

14

Petroleum geology

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ABSTRACT

A great variety of proven hydrocarbon plays and trap styles is present in the sedimentary succession in the subsurface of the Netherlands. This sedimentary succession started to develop in the middle Paleozoic and has been deformed by several periods of tectonic structuration.

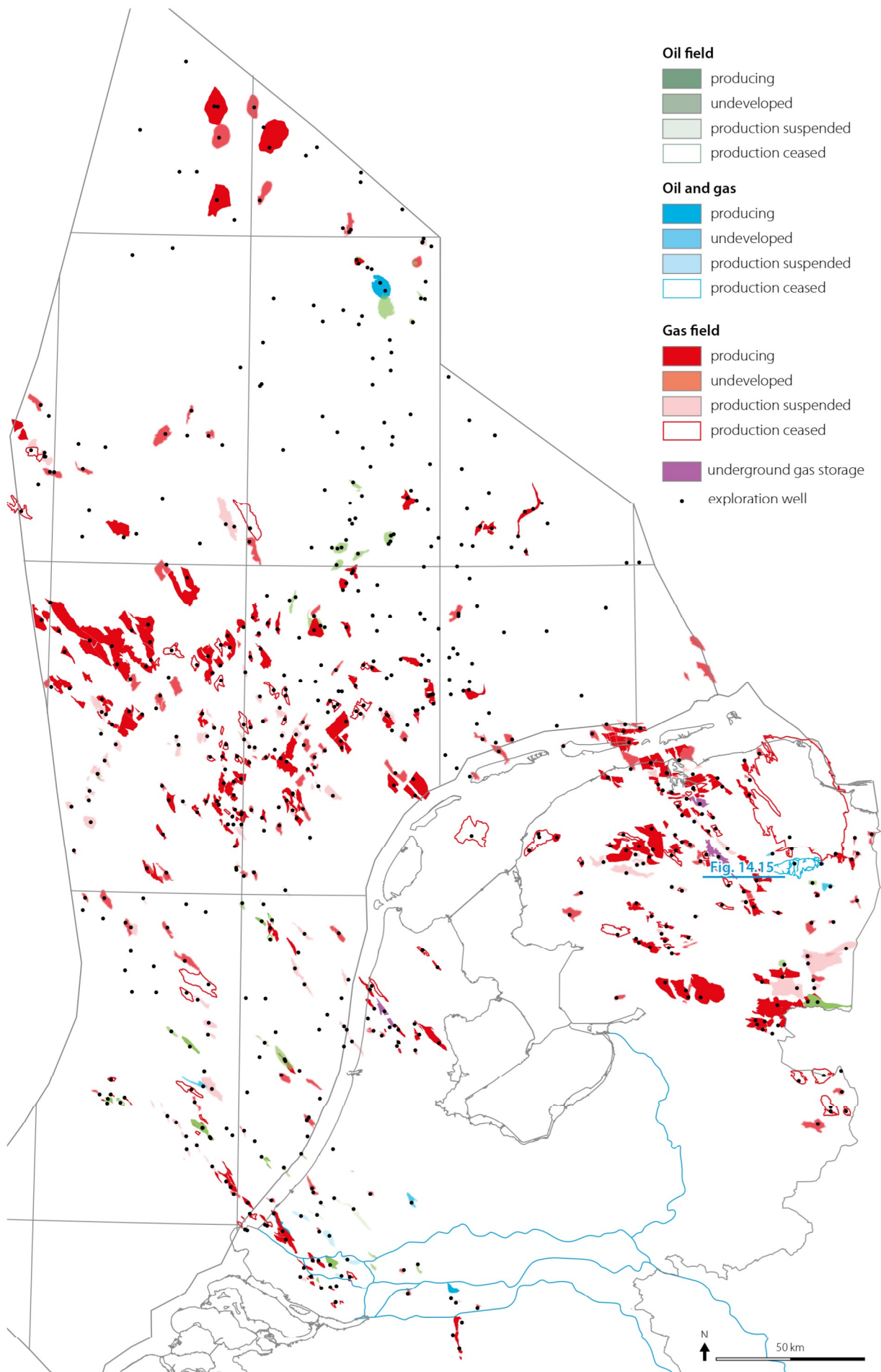
In much of the subsurface, the thick Permian Zechstein salt provides an effective seal between a prolific Paleozoic gas system and a mixed, oil and gas-prone Mesozoic hydrocarbon system.

The dominating Rotliegend play is formed by a near-ideal superposition of i) a thick upper Carboniferous (Westphalian) succession with abundant coal measures as the source rocks for gas, ii) well developed fluvial and eolian reservoir sandstones of the Permian Upper Rotliegend Group, and iii) the excellent seal of the Zechstein salt. The giant Groningen field is by far the largest representative of this play and represents two thirds of the total recoverable Dutch gas reserves, containing an initial recoverable gas volume of ca. $2800 \times 10^9 \text{ m}^3$. Production of the Groningen gas was very profitable for decades, but eventually the impact of production induced seismicity resulted in a premature cessation of production.

Triassic plays are second in importance with respect to proven gas accumulations. Relatively minor gas reserves occur in Permian Zechstein carbonates, Upper Jurassic and Lower Cretaceous sandstones, Upper Cretaceous chalk as well as in shallow, unconsolidated sands of Cenozoic age.

Producible oil occurs within Upper Jurassic and Lower Cretaceous rift-basin sediments in a variety of sandstone reservoirs and trap styles. Minor amounts of oil have also been produced from the Upper Cretaceous chalk and the Triassic sandstones. The exploration of the Dutch hydrocarbon plays is in a mature stage and many of the current gas fields will be depleted in the next decade. The urge for energy transition is growing and moreover diminishing public acceptance is restricting exploration and production activities. Consequently, exploration and production are concentrating on the offshore area. The role of fossil fuels in the energy system will decrease significantly in the coming decades and is expected to cease (almost) completely in 2050.

<< G14-B production platform (now Eni Energy Netherlands B.V.), producing gas from the Triassic Volpriehausen Formation in the Dutch northeastern offshore. Photo: Neptune Energy.



Introduction

In terms of natural resources, The Netherlands is a natural gas country and the history of Dutch natural gas is dominated by the giant Groningen field in the northeast of the country (Fig. 14.1). The Netherlands has produced over $3500 \times 10^9 \text{ m}^3$ of natural gas since the first gas field came on stream in 1951. Approximately $2100 \times 10^9 \text{ m}^3$ (60%) of that volume came from the Groningen field.

Since the discovery of the Groningen field in 1959, the Netherlands has developed into the main gas 'hub' of Western Europe. At the time all exploration activities were focussed on finding oil as the domestic gas market was deemed to be saturated with so-called 'town gas'. In fact, before the 1960s, encountering gas was considered an exploration risk. Once the size of Groningen was recognized, the European energy supply changed fundamentally with natural gas dominating the Dutch energy market as well as much of the European market. The discovery of the Groningen field close to a large potential market served as a magnet for the oil & gas industry to explore the rest of the onshore and later also the North Sea (Van de Graaff, 2001).

For 60 years the Groningen field outnumbered other gas fields in terms of reserves- and production. These other fields were therefore called 'small fields' as they were at least 40 to even 1000 times smaller than the Groningen field. Groningen originally contained almost $2800 \times 10^9 \text{ m}^3$ producible gas. The second largest gas field (Annerveen – which adjoins the Groningen field) contains just over $70 \times 10^9 \text{ m}^3$ of gas (2.5% of the Groningen field). Most of the small fields initially contained in between 1 to $10 \times 10^9 \text{ m}^3$ of gas. In total 499 gas discoveries have been made of which 386 were developed as fields and for another 26 development is pending (Ministry of Economic Affairs and Climate Policy (MEACP, 2022)). Using the Groningen field as a swing producer to accommodate seasonal variations in demand enabled all the other fields to optimize their production and economics. This so-called 'small fields policy' (*kleineveldenbeleid*) strongly contributed to the success of the development of the oil and gas resources in the country. Most gas is contained in upper Permian sandstones of the Upper Rotliegend Group (Bouroullec & Geel, 2025, this volume). Other hydrocarbon plays, ranging from Carboniferous to Quaternary in age, are present as well (Fig. 14.2).

Since the late 1980s, however, gas production has induced over 1500 earth tremors with magnitude >1 (larger than 1 Richter) in the Groningen field (Dost et al., 2025,

this volume) and eventually these earth tremors resulted in serious damage to many houses and buildings and, more importantly, in a severe feeling of insecurity amongst the people living above the gas field. The 2012 Huizinge earthquake with a magnitude of 3.6 on the Richter scale ($M_L = 3.6$) was the largest one ever registered and was recognized as the tipping point. The government committed to an early closure of the gas field in 2023/2024 to end the seismic threat. Consequently, approximately $500 \times 10^9 \text{ m}^3$ of technically recoverable gas will be left stranded. Depletion of the remaining gas resources from the small fields is expected to last at least for another two decades. Natural gas is considered the preferred fossil energy source in the transition towards a sustainable energy system thanks to its relatively low carbon footprint compared to the other fossil fuel types.

