
FORMATION AND
CLASSIFICATION OF COAL
Author
HATİCE KARA
BİDGE

BIDGE Publications

FORMATION AND CLASSIFICATION OF COAL

Author: HATİCE KARA

ISBN: 978-625-372-623-2

Page Layout: Gözde YÜCEL

1st Edition:

Publication Date: 10.03.2025

BIDGE Publications,

Certificate No: 71374

www.bidgeyayinlari.com.tr - bidgeyayinlari@gmail.com

Krc Bilişim Ticaret ve Organizasyon Ltd. Şti.

Güzeltepe Mahallesi Abidin Daver Sokak Sefer Apartmanı No: 7/9 Çankaya / Ankara

Introduction

Over millions of years, plant matter breaks down into peat, which is a sole-like, partially decayed plant material that builds up in peat. The peat is subsequently converted to coal by the heat and pressure of deep burial. This black or brownish-black sedimentary rock is flammable and contains different amounts of carbon (often greater than 50 weight percent) and other elements (mostly nitrogen, oxygen, sulfur, and hydrogen). It manifests as peat, lignite, subbituminous coal, bituminous coal, anthracite, graphite, cannel coal, and coking coal and is found in underground formations known as "coal beds" that are roughly 1500 km long and 30 m thick. Another way to categorize coal is by its macroscopic appearance, which is also known as the coal rock type, lithotype, or kohlentype. The four main categories that are distinguished are vitrain, clarain, durain, and fusain.

Coal is still an important economic resource in many countries globally. Coal is still used for electric power generation and currently meets the majority of global electricity demand [World Coal Association, 2017]. About 40% of the world's power and 25% of its primary energy comes from coal, one of the three fossil fuels (the others being gas and oil). In 2040, coal will continue to account for 22% of power output, making it the world's greatest single source of electricity, according to the World Coal Association [2017]. Several coals are rich in Ge, Ga, U, V, Se, rare earth elements, critical elements like Y, Sc, Y, Au, and Ag, and base metals like Al and Mg.

They are also utilized in large quantities for metallurgical processes, gasification, cement industries, bioconversion into high-value agricultural products, and as a raw material for numerous common and industrial chemicals [Dai & Finkelman, 2018].

Understanding the intricacy of different coal types in terms of their composition as well as their nature, formation, types, rank, etc., is made possible by studying coal chemistry and geology. In this study, the carbonization process that gradually converts plant residues into coal with the passage of heat, pressure and time is described. In addition to discussing structural changes in coal during coalification, chemical changes during peatification and coalification are also detailed.

1. 1.Formation and Classification of Coal

Coal is an organic origin rock that can burn directly with the oxygen of the air and contains 55-95% free and combined carbon. The change in the stages until the plant residues pass through the peat, lignite, bituminous coals and anthracite stages and turn into meta-anthracite is defined as coalification (Figure 1, 2, and 3). In coals formed over geological time, coalification first starts from the peat phase. Coals are divided into four categories according to rank classification (calorific value) as lignite (<4165 Kcal/Kg), sub-bituminous coals (4165-5700 Kcal/Kg), bituminous coals (5700-7780 Kcal/Kg) and anthracite (>7780 Kcal/Kg) [Hower et al., 2017]. The many forms of coal are listed in Table 1 according to their heat, moisture, volatile, and carbon contents.

Table 1. Types of coal

Coal	Dry, Carbon content (%)	Moisture content before drying (%)	Dry, volatile content (%)	Heat Content (MJ/ kg)
Anthracite	86–92	7–10	3–14	32–33
Bituminous coal	76–86	8–18	14–46	23–33
Sub-bituminous coal	70–76	18–38	42–53	18–23
Lignite	65–70	35–55	53–63	17–18
Peat	< 60	75	63–69	15

[Breeze, 2015]

Figure 1. The lowest rank of coal is lignite

[URL1].

Figure 2. Bituminous coal is a banded sedimentary rock (Coal material is shown in this image in both brilliant and dull bands that are horizontally orientated across the specimen. The well-preserved woody material, including branches or stems, is what gives the colorful bands their color. Degraded plant matter, charcoal from marsh fires, or mineral particles carried into the swamp by streams can all be found in the drab bands).

[URL1].

Figure 3. Anthracite has the highest coal quality

[URL1].

During the combustion of coal, carbon and some other elements can be oxidized or vaporized. However, the residue consisting of unburned substances is called coal ash. Coal ash; It can be inorganic ash, that is, ash coming from plants that form coal. In addition, external ash is inorganic substances mixed from outside during coalification, other than plants. A large part of these can consist of silicon, aluminum and iron oxides. Therefore, a significant part of the minerals in question turns into a residue, namely coal ash, consisting of non-combustible mineral matter found in coal and a smaller amount of partially burnt coal [Hower et al., 2017].

