

### Abstract

Copper deposits occur in rocks of all ages and are formed as a result of geological processes that concentrated copper initially dispersed through large volumes of magma or rock. The majority of copper deposits were created by hydrothermal processes when metal sulfides were precipitated from hot waters in fractures and permeable rocks in the subsurface and at seafloor hydrothermal vents. Copper minerals can also crystallise in magma chambers or form as a result of secondary enrichment processes when primary copper deposits are weathered. Porphyry copper and associated skarn, vein and replacement deposits are the most important type of copper deposits accounting for some 60% of current world copper production. Sediment-hosted stratiform copper deposits in sedimentary basins account for some 20% of historic world copper production and were some of the earliest copper ores mined. Volcanic-hosted massive sulfide deposits occur in submarine volcanic rocks and are observed forming today at seafloor hydrothermal vents. Magmatic nickel-copper sulfide deposits in igneous rocks have a very different origin than the hydrothermal copper deposits that dominate current and historic world copper production. This type of deposit forms when mafic and ultramafic magmas separate a metal-sulfide magma that sinks to the bottom of the magma chamber or flow conduit.

Copper sulfide orebodies exposed at the surface are subject to weathering processes and typically show a progression from an iron-rich cap through leached rock to oxidised ore that contains copper minerals such as malachite, azurite, cuprite and chrysocolla. Copper liberated from the breakdown of sulfide minerals may also be precipitated as native copper and secondary sulfides such as covellite and chalcocite in the vicinity of the water table. The most common copper minerals in primary ores are chalcopyrite, bornite and tetrahedrite-tennantite. The earliest metalsmiths exploited near surface deposits of copper oxide and carbonate minerals, which were easier to mine and not as difficult to smelt as the underlying sulfide ores.

Coal is a combustible sedimentary rock composed of the altered remains of plants that accumulated in vast swamps and peat bogs. Increasing temperature and pressure as a result of gradual burial beneath overlying sediments subsequently transformed the plant remains into coal. Significant coal formation first occurred some 360 million years ago during the Carboniferous Period. Coal varies greatly in its physical and chemical properties because coal type and rank are independent variables that reflect depositional environment and coalification history, respectively. Humic coals are the most common coal type that form largely from woody plant remains. Sapropelic coals are less common and dominated by non-woody plant materials. Coalification is the process that produces coals of different rank, with higher rank coals having a higher carbon content and higher calorific value than low rank coals.

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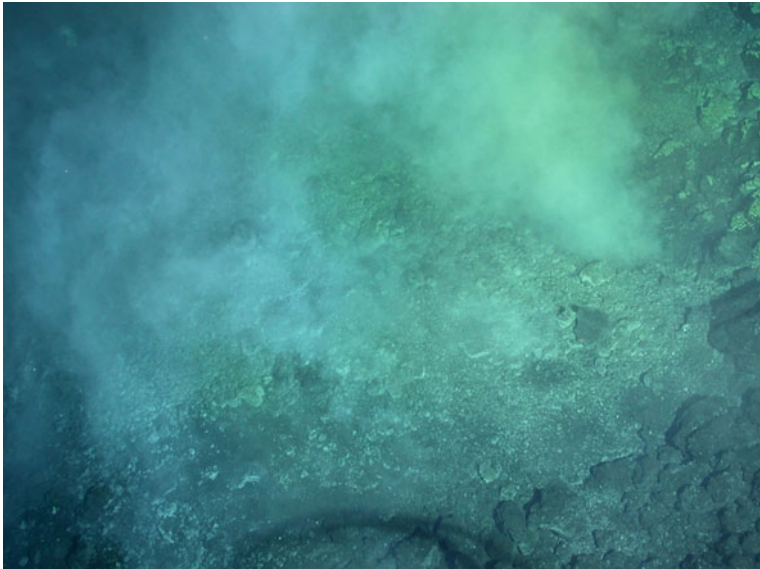
## 2.1 Copper Mineralogy and Formation

The average concentration of copper in the Earth's crust is some 0.006%, whereas currently mined copper deposits contain at least 0.4% copper and possibly minor amounts of gold, silver and molybdenum. Deposits of copper occur in rocks of all ages and formed through a variety of geological processes that concentrated copper initially dispersed through large volumes of magma or rock. The most common types of copper deposits formed as a result of hydrothermal processes when copper and copper-iron sulfides were precipitated from hot waters in fractures and permeable rocks in the subsurface and on the seafloor at hydrothermal vents (Fig. 2.1). These deposits are often associated with intrusion of magma but can form wherever there is an elevated geothermal gradient and so are most commonly located in areas where tectonic plates collide or diverge.<sup>1</sup> Copper minerals can also crystallise in magma chambers or form as a result of secondary enrichment processes when primary copper deposits are weathered. The most important deposit types are porphyry copper and associated skarn, vein and replacement deposits, sediment-hosted copper deposits, volcanic-hosted sulfide deposits and magmatic sulfide deposits in mafic and ultramafic rocks (Kesler 1994).