The Netherlands has a modest share of oil as well. The Schoonebeek oil field is the largest onshore oil field of western Europe. Other oil fields occur onshore in the western Netherlands and in the Dutch offshore (Fig. 14.1). Up to 2022, 52 oil discoveries were reported (MEACP, 2022). Of these, 23 oil fields have been developed, of which 10 are still producing. Another four may come on stream within five years. Development of the other discoveries is presently not economically viable. Remaining reserves and contingent resources (according to the SPE Petroleum Resource Management System (www.spe.org/en/industry/reserves)) add up to a modest 34.8 million m^3 of oil.

Throughout this paper reference is made to structural units that are shown in Figure 14.3. Locations of individual fields and wells mentioned in the text can best be located on the maps of www.nlog.nl. This website shows a complete and updated overview of these data.

Data

As a result of exploration and development activities, a wealth of subsurface data is available. Currently, a total of ca. 64,000 km^2 (ca. 65%) of the total Dutch on- and offshore surface territory is covered with high-quality 3D seismic data (Fig. 14.4). Significant parts of the remaining 35% are covered by 2D surveys (www.nlog.nl). This makes the Netherlands rank amongst the countries that have the seismically best imaged subsurface geology in the world (Dessens, 1996). The seismic data set allows a good appreciation of the vast variety of geological settings and

← **Figure 14.1.** Gas and oil fields identified by status as well as underground gas storage locations and exploration wells. Total reserves are dominated by the giant Groningen gas field in the northeast onshore. (Gas and oil fields from www.nlog.nl, retrieved on 13.12.2022).

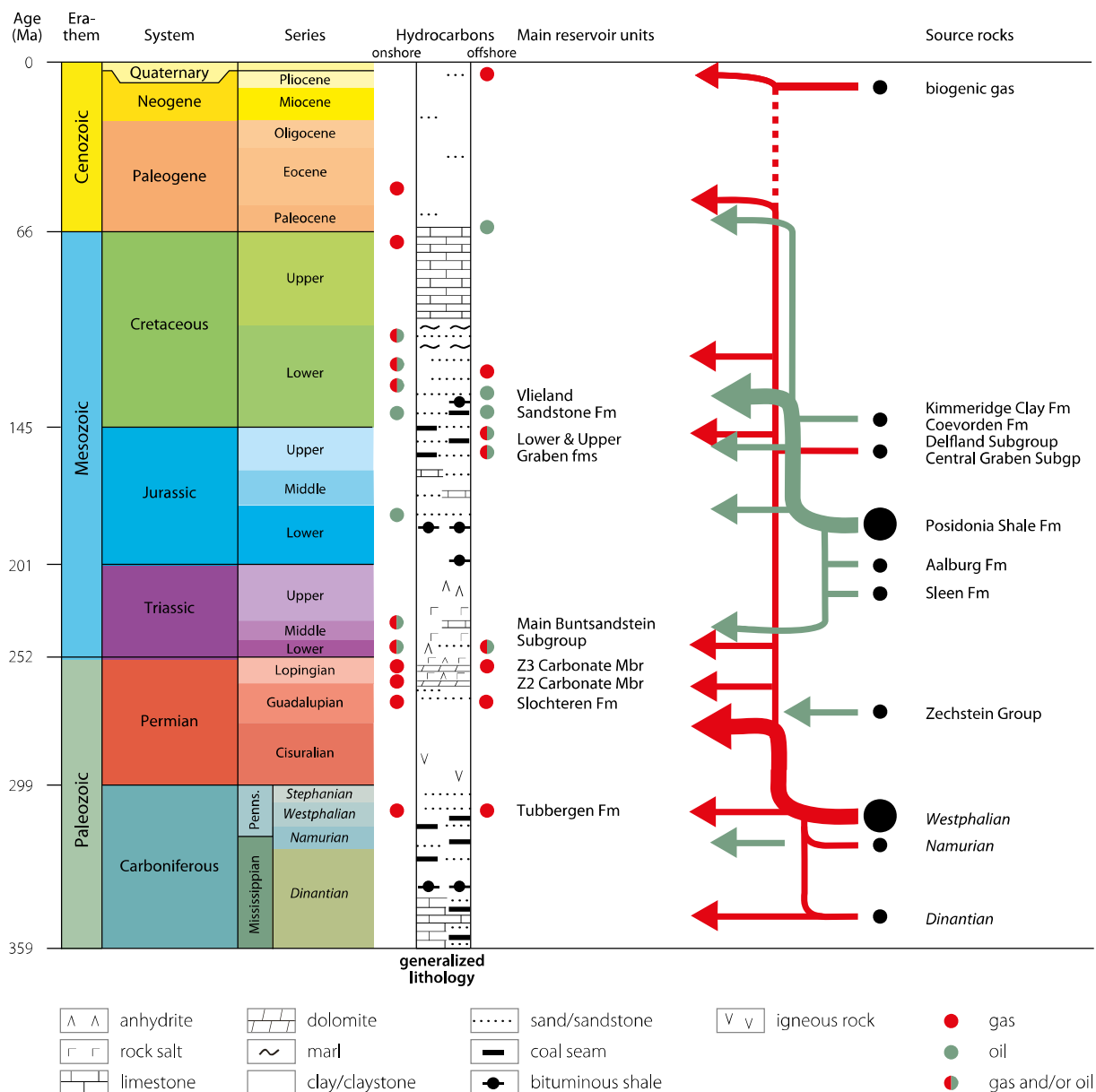


Figure 14.2. Hydrocarbon systems in the Dutch subsurface. Arrows show from which source rocks the main reservoirs have been charged with gas and/or oil. The Upper Permian Zechstein salt, present in much of the subsurface, provides a regional seal between a Paleozoic gas and a Mesozoic oil and gas system. Not acknowledged here is that with time probably >95% of the generated hydrocarbons escaped into the biosphere (see Textbox). Modified from De Jager and Geluk (2007).

structural styles in the Dutch subsurface. On January 1st, 2022, the oil and gas exploration & production (E&P) industry had drilled a total of 1417 exploration wells (Fig. 14.5), 498 appraisal wells and 2382 production wells (MEACP, 2022). All seismic data, well-log measurements and rock samples (including core analysis) are made publicly accessible after a five-year confidentiality period. Much of the data is freely downloadable at www.nlog.nl. The quest for geothermal energy, the plans for underground storage of carbon-dioxide as well as the foreseen need for subsurface storage of hydrogen and compressed air, they all benefit substantially from these data.

Exploration and production activities over the years

A brief summary of the history of oil and gas exploration in the Netherlands follows below. Reference is made to the more extensive overviews published by Knaap & Coenen (1987), Breunese & Rispen (1996), Glennie (2001), Breunese et al., (2010), Kombrink et al. (2012) and Doornenbal et al. (2019). An annual update on E&P activities is published by the Ministry of Economic Affairs and Climate Policy, under the title 'Natural resources and geothermal energy in the Netherlands' (available from www.nlog.nl/en/annual-reports).

The first Dutch oil was found in 1923, near Corle, close to the German border, where 1.5 barrels of oil (240 l) were recovered from Zechstein anhydrites and Carboniferous sandstones (Fig. 14.5). A blowout in 1938 at Bad Bentheim in Germany, ca. 50 km NE of Corle, indicated the presence of gas at Zechstein level (Knaap & Coenen, 1987). The second indication for oil was found in 1938, during an exhibition in The Hague where the Bataafsche Petroleum Maatschappij, an operating company of Shell, drilled a demonstration well. At a depth of 460 m, the drillers unexpectedly encountered oil stains. The first commercial oil discovery dates from 1943 in the Lower Cretaceous sandstones of the Schoonebeek field in the southeast of the province of Drenthe at a depth of ca. 800 m. With an initial in-place volume of ca. 1 billion barrels ($160 \times 10^6 \text{ m}^3$), this is the largest onshore oil field in Western Europe. The Schoonebeek field was closed-in in 1996 as it became uneconomic after 25% of the viscous oil (25° API) had been produced. However, after a shut-in period of 15 years, production resumed in 2011 with the application of

steam solution (solution gas drive) so as to deliver another 10-15% (NAM, 2008).

After World War II, exploration resumed with further oil discoveries in the West Netherlands Basin (e.g. the Rijswijk, IJsselmonde, Wassenaar, Ridderkerk and Rotterdam fields) and gas discoveries in the east of the country (e.g. the Coevorden, De Wijk, Wanneperveen and Tubbergen fields). Until the end of the 1950s Zechstein carbonates and Lower Cretaceous sandstones were considered the most prospective hydrocarbon reservoirs.