Peat is formed first. This is where coal comes from. In order to prevent stored plant matter from decomposing, peat formation requires permanently present stagnant groundwater above or near the ground surface. This typically happens in coastal flatlands when freshwater runoff is impeded by seawater. We refer to these places as marshes. They are linked to the coastlines of enormous interior

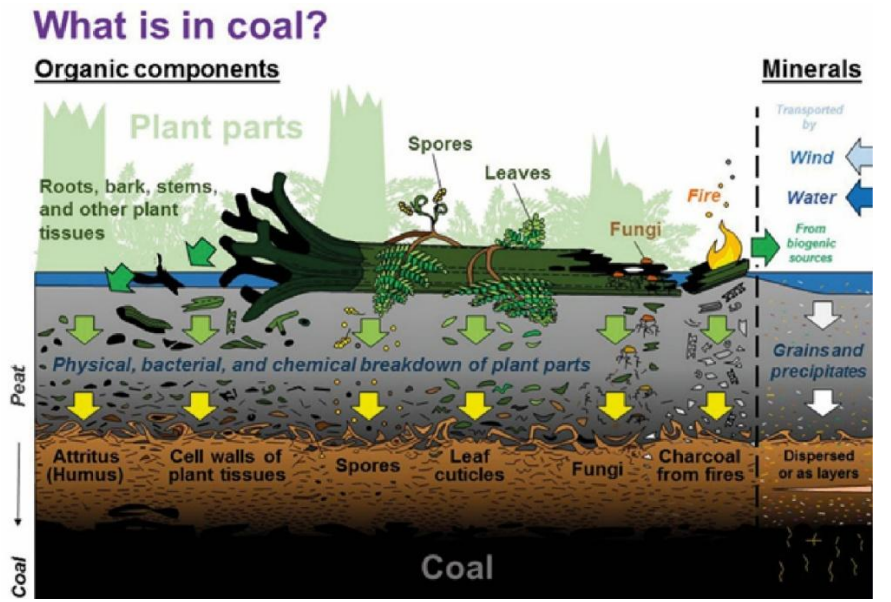
lakes or the coasts of the sea [Thomas, 2002]. Coal beds are made up of bands or layers of coal that are occasionally separated by thin sedimentary rock layers, known as weatherings, which are often shale. The terms types and lithotypes are used to define coal belts. The peat that makes up coal bands is primarily plant debris with a few minerals. Flooding the original coal-forming peat resulted in the formation of fine sediment weatherings in the majority of coals. Modified plant parts, including roots, leaves, stems, and spores, make up different forms of coal and lithotypes. Different plant elements are partially broken down and transformed into tiny organic particles and gels known as macerals during the peatification and subsequent coalification processes. Coal-forming peat and subsequent coal also contain dispersed inorganic particles called minerals. The proportion and types of macerals and minerals in a coal bed affect its quality and how it can be used [Stach et al., 1982; Bustin et al., 1983; Teichmüller et al., 1989].

Coal components arise in a variety of ways because to the several processes that occur during peat deposition and subsequent geological events during diagenesis and epigenesis. Coal is a very heterogeneous and complicated material that can:1) form from the buildup of bone fragments and other biogenic elements inside the peat deposit, as well as from a range of precursor plants with wildly disparate chemistry; 2) get inorganic material from a range of sources, including fluids, volcanogenic ash, and detrital; 3) experience a broad spectrum of pressures, temperatures, and chemically active fluids across geologic time; and 4) undergo constituent oxidation, reduction, leaching, and precipitation. Therefore, it is irrational to expect that the modes of occurrence of elements in coal from various geologic periods, ranks, areas, and coal types will be comparable. However, all coals share the following characteristics: Over geologic time, all coals undergo reducing circumstances and a broad range of increased temperatures

and pressures; they are all formed from degraded plant material; and they all get detrital particles from common crustal rocks. Many elements have common ways of occurrence as a result of these universal circumstances. For instance, silicon (Si) is frequently found in quartz and clays; aluminum (Al) is mostly found in clays; calcium (Ca) is found in a variety of carbonates; zirconium (Zr) is found in zircon; and iron (Fe) is found in pyrite and siderite [Dai et al., 2021].

Coal is formed by the physical and chemical alteration of peat. Peat is formed from plant material deposited in wetlands (peatlands and bogs) that has been broken down by the peat bog process. If peat is buried, it can be converted into different grades of coal by the coalification process (Figure 4).

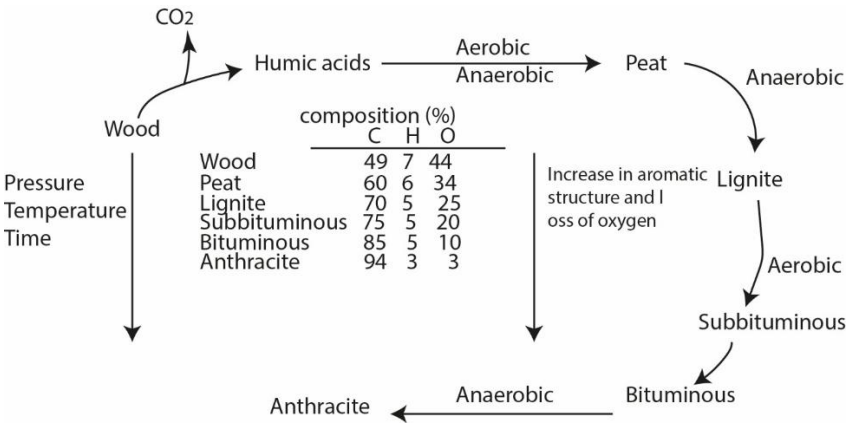
Figure 4. Coal beds showing organic components from plants and mineral components from various sources



[URL2].