From a metallurgical perspective, copper ores are divided into native copper, and oxide and sulfide ores that require very different levels of technology to extract the copper from the ore. The earliest metalsmiths exploited high grade, near surface deposits of copper oxide and carbonate minerals, which were easier to mine and not as difficult to smelt as the underlying sulfide ores. The most common copper minerals in these different ore types are shown in Table 2.1. The mineral

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<sup>1</sup>Plate tectonic theory is a unifying theory like Charles Darwin's theory of evolution that explains how the Earth works. It is based on the observation that the outer most layer of the Earth (lithosphere) is made up of a number of rigid pieces or plates that move with respect to each other. Plates collide in subduction zones, pull apart at mid-ocean ridges and can also slide past each other at transform boundaries. Volcanic activity and earthquakes mostly occur at plate boundaries.



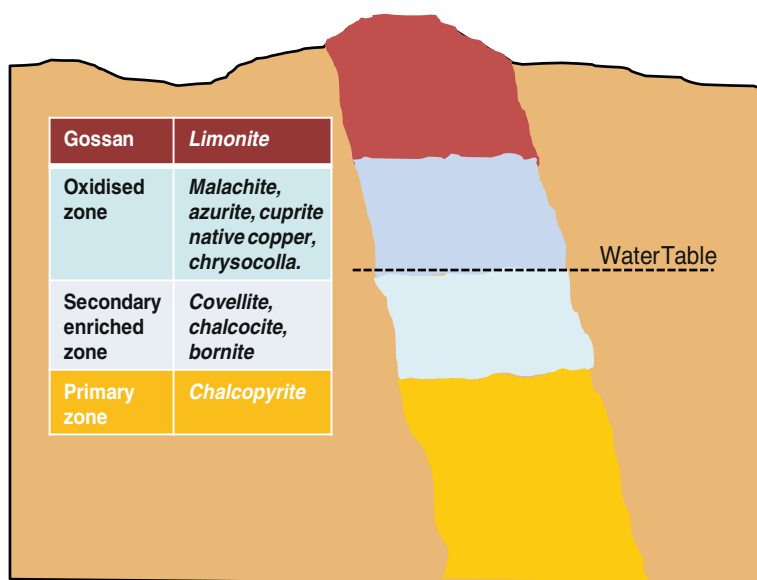
**Fig. 2.1** Hydrothermal fluids venting from chimneys on the seafloor (Pacific Ring of Fire 2004 Expedition—NOAA Office of Ocean Exploration; Dr. Bob Embley, NOAA PMEL, Chief Scientist)

**Table 2.1** Commercially important copper minerals

Ore type	Formation	Name	Composition	% Cu
Native ores		Native Copper	Cu	100.0
Oxide ores		Cuprite	Cu <sub>2</sub> O	88.8
		Malachite	Cu <sub>2</sub> CO <sub>3</sub> (OH) <sub>2</sub>	57.5
		Azurite	Cu <sub>2</sub> (CO <sub>3</sub> ) <sub>2</sub> (OH) <sub>2</sub>	55.3
Sulfide ores	Secondary	Covellite <sup>a</sup>	CuS	66.5
		Chalcocite <sup>a</sup>	Cu <sub>2</sub> S	79.8
	Primary	Chalcopyrite	CuFeS <sub>2</sub>	34.6
		Bornite <sup>b</sup>	Cu <sub>5</sub> FeS <sub>4</sub>	63.3
		Tetrahedrite	Cu <sub>6</sub> [Cu <sub>4</sub> (Fe,Zn) <sub>2</sub> ]Sb <sub>4</sub> S <sub>13</sub>	35.8
		Tennantite	Cu <sub>6</sub> [Cu <sub>4</sub> (Fe,Zn) <sub>2</sub> ]As <sub>4</sub> S <sub>13</sub>	47.5

