

Part IV

Coal and Coal Petrography

1. INTRODUCTION

1.1. What is Coal ?

Definition: *coal is defined as a biogenic sedimentary rock in the group of sedimentary hydrocarbons.*

It is a combustible, (generally) black rock consisting mainly of carbon. It is created out of vegetation that accumulated in mostly swamp type environments over millions of years.

The quality of coal is determined by temperature and pressure and by the length of time in formation, which is referred to as its “*organic maturity*”.

Generally distinguished classes were:

1. **Brown coal or lignite**⁴⁹: low organic maturity and dark black to various shades of brown.
2. **Sub-bituminous coal**: progressive increase in organic maturity and removal of water.
3. **Bituminous**⁵⁰ **or hard coals**: further chemical and physical change, gas slowly removes. The coal becomes harder and blacker.
4. **Anthracite**⁵¹: Progressive increase in the organic maturity, all gases and many other C-O-H chains are destroyed.

According to ICCP (1998)⁵², these terms have been replaced by:

- | | |
|-----------------------------|-----------------------------------------------------|
| 1. Low Rank Coal: | formerly Brown Coal (=Lignite) + Subbituminous Coal |
| 2. Medium Rank Coal: | formerly Bituminous Coal |
| 3. High Rank Coal: | formerly Anthracite (+Semi-Anthracite) |

However, the old classification is still in use, its names are still commonplace. Therefore this classification will be treated here as well. As most of the new terms are combinations of older terms, it is fairly easy to work with the new classification, even when the old classification has been learned. Furthermore, in order to work with older literature, it is necessary to know the old classification as well.

⁴⁹ Origin of the name: from Latin, *lignum* = wood.

⁵⁰ Origin of the name: like or containing *bitumen* (Latin: *tar, asphalt*).

⁵¹ Origin of the name: from *Latin*, and before from *Ancient Greek* ἀνθρακίτης (*anthrakitis*, “a kind of coal”), from ἄνθραξ (*anthrax*, “charcoal”).

⁵² ICCP (1998) The new vitrinite classification (ICCP System 1994), *Fuel*, 77, 5, 349 - 358

2. ENVIRONMENT OF DEPOSITION

2.1. A General Introduction

Coal is created out of vegetation that accumulated in mostly swamp type environments over millions of years. In the nature coal is present in geological formations varying in age from Carboniferous till Miocene. In Northwestern Europe, productive coal seams are mostly of Carboniferous or Pennsylvanian age (ca 300×10^6 year). Brown coal or lignites are usually present in formations younger than the Cretaceous sub-era ($< \text{ca } 65 \times 10^6$ year). During the Carboniferous and other warm periods, the earth's climate was extremely favorable for plant growth, often situated in stagnant swamps. These were low in oxygen and as a result reduced decomposition, creating carbon accumulations. In due course, sea rise and/or subsidence submerged swamps at (ir)regular intervals and covered them with sand, clay and other debris.

Over eons of burial history, the organic material was heated up and compacted under the weight of the overlying sediments, which slowly transformed it from peat, through brown coal, via bituminous coal to anthracite.

The quality of each coal deposit is determined by temperature and pressure and by the length of time in formation, which is referred to as its 'organic maturity'. Initially the peat is converted into lignite or 'brown coal' – these are coal-types with low organic maturity. In comparison to other coals, lignite is quite soft and its color can range from dark black to various shades of brown. Over many more millions of years, the continuing effects of temperature and pressure produces further change in the lignite, progressively increasing its organic maturity and transforming it into the range known as 'sub-bituminous' coals. Further chemical and physical changes occur until these coals became harder and blacker, forming the 'bituminous' or 'hard coals'. Under the right conditions, the progressive increase in the organic maturity can continue, finally forming anthracite.

2.2. Original Environments of Deposition of Coal

(This part of the text is based largely on: L.Thomas, Coal Geology, 2005)

Coals are the result of the accumulation of vegetation debris in specific depositional environments. Buildup of these debris have been affected by synsedimentary and postsedimentary events first to create very carbon accumulations and later to produce coal seams of differing rank and degrees of structural complexity. Sedimentary successions of different era and geographical areas show comparable lithological structures. The origin of coal has been studied for over a century and a variety of models exist. They all try to classify the depositional environment. However, it is difficult to provide an acceptable clarification for the lateral continuity, cyclic nature and physical and chemical features of coal and coal sequences.

As mentioned before, peat is the source for coal. Fundamentals for the growth of thick peat deposits are (from Diessel, 1992):

- a slow continuous rise of the groundwater table which maintains a more or less constant relationship between the water table and the upper surface of the peat deposit, that is, effectively, subsidence;
- protection of the mire (by beaches, sand bars and the like) against major and prolonged flooding by the sea, and by natural levees against river flood-waters; and
- □physiographic and other conditions affecting the supply of sediments which allow peat to form over prolonged periods without interruption by the deposition of fluvial sediments.

If the groundwater table rises too quickly, either because of rapid subsidence or, in paralic settings, because of a combination of subsidence and eustatic sea-level rise, the mire will be drowned or limnic or marine sediments will be deposited. If subsidence is too slow, the plant material on the surface will rot and the peat which has already formed will be eroded. Seam formation thus depends on the relationships between paleogeography and tectonic movements within the sedimentary area.

Hence, peat formation depends on permanent present stagnant groundwater, above or close to the ground surface so that accumulated plant material will not decompose. These conditions occur most commonly in coastal flatlands where sea water dams up fresh water coming off the land. Therefore, most swamps are associated with sea coasts or the shores of large inland lakes. Depending on their geographical position at the time of deposition, coal deposits are referred to as paralic (close to the sea coast) or limnic (inland). It should be emphasized that it is rare for coals to be entirely paralic or entirely limnic in character, usually they are a mixture of transitional types.

Diessel (1992) lists some twenty coalproducing environments within the following groups:

- the braid plain
- the alluvial valley and upper delta plain the lower delta plain
- the barrier beach/strand plain system, and the estuary.

The coals formed in each of these systems tend to occur in seams of characteristic form and distribution, and to have properties related to their depositional environment. For example; many coal seams deposited in lower delta plains are characterized by large extent and thickness and by association with shales, whereas seams deposited in upper delta plains (within inter-channel areas) are discontinuous, of variable thickness and often associated with sandstones.

The recognition of depositional models to explain the origin of coal-bearing sequences and their relationship to surrounding sediments has been achieved by a comparison of the environments under which modern peats are formed and ancient sequences containing coals. The traditional depositional model was based on the “cyclothem”, a series of lithotypes occurring in repeated 'cycles'. This concept has been modified to a model that relates lateral and vertical sequential changes to depositional settings that have been recognized in modern fluvial, deltaic and coastal barrier systems.

Apart from rank, which is governed by burial and subsequent tectonic history, the remaining properties are determined by factors controlling the mire where the peat originally formed. These factors include type of mire, type(s) of vegetation, growth rate, degree of humification, base-level changes, and rate of clastic sediment input (McCabe and Parrish 1992). About 3% of the earth's surface is covered by peat, totaling 310 million hectares (World Energy Council 1998). This includes the tropical peats, (>1 m thick) of Southeast Asia which cover almost 200 000 km².

Diessel (1992) divides peat-producing wetlands into ombrogenous peatlands or mires (owing their origin to rainfall) and topogenous peatlands, (owing their origin to a place and its surface/groundwater regime). A great variety of topogenous peats, form when waterlogging of vegetation is caused by groundwater, but ombrogenous peats are of greater extent but less varied in character. The inorganic content of mires is seen to increase in the topogenous rheotrophic mires. The classification of the two hydrological categories of mire lists a number of widely used terms. Moore (1987) has defined a number of these:

- *Mire* is now accepted as a general term for peat-forming ecosystems of all types.
- *Bog* is generally confined to ombrotrophic peat-forming ecosystems.
- *Bog forest* consists of ombrotrophic forested vegetation, usually an upper storey of coniferous trees and a ground layer of *sphagnum moss*.
- *Marsh* is an imprecise term used to denote wetlands characterized by floating vegetation of different kinds including reeds and sedges, but controlled by

- rheotrophic hydrology.
- *Fen* is a rheotrophic ecosystem in which the dry season water table may be below the surface of the peat.
 - *Swamps* are a rheotrophic ecosystem in which the dry season water table is almost always above the surface of the sediment. It is an aquatic ecosystem dominated by emergent vegetation.
 - *Floating swamps* develop around the fringes of lakes and estuaries and extend out over open water. These platforms can be thick and extensive particularly in tropical areas.
 - *Swamp forest* is a specific type of swamp in which trees are an important constituent, e.g. mangrove swamps.

The resultant characteristics of coals are primarily influenced by the following factors during peat formation:

- type of deposition,
- the peat-forming plant communities,
- the nutrient supply,
- acidity,
- bacterial activity,
- temperature and
- redox potential.

In order for a mire to build up and for peat to accumulate, the following equation must balance.

$$\text{Inflow} + \text{Precipitation} = \text{Outflow} + \text{Evapotranspiration} + \text{Retention}$$

The conditions necessary for peat accumulation are therefore a balance between plant production and organic decay. Both are a function of climate, plant production and organic decay; such decay of plant material within the peat profile is known as humification. The upper part of the peat profile is subject to fluctuations in the water table and is where humification is most active. The preservation of organic matter requires rapid burial or anoxic conditions (McCabe and Parrish 1992), the latter being present in the waterlogged section of the peat profile. In addition, an organic-rich system will become anoxic faster than an organic-poor one as the decay process consumes oxygen. This process is influenced by higher temperatures, decay rates being fastest in hot climates. Rates of humification are also affected by the acidity of the groundwater, as high acidity suppresses microbial activity in the peat.

Peat formation can be initiated by:

- terrestrialisation, which is the replacement, due to the setting up of a body of water (pond, lake, lagoon, intertributary bay) by a mire;
- paludification, which is the replacement of dry land by a mire, e.g. due to a rising groundwater table.

As peat is relatively impermeable, its growth may progressively impede drainage over wide areas, so that low-lying mires may become very extensive. In those areas where annual precipitation exceeds evaporation, and where there are no long dry periods, a raised mire may develop. Such mires are able to build upwards because they maintain their own water table. The progression of a peat-forming environment from the infilling of a watercourse or lake, to a low-lying mire and finally to a raised mire should produce zonation in the peat accumulated.

3. COAL CLASSIFICATIONS

The classification of coal is generally based on the *content of volatiles* (which is a measure for its “*organic maturity*”). However, the exact classification varies between countries. Also the number of distinguished classes varies. Especially, there was a discrepancy between European and USA systems. Below the old German, Dutch, English and American classifications are given. The latest classification according to the ICCP is given in Column 5.

German Classification	Dutch Classification	English Designation	USA Classification	ICCP Classification	Volatiles ⁵³ %	Carbon ⁵⁴ %
<i>Torf</i>	<i>Turf</i>	<i>Peat</i>	<i>Peat</i>	<i>Peat</i>	>60	60
<i>Braunkohle</i>	<i>Bruinkool</i>	<i>Lignite</i>	<i>Lignite</i>	<i>Low rank coal</i>	45-60	60- 75
<i>Flammkohle</i>	<i>Vlamkool</i>	<i>Flame coal</i>	<i>Sub-bituminous coal/Medium volatile bituminuous coal</i>	<i>Low rank coal</i>	40-45	75 – 82
<i>Gasflammkohle</i>	<i>Gasvlamkool</i>	<i>Gas flame coal</i>	<i>Medium volatile bituminuous coal</i>	<i>Medium Rank Coal</i>	35-40	82 – 85
<i>Gaskohle</i>	<i>Gaskool</i>	<i>Gas coal</i>	<i>Medium volatile bituminuous coal</i>	<i>Medium Rank Coal</i>	28-35	85 – 87.5
<i>Fettkohle</i>	<i>Vetkool</i>	<i>Fat coal</i>	<i>Medium volatile bituminuous coal</i>	<i>Medium Rank Coal</i>	19-28	87.5 – 89.5
<i>Esskohle</i>	<i>Esskool</i>	<i>Forge coal</i>	<i>Low volatile bituminuous coal</i>	<i>Medium Rank Coal</i>	14-19	89.5 – 90.5
<i>Magerkohle</i>	<i>Magerkool</i>	<i>Non baking coal</i>	<i>Semi-Anthracite</i>	<i>High Rank Coal</i>	10-14	90.5 – 91.5
<i>Anthrazit</i>	<i>Anthraciet</i>	<i>Anthracite</i>	<i>Anthracite</i>	<i>High Rank Coal</i>	<10	91.5 – 98

There are still older names that sometimes occur. Steam coal is a grade between bituminous coal and anthracite, once widely used as a fuel for steam locomotives. The term is not used anymore. The modern term is Thermal Coal. It is a subclass of Bituminous Coal. Metallurgical Coal is another subclass of Bituminous Coal. This type of coal is used to make coke, necessary for iron and steel production.

