15

Peat, coal and coalbed methane

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ABSTRACT

Multiple stratigraphic intervals in the subsurface of the Netherlands contain layers of peat and coal. These include (pre-)Holocene peat, Miocene lignite and upper Carboniferous (Westphalian) bituminous coal and anthracite, all of which have played important roles as energy sources in the country. In the Netherlands, total peat mining between the 13th and 20th centuries reached ca. 9.4 x 10^9 m^3, while peak annual lignite production reached 1.5 Mt. Total production of bituminous coal and anthracite in the 20th century amounted to 568 Mt. Production of these energy sources ceased during the 20th century. Current resources of lignite are estimated to be at least 1700 Mt; estimates for bituminous and anthracite coal resources shallower than 1500 m below surface are between 4000 and 38000 Mt. At the turn of the 21st century, interest in coalbed methane, i.e. gas that is contained in bituminous coal started to increase. Estimates for the theoretically recoverable volumes of coalbed methane shallower than 1500 m below surface are between 7 and 107 x 10^9 m^3. The possibility to combine the production of this gas while simultaneously storing CO_2 within the coal (considered as a sink for the CO_2) was investigated but is technologically challenging. While the subsurface coal and coalbed methane resources in the Netherlands are significant, there is no desire to exploit them currently, at a time when dependency on fossil fuels is diminishing in order to avoid further increase in CO_2 emissions. Substantial volumes of peat are still present in the subsurface, but its organic nature and high porosity causes land subsidence and brings challenges to the built environment. Furthermore, peat oxidation induced by drainage, especially in agricultural areas, is estimated to contribute 4.246 Mt/yr or ca. 2% of the Netherlands' annual CO_2 emissions. The remaining peat has the potential to emit 2.0 Gt CO_2 into the atmosphere and regardless of the energy content of the organic rich layers, this does not fit in a sustainable energy supply system. It is therefore important to increase knowledge and understanding of the characteristics and behaviour of these layers in the Dutch subsurface.

<< Coal miner in the Oranje Nassau mine (Heerlen, southeastern Netherlands, 1952-1953).
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Introduction

The world has been relying on peat and coal for a large portion of its energy demands for centuries. In the Netherlands, large scale commercial peat mining for energy production commenced in the 14th century (Van Dam, 2001), but gradually became replaced by coal as a main source of energy from the 19th century onwards (Gerding et al., 2015). Despite a significant shift over the last decades towards gas and renewables for electricity production, 14% of the electricity in 2021 was still generated from coal-fired power plants, with an associated CO_2 emission of 11.2 Megaton (CBS, 2022a,b). Although the usage of coal has been phasing out in the Netherlands, it is likely that globally the world will continue to rely on coal for several decades to come. In its 2020 World Energy Outlook, the International Energy Agency predicts a relatively stable demand for coal until 2030, albeit lower than the 2019 demand (IEA, 2020). Currently it seems very unlikely that further exploitation of the natural coal and peat resources in the Netherlands as fossil fuel will ever be reconsidered, given the likely impact that exploitation would have on society and the associated emission of greenhouse gases. However, the subsurface is envisaged to play a key role in the energy transition for extraction of heat and storage of fluids and gases. Organic rich layers are an integral part of the subsurface that need to be taken into account, as they show different responses to temperature and pressure changes compared to other rocks and sediments. Understanding of the nature of these layers and prediction of their behaviour under changing conditions will therefore remain of utmost importance. Peat, coal and coalbed methane are consecutively described by briefly discussing their formation, their exploitation history and the chapter concludes with a high-level resource assessment.

Peat

Peat is one of the most peculiar lithologies encountered in the shallow subsurface of the Netherlands. Its organic composition makes it suitable for various uses, but very prone to degradation. The reclamation of vast peatlands has boosted the country's economy for centuries as an energy source for domestic and industrial use, as agricultural land, and even as a reservoir for sea salt mining. Nevertheless, its utilization, has led to severe land subsidence due to volumetric loss by mining, decomposition by microbial oxidation following drainage for land reclamation, and by peat compaction through reduced pore water pressures and anthropogenic loading. Land subsidence results in higher flood risks and damage to buildings and infrastructure. In addition, the oxidation of shallow peat beds is a prime source of greenhouse gas emissions, and its weak organic structure brings engineering challenges to the built environment.

Formation and composition

Peat forms under waterlogged anoxic conditions in wetlands, where organic matter production from decaying vegetation exceeds decomposition by biochemical processes. In the Netherlands, wetlands of Holocene age can be divided into low-lying fens and elevated bogs (Verhoeven, 1992). Fens develop under influence of groundwater and are situated in delta and coastal plains, brook valleys, and areas with groundwater seepage. Bogs are elevated above regional groundwater levels and are primarily precipitation fed. Remnants of bogs can be found in pre-Holocene elevated substrates, as well as superimposed on coastal fens (Pons, 1992). Peat of Holocene age typically has organic matter dry mass percentages of 20 to 90% (Den Haan & Kruse, 2006; Koster, 2017;

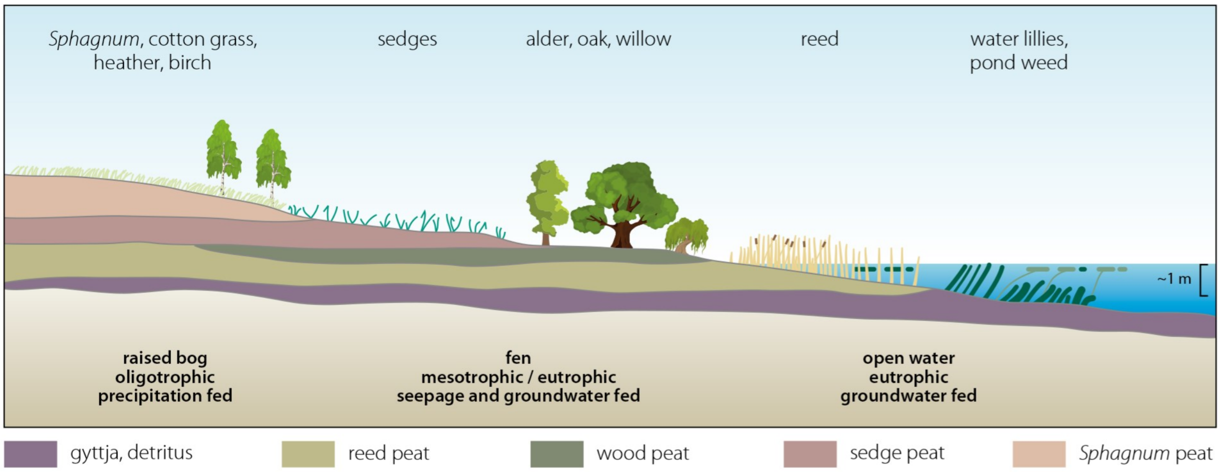

Figure 15.1. Schematic diagram of the depositional setting of various peat types (after Hobbs, 1986).

Koster et al., 2018a) and in pristine settings has porosities up to 95%, owing to the low specific weight of organic matter (Landva, 2006). The high porosity of peat substantially decreases during compression by loading of younger, higher density sediments, leading to substantial volumetric loss (Van Asselen et al., 2009). This process occurs naturally and has influenced for instance sedimentation patterns of the Rhine and Meuse rivers during the Holocene, as the loading of peat by clastic sediments has provided locally 40% additional accommodation space (Van Asselen, 2011). Peat often contains clastic admixtures that are naturally introduced by water, air, or bioturbation, thereby changing its composition and reducing its porosity. The content of clastic sediments in peat beds often increases at its vertical and horizontal boundaries, thereby reflecting transitions in depositional environments (Koster et al., 2018b).
The type of peat-forming vegetation depends mostly on the nutrient level of the accommodating water and water depth (Den Held et al., 1992). Major peat-forming vegetation in the Netherlands during the Holocene were i) eutrophic reed peat in deeper water (ca. 1 m) influenced by fluvial and tidal systems, ii) eutrophic to mesotrophic wood peat (alder, oak, willow) in shallow (ca. 0.1 m) slightly less nutrient-rich fluvial dominated zones, iii) mesotrophic sedge peat in areas of seepage and in shallow zones (ca. 0.3 m) distal to rivers, and iv) oligotrophic peat domes that are precipitation fed and primarily consist of mosses and heather.

Organic lake deposits are also encountered in the subsurface of the Netherlands. Gyttja is a brown to greenish fine-grained organic deposit that accumulates in fresh eutrophic standing water too deep to accommodate peat forming vegetation (ca. >1 m). It consists of decayed organic constituents present in the water column such as algae, water plants and humic acids, and can have a white-yellowish appearance when formed in water saturated with calcium carbonate. Although gyttja is very amorphous, it can contain macroscopically visible remains of water flora and fauna. Detritus found in areas where peat beds were eroded, mechanically broken down during transport and subsequently deposited consists of small peat, plant and/or wood fragments and is typically encountered at former lake shores, such as at the edge of the former Almere lake system (Menke et al., 1998). Detritus often contains admixed clastic sediments and in contrast to peat is not very cohesive.

Geological setting

Most peat currently found in the subsurface of the Netherlands formed during the Holocene, although shallow peat beds of Pleistocene age are locally present as well

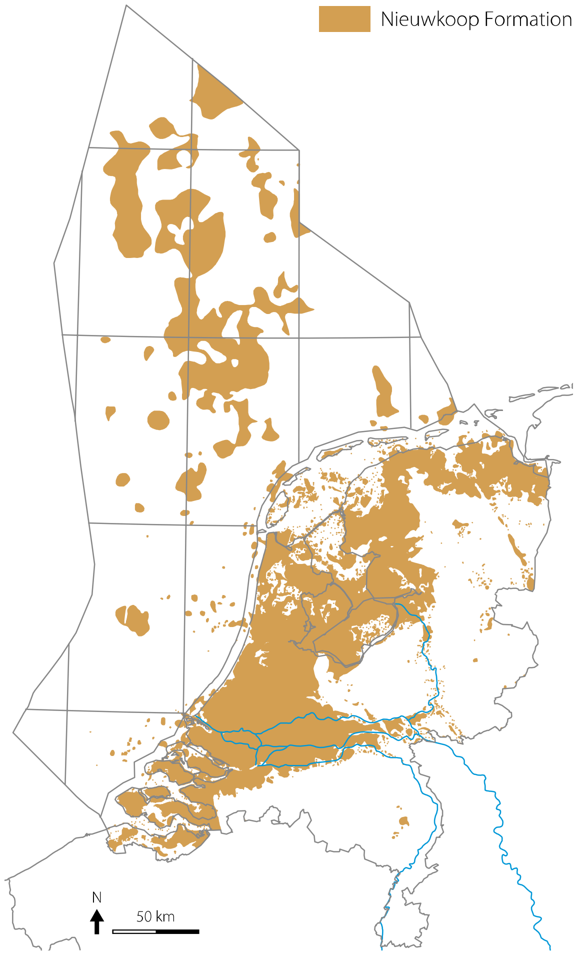

Figure 15.2. Present-day distribution of Holocene peat of the Nieuwkoop Formation in the Netherlands (TNO-GDN, 2022d). The original distribution of peat was much wider (see e.g. Vos, 2015) but through the centuries has been significantly affected by excavation activities that completely removed peat from certain areas.