The giant Groningen gas field, which would change the exploration outlook forever, was discovered in 1959 with the Slochteren-1 well. It has repeatedly been reported that the sheer size of this field was initially not recognized. The discovery well's target was a small structural closure at the level of the basal Zechstein carbonates in which gas had already been encountered in southeast Drenthe. Unexpectedly, the underlying sandstones of the Slochteren Formation (Upper Permian) at approximately 3 km depth turned out to contain gas as well. Only after several

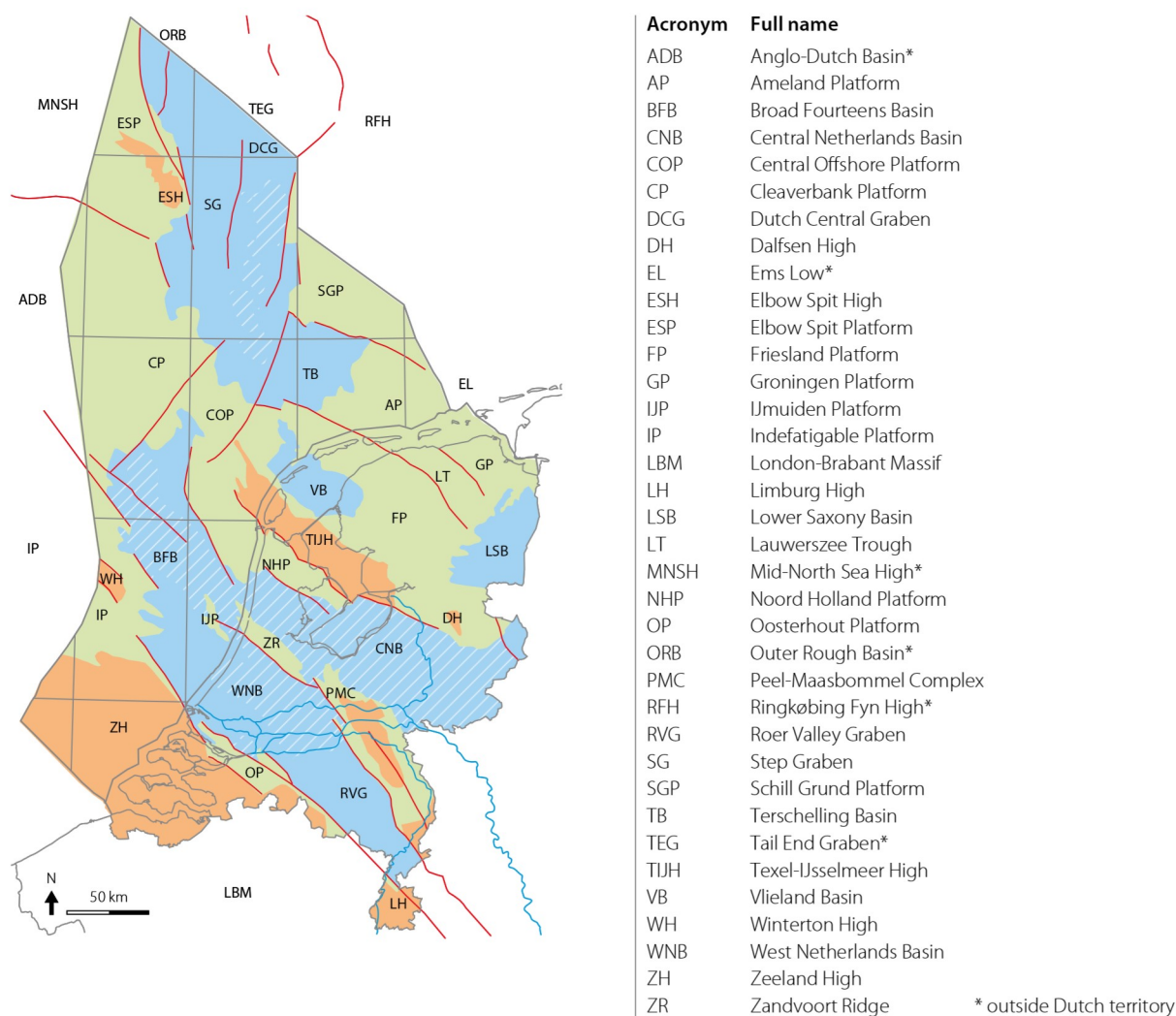


Figure 14.3. Main Mesozoic structural elements of the Dutch subsurface (after de Jager et al. 2025, this volume).

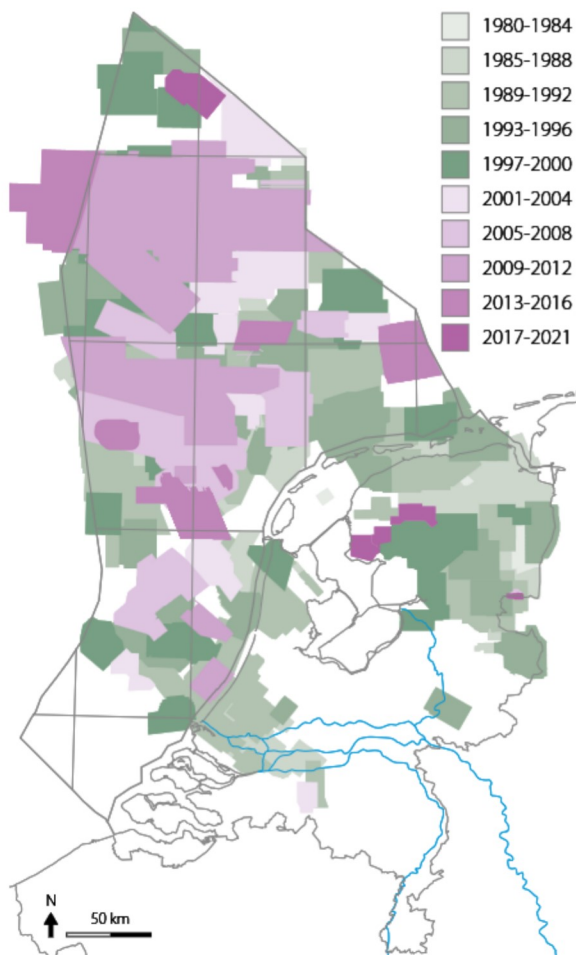


Figure 14.4. Coverage of 3D seismic surveys. In total ca. 64,000 km² of 3D seismic data has been acquired, covering ca. 65% of the Dutch on- and offshore areas.

wells were drilled it was realized that the small structure that was targeted, was in fact much larger with a length of more than 40 km and a width of almost 30 km. With initial recoverable reserves of ca. 2800×10^9 m³ of gas, the Groningen gas field is by far the largest of Europe and it contained two thirds of the total recoverable gas resources in the Netherlands. Following the discovery of the Groningen field, the first careful steps into the offshore were made in the early 1960s with the near-coastal well Kijkduin Zee-1. Legislation to regulate offshore exploration activities became effective in the mid-sixties, the first offshore gas discovery was in block P6 in 1968 and was followed in 1970 by the first oil discovery in block F18. Offshore gas production started in 1975 from the large L10 Rotliegend gas field and the first offshore oil was delivered in 1982 from the Cretaceous in block Q1. The introduction of 3D seismic in the 1980s very much improved the exploration efficiency. In 1987 the first gas in Cenozoic reservoirs was discovered (A18). However, it took another twenty years before reservoirs from this play came on

