of H_2O to lower the temperature of the burning material (heat removal). Covering the burning material with H_2O also stops the combustion reaction by oxygen exclusion. To raise the H_2O level, dams are constructed underground. The H_2O level must cover not only the burning coal, but must also reach the overlying heated rock. This method is limited to use on fires that are small, fairly accessible, at or near the H_2O table and have been burning for a relatively short time to minimize the amount of stored heat. Another inundation method provides for the continuous flow of H_2O through the hot material. This can be accomplished by continuous pumping or by gravity flow from a surface impoundment. The volume of H_2O required, the cost of high-capacity pumps, and time considerations have limited the utility of continuous pumping.

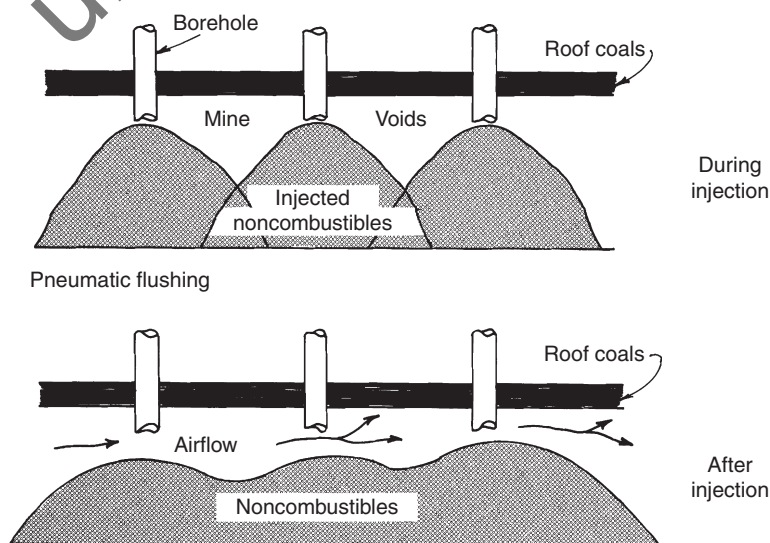
p0770 The gravity flow method has apparently been tried on waste banks by excavating a reservoir on the top of the bank and allowing H₂O to flow naturally downward (Bruhn and Michalski, 1989). The constraint on either of these methods is that the H₂O is not uniformly distributed. It may flow through channels and may bypass the fire zone. Even if the H₂O fails to cool a small amount of material, the probability of reignition is high.

p0780 Flushing is designed to fill the voids in an underground fire zone with fine, noncombustible solids. The noncombustible material is intended to cover the burning material and fill the interstices in adjacent rock, limiting the amount of oxygen in the system and absorbing heat. The high percentage of incombustible material, if properly emplaced, is expected to form a barrier to further propagation of the fire. Flushing can be effective where deposition of the noncombustible material can be controlled, where the voids have a relatively simple geometry, and where the injected material will remain in place.

p0790 Sand, silt, **red dog**, crushed limestone, and fly ash are the most commonly injected materials. Air or H₂O is usually used to carry the material through a borehole into the mine. With pneumatic (air) flushing, the noncombustible material is deposited at the bottom of the borehole. It forms a conical pile that theoretically reaches to the roof of the mine. Material is pumped into the hole to rejection, when it is assumed that the void is filled.

p0800 Pneumatic injection has two constraints: the material does not penetrate rubbleized strata and the material tends to slump which reduces the contact with overlying strata (Figure 1.2.6). This allows air to flow near the roof. In hydraulic flushing, H₂O is used to produce a slurry of the incombustible material. When the material is emplaced in the mine, the solids settle as the H₂O drains down dip. This method is believed to carry material further than dry flushing and to have some penetration through rubbleized material.

p0810 Grout slurries have been pumped underground to form fire control barriers. Cement in the grout slurry solidifies to form a competent seal, which also adds support to collapsed strata. The addition of foaming agents and incombustible materials, like sand or soil, has been used to produce a lower density foam grout that hardens to a cellular concrete (Colaizzi, 2004). The grout encapsulates the burning coal and limits combustion by limiting exposure to oxygen. The foamed grout has a low thermal conductivity, between 80 and 228 cal/min/m²/°C/cm and acts as an insulator, retaining heat within the coal. To remove heat, a thermal aggregate like small metal particles can be added to the grout (Terry, 1987). To be effective, the remotely emplaced grout seal must be complete, encapsulating all burning material and isolating it from other combustible materials (Figure 1.2.7), and the grout barrier must be stable for extended periods of time while the material cools.



f0130 **Figure 1.2.6.** Sketch of pneumatic injection through boreholes, allowing slump of injected material and continued airflow near roof coals. From Kim and Chaiken 1993, p. 36.