(Schokker et al., 2007; Peeters et al., 2015). In general, two areas of Holocene peat formation are distinguished based on their hydrological regimes (Pons, 1992): the coastal and delta plains where fen and bog peat formed under influence of relative sea-level rise, and the higher elevated pre-Holocene substrates where fen peat formed in swampy brook-valleys and bog peat on plateaus under influence of seepage and precipitation (Fig. 15.1).

The formation of a basal peat bed (Nieuwkoop Formation; Basisveen Bed; see Figs 15.2, 15.3) lying directly on top of the Pleistocene surface commenced around 10,900 year BP, when this surface drowned under influence of relative sea-level rise (Jelgersma, 1961; Hijma & Cohen, 2010). These basal peat beds are situated around 23 to 24 m below present mean sea-level. Offshore, this basal peat bed is encountered even deeper, at depths up to ca. 60 m below mean sea-level. There, basal peat beds have an age of ca. 12,700 to 13,800 years BP (Lippmann et al., 2021), coinciding with the Late Glacial Allerød interstadial. Basal peat consists primarily of eutrophic and mesotrophic peat formed in fens, locally alternating with organic deposits and oligotrophic bogs, the latter primarily at locations of groundwater seepage (Bos et al., 2012). This peat layer is overlain by clastic tidal basin and fluvial deposits of the Naaldwijk Formation and Echteld Formation respectively (TNO-GDN, 2022a,c). These tidal basin and fluvial deposits themselves are also locally embedded with thin peat layers that formed during relatively short intervals of non-deposition in the Early Holocene. The formation of the up to metres thick vast peat beds that are found in the shallow subsurface of the present-day coastal plains com-

The vanished peat

During many millennia large parts of the Netherlands were covered with swamps, in which metres thick peat beds accumulated. At present, most of these swamps and the peat beds are gone. For peat to form, a high groundwater table is needed to prevent oxidation of vegetation remains. Natural conditions in the Netherlands favour peat formation, because of its low-lying near-coastal position and abundant precipitation. Even further away from the coast, large-scale peat growth in swamps and raised bogs occurred.

Peat swamps provide unfavourable conditions for humans to live in. Initially, swamps were used merely for hunting and performing rituals. The soggy conditions of peat swamps made them difficult to access and unsuitable for agricultural practices. Archeological finds indicate that already from the Bronze Age onwards, over 3000 years ago, people started to construct infrastructural works to allow for access into the swamps. During the Iron Age, and later in Roman Times, technological advancements allowed people to manage peatlands, by draining and cultivating them. However, by draining the peat, the vegetational remains were exposed to oxygen and started to degrade. This marked the onset, on a local scale, of the disappearance of peat.

It was not until the Middle Ages that the vanishing of peat commenced on large regional scales, when it was mined for fuel and salt, and drained and dug to create agricultural lands. Today, almost all swamps have disappeared. The few that remain are now in use as nature reserve areas, such as the national parks 'De Groote Peel' and 'Weerribben-Wieden'. Although these swamps are preserved, their water dynamics and therefore peat growth are still heavily controlled by humans.

In the low-lying coastal areas most of the peat has been exploited and the thick peat layers that once characterized the area are now strongly reduced. This can best be seen underneath centuries old earthen structures that very locally shielded-off the peat from human-induced degradation. Examples are for instance embankments, but also dwelling mounds ('terpen').

The image shows two samples of the same peat layer: on the left a sample taken from a dug exposure and on the right one from a cored borehole (Vos, 2011). On the left, the peat has vanished and been degraded to faint black lines embedded within clay. On the right the peat was shielded-off by a dwelling mound, which preserved it from degradation. It has a thickness of some decimetres. Note the thin clay bed within the peat layer, indicative of a flood event and visible in both samples. It can be used to correlate the vanished with the fresh peat bed. The diameter of the core is 3 cm. To prevent the remaining peat in the Netherlands from vanishing it is important to keep the remaining swamps and peat beds waterlogged.

menced around 6000-5500 year BP (Nieuwkoop Formation; Hollandveen Member), when the open tidal basins transformed into an enclosed fresh water fed area (Beets & Van der Spek, 2000). This was the result of the maturation of a coastal-barrier complex under influence of decelerating relative sea-level rise, closing-off the inland from saline water and sediments, thereby providing freshwater accommodation space for peat formation. Locally, the peat of the Hollandveen Member was elevated in rainwater fed peat bogs and furthermore, in the Flevoland and IJsselmeer area, within the peatlands of the Hollandveen Member, the regional Flevomeer lake system developed. Within this lake system, gyttja and detritus were deposited, stratigraphically interfingering with peat beds of the Hollandveen Member (Nieuwkoop Formation; Flevomeer Bed).

Peat formation in brook valleys and on elevated plateaus (Nieuwkoop Formation; Griendtsveen Member) commenced in two phases. Locally, mesotrophic peat started to develop as early as the relatively warm Allerød and Bølling interstadials during the Late Glacial (Quik et al., 2021). However, largescale peat formation developed relatively late, around 5600 years BP, simultaneously to the widespread peat formation in the coastal plain that followed the maturation of the barrier complex. The latter most likely influenced the local drainage conditions on the higher elevated plateaus as well (Quik et al., 2021). The second phase of formation of the Griendtsveen Member took place in less nutrient-rich conditions. It often consists of oligotrophic bogs, with an amorphous highly organic base layer (*gliede*), locally alternating with mesotrophic fen peat.

Historical development and economics

Inhabitants of the coastal plains of the Netherlands have been exploiting Holocene peat on a local scale for millennia, inevitably contributing to subsidence and thereby precipitating a series of floods that repeatedly destroyed arable land and settlements. For instance, peat areas adjacent to the former estuaries of the Scheldt and Meuse rivers were already artificially being drained during the Late Iron Age around 2500 years BP and the consequent subsidence due especially to peat oxidation, led to series of severe floods and the eventual abandonment of the areas until Roman times (Vos & Van Heeringen, 1997; Vos, 2017).
Large scale more centrally organized reclamation of the peat areas commenced between 800-1000 AD (Van Dam, 2001). Since then, this has resulted in a loss of 19.8 x 10^9 m^3 of peat from the coastal plain alone, of which the majority (14.6 x 10^9 m^3) has disappeared through oxidation (Erkens et al., 2016). The natural process of peat oxidation and the combustion of excavated peat as a fuel emitted total 2.02-5.72 Gton CO_2 (Erkens et al., 2016).

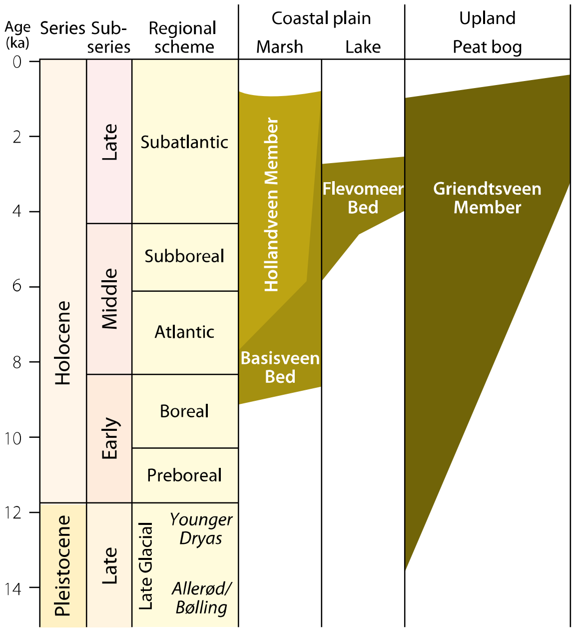

Figure 15.3. Chronostratigraphy and lithostratigraphy of Holocene peat units in the Netherlands (from Vos, 2015).

During the early Middle Ages, peat was primarily mined at the higher elevated plateaus in the north eastern Netherlands, in parallel to north western Germany and northern Flanders. This *turf* (brick-sized blocks of dried peat) was used predominantly as a fuel. Eventually, production shifted from northern Flanders and western Brabant to the northern Netherlands, Holland, and Utrecht (Fig. 15.4). In the provinces of Friesland, Groningen, Drenthe and Overijssel, about 1420 km^2 of peat bogs were excavated for the production of turf. This turf is estimated to represent a total of 3.5 x 10^9 Gigajoules of energy (Gerding, 1995).

Until the 14th century, farmers exploited the extensive peatlands in the coastal plains for the production of grain. However, subsidence resulted in a relative groundwater level rise, making circumstances unsuitable for agriculture (Van Dam, 2001). Instead, the remnants of the subsiding peat bogs were mined for fuel, even below regional ground-water levels, turning the areas into open water, which expanded in vast lakes during storm surges (Borger, 1992). Large scale land subsidence in the coastal plains as a result of mainly peat mining and peat drainage for land reclamation led to centuries of flooding, especially in areas adjacent to estuaries and tidal inlets (Vos, 2015). In parallel to the peatland reclamations, peatland flooded by saline water was also mined and combusted to extract trapped sea salt (*selnering*), which remained as a residue (De Kraker, 2006).

Local authorities were aware of the relation between peat mining, subsidence, and floods. The counts of the provinces of Holland and Zeeland for instance demanded in 1404 AD the termination of all mining and drainage activities in the peatlands surrounding Dordrecht (which were primarily related to the sea salt mining industry), imposing as punishment the cutting off one's right hand (Tuinstra, 1951). Despite such repressive measures, the area continued to subside and was struck in 1421 AD by the St. Elisabeth's flood, one of the most devastating floods recorded in the Netherlands, from both landscape and socio-economic points-of-view.

Between 1700 and 1900 AD, most of the remaining raised bogs on the elevated plateaus were mined for fuel or were burned to create arable lands. Major peat mining for turf production gradually stopped between the two World Wars. Based on annual production data, it is estimated that 9.4 x 10^9 m^3 of turf was produced from 1200 to 1950, production from the Peel area not included (Leenders, 1987; Fig. 15.4).