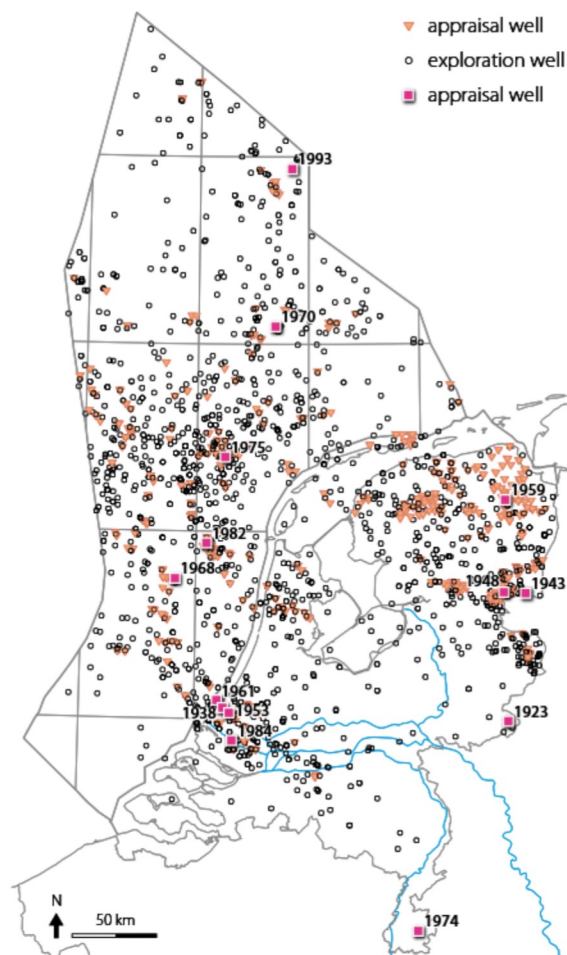
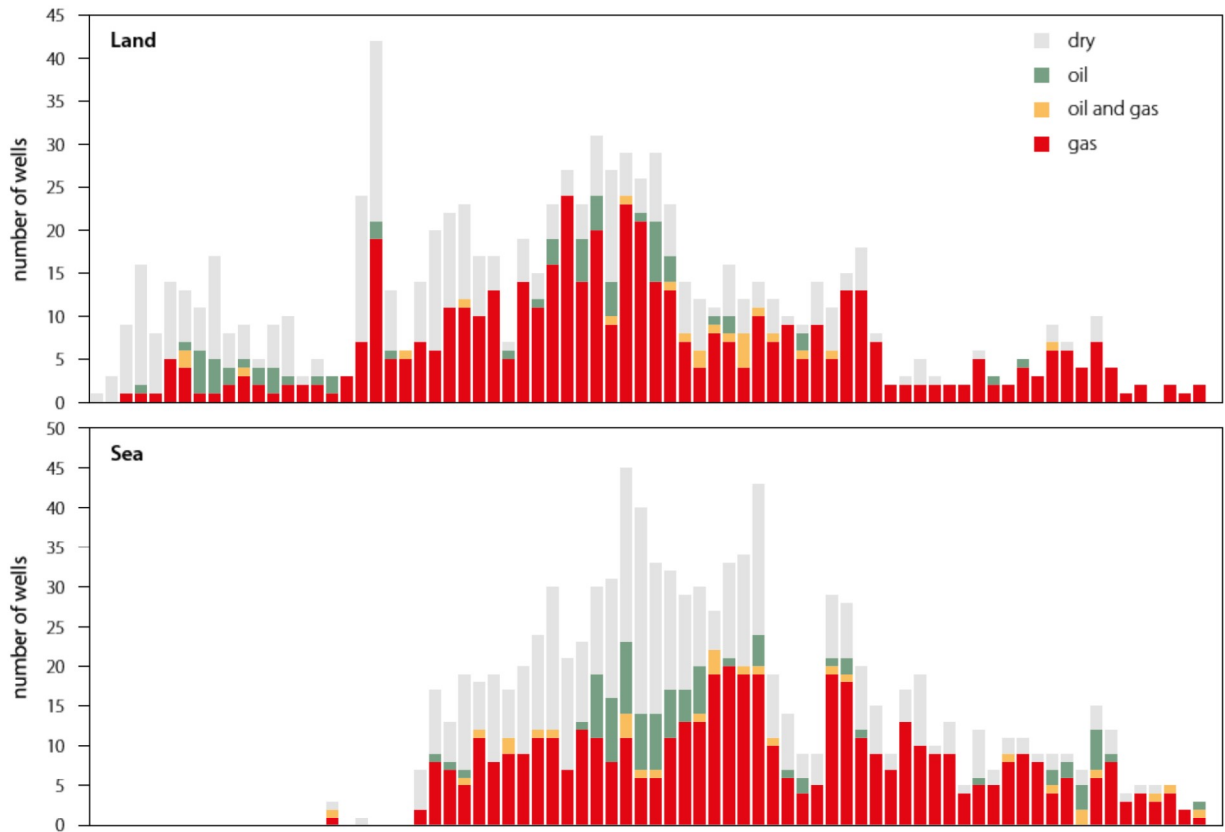


Figure 14.5. Hydrocarbon exploration and appraisal wells. A total of 1417 exploration wells and 498 appraisal wells had been drilled by the end of 2021. Also shown are the milestones in the Dutch exploration and production history (after PGK, 1993). 1923 = Corle oil show; 1938 = The Hague oil show; 1943 = Schoonebeek oil discovery (on stream in 1945); 1948 = Coevorden gas discovery (first production in 1951); 1953 = Rijswijk oil discovery (first production in 1954); 1959 = Slochteren gas discovery (Groningen field on stream in 1963); 1961 = first offshore well (Kijkduin Zee-1); 1968 = first offshore gas discovery (P6); 1970 = first offshore oil discovery (F18); 1974 = last coal mine in Zuid-Limburg closed; 1974 = first offshore gas production (L10); 1982 = first offshore oil production (Q1); 1984 = Botlek gas discovery in Rijswijk concession; 1987 = discovery of shallow gas in A18; 1993 = F3 oil field on stream; 2017 = discovery Basal Slochteren Clastics (Upper Rotliegend Group).

stream. Recently, recoverable gas was discovered in the Basal Slochteren Sandstones in the N blocks, which is an extension of the well-known Rotliegend play (Burgess et al., 2018). Although the first discovery (No5-01, 2017) appears very promising, the potential of this play remains uncertain.

A. Exploration and appraisal wells



B. Production wells

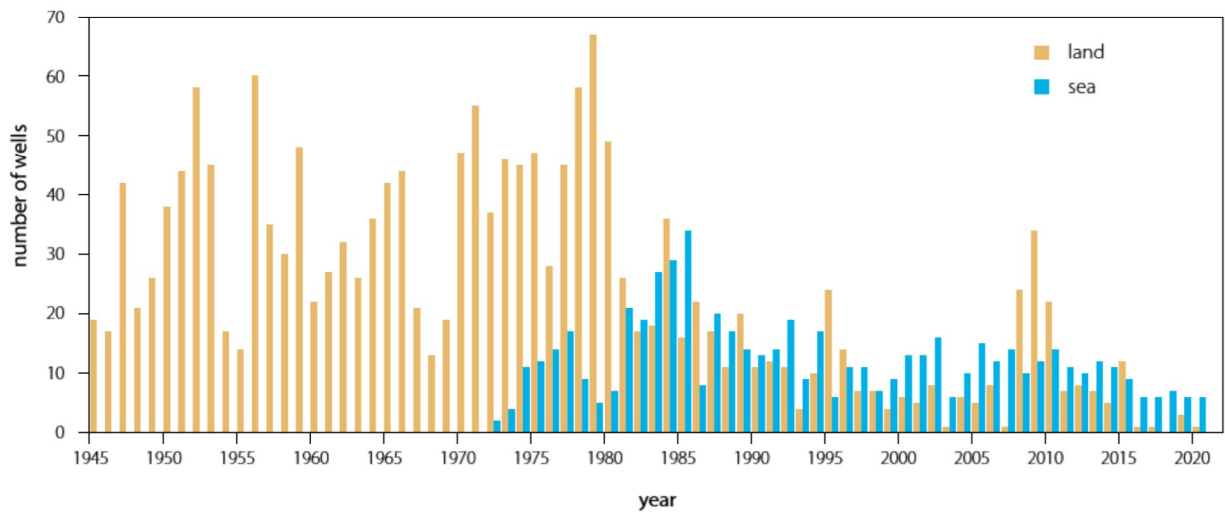


Figure 14.6. The onshore and offshore drilling sequence since 1946 reflects the exploration and on- and offshore appraisal history (a) and the overview of the consequent production wells (b). Source: MEACP (2022).