The plant materials/plant parts accumulate in suitable swamp environments and then precipitate (Figure 5). Over time, they are buried underground with geological factors. These organic accumulations are then affected first by pressure conditions and then by the temperature conditions of the environment. Physical and chemical changes occur in the organic matter under the effect of temperature and pressure. From peat to coal, water and water vapor, CO_2, and oxygen are removed from the environment, respectively, and in the anthracite stage, hydrogen leaves the substance [Speight, 2012].

Figure 5. Schematic representation of the coalification process



[Speight, 2012]

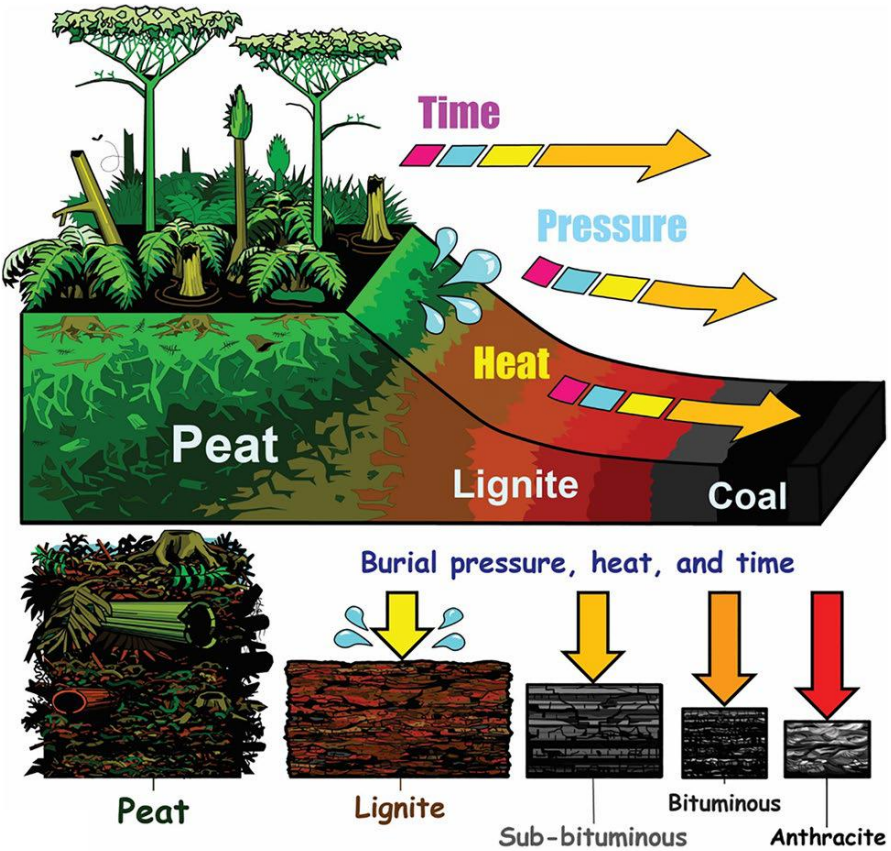
With a carbon concentration of 65% to 70%, lignite, often known as brown coal, is the least valuable of coal [Breeze, 2015]. It has the highest concentration of non-carbon chemicals, like sulfur and mercury, when compared to other forms of coal. With an approximate age of 60 million years, lignite is the youngest fossil fuel. At 18 MJ/kg, its energy density is relatively low (Table 1). Compared to other higher-grade coals (Table 1), lignite has a higher moisture content and a lower carbon content, which lowers carbon dioxide emissions.

Between low-quality lignite and higher-quality bituminous coal, sub-bituminous coal, often known as black lignite, is a greyish black to dark brown coal that can range in softness from hard. Sub-bituminous coal ranges from 70 to 76 percent carbon [Kraushaar and Ristinen, 2015]. It is roughly 251 million years old and a member of the younger coals. As a result, its energy density, which ranges from 18 to 23 MJ/kg, increases with longer burial period in comparison to lignite. With 30% of coal deposits being sub-bituminous, this is the most often used type of coal. With a carbon concentration of 76–86%, bituminous coal is the second-highest quality coal [Kraushaar and Ristinen, 2015]. With an estimated age of 300 million years, it is the most prevalent kind and one of the longest-buried fossil fuels. Consequently, its energy density, which ranges from 23 to 33 MJ/kg, is very high. This kind of coal's high carbon and low moisture content make it perfect for power generation, coke manufacturing, and the manufacture of steel and cement [Feulner, 2017]. The best quality coal is anthracite, which is dark black. It contains over 95% carbon, is extremely hard, and has a low moisture content [Kraushaar and Ristinen, 2015]. Because it was generated from biomass that was buried 350 million years ago, anthracite is often the oldest sort of coal. It has the highest calorific value of all coal kinds, with an energy density of 33 MJ/kg [Breeze, 2015].