Present-day challenges

At present, ca. 15 x 10^9 m^3 of Holocene peat remains in the coastal and delta plains of the Netherlands, often at shallow depths, bringing new challenges to society (Koster et al., 2018b). Its high porosity and mechanically weak organic structure make it very compactable, causing it to be the most undesirable soil layer from an engineering perspective (Ngan-Tillard et al., 2010; Van Asselen et al., 2018). Yet, the Netherlands is burdened with a substantial construction task, especially in the heavily populated peat-rich coastal plains, to address the housing shortage, increase railroad capacity and deploy subsurface infrastructure to facilitate the energy transition. Activities that include the construction of buildings as well as the installation of below- and above-ground infrastructures must all take the disadvantageous peat properties into account. Koster et al. (2016) for instance, calculated that the overburden of an earthen embankment adjacent to the Markermeer reduced the thickness of an underlying peat layer by between 35 and 95% and this has demanded periodic heightening of the embankment in the recent past to compensate for the elevation loss. Ngan-Tillard et al. (2010) emphasized that during construction of line infrastructures such as roads in peat areas, the heterogeneous character of the subsurface should always be taken into account, in order to avoid differential settlement, damage, and eventually high maintenance costs.

Another challenge is related to global climate change. The Dutch government has committed to the Paris climate agreement to reduce CO_2 emissions by 49% in 2030 and 95% in 2050 (UNTC, 2016). Shallow and aerated peat layers have been identified as substantial contributors to our annual CO_2 emissions budget. It is estimated that microbial oxidation of peat organic carbon leads to a CO_2 emission of 4246 Mt/yr, amounting to ca. 2% of all the Netherlands' annual CO_2 emissions (Kuikman et al., 2005; Arets et al., 2019), while the remaining peat layers in the coastal plains have the potential to emit 2.0 Gt CO_2 when completely oxidized (Koster et al., 2018b). To minimize this process it is critical to keep peat waterlogged, especially in agricultural areas (Weideveld et al., 2021).

To meet the stated climate goals, a transition in land use in agricultural areas may be inevitable to prevent the remaining peat from further degradation that might be exacerbated by climate change. It is predicted that the severity and frequency of extreme droughts in northwestern Europe will increase in the next decades (Spinoni et al., 2018). Droughts are expected to accelerate peat shrinkage and oxidation by diminishing soil moisture content and raising soil temperatures (Kechavarzi et al., 2010), increasing CO_2 emissions even more, as well as enhancing mechanical breakdown of organic matter. Indeed, pilots have

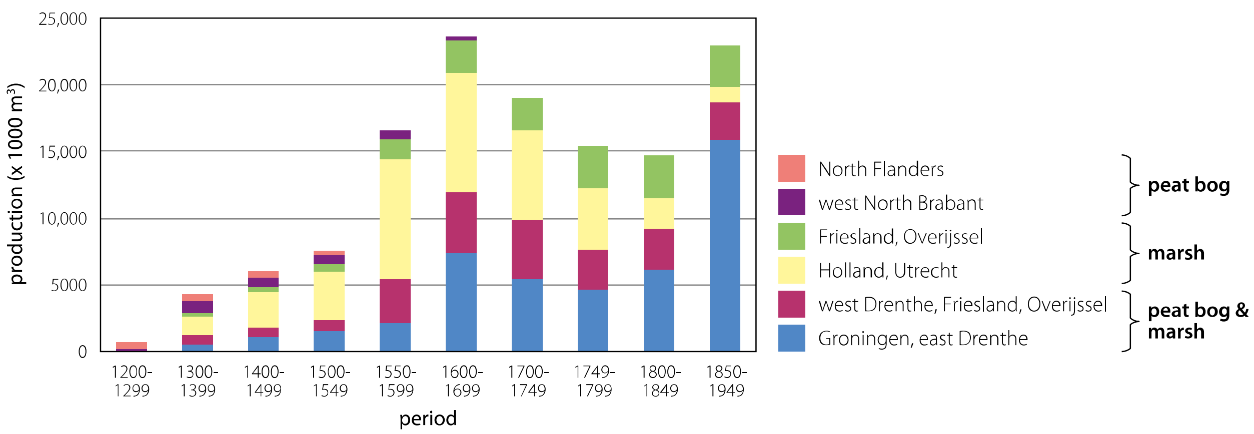

Figure 15.4. *Volumes of peat mined in the Netherlands and the north of Flanders (Belgium), per period and per region. Note the differences in the duration of the time periods. Figures indicate average yearly production and do not include the Peel area (east North Brabant and northern Limburg). After data of Leenders (1987). Modified from Van Bergen et al. (2007).*

started in recent years to actively keep groundwater levels high in peaty areas (Hoogland et al., 2020; Weideveld et al., 2021), indicating that a transition in agricultural use of peatlands is feasible.

High groundwater levels will in the best case only slow down peat oxidation. However, studies from the peat-rich and heavily subsiding Sacramento-San Joaquin delta (United States) have shown that shifting land use from meadows to wet rice-agriculture completely stopped subsidence and strongly reduced CO_2 emissions (Deverel et al., 2016). Although a transition to rice paddies is probably not realistic for the Netherlands, the Sacramento-San Joaquin case proves that a drastic shift in land use can prevent the remaining peat from oxidizing. However, while through a transition to wet agriculture the remaining peat is preserved, the peat does not regain its natural carbon sink function (Chmura et al., 2003). To stop oxidation and transform peat into carbon sinks, peat areas ought to be inundated again, allowing them to form naturally. Although groundwater levels will still be managed, this situation would approaches natural conditions that prevailed in the coastal plains and higher sandy areas during the major part of the Holocene.

Coal

Coal is generally brown to black and consists of an aggregate of mainly organic constituents called macerals, which are associated with minor to moderate amounts of mineral matter (Karayiğit & Köksoy, 1994; Taylor et al., 1998). Differences between types of coal result from variations in peat forming environments, as well as on different degrees of coalification. With increasing pressure and temperature during burial, peat changes with time first into lignite, then into bituminous coal and finally into anthracite (Fig. 15.5). During this coalification process, hydrocarbons are generated and expelled biogenically and thermogenically.

Carboniferous coal deposits of Westphalian (Pennsylvanian) age, which underlie most of the Netherlands, are the main source rock for natural gas accumulations, with an estimated contribution of more than 95%. The giant Groningen field with its initial recoverable reserves of ca. 2900 x 10^9 m^3 of gas (81% methane; Lokhorst et al., 1997) has also been sourced from Westphalian coals. Given the large volumes of gas-mature Westphalian coal in the subsurface it can be estimated that far more gas has been generated and expelled in the geological past than is currently accumulated in traps in the subsurface of the Netherlands. Probably only 1.5% or less of the total generated volume of gas through time has been trapped, the remainder having escaped to the surface during geological history (Van

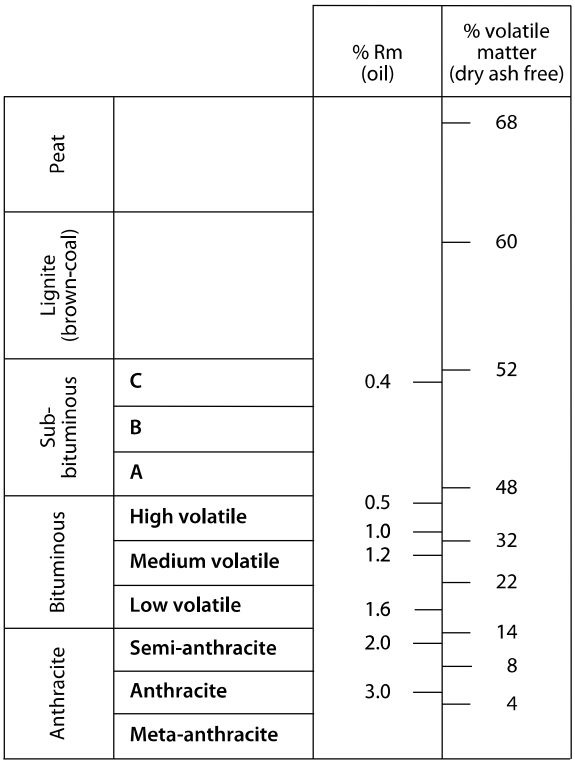

Figure 15.5. Overview of ASTM (American Society for Testing and Materials) coal rank classification (after Stach et al., 1982; Taylor et al., 1998). The stage of coalification is indicated by the rank of the coal, most commonly expressed in percentage vitrinite reflectance (% Rm) or in percentage of volatile matter (dry ash free, daf). Coalification is the progressive change in composition and structure of peat deposits and any other carbon components within sediments during burial, as a result of various interrelated physical, chemical and biological processes (Levine, 1993). The nature of these processes changes significantly with the different stages of coalification (Stach et al., 1982; Taylor et al., 1998). With advancing coalification, biochemical processes become less active (anaerobic microbial processes have some influence until the formation of lignite). During further burial, only physical factors (pressure, temperature) play a role (Van Krevelen, 1993). Lignite has a higher density, lower porosity and lower moisture content than peat. Further coalification of lignite into bituminous coal, and finally into anthracite, occurs as a result of loss of water and thermally controlled chemical alteration of the organic matter. These processes result in volumetric shrinkage due to physical compaction. Modified from Van Bergen et al. (2007).

Buggenum & Den Hartog Jager, 2007; Remmelts et al., 2025, this volume). Part of the generated methane has not been expelled but is retained within the coal itself. Depending on the (technical) process that releases the gas from the coal, this resource is referred to as coalmine methane or coalbed methane.

Lignite

Geological setting

The lignite, or brown coal, deposits in the province of Limburg are part of extensive lignite deposits that were formed during the Miocene in the lower Rhine Embayment north of the Eifel and Ardennes uplands (Fig. 15.6) and it is therefore relevant to include an evaluation of the deposits outside the Netherlands. Lignite deposits reach a thickness of 100 m in Germany (Zagwijn & Hager, 1987; Van der Burgh et al., 1988; NITG-TNO, 1999; Gąsiewicz et al., 2010; Stock et al., 2015; Fig. 15.7), implying by analogy with studies of peat layers in alluvial floodplains that have already compacted up to 43% within a few centuries (Van Asselen et al., 2010) that its original thickness must have been even 2-3 times larger. Further compaction is expected with conversion to lignite. Locally up to 300 m thick peats were deposited to form the main seam (Hager, 1993; Stock et al., 2015) These lignite deposits are part of the Ville Formation in Germany that contains, from oldest to youngest, the Morken, Frimmersdorf and Garzweiler seams (Stock et al., 2015; Fig. 15.7). Towards the west, these deposits include more and more sand intercalations which in effect split a seam into several lignite beds that can be defined as members (Zagwijn & Hager, 1987). The Ville Formation grades laterally in South Limburg into unconsolidated sand with three to four lignite beds belonging to the Middle Miocene Heksenberg Member (Fig. 15.8; Engelen, 1987). This member is up to 100 m thick with its upper and lower limits defined by the Frimmersdorf 1 and 2 coal seams (Munsterman et al., 2019). Individual zones with lignite exceed 15 m (NITG-TNO, 1999; TNO-GDN, 2022b) but decrease markedly towards the west and northwest as they continue into Belgium and North Brabant. Thinner seams continue into the Late Miocene, e.g. within the Kieseloolite Formation.