Anthracite is the most metamorphosed type of coal (but still represents low-grade metamorphism), in which the carbon content is between 91.5% and 98%. The term is applied to those varieties of coal which do not give off tarry or other hydrocarbon vapors when heated below their point of ignition. Below some images of the different coal types are given.

⁵³ Volatile matter - dry mineral matter free basis (dmmf). See: Chapter VI.3.1. Basis of Analytical data for an explanation of this terminology.

⁵⁴ Given as Weight Percent (wt%)



Figure 1. Peat. Source: Thinkquest.org



Figure 2. Lignite. Source: internet.



Figure 3. Bituminous coal. Source: Wikipedia.



Figure 4. Anthracite coal. Source: Wikipedia.

4. THE AGE AND OCCURRENCE OF COAL

Coal is most well-known from the geological epoch called the Carboniferous. However sedimentary sequences containing peat or coal are found from the Upper Palaeozoic to Recent. Although plant life is known as early as the Devonian Period, significant plant cover was only developed in the Upper Palaeozoic, i.e. the Carboniferous and the Permian. During the Earth's history, there have been three major periods of coal accumulations.

The first took place during the Late Carboniferous – Early Permian Period. Coals formed at this time now form the bulk of the black coal reserves of the world, and they are represented on all the continents.

The second period took place during the Jurassic – Cretaceous Period. Coals from this age are known from Canada, China, and the CIS⁵⁵.

The third major period took place during the Tertiary Period (now divided into Palaeogene and Neogene). Coals from this period range from lignite to anthracite. Tertiary coals form the bulk of the World's brown coal reserves, but also make up a significant percentage of the black coals currently mined. Tertiary coals are also found world-wide.

⁵⁵ CIS: Commonwealth of Independent States, i.e. the former USSR.

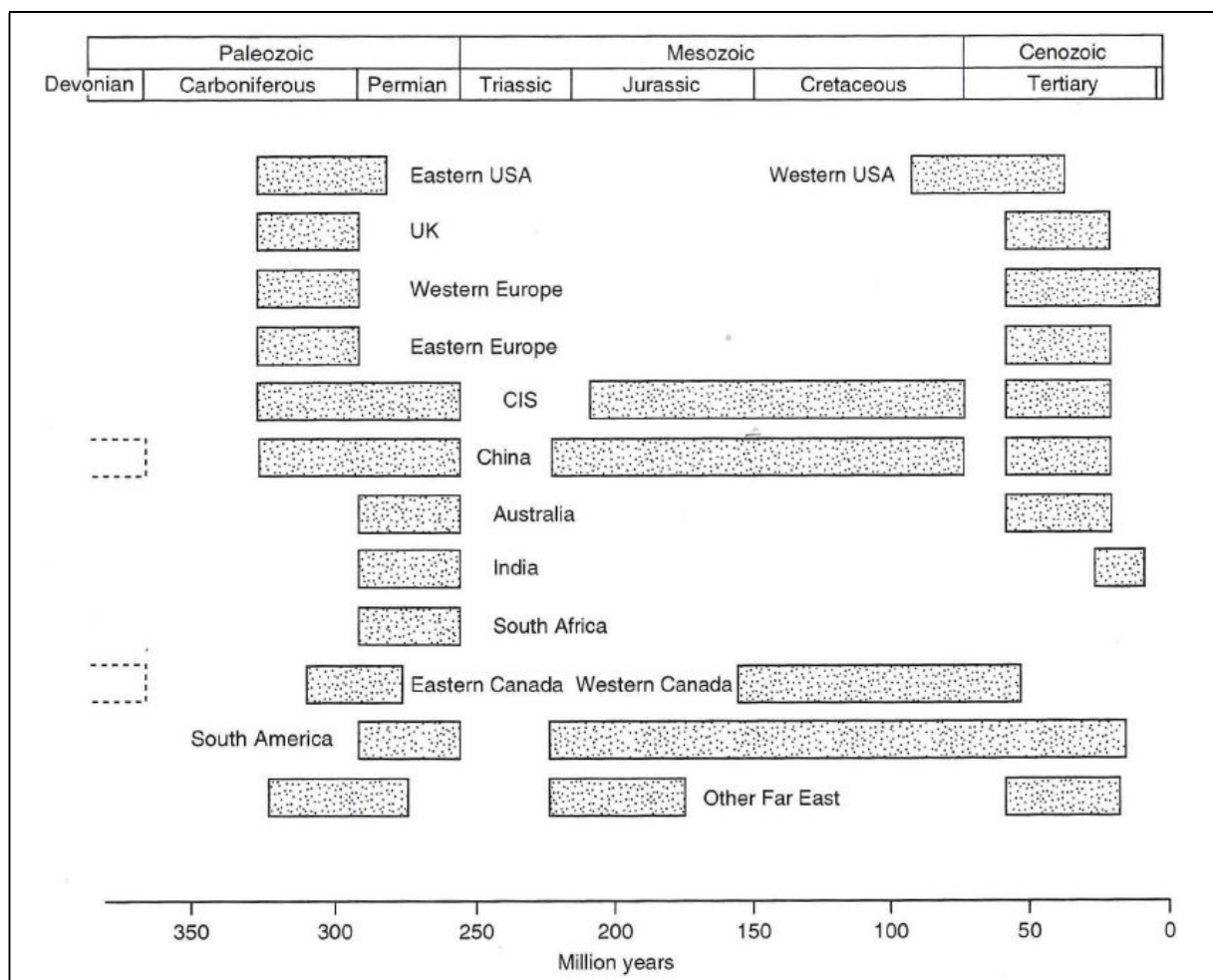


Figure 5. Geological age distribution of the World's principal black coal and lignite deposits. After Thomas (2005).

It has been estimated that there are over 847 billion tonnes of proven coal reserves worldwide. This means that there is enough coal to last us around 118 years at current rates of production. In contrast, proven oil and gas reserves are equivalent to around 46 and 59 years at current production levels (World Coal Association, 2012⁵⁶).

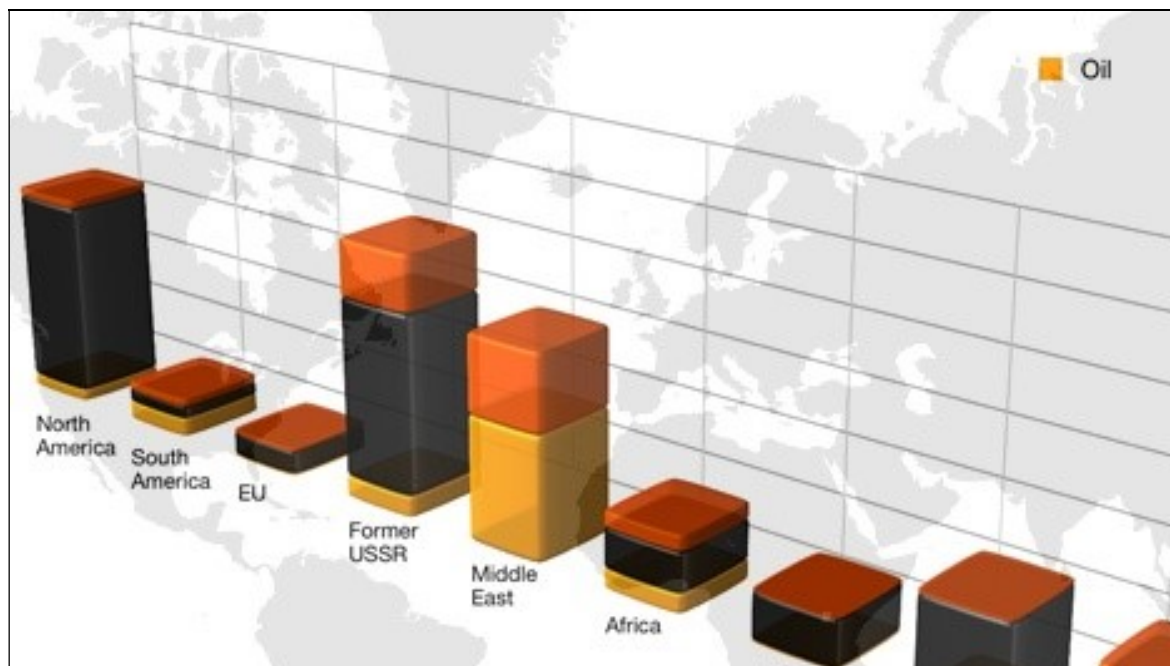


Figure 6. Where is coal found? (World Coal Association, 2012⁸).

5. FOSSILS

Many fossils of especially *Carboniferous* plants are known. Below an impression is given of some well-known *Carboniferous* plants (both reconstructions and fossils). The fossils are not of importance for coal as such, nor for its technological applications, but give paleobotanists a very good idea of what kind plants were common in the Carboniferous periods. The same holds for the other periods of coal formation. Below some pictures of Carboniferous fossils are given for illustration.

⁵⁶ <http://www.worldcoal.org>

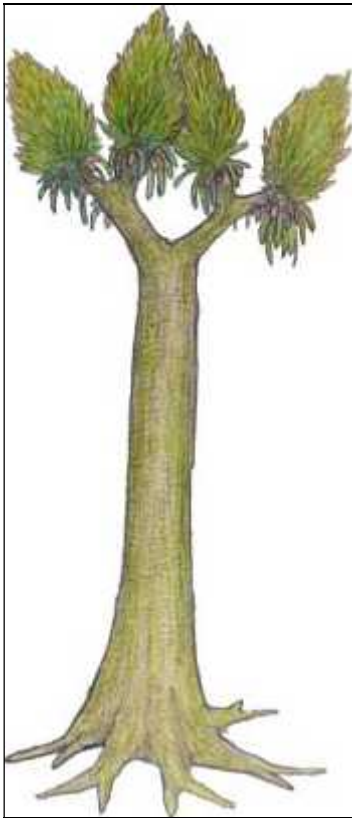


Figure 7. *Sigillaria*, reconstruction of a common plant during the Carboniferous.

Source: <http://bio1152.nicerweb.net/Locked/media/ch29>

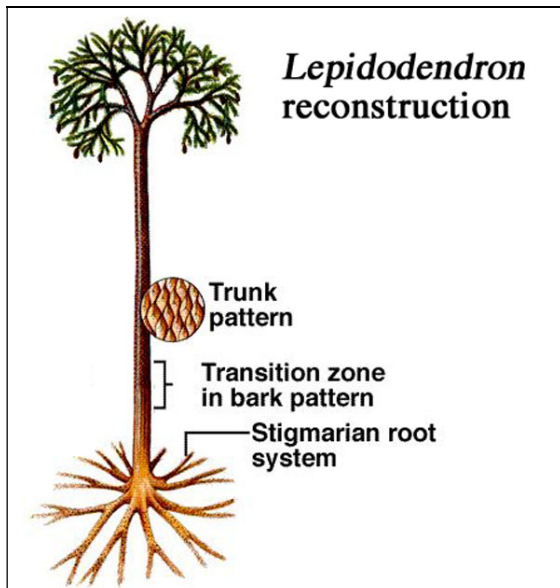


Figure 8. *Lepidodendron*, reconstruction of a common plant during the Carboniferous.