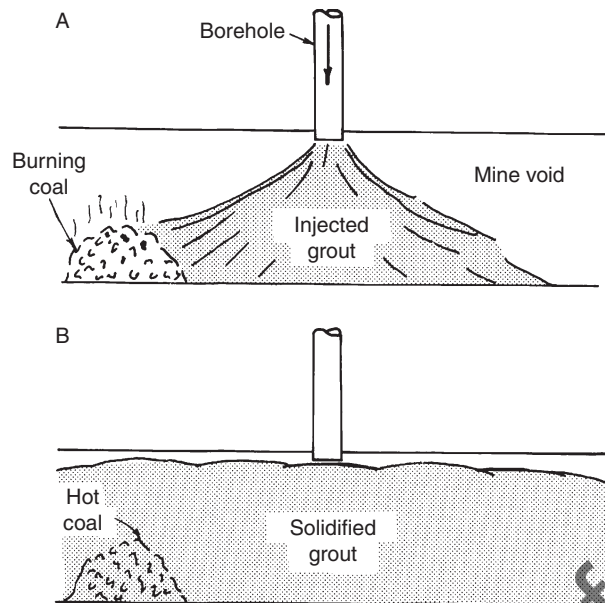


Figure 1.2.7. Sketch of the use of grout with concrete to encapsulate burning coal. A: Injection to encapsulate burning coal; B: Solidified grout for O₂ exclusion while hot material cools to below the reignition point. From Kim and Chaiken 1993, p. 36.

Surface sealing is a relatively inexpensive method of controlling abandoned mine fires. It is intended to inhibit ventilation of the fire zone. The exclusion of air and the accumulation of combustion products suppress the rate of fire propagation. If the seal can be maintained while all the stored heat dissipates, the fire may eventually be extinguished. During this period, the seal must be maintained. In general, most surface seals can be expected to fail between 1 and 3 years after construction. Failure may be related to settling, shrinkage, drying, or increased fire activity.

In the Western United States, 85% of fire abatement projects were surface seals. This is due to the relatively low cost, the topography of the area, and the lack of H₂O needed to implement other methods (Shellenberger and Donner, 1979).

Surface sealing suppresses surface evidence of a fire. If the seal is maintained for a sufficient length of time (10–20 years), the fire may be extinguished. Surface seals adequately control subsidence, inhibit unsightly venting and limit the emission of noxious fumes. In these circumstances, surface seals with regular and periodic maintenance provide an adequate control mechanism (Kim and Chaiken, 1993).

Conventional methods of controlling and/or extinguishing AML fires comprise a limited arsenal of dealing with the problem. None of the methods are routinely successful. Most of the methods involve some degree of hazard, have varying costs and may disrupt more surface area than the fire threatens.

Conclusions

The problem of coal fires is a serious one. Such fires can involve a high degree of hazard and can be less amenable to solution. Given the nature of these fires, it is unlikely that the extent of the problem or the cost of solutions will decrease in the near future. Although new techniques for locating fires and for controlling and extinguishing fires may be developed, the majority of current fire control projects utilize conventional methods and techniques.

Coal fires have occurred in the United States for over 200 years and, they may continue to occur. Experience has shown that they are difficult and expensive to control. Currently available technology used to control them is less than 70% effective. Research in new technology and in the adaptation of technology available in other fields may significantly improve the effectiveness of fire-control methods.

Acknowledgments

I wish to acknowledge Maurice Deul and Robert F. Chaiken, my supervisors at the US Bureau of Mines, who generously shared their extensive knowledge of coal geology and coal-mine fires.