Historical development and economics

In Germany, in the area between Cologne, Bonn and Aachen, small-scale lignite mining started during the 16th century. In South Limburg, small-scale, though illegal, exploitation commenced between 1865 and 1868 near Eygelshoven (Engelen, 1989a). The first mining conces-

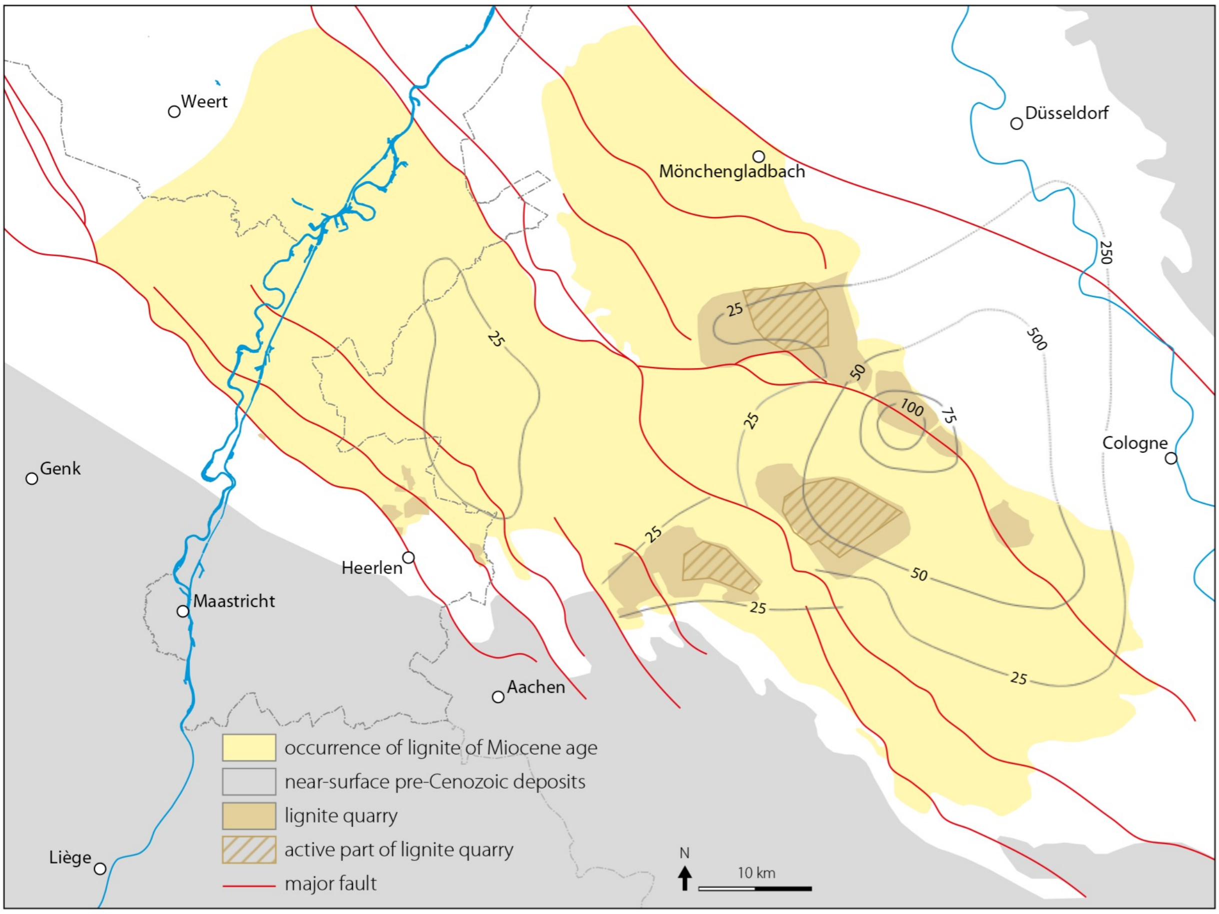

Figure 15.6. The occurrence and thickness (in metres) of Miocene lignite deposits in the Lower Rhine Graben (modified from Zagwijn & Hager, 1987; GD-NRW, 2023; in-house data of TNO-GDN, 2023). Bounds of lignite quarries in the Netherlands after Jongmans & Van Rummelen (1930) and in Germany after T. Römer (commons.wikimedia.org/w/index.php?curid=11539190 used under CC BY-SA 2.0).

Figure 15.7. Picture of the opencast lignite mine of Garzweiler (Germany), exposing the Neogene sedimentary infill of the Lower Rhine Embayment and with the three regional lignite seams indicated. The location of the mine is given in Figure 15.6. Photo: Jan Stafleu.

sion was granted in 1906 near Heerlerheide, but the exploitation was not successful (Engelen, 1987). It took until 1917, when fuel became scarce during the First World War, before new lignite extraction started in several villages near Heerlen. Dutch lignite production peaked at about 1.5 Mt/yr around the end of the war (1918-1919). By 1921 production had decreased to less than 0.13 Mt. In the following years most quarries ceased operations and only the Carisborg I quarry was kept open (NITG-TNO, 1999). Renewed production commenced during the Second World War and lasted until 1962. The quarries 'de Energie' and 'de Herman' were brought back to production and 'de Anna' was opened (NITG-TNO, 1999). Production reached over 0.2 Mt/yr during these last years (Engelen, 1989a). The lignite resources in the Netherlands are calculated to exceed 1700 Mt (Van der Burgh et al., 1988). However, despite their relatively shallow depth, any future mining is unlikely because of environmental concerns and population density.

The lignite of the Lower Rhine Embayment in Germany continues to be mined intensively, providing cheap fuel for the large power plants in the area between Cologne and Aachen, not far from the border with the Netherlands. It is mined in very large open pits to a depth of 399 m below the original surface (293 m below sea level) in the Hambach quarry (Eifelnatur.de, 2023). The annual lignite production from the Garzweiler, Neurath and Hambach open pit mines declined from 95.2 Mt in 2015 (BGR, 2016) to 51.4 Mt in 2021 (BGR, 2022). The original recoverable reserves were estimated to be about 50,000 Mt (Van Montfrans et al., 1988) or 55,000 Mt (Hager, 1993; DEBRIV, 2023) of which around 30,000 Mt was considered technically recoverable. The production of lignite in the area is expected to cease in 2030 (DEBRIV, 2023). During mining, millions of cubic metres of groundwater are pumped off and discharged. As a consequence, the groundwater system changed from a condition with upward seepage into a situation with downward infiltration (NITG-TNO, 2001; De Vries, 2007; Stuurman et al., 2007).

Bituminous coal and anthracite

Geological setting

Carboniferous sedimentary rocks of the Netherlands and surrounding areas accumulated in an east-west striking

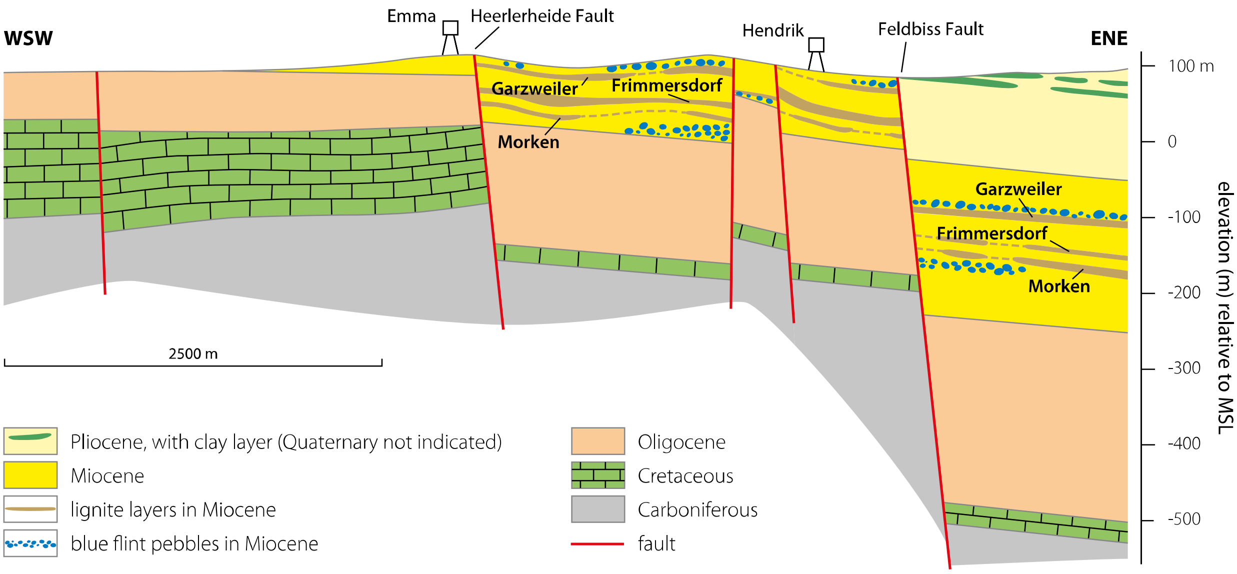

Figure 15.8. Cross section through Cenozoic strata near Heerlen in the northeastern part of South Limburg, showing the depth of the lignite-bearing Miocene silver sands (adapted from Jongmans & Van Rummelen, 1930; Pannekoek, 1956; De Jong & Van der Waals, 1971). For location of the Emma and Hendrik mines see Figure 15.12.

basin over a period of 60 million years (359-299 Myr) and have a present-day (thus compacted) maximum thickness of 5.5 km (Van Buggenum & Den Hartog Jager, 2007; Kombrink, 2008). These deposits contain numerous organic rich layers that, depending on their maturity, are classified as anthracite or bituminous coal (Figs 15.5, 15.9). At the same location both types can occur with the anthracite buried deeper than the bituminous coal. In this chapter both are referred to as coal. The main coal-bearing formations in the Netherlands were part of this succession and were deposited during the late Carboniferous (mainly during the Westphalian) in the Northwest European Coal Basin. During a phase of deformation and uplift at the end of the Carboniferous about 2000 m of Carboniferous strata were eroded across large parts of the country, leading to the current configuration of the Carboniferous subcrop below the basal Permian unconformity (Pagnier et al., 1987; Van Buggenum & Den Hartog Jager, 2007; Huis in 't Veld & Den Hartog Jager, 2025, this volume). At present, the coal-bearing deposits are found at shallow depth in the southernmost Netherlands but deepen northward to more than 3 km, where offshore the top of the Carboniferous can be as deep as 10 km in the northern Central Graben (De Bruin et al., 2015).