<sup>a</sup>Sometimes primary  
<sup>b</sup>Sometimes secondary

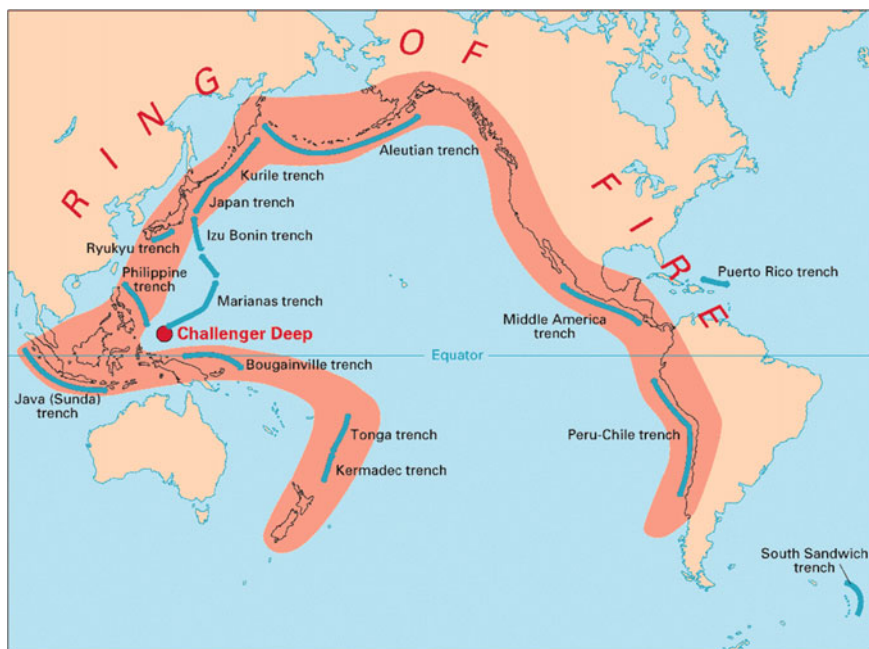
assemblage of a copper deposit depends on the conditions of formation including the host rock and solution chemistry in the case of hydrothermal ores as well as temperature and pressure. Copper ores exposed to air in weathering environments tend to be oxidised, whereas those in oxygen-poor subsurface environments are dominated by sulfide minerals. The upper parts of copper deposits exposed at the surface typically show a progression from an iron-rich cap or gossan through leached rock to oxidised ore that contains copper minerals such as malachite, azurite, cuprite and chrysocolla (Fig. 2.2).



**Fig. 2.2** Typical copper orebody with secondary minerals resulting from weathering processes

Copper carbonate and oxide minerals form more or less in situ in the near surface oxidised zone, whereas copper liberated from the breakdown of copper sulfide minerals may also migrate downwards and be precipitated as native copper and secondary copper and copper–iron sulfides such as covellite, chalcocite and bornite in the reducing environment in the vicinity of the water table (Fig. 2.2). As a result, the copper grade of the secondary enrichment zone may be significantly higher than the primary mineralisation. The most common copper minerals in primary ores are chalcopyrite, bornite and tetrahedrite-tennantite (Table 2.1).

Porphyry copper and associated skarn, vein and replacement deposits are the most important type of copper deposits mined today accounting for some 60% of world production (Johnson et al. 2014). This deposit type was exploited in Utah at the mine now known as Bingham Canyon where large-scale mining began in 1906. Northern Chile currently has the largest number of major porphyry copper deposits that include Chuquibambilla, El Teniente and Escondida. The majority of porphyry copper deposits occur in relatively young volcanic belts around the margins of the Pacific Ocean in the Ring of Fire (Fig. 2.3). They formed when hydrothermal fluids were expelled from cooling igneous intrusions producing a shattered and mineralised volume of rock that can be mined by open pit or underground mass mining methods. The name comes from the characteristic porphyry texture of the intrusions that have large early formed crystals in a finer matrix. This texture is common in igneous intrusions that crystallise at shallow levels beneath volcanoes.