Drilling activity since 1946 reflects the E&P history as summarized above. Drilling started onshore with relatively low success ratios (Fig. 14.6a) with increased activity in the mid-sixties following the discovery of the Groningen field. By the end of the sixties offshore drilling commenced. Activities remained high during the 20th century with peak periods from 1975-1985 onshore and slightly later off-

shore (1985-1997). Since 2000, drilling activity has strongly declined, especially onshore. Most recent exploration can be categorized as near-field drilling, i.e. drilling either blocks adjacent to producing fields or prospects well within reach of existing infrastructure in order to lower the economic hurdle. This reflects the maturity of the Dutch petroleum province. Numerous production wells were

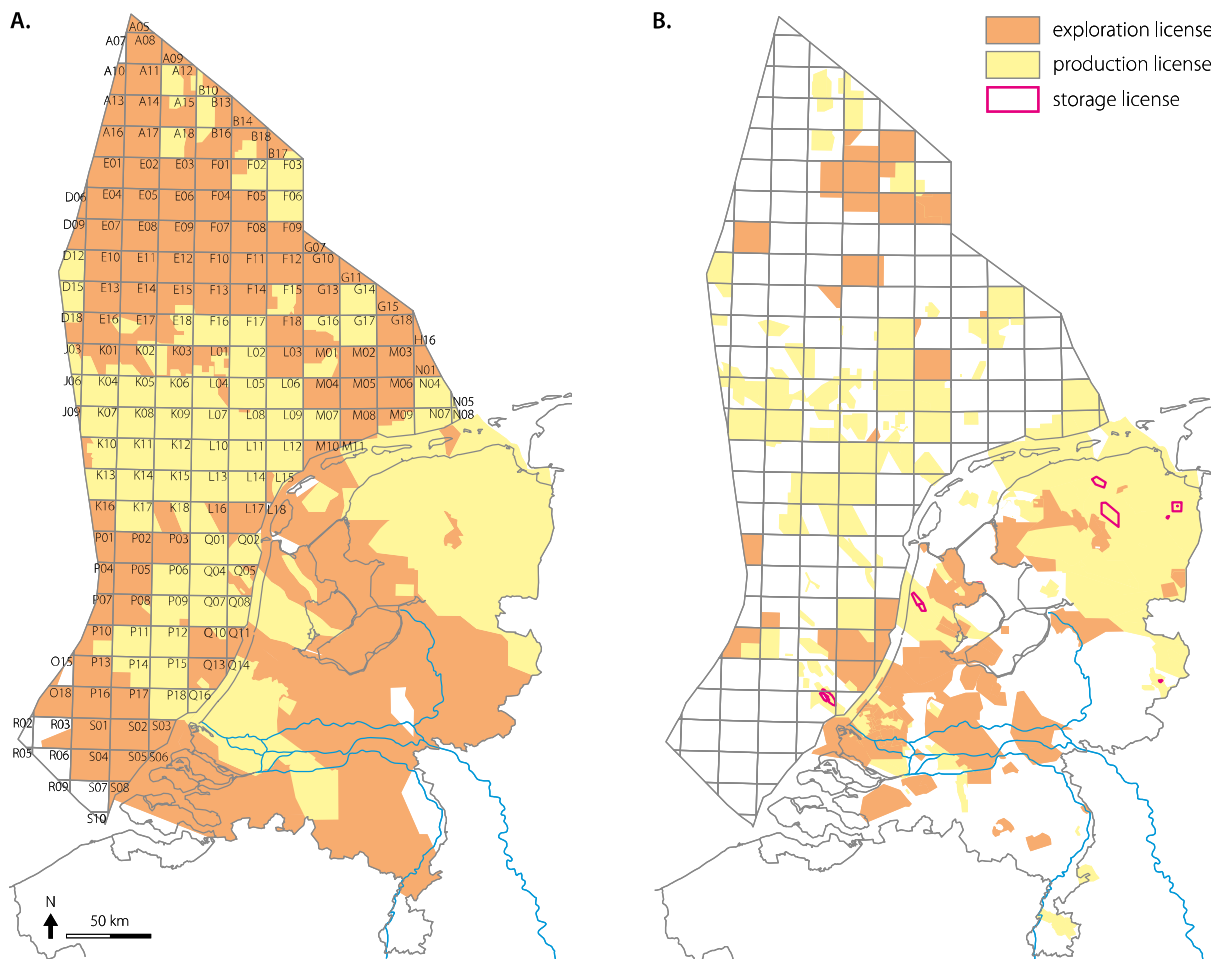


Figure 14.7. a) All license areas ever issued onshore and offshore the Netherlands. Total licensed area is 94,912 km². This equals 96.3% of the total Dutch onshore and offshore territory. b) License situation as of April 2023. Source: www.nlog.nl.

drilled up to the eighties to develop the large Groningen, Annerveen and Schoonebeek fields (Fig. 14.6b).

Since the beginning of the 21st century 111 gas discoveries have been made in the Netherlands, of which 30 are onshore and 81 offshore. Oil discoveries are restricted to 5 offshore and 1 onshore. Most of these gas discoveries have already been put on stream (77% offshore and 87% onshore). The Rotliegend play is dominant with 54% of all the gas discoveries since 2000. The Triassic play represents 34% and the remaining 12% are Carboniferous, Lower Cretaceous and Zechstein discoveries. Most discoveries are of modest size (less than 2×10^9 m³ recoverable gas). Of the oil finds, only one onshore and one offshore field is currently producing. Economically viable development of the other four offshore oil discoveries has not yet been proven.

Over the years, almost the entire Dutch onshore and offshore acreage has been covered by exploration and/or production licences (Fig 14.7a). Successful exploration licences have matured into production licences, while less successful licences were (partly) relinquished, as were pro-

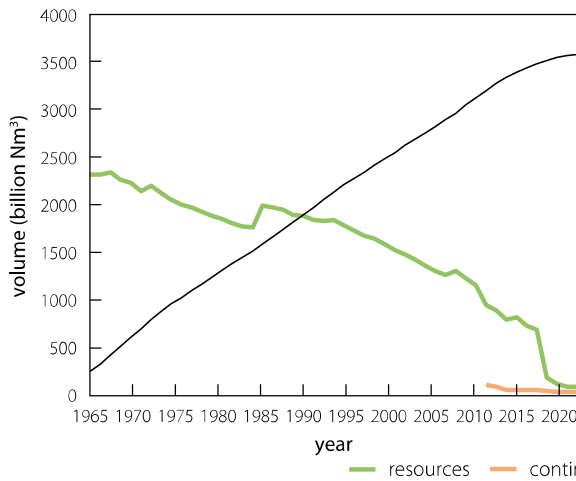
duction licences after depletion of the relevant oil and gas fields. This resulted in the current licence situation (April 2023, Fig. 14.7b).

Production

The Dutch cumulative gas production up to January 1st, 2022, amounted to 3.589×10^9 m³ of gas and 944 million barrels (150×10^6 m³) of oil. Remaining proven reserves are 150×10^9 m³ of gas and 69 million barrels (11×10^6 m³) of oil (Fig. 14.8). Production has come from 221 gas fields, with an annual production of some 19×10^9 m³. This is 44% of the present total Dutch gas consumption of ca. 43×10^9 m³ per year. The annual oil production of almost 5.6 million barrels (0.9×10^6 m³) from 10 fields is relatively modest.

In 2018, the Netherlands became a net gas importer (Van Geuns et al., 2017; MEACP, 2022) as the Dutch government decided to rapidly decrease production from the Groningen gas field with a planned complete cessation of production in 2024. Ever since the seventies the Groningen field was used as a swing producer to match the (sea-

A. Natural gas resources, 1965-2022



B. Oil resources, 1970-2022



Figure 14.8. a) Natural gas reserves and cumulative production from 1965-2022 in billion Nm^3 as of January 1, 2022 (MEACP, 2022). The strong reduction in natural gas reserves in 2018 with some $500 \times 10^9 \text{ m}^3$ results from the government's decision to cease gas production from the Groningen field – i.e. this reflects a 'de-booking' phenomenon rather than a failure in the production of gas. Contingent resources registered since 2013. b) Oil reserves and cumulative production (1970-2022) in million Sm^3 as of January 1, 2022 (MEACP, 2022). Contingent resources registered since 2013.

sonal) variation in gas demand by adjusting its production rate. Due to ongoing production and the corresponding pressure decline in the Groningen gas field, its capacity to act as a swing producer during extreme cold weather spells was decreasing. To provide additional swing production capacity, three underground gas storage facilities (Grijpskerk, Norg and Alkmaar) were therefore installed in 1996. More recently, this swing capacity was increased with implementation of the Bergermeer and the Zuidwending facilities. Storage in the latter is in several salt caverns rather than in originally gas-bearing sandstone or carbonate reservoir rocks (see Juez-Larré et al., 2025, this volume). Currently, with the cessation of the Groningen production, all swing production capacity is provided by these underground gas storage facilities. The remaining part of the gas demand will have to be covered by import of gas through international pipelines or by ship (LNG).

From a commercial perspective, two types of gas are distinguished in the Netherlands: gas with a low heating value ('low cal' gas or Groningen quality gas) and a nitrogen content of ca. 10-12% and gas with a high heating value ('high cal' gas) that contains little or no non-hydrocarbon components. There are separate pipeline systems for the two different gas types. The low-cal gas is predominantly distributed to Dutch households, buildings, and greenhouses, while high-cal gas is mainly for export and industrial use. An overview of the composition of the gases in the Netherlands is presented later in this chapter and in more detail in the Northwest European Gas Atlas (Lokhorst, 1997).

In 2021 the total hydrocarbon production provided the Dutch State with an income of a mere 32 million Euros (MEACP, 2022). In previous years, these revenues have been significantly higher. Between 2006 and 2014 annual revenues were on average around €11 billion, adding up to a grand total of €417 billion since 1965 (CBS, 2019). Gas revenues are expected to decrease significantly due to the decreasing production. However, extremely high gas prices in 2022 resulted in a much higher revenue.