The Epen Formation of Namurian age consists mainly of lacustrine, marine, and deltaic shale with some sandstone intervals that locally are overlain by coal beds. Namurian aged coal beds are generally not well developed in the Netherlands, whereas they are well represented further to the east in Germany and Poland (Kombrink, 2008). The main coal-bearing deposits belong to the Baarlo, Ruurlo and Maurits formations of Langsettian to lower Bolsovian age (±321-311 Ma; Huis in 't Veld & Den Hartog Jager, 2025, this volume). The Westphalian sedimentary succession reflects continued aggradation at or near emergent conditions, comprising deltaic to fluvio-lacustrine deposits with numerous coal layers in the early Westphalian that give way to well drained fluvial sediments (eventually red beds) in the late Westphalian (Kombrink, 2008). These formations have a total thickness up to 3000 m, were deposited in a cyclic river-dominated environment and have coal contents between 1.0 and 2.1% (Van Buggenum & Den Hartog Jager, 2007). Other authors have given higher estimates of up to 3.5% based on onshore observations along the southern basin margin (e.g. Van Wijhe & Bless, 1974; Hedemann et al., 1984). Facies maps suggest lower average coal percentages for the offshore (Huis in 't Veld & Den Hartog Jager, 2025, this volume). The younger fluvial sandstone and shale sequence of the Bolsovian and

Figure 15.9. *Mining equipment (kolenschaaf) in a pillar in the Oranje Nassau Mines taken around 1952. In the background a Westphalian coal seam is visible with the typical layering and break-out patterns of coal. © Nico Jesse / Nederlands Fotomuseum.*

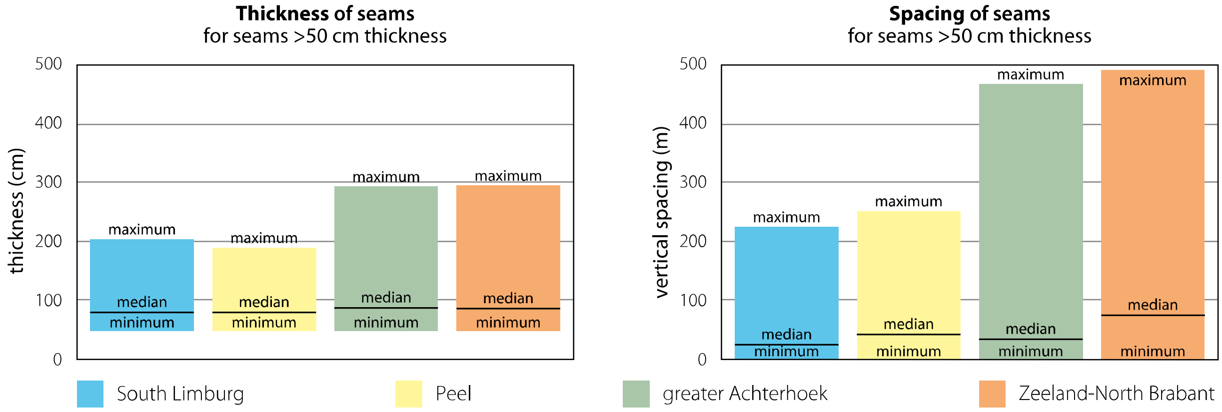

Figure 15.10. Thickness (>50 cm thickness) and spacing of Westphalian coal seams in the areas shown in Figure 15.12 (South Limburg: depth <1500 m; Peel: depth <1500 m; greater Achterhoek/south Overijssel area: depth <2000 m; Zeeland-Noord Brabant: depth 1500-2000 m). The number of evaluated coal seams varies per area from 21 encountered in 2 wells in Zeeland-North Brabant, to well over 100 seams in other areas. For a limited number of coal-exploration wells, the coal-seam thickness was known from cores, otherwise geophysical well logs (sonic, density) were used (from Van Bergen et al., 2000).

Asturian locally contains thin coal seams (Van Adrichem Boogaert & Kouwe, 1995). The rank of these coal seams is mainly bituminous, but anthracite occurs locally, especially in South Limburg where most likely a major Variscan thrust sequence has been eroded (NITG-TNO, 1999; Huis in 't Veld & Den Hartog Jager, 2025, this volume).

Coal-clastic cycles, also known as 'cyclothems', are metre- to decametre-scale alternations of (marginal) marine shales and terrestrial shales, sands and coal beds (Weller, 1930; Greb et al., 2008; Van den Belt, 2012). These cycles may (Veevers & Powell, 1987; Klein & Willard, 1989) or may not (Wilkinson et al., 2003) have resulted from glacio-eustatic sea level fluctuations in the Milankovitch frequency band. Van den Belt (2012) suggested that carbon storage in the late Paleozoic terrestrial system was controlled by climate rather than by local sedimentary conditions. Core analysis indicates that a distinct two-fold cyclicity at wavelengths of ~255 m (~395 ky) and ~60 m (93 ky) is present, as is shown in Carboniferous cores, indicating long and short-eccentricity control (Van den Belt, 2012). Based on Markov analysis, para-sequence thicknesses in the Westphalian deposits were quantified with cycle thicknesses for the Langsettian and Duckmantian at around 10 m, while not all cycles contain coal (Pagnier et al., 1987). Average duration of individual cyclothems with highly variable thicknesses was ~21 ky (Van den Belt, 2012). The estimated coal-accumulation rate in the Netherlands was 5-10 m/My for the Langsettian and Duckmantian (ca. 320-316 Ma) and increased abruptly to ~25 m/My at 315 Ma. Spacing between the individual seams as measured in wells is shown in Figure 15.10. Based on five coal-exploration wells drilled in the 1980s in the Achterhoek and in South Limburg, the mean thickness of Westphalian coal seams (of >50 cm) is 1 m (RGD, 1986). According to Van Bergen et al. (2000) the median thickness of such seams in the areas mentioned is 88 and 80 cm, respectively. Individual coal-layer thicknesses reach up to 3 m in the greater Achterhoek area, or, in terms of cumulative thickness, even up to 3.5 m (RGD, 1986; Pagnier et al., 1987; Fig. 15.11).

Historical development and economics

South Limburg

The lower part of the Westphalian coal measures lies at or near the surface in the valley of the river Worm north of the German city of Aachen, where it has been mined from Roman times onwards in simple open pits (Visser & Zonneveld, 1987; NITG-TNO, 1999). Coal has been mined in the Kerkrade area since medieval times (Bless et al., 1984). The Annales Rodenses of 1113 AD, the chronicles of Kloosterrade (Rolduc Abbey), situated in the Worm Valley of Kerkrade, contain a transfer of land named 'kalculen'. The etymology is thought to refer to a small open pit coal mining area, which could be regarded as the oldest official recordings of coal production in Europe (Moonen, 2012). Underground mining in galleries started early in the 14th century (Visser & Zonneveld, 1987; NITG-TNO, 1999). The Limburg dialect word *Koul*, (e.g. the Sittard district Kemperkoul or the small hamlet of Koulen, near Valkenburg) refers to such small open pits that were dug to produce near-surface coal or to store coal or gravel until the 18th century. In the 16th century, when exploitation began to require more technical and financial resources, an industry developed that was based on the early capitalist system (Raedts, 1971; Engelen, 1989b; NITG-TNO, 1999). At the beginning of the 18th century, the abbey of Kloosterrade (Rolduc) began developing coal mines. By the

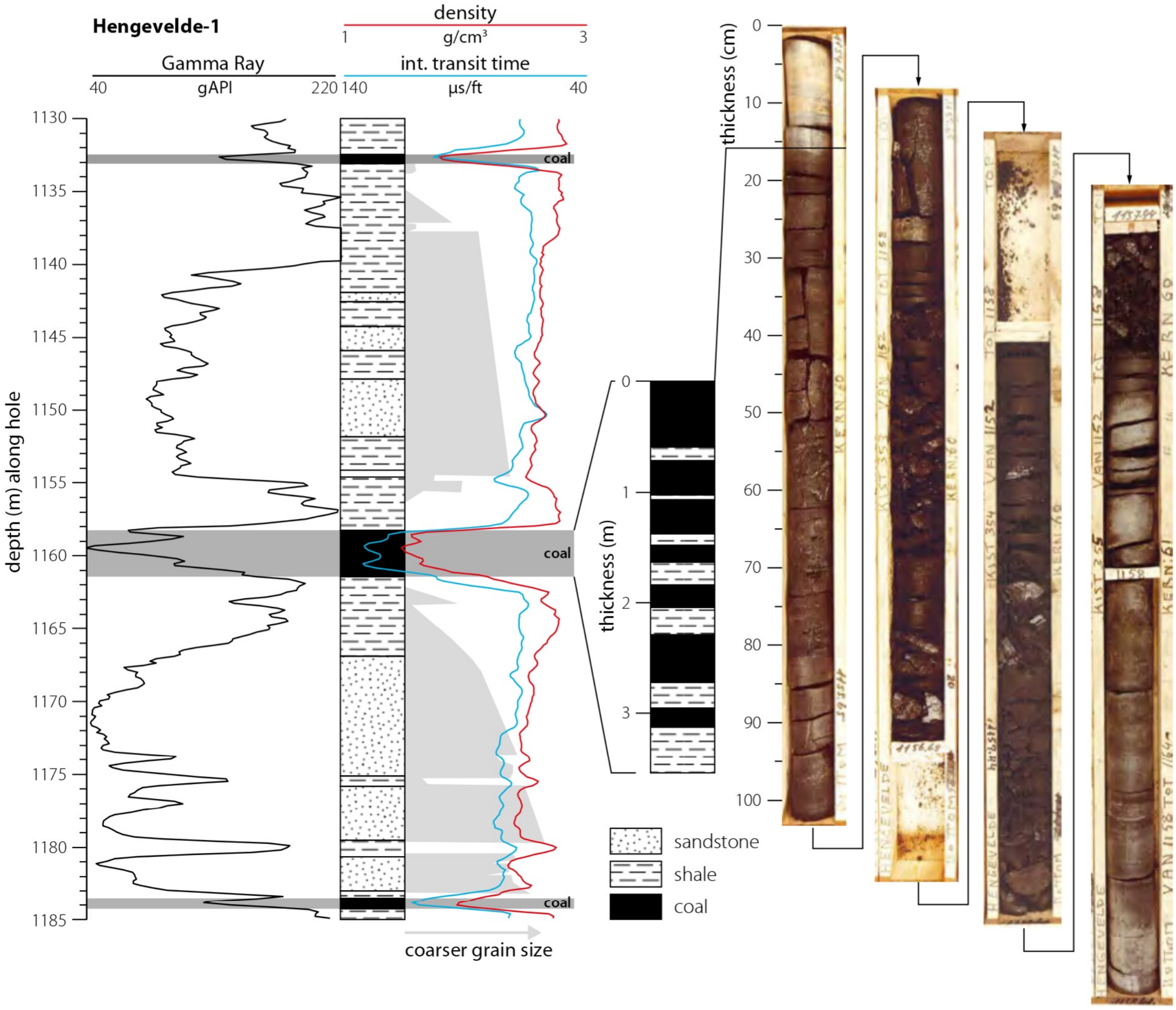

Figure 15.11. Log response with core description and core pictures of the thickest coal seam encountered in the well Hengevelde-1, where a cumulative thickness of 356 cm is encountered. Core analysis indicates that this coal seam (named seam VI) is actually composed of smaller coal (grey) and shale (brown) intervals as shown by the picture in the centre. This coal is classified as a high volatile bituminous coal based on a vitrinite reflectance (Rm) of 0.77%, which is not fully consistent with the measured volatile matter content of 51.62% (dry ash free). Ash was 15.88% and sulphur 1.27% (dry basis). The layers in this section dip at 8-25°. The alternation of sandstone, shale coal, shale, sandstone, shale and coal are expressions of (non-ideal) cyclothems. Core photos from Rijks Geologische Dienst.

middle of that century mining was conducted from small shafts and with small mining corridors from the western wall of the Worm Valley where the Rolduc Abbey is situated. The first shaft mining started during the French occupation in 1797 on the nearby Kerkrade Plateau, after the mines were nationalized. Following the invention of the steam engine, it became possible to handle the vast amounts of ground water and to deepen the mine shafts.