**Fig. 2.3** The Ring of Fire (courtesy U.S. geological survey)

Copper sulfides and copper-iron sulfides occur with quartz in veinlets and disseminated along fractures in the host porphyry and the surrounding country rocks, which are variably altered as a result of chemical reaction with the hydrothermal fluids. Copper grades in the primary copper sulfide ores typically range between 0.4 and 1.0%; however, many porphyry copper deposits particularly those in the western U.S. and Chile have well-developed zones of oxidised and supergene copper ore that facilitated their exploitation by early miners. At Chuquicamata, near surface oxidised copper ores containing copper sulfate and copper chloride minerals are underlain by partially oxidised and supergene-enriched copper sulfide ore, with primary sulfide mineralisation at deeper levels (Park and MacDiarmid 1964). Atacamite, a hydrous copper chloride ( $\text{Cu}_2\text{Cl}(\text{OH})_3$ ), is a common phase in the upper part of the oxide zone at Chuquicamata (Fig. 2.4), and occurs with other oxide minerals in a number of porphyry copper deposits in northern Chile but is otherwise quite rare. Antlerite, a hydrous copper sulfate ( $\text{Cu}_3(\text{SO}_4)(\text{OH})_4$ ), is the principle ore mineral at deeper levels in the oxide zone at Chuquicamata and occurs in the oxidised zone of copper deposits in arid regions around the world. Atacamite is soluble in fresh water so it likely formed by replacement of pre-existing oxide minerals as a result of interaction with migrating saline waters since the onset of hyperaridity in northern Chile (Cameron et al. 2007). Dating of the mineral gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) that occurs with atacamite at



**Fig. 2.4** Atacamite from the oxide zone at Chuquicamata mine, Chile

Chuquicamata suggests that atacamite has formed and been preserved only over the last 1.5 million years reflecting the modern hyperarid climate in the Atacama Desert (Reich et al. 2009).

Higher grade skarn ores form where hot metal-rich fluids released from the cooling igneous intrusion react with limestones producing rock rich in calcium silicate minerals and metal oxides and sulfides. Copper minerals in vein and replacement deposits are the product of hydrothermal fluids that were focused through fractures and permeable zones in the subsurface. Vein type deposits comprise the minerals precipitated from the hydrothermal fluid mainly sulfides with quartz and carbonate minerals, whereas replacement bodies form where hydrothermal fluids react with the host rock and locally replace it with sulfide minerals. Skarns are a specific type of replacement body that form at the contact of igneous intrusions, but igneous intrusions are not essential for the formation of replacement deposits that can also occur in sedimentary and metamorphic rocks. The classic vein deposits in Cornwall mined variously for copper, tin, arsenic and lead formed some 350 million years ago when granitic magmas intruded the slates that make up much of Cornwall. Skarn, vein and replacement deposits of copper are more widely distributed than porphyry copper deposits reflecting the range of geological settings in which hydrothermal ore deposits may form. They are less important volumetrically than porphyry copper deposits but remain an important

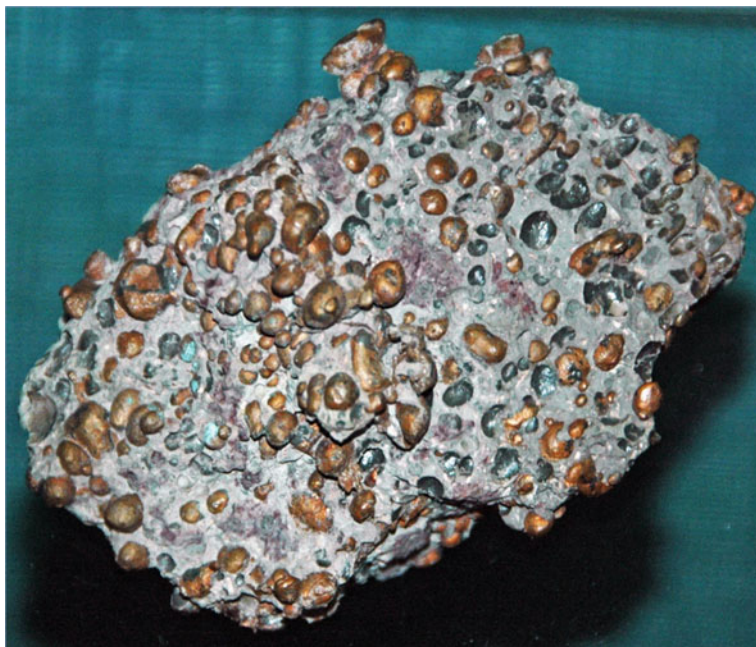


source of copper because of their high copper grades. One such ore deposit is the Enterprise Mine at Mount Isa in Queensland where the ore contains some 2.9% copper (Glencore 2015).