Source: <http://www.plantbiology.siu.edu/plb304/lecture07pterid/ferns.html>



Figure 9. *Sigillaria* fossil. Geological and Mineralogical Museum, Delft.



Figure 10. *Lepidodendron* fossil from the Carboniferous. Source: <http://www.paleodirect.com/pl-001.htm>

6. AVAILABILITY AND APPLICATIONS OF COAL

6.1. Abundance, Availability and Price of Coal

Coal is abundant and widespread. It is present in many countries in the world: commercial mining takes place in over 50 countries. Coal is considered the most abundant and economical of fossil fuels. Widespread abundance of coal also guards against dependence on a few countries or cartels. Also this protects against price shocks, such as occurred with oil in the 1970's.

Coal is readily available. There is a wide variety of sources in a worldwide market. Coals also can be transported to places of demand safely and easily by ship and by rail. Many suppliers are operative, which ensures competitive behaviour. Storage of coal is easy, and unlike gaseous or liquid sources, coal can be stockpiled at the power station and can be drawn from stocks to meet demand.

Coal is also an affordable source of energy. Coal prices have historically been lower and more stable than oil and gas prices. Coal is likely to remain the most affordable fuel for power generation in many developed and industrialising countries for many years to come.

6.2. Energy Raw Material

Coal is an important raw material in the world demand for energy. Coal-based electricity is well-established and highly reliable. Over 41% of global electricity is currently based on coal (*World Coal Association, 2012*). The generation technologies are well-established and technical capacity and human expertise is widespread. There is worldwide on-going research to improve and expand technology and expertise in energy efficiency and environmental safety. A few (natural and man-made) processes will be mentioned more in detail.

6.2.1. Coalbed Methane (CBM)

The major products from the coalification process is *Coal Bed Methane* (CH_4), CO_2 , N_2 , and H_2O . CBM may be generated in two ways. During the earlier stages of coalification, at temperatures below 50°C methane may be produced. This is called biogenic methane, and it is formed by decomposition of organic material, and where biological activity induces reducing conditions which remove oxygen and sulphate. Where subsidence and burial are rapid, CBM may be trapped in shallow gas reservoirs. Catagenesis, the process by which organic material is altered as a result of increasing temperature, generates CBM at temperatures in excess of 50°C . This referred to as thermogenic methane.

6.2.2. Underground Coal Gasification (UCG)

The chemistry involved in UCG is complex, but essentially the process is a combination of three reactions:

- 1) The producer gas reaction. Oxygen is passed over through hot coal, where it combines with carbon to form CO. This reaction is exothermic. Care must be taken not to inject too much oxygen, because this will lead to the formation of inert CO₂.
- 2) The water-gas reaction. When water or steam is passed over/through heated coal, the oxygen combines with carbon to form CO, and releases the hydrogen content. This reaction is endothermic: it requires the addition of heat to sustain it. In UCG the reaction 1 and 2 are carried out simultaneously, and the reaction temperature is regulated by adjusting the O₂/H₂O ratio.
- 3) The methane synthesis reaction. This is achievable at high pressures in the gasification of deep coal. H₂ combines with C to form methane (CH₄).

UCG is carried out in situ, and does not require mining, gasification reactors, or ash disposal. Permeability of the coal between two boreholes must be well enhanced.

6.2.3. Coal liquefaction

Coal liquefaction is the process to transform coal into a fluid, into oil.

Yes, indeed: *coal can be used as an alternative to oil !!*

There are various methods of coal liquefaction, the main problem being the deficiency of hydrogen in coal, compared to liquid fuels. This can be overcome by adding hydrogen to the coal by a number of processes.

- 1) Direct liquefaction by *hydrogenation*⁵⁷
- 2) Indirect liquefaction by *Fischer-Tropsch Synthesis* (see below).
- 3) Removal of part of the carbon content of the coal by pyrolysis.

6.2.3.1. Coal properties for liquefaction

Coal quality requirements vary according to the method used for coal liquefaction. In both pyrolysis and hydrogenation the use of low rank coals with high hydrogen contents enhances the liquid yields. The required high H/C ratio is closely linked to rank and petrographic composition. Typically, a high proportion of vitrinite and liptinite is favourable. The gasification processes are comparatively insensitive to coal properties, and can utilise coals which are unsuitable for other purposes.

⁵⁷ *Hydrogenation*, or to treat with hydrogen, is a chemical reaction between molecular hydrogen (H₂) and another element, here obviously carbon, and in the presence of a catalyst.

The characteristics favourable for coal hydrogenation are (Thomas, 2005):

<i>Vitrinite reflectance</i>	<0.8%
<i>H/C atomic ratio</i>	>0.75%
<i>Vitrinite + liptinite</i>	> 60%
<i>Volatile matter (d.a.f.)</i>	> 35%
<i>Low concentrations of nitrogen, oxygen, sulfur, phosphorus, chlorine etc.</i>	

Coal liquefaction is presently only applied on a limited scale, because of the high costs.

6.2.3.2. Fischer-Tropsch Synthesis

Since the invention of the original process in the 1920's by *Franz Fischer* (1877 - 1947) and *Hans Tropsch* (1889 – 1935), working at the German *Kaiser-Wilhelm-Gesellschaft zur Förderung der Wissenschaften* (*Kaiser Wilhelm Society for the Advancement of Science* – now the *Max Planck Society*), many refinements and adjustments have been made. The process was commercialised in Germany in 1936.



Figure 11. Franz Fischer (left), and Hans Tropsch.

Source: Max Planck Institute of Coal Research.

Being petroleum-poor but coal-rich, Germany used the *Fischer-Tropsch Process* during World War II to produce the so-called “**ersatz**”-**fuels** (fully in German: *Ersatz-Brennstoffe*), or “*replacement-fuels*”. During WW-II, a part of the German motorised war machinery, from motorbikes to cars, trucks, panzers, ships, U-boats, and aircraft (bombers and fighters) initially ran on “ersatz-fuels”.

South Africa, having no oil-reserves itself, and suffering from oil-embargos during the years of the Apartheid, perfected the process. The **SASOL**⁵⁸ plant, established in the 1950's, is one of the most advanced factories for producing diesel, petrol and kerosene from coal. The Fischer-Tropsch Synthesis applied by SASOL utilises inertinite-rich high volatile bituminous coal with a high ash content.

⁵⁸ **SASOL** stands for *South African Synthetic Oil Limited* or *Suid-Afrikaanse Steenkool en OLie* (South African Coal and Oil).



Figure 12. The SASOL plant in South Africa

6.2.4. Metallurgical Applications

Coal is also important in metallurgical applications: ***metallurgical coal*** is sometimes referred to as ***coking coal***, because it is used in the process of creating coke necessary for iron- and steel-making. As mentioned before, this type of coal is also called bituminous coal.

Nowadays, the most valuable coal is metallurgical coal.

Coke will be explained more in detail in Chapter VI.4.

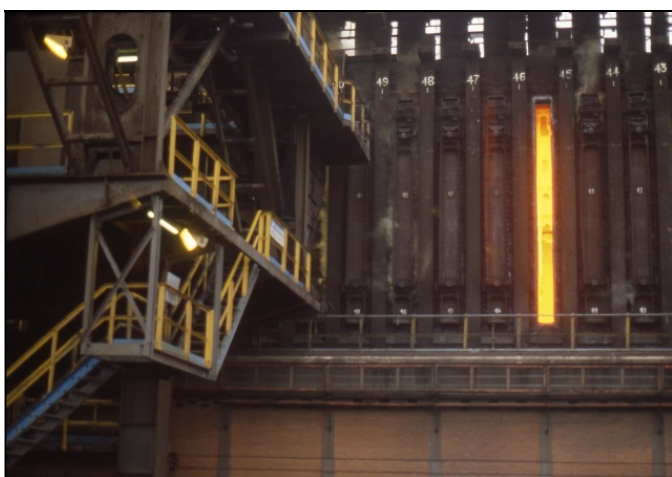


Figure 13. Cokes furnaces. Source: Wikipedia



Figure 14. Coke, size of the particles is 1 cm to several cm's.

Source: Wikipedia.

7. WHAT IS COAL PETROLOGY?

7.1. Introduction

Coal petrology⁵⁹ is *the study of the organic and inorganic constituents of coal and their transformation via metamorphism*. Coal petrology is applied to the studies of the depositional environments of coals, correlation of coals for geological studies, and the investigation of coals for their industrial utilization. Coal Petrology is also called organic petrology.

Coal petrography¹⁰ is a very important *aid* for coal petrology, just as “common” mineralogy and petrography is essential for “common” sedimentary, metamorphic and igneous petrology.

Coal petrology is used in:

- Evaluation of coals for
 1. beneficiation (coal preparation for downstream utilization),
 2. combustion,
 3. coalbed methane production
 4. the investigation of organic-rich rocks to evaluate source rocks in petroleum and natural gas exploration.
- The optimization of coal blends for the production of metallurgical coke.

Coal is an extremely complex heterogeneous material that is difficult to characterise. Coal is a rock formed by geological processes and is composed of a number of distinct organic entities called *macerals* and lesser amounts of inorganic substances: *minerals*. The essence of the petrographic approach to the study of coal composition is the idea that coal is

⁵⁹ **Petrology** is the science and understanding of the formation of rocks (petros = rock and logos = knowledge). **Petrography**, refers to the description of rocks, generally by microscopic techniques (petros = rock, graphein = to write).

composed of **macerals**, which each have a distinct set of physical and chemical properties that control the behaviour of coal.

The term **maceral** was first introduced by *Dr. Marie Stopes*⁶⁰ (1935) who said that:

"These organic units, composing the coal mass, I propose to call macerals, and they are the descriptive equivalent of the inorganic units composing rock masses and universally called minerals, and to which petrologists are well accustomed to give distinctive names."



Figure 15. Marie Stopes.

Macerals thus are the organic constituents in coal and non-coal organic-rich rocks. More precise they are the (optical) microscopically identifiable constituents in coal, somewhat analogous to minerals in an inorganic rock. Macerals are considered to be dehydrogenated plant fragments. Evidence for this includes remnant pollen spores, fossilised leaves, remnant cellular structures and similar.

Later the system was expanded for industrial purposes, and was called the *Stopes-Heerlen* classification system⁶¹. The ICCP introduced a new classification for vitrinite (ICCP, 1998⁶²), inertinite (ICCP, 2001⁶³), and a classification for huminite (ICCP, 2005⁶⁴)

⁶⁰ Marie Charlotte Carmichael Stopes, (1880 –1958) was a British author, palaeobotanist, coal expert, campaigner for women's rights and pioneer in the field of birth control. Her classical paper is: *Stopes, M. C. (1935) On the petrology of banded bituminous coals. Fuel, vol. 14, p. 4-13.*

⁶¹ After the “Carboniferous” congresses” held in Heerlen, The Netherlands..

⁶² ICCP (1998) The new vitrinite classification (ICCP System 1994), *Fuel*, 1998, Vol. 5, 349 - 358

⁶³ ICCP (2001) The new inertinite classification (ICCP System 1994), *Fuel*, 80, 459 – 471

⁶⁴ ICCP (2005) Classification of huminite (ICCP System 1994). *Intern. Journ. Coal Geology*, 62, 85 - 106

Macerals are divided into:

1. the **vitronite** group,
2. the **liptinite** or **exinite** group,
3. the **inertinite** group.

By convention, maceral names always have an “-inite” suffix.

The name **kerogen** is used for the same in a broader sense, and particularly for dispersed organic material.

In the new system (ICCP, 1998):

- the **maceral groups** are *defined* by the *level of reflectance*,
- the **maceral subgroups** are *defined* by the *level of destruction*,
- the **macerals** are *defined* by the *morphology and/or degree of gelification*.

The present categories of **maceral groups**, **maceral subgroups** and **macerals** (Stopes, 1935, McCabe, 1984; ICCP, 1998, 2001) are given in the following table. Detailed descriptions are given in Chapter IV.