However, during the French occupation of 1794-1815, mining came to a near standstill as a result of seizure and incompetent management (NITG-TNO, 1999). During the French period, all natural resources became the property of the State under the Napoleonic law of 1810 and under this law, concessions for exploitation were granted by the State. Exploitation in the state-owned mines was unsuccessful after 1815. The Domaniale concession was therefore leased to a private enterprise in 1845. Administration of commercial coal production in South Limburg started in 1847, but mining became truly established at the end of the 19th century when the arrival of a railway line improved access to eastern South Limburg (NITG-TNO, 1999). During this period, the large Oranje-Nassau concession was awarded, and the Oranje-Nassau I mine became operational in 1899.

From 1902 onwards the 'State Collieries' (Staatsmijnen) Wilhelmina, Emma, Hendrik and Maurits were established in the substantial areas not yet covered by earlier concessions. The new concessions were repeatedly extended dur-

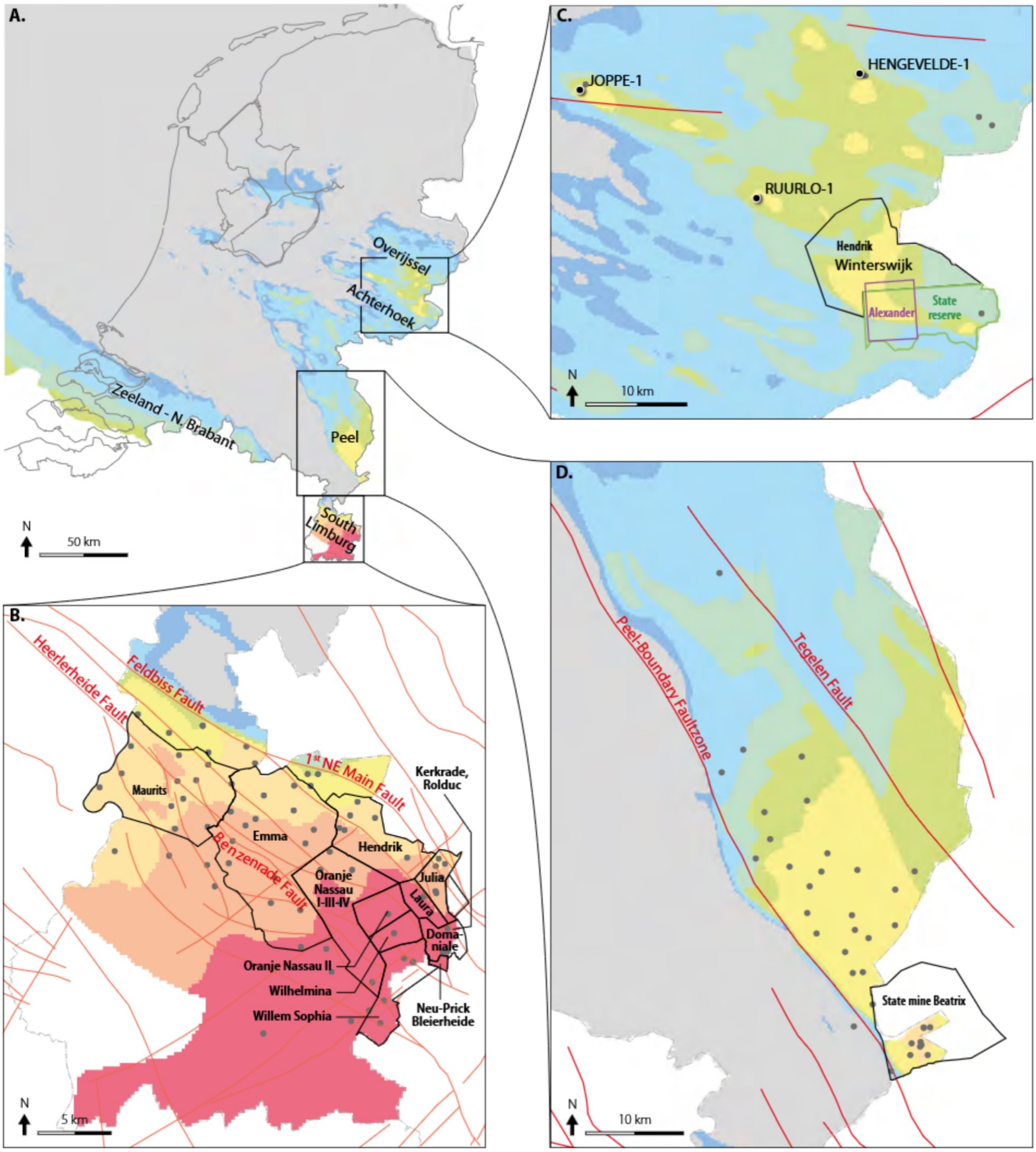

Figure 15.12. Depth map of the top of the coal-bearing Carboniferous deposits (a). The lower limit for traditional coal mining was defined at more or less 1000 m below surface, although down to 1500 m was considered technically reachable in the foreseeable future. The main areas with Westphalian coal-bearing deposits above 1500 m are South Limburg (b), the Greater Achterhoek area including southern Overijssel (c), and the Peel area (d). The insets show the South Limburg mining district, with major faults and coal concessions in 1960 (after Raedts, 1971), the Peel area with the location of the State mine Beatrix that was never taken into production and the Achterhoek/southern Overijssel area with the former concession for coal and salt exploration. The application for the Alexander concession by private companies had to be withdrawn after it had been established a State reserve by law in 1924 (Visser, 1987).

ing the first half of the 20th century. Smaller enterprises opened mines along the German border.

Coal mining in Limburg took place between the Benzenrade Fault and the First NE Main Fault (Fig. 15.12). As a result of the north to northeast dip of bedding and because of faulting, the depths at which exploitation took place varied considerably. The bottom of a shaft of the Domaniale mine was only 22 m below surface level, whereas a shaft of the State Colliery Hendrik extended down to 1008 m. A total of 248 coal seams with a cumulative coal thickness of over 73 m (IGCP 166, 1980) is present. Approximately 65 of these seams are exploitable, with thicknesses ranging roughly from 50 to 150 cm (Kuyl, 1980).

After the global economic crisis in the late twenties and early thirties, the Dutch coal-mining industry experienced a boom that lasted until after World War II. Twelve surface facilities were in operation, with a combined annual production of about 12.6 Mt (Engelen, 1989b). In the early 1960s, when production was peaking, the mines provided work for more than 28,000 workers underground and nearly 23,000 at the surface (Westen, 1971). Interest in coal outside South Limburg diminished rapidly after the discovery of the giant Groningen gas field in 1959 (Van Tongeren, 1987). This discovery, together with low world-energy prices and rising exploitation costs, led to the collapse of coal mining industry in the Netherlands (Raedts, 1971; Van Tongeren, 1987). The period from 1967-1974 saw the rapid closure of the mines.

Coal production stopped with the closure of the Oranje Nassau mine in 1974 (Fig. 15.13). During the previous 128 years, an estimated 582 Mt of coal were produced from thirteen mines (four state-owned and nine private),

Figure 15.13. *Picture of the last piece of produced coal, in custody of OneDyas, extracted from the Oranje-Nassau I mine on 31 December 1974, showing the centimetre-scale internal fracture (cleat) system of the coal. Production from this last operational mine in the Netherlands reached 427,000 tons coal in that last year. Photo: Richard Huis in 't Veld.*

all in South Limburg (Fig. 15.14; Westen, 1971; Stuffken, 1987). This is only a fraction of the coal volumes present in the subsurface and enormous coal resources remain in Limburg and elsewhere. In the Peel and Achterhoek, numerous exploration wells for coal have been drilled but no mining has taken place (Peelcommissie, 1963; RGD, 1986). During the 1980s, interest in coal was renewed, induced by the second oil crisis and also triggered by new techniques such as underground coal gasification. This led to an inventory of coal deposits down to a depth of 1500 m (RGD, 1986; Pagnier et al., 1987; Van Tongeren, 1987), the results of which indicate that the fault block between the Tegelen Fault and the Peel-Boundary Faultzone, north of the former mining area, contains a coal resource of 591 Mt (RGD, 1986). Underground coal gasification was considered as early as 1946 (Visser, 1987), but no applications have been made, although elsewhere, especially in the United States, demonstration projects have been conducted.