Figure 6 shows a schematic representation of the coal type formation process. Graphite, cannel coal, and coking coal are the three additional coal kinds that are occasionally referenced in the literature. Because it is hard to burn, graphite is primarily utilized in pencils or as lubricant powder [Schopf, 1966] (Fig. 7). Cannel coal, sometimes known as candle coal, is a high-rank, finely powdered coal that contains a significant amount of hydrogen. It is primarily composed of liptinite, which is a finely ground mineral found in coal beds [Hutton & Hower, 1999]. Steel is made by burning coking coal, also known as metallurgical coal, at high temperatures. Otherwise,

Hilt′s law, which is based on the geological fact that the deeper the coal, the higher its rank (or grade), defines the coal quality (coal rank) within a given area. Because metamorphism can result in lateral changes in rank at any level, it should be highlighted that it is applicable when the temperature gradient is entirely vertical.

Figure 6. Scheme of formation of different coal types.



[URL2].

Figure 7. Sample of graphite

[URL3].

2.Lithotypes and types of coal

A particular geological classification known as "coal type" is based on the overall look of the coal and describes its rank of the coal or the grade of coal. Banding, or internal layering, is seen in the majority of coals. The presence or lack of banding and the brightness or opacity of each band determine the type of coal and subsets of types known as lithotypes. Coal lithotypes are further subdivided into microscopic microlithotypes, which consist of different types of microscopic coal components, called macerals. Macerals are to coal what minerals are to rocks [Stach et al., 1982; Hutton and Hower, 1999; O'Keefe et al., 2013]. According to this viewpoint, humic (banded) and sapropelic (non-banded) coal are the two fundamental forms of coal that can both be found in a same coal seam.

Mostly woody and/or reed/sedge remnants gave rise to humic coals through peatification processes, which mostly take place in the comparatively wet aerobic zone of a mire (humification). As a result, they usually form in thin layers from organic mud secondary to wood or peat rich in reeds and sedges. Macroscopically, humic coals can be banded, with vitrain layers alternating with other lithotypes, or

vitrains or bright clarains. They include duroclarite, inertite, vitrite, clarite, and vitrinertite by microlithotype. The predominant maceral percentage composition is either vitrinite or inertinite, particularly fusinite and semifusinite. Humic coals fracture along both the banding and cleat planes and are typically dark brown to black in color [O'Keefe et al., 2013].

Sapropelic coals were created by putrefaction, or decay in standing or stagnant water, mostly in the anaerobic zone, from a mostly nonwoody source (algae, spores, pollen, cuticles, various leaf waxes, and macerated herbaceous plant remnants). They are dull clarains and durains on a macroscopic level, having a tendency to be matte black and fracture conchoidally as opposed to along bands or cleats. Liptite, vitrinertoliptite, and durite are the microlithotypes of sapropelic coals. Liptinite, particularly alginite (in the case of boghead coal or torbanite) or sporinite (in the case of cannel coal), dominates their maceral makeup. Organic muds (gyttja in periglacial settings) or organic-rich oozes that occur in mostly freshwater environments are the predecessors to sapropelic coals in the early phases of coalification [O'Keefe et al., 2013].