Sediment-hosted stratiform copper deposits in sedimentary basins account for some 20% of historic world copper production and were some of the earliest copper ores mined in Europe and the Middle East (Zientek et al. 2010). The copper ores are said to be stratiform because the copper minerals are concentrated in dark-coloured sedimentary layers within or underlain by red beds. These copper ores formed when copper-bearing oxidising sedimentary brines reacted with organic matter-rich rock types or mixed with reduced low salinity water in sandstones. Important examples include the White Pine copper deposit in Michigan, the Kupferschiefer deposits in Germany and Poland, and the African Copper Belt that runs through the southern Democratic Republic of Congo into northern Zambia. The ore mineralogy of these deposits is quite complex and may include disseminated and veinlet chalcocite, bornite and chalcopyrite as well as native copper. At the historic copper deposits of the Timna Valley in southern Israel, copper sulfide nodules in sandstone are partially or completely altered to malachite, copper silicates and halides including paratacamite ( $(\text{Cu,Zn})_2\text{Cl}(\text{OH})_3$ ), which may reflect lowering of the water table (Asael et al. 2012). Volcanic red bed deposits such as the copper deposits of the Keweenaw Peninsula in Michigan formed in a similar way to the sediment-hosted copper deposits when native copper and silver were deposited from migrating brines in cavities in terrestrial basalt flows and conglomerates (Fig. 2.5).

Volcanic-hosted massive sulfide (VHMS) deposits occur in submarine volcanic rocks and are observed forming today at or near the seafloor where hydrothermal fluids vent at mid-ocean ridges and in rift zones (Shanks III and Koski 2012). Metal sulfides precipitate as a result of mixing between the hydrothermal fluids that commonly have temperatures exceeding 300°C and near freezing seawater. The first active seafloor hydrothermal vents were discovered by the submersible Alvin in 1977 in the eastern Pacific Ocean. They were termed ‘black smokers’ because dark-coloured, particle-rich water was seen issuing from chimneys that were found to be composed of sulfide and sulfate minerals. What was even more surprising was the presence of a variety of strange life forms such as tube worms, giant clams, long-necked barnacles and spider crabs (Fig. 2.6). Life is only possible in such an extreme environment because microbes metabolise hydrogen sulfide and methane in the vent fluids and carbon dioxide in seawater to form carbohydrates through a process called chemosynthesis. Some of the exotic life forms feed directly on these carbohydrates, whereas others are scavengers or predators.

A typical VHMS deposit consists of lenses of pyrite-chalcopyrite-sphalerite-galenite (*massive sulfide ores*) overlying a pipe-shaped replacement body with veinlets of chalcopyrite and pyrite that crosscut the underlying volcanics (*footwall stringer ores*). The stringer zone represents the pathway through which the metal-bearing hydrothermal fluids reached the seafloor, whereas the massive sulfide lenses formed on the seafloor. VHMS deposits are mostly polymetallic and may be Cu, Cu–Zn or Zn–Pb–Cu dominated (Large 1992). They are widely distributed although the majority of deposits occur in the northern hemisphere and range in size



**Fig. 2.5** Native copper infilling cavities in basalt, Wolverine Mine, Michigan, USA (courtesy of James St John—CC-BY-2)



**Fig. 2.6** Giant tube worms surrounding hydrothermal vents (NOAA Okeanos Explorer Program, Galapagos Rift Expedition 2011)



from a few million tonnes to world class deposits like Rio Tinto and Tharsis (Spain), Brunswick No. 12 (Canada), Ducktown (USA) and Mt Lyell (Australia).

Rio Tinto, Tharsis and other VHMS deposits in the Iberian pyrite belt differ from the majority of VHMS deposits in that the bulk of the material mined was pyrite used to produce sulfuric acid for the chemical industry. Copper was produced in significant quantity, however, from low grade copper ores and cuprous pyrite initially using hydrometallurgical methods described in the next chapter. In addition, the host rocks overlying the pyrite lenses are typically of sedimentary origin such that the Rio Tinto and Tharsis deposits have hybrid characteristics intermediate between sediment-hosted copper and VHMS deposits.

Magmatic sulfide deposits in ultramafic and mafic igneous rocks have a very different origin than the hydrothermal copper deposits that dominate current and historic world copper production. Different silicate minerals crystallise over a range of temperatures in magma chambers that is the process of fractional crystallisation. This enriches the residual magma in metals and gases that can escape through the top and sides of the magma chamber forming hydrothermal ore deposits. In certain situations, the magma can separate into two different immiscible magmas. This happens most commonly with mafic and ultramafic<sup>2</sup> magmas that separate an immiscible metal-sulfide magma, which sinks to the bottom of the magma chamber to form metal-sulfide orebodies (Kesler 1994). Sulfide immiscibility results from contamination of the magma with sulfur as a result of interaction with sulfur-rich crustal rocks. Economically important nickel–copper deposits with copper grades higher than 0.5% such as Voisey’s Bay (Canada), Noril’sk (Russia) and Jinchuan (China) occur in magma conduits rather than layered igneous intrusions (Song et al. 2011). The giant Sudbury deposit (Canada) is an exception that formed when a catastrophic meteorite impact melted crust and mantle rocks forming a layered igneous intrusion with nickel–copper orebodies at its base.