Legislation

On January 1st, 2003, a new Mining Act (*Mijnbouwwet*) became effective, governing exploration and exploitation of oil and gas for both the onshore and offshore. Licences are mandatory for all exploration and production activities, as well as for the underground storage of hydrocarbons or other substances. The Mining Act also covers mining installations and pipelines. A production licence may be obtained once production is deemed economically viable. However, before production may start, ministerial consent to the mandatory production plan is required. Further details on implementing the Mining Act are elaborated in a separate decree (*Mijnbouwbesluit*) and regulation (*Mijnbouwregeling*).

The petroleum industry and society

In the densely populated and low-lying country of the Netherlands, there are increasing concerns that exploration and production activities may negatively influence

the environment, or the well-being or comfort of the people. The main concerns are about surface subsidence, earth tremors, operations in environmentally sensitive areas and any activities to do with shale gas.

Subsidence

The depletion of oil or gas fields may cause surface subsidence due to the compaction of reservoir rocks as the pressure in the reservoir declines. For most gas fields in the Netherlands this subsidence is well below 0.1 m. Above some of the larger and thicker reservoirs, subsidence may reach between 0.1 and 0.3 m, with an expected maximum subsidence of 0.46 m at the centre of the Groningen field (NAM, 2020; VEN B.V, 2020). Subsidence due to oil production is very minor as the reservoir pressure decrease is much lower as compared to gas fields.

Land surface subsidence affects surface water run-off and reduces the distance to the groundwater table. Especially in polders and other onshore areas in the north and west of the Netherlands that lie below sea-level, this may be a serious issue. Depending on the situation, if surface subsidence exceeds 0.05-0.1 m, mitigating measures may have to be taken by the local Waterboard (*Waterschap*). For built structures such as houses, subsidence caused by gas production is not expected to cause any structural damage as the vertical subsidence is small in relation to the horizontal extent (Van Staalduinen et al., 2019; Huijgen et al., 2020). The cause of structural damage often lies in the upper part of the subsurface, particularly in areas underlain by surface peat alternating with more solid rock types such as sandstones. Although the physics of surface subsidence is well understood, this does not necessarily re-assure the

Most gas escapes to the atmosphere

Combustible gas is unquestionably the main commodity obtained from the Dutch subsurface. It is estimated that over 95% of all gas discovered in the Netherlands was generated from Carboniferous (Westphalian) coals, with the remainder originating from other source rocks such as the Jurassic Posidonia Shale.

Based on thickness maps, the total volume of upper Carboniferous (Namurian and Westphalian) deposits in the Dutch on- and offshore is estimated to be 231,000 km³. This corresponds to an average thickness of 2.35 km. Average coal percentages per stage are estimated between 0.1 and 2.1% (in-house studies by Nederlandse Aardolie Maatschappij). These percentages can be considered conservative; other studies report higher estimates of up to 3.5% (e.g. Van Wijhe & Bless, 1974; Hedemann, 2001). However, those estimates are based on onshore observations from the coal mines along the southern basin margin. Studies of the depositional environment suggest lower average coal percentages for the present-day offshore area.

Based on a back-of-the-envelope calculation of rock, coal and combustible gas volumes for the upper Carboniferous, an estimate was made of the total volume of gas in the subsurface of the Netherlands that was generated over geological time. Using an average density of coal of 1.5 g/cm³ (i.e. low-volatile bituminous to anthracitic coal) and the rule-of-thumb that 1000 kg of this type of coal generated some 136 m³ of combustible gas (Rightmire et al., 1984), a volume of 300 x 10¹² m³ of generated combustible gas can be estimated. Less than 1.5% of this volume has been proven in discovered accumulations, so it is safe to assume that by far the bulk (>95%) of the gas ever generated has leaked away to the surface or may still be escaping through surface seeps.

Estimated rock, coal and combustible gas volumes for the upper Carboniferous in the Dutch on- and offshore (after Van Buggenum & Den Hartog Jager, 2007).

Stratigraphy	Rock volume (10 ³ km ³)	Coal % (av. est.)	Coal volume (km ³)	Coal weight (10 ¹² kg)	Combustible gas generated (10 ¹² m ³)
Asturian (WF-D)	3	0.1	3	5	1
Bolsovian (WF-C)	7	1.6	114	170	23
Duckmantian (WF-B)	23	2.1	477	715	97
Langsettian (WF-A)	82	1.0	820	1230	167
Namurian	116	0.1	116	174	24
Total	231		1530	2294	312

public. Reasons for this include the physical complexity of this process, combined with a lack of trust in the oil & gas industry and in many cases also a lack of trust in the government.

The subsidence caused by hydrocarbon production is monitored at regular intervals (2-5 years) and the environmental implications are carefully evaluated. Prior to the start of production, predictions of expected future subsidence are required for all onshore oil and gas fields as part of the mandatory production plans.

Induced earthquakes

Gas production will inevitably cause a drop of the pore pressure in the reservoir that it is being produced from. This pressure drop will in turn cause changes in the in-situ stress field in the subsurface. Such production induced changes in subsurface stresses can in some cases give rise to earthquakes and this is called induced seismicity. The induced earthquakes in the Netherlands seem to be correlated with faults within or at the boundaries of producing gas fields. A reactivation of existing zones of weakness is, as in the case of natural earthquakes, considered the most likely mechanism. Some small fields in the provinces of North-Holland, Drenthe, Friesland and Groningen have experienced earthquakes, but by far the most severe case in the Netherlands is undoubtedly the Groningen field where, since the late 1980s over 1500 events of $M_L > 1$ related to gas production have occurred. To date, the strongest registered earth tremor in the Groningen field was the Huizinge earthquake ($M_L = 3.6$) in 2012. It was this Huizinge event which fundamentally changed perception about the safety of gas production from the Groningen field. For the people living on top of the Groningen field who are directly affected by these induced earthquakes. It resulted in a severe feeling of discomfort, fear and insecurity. Consequently, public opposition against onshore gas production has strongly increased since the 2012 Huizinge event. Eventually, after years of protest and unsuccessful attempts by the operator and the Dutch government to mitigate this problem, it has led to the premature cessation of production of the Groningen gas field with approximately 500 billion Nm^3 of producible gas still in the reservoir.

Operations in sensitive areas

The Mining Act stipulates the permits and related procedures for exploration and production operations. Other acts also play a role in the permitting and execution of these operations: the *Wet Ruimtelijke Ordening* (Spatial Planning Act), *Wet Milieubeheer* (Environmental Act) and the *Natuurbeschermingswet* (Nature Protection Act) – recently replaced by the *Omgevingswet* (Environment and Planning Act). Permitting requirements vary according to the nature of the area involved. Onshore, the areas with

the highest level of protection include ecologically designated areas, ‘silence preservation areas’, soil-conservation areas, birdland habitat-directive areas and nature-protection areas. Offshore, restrictions apply in ecologically designated areas, shipping lanes and military exercise areas. Moreover, for all new onshore drilling or production locations a building permit issued by the local municipality is required. For activities in sensitive areas a location permit from the Ministry of Economic Affairs, coupled to an environmental impact assessment (in Dutch: MER, *Milieu Effect Rapportage*) must be obtained. Other permits may be required for nature-protection and environmental issues. For all exploration wells an environmental permit from the Ministry of Economic Affairs is needed and production may only commence (or proceed in the case of fields already developed) after the Ministry’s consent to the submitted production plan (comparable to a summary field development plan). Together with the application for a production permit, the operator must also submit a comprehensive field development plan. During all permitting procedures there is an option to file comments and objections. For activities in or near sensitive areas it may take several years before all permits are secured.

The exploration and production of gas from below the Wadden Sea (UNESCO World Heritage Site since 2009) has met with strong objections and received considerable media attention. In 1984 exploration in the Wadden Sea was put on hold and only after extensive studies concerning the environmental impact, Parliament endorsed exploration and production in 2004 under strict conditions. The main concern was that surface subsidence due to gas production might result in the drowning of the tidal flats with their unique ecological system. To prevent the possible damage to the tidal flats, gas production is constrained by a maximum rate of subsidence which may be compensated by the natural sedimentation rate of the Wadden Sea system. If the observed subsidence rate is too high, gas production will be reduced to stay within the agreed limit.