Peel

In view of the coal resources immediately across the border in Germany, the State Service for the Exploration of Mineral Resources (ROD) carried out a drilling campaign between 1903 and 1916 to investigate the occurrence of exploitable quantities of coal in the Peel area (Fig. 15.12). Based on the results from 13 deep wells and many shallow boreholes, the ROD calculated that reserves of about 2500 Mt of coal exist above 1500 m below mean sea level in seams of exploitable thickness (Van Waterschoot van der Gracht, 1918). During the Second World War, a gravimetric survey was carried out in the Peel and adjacent areas (De Sitter et al., 1949; Van Weelden, 1957) and halfway through the 20th century, the State Collieries drilled 12 wells (NITG-TNO, 2001). In 1952, exploration intensified after establishment of the advisory Peelcommissie. It included the surveying of 368 km of seismic data and the drilling of eight additional wells. The committee calculated that a geological reserve of approximately 2900 Mt of coal in seams over 50 cm thick is present in the evaluated areas but observed that the net cumulative coal thickness in the area is less than in South Limburg (Peelcommissie, 1963). Meanwhile, the construction of two shafts for the new Beatrix State Colliery in the eastern Peel area commenced in 1952; it was subsequently suspended in 1962 as a result of a change in energy policy (Peelcommissie, 1963; NITG-TNO, 2001). In 1984, further investigations were carried out by the Geological Survey (RGD, 1986; Pagnier et al., 1987). Seven seismic lines with a total length of 115 km were acquired, covering about 220 km^2. The results of this research confirmed the conclusions of the Peelcommissie. They also showed that the Carboniferous to the north of the Peel area is represented by less productive coal seams of the Namurian and Westphalian

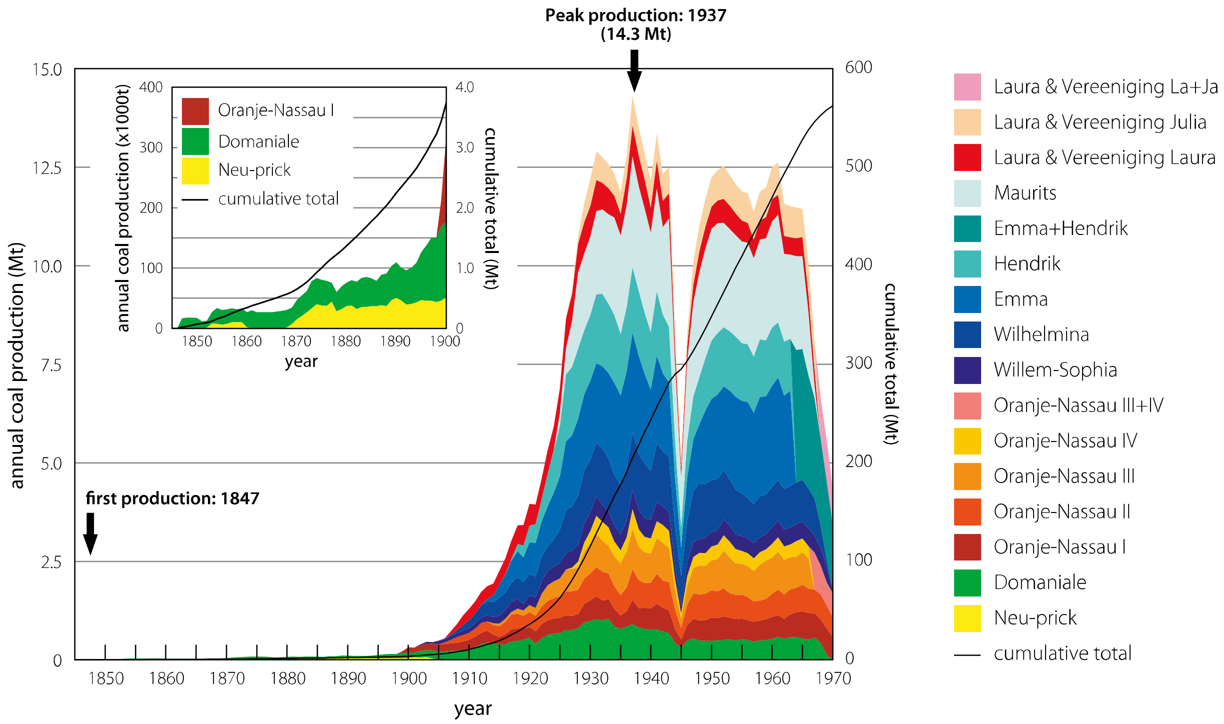

Figure 15.14. *Net annual coal production from 1847 to 1970 from mines in South Limburg (after data of Westen, 1971). Data up to 1929 without coal sludge; since 1929 including coal sludge. Extrapolation of the declining production curves indicates a cumulative production of ca. 8.5 Mt in the period from 1971 until the closure of the last mine in 1974. Modified from Van Bergen et al. (2007).*

A (NITG-TNO, 2001). The latest evaluation of the Peel area covered twelve fault blocks, some of which are located in Germany, but which fall under a Dutch concession according to an agreement reached in 1959 (Peelcommissie, 1963). The resources of the area (P50: 3300 Mt; Fig. 15.15a; Van Bergen et al., 2000) are slightly higher than those reported earlier by the Peelcommissie (1963).

Achterhoek (and southern Overijssel)

A concession for coal and rock-salt exploitation in the Achterhoek was granted in 1930, after Carboniferous coal measures had been identified near Winterswijk by the State Service for the Exploration of Mineral Resources (Fig. 15.12). The area of this 'Gelria' concession is greater than 100 km². At that time, the reserves of bituminous coal in this area at depths between 900 and 1500 m were estimated at about 360 Mt. However, mining never took place because of high costs and the risk involved, not to mention an economic slump (Visser, 1987).

In the 1980s, further investigations were carried out by the Geological Survey (RGD, 1986; Pagnier et al., 1987). Within the framework of this study, seismic lines with a total length of 79 km were aquired and 375 km of previously existing lines were re-evaluated. The resources of three coal seams from the top of the Carboniferous to 1500 m, in a triangular area of 157 km², between the coal exploration wells Joppe-1, Hengevelde-1 and Ruurlo-1 were estimated at 693 Mt (RGD, 1986). For the greater Achterhoek area, including south Overijssel, the total coal resources shallower than 1500 m were estimated to be about 9100 Mt in the latest inventory (P50; Fig. 15.15a; Van Bergen et al., 2000).

Zeeland and North Brabant

Exploration wells were drilled throughout the Netherlands in search of coal by the Rijks Opsporingsdienst Voor Delfstoffen just before World War I. During this campaign well Woensdrecht-01 drilled down to a depth of 1205 m, but found that coal measures were missing. Since then, a number of wells drilled into the Carboniferous in this area, but further to the north encountered coal seams, mostly at depths greater than 1500 m. Given the large area, the total resources are substantial but the seams lie too deep and are too widely spaced.

Coalbed methane

At the turn of the 21st century attention to the coal resources of the Netherlands resumed, this time not for exploitation of the coal itself but for the gas that is contained in the coal seams. Coalbed methane, or CBM, is the

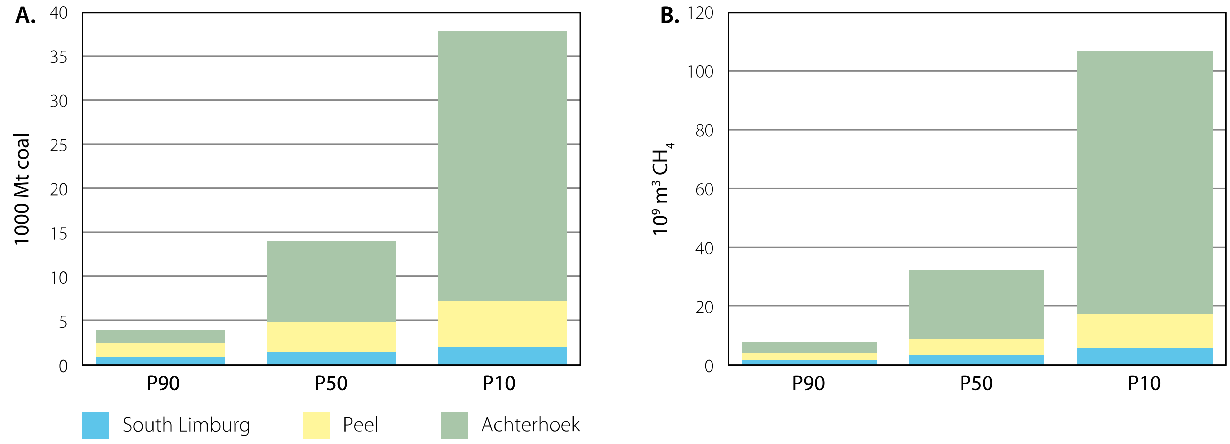

Figure 15.15. *Calculated quantities expressed in probability values, of (a) coal resources and (b) potentially producible (technically recoverable) coalbed methane (CBM) in the Netherlands from Westphalian coals shallower than 1500 m depth (after Van Bergen et al., 2000). The (theoretically) technically recoverable amount of CBM depends on high net coal thickness (Pashin & Hinkle, 1997), while producibility depends on several critical factors, including hydrodynamics, depositional setting and coal distribution, tectonic and structural setting, coal rank and gas generation, permeability, and gas content (Scott, 2002). In the calculations by Van Bergen et al, (2000) these dependencies were represented by a completion and a recovery factor. The completion factor will be high in thick, closely spaced seams, and low in thin, sparsely spaced seams. The recovery factor is the percentage of gas that can be produced from the contributing coals. In CBM production as applied in the United States, this depends strongly on the pressure drop that can be achieved in the coal seams by the pumping of large volumes of water; normally 20 to 80% of the gas originally in place can be recovered. The South Limburg area has potentially the highest producible methane content per square kilometre due to its high net cumulative coal thickness, but the potential for total producible methane is highest in the large, greater Achterhoek area (including southern Overijssel) and fairly high in the medium-sized Peel area. In addition to the inventory down to 1500 m, methane resources for the depth interval between 1500 and 2000 m are largely due to potentially large amounts of coal and the high pressure. Estimated resources in the greater Achterhoek and Zeeland and North Brabant areas amount to 50 and 118 × 10^9 m³ gas respectively (P50 values). However, the producibility of these deeper resources is technically and economically questionable at present because the permeability of deeper coal seams is expected to be too low and the costs of drilling too high (Van Bergen et al., 2000; Scott, 2002). Modified from Van Bergen et al. (2007).*

natural gas that is retained in coal in the subsurface. It is known as mine gas, or coal mine methane in the mining industry, where it is dangerous due to its explosive nature. From the 1970s onwards interest has grown in coalbed methane as a fuel and a related industry has developed in the United States as a mainstream natural gas producer (Saulsberry et al., 1996; Ayers, 2002). This has also triggered interest in many of the European countries with coal resources, because the Carboniferous deposits in western Europe show many similarities to those producing from Variscan foredeep basin in the USA, such as the Black Warrior Basin in Alabama (Fails, 1996; Pashin, 1998). In Europe, particular interest has been raised in the production of CBM while simultaneously storing CO_2 in the coal seams. This could become a climate-friendly way of producing energy as discussed below. To evaluate the scope for exploration for CBM, an update of the coal resources in the Netherlands was made for the relatively shallow occurrences of the Carboniferous in the year 2000 (Fig. 15.15; Van Bergen et al., 2000). Deep coal seams were considered to be of limited economic significance.