The majority of production of particular commodities including copper comes from a small number of giant to supergiant deposits that are defined on the basis of contained metal normalised to standard continental crust (Laznicka 2014). This author identified 26 supergiants and 236 giant copper deposits using these criteria, the largest of which were porphyry copper, sediment-hosted or magmatic sulfide deposits. In a similar vein, the world’s 20 largest copper mines accounted for almost 40% of world copper capacity in 2014 (ICSG 2015). The historical importance of specific copper deposits does not always correlate with size, however, as location, depth and ore type were major factors that governed whether a deposit could be economically exploited. Near surface native and oxide ores were exploited first followed by high-grade sulfide ores once smelting techniques had been developed that is the subject of the next chapter.

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<sup>2</sup>Ultramafic and mafic magmas have relatively low silica and high magnesium and iron contents, and form by partial melting of the mantle that is the layer between the crust and core of the Earth. Felsic magmas have relatively high silica and low magnesium and iron contents and can form by partial melting of crustal rocks or the process of fractional crystallisation of mafic magma.

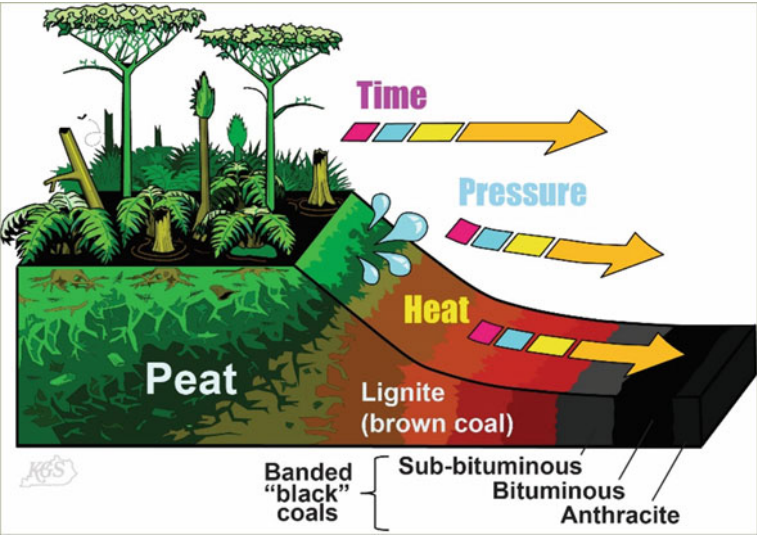
## 2.2 Coal Composition and Formation

Coal is an organic matter rich, combustible sedimentary rock composed of the altered remains of plants that accumulated in vast swamps and peat bogs. Plant debris accumulates in such settings because the swamp waters are deficient in oxygen that limits decay of organic matter. The water level needs to remain relatively constant over many thousands of years to accumulate sufficient plant debris to form a coal seam as some ten metres of peat are required to form one metre of black coal (Diessel 2012). Increasing temperature and pressure resulting from gradual burial beneath overlying sediments subsequently modified the plant remains transforming them into coal (Fig. 2.7). This process is called coalification and is a major factor determining coal composition. Water and volatile matter are progressively removed from coal during coalification that produces coals of increasing rank. The chemical and physical properties of coal vary systematically with coal rank as the coal changes from peat to lignite, sub-bituminous coal, bituminous coal and finally anthracite. Lignite popularly called brown coal has a lower fixed carbon content and higher moisture and volatile content than higher rank black coals so is lighter coloured and less dense. The mineral matter content of coal is also important and varies from a few percent to 49%; sedimentary rocks with less than 50% organic matter are by definition carbonaceous mudstones.

Significant coal formation first occurred some 360 million years ago during the Carboniferous Period (Table 2.2), which was named for the large deposits of coal in rocks of this age in England and Wales.<sup>3</sup> The first land plants appeared some 130 million years earlier in the Ordovician Period but lacked vascular tissue that restricted their size and distribution. By the late Devonian, plants with leaves and roots had evolved and trees with true wood grew together in the world's first forests. Plant life proliferated in the Carboniferous in the tropical lowland swamp forests of Euramerica that straddled the equator and included terranes later to become part of North America and Europe through the process of continent assembly and breakup. The supercontinent Gondwana lay to the south at this time close to the South Pole and was subject to periodic glaciation. Giant club mosses and tree ferns dominated the coal producing Carboniferous swamps that represent the most extensive tropical mire systems in Earth history (Greb et al. 2003). Carboniferous coals occur in basins in the USA, Canada, Britain, Europe and East Asia. Geographical proximity to Carboniferous coal deposits was a major factor influencing industrial development in Britain and Europe in the eighteenth and nineteenth centuries through the development of steam power and coke for metal smelting.