3.Peatification and Coalification

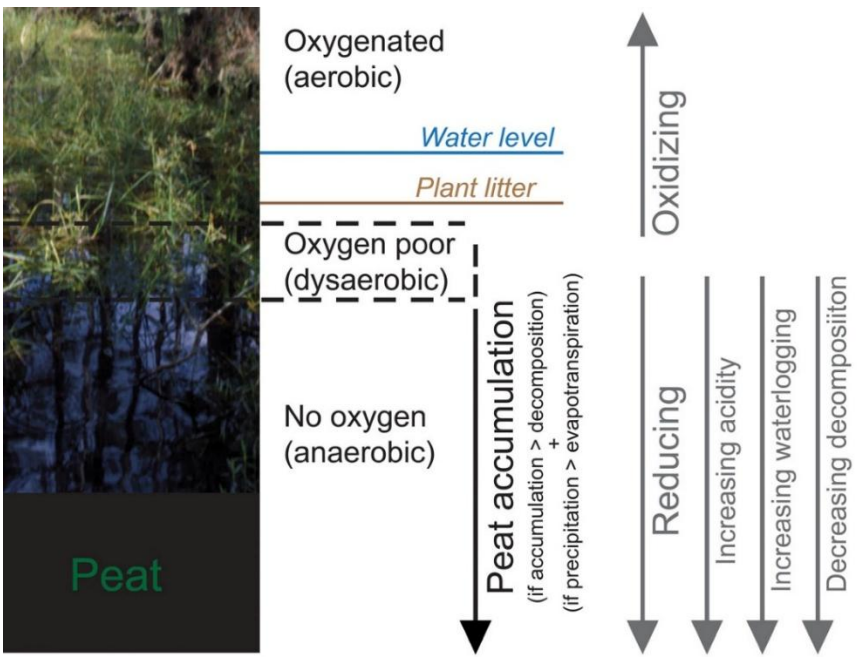
3.1.Peatification

Peat is the precursor material from which coal is made. It is a soil-like, partially decomposed plant material that builds up in wetlands, which are unique ecosystems that are submerged under water [URL4; Hatcher et al., 1990]. At least three factors influence the formation of peat: (1) the evolution of plant life; (2) the climate (warm enough to encourage plant growth and moist enough to permit partial plant material decomposition and preserve peat); and (3) the physical characteristics of the region (geography in relation to the sea or other bodies of water, rates of subsidence or uplift, etc.) [URL5; Xintu, 2009; Diessel, 1992]. Bright coal, often referred to as

bituminous coal, is produced in warm, humid areas and is distinguished by its fine banding and high levels of moisture, sulfur, and nitrogen. However, in cooler temperate areas, relatively little brilliant coal is needed to produce so-called detrital coal. Peatification is the partial decomposition of plant matter that has accumulated in wetlands [URL4; Hatcher et al., 1990; Xintu, 2009; Topcuoğlu and Turan, 2018] (Fig. 8).

Former plant parts and decomposing plant parts, along with other decomposition products, silt, and charcoal, are all examples of peat deposits. The resultant coals created during the peatification process contain a broad range of organic and inorganic components, including different minerals that are derived from sediments that are delivered by water and wind.

Figure 8. Some of the processes that decompose and maintain the organic matter in peat.



[URL6].

Peatification, sometimes referred to as "biochemical coalification," involves both chemical and microbiological change (Figure 9 and Figure 10). The most significant modification occurs in the peatigenic layer, which is the peat layer that extends from the peat's top to a depth of around 0.5 meters. Fungi, aerobic bacteria, and actinomyces a class of anaerobic bacteria are active in this stratum. These species vanish as depth increases, and only anaerobic bacteria remain. Microbial life decreases with increasing depth and eventually vanishes entirely as the readily absorbed chemicals gradually disappear. At depths below 10 meters, the latter is typically the case. Only chemical reactions, primarily condensation, polymerization, and reduction, take place at deeper depths [Zeng, 2016]. The most crucial step in the peatification process is humification, which forms the humic compounds. The carbon content of a peat profile rises quickly with depth. The microbial breakdown of oxygen-rich molecules in this layer, especially cellulose and hemicellulose, is the source of this. As a result, the newly generated humic acids and lignin, which is relatively rich in carbon, are enriched. The carbon content of the peatigenic layer may increase from 35–50% to 55–60%. However, the carbon content little alters at deeper depths. Additionally, the moisture content decreases quickly as depth increases. Peats include free cellulose, which serves as a gauge for the level of diagenesis in the material. Therefore, the characteristics that are used to distinguish between peat and soft brown coals include moisture content, carbon content, and the presence of free cellulose [Zeng, 2016].

Figure 9. A pile of freshly deposited, partially carbonized plant detritus is called peat. Although the source of this material is still clearly identifiable as plant detritus, it is on its way to becoming coal.

[URL1].

Figure 10. Drying peat (At the side of the place where it was chopped, there are tidy piles of peat drying)

[URL7].

Although it is not definitive between peat and lignite, some criteria can be used to distinguish between the two (Table 2).

Table 2. Criteria distinguishing between lignite and peat.

	peat	lignite
Moisture (%)	>75	≤75
Carbon (%)	<60	≥60
Free cellulose	Yes	No
Cutability	Yes	No

[Kural, 1991].

3.2.Coalification

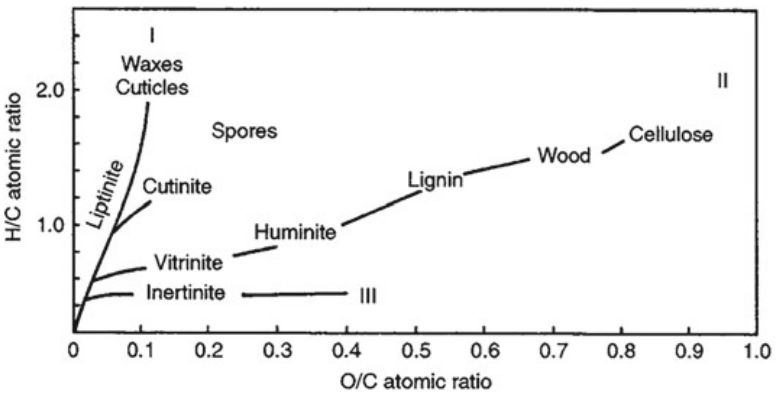
The transformation of peat into various grades of coal, lignite, semi-bituminous and bituminous coal, anthracite and metaanthracite under the influence of geological and chemical factors is called 'coalification'. Duration, increasing temperature, and