Maceral Group	Maceral Subgroup	Maceral	Maceral Definition	Morphology	Origin
Vitrinite	Telovitrinite	Telinite	Clearly recognisable cell walls of more or less intact plant tissue.	Size shape and openness of cell lumens variable depending on original plant material and orientation of the section. Shape of cells sub-spherical, or oval, often deformed. Cell walls always gelified. and rarely show internal structure. Cell lumens occasionally empty, usually filled with other macerals or minerals	Woody tissues of roots, stems, barks, and leaves composed of cellulose and lignin.
		Collotelinite	Vitrinites with a homogeneous more or less structureless appearance.	More or less structureless forms	See Telinite.
	Detrovitrinite	Vitrodetrinite	Vitrinites with discrete small fragments of varying shape, that become discernible when surrounded by non-vitrinitic material.	Finely vitrinitised plant remains occurring either isolated or cemented by vitrinitic matter	See Telinite.
		Collodetrinite	Mottled vitrinitic groundmass binding other coal components.	Component particles are not clearly visible in the microscope due to a high degree of homogenisation	See Telinite.
	Gelovitrinite	Corpogelinite	Homogeneous and discrete bodies representing cell infillings.	Structureless bodies of humic cell fillings, in situ or isolated.	May be of primary origin, corresponding to cell contents or secretions from the cell walls. Alternatively, secondary infillings of tissue cavities by humic solutions precipitated as gels.
		Gelinite	Homogenous and structureless infillings of cracks and other voids.	Of secondary origin. As matrix of mylonitised coal particles in microfaults within coal seams, or as impregnation of cell cavities of sclerotinite, fusinite or semifusinite.	From humic colloids originating during the early diagenesis of plant material and secondarily impregnating source material followed by precipitation as

					colloidal gel.
Exinite (liptinite)		Resinite		Cell filling layers or dispersed	Plant resins, waxes, and other secretions
		Alginite		Fossil form	Algae
		Liptodetrinite		Fragments of exinite	Degradation residues
Inertinite		Fusinite	Highly reflecting well preserved cellular structure of at least one cell.	Discrete lenses, fillings or bands. Some fusinite derived from wildfires.	Oxidised plant material – mostly charcoal from burning of vegetation
		Semi-fusinite	Intermediate between fusinite and humotelinite/vitrinite.	Cellular Structure	Tissues of stems, herbaceous plants, leaves, composed of cellulose and lignin. Wildfires e.g. can produce material of suitable reflectance to be categorised as semifusinite
		Funginite	Highly reflecting fungal spore remains in coals and sedimentary rocks	Single cells, multicellular, spindle shaped forms, multicellular roundish forms.	Fungi, fungal spores
		Secretinite	Composed of commonly round, vesicled to non-vesicled and equant to elongate bodies without obvious plant structure.	Although commonly subspherical to oblate, secretinite may also appear in crescent, polygonal and vesicular forms.	
		Macrinite	Occurs either as amorphous matrix, or as discrete structureless bodies of variable shapes, which are commonly elongated when viewed perpendicular to bedding. Appears as a groundmass, or in the form of bands or lenses (perpendicular to bedding)	Amorphous “cement”	Oxidised gel material
		Micrinite	Very small rounded grains	Similar to inertodetrinite, but grains < 2 µm	Very fine grained form of inertinite
		Inertodetrinite	Discrete very small inertinite fragments of	Similar to micrinite, but > 2 µm.	Coarser than micrinite

			varying shape		
--	--	--	---------------	--	--

The three basic groups of macerals comprise each several macerals, belonging together. The vitrinite group is derived from coalified woody tissue, the liptinite group is derived from the resinous and waxy parts of plants and the inertinite group is derived from charred and biochemically altered plant cell wall material.

In principle, the macerals are free of mineral inclusions. However they may contain certain components submicroscopic size, which were already present in the original plant material, or which formed during the first stage of the coalification process as complex compounds of organic and inorganic matter. These inorganic admixtures are called “inherent ash”. Microscopically visible minerals are called “adventitious ash”. They are not considered part of the macerals, and should in microscopic analyses be recorded separately.

7.2. Microscopic Study of Coal.

The microscopic study of coal is carried out in reflected polarised light. Observations are done in air or in immersion oil. We can discriminate qualitative and quantitative data (Kühnel, 1982).

7.2.1. Qualitative data (with polarizer only)

- Mode of occurrence (shape and size of present constituents, their spatial distribution and mutual intergrowths).
- Colours in comparison with neighbouring constituents
- Relative polishing hardness (relief).

7.2.2. Qualitative data (with crossed polars)

- Anisotropy
- Extinction
- Internal reflections and their colors

7.2.3. Quantitative data (with polarizer only)

- Reflectance (in white light, 546 nm or better in monochromatic light)
- Bireflectance
- Indentation microhardness (prints often disappear due to the elasticity of the coal).

7.2.4. Vitrinite reflectance

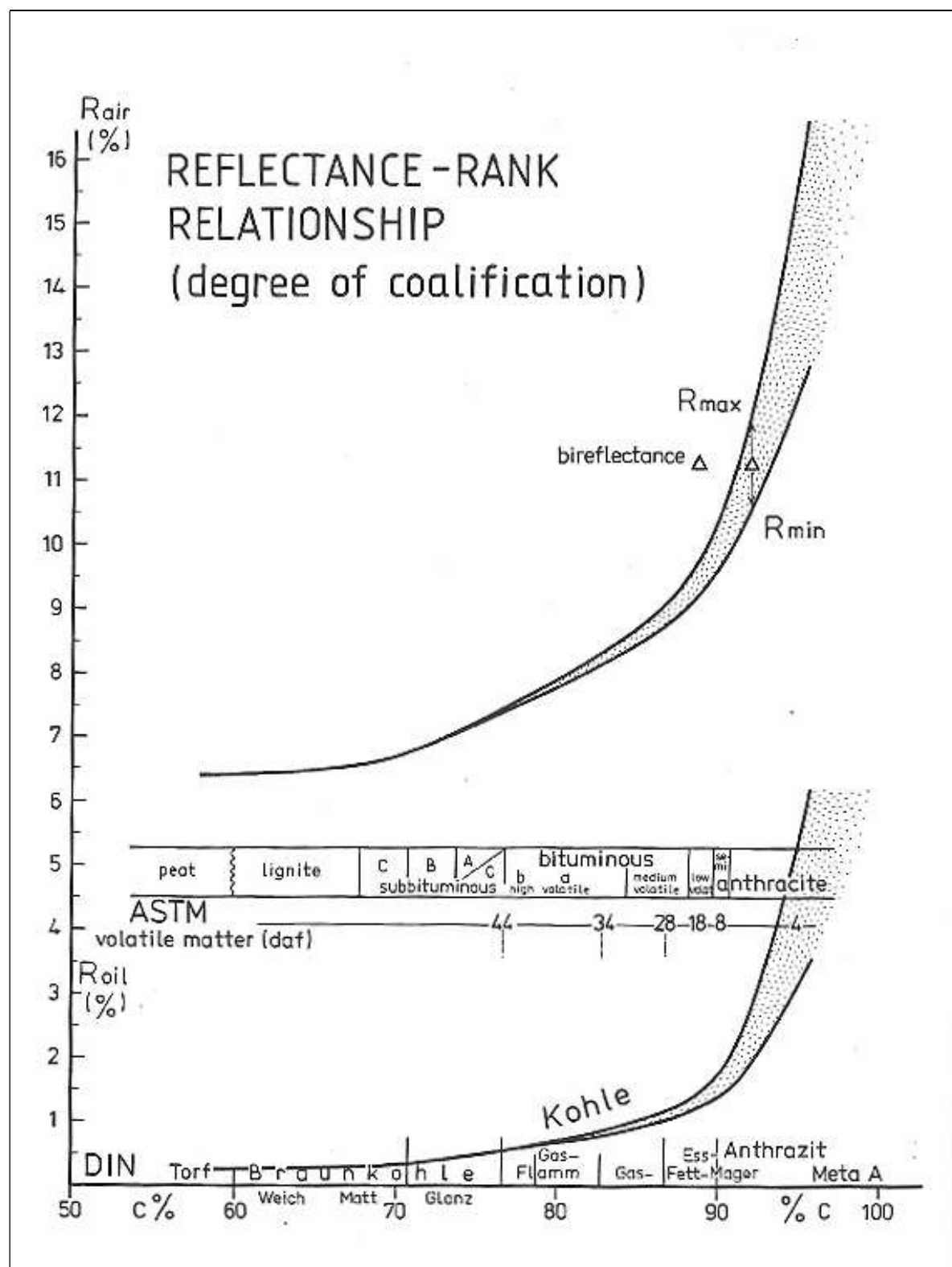
The *reflectance of vitrinite* is a way to diagnose the *thermal maturity*, or *rank*, of coal beds. In other words, it gives the degree of coalification. The petrographic properties of vitrinite change uniformly with increasing rank. In reflected light the reflectance progressively increases.

The following table shows the change in reflection with increasing rank (Thomas, 2005. After Ward, 1984).

Rank Stage	% Vitrinite Reflectance Random (R_0)	% Vitrinite Reflectance (R_{max})
Peat	0.20	0.20
Brown Coal	0.40	0.42
Subbituminous Coal	0.60	0.63
High Volatile Bituminous Coal	0.97	1.03
Medium Volatile Bituminous Coal	1.49	1.58
Low Volatile Bituminous Coal	1.85	1.97
Semi-anthracite	2.65	2.83
Anthracite	6.55	7.00

This is depicted graphically in figure 15 (next page). The lower horizontal part of the figure gives German terminology for the coal rank. The horizontal row above gives the English classification.

Reflectance is considered the best rank parameter for anthracites, to medium volatile bituminous coal (Teichmüller and Teichmüller, 1982; Thomas, 2005). Rank classes can be



7.3. Description of the Macerals

Images in this chapter are taken from *Crelling (2012)*⁶⁵ and *The Indiana Geological Survey*⁶⁶. All photographs from Crelling are taken with *oil immersion* (i.e. with an oil with a specified refractive index between sample and objective lens).

7.3.1. The Vitrinite Group

Vitrinite is the most frequent and the most important maceral group in bituminous coals. Vitrinite is subdivided into the following subgroups:

7.3.1.1. Telovitrinite

The macerals in this group, telinite and collotelinite, generally originate from tree trunks, branches, leaves, stems and roots. Sometimes it is possible to recognise cellular textures from vegetable material under the microscope, especially in low-rank coals. The cell walls are called telinite (from tela = tissue). The maceral consists of clearly recognisable cell walls of more or less intact plant tissue.

Telinite

The size, shape and openness of cell lumens⁶⁷ is variable and depending on original plant material and orientation of the section. The shape of cells is sub-spherical, or oval, often deformed. Cell walls are allways gelified. and rarely show internal structure. Cell lumens are occasionally empty, but usually filled with other macerals or minerals

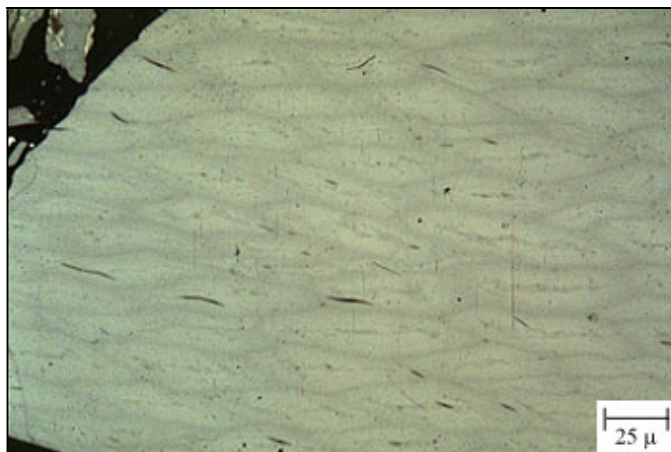


Figure 17. Telovitrinite with cell structure. Only with polarizer.

The uniform grey material in Figure 17 is vitrinite showing a well-developed cell structure.