Although coal seams in the subsurface generally contain large amounts of gas (mainly methane), there is at present no interest in producing coalbed methane as the Netherlands are shifting away from fossil fuel for its energy production. This is, however, a relatively new development, as methane has been considered as a ‘transition fuel’ in the 1990s-2000s, that could support a society with lower CO_2 emissions by replacing coal-fired by gas-fired power plants. Efforts were therefore undertaken to investigate the potential of CBM production in the Netherlands. Following the success in coalbed-methane production in the United States, the Peer well was drilled in 1992 in the Campine Basin in northeastern Belgium, close to South Limburg. This remains the only well close to the Netherlands that was drilled and tested for coalbed methane production. Only a limited amount of CH_4 was produced because the inflow of water in the well was too high to reduce the pressure sufficiently to allow substantial gas desorption. Wenselaers et al. (1996) concluded that these unfavourable hydrological conditions were due to the proximity of the well to a major open fault (the

'Donderslagbreuk'). According to Wenselaers et al. (1996) perspectives for coalbed methane production could exist in the Campine Basin, with more than enough coal and gas present, despite the low productivity observed. Nevertheless, no further CBM wells have been drilled until present.

The investigations into the potential for CBM production in the Netherlands did trigger major research efforts to understand the presence of this fuel in the context of the geology and reservoir conditions. Fails (1996) established that the depositional setting and coal distribution of the Eastern Ruhr Basin are favourable for CBM. As the coal basins in the Netherlands resemble the Eastern Ruhr Basin in the sense that the coal-bearing deposits are of the same age and the basins are located on a similar position with respect to the Variscan front, it could be assumed that their depositional setting and coal distribution were suitable for CBM production. However, the tectonic history and structural setting in the Netherlands is in general more complex than CBM producing basins in the United States and this affects the production potential. The basins are heavily faulted and locally also folding occurs, especially near the Variscan front (e.g. in South Limburg). Still, tectonic fault blocks of substantial size with continuous coal seams are present. During the geological history of parts of the Netherlands, in South Limburg, coal seams have been buried deeper than their present depth. The Carboniferous coal in the Netherlands is bituminous or anthracitic, indicating that large volumes of thermogenic gas have been generated during coalification. Contributions from secondary biogenic gas generation have so-far not been reported and seem unlikely due to the depth of the coal. In coal at around 1000 m below surface, permeability of 0.1 to 1 (maximal about 5) m is to be expected in the Netherlands which is on the low end of the permeability range (0.5 and 100 m) established for the most highly productive wells (Scott, 2002). Permeability in coal beds is determined by its fracture (cleat) system, which is in turn largely controlled by the tectonic/structural regime (Fig. 15.13; Scott, 2002) and is strongly dependent on present-day in situ stress orientation. The permeability in the aforementioned Peer well was less than 1 m in Langsettian and Duckmantianseams at depths between 850 and 1250 m, i.e. about 450 m above their maximum paleo-burial depth (Wenselaers et al., 1996). In view of the lack of coal-mining activities in the Netherlands since 1974 and of coal exploration since 1985, the gas content can only be estimated by indirect methods. Stuffken (1957) investigated the methane content of coals in South Limburg on the basis of data from mine ventilation air and found a U-shaped relation between rank and gas content, with a maximum at about 25 wt% V.M. However, it is difficult to convert these data from ventilation air into gas content per in situ coal volume. The majority of the gas is not in the pore system of the coal, as is for example the case in sandstones, but is adsorbed onto the coal surface. Resource estimates for CBM are therefore in general based on the sorption capacity of coal. The multiple parametres that influence this are generally interpreted to depend on pressure, temperature and coal characteristics (e.g. Kim, 1977; Yang & Saunders, 1985; Levy et al., 1997; Bustin & Clarkson, 1998). Coal characteristics that affect sorption capacity are maceral composition, rank, ash content and moisture content (e.g. Ettinger et al., 1966). Opposing effects of pressure and temperature result in a maximum in gas-sorption capacity around a depth of 1500 m (Fig. 15.16).

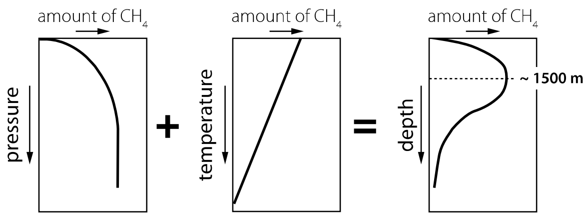

Figure 15.16. Effects of increasing pressure, temperature and depth on the amount of methane adsorbed on coal, assuming a normal geothermal gradient and hydrostatic pressure comparable to those in the Carboniferous of the Ruhr Basin in Germany (Freudenberg et al., 1996). This figure shows a linear decrease (after Kim, 1977; Levy et al., 1997; Bustin & Clarkson, 1998), but an exponential decrease is also reported (Yang & Saunders, 1985). Modified from Van Bergen et al. (2007).

Coppens (1967) showed that the sorption capacity of coal samples from the Belgian part of the Campine Basin varies, depending on rank, between 5 and 9 m^3/t. A small set of isotherms is available for the Netherlands from core samples that were taken from wells in the Achterhoek area (Krooss et al., 2002). Sorption capacities of the investigated dry coals were measured to be about 15 m^3/t, while the sorption capacities of moist coal were found to be lower (Krooss et al., 2002). No rank effect could be discerned on these samples, probably due to the small number of samples (Krooss et al., 2002).

The resources of coalbed methane have been inventoried in several studies based mainly on isotherm data and on relations between rank and gas content. However, the hydrological conditions should be considered in follow-up studies as hydrodynamics strongly affect CBM producibility (Scott, 2002; Van Bergen et al., 2007). An estimation by Wolf et al. (1997) indicated very high resources of 770 x 10^9 m^3 down to a depth of 2000 m and 1400 x 10^9 m^3 in deeper seams. However, the negative impact of increased temperatures below 2000 m was not taken into consideration in this evaluation, and the resources are therefore probably overestimated (Fig. 15.16).

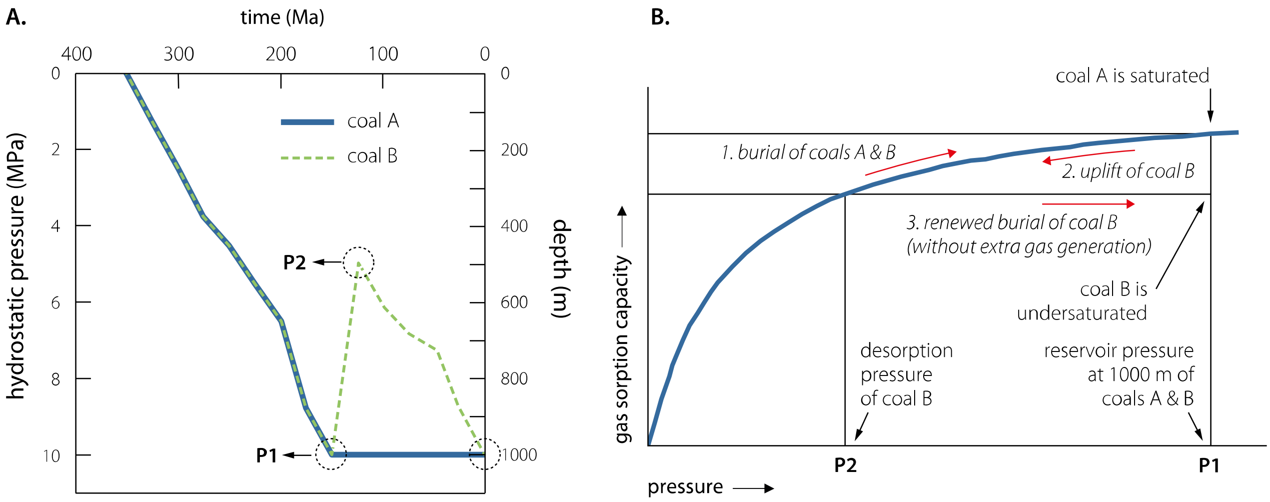

Figure 15.17. In tectonically active areas, coal seams were often buried deeper during geological history than at present. As a result of irreversible compaction during burial, present-day reservoir properties, such as porosity and permeability are affected by paleo-burial depth effects. Uplift can also possibly result in degassing of coal beds. This figure shows the effect of burial history on the amount of adsorbed methane. a) Coals A and B were buried to depths of 1000 m. While coal A remained at that depth, coal B experienced a phase of uplift, after which it was reburied to 1000 m. b) During the uplift, coal B released some of its adsorbed methane. Assuming no renewed gas charge, coal B will not adsorb more methane during reburial, and hence becomes undersaturated (adapted from McElhiney et al., 1993). Undersaturation of coal implies that it holds a lower gas content at a certain pressure and temperature than can be expected on the basis of its sorption capacity (Scott et al., 1994; Van Bergen et al., 2000; McCants et al., 2001). Modified from Van Bergen et al. (2007).

The technically recoverable quantity of such gas in the Netherlands was estimated to range from 5 to 27 x 10^9 m^3 (GAPS, 1994; NITG-TNO, 1999). Van Bergen et al. (2000) focused on the resources within Westphalian coal seams shallower than 1500 m, and calculated slightly higher total recoverable resources of 32 x 10^9 m^3 for the three evaluated areas (P50 value; Fig. 15.15b). In the latter inventory also the impact of tectonic uplift on the gas content of the coal, which is highly relevant depending on burial history of the coal seams was taken into account (Fig. 15.17).

Apart from the earlier mentioned interest in CBM as a transition fuel, efforts were undertaken in the beginning of the century to investigate the possibility of combining CBM production with CO_2 injection for storage in the underground coal seams. At that time this was considered to have potential to reduce CO_2 emissions while producing a relatively clean fossil fuel. Gas adsorption has proven stable through geological time, and the risk of future CO_2 release was considered low. Calculations of the amounts of CO_2 that could potentially be stored in coal seams shallower than 1500 m in the Netherlands ranged from 35 to almost 600 Mt (Van Bergen et al., 2000; Hamelinck et al., 2001), up to 3 or 4 times the total annual emission of CO_2 in the Netherlands at the time. Under the assumptions prevalent at that time, it was concluded that CO_2 sequestration in coal could be economically feasible in the Netherlands if the technology proved to be applicable and infrastructural, societal and environmental issues were fully addressed (Hamelinck et al., 2001). It was expected that incentives would be required to make this technology attractive for industry. Several demonstration sites were developed worldwide, e.g. in Canada, the United States, Poland, and Japan (Gunter et al., 1997, 1998; Erickson & Jensen, 2000; Schoeling & McGovern, 2000; Van Bergen et al., 2006) but it appeared both commercially and technically challenging to scale-up these demonstrations. Most of these sites have experienced permeability reduction in the coal seams, generally thought to be caused by swelling of the coal as the result of CO_2 injection as also observed in the laboratory. Understanding and managing the development of swelling with time was considered one of the most critical factors but appeared to be difficult (Van Bergen, 2009).

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Digital map data

Spatial data of figures in this chapter for use in geographical information systems can be downloaded here: https://doi.org/10.5117/aup.28164248.

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