Shale gas

Spurred by the commercial success of shale gas in the United States, several licence applications for shale gas exploration were submitted in 2008 to the Ministry of Economic Affairs. These plans to explore for shale gas quickly gave rise to significant public opposition, most of which was related to the use of hydraulic fracking that is needed to produce gas at economic rates from low permeability rocks. Fracking requires large quantities of frack fluids to be injected under high pressure into the target layer. Environmental concerns centred around the composition of the chemical additives to the frack fluid, and the risks these might pose to people and the environment in the event of accidental spills. Also concerns were about the

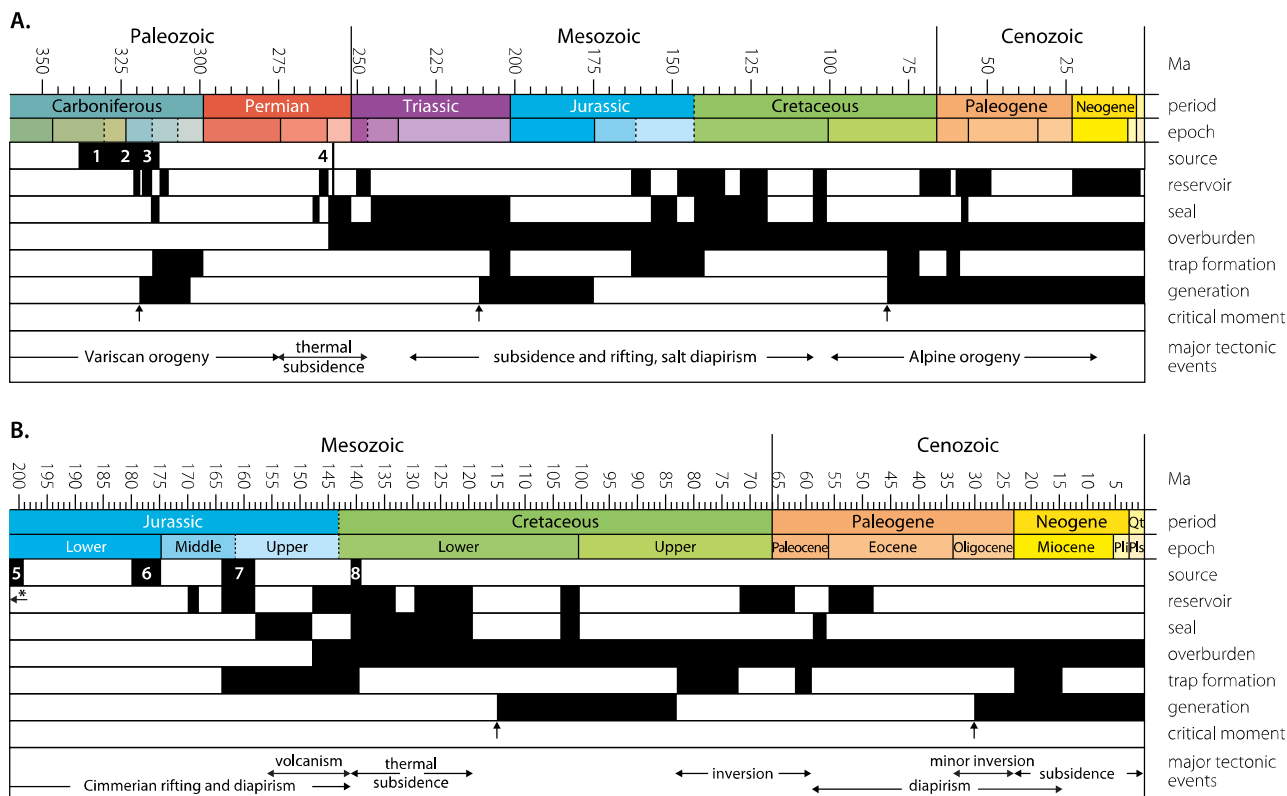


Figure 14.9. Petroleum system element chart (PSE) for (a) Paleozoic source rocks and (b) Mesozoic source rocks. For both petroleum systems the graphs show the timing of deposition of the main elements (source, reservoir, seal) as well as trap formation, generation and related critical moment related to the main tectonic events. The Paleozoic systems consist of 1) lower Carboniferous coals (Elleboog and Yoredale formations), 2) Namurian shales (Geverik Member and Epen Formation), 3) Westphalian coals (Baarlo, Ruurlo, Klaverbank and Maurits formations), 4) Zechstein Carbonates (Z1 Coppershale and Z2 Carbonate members). The Mesozoic systems consist of 5) The Sleen and lowermost Altena formations, 6) Posidonia Shale Formation, 7) Middle to Upper Jurassic coals (Middle and Upper Graben formations and Rifgronden Member), 8) Lower Cretaceous marine shales (Lutine Formation, northern offshore) and Lower Cretaceous lacustrine shales (Coevorden Formation, eastern onshore). Cross-fault migration into Triassic reservoirs indicated with *.

risk of induced earth tremors and potential risks to public health from the emissions associated with shale gas extraction. In addition, the spatial implications of the necessary dense spacing of drilling pads and consequent activities (traffic, drilling, and fracking operations) were a concern. After an extensive period of public consultations, debates, and an environmental impact assessment (MEA, 2015), in 2015 the ministry decided to put a moratorium on shale-gas exploration (De Boer, 2015; Kamp, 2015) which became irrevocable in 2018 (Kamerstukken 32849 en 33529 nr. 126).

Hydrocarbon source rocks

Hydrocarbon source rocks are sedimentary rocks that contain high percentages of organic matter (generally >2 wt% C_{org} , Tissot & Welte, 2013). This organic matter is termed kerogen and is derived from plants and other biomass

(bacteria, archaea, animals). Source rocks can be classified depending on the origin of the kerogen and the related type of hydrocarbon that may be generated by it. Type I kerogen is mostly derived from algal biomass, deposited under oxygen-deficient freshwater conditions, such as in lake deposits. It is characterized by a high initial hydrogen/carbon ratio with a low oxygen/carbon ratio and produces mostly oil during maturation. Type II kerogens were mostly deposited under marine dys- to anoxic conditions and are often derived from algal or plankton biomass. They are characterized by intermediate H/C and low O/C ratios and generate mostly oil but also gas at higher maturities. Type III kerogen is derived from terrestrial plant matter such as coal and is characterized by high O/C ratios and lower H/C ratios. Type III kerogen has only very limited oil generation potential, but high natural gas generation potential (e.g. Killips & Killips, 2005).

In the Dutch subsurface gas plays are volumetrically and economically much more important than oil plays. With

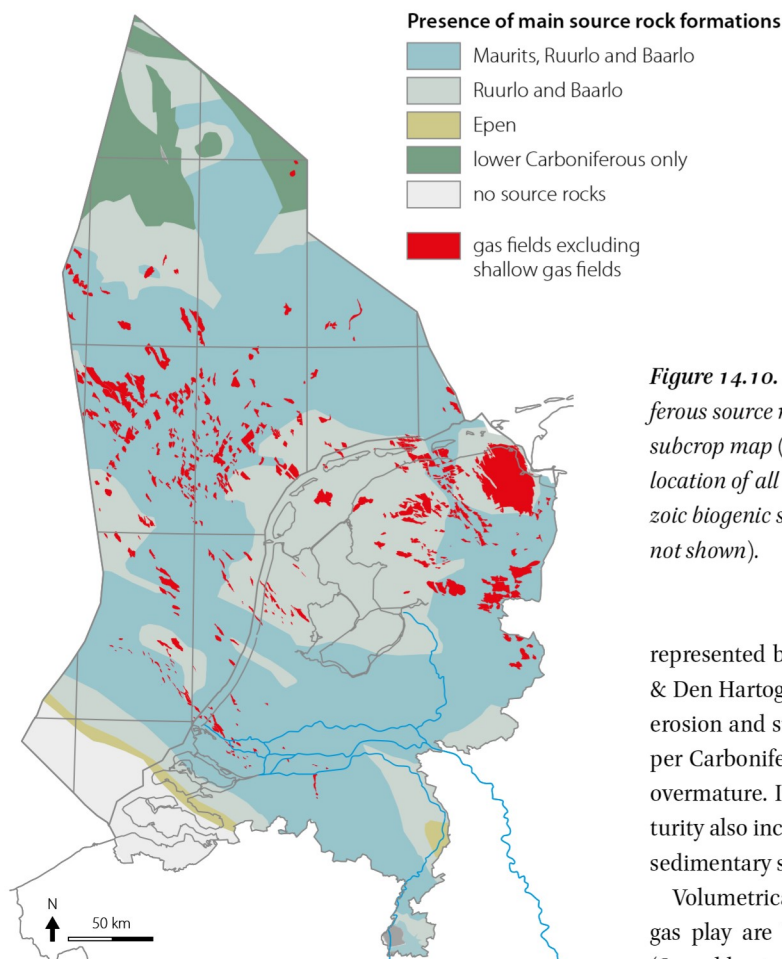


Figure 14.10. Present-day distribution of the main Carboniferous source rock intervals based on the Base Permian subcrop map (Bouroullec & Geel, 2025, this volume). The location of all thermogenic gas fields is shown in red (Cenozoic biogenic shallow gas fields in the northern offshore are not shown).

respect to the age of the source rocks, reservoirs and seals of these gas plays, the dominant hydrocarbon system is of Paleozoic age (Fig. 14.9a). Where the thick Permian Zechstein salt is present, it provides an effective seal between this system and the overlying oil plays which belong almost entirely to the Mesozoic hydrocarbon systems (Fig. 14.9b). The Cenozoic shallow gas plays are thought to be predominantly of biogenic origin with only minor contributions from thermogenic gas.