⁶⁵ Crelling, J.C.(2012) Petrographic Atlas of Coals, Cokes, Chars, Carbons & Graphites
<http://mccoy.lib.siu.edu/projects/crelling2/atlas>

⁶⁶ <http://igs.indiana.edu/Coal>

⁶⁷ Cell Lumen: the cavity bounded by a plant cell wall.

This material is derived from coalified woody tissue. In this case the cell texture is very similar to the cell structure found in fossil *Lepidodendron* wood of Carboniferous age.



Figure 18. Lepidodendron bark. Size: 150 mm by 60 mm by 40 mm thick. Mississippian (Lower Carboniferous, 325 million years old).

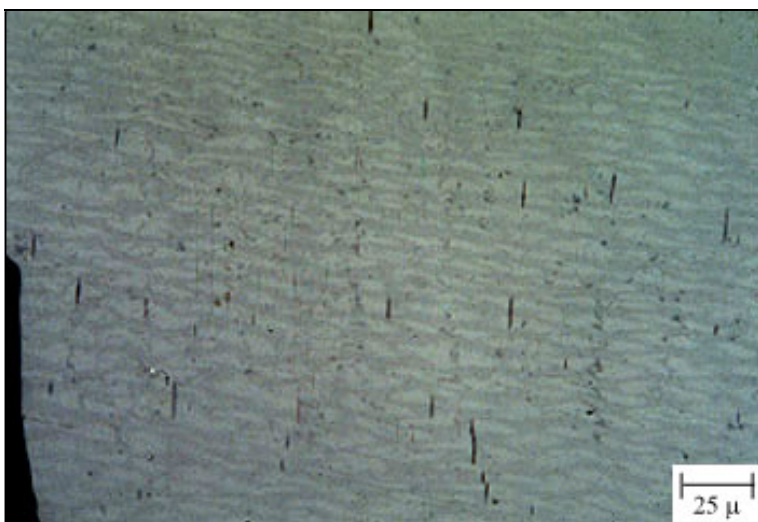


Figure 19. Telovitrinite with cell structure. Only with polarizer. Material is derived from coalified woody tissue.

7.3.1.2. Collotelinite

The term collinite is derived from the Greek word *kolla* (glue). It is structure less gel-like constituent of vitrinite. In vitrinite showing texture, the cells are frequently filled with collinite, whereas the cell walls consist of telinite.

7.3.1.3. Detrovitrinite

Vitrinite, like other macerals can occur in the form of detritus. These fragments generally originate from plants or humic–peat particles which were degraded at a very early stage. Rarely, they are fragments of vitrinite crushed by pressure. Detrovitrinite consists of finely fragmented vitrinitized plant remains occurring either isolated or cemented by amorphous vitrinic matter.

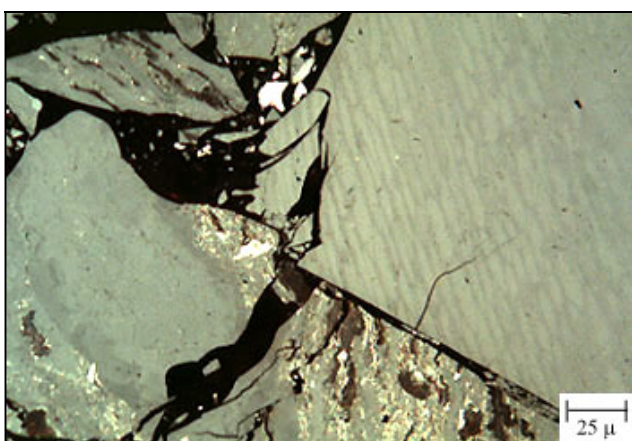


Figure 20. Telovitrinite and Vitrodetrinite particles. The particle at the right is telovitrinite showing well preserved cell structure. All of the other particles are of vitrodetrinite. The vitrodetrinite acts a matrix holding dark particles of liptinite macerals and bright particles of inertinite macerals. Polariser: in.

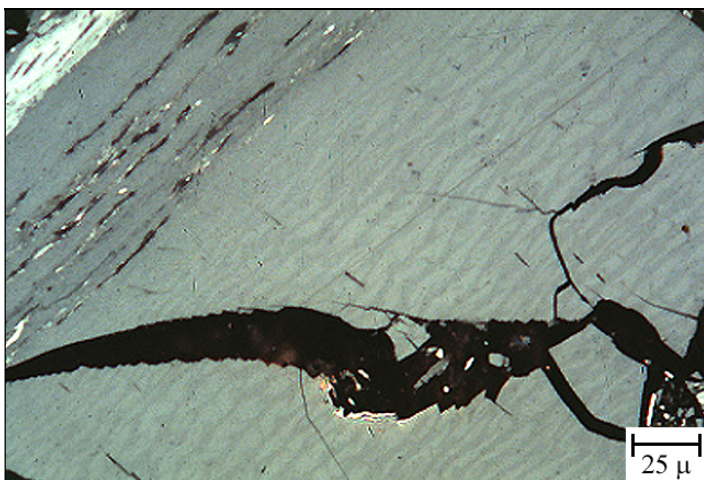


Figure 21. Telovitrinite and Vitrodetrinite in High Volatile Bituminous coal.

The uniform gray material in Figure 20 showing a well-developed cell structure in the right half of the frame is telovitrinite. The gray material in the upper left is Vitrodetrinite which acts as a matrix for dark stringers of sporinite and bright particles of inertinite.

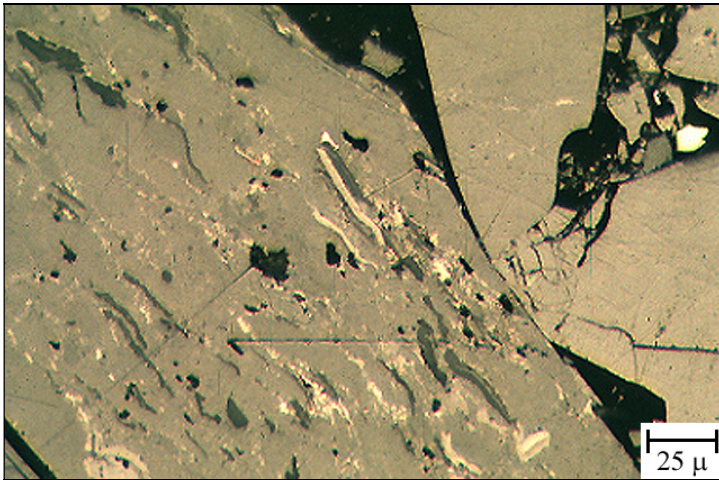


Figure 22. Telovitrinite and Vitrodetrinite in High Volatile Bituminous coal.

Vitrodetrinite

These are vitrinites with discrete small fragments of varying shape, that become discernible when surrounded by non-vitrinitic material.

Collodetrinite

Collodetrinite occurs as a mottled vitrinitic ground mass binding other coal components

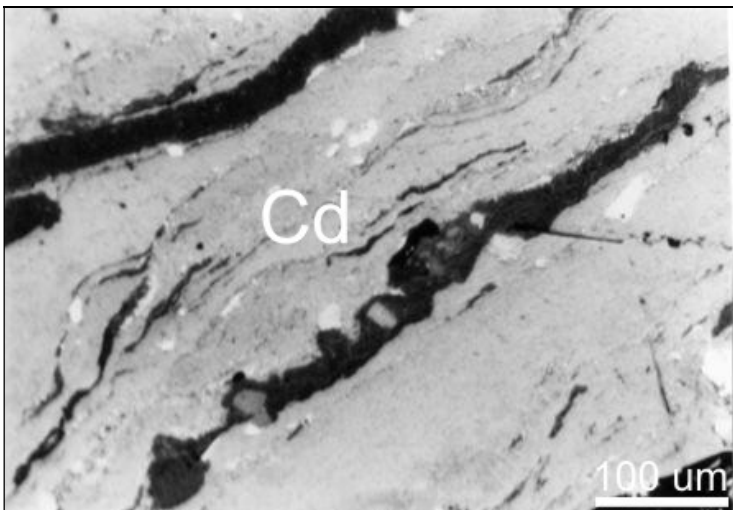


Figure 23. Collodetrinite (Cd).

7.3.1.4. Sporinite

The term sporinite is used designate the skins of spores and pollens in lignite and bituminous coal. A distinction is made between megaspores and microspores. A term combining both is miospores.

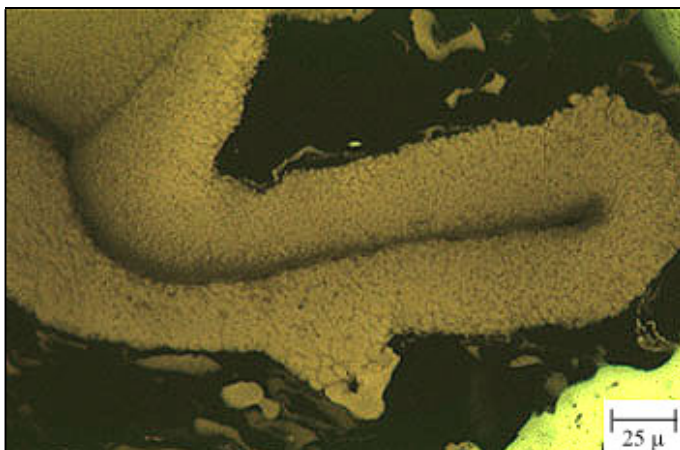


Figure 24. Typical megaspore structure. The sample has been excited with ultra-violet light and the sporinite fluoresces with a yellow color. No polarisers.

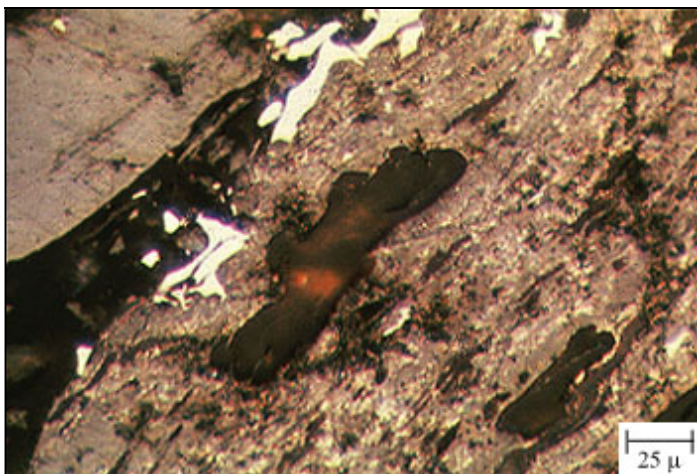


Figure 25. Typical megaspore structure. The dark structure in the centre of the field is also typical megaspore. It has a reflectance darker than vitrinite and displays bilateral symmetry around a central fissure. The orange spot on the megaspore is due to internal reflections and is a common feature of megaspores. The much smaller dark bodies seen around the megaspore are microspores and show a similar but less developed symmetry. Polariser: in.

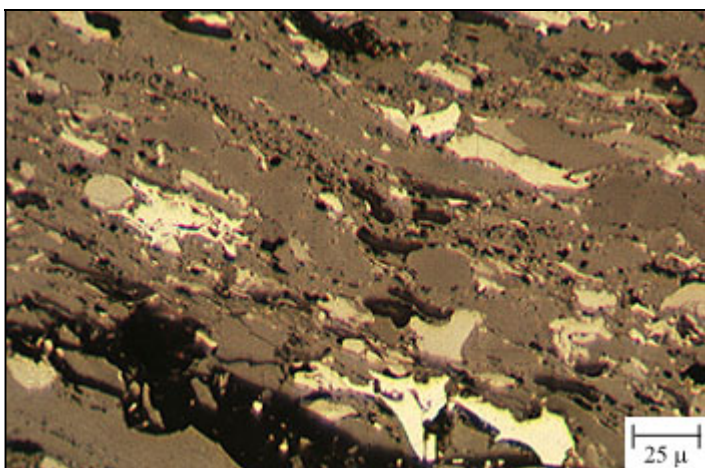


Figure 26. The small dark structures are typical megaspores. They are set in a vitrinite matrix with brighter particles of inertinite.