increasing pressure are the three key physical variables that might affect the coalification process [Teichmueller, 1989;, Straka & Sykorova, 2018; Barker, 1983]. In general, it was discovered that a coal's geological age had no bearing on its rank; in other words, time was not seen to be a significant element affecting coal rung. However, recent studies have demonstrated that rank can also be influenced by the duration of exposure to high heating for the coal and organic chemicals [88]. Furthermore, coalification and organic maturation include varying rates of chemical and physical changes, which may be regarded as time-influenced characteristics [Burnham & Sweeney, 1989]. The theory that coalification occurs in reaction to increasing temperatures is the most commonly recognized. Temperature generally increases with depth, averaging roughly 30 °C per kilometer. In locations experiencing extremely quick subsidence, the temperature gradient is less than 10 °C per kilometer, whereas in areas experiencing igneous activity, it is greater than 100 °C per kilometer. Anthracite coal can be produced at temperatures below 200 °C, according on measurements of the sedimentary cover thicknesses and the related coal ranks. Coalification is not believed to be caused by increasing pressure brought on by burial depth [16, Teichmueller, 1989].

Not every maceral has the same coalification behavior. During coalification, carbon dioxide, water, and a small amount of methane are produced. During this stage, some liquid hydrocarbons are also produced if the coals are rich in resinite [Zeng, 2016]. At the border between the dull and bright brown coal stages, there are noticeable petrographic variations. The gelification (vitrinization) of humic compounds is a common chemical transformation. Initially brown, the coals turn black and shiny at this point. Due to the elimination of aliphatic and alicyclic groups as well as the growing aromatization of humic complexes, the amount of volatile matter rapidly declines in the final stages of bituminous coal [Zeng, 2016]

(Figure11). The anthracite stage is distinguished by a sharp rise in reflectivity and optical anisotropy, as well as a sharp decline in the hydrogen content and, consequently, the atomic H/C ratio [Zeng, 2016]. Several structural groupings in coal decrease in number and eventually vanish throughout the peatification and coalification processes. Peat contains a lot of hydroxyl, whereas higher rank coals have less of it, and anthracite has none at all. According to Chen et al. [2012], all other groups exhibit an increase in the early phases of coalification, followed by a reduction and eventual elimination.

Figure 11. Coalification tracks of different macerals based on H/C versus O/C atomic ratio.



[From Bustin et al., 1983].

Coalification is the process that turns plant residues into coal. The procedure begins with the remains of dead plants, which, in order to prevent total decomposition, must be buried in an oxygen-free or oxygen-poor environment. These are typically swamp-type environments. Over millions of years, the coalification process occurs. Geological formations that range in age from Carboniferous to Miocene (358.9 Ma to 5.33 Ma) include coal. Large coal deposits were generated practically everywhere in the planet during two significant periods in Earth's history: the Tertiary (Paleogene) period

and the Upper-Carboniferous—Permian period. Refer to Figure 12. [Voncken, 2020].

4.Coal Petrography

The study of coal's organic and inorganic components and how metamorphism affects them is known as coal petrography. Coal petrography is used to investigate coals for industrial utilization (e.g., coke manufacturing), as well as to study the depositional settings of coal and coal geology [Voncke, 2020].

At the microscopic level, coal consists of organic particles called macerals. Macerals are altered remains and byproducts of the original plant material from which the coal-forming peat originated. Macerals resemble coal, and sediment grains and cements resemble sedimentary rocks. Macerals are divided into three groups: inertinite—oxidized plant material, exinite (Liptinite), Huminite/Vitrinite—woody materia. These groups are identified by their greyness in reflected light under the microscope. Liptinites are dark grey, vitrinites are medium to light grey and inertinites are white and can be very shiny [Stach et al., 1982; Bustin et al., 1983; Teichmüller et al., 1989] [Table 3 and Table 4].

Table 3. Classification of macerals of hard coal.

Maceral Group	Maceral	Submaceral	Maceral Variety
Vitrinite	Telinite	Telinite 1 Telinite 2	Cordaitotelinite Lepidophytotelinite Conifero-Ginkgophytotelinite Sigilariotelinite Fungotelinite
	Collinite	Telocollinite Desmocollinite Gelocollinite Corpocollinite	
	Vitrodetrinite		
Semivitrinite	Semitelinite		
	Semicollinite	Telosemicollinite Desmosemicollinite Corposemicollinite	
	Semivitrodetrinite		
Inertinite	Fusinite	Pyrfusinite Degradofusinite	Lepidophytofudinite Psaronifusinite Conifero-ginkgophytofusinite
	Semifusinite		
	Macrinite	Macrinite 1 Macrinite 2	
	Micrinite		
	Sclerotinite	Sclerotinite 1 Sclerotinite 2	
	Inertodetrinite		
Lipitinite (Exinite)	Sporinite	Macrosporinite Microsporinite	
	Ctinite Suberinite Barkinite Resinite		
	Alginite	Telalginite Lamalginite	Pila-alginite Reinschia-alginite
	Bituminite Exsudanite Fluorinite Lipitodetrinite		

[Zeng, 2016].

Table 4. Classification of macerals of lignite.

Maceral Group	Maceral Subgroup	Maceral	Maceral Type	Maceral Variety
Huminite	Humotelinite	Textinite		Pinotextinite Betulotextinite Taxodioditextinte Fungotextenite
		Ulminite	Texto-ulminite Eu-ulminite	
	Humodetrinite	Attrinite		
		Densinite		
	Humocollinite	Gelinite	Phlobaphinite Pseudo-phlobaphinite	
		Corpohuminite		
Liptinite		Sporopolleninite	Mascrosporinite Microsporinite Polleninite	Pinopolleninite
		Cutinite		
		Resinite		
		Suberinite		
		Chlorophyllinite		
		Bituminite		
		Exsudatinite		
		Fluorinite		
		Alginite		
		Liptodetrinite		
Inertinite		Fusinite		
		Semifusinite		
		Macrinite	Primary Macrinite Oxymacrinite	
		Sclerotinite		
		Inertodetrinite		

[Zeng, 2016].

Finkelman [1980] identified the locations and concentrations of trace elements and minerals in U.S. coal macerals. The macerals separated into vitrinite (V), carbominerite (CM), semifusinite (an additional inertinite maceral, In), and fusinite (an inertinite maceral, In). Syndepositional minerals were mostly classified as detrital minerals concentrated in carbominerite bands, authogenic growths or overgrowths, which are primarily found in inertinite pores and to

a lesser extent in vitrinite and liptinite. Chalcopyrite, sphalerite, "clausthalite," crandallite, and several rare earth elements (REE) such phosphates, Ti-0 minerals, apatite, and barite were all considered authorigenic minerals.

5.Elemental Components of Coal

Coal is a sedimentary, organic, combustible rock that was deposited in the upper continental crust (UCC) regime and compositional similarities with the UCC. However, it has a significantly higher concentration of organic materials (mostly made up of C, S, H, O, and N,) [Dai et al., 2021].

The silicate minerals make up about 90% of the crust. Feldspars make up 51% of the silicates that are most prevalent. Amphiboles (5%), micas (5%), pyroxenes (11%), clay minerals (5%), and quartz (12%) are further prevalent silicate minerals. Nonsilicate minerals such carbonates, oxides, phosphates, sulfides, etc. make up only 8% of the crust [URL8]. Sulfides like pyrite and numerous other accessory minerals are extensively distributed, while carbonates like calcite and dolomite are plentiful locally. The minerals that can be found in coals are influenced by the decreasing acidic environment in which most coals develop. In this setting, feldspars, micas, and ferromagnesian minerals (olivines, amphiboles, pyroxenes, etc.) become unstable and undergo partial alteration or dissolution. Then, releasing elements or forming clays, chlorites, and other authigenic minerals in the precursor peat [Dai et al., 2021].

Elements in coal can exist in a wide variety of intricate ways. This is because the elements and minerals come from a wide range of sources, and the coalification process has a lengthy and intricate history. Some of the various sources of the elements found in coal include the precursor plants and the elements they contain, detrital input from one or more source areas, elements dissolved in the

surface and rainwater that feeds the swamp, fallout from airborne dust and volcanic ash, igneous intrusions, hydrothermal solutions, and elements in ground water that percolate through the peat and coal. In addition to adding elements to coal, groundwater can also extract elements that are soluble in water. Coal minerals can have detrital, authigenic, or epigenetic origins, and diagenesis and epigenesis can alter all three [Dai et al., 2021]. In addition to the main elements (>1% wt) and minor elements (0.1–1% wt), Zevenhoven & Kilpinen [2001] define "trace elements" as chemical components found in a natural substance at concentrations less than 0.1% wt. The most significant main elements for coal are the ash-forming elements, which include silicon (Si), aluminum (Al), iron (Fe), calcium (Ca), magnesium (Mg), and occasionally the alkali elements, potassium (K) and sodium (Na). Although the elements beryllium (Be) and boron (B) should also be included, trace elements essentially cover the entire periodic table of the elements after Ca.

References

Barker, C.E. (1983). Influence of time on metamorphism of sedimentary organic matter in liquid-dominated geothermal systems, *Western North America. Geology*, 11, 384–388.

Burnham, A.K. & Sweeney, J.J. (1989). A chemical kinetic model of vitrinite maturation and reflectance. *Geochim Cosmochim Acta*, 53:2649–2657.

Bustin, R.M., Cameron, A.R., Grieve, D.A. & Kalkreuth. W.D. (1983). Coal petrology: Its principles, methods and applications. *Geological Association of Canada*, 230.

Breeze, P. (2015). *Coal types and the production and trade in coal*. In: Coal-fired generation. Chapter 2, Academic Press, Cambridge, 9–16.

Chen, Y., Mastalerz, M. & Schimmelmann, A. (2012). Characterization of chemical functional groups in macerals across different coal ranks via micro-FTIR-spectroscopy. *Int J Coal Geol*., 104, 22–33.

Dai, S. & Finkelman, R.B. (2018).Coal as a promising source of critical elements: Progress and future prospects. *International Journal of Coal Geology*, 186, 155–164.

Diessel, C.F.K. (1992). The conditions of peat formation. In: Coalbearing depositional systems. Springer, Berlin, 5–39.

Feulner, G. (2017). Formation of most of our coal brought Earth close to global glaciation. Proc Nat Acad Sci 114:11333–11337

Hatcher, P.G., Lerch, H.E. & Verheyen, T.V. (1990). Organic geochemical studies of the transformation of gymnospermous xylem during peatification and coalification to subbituminous coal. *Int J Coal Geol.,* 16, 193–196.

Hower, J.C., Groppo, J.G., Graham, U.M. Ward, C.R. & Kostova, I.J. (2017). Coal-derived unburned carbons in fly ash: a review. *International Journal of Coal Geology*, 179, 11-27.

Hutton, A.C. & Hower, J.C. (1999). Cannel coals: implications for classification and terminology. *Int J Coal Geol*., 41, 157–188.

Kural, O. (1991). *Kömür*. Kurti Matbaası, İstanbul, 17-49.

Kraushaar, J. & Ristinen, R. (2015). *Energy and the environment* (2nd edition). John Wiley & Sons, Hoboken, 384.

O'Keefe, J.M., Bechtel, A., Christanis, K., Dai, S., DiMichele, W.A., Eble, C.F., Esterle, J.S., Mastalerz, M., Raymond, A.L., Valentim, B.V., Wagner, N.J., Ward, C.R. & Hower, J.C. (2013). On the fundamental difference between coal rank and coal type. *Int J Coal Geol.,* 118, 58–87.

Schopf, J.M. (1966). Definitions of peat and coal and of graphite that terminates the coal series (graphocite). *J Geol.,* 74, 584–592.

Schweinfurth, S. P. (2009). *An introduction to coal quality. In: The national coal resource assessment overview*.B S Pierce, K O Dennen (Eds.). Professional US Geological Survey professional paper 1625-F, Reston, VA, USA, US Geological Survey (USGS), Chapter C, pp. 16.

Speight, J. G. (2012). *The chemistry and technology of coal*. United States: CRC press.

Stach, E., Mackowsky, M.T.H., Teichmüller, M., Taylor, G.H., Chandra, D. & Teichmüller, R. (1982). *Coal Petrology*. Gebruder Borntraeger, Berlin, Stuttgart, p 428.

Straka, P. & Sykorova, I. (2018). Coalification and coal alteration under mild thermal conditions. *Int J Coal Sci Technol*, 5, 358–173.

Teichmüller, M. (1989). The genesis of coal from the viewpoint of coal petrology. *International Journal of Coal Geology*, 12, 1–87.

Thomas, L. (2002). *Coal geology*. Wiley, Chichester, England, 384 pp.

Topcuoğlu, B. & Turan, M. (2018). Introductory chapter: Introduction to Peat. In: Topcuoğlu B (ed) Peat. IntechOpen, London, 3–8.

Xintu, L. (2009). *Conditions of peat formation*. In: Encyclopedia of life lupport lystems: coal, oil shale, natural bitumen, heavy oil and peat Vol. II. Jinsheng G (ed.), UNESCO-EOLSS 298–308.

World Coal Association, 2017. https://www.iea.org/reports/coal-2017

Voncken, J.H.L. (2020). *Geology of Coal Deposits of South Limburg*. The Netherlands. Springer Briefs in Earth Sciences, 25-40.

Zeng, F. (2016). *Organic and inorganic geochemistry of coal. In: Coal oil shale bitumen heavy oil and peat*. vol 1. Encyclopedia of Life Support Systems, Developed under the Auspices of the UNESCO, EOLSS Publishers, Paris, France

Zevenhoven, R. & Kilpinen, P. (2001). *Control of pollutants in flue gases and* fuel gases. TKK-ENY-4,Espoo, Finland, Helsinki University of Technology, www.hut.fi/~rzevenho/gasbook

URL1: https://geology.com/rocks/coal.shtml

URL2:Kentucky Geological Survey (2025). http://www.uky.edu/KGS/coal/, with permission).

URL3: https:// commo ns. wikim edia. org/ wiki/ File: Native_ Carbon_ Graphite. jpg

URL4: https:// www. uky. edu/ KGS/ coal/ index. php. Accessed 20 Dec 2022

URL5: https:// www. brita nnica. com/ scien ce/ coal- fossil-fuel/ Coal- types. Accessed 20 Feb 2025

URL6: https://www.uky.edu/KGS/coal/coal-peat.php

URL7:https://www.geograph.ie/photo/3621272

URL8: https://www.sandatlas.org/composition-of-the-earths-crust/