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<sup>3</sup>The geological time scale is divided into a number of defined stratigraphic units based on actual sequences of rocks and the fossils contained in them (Table 2.2). The boundary ages of these units are described in terms of years before the present day based on radiometric dating of suitable rock types. Absolute age dating of rocks was developed in the early twentieth century. Prior to that time the geological time scale was relative although geologists and paleontologists recognised the great antiquity of the Earth.



**Fig. 2.7** Burial, compaction and coalification forms coal from peat (courtesy of Stephen Greb, Kentucky Geological Survey and University of Kentucky)

**Table 2.2** Summary geological time scale with division boundaries based on recommendations in USGS (2010)—Fact Sheet 3059; the Tertiary Period is not recognised in some modern time scales but is still widely used on geological maps and in reports

Eon/Era	Period	Epoch	Years before present
Hadean			4.6–4.0 billion years
Archean			4.0–2.5 billion years
Proterozoic			2.5 billion–542 million years
Paleozoic	Cambrian		542–488 million years
	Ordovician		488–444 million years
	Silurian		444–416 million years
	Devonian		416–359 million years
	Carboniferous		359–299 million years
	Permian		299–251 million years
Mesozoic	Triassic		251–200 million years
	Jurassic		200–145 million years
	Cretaceous		145–65 million years
Cenozoic	Tertiary	Palaeocene	65–56 million years
		Eocene	56–34 million years
		Oligocene	34–23 million years
		Miocene	23–5.3 million years
		Pliocene	5.3–2.6 million years
	Quaternary	Pleistocene	2.6 million–11,700 years
		Holocene	11,700 years to the present

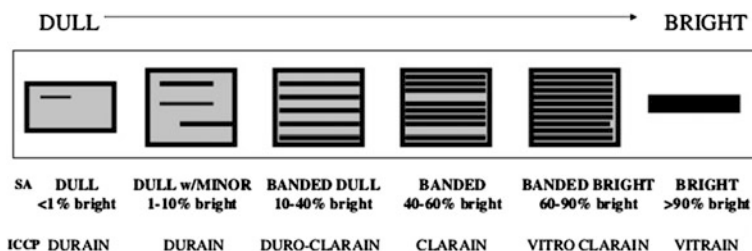
Coal formation has continued since the Carboniferous with three main episodes of coal accumulation (Thompson 2012). Coals formed during the Carboniferous and Permian periods comprise the bulk of the world's black coal resources. They include the tropical Carboniferous coals of Euramerica and the temperate Permian coals of Gondwana that formed under varied cool to cold conditions from the distinctive glossopteris flora. Glossopteris was a new type of plant with fern-like fronds but seeds rather than spores (Fig. 2.8), which dominated the deciduous forests of the southern hemisphere during the Permian Period. Identification of glossopteris fossils in Australia, Antarctica, Southern Africa, India and South America provided evidence that these land masses were once joined in the super-continent Gondwana. The second episode of coal accumulation occurred during the Jurassic-Cretaceous with black coals of this age in both the northern and southern hemispheres. Primitive conifers were the dominant trees in the humid coal forming swamps of this period with a diverse understory of cycads, ferns, mosses and liverworts. The third major period of coal accumulation was the Tertiary Period. Younger coals are typically lower rank than older coals and the majority of the world's brown coal resources are of Tertiary age.

**Fig. 2.8** The genus *Glossopteris* was a seed bearing plant with fern-like foliage; the name refers to the fossilised leaves that are common in Permian coal deposits (courtesy Daderot CC-zero—Exhibit in the Houston Museum of Natural Science, Texas, USA)



Coal types are distinguished on the basis of the constituent plant materials. The majority of black coals are banded and vary from dull banded to bright banded, with four main lithotypes (vitrain, clarain, durain, fusain) distinguished at the macroscopic scale (Fig. 2.9). Vitrain has a bright lustre and breaks smoothly; it occurs mostly in thin bands or lenses. Clarain has a semi-bright to silky appearance and commonly contains thin vitrain bands. Vitrain and clarain are the major constituents of bright coal. Durain has a dull, granular appearance and is harder than vitrain. Dull coals are dominated by durain bands. Fusain is a dull, sooty black with a charcoal like appearance and occurs in thin irregular bands. This system developed from the work of Dr. Marie Stopes, a paleobotanist, who is probably better known as a pioneer campaigner for family planning in the United Kingdom.