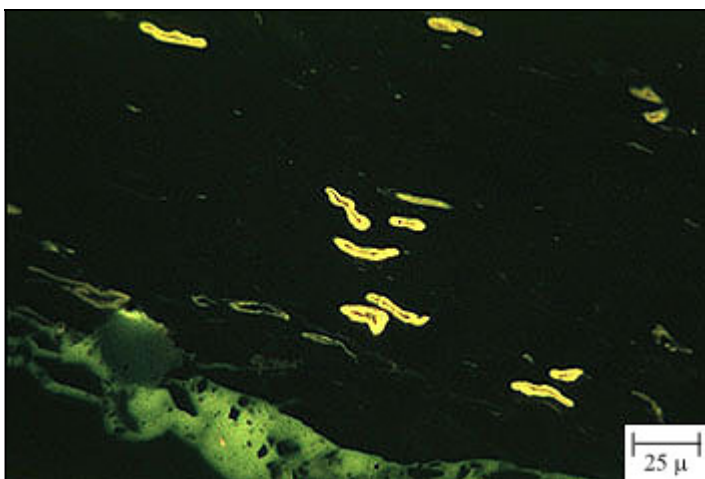


Figure 27. Typical microspores (no polarisers). The sample has been excited with ultra-violet light and the microspores fluoresce with a bright yellow colour. Note how the fluorescence makes the microspores easier to see.

7.3.1.5. Cutinite

Cutine forms the outer layers of leaves or cuticles. Cuticles (cuticula) are protective, hydrophobic, waxy coverings produced by the epidermal cells of leaves, young shoots and all other aerial plant organs.



Figure 28. Typical cutinite (Polariser: in). The dark structure in the centre of the field is cutinite. It is distinguished by its linear aspect and having one surface flat and the other crenulated.



Figure 29. Typical cutinite (no polars). Same as above: in this case the sample has been excited with ultra-violet light and the cutinite fluoresces a dull yellow.



Figure 30. Typical cutinite. Ultra-violet light. Note how the cutinite fluoresces.

7.3.2. The Exinite group

7.3.2.1. Resinite

All natural resins are products of the metabolism of plants. Their chemical and physical properties differ widely. The resinite of coals comprises not only resins from plants, but also certain other secretions, such as essential oils occurring in the leaves which have been converted into resin.

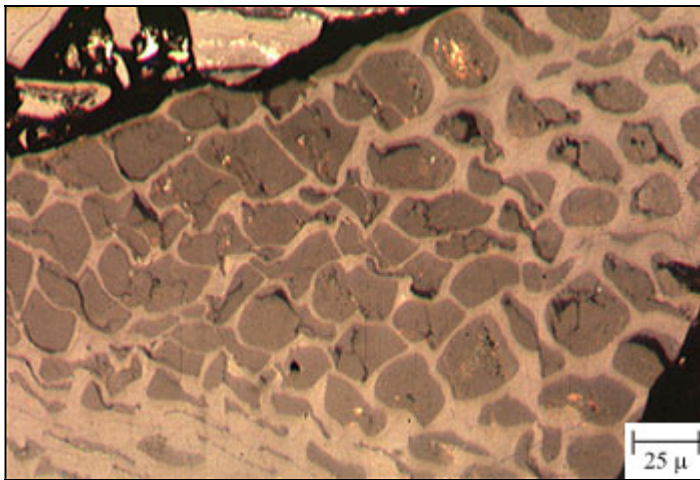


Figure 31. Vitrinite with cell structure filled with resinite.

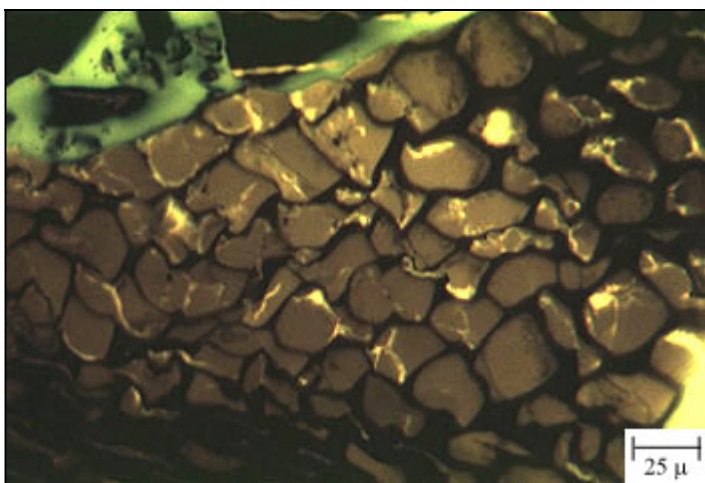


Figure 32. Same as fig. 27, but now the sample has been excited with ultra-violet light and the resinite filling the cells fluoresces with a yellow color. The yellow fluorescence colour of the cell fillings is characteristic of resinite. The vitrinite does not appear to fluoresce. This difference in fluorescence properties is commonly used to distinguish these macerals from each other. No polarisers.

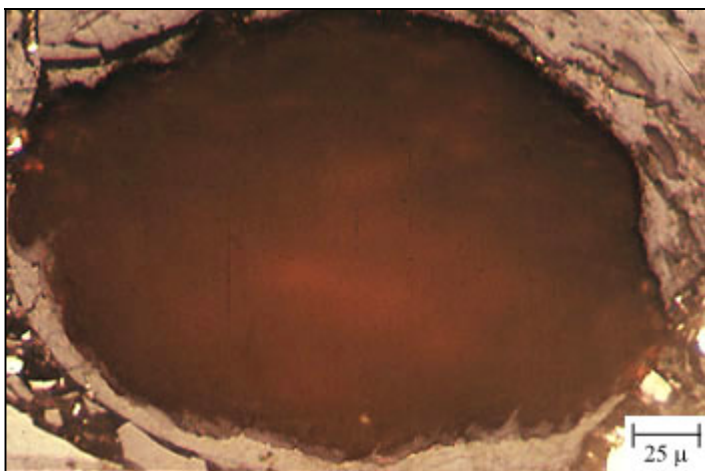


Figure 33. Resinite ovoid. This structureless ovoid is a typical occurrence of resinite. The dark orange colour is common although resinite macerals also can range from black to light grey in reflected white light. Polariser: in.

7.3.2.2. Alginite

This maceral occurs only in certain specific coals. It is not found in normal humic coals. It appears quite dark on polished surfaces under oil immersion. Alginite originates from certain types of algae, which were first identified and described in the course of studies of thin sections. Alginite has been found mostly in Palaeozoic boghead coals.

7.3.2.3. Liptodetrinite

Liptodetrinite is a collective term for liptinite (=exinite) constituents of different form, low reflectance and fluorescence, which because of their finely detrital condition cannot be assigned to any other maceral of the exinite group. Liptodetrinite may consist of fragments or degradation residues of spores, cuticles, resinous bodies or algae.

7.3.2.4. Fusinite

The maceral fusinite is the richest in carbon of all the constituents of coal. It frequently originates from charcoal. They occur in peat as well as in brown coal. Fusinites are particularly common in bituminous coals. The cell structure of the original plants is usually well preserved. Even intercellular spaces may be recognisable. The cell lumens are usually empty, but may be filled with minerals, for instance pyrite. If the cells are empty, the structure is sometimes similar to a perforated screen – some authors have used the term screen structure instead of fusinite.



Figure 34. Typical Fusinite. The bright reflectance and open cell structure characterize fusinite. It is the structure of pyrolysed woody tissue and its appearance is very similar that of charcoal. Polarisers: in.

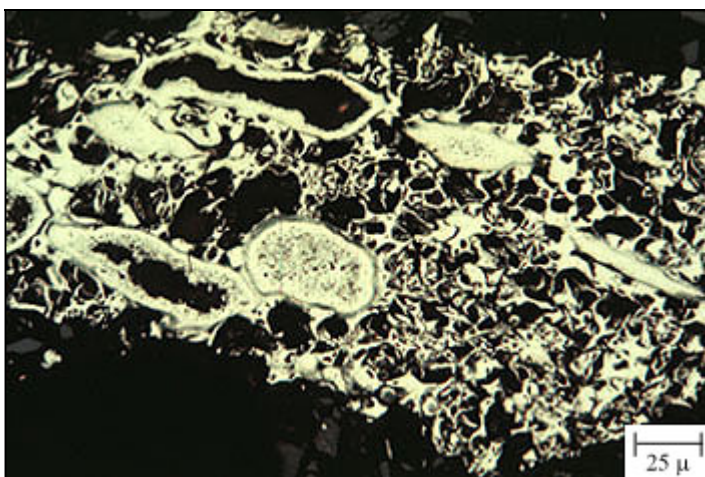


Figure 35. Typical Fusinite. The bright reflectance and open cell structure characterize fusinite. It is the structure of pyrolysed woody tissue and its appearance is very similar that of charcoal. Note the delicate plant derived cell structures that are well preserved. Polariser: in.

7.3.2.5. Semifusinite

This is an intermediate stage between fusinite and telinite. The particles under consideration originate from plant tissues which have been only partly charred.

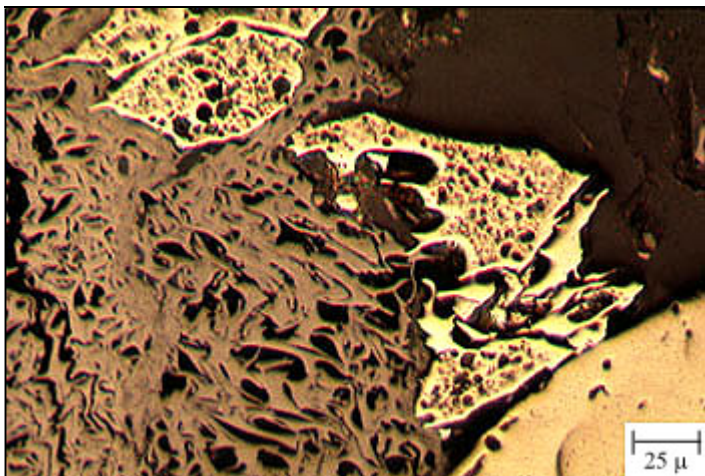


Figure 36. The bright material with open cell structure is fusinite and the lower reflectance material with open cell structure is semifusinite, Semifusinite is the most commonly occurring of the inertinite macerals. Polariser: in.

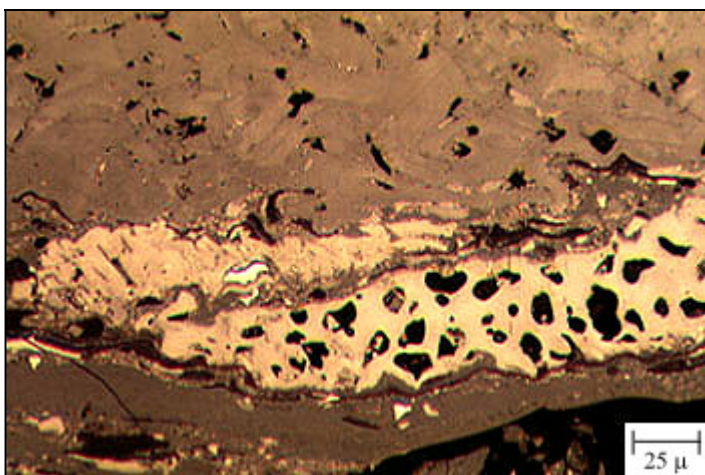


Figure 37. The three kinds of material in the upper three-fourths of the field are semifusinite. All three have open cell structure and reflectance between that of vitrinite and fusinite. The semifusinite macerals have the largest range of reflectance of any maceral. The layer at the bottom of the field is vitrinite. Polariser: in.

7.3.2.6. Macrinite

Macrinite is a more or less amorphous groundmass, showing no, or practically no structure. Apart from groundmass, macrinite may occur as isolated particles, with straight, or more usually, rounded contours.