s0280

Important Terms

p0880

| | |
|------------------------------|--|
| Angiosperms | A flowering seed plant, as opposed to nonflowering seed plants (gymnosperms), such as conifers. |
| Allochthonous | Formed or produced elsewhere than in its present place; applied to coal or peat that originated from plant material transported from its place of growth. |
| Autochthonous | Formed or produced in its current location; applied to coal or peat that originated at the place where its constituent plants grew and decayed. |
| Barrier pillar | A solid block or rib of coal, etc., left unworked between two mines for security against an influx of H ₂ O. The unmined block of coal between adjacent mines or between the mine workings and the outcrop. |
| Carbonaceous shale | A coal-like material containing too much mineral matter to be considered coal, frequently formed by an influx of inorganic sediment into the coal swamp. |
| Coalification | Processes in response to diagenetic and metamorphic agents that determine the genetic and metamorphic history of coalbeds. |
| Dehydroxylation | Removal of hydroxyl ions (OH ⁻) from a compound or radical. |
| Demethylation | Removal of a methyl group (CH ₃) from a compound. |
| Dip | The angle at which a stratum or any horizontal feature is inclined to the horizontal. |
| Drift coal | Coal that originates from an accumulation of plant material that has been transported from its place of growth, allochthonous coal. |
| Epeirogenic | Pertaining to the uplift and subsidence of extensive areas of the earth's crust. |
| Epigenetic | Pertaining to a mineral deposit formed later than the enclosing rock; in ore petrology, mineral deposits of later origin than the enclosing rocks or to the formation of secondary minerals by alteration. |
| Ether cleavage | The reaction of an ether (CH ₃ -O-CH ₃) containing molecule with a strong acid (HBr) to form an alkyl halide (CH ₃ Br) and an alcohol (CH ₃ OH). |
| Eustatic | Pertaining to worldwide changes of sea level that affect all the oceans. |
| Exothermic | A chemical reaction producing heat. |
| Hilt's Rule | In a vertical sequence at any given point in a coalfield, the rank of the coal of the successive seams increases with increasing depth. |
| Lignin | The major noncarbohydrate portion of wood, an amorphous polymeric substance that cements the fibrous portions (cellulose) together. |
| Lithotype | A macroscopically visible band in humic coals. |
| Maceral | An elementary microscopic constituent of coal, analogous to mineral as used in petrography; organic units composing the coal mass, having the termination -inite; i. e., vitrinite, exinites, and inertinites. |
| Pitch | In structural geology, the angle that a line in a plane makes with a horizontal line in that plane. |
| Proximate composition | The compounds contained in a mixture, particularly the concentrations of moisture, volatile matter, mineral matter and fixed carbon in coal. |

| | |
|-------------------------------|--|
| Pyrolytic condensation | A reaction at high temperature in which two molecules combine with the elimination of H ₂ O or other small molecule. |
| Rank | Describes the stage of coalification attained by a given coal; the place occupied by a coal in a classification of coals according to their degree of metamorphism, or progressive alteration, in the order: lignite, subbituminous, bituminous, anthracite. |
| Red dog | Material of a reddish color resulting from the combustion of carbonaceous shale and other mine waste in surface mine dumps or waste banks. |
| Roof coal | The layer immediately over the main-coal seam. It may be coal of poor quality or carbonaceous shale, and is frequently left in place. |
| Room-and-pillar mining | A system of mining in which typically flat-lying beds of coal are mined in rooms separated by pillars of undisturbed coal left for roof support. |
| Syngenetic | A mineral formed contemporaneously with the enclosing rocks. |
| Ultimate composition | The elements contained in a compound, as distinguished from proximate analysis, which is the determination of the compounds contained in a mixture. In the case of coal and coke, the determination of carbon, hydrogen, sulfur, nitrogen, and oxygen. |
| Vitrinite reflectance | As coal rank increases, the vitrinite macerals become increasingly reflective. The percentage reflection of a beam of normal incident white light from the surface of polished vitrinite is a function of the rank (maturity) of the maceral. The reflectivity (R) may either be recorded as R_v max% or R_o %. Both are measurements of the percentage of light reflected from the sample, calibrated against a material which shows ~100% reflectance. |
| Wasted-coal fires | Wasted coal is that left in mines or disposed of on the surface. Wasted-coal fires occur in inactive or abandoned coal mines and coal-waste banks. Also called “Abandoned Mined Lands” fires. |

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WWW Addresses: Additional Reading

- (1) **Dictionary of Mining, Mineral, and Related Terms**
<http://www.maden.hacettepe.edu.tr/dmmrt>
- (2) **Kentucky Geological Survey**
http://www.uky.edu/KGS/coal/coal_information.htm
- (3) **Electronic Field Trip to a Coal Mine**
<http://www.ket.org/Trips/Coal/AGSMM/agsmmintro.html>
- (4) **Office of Surface Mining Search Engine**
<http://www.wrcc.osmre.gov/GLAS/Search/BrowseList.asp>
- (5) **Office of Surface Mining Technical Library**
<http://www.techtransfer.osmre.gov/NTTMainSite/osmlibrary.htm>
- (6) **National Institute of Occupational Safety and Health**
<http://www.cdc.gov/niosh/mining/pubs>
- (7) **United States Geological Survey Coal Resources**
<http://www.usgs.gov/science/science.php?term=172>
- (8) **Energy Information Administration**
<http://www.eia.doe.gov/>
- (9) **Coal Fires - a natural or man made hazard?**
<http://www.gi.alaska.edu/~prakash/coalfires/coalfires.html>
- (10) **The Encyclopedia of Earth: Coal Fires**
http://www.eoearth.org/article/Coal_fires
http://www.eoearth.org/article/Natural_and_anthropogenic_coal_fires
- (11) **Smithsonian Magazine: Fire in the Hole**
<http://www.smithsonianmag.com/travel/firehole.html>