Microscopic examination of coal reveals the presence of different components that are called macerals. Macerals are grouped into three subdivisions based on their physical and chemical characteristics, which are vitrinite, liptinite and inertinite. Vitrinite is the most common maceral that forms from plant cell wall material and woody tissue. The brightness (reflectance) of vitrinite increases with increasing temperature and is used to determine the level of maturity or rank of coal and other organic matter. Liptinite forms from waxy or oily plant parts such as algae, spores and resin, and is enriched in hydrogen relative to vitrinite and inertinite. Coal oil also known as kerosene was sourced historically from coal rich in liptinite; kerosene was subsequently distilled from petroleum. Inertinite is partially oxidised plant material that may have been burnt in periodic wildfires or subject to oxidation when water levels dropped in the mire. Apart from the rare cannel coals rich in liptinite, coals range in maceral composition from mostly vitrinite to mostly inertinite reflecting the extent of oxidation of the plant materials. In this context, Permian Gondwana coals show a greater range of maceral compositions and a higher inertinite content than the Carboniferous Euramerica coals that indicates a more variable and seasonal climate (Diessel 2012). On the other hand, some coals of the Jurassic and Cretaceous periods have higher liptinite contents because peat mire communities at this time included conifer species that were rich in resinous material.



**Fig. 2.9** Macroscopic classification of bituminous coal showing the Australian (SA) and International Committee for Coal and Organic Petrology (ICCP) schemes (courtesy Joan Esterle, University of Queensland)



The mineral matter content of coal is another important characteristic that influences how a coal behaves when it is combusted or made into coke. Mineral grains may be washed into the peat mire or ash deposited in the aftermath of volcanic eruptions. Minerals can also form after the peat has been buried as a result of groundwater moving through the coal bed. The most common minerals in coal are clays, quartz, pyrite and calcite that can occur as separate grains or fill fractures and smaller voids in the coal. In general, Gondwana coals have higher mineral matter content but lower sulfur content than the coals of Euramerica (Thompson 2012).

Differences between coals reflect plant evolutionary changes, the environmental conditions of formation and geological factors particularly age and coalification history. Floral communities vary even within the same bog-lake complex that is evident from study of peats formed since the end of the Ice Age some 12,000 years ago. The most extensive modern peatlands occur in northern, cool temperate to subpolar latitudes, whereas the thickest modern peats are located at low latitude in Indonesia and Malaysia (Greb et al. 2003). The Vasyugan Bog Complex is part of a much larger system of raised peat bogs, lakes and river channels in Western Siberia that is comparable in size to the Permian Gondwana coal basins. It shows considerable plant diversity with swamp and forest landscapes and a range of peat deposit types. The Indonesian and Malaysian peats are limited in extent by the coastal geography and not as extensive as the vast Carboniferous coal deposits of Euramerica (Greb et al. 2003). Nevertheless, a comparison between modern temperate and tropical peatlands shows that the major factors influencing coal type are water table level and the degree to which this fluctuated (Moore and Shearer 2012).

Coal varies greatly in its physical and chemical properties because coal type and rank are independent variables that reflect depositional environment and coalification history, respectively (O'Keefe et al. 2013). Humic coals are the most common coal type that form largely from woody plant remains and show a range from dull to bright lithotypes as previously discussed. Sapropelic coals are less common and dominated by non woody plant materials. Vitrinite and inertinite are the dominant macerals in humic coals, whereas liptinite is the dominant maceral in sapropelic coals. Coalification is the process that produces coals of different rank, with higher rank coals having a higher carbon content and higher calorific value than low rank coals. Coal grade refers to the overall proportion of mineral matter in the coal that is a product of the depositional environment and processes affecting the coal after burial. Coal quality is a more nebulous concept as it relates to how inorganic impurities in the coal impact on utilisation. Historically, sulfide and organic sulfur were considered the most deleterious impurities as they produced sulfurous fumes that impacted coal use for heating in the home, industrial drying as in brewing and various metallurgical smelting applications. The development of the coking process detailed in the next chapter solved many of these problems, but there are still issues and opportunities today in relation to the trace metal content of different coals.

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Metals, Energy and Sustainability

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Golding, B.; Golding, S.D.

2017, XIX, 196 p. 80 illus., 68 illus. in color., Hardcover

ISBN: 978-3-319-51173-3