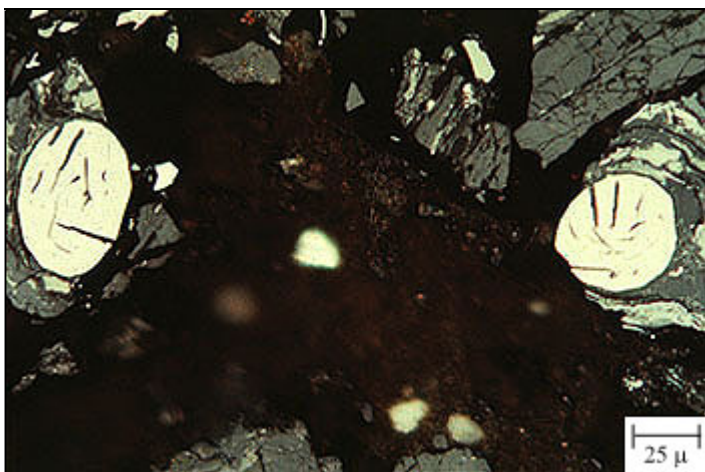


Figure 38. The two bright round bodies are macrinite. They are characterized by the high reflectance of fusinite and a lack of cell structure. Similar materials with a reflectance equal to semifusinite are called semimacrinite. Polariser: in.

7.3.3. The Inertinite group

7.3.3.1. Inertodetrinite

Inertodetrinite consist of more or less strongly reflecting fine particles, usually < 30 microns. In general they are fragments or remains of fusinite, semifusinite micrinite and sclerotinite. Due to their small size, they can in most cases not be assigned to a particular maceral of the inertinite group. For this reason they are grouped together under the collective name inertodetrinite.

7.3.3.2. Micrinite

Micrinite is characterised by rounded shape and the very small size of the grains, which are commonly < 1 micron across. Micrinite can occur as cell fillings in vitrinite, but it can also occur that the cell walls themselves have been transformed into micrinite. Micrinite frequently occurs finely dispersed in collinite.

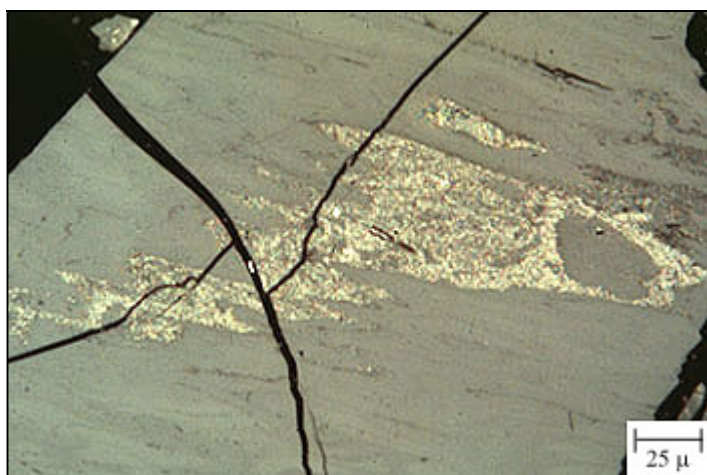


Figure 39. The bright fine-grained material seen in this field is micrinite. It is characterized by its brightness and small grain size. In this field the shape of the micrinite occurrence are similar to occurrences of cutinite suggesting a replacement process. Polariser: in.

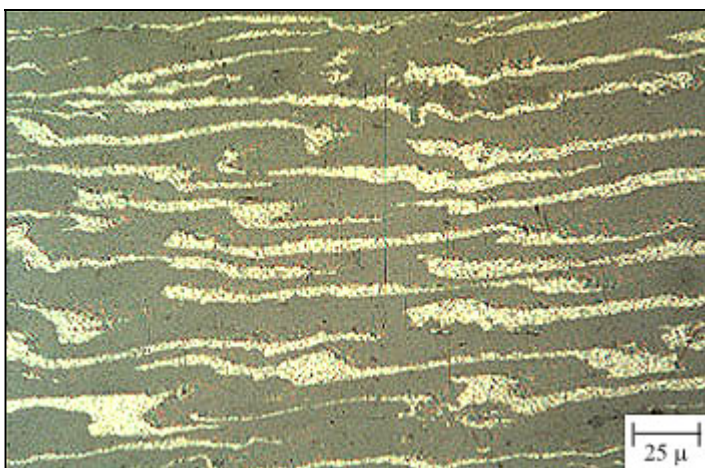


Figure 40. The bright fine-grained material seen in this field is micrinite. It is characterized by its brightness and small grain size. In this field the shape of the micrinite occurrence is similar to occurrences of sporinite suggesting a replacement process. Polariser: in.

7.3.3.3. Sclerotinite

The name is derived from the Greek word scleros, which means hard, rigid, brittle. The name sclerotinite covers all strongly reflecting fungal remains. Fungi are more common in Tertiary coals compared to Carboniferous and Permian coals.

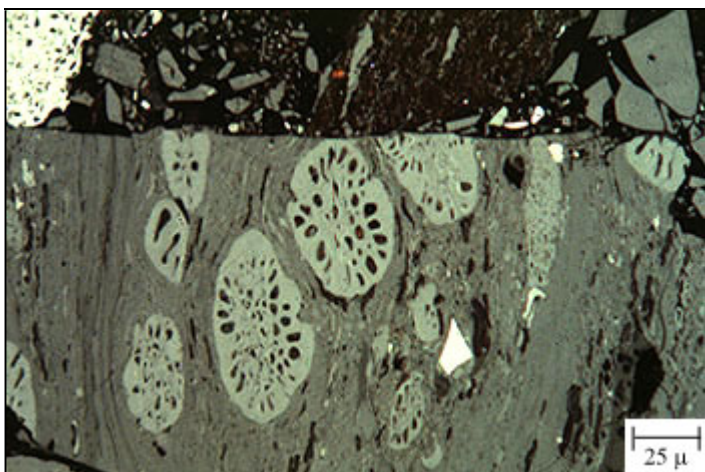


Figure 41. The round bodies with open cell structure are sclerotinite. They are derived from certain parts of various types of fungus. They are not found in coals of Carboniferous age. Polariser: in.

8. MICROLITHOTYPES

8.1. General

The macerals of coal rarely occur by themselves. They are more usually associated with macerals of the same or of the two other maceral groups. Such associations are called *microlithotypes*. They are divided into three groups: monomaceral, bimaceral or trimaceral microlithotypes, according to whether a microlithotype consist of one, two, or three maceral groups. All microlithotypes bear the suffix “-ite”, so as to distinguish them from the macerals.

The ICCP⁶⁸ has agreed upon the following conventions:

- the minimum band width of microns,
- the so-called 5%-rule.

The first means that in analyses a microlithotype can only be recorded as such, if on a polished surface perpendicular to the bedding plane it shows a width of at least 50 microns, or covers a surface of 50 x 50 microns. The 5%-rule arises from the fact that neither the mono- nor the bimaceral lithotypes are composed purely and exclusively of macerals from one or two maceral groups respectively. A monomaceral or bimaceral microlithotype may contain up to 5% of accessory macerals (which are not typical of it). For example: the microlithotype “*vitrite*” must contain not less than 95% of vitrinite, and not more than 5% of exinite and/or inertinite. The following table (after McCabe, 1984) gives the composition of the various microlithotypes.

<i>Microlithotype</i>	<i>Composition</i>
Vitrite	<i>Vitrinite > 95%</i>
Liptite	<i>Exinite > 95%</i>
Inertite	<i>Inertinite > 95%</i>
Fusite	<i>Inertite with no macrinite or micrinite</i>
Clarite	<i>Vitrinite and exinite > 95%</i>
Durite	<i>Exinite and inertinite > 95%</i>
Vitrinertite	<i>Vitrinite and inertinite > 95%</i>
Trimacerite	<i>Vitrinite, exinite, inertinite, each > 5%</i>

All microlithotypes may contain amounts of mineral matter: if this reaches 20%, the microlithotype is referred to as a *carbominerite*.

⁶⁸ International Committee for Coal and organic Petrology (also as ICCOP). The ICCP is a professional organization of more than 200 scientists representing more than 35 countries. Its members are engaged in many different branches, fundamental and applied, of coal and organic petrology.

8.2. Carbominerites

The classification of coal-mineral associations is based on the separation densities. Coals have a mean density < 1.5 g/ml. **Carbominerites** are associations of coal and minerals having a density $d = 1.5 - 2.0$ g/ml.

Carbominerites thus are impure coals and carbonaceous sediments consisting of macerals and minerals. According to the character of the minerals, there are recognized (Stach et al., 1982, Kühnel, 1982):

1. *Carbargillite*: coal + 20 – 60% clay minerals
2. *Carbopyrite*: coal + 5 – 20 % sulphide minerals
3. *Carbankerite*: coal + 20 – 60 % carbonate minerals
4. *Carbosilicate*: coal + 20 – 60 % quartz
5. *Carbopolyminerite*: coal + 20 – 60 % various minerals

Among the microscopically distinguishable carbominerites, **carbargillite** is the most common. The limit between carbargillite and argillaceous shale has been drawn at a clay content of more than 60% per volume and a density of 2.0 g/ml.

8.3. Minerals in Coal

The main minerals in coal are:

- Clay minerals (illite-sercite, montmorillonite, kaolinite),
- Sulphide (pyrite),
- Sulphates (barite, gypsum),
- Carbonates (siderite, ankerite, calcite),
- Oxides (quartz).

Pyrite often occurs as so-called **framboids**: these are roughly spherical aggregates of discrete equi-regular euhedral microcrystallites of around 0.5 μm in diameter, with the average aggregate size ranging from 5-20 μm

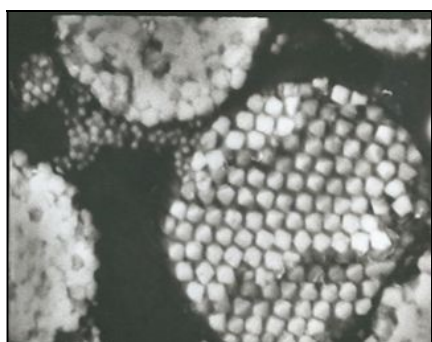


Figure 42. Pyrite framboids. SEM image.
Source: Internet.

Pyrite framboids typically occur in coals overlain by marine strata (Stach et al., 1982). They easily react with oxygen (large surface area, and this increases the danger of spontaneous combustion).

Minerals in coal are either primary (detritic or syngenetic), or secondary (epigenetic). The latter ones are often deposited in cavities and fissures, or they replace primary minerals. They occur in coal as separated grains intergrown with macerals, or as separated bands, lenses and laminae, up to thicker intercalations.

9. COAL PROPERTIES

9.1. Introduction

In this chapter, an overview is given of the different properties of coal, and of some standard test methods to determine these properties. Microscopic and macroscopic properties both contribute to the optimum use of coals.

9.1.1. Metallurgical Coal versus Thermal Coal

Bituminous coal includes two subtypes: thermal and metallurgical coal. *Nowadays, the most valuable coal is so-called metallurgical coal.* This is also known as *coking coal*. Coking coal is in fact bituminous coal. This kind of coal has very strict requirements, and is different from coal used for combustion, which is called *thermal coal*. Thermal coal is also called steam(ing) coal. Metallurgical coal is used in the process of creating coke necessary as a reduction agent for iron and steel-making. Although this is the main application, coke is also used in other HT-processes as an industrial reducing agent. Examples are the reduction of phosphate to phosphorus, which in turn has a myriad of applications, but also the reduction of very pure quartz powder to produce silicon metal (Si), which is invaluable for the computer industry. The latter coke must completely be Fe-free, to prevent the formation of Si-Fe-alloys, which are worthless.

9.2. Coal Properties

The properties of coal can be divided into microscopical properties, chemical properties and physical properties.

Microscopic Properties	Chemical Properties	Physical Properties
<i>Maceral composition (Vol. %)</i>	<i>Moisture (wt%)</i>	<i>Caking Properties</i>
<i>Mineral composition (Vol. %)</i>	<i>Ash Content (wt%)</i>	<i>Properties of Coal Ash</i>
<i>Particle (grain size) in μm</i>	<i>Carbon (dry, mineral-matter free basis)</i>	<i>Combustion Characteristics</i>
<i>Fabric (mode of occurrence, spatial distribution, mutual interrelations, orientation)</i>	<i>Hydrogen content</i>	<i>Grindability</i>
<i>Reflectance</i>	<i>Oxygen content</i>	<i>Float-Sink Properties</i>
<i>Anisotropy (bireflectance)</i>	<i>Volatile matter (Aromatic C/total C)</i>	
<i>Fluorescence</i>	<i>Density (g/cm^3)</i>	
<i>Microhardness</i>	<i>Calorific value MJ (kcal)</i>	

In addition to this, numerous other properties are determined, like:

1. *chemical structure,*
2. *reactivity,*
3. *forms of sulphur (organic, inorganic),*
4. *determination of nitrogen,*
5. *chlorine content, etc..*

9.3. Chemical Properties of Coal

Very simply speaking, coal can be regarded as being made up of carbon, moisture and mineral matter. The moisture consist of surface moisture and chemically bound moisture. The coal itself is the amount of organic matter present, and the mineral matter is the amount of inorganic material present. The latter produces ash when the coal is burned.

Coal analyses are often reported as **proximate** or **ultimate analyses**. Before turning towards these, it is necessary to evaluate on what basis the data are presented.

9.3.1. Basis of Analytical data

It is important to understand how the moisture, ash, volatile matter and fixed carbon relate to one another. Coal analyses may be reported as follows:

- 1) **As Received (a.r.)**. The coal is not dried before measuring.
- 2) **Air Dried Basis (a.d.b.)**. The coal is dried in air but not at elevated temperatures.
- 3) **Dry Basis (dry)**. All moisture has been removed.
- 4) **Dry Ash Free Basis (d.a.f.)**. By recalculation the moisture and ash are removed, and only volatile matter and fixed carbon is reported.
- 5) **Dry, Mineral Matter Free (d.m.m.f.)**. Here it is necessary that the total amount of mineral matter is rather than ash is determined, so that the volatile matter content in the mineral matter can be removed.

9.3.2. Proximate Analyses

The proximate analysis is a broad analysis of amounts of moisture, volatile matter, fixed carbon and ash. It is the most fundamental of all coal analyses, and is of great importance in the practical use of coal. Procedures differ, and results are highly dependent on the procedure used.

9.3.2.1. Moisture.

The terminology used to describe the moisture content of coal can be confusing. Most confusing is the term “inherent moisture”, which has many definitions, and should be avoided. There is no exact method of determining moisture. Recognised are, however:

1. Surface moisture. This can be removed by low temperature air drying (40°C).
2. As received moisture. Total moisture of the coal sample when received at the laboratory.
3. Total moisture. All the moisture that can be removed by aggressive drying (ca. 150°C in vacuum or nitrogen atmosphere).
4. Air-dried moisture. Moisture remaining after air drying, and which can be removed by aggressive drying.

9.3.2.2. Ash

The ash of the coal is the inorganic matter that remains after combustion. It must be emphasized that the determined mineral content of the coal is not the same as the ash

content. It does however, represent the bulk of the mineral matter in the coal after losing the volatile components such as CO₂, SO₂, and H₂O, which have been driven off from mineral compounds such as carbonates sulphates and clay.

9.3.2.3. Volatile Matter

Volatile matter represents that component of the coal, except for moisture, that is liberated at high temperature in the absence of air. This material is chiefly derived from the organic matter of the coal, but minor amounts may also be from the mineral matter present.

9.3.2.4. Fixed Carbon

The fixed carbon content of coal is that carbon found in the residue remaining after the volatile matter has been liberated. It cannot be determined directly, but is found by subtracting the moisture, ash and volatile matter from 100%.

9.3.3. Ultimate Analyses

The ultimate analysis is the determination of the chemical elements in coal, which are carbon, **hydrogen, oxygen, nitrogen and sulphur**. Sulphur in coal is an important impurity, causing hazardous air pollution as a result of combustion products (sulphur oxides). Three main sources of sulphur are recognised: *sulphates, sulphides and organic compounds*. Furthermore there are **chlorine, phosphorus**, and the **elements** that make up the **mineral matter**.

9.4. Physical Properties of Coal

9.4.1. Caking Properties of Coals

This is a unique property of coals in the bituminous group of coals and is an essential property for coals which are required for **coking**. As a **caking coal** is heated it passes through a region where it becomes very plastic, softens, swells and then re-solidifies. The residue is a cellular coke mass. Coals which do not cake are simply form a non-coherent or weakly coherent char.

A number of tests have been devised to classify the caking properties of coals including the

- *Roga test*,
- *Free Swelling Index*,
- *Gray-King test*

9.4.1.1. The Roga test

The Roga test indicates the caking properties of coal. A sample of coal is combined with a standard measure of anthracite and then heated. The resultant button is tested for mechanical strength rather than the change in dimensions by being rotated in a drum for a specific time.

There is a correlation between the Roga index values and the free swelling index.

9.4.1.2. Free Swelling Index Test

The free swelling index test entails heating a standard powder of the coal in a crucible and comparing the resultant "button" with a standard profile. The test is a gram of very finely ground coal in a silica crucible, tapped down, covered and heated strongly with a powerful gas burner for 2.5 minutes. It is generally done in at least triplicate, frequently quintuplicate.

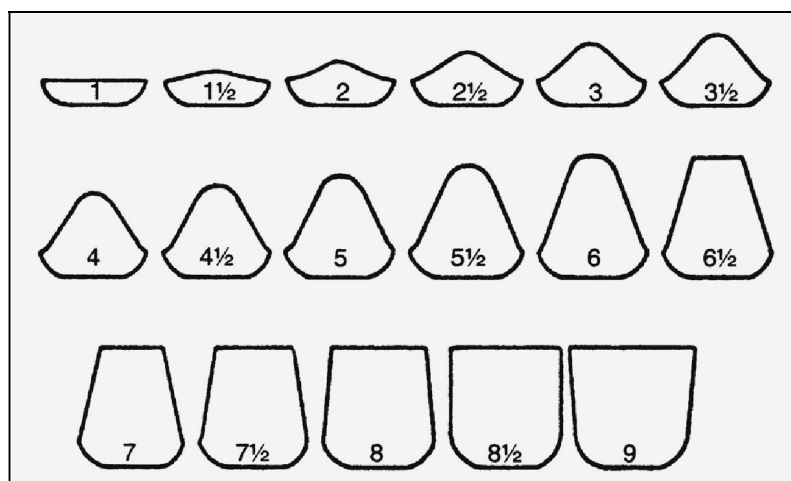


Figure 43. Standard profiles of coke buttons for different values of the crucible swelling number (Free Swelling Index).

When cooled, the coke button is compared with a set of standard profiles (Figure 35), and an index is given between 0 and 9. A non-coherent sample is given 0. Generally 0 - 3 implies marginal caking behaviour.

9.4.1.3. Gray – King test

Finely crushed coal is heated slowly in a sealed tube, and the appearance and the texture of the coke residue is compared to standards, and assigned a letter, the Gray-King coke type. Values range from A, no coking properties at all, to G, where the coal has retained its volume, and forms a well fused product.

The caking behaviour is critical to coke making. A successful coke must be strong and not powdery. Prime coking coals have GK indexes of G (and its subdivisions). Much less and a weak coke unstable coke is made.

9.4.2. Properties of Coal Ash.

Most important is the ash-fusion temperature. This determines how the coal's ash residue reacts at high temperatures. This can be critical for selecting coals for combustion: how will the coal behave in a furnace or boiler.

To determine this, tests are carried out, in which the ash from a coal is moulded in a certain predetermined shape, and heated in an oxidising or mildly reducing atmosphere, usually to about 1000 – 1600 °C. Among others, initial deformation temperature, softening temperature, and fluid temperature (where the ash has become completely liquid) are determined.

9.4.3. Combustion Characteristics

These can be determined by combustion test in either a ***Bomb-Calorimeter***⁶⁹, or with a ***Thermobalance***⁷⁰. Most important is the determination of the ***Calorific Value***. This is the amount of heat per unit mass of coal when combusted. Also loss of moisture and dehydroxylation and dehydrogenisation are determined in these tests.

9.4.4. Grindability Test

In modern commercial operations, coals are required to be crushed to a fine powder before being fed into a boiler. The relative ease with which a coal can be pulverised depends on the strength of the coal, and it is measured by the ***Hardgrove Grindability Index (HGI)***⁷¹. The test is an empirical test and not linked with a known physical property of coal. It was developed in the 1930's.

9.4.5. Float-Sink Tests

⁶⁹ A **Bomb-Calorimeter** is a type of constant-volume calorimeter used in measuring the heat of combustion of a particular reaction.

⁷⁰ A **Thermobalance** is used in thermogravimetry (also known by the acronym "TG"). Thermogravimetry is based on continuous recording of mass changes of a sample of material, as a function of a combination of temperature with time, and additionally of pressure and gas composition. It is for instance used in determining the loss of moisture.

⁷¹ The **Hardgrove Grindability Index (HGI)** was developed in the 1930s from experimental work by R. Hardgrove to determine the relative difficulty of reducing various coals to a particle size required for efficient combustion in pulverized coal boiler furnaces. The HGI is now commonly applied to specifications for coal to be used in the iron making, cement and chemical processes. HGI-values may be correlated with the ***Work Index*** in Bond's method for determining grindability.

The particles of coal are of relative different densities. The densities represent the varying amounts of mineral matter present. Consequently the coal preparation process is designed to remove these, so that the ash level of the coal is reduced, and the coal product is improved. Coal particles are separated into density fractions by immersion in a series of liquids of known relative density, usually ranging from 1.3 to 2.00. Commencing with the lowest relative density range, the sinking fraction is transferred to the next liquid in the series, and so on.

9.5. Cokes and Petrographic Characterisation of Coal

The microscopic study of coal enables a better understanding of the organic and mineral components and its industrial utilisation. The principal use of black coal on a worldwide basis is for the generation of electricity, and to produce iron and steel. The latter still depends on coal, to make coke, which in turn is used as industrial reduction agent to convert iron oxides to metallic iron.

Coals that are to be used for conventional coke production must have three essential properties:

1. They must be within a specific range in rank for the coking process to occur: this is bituminous coal.
2. They must contain a *high proportion of fusible macerals* (>40% vitrinite), to form a strong well-fused coke. ***Here coal petrography comes along.***
3. They must have low levels of certain elements, notably sulphur and phosphorus, and in general be low in mineral matter.

In coke production, vitrinite is the maceral group that contributes most to the formation of coke. However, a stronger coke is formed if the vitrinite is reinforced by inertinite. The liptinite group is characterised by high H/C ratios, and therefore produces large amounts of gas on heating, all of which contribute to the fluidity and swelling characteristics of the coal (see VI.3).

However, abundant liptinites are relatively thermally resistant to thermal breakdown and remain after vitrinite has become plastic. In the inertinite maceral group fusinite and semi-fusinite do not fuse during carbonisation due to their insufficient hydrogen content. These macerals are characterised by higher O/C ratios. The inertinite maceral group is thought to have little influence during coke-making, although there are studies that show that some inertinite is completely fused during the coke-making process.

9.6. Famous Pioneering People in the Field of Coal Science and of Coal Petrography & Coal Petrology

- **Van Krevelen, Dirk Willem** (1914-2001) Dutch chemist, known among others for his work on coal combustion, the composition of coals, and their occurrence (DSM, TH Delft).
- **Stach, Erich** (1896–1987) Eminent German coal petrologist and coal petrographer. Mentor of Marlies and Rolf Teichmüller (Humboldt University Berlin).
- **Stopes, Marie Charlotte Carmichael** (1880 –1958). British scientist. Founder of the field of Coal Petrology and Coal Science (University College London, University of Manchester).
- **Teichmüller, Marlies** (1914 – 2000) Eminent German coal petrographer and coal petrologist. (Humboldt University Berlin).
- **Teichmüller, Rolf** (1904–1983) German coal petrographer and coal petrologist. Husband of Marlies. (Humboldt University Berlin).

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