Gas: source rocks and generation

The principal source rocks for gas are the upper Carboniferous (Westphalian) coals and carbonaceous shales that underlie most of the Dutch territory (Fig. 14.10; Lokhorst, 1997; Gerling et al., 1999; Breunese et al., 2010; Doornenbal et al., 2019). The depositional thickness of the upper Carboniferous ranges from more than 5.5 km in the south to less than 2 km in the northern offshore. The cumulative thickness of the upper Carboniferous coals is estimated to be several tens of metres. Carboniferous peats accumulated from the late Namurian (Yeadonian) to the late Westphalian (early Asturian). Most coal-forming peats accumulated during the Westphalian B (late Duckmantian) and early Westphalian C (early Bolsovian) and are

represented by the Maurits Formation (see Huis in 't Veld & Den Hartog Jager, 2025, this volume). Due to differential erosion and structural complexity, the maturity of the upper Carboniferous coals varies spatially from immature to overmature. In areas with thick preserved sequences, maturity also increases significantly from top to bottom of the sedimentary sequence.

Volumetrically minor contributions to the Paleozoic gas play are believed to originate from basal Namurian (Serpukhovian, Epen Formation) organic-rich shales (Lokhorst, 1997; NITG, 1998; Gerling et al., 1999) and coals of the Elleboog and Yoredale formations (late Viséan; e.g. Ter Borgh et al., 2018). In most places these Dinantian and Namurian source rocks became overmature during deep burial prior to the main Mesozoic uplift and erosion phases. However, in the northernmost part of the offshore territory and along the London-Brabant Massif in the south, these Namurian source rock intervals are presently in the gas generation window and could be viable source rocks in areas where Westphalian coals are absent or immature (Fig. 14.10).

Gas-prone source rocks also occur in several Mesozoic intervals, mostly as coals in the Upper Jurassic and Lower Cretaceous Delfland Subgroup in the West Netherlands and Broad Fourteens basins, and in the Central Graben Subgroup of the Dutch Central Graben and Terschelling Basin.

Gas generation in the main depocentres started during the late Carboniferous and was widespread until the Middle Jurassic. At that time source rocks of the lower Carboniferous and at the base of the Westphalian already reached over-maturity in the West Netherlands and Broad Fourteens basins and in the Dutch Central Graben. After the Middle Jurassic, a distinction must be made between rift basins and adjoining platforms and highs (Fig. 14.3).

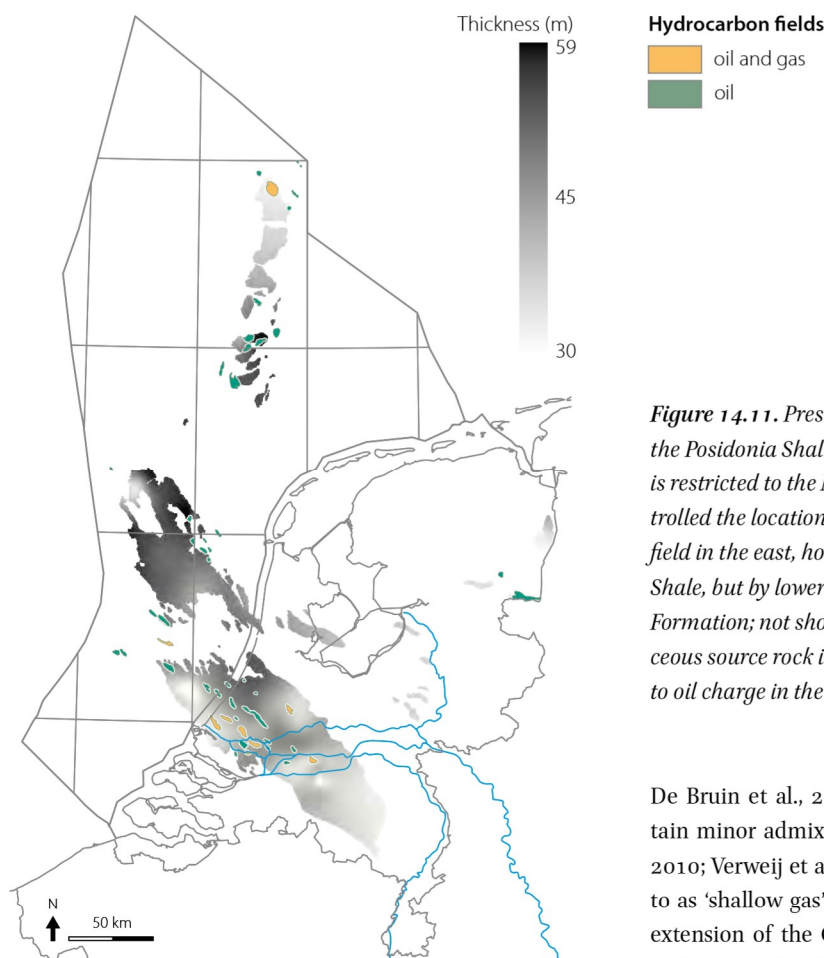


Figure 14.11. Present-day distribution and thickness map of the Posidonia Shale Formation. The present-day distribution is restricted to the Mesozoic rift basins and has clearly controlled the location of the oil fields. The large Schoonebeek field in the east, however, was not sourced by the Posidonia Shale, but by lowermost Cretaceous source rocks (Coevorden Formation; not shown). Other Upper Jurassic to Lower Cretaceous source rock intervals are believed to have contributed to oil charge in the Dutch Central Graben area.

During the Late Jurassic to Early Cretaceous, increased subsidence within the rift basins resulted in accelerated hydrocarbon generation. Gas generation ceased during the Late Cretaceous due to inversion-related uplift and declining heat flow. In parts of these inverted rift basins, the subsequent burial was not strong enough to revive hydrocarbon generation, resulting in the so-called burial anomaly where no hydrocarbon generation occurred since the Late Cretaceous (Pluymaekers et al., 2012; Nelskamp et al., 2021). At the basin margins, for example on the southwest margin of the West Netherlands Basin where uplift due to inversion was limited and was followed by strong subsidence, gas charge from Westphalian coals resumed during the Cenozoic and continues until the present day (De Jager et al., 1996). The platforms and highs, on the other hand, were uplifted during the Late Jurassic rifting, interrupting hydrocarbon generation. Where subsequent re-burial caused temperatures at the Westphalian source-rock levels to exceed the maximum temperatures reached earlier, gas generation resumed.

Apart from the thermogenic gas plays described above, there are also gas accumulations at depths shallower than 1000 m that are mainly of microbial origin (biogenic gas,

De Bruin et al., 2022), although some of them may contain minor admixtures of thermogenic gas (Pletsch et al., 2010; Verweij et al., 2018). These occurrences are referred to as 'shallow gas' and are mostly located in the northern extension of the Central Graben area, typically occurring in deposits of the Neogene Eridanos Delta. Several of these shallow gas fields have recently been taken into production (Doornenbal et al., 2019). A detailed overview of the occurrences of 'shallow gas' in the Dutch offshore region was recently published by Ecclestone et al. (2021).

Oil: source rocks and generation

The Lower Jurassic Posidonia Shale Formation is the main oil-prone source rock in the Netherlands. This marine, Type-II source rock is only preserved in the Late Jurassic rift basins of the Netherlands and northern Germany. Time-equivalents also occur in Belgium, Luxemburg, and the French Paris Basin (Schistes Carton) as well as in northern England (Jet Rock of the Whitby Mudstone Formation, Lott et al., 2010; Song et al., 2015).

The Posidonia Shale Formation has a gross thickness of approximately 36 m with, locally, thicknesses of up to 46 m (Fig. 14.11). It has an average total organic carbon content (TOC) of 10%, which can locally reach up to 17%, with a Hydrogen Index (HI) of up to 700 mg HC/g TOC. It forms a very distinct interval throughout the subsurface of the Netherlands and is easily recognizable on seismic data and wire-line logs (Van Adrichem Boogaert & Kouwe, 1993). The Posidonia Shale Formation shows a strong cyclic signal and little lateral heterogeneity with respect to thickness. Correlation across basins can easily

be achieved using stable carbon isotope measurements on the organic material (Houben et al., 2021). Total organic carbon (TOC) content is generally higher in the lower half of the formation, as indicated by both laboratory measurements and calculated TOC logs. Geochemical proxies, biomarkers and palynological facies all point towards a sharp chemocline and anoxic to euxinic water-column conditