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Coal Geology: The Origin of Coal

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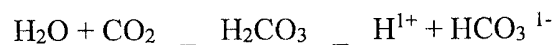


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COAL GEOLOGY: THE ORIGIN OF COAL

The Source of Plants: Coal forms from the tissues of plants with the major contributor being the woody tissues, cellulose and lignin, from trees growing in fresh-water wetlands. Land plants first evolved during the early Devonian and by the end of the period had adapted to most terrestrial environments. Beginning in early Pennsylvanian time, vast portions of the eastern portion of Laurentia were covered with coal-forming swamps and bogs, environments that were to be repeated throughout the remainder of the Paleozoic Era and again in the Jurassic, Cretaceous and Tertiary Periods. It was during these times that the combination of climatic conditions and wetland environments developed that were conducive to the growth and preservation of large volumes of wood-rich plant remains in the form of coal-forming peats, largely as a result of tectonic events that placed the continents into the proper climatic zones while at the same time producing the topographic settings under which vast peat-forming environments could be maintained for long periods of time. Some coals, such as those of the western United States, formed from peat that accumulated in land-locked basins created by the extensional tectonics that affected the region in the Mesozoic time while others such as our eastern coals formed in areas of low topographic relief along the margins of continents where they were near to but, as we will see later, were not chemically influenced by the marine waters.

Peat-Accumulating Environments: Much confusion has been introduced into the literature because of the terminology applied to peat-forming environments, especially the widespread use of the term *swamp*. In recent years, the term **mire** has been adopted by coal geologists for all **freshwater peat-forming environments** with the particular type of mire being primarily based on the relative dominance of **rainwater** and **groundwater**. The importance of rainwater and groundwater lies in the difference in their chemistry. Rainwater is almost always acidic because of its content of carbonic acid produced by the reaction of the falling rain and the carbon dioxide content of the atmosphere:



Groundwater, on the other hand, because of the influx of the soluble bicarbonates of K^+ , Na^+ ,

Ca^{2+} , and Mg^{2+} from the chemical weathering of all of the major rock-forming silicate minerals (except for quartz - SiO_2) is neutral to alkaline. Mires that are totally influenced by rainwater are found in **ever-wet** regions that receive precipitation during 10 to 11 months of the year. Such mires are termed **ombrotrophic** and are referred to as **bogs**. Bogs where the vegetation is dominated by trees are referred to as **bog forests**. Because of the ever-wet conditions that characterize the ombrotrophic mires, precipitation always dominates over evaporation, resulting in high rates of vegetal growth. The combination of the high rates of plant litter accumulation and the reduced microbial activity due to the acidic waters, the peat surfaces in ombrotrophic mires become elevated above the influence of groundwater, forming **domed peats**. Because the peat within the ombrotrophic mires is constantly subjected to percolation acidic water, much of the inorganic constituents originally present in the plant remains and subsequently formed peat are removed by dissolution. As a result, domed peats are the precursors to high quality low-ash, low-sulfur coals. In tropical and sub-tropical regions, such forests are dominated by angiosperms; modern analogs being the peat-forming bog forests of Indonesia.

In regions with more seasonal rainfall, that is with periods of wet and dry throughout the year, mires are subjected to a combination of rainwater and groundwater. Such mires are termed **rheotrophic**. Because of the increased microbial activity resulting from the higher-pH waters, doming of the peat does not take place and the peat mat tends to develop laterally to form **planar peats** with the upper surface of the peat essentially located at the watertable. Examples of rheotrophic mires are estuarine and maritime wetlands such as saltwater marshes and coastal mangrove swamps. However, in such settings, the high rates of microbial degradation often precludes the accumulation of peat, certainly peats that would be precursors to coal. At best, such environments would give rise to carbonaceous shales. As we see in later discussions, the fundamental differences in the chemistry of acid rainwater and neutral to alkaline groundwater is responsible for many of the compositional differences seen in coal, in particular, in the **quality** of the coal which is determined by the relative concentration of ash and sulfur.

The term **swamp** is now restricted to the rheotrophic wetlands in which the water table during the dry season is almost always above the surface of the underlying sediment. The term **swamp forest** usually refers to a tropical or subtropical swamp such as the mangrove swamps of

southern Florida where trees make up the major portion of the vegetation. Rheotrophic wetlands located in temperate regions are usually referred to by the Scandinavian term, **carr**. It is important to note that the modern analogs to the “coal-forming swamps” of the past are, in fact, **not** rheotrophic swamp forests but rather are **ombrotrophic bog forests**.

Effect of Swamp Water pH: Studies have shown that when the pH of the swamp waters is below pH3, microbial activity is very low and remains low so long as the pH remained below pH5. Above pH5, however, microbial activity increased markedly and reached a maximum at pH7. Such studies clearly indicate that in order to accumulate the mass of peat needed to form a coal, the peat must accumulate in an acidic environment, certainly below pH3 - 4. Swamps where the pH rose above Ph5 would not accumulate sufficient volumes of peat to be a precursor to a mineable coal. In addition, the increased decomposition of the organic components of the plants results in the concentration and subsequent increase in the inorganic components of the plants. For example, peat samples taken from marine-influenced coastal swamps invariably showed the inorganic component of the peat in excess of 50%. Such environments would perhaps be precursors to coaly zones and more than likely to black shales, but they certainly not represent depositional environments within which coal-forming peats would accumulate. Such studies of modern swamps soon demonstrated that **all** coal-forming peats accumulated in fresh water conditions with the specific water chemistry depended on primarily on the type of bedrock and the relative influence of acidic rainfall and neutral to slightly alkaline groundwater determining the temporal variations in swamp water chemistry. Under the more acidic conditions, those below pH2 - 2.5, preservation of organic matter was favored resulting in the formation of the brighter bands within a coal bed. At higher, but still favorable conditions of pH, the duller coal bands formed as the relative concentration of mineral matter versus organic matter increased. Before the data from such studies were made available, the accepted analog for a coal-forming peat swamp were the marine-influenced swamps that developed along continental margins and on major deltas such as the Mississippi Delta. Workers of that time subdivided deltaic environments into *lower-*, *middle-*, and *upper-delta plain* coals. Subsequent studies indicated that even the slightest introduction of marine waters into such coastal environments

would result in pH values far above pH5. In addition to the fact that the data clearly indicated that the water chemistry of any swamp that had even the slightest marine influence would preclude the accumulation of a coal-forming peat, the areal dimensions of the various deltaic environments were far too small to account for the areal extent of known mineable coals.

Plant Composition: As is the case with most living organisms, water makes up most of the mass of a plant. Typically, the dry weight of combined plant materials is only about 10% of the original bulk weight with enclosed **mineral matter** (ash) making up about 10% of the dried plant materials. Although the complete range of plant parts are found in coal, most of the volume of a typical coal is composed of the remains of the **woody tissues**. Compared to other plant parts, wood contains the least amount of water with the dry weight of the wood being about 50%.

The organic components of the plant debris consists of a number of different organic materials including: 1) *protoplasm*, 2) *chlorophyll*, 3) *oils*, 4) *carbohydrates* which, in turn, consist of *starches* and *cellulose*, 5) *proteins*, 6) *lignin*, 7) *epidermis*, 8) *seed coats*, 9) *cuticles*, 10) spore and pollen *exines*, 11) *waxes*, and 12) *resins*. Protoplasm, chlorophyll and oils decompose rapidly and quickly disappear while the last six are very resistant and are commonly found in coal in recognizable forms. From the standpoint of peat formation, the principle components are: **carbohydrates** (10 - 55%), 2) **protein** (0.2 - 18%), and 3) **lignin** (10 - 35%).

Carbohydrates are long-chained organic compounds that include the **monosaccharides** (simple sugars such as glucose, $C_6H_{12}O_6$), and **monosaccharides polymers** such as starch (the form in which plants store glucose) and **cellulose**. Cellulose, $(C_6H_{10}O_5)_n$, forms the basic framework of the plant cell walls and is the most abundant glucose polymer, containing approximately half of all the organic carbon in the biosphere. From the standpoint of coal formation, cellulose is the most important carbohydrate.

Proteins are complex chain structures consisting of at least 50 amino acids. An **amino acid** is a **carboxylic acid** with an amine group (NH_2) on the carbon chain. A carboxylic acid is a carbon chain ending with a carboxyl group, ($-COOH$).

Lignin consists of an aromatic nucleus (one made from benzene rings), a side chain with three carbon atoms, hydroxyl groups ($-OH$), and methoxyl groups ($-OCH_3$). The lignin content of

wood ranges from 25% to 30%. Lignin and cellulose are the primary plant components from which the great volume of coal forms.

Rates of Accumulation of Plant Debris: The rate at which plant debris accumulates varies greatly with the particular type of plant. For example, from the standpoint of dry matter accumulation, the most prolific of the modern plants are the cat-tails (*Typha*) that provide plant debris at rates from 5 kg/m²/yr to as much as 15 kg/m²/yr. Cat-tail remains are converted into peat that adds to the surface of the peat mat at a rate of about 0.5 to 1.0 mm/yr. In comparison, swamp forests in Florida generate plant debris at a rate of about 2 to 3 kg/m²/yr with subsequent peat accumulation of about 1 to 2 mm/yr; the higher rate of peat accumulation reflecting the higher concentration of woody tissue in the mangrove trees that inhabit the Florida swamp forests. In temperate and cooler boreal regions (tundra and taiga), plant accumulation rates rarely exceed 1 kg/m²/yr due to the lack of large wood-rich trees. However, because the cooler climates inhibit the microbial activity responsible for plant decay, peat deposits are widespread.

From these few data, one can see that the rates of peat accumulation depends on factors other than plant productivity. A simple, and speculative, model relates peat accumulation rates to the mean temperature and the annual precipitation. Under temperate conditions where cooler temperatures and limited rainfall inhibit microbial activity, the rate of accumulation of plant litter increases with increased precipitation, reaching a maximum of about 1.3 kg/m²/yr at a precipitation level of 2.2 m/yr after which the accumulation rate decreases with increasing precipitation. Under such conditions, peat may form even on non-wetland, sloping surfaces with annual precipitation rates of only 1.5 m/yr. Under tropical conditions, the rate of litter accumulation increases to a maximum of about 4 kg/m²/yr at an annual precipitation of 2.8 m. Again, increased precipitation results in decreased accumulation. It is important to note that in tropical regions, except for basins where water may accumulate, very high rates of precipitation are required for the accumulation of peat. Studies have shown that even under suitable wetland conditions, the increased rate of microbial degradation of the plant litter in tropical areas requires a minimum of 2 m of annual precipitation just to maintain a peat mat.

Microbial Degradation

Introduction: The process of **coalification** begins with the microbial attack on the accumulated plant debris. Aerobic conditions at the surface of the mire support the life processes of microbes including **fungi, bacteria, and actinomycetes** (micro-organisms resembling both fungi and bacteria), all of which take part in the biochemical reactions that initiate the transformation of cellulose and lignin into peat. In order for peat to accumulate, the rate of plant growth must obviously exceed the rate at which the micro-organism decompose the plant debris. In order for this to occur, the decaying materials must be transferred into an environment where microbial activity progressively decreases; the most effective environment being a waterlogged site (a wetland) with living plants at the surface dead plants undergoing decomposition immediately below the surface that serve as a major source of nutrients for the living plants, all underlain by a mass of decayed plant debris undergoing decreasing rates of microbial decomposition.

Controls of Microbial Activity: Under most non-wetland surface conditions, plant debris is totally decomposed by a combination of microbial activity and chemical oxidation and is recycled. In order for a coal-forming peat to accumulate, processes of plant decay must be reduced to the point where the rate of litter accumulation exceeds the rate of litter decay. The major process that must be affected is microbial activity.

Microbial activity is largely controlled by: 1) *availability of moisture*, 2) *temperature*, 3) *supply of nutrients*, and 4) the *acidity/alkalinity* of the water. Of the four, the **availability of moisture** is the main factor. Excessive moisture, such as in waterlogged mires, reduces the overall activity of bacteria to a minimum by excluding air from the aerobic bacteria while at the same time allowing the continued growth of plants at the surface of the mire. As long as the mire is kept wet by either high levels of precipitation or poor drainage or a combination of both, the rate of decomposition will be depressed relative to the rate of plant growth and peat will accumulate. Note also that under typical wetland conditions, chemical oxidation is severely inhibited as available dissolved oxygen reacts with the abundantly available carbon to form CO₂.

Assuming adequate availability of moisture, the rates of both plant growth and bacterial activity increase with increasing **temperature**. Because plants are less affected by variations in

temperature than are bacteria, bacterial activity decreases at a faster rate than plant growth with decreasing temperatures. As a result, while plant growth may be maintained in cool, temperate climates, bacterial activity may be reduced to the point that increased amounts of plant debris undergoes preservation and is subsequently transformed into peat; explaining why modern peat development is most extensive at latitudes greater than 45°. Another example of peat accumulation in cool, moist climates is located in Europe along the Atlantic coast where the combined effects of high rainfall, dense clouds, and cool summer prevail. In comparison, the accumulation of peat in tropical regions requires bacterial activity to be reduced to such a level that the rate of plant growth greatly exceeds that of decay; a scenario that requires either the presence of acidic waters such as is found in the domed swamps or the presence of toxic materials generated during the decomposition process.

The inorganic nutrients required by bacteria and fungi, namely, **potassium**, **phosphate**, and **lime**, are similar in kind but not in abundance to those needed by green plants. In general, the abundance of nutrients in mire waters is dependent on the acidity/alkalinity of the water.

Acidic water will contain relative few nutrients while nutrients will be more abundant in neutral to alkaline waters because of their higher ionic strength. While more extensive plant growth and subsequent increased masses of plant litter will occur on rich soils or in waters with high mineral contents, the debris will be subjected to high bacterial populations and, therefore, high rates of bacterial decay. On the other hand, plant debris derived from plants growing in poor or impoverished soils or in water low in dissolved solids will be subjected to lower rates of bacterial activity, resulting in increased rates of peat accumulations.

Effect of Burial on Bacterial Activity: During the initial phases of coalification, the biological/bacterial processes take place at atmospheric temperatures and pressures. Within the peat layer, the availability of dissolved oxygen decreases with depth as do the number of aerobic micro-organisms until eventually the biochemical processes affecting the peat are totally driven by **anaerobic bacteria**. Because of the ease with which they can be utilized by the micro-organisms, cellulose and its decomposition products remain the most important sources of carbon for micro-organisms under both aerobic and anaerobic conditions. Only with the onset of

the more severe conditions that develop within the peat layer with increased depth does lignin begin to decompose.

Once the peat layer has been buried by sedimentation, usually fluvial in origin, a major change takes place within the buried peat largely due to the geothermal gradient. Once the temperature reaches and exceeds 100°C, microbial activity is precluded, bringing the microbiological phase of coal formation to an end, from which point the physical-chemical processes take over.

Physical-Chemical Processes of Coalification

Introduction: Once microbial activity ceases, continued coalification is dependent on three physical parameters: 1) *pressure*, 2) *temperature*, and 3) *time*. Notwithstanding the importance of time, temperature is the most important of the three with pressure actually inhibiting the coalification process.

After burial, most coalification processes take place at temperatures between 100°C and 200°C; the process commonly being compared to baking in a “slow” oven. Although the temperatures seem to be quite low, they are able to support reactions that modify the composition and structure of the organic components of the peat including **decarboxylation, condensation, desiccation**, and various structural rearrangements that occur during continued coalification.

Once coalification proceeds beyond the lignite stage of coal rank (rank will be discussed later) the chemical and physical conditions are of such severity that the process must be considered **metamorphic** in character. Because organic materials are far less resistant to heat than are inorganic materials, the organic coal materials will undergo major metamorphic changes even though the rocks around them will show no alteration. As coalification proceeds, the initial base-soluble organic materials such as **humic acids** are converted into increasingly insoluble materials with concurrent structural rearrangements within the coal mass resulting in an increase in the aromaticity of the coal molecule. By the time coalification reaches the anthracite stage, the coal molecule is composed entirely of condensed benzene rings.

Processes of Coalification

Introduction: Three processes are involved in the transformation of plant debris during the peat-brown coal stages of rank development: 1) *peatification*, 2) *humification* and 3) *gelification*.

Peatification: The first step in coalification begins with the attack of the accumulated plant debris by bacteria and fungi during which the easily hydrolyzed plant components such as **sugars, starches, cellulose, and proteins** are decomposed. A goodly portion of these components decompose under aerobic conditions to carbon dioxide (CO₂), ammonia (NH₃), methane (CH₄), and water which are either removed in solution or escape into the atmosphere. The major result of these early coalification processes is the concentration of the relative stable lignins and mineral matter in the peat.

Humification: Of all of the coalification processes, **humification** is probably the most important. Humification is a slow oxidation process, although it may be accelerated by the introduction of additional oxygen into the peat such as during periods of drought when the watertable is depressed or at sites where oxygenated water is introduced into the mire. The process of humification is most severe on and immediately below the peat surface in what is referred to as the *peatigenic layer*.

The major plant tissues that are precursors to coal are cellulose and lignin. During the rotting of plant tissues, the linear macro-molecular (aliphatic) structure of cellulose is rapidly attacked by micro-organisms to form glucose which is, in turn, used by the plants as an energy source and to make their body parts. Experiments have shown that in the presence of the nitrogen provided by the ammonia (NH₃) generated during coalification, cellulose will decompose fifteen times faster than lignin. The reason why lignin decomposes more slowly than cellulose is because the combined 3-D aliphatic-aromatic structural units of lignin are far more resistant to the microbial bond-breaking processes that easily break the long-chain structures of cellulose. Once the cellulose fibrils are removed from the cell walls, the lignin within the cell becomes accessible to oxidative degradation. Because lignin decomposes much more slowly than cellulose, lignin becomes, with time, an increasingly more important material for the formation

of the humic substances from which coal forms.

Oxygen is necessary for the humification of lignin. In the presence of oxygen and following the removal of the cellulose-rich cell walls, the first attack on lignin is made by wood-destroying fungi followed by aerobic bacteria, converting the lignin into **humic acids**. By definition, humic acids are those organic materials that are insoluble in acids and organic solvents but are soluble in alkalis. The microbial attack on lignin first removes the aliphatic side chains from the aromatic ring structures that serve as its core and then attacks the ring structures themselves. The smaller molecular units that are subsequently formed then become the basis for the formation of the humic acids. As the process continues and the -OH and -COOH groups are removed from the humic acids, they lose their acidic character and are converted into **humins**, the precursors to the **vitronite macerals** (to be discussed).

Gelification: The process of **gelification** follows humification and leads to the formation of vitronite by the sub-bituminous stage of rank development. Studies have indicated that the gelification process entails bringing the humins into *colloidal solution* with the formation of a **gel** which is subsequently desiccated. Two types of gelification are recognized: 1) *biochemical* and 2) *geochemical*.

Biochemical gelification initiates the process during the peat and soft brown coal stages (pre-lignite); the process being governed by the original materials, the kinds and abundances of ions available in the interstitial water, the acidity/alkalinity of the water, and the redox potential (reduction-oxidation) of the system. **Geochemical gelification** affects the humins once the materials have attained the boundary between dull and bright hard brown coal (lignite and sub-bituminous coal). Unlike biochemical gelification that goes on at atmospheric temperatures, geochemical gelification requires elevated rock temperatures that are attained only after the peat has undergone a certain amount of burial. The major change brought about by geochemical gelification is the conversion of the humins into the vitronite coal macerals. By the time coalification has progressed to the bituminous stage, the vitronite consists of humins that are totally insoluble in alkalis.

The Coal Macerals

Introduction: Macerals are to coal what minerals are to rocks; they are the microscopic entities of which the organic portion of coal is made. There are three maceral groups: 1) *vitronite*, 2) *exinite*, and 3) *inertinite*. Because most modern coal petrography is performed on polished coal surfaces using reflected light and oil immersion lenses rather than using thin sections and transmitted light, the maceral types are identified primarily on their relative colors and the degree to which they reflect incident light (brightness). **Vitronite**, for example, is usually light to dark gray in color while **exinite** is much darker. **Inertinite** is the most reflective of light and are therefore the brightest macerals when viewed under the microscope. In addition to being very bright, the inertinites are also the hardest of the maceral types and therefore commonly stand out in relief above the polished surface of the coal mount. Within the same rank, vitronite contains relatively more oxygen, exinite more hydrogen, and inertinite more carbon. Of the three, exinite contains the highest concentration of volatile matter (35 wt%) and inertinite has the lowest volatile content (23 wt%).

Vitronite: Volumetrically, **vitronite** is the most abundant of all the macerals and is responsible for the brilliant, black bands one sees in coal. Vitronite forms primarily from trunks, branches, stems, leaves, and roots. There are three types of vitronite: 1) *telinite* which forms from the remains of cell walls and within which the cell structures are still visible, 2) *collinite* which is the structureless constituent of vitronite formed from preserved cell fillings, and 3) *vitrodetrinite* which consists of aggregates of small, irregular-shaped fragments of vitronite that cannot be assigned with any assurance to either of the other two types. Many observations of detrovitronite indicate that the vitronite components actually formed early in the degradational history of the peat materials and do not simply represent fragments of vitronite that have been formed by the pressure-crushing of existing vitronite.

Often, the **telinite** (cell walls) is filled with **collinite**. Collinite is considered to be a preserved gel, explaining the structureless appearance. The name is derived from the Greek word *kolla* meaning glue. Collinite does in fact commonly serve as the binder or *glue* with which the

other coal components are held together. In cases where cell structures are difficult to see, the telinite maceral is simply recorded as vitrinite. Pure telinite is relatively rare.

Compositionally, vitrinite consists of aromatic nuclei surrounded by aliphatic groups such as -OH, -COOH, and -CH₃. With increasing rank, the peripheral aliphatic groups are lost and the aromatic nuclei increase in size.

Exinite: **Exinite**, also called *liptinite*, is derived from the remains of the most chemically resistant plant components, namely, spores, cuticles, resins, and algae giving rise to the four kinds of exinite macerals: 1) *sporonite*, 2) *cutinite*, 3) *resinite*, and 4) *algenite*. A fifth exinite maceral, *liptodetrinite*, is to the exinite maceral group what vitrodetrinite is to the vitrinite maceral group. As a result of compositional changes that take place within the exinite materials during metamorphism, exinite cannot be microscopically distinguished from vitrinite beyond the upper end of the low-volatile bituminous rank.

Sporonite consists of the skins of spores and pollen. In most Paleozoic bituminous coals, sporonite is overwhelmingly the major maceral of the exinite group. It is estimated that, on the average, a gram of Paleozoic coal contains 5 million spores. Spores are easily recognized under reflected light because of their dark colors. Because spores are invariably compressed by burial, they are identified by their cross-sectional shapes. Spores are classified based on two parameters: 1) size as **megaspores** (> 200 microns) and **microspores** and 2) the thickness of the cell wall as either **tenuispores** (thin-walled) or **crassisporos** (thick-walled).

Megaspores have been identified with diameters as large as 3 mm. The composition of sporonite is thought to be similar to that of vitrinite (aromatic ring structures with aliphatic side chains) but with fewer condensed rings. When heated, sporonite yields more gas than the total coal sample and typically generates exceptionally high tar yields.

Cutinite is made up of the highly resistant skin, or *cutin*, that covers and protects the surfaces of leaves, needles, shoots, stalks, and the thin stems of plants. Some plants that grow under water do not possess cutin. The widespread occurrence of cutinite in coal is due to several factors including the high resistance of cutin to chemical reactions, its resistance to heat, and the fact that it is not accepted as a food supply by bacteria and fungi. In Paleozoic bituminous coals,

cutinite is less abundant than spononite. The characteristic compositional feature of cutinite is its high hydrogen content (~50 atomic%).

Resinite includes all the resinous substances in coal. Resins, such as sap, are the products of plant metabolism. With increasing metamorphism, much of the resinite present in lower-rank coals is converted into vitrinite. Typical of exinites, resinite is enriched in hydrogen; in fact, studies have shown that resinite contains more hydrogen than spononites of the same carbon content.

Algenite is preserved algae and has the lowest reflectivity and therefore appears as the darkest bodies under reflected light. Algenite is not usually found in humic (layered) coals but is abundant in boghead coals where it represents the preserved remains of the algae *Pila* and *Reinschia*.

Liptodetrinite is the catch-all classification for finely divided particles of exinite that cannot be assigned with reasonable certainty to any other member of the exinite group.

From the standpoint of coal utilization (to be discussed later), especially the conversion of coal into gaseous and liquid fuels, the exinite macerals are the most important. Because exinite is enriched in hydrogen, it produces the greatest volume of tars upon heating. The tar yield from spores and cuticles ranges from 20% to 40% while waxes and resin produce as much as 80% to 90% tar.

Inertinite: The term **inertinite** derives from the fact that while the vitrinite and exinite macerals soften during the coking process (the roasting of coal to produce a carbon-rich product) the inertinite macerals are little affected. Compared to exinite, inertinite is poor in hydrogen and rich in carbon. The inertinite maceral group consists of *fusinite*, *semi-fusinite*, *macrinite*, *micrinite*, *sclerotinite*, and *inertodetrinite*.

Fusinite and vitrinite form from the same plant materials. Although particularly common in bituminous coals, fusinite rarely exceeds a few percent by volume. Based on the mode or origin, fusinite is subdivided into **pyrofusinite** and **degradofusinite**. Pyrofusinite is the charred remains of woody tissue that forms by rapid oxidation such as swamp fires while degradofusinite is the result of slow, chemical oxidation.

Studies of woody tissue taken from modern peat that has been subjected to swamp fires have shown a continuous transition between unoxidized wood to partially charred wood (*semi-fusinite*) to totally carbonized wood (*pyrofusinite*). Comparable transitions have been found in preserved wood specimens within coal where one end of the wood fragment has been completely burned and converted to fusinite while the other unburned end has been converted to vitrinite. Most of the fusinite found in Carboniferous and Permian coals is degradofusinite that forms during the moldering of the peat by bacteria and fungi at the surface of the peat mat where the supply of oxygen is at a maximum.

Fusinite is characterized by high carbon and low hydrogen contents with both physical and chemical properties showing little change with increasing rank. It might also be pointed out that it is the fusinite content of coal that makes it “dirty” and which coats miners faces at the end of the work day.

Semifusinite is an intermediate stage between fusinite (total carbonization) and tellinite (no charring). Most of the fusinite in Carboniferous and Permian coals is of the degradosemifusinite type.

Macrinite is a more or less amorphous, non-granular groundmass exhibiting high reflectance. As a maceral, macrinite is relatively rare and appears mostly in durites and clarodurites (coal lithotypes that will be discussed below).

Micrinite is characterized by its rounded shape and small size (about 1 micron in diameter). Micrinite can occur in all lithotypes but is especially abundant in durites.

Sclerotinite forms from the sclerotia of fungi (masses of branched structures within which food is stored). Compared to Tertiary coals, sclerotinite is relatively rare in Carboniferous and Permian coals.

COAL LITHOTYPES

Introduction: Coals are classified based on their structure and source of origin as being either *humic* or *sapropelic*. **Humic coals** are *layered* or *banded* and form from peat that accumulated in swamps and that formed from *plant debris* by the process of *peatification*. **Sapropelic coals**, on

the other hand, are *non-stratified* and form from a mixture of *finely divided plant debris, spores, and algae* that accumulated in *stagnant or standing bodies of water* and are initially converted by the process of *putrefaction*. Sapropelic coals include *cannel coals* and *boghead coals*, both of which are relatively high in volatiles and are typically dull in appearance. Humic coals are, by far, the more abundant of the two; sapropelic coals are, in fact, quite rare.

Humic Coals: Humic coals are characterized by macroscopic layers or bands called **lithotypes** that are identified based on their degree of brightness and differ compositionally in their relative abundance of the various macerals. There are four basic humic coal lithotypes: 1) **vitrain** (bright bands), 2) **clarain** (semi-bright bands), **durains** (dull bands), and **fusain** (mineral charcoal). **Duroclarain** and **clarodurain** represent the transition between clarain and durain. The coal lithotypes and their characteristic maceral groups and individual maceral types are summarized in the following table:

LITHOTYPE	MACERAL GROUP
	INDIVIDUAL MACERAL TYPES
Vitrain	vitrinite (Vt) collinite (cell fillings) telinite (cell walls)
	micrinite massive (inertinite detritus) fine (microspore protoplasm)
Fusain	inertinite (I) semifusinite fusinite sclerotinite (fungal remains)
	cutinite (skins of leaves) resinite (resin bodies, cell fillings) sporonite (spore remains)
	Exinite (E) algenite (algae, <i>Pila</i> , <i>Reinschia</i>)
Clarain	Vt + E
Duroclarain	Vt + E + I
Clarodurain	I + E + Vt
Durain	I + E

Sapropelic Coals: Sapropelic coals are subdivided into two lithotypes: 1) *cannel coals* and 2) *boghead coals* with transitions in between. As previously pointed out, the major difference between humic and sapropelic coals is that humic coals are layered or banded while sapropelic coals are not. Because of their composition and lack of internal structure, sapropelic coals are dull, dense, and very strong. From prehistoric times, sapropelic coals have been carved into statuary and jewelry. Even today, cannel coals are used in the production of “coal art”.

Macroscopically, cannel coals and boghead coals are difficult to distinguish; both being dull black and exhibiting a greasy luster and conchoidal fracture. Microscopically, however, they differ in that cannel coals show micro-stratification, contain little or no algenite, and are commonly rich in spores. Boghead coals, on the otherhand, are non-stratified and are composed primarily of algenite.

COAL RANK

Introduction: Coal **rank** refers to the degree of coalification or metamorphism to which the plant materials have been subjected and takes into account all of the chemical and physical changes that take place within the material. The rank series begins with *peat* as the lowest rank coal and ends with *meta-anthracite* as the highest rank of coal. Metamorphism beyond the meta-anthracite stage results in the formation of **graphite**. The following table summarizes the various coal ranks and the pertinent compositional parameters that distinguish each rank. The numbers in the table represent the estimated averages for the mid-range rank. Note that sub-bituminous A and high-vol bituminous ranks are the same. The higher rank designation was initiated strictly for sales purposes and has no geological significance.

In the following chart and in subsequent discussions, **vitroinite reflectance** (%Ro) is the *percent of light* reflected from a polished coal surface as determined by a microscope equipped with a photocell. The designation, **d.a.f.** stands for *dry ash free* and **a.f.** stands for *ash free*.

Rank	Vit. Refl.	d.a.f.	d.a.f (%Ro). carbon	volatile BTU/#
	matter			
meta-anthracite		4	2 15,500	95%
anthracite		3.2	5% 15,500	95%
	----- 2.5 ----- 8% ----- 92% -----			
semi-anthracite		2.1	11% 15,500	90%
low vol. bituminous		1.7	18% 15,500	89%
med.vol. Bituminous		1.3	29% 15,500	87%
high A		0.82	35% 14,100	82%
vol. B		0.72	41% 13,000	78%
bitum. C		0.60	45% 12,000	75%
	A	0.60	45% 12,000	75%
sub. B		0.45	48% 9,900	72%
bitum. C		0.40	51% 9,000	69%

lignite	0.32	58%
	65%	7,000
peat	0.25	67%
	55%	4,500

During the first stages of coalification, the biological-bacterial processes dominate and convert plant debris into the lowest rank coal, **peat**. By the time rank has risen to the lignite stage, conditions of temperature and pressure preclude the survival of microorganisms and the process becomes purely chemical or physical in nature with most of the energy used to drive the coalification process being provided by *heat*. Beyond the lignite stage, the changes that take place within the coal are sufficiently severe that the coalification process can realistically be considered metamorphic in character.

Effect of Depth of Burial: In most cases, the primary factor driving the metamorphic process is the heat provided by the *geothermal gradient*. Studies have shown in a few isolated cases, the heat was provided by magmatic sources located below the basin of accumulation. Overburden pressure, although responsible for physical changes such as the compaction that takes place within the coal, is **not** responsible for any of the chemical changes that take place with increasing rank. In fact, experiments conducted under the same temperatures and for the same lengths of time but under different pressures showed that the degree of carbonization as measured by vitrinite reflectance *decreased* with *increasing* pressure. It is important, however, to note that carbonization is accelerated by *tectonic pressure*. Studies have definitely shown that the coalification from the meta-anthracite rank to graphite requires conditions brought about by the tectonic deformation resulting from plate collisions where the important agent was the involvement of **tectonic shear**. It is also important to repeat the fact that, except for the change of anthracite to graphite where temperatures in the range of 300°C to 350°C (and higher) are involved, the temperatures during the coalification process rarely exceed 200°C.

In the discussions that follow, keep in mind the factor of *time*. Shallow burial of peat over long periods of time can produce the same result as deep burial over short periods of time. It is

also important to note that the entire coalification process from peat to the beginnings of the conditions that result in the formation of anthracite coal rank has taken place before any change (diagenesis) in the surrounding sedimentary materials has begun.

One of the first studies to document the effect of depth of burial on the coalification process was reported in 1963 based on samples removed from the German Munsterland I borehole in the Saar region of western Germany. At the time, the borehole was the deepest in Europe. The maximum temperature measured in the borehole was 209°C at a depth of 5,956 meters (19,541 feet). The borehole encountered about 100 coal beds and thin coal bands with the uppermost Carboniferous beds encountered at 1,844 meters (6,050 feet) and the deepest coal was encountered at 3,445 meters (11,302 feet). Data from the study showed that with increasing depth: a) the *d.a.f.* (dry ash free) *volatile matter* decreased almost linearly from 35% to about 5%, b) the *moisture content* decreased from 4% to 0.8%, c) *vitrinite reflectance* increased from slightly more than 1%Ro to almost 4%Ro, d) *d.a.f. carbon* increased from 80.5% to 90%, and e) *a.f.* (ash free) *calorific content* increased from 7,600 kcal/kg to 8,700 kcal/kg. Another important discovery from this and similar studies was that the increase in rank with depth of burial is totally independent of the composition of the coal.

Determination of Rank: Because of the systematic changes in the various coal parameters with rank, any one of the discussed parameters could be used to determine rank. The parameter(s) used depend primarily on the rank itself. For example, for coals lower in rank than medium-volatile bituminous, changes in *d.a.f. carbon*, *d.a.f. volatile matter*, and *vitrinite reflectance* are not only irregular but change very little with any incremental change in rank. As a result, these are not the best parameters to determine rank below the rank of medium-volatile bituminous. On the otherhand, the *a.f. moisture* and *calorific values* for these coals show marked changes with rank and, therefore, are the best indicators of rank.

As rank increases beyond the high-volatile bituminous rank, moisture and moisture-dependent calorific content change little with increasing rank. From medium-volatile bituminous to semi-anthracite (between 30% and 8% volatile matter), *volatile matter* and *vitrinite reflectance* are the best determiners of rank. The most common parameter used to determine the

rank of bituminous and anthracite coals is vitrinite reflectance (%Ro) which is a measure of the percent of incident light reflected from a polished coal surface. Once rank has attained the anthracite and meta-anthracite levels of rank, *hydrogen content* is the best rank indicator.

Compositional and Physical Changes with Increasing Rank: In the lignite to sub-bituminous range (the hard brown-coal stage), vitrinite undergoes profound physical changes. Below the rank of lignite, cell walls and cell contents are readily visible in the stems of plants. As the coal enters the lignite rank, the process of **gelification** has resulted in the compaction and homogenization of the cell tissues leading to the formation of a *gel* from which the **homogenous vitrinite** of bituminous coal forms. As a result of these combined chemical/physical modifications, the coal changes from soft, brown, and dull to hard, black, and bright. Water is expelled as the change takes place, explaining the marked decrease in moisture content during early coalification. Because the calorific content of ash-free coal is highly dependent on the moisture content, the decrease in moisture is accompanied by a parallel increase in calorific content. During this stage of coalification, the humic substances lose increased numbers of -COOH, -C=O, -OCH₃, and -OH groups from their aromatic cores resulting in the concurrent increase in the aromaticity of the coal and a decrease in the oxygen content.

At approximately 87% carbon and 29% volatile matter (medium-volatile bituminous rank), an important change referred to as the **coalification break** takes place. By this time, desiccation of the humic gel formed by the gelification process is near complete. With increasing rank, the hydrogen-rich methyl (-CH₃) groups associated with the aromatic core are reduced and methane (CH₄) begins to evolve. With the loss of the methyl groups, the aromatic clusters begin to condense into larger groupings, further concentrating the aromatic carbon and subsequently resulting in an increase in the vitrinite reflectance.

The rank stages and a summary of the basic coal characteristics are listed below:

Rank Stage

**% d.a.f. %
d.a.f. vitrinite
moisture**

	Carbon refl. (%Ro)	BTU/lb. vol. mat. %
meta-anthr. anthracite	91	15,500
semi-anthrac. low-vol bitu.	87	15,500
med-vol bitu.	77	12,600
high-vol bitu.	71	9,900
sub-bitum.	53	7,200
lignite	60	75
brown coal		
peat		

COAL QUALITY

Coal quality is determined by the ash and sulfur content of the coal and is subdivided into *high*-, *medium*-, and *low-quality*. Because of their common source is the plant debris, the content of ash and sulfur generally increase and decrease together. The conditions responsible for the incorporation of both ash and sulfur into the coal will be discussed later. The subdivision into the three levels of coal quality is purely arbitrary. Generally, **high-quality** coal is any coal whose ash content is less than 10% and whose sulfur content is less than 1%. Experience have shown that coals containing less than 10% ash and 1% sulfur can be mined and utilized with little or no environmental impact. however, as the ash and sulfur exceed these levels, problems involving the generation of acid mine drainange (AMD) during and following the mining of the coal and the problem of air pollution when the coal is burned become increasingly troublesome.

Unlike the standards set for high-quality coal, the original specifications separating medium- and low-quality coal depended more on the potential environmental impact of the purpose to which the coal was being put. Generally, medium-quality coals were those whose ash and sulfur contents could be reduced by various cleaning operations to produce a coal that would

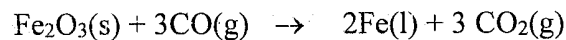
be acceptable for a coal-burning power plant. Coals that would be acceptable as medium-quality would be those containing from 15% to 30% ash and 1% to 3% sulfur. Coals with ash contents in excess of 30% and sulfur contents over 3% would normally be considered of poor quality.

It should be noted that the EPA Clean Air Act of 1967 defined a **compliance coal** to be used in coal-burning power plants. The requirement is that the coal produce no more than 1.2 pounds of SO₂ per million BTU of heat generated which is equivalent to a total sulfur content of 1.2% or less. Because ash contributes no environmental problems, there is no limit placed on the ash content of compliance coals. The requirements for coal-burning power plants will be discussed more fully in the next section.

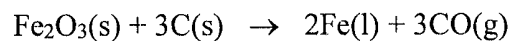
COAL UTILIZATION

Introduction: Historically, coal has been used for two purposes: 1) the production of **coke** and 2) the generation of **steam**. Since the Industrial Revolution of the mid-1700s, the major use of coal has been to produce steam; first to drive steam engines and more recently, to drive steam-driven turbines. Today, most coal is used to drive steam turbines to produce electricity.

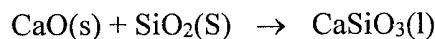
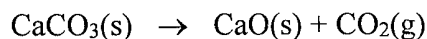
Coking Coal: **Coke** is coal that has been *roasted* in an anoxic environment to drive off the volatiles and thereby concentrate the carbon. The major use of coke is the reduction of iron ore to free iron in blast furnaces (Figure XX). The furnace is charged from the top with a mixture of crushed iron ore (Fe₂O₃), coke (C), and limestone (CaCO₃). Blasts of hot air or oxygen are injected into the bottom of the furnace. The oxidation of the carbon to carbon monoxide (CO) generates additional heat and the carbon monoxide reduces the iron ore in a series of steps. The overall reaction is as follows:



some of the iron ore is reduced by the carbon as well:

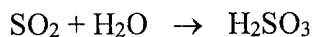


The limestone is converted to calcium oxide that removes the silica from the ore as a mixture of molten calcium silicates called **slag**:



The requirements for coking coal are very stringent; less than 6% ash and 0.5% sulfur. In addition, any impurities in the coal used to make coke could potentially be transferred to the molten iron which, in turn, would affect the quality of any steel produced from the iron. As a result, only the highest quality coals are used to make coke. Although bituminous coals are preferred, there are no rank requirements for coking coal. Because of the carcinogenic volatiles generated during the coking process and their potential environmental problems, most of the coking coke used in the United States is imported.

Steam Coal: Until the Environmental Protection Act of 1967, any coal that did not qualify as a coking coal was considered a **steam coal**. The major environmental problems associated with the use of coal as a fuel for power plants is that during the combustion of the coal, all of the sulfur is converted into sulfurous gases (SO_x) which, if allowed to enter the atmosphere, react with water to produce sulfurous and sulfuric acids, both of which are very strong acids:



The combination of sulfurous and sulfuric acids from coal-fired power plants combined with the nitrous and nitric acids generated from the reaction between NO_x gases produced by internal combustion engines are responsible for most of the **acid rain** that affects the industrialized countries of the world. Because of the air pollution problems that arose due to the widespread

burning of coal, especially during the past century, laws being enacted to limit the volume of SO_x gases being released into the atmosphere. The compliance coals previous discussed are the result of such legislation in the United States.

Within the United States, considerable variability exists in coal quality. Most of the western coals are Cretaceous and younger in age. Except for some bituminous coals in the Book Cliffs region of Utah, all western coals are either sub-bituminous or lignite in rank and all are high quality coals containing less than 1 wt% sulfur. Because they all qualify as compliance coals, the western coals need no pre-use treatments; the coals are mined and shipped by 100-car trains directly to centrally located power plants where they are burned to generate electricity. Of the western states, Wyoming is the major coal producer and, nationwide, vies with West Virginia for the #1 coal producer.

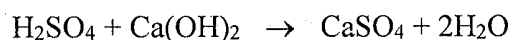
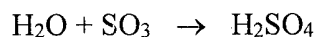
The eastern coals come from three relatively large coal basin: 1) the *Mid-Continent Basin*, 2) the *Illinois Basin*, and 3) the *Appalachian Basin*. A fourth coal basin, the Michigan Basin, produced no commercial coal. Except for a small region of anthracite production in eastern Pennsylvania in the Scranton-Wilkesbarre area, all of the eastern coal basins produce bituminous coal. The eastern coals vary in coal quality with **high rank, compliance coals** being produced in the southern Appalachian Basin (southern West Virginia and eastern Kentucky), **medium-quality coals** from the northern Appalachian Basin (northern West Virginia, western Pennsylvania, eastern Ohio, and western Maryland) with one medium-quality coal from the Illinois Basin, the Herron #6. The remaining coals in the Illinois Basin and nearly all of the coals in the Mid-Continent Basin are of **low-quality**.

In general, the sulfur present in coals containing less than 1% total sulfur is in the form of **organic sulfur**, which cannot be removed either physically or chemically, and small concentrations of **framboidal pyrite** (FeS₂). When the total sulfur of coal exceeds 1%, the reason for the excess is the presence of pyrite in the form of massive **cell fillings** and **fracture fillings**, rendering them medium-quality. Before medium-quality coals can be considered for use as steam coal, the sulfur contents must be reduced by either *cleaning* or *blending*. **Coal cleaning** involves crushing the coal and attempting to remove as much of the massive pyrite as possible by gravity separation float-sink methods. All eastern coals are subjected to float-sink

cleaning processes. Because of its high sulfur content, the disposal of the reject material, called **coal refuse**, has historically been a major environmental problem for coal producers.

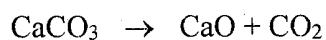
Assuming that the cleaning process was not successful in producing a compliance coal, the cleaned coal can then be **blended** with the necessary volume of high-quality coal to produce a blend that is within the requirements of compliance. Most eastern power plants use coals from several sources in order to provide the compliance coal required by law.

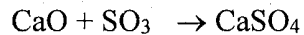
In addition to the treatment processes of cleaning and blending, other processes are now available which allow the sulfur problem to be solved by capturing the SO_x gases before they have the opportunity to escape to the atmosphere. One such solution is the use of a **scrubber**. Scrubbers are mechanical devices located between the combustion chamber and the exhaust stack that literally *scrub* the gases emerging from the firebox with an alkaline solution that generates and subsequently neutralizes the sulfurous and sulfuric acids before they have the opportunity to escape to the atmosphere:



Note that the first reaction that that goes on within the scrubber is the same as that which would have produced the acid in the atmosphere had the SO_x gases been allowed to escape. Note also that the products of the scrubber, an inert sulfate and water, are removed from the scrubber and disposed of without harm to the environment. Since 1985, all new coal-fired power plants must incorporate scrubbers in their initial design and all older power plants are required to install scrubbers.

A relatively recent development to mitigate the sulfur problem in coal-fired power plants is the use of a **getter** which is a chemical that is added to the combustion chamber along with the fuel that "*gets*" (reacts with) the SO_x gases as they are being produced. The most commonly used chemical is powdered limestone (CaCO₃). In the combustion chamber, the limestone is thermally decomposed into calcium oxide (CaO) and CO₂. The calcium oxide then reacts with the SO_x gases to produce an inert sulfate that is removed with the ash:





Note that in the above discussion, the word "**fuel**" was used instead of coal. Because systems utilizing getters are so efficient, carbon-rich materials of *any* sulfur content can be used as fuel. Not only can coal of any quality be used as a fuel but also the high-sulfur refuse from coal cleaning plants that have always been a disposal problem can now be used as a fuel. Facilities employing getters have computers that constantly monitor the sulfur content of the fuel and calculate the amount of the getter that must be introduced into the combustion chamber along with the fuel to react with 100% of the SO_x produced during combustion. A local facility, for example, burns a mixture of 60% high-sulfur refuse from coal cleaning plants and 40% coal. Plants employing getter technology could, in fact, burn 100% refuse. An additional plus for plants using getters is that if the amount of limestone added to the fuel is in excess of that needed to react with all generated SO_x gases, the ash contains a combination of CaO, Ca(OH)₂, and unused CaCO₃, making the ash a very effective ameliorant for acid mine drainage (AMD) generated from toxic mine wastes disposed of in reclamation sites. The CaO reacts with water to produce additional Ca(OH)₂ to create an immediate high-alkalinity solution to neutralize existing acid while the CaCO₃ dissolves slowly over time to sustain an alkaline environment. The initial high levels of alkalinity inhibit the microbial production of AMD until the toxic wastes can be disposed of in such fashion to minimize further oxidation. Once buried, the CaCO₃ content can provide the lower levels of alkalinity needed to maintain the abiotic conditions that preclude the future generation of acid within the reclamation site.

MINERALS IN COAL

Introduction: By definition, coal must consist of at least 50% organic material by volume, the remainder being **mineral matter**. As we have seen, the amount of mineral matter in coal is one of the parameters (ash) that determines the **quality** of the coal. In terms of volume, mineral matter consists primarily of a variety of silicate minerals followed in abundance by lesser concentrations of carbonates and disulphide minerals

Silicate Minerals: As a group, the silicate minerals comprise 80-90 wt% of all the minerals

COAL IN THE UNITED STATES

GEOGRAPHIC LOCATION

The distribution of coal within the lower 48 states are located in two major areas referred to as the eastern and western coal basins. The eastern coal production comes from the Appalachian Basin and its southern extension, the Black Warrior Basin, the Illinois Basin, and the Mid-Continent Basin. The western coals are found in a large number of small basins throughout the Rock Mountain and Mid-Continent regions.

ENVIRONMENTS OF FORMATION

While coals are commonly considered to form from woody tissues that are preserved as peat in wetlands called swamps, a better term for the environments in which coal-forming peats accumulate is the mire. While a swamp is simply defined as a wetland dominated by trees and shrubs; not requiring the accumulation of coal-forming peat, a mire is defined as any peat-accumulating wetland. Two types of mires were responsible for coals; domed and planar. Domed mires form in tropical and sub-tropical climates characterized by ever-hot, ever-wet condition. The nearly daily precipitation of rain and ever-hot climatic condition promoted the growth of large volumes of swamp vegetation which resulted in thick layers of plant debris accumulating on the floor of the wetland. As the plant debris rapidly accumulates and is converted to peat, the peat surface quickly builds up above the regional watertable to form a domed mire structure (Figure xx). Because most of the peat is located above the regional watertable, it is not affected by the alkaline groundwater but rather, the peat undergoes near-continuous leaching by the acidic rainwater which maintains the pH of the mire water below about pH3. A pH of 3 appears to be a critical point for the preservation of sufficient woody tissues to create a coal-forming peat. At

lower pH levels, preservation of woody tissues increases while the sulfur and inorganic components of the peat are largely removed from the peat by dissolution and carried off in the groundwater. As a result, the peat that accumulates in a domed mire gives rise to low ash, low sulfur coals such as those of the southern Appalachian Basin.

Planar mires form in regions that, although still sub-tropical, have a more seasonal climate characterized by both rainy and dry seasons. Because of the lower and more cyclic availability of rainfall, the amount of vegetation growing within the swamp is less that which characterizes a domed mire. As a result, rather than building vertically, the peat tends to spread laterally, giving rise to a “planar” structure. Because the alkaline groundwater may elevate the pH of the mire waters during the periods of low rainfall above pH3, the peat is subjected to less acidic leaching thereby resulting in higher concentrations of ash and sulfur.

GEOLOGIC SETTING

The eastern coals formed between 350 million to about 250 million years ago during what is known as the Pennsylvanian Period. What is now the Appalachian Basin was a broad coastal plain extending from a range of mountains located along our present east coast westward to the ocean which occupied much of the continental interior. During the early Pennsylvanian Period, the climate of the region was tropical to subtropical, ever-hot and ever-wet. The coastal plain was characterized by many wetlands, both marshes (grass dominated) and mires (peat accumulating wetlands) separated by meandering streams. Because the climate, forests of trees grew rapidly, giving rise to coal-forming peat that built up above the level of the level of water in the streams. Located above the watertable, the peat underwent intense leaching by acidic rainwater that removed most of the sulfur and the inorganic components that eventually gave rise to low sulfur

and low ash coals. Over time, meandering streams buried the mires before a thick mat of peat could accumulate only to be followed by newer mires than formed on the surface of the stream deposits. As a result, the southern Appalachian Basin consists of numerous, relatively thin, high quality bituminous coal beds. Early mining was by drift mines and contour mining during which the coal was removed along the outcrop following the contours of the slopes. Augers were often used to remove the coal further back into the hillside. Today, the coal is removed by “mountaintop removal” during which overburden is removed beginning at a hilltop, exposing the sequence of underlying coal beds. Each coal bed removed as it is uncovered, while the overburden is transported to an adjacent valley for disposal. The process is then repeated for each of the lower coal beds. While mountaintop removal is the most efficient way to mine these coals, it is not yet clear how the disagreements over its use will be resolved.

By the time the coal-forming peat of the northern portion of the Appalachian Basin was accumulating during the late Pennsylvanian Period, the climate had changed to a more seasonal sub-tropical climate with seasonal episodes of rainfall separated by periods of sparse rainfall. As a result, the mires were subjected to periods of leaching by acidic rainwater followed by periods when they were subjected to the more alkaline groundwater. Rather than accumulating vertically, the northern mires spread laterally, creating vast mires that were both more extensive in area and longer lived than those of the southern Appalachian Basin resulting in fewer but thicker coals. With less acidic rainfall leaching the peat, more sulfur and inorganic components were retained, resulting in higher contents of sulfur and ash in the coals.

The coal-forming mires of the Pennsylvanian Period were dominated by trees such as *Lepidodendron*, *Sigillaria* and *Calamites*. While many of these trees reached heights of 100 feet

with trunks 5 to 6 feet in diameter, they provided limited amounts of woody tissue to the formation of peat. The trees had pith-filled trunks with the only woody tissue found around the outermost portion of the trunk. As a result, a 6 foot diameter log might be compressed to a only a few inches of wood; The thickest coal in the Appalachian Basin, the Pittsburgh coal, averages only 13 feet.

By the time the western coals began to form nearly 150 million years later during the Cretaceous Period, the hollow-stemmed trees of the Pennsylvanian Period had long gone to extinction and had been replaced with modern types in which the entire tree trunk consisted of woody tissues. With each tree contributing large amounts of wood, the volume of peat significantly increased over that of the eastern basins, resulting in the production of thicker coal beds. The Hiawatha Mine outside of Gillette, Wyoming, for example, is a surface mine that contains 100 feet of coal under 20 feet of overburden.

COALIFICATION PROCESS

Under normal conditions, plant debris that falls and accumulates on the surface of the ground is rapidly decomposed by the combination of oxidation and microbial activity to form humus. In order to preserve a sufficient amount of woody tissue to create a coal-forming peat, the plant debris must be isolated from both of these two agents of decomposition. The mire is the depositional environment that inhibits both oxidation and microbial activity and allows the accumulation of coal-forming peat.

Oxidation: For oxygen to be an effective agent of decomposition at atmospheric temperatures, it must be dissolved in water. Gaseous oxygen only becomes an effective oxidizing agent at high temperatures such as fires. The oxygen content of the water in a coal-forming mire is the low for

two reasons. First, because the water within the mire moves very slowly, there is little to no opportunity for it to become aerated as it would be in the case in a turbulent, fast-moving stream. Secondly, the dissolved oxygen reacts with the readily available decomposing carbon-rich plant tissues to make CO₂ which bubbles to the surface of the water and is released back into the atmosphere.

Microbial Activity: Most of the degradation of the plant debris is the result of microbes that consume plant tissues to obtain their required nutrients. Maximum microbial activity takes place at pH7. At pH7 the rate of microbial activity would be so high that an insufficient amount of woody tissues would be preserved in order to produce a coal-forming peat. The carbonic acid, H₂CO₃, and a variety of organic acids contained in the mire waters decrease the swamp water pH. Below pH3, preservation of the woody tissues increase as the microbial activity decreases. Below pH 3, sufficient woody tissues would be preserved to form a coal-forming peat. Because of the demand for low values of pH, freshwater, as opposed to marine water, must dominate all coal-forming peat environments.

Coalification: The coalification process begins in the mire with the accumulation of woody tissues. Any organic substance is composed of two components; carbon and volatiles. On the average, wood consists of 45% carbon and 55% volatiles. Wood is converted into peat in the mire as the volatiles are driven off the woody tissues, concentrating the carbon content. For the coalification process to continue, the peat must be buried and subjected to low pressures and relatively low temperatures. The burial is accomplished as repeated flooding of meandering streams deposit sediments on top of the former mire. Because pressure actually inhibits the coalification process, the initial depth of burial is never much beyond a few hundred feet

throughout the coalification process. With shallow burial, the peat is subjected to heat generated by continued decomposition of plant debris to temperatures of no more than about 250°C (482°F). During burial, the coalification process continues, converting the peat to other forms of coal. Coalification up through the lignite, sub-bituminous and bituminous coal stage is accomplished during shallow burial. The high carbon content of anthracite coal, >95%, requires much higher levels of both heat and pressure; conditions that are provided by being involved in a mountain-building episode.

Following the completion of the process of coalification, the coal may be buried under thousands of feet of sediment provided by meandering streams carrying sediment from a nearby mountain range. At this point, the composition of the coal is no longer being changed. Over time, the erosion of these overlying sediments bring the coals to depths that can be reached by modern mining techniques. In some cases, the coals lie under a relatively few tens of feet of sediment and are surface mined. In other cases, the coals may be at depths ranging from 1,000 to 2,000 feet (305 to 610 m). Most coal mines entered by vertical shafts are usually at depths of no more than 1000 to 1500 feet.

COAL RANK and COAL QUALITY

Coal Rank: Coal rank depends on the carbon content with rank increasing with increasing carbon content which, in turn, determines the amount of heat that is released when the coal is burned. Heat is measured in BTUs/lb (British Thermal Units per pound). The heat potential of coal ranges from about 7,000 BTU/lb for peat to 15,000 BTU/lb for anthracite. Except for the anthracite coal of eastern Pennsylvania, the eastern coals are all bituminous in rank. In contrast, excluding the bituminous coals of the Book Cliffs region of northern Utah, the western coals are lower rank

sub-bituminous and lignite.

Coal Quality: Coal quality is determined by the amount of ash and sulfur contained in the coal.

Ash and sulfur generally increase and decrease together because they both originate from the wood of the original tree. Sulfur is one of the six elements required of life as we know it; C, H, O, N, P, and S. The ash represents elements that most plants do not want or need. These elements are removed from the water as it rises through the vascular system and is stored in the dead wood cells. When the wood is transformed to coal during the coalification process, these unwanted elements are transferred to the coal and give rise to the ash.

High quality coals are those with ash and sulfur contents of less than 10% and 1% by weight respectively. While there is no agreed-upon division between medium and low quality, generally it would be about 30% ash and 3% sulfur. The coals within the southern Appalachian Basin, southern West Virginia and eastern Kentucky, are high quality. In comparison, the coals of the northern Appalachian Basin that includes northern West Virginia, western Pennsylvania, and parts of western Maryland are dominantly medium quality. The average ash and sulfur content of the Pittsburgh coal, for example, is 13% and 2.1% respectively. Only a few of the coals of the combined Illinois and Mid-Continent basins are of mineable quality. However, future combustion techniques may make these coals of commercial interest. The western coals are all high-quality with ash contents less than 10% and sulfur contents less than 1%.

U.S. COAL PRODUCTION and UTILIZATION

Coal accounts for 20% of the total energy demands of our country. Nearly all of the coal mined in the U.S. is used to generate electricity in coal-fired power plants with coal responsible for nearly 45% of all the U.S. production of electricity. Most of the U.S. coal production comes from

Wyoming, West Virginia, and Kentucky and is used for domestic purposes. Only 5% of our total coal production is exported with a small amount of coal being imported to fuel the power plants along the Atlantic and Gulf coasts.

With the acid rain problems solved with the mandatory use of scrubbers and/or getters, the major problem remaining from the burning of coal in coal-fired power plants is CO₂ with power plants responsible for 37% of the amount of CO₂ being released into the atmosphere. While many consider the amount of CO₂ released by the burning of fossil fuels to be a major cause of global warming, a significant number of scientists believe that present warming trend is due to the fact that since 1850, Earth has been coming out of the “Little Ice Age” that gripped the Northern Hemisphere beginning in the 1500s. Scientists are presently developing techniques by which 90% of the CO₂ generated by the burning of coal can be captured before it enters into the atmosphere and sequestered underground.

Coal Utilization: For many years, coals were categorized as either coking coal or steam coal, based on the quality of the coal. Coke is used to liberate iron from iron ore in blast furnaces. The requirement of less than 1% and 0.5% for ash and sulfur respectively is required to minimize the contamination of the molten iron. Coal that did not qualify as a coking coal was considered a steam coal and was burned in power plants to generate electricity. With the Clean Air Act of 1970, the carcinogenic properties of the vapors released during the coking process shut down most coking operations throughout the U.S.. The Clean Air Act also specified that sulfur content of coal burned in coal-fired power plants could not exceed 1.2%; the so-called “compliance coal” The coals of the southern Appalachian Basin and all of the western coals are compliance coals while most of the coals mined in the northern Appalachian Basin.. In order for such coals to be

advent in 1908 of Henry Ford's gasoline-powered Model T car and its subsequent mass production, petroleum became the world's major energy source with coal dropping to the number two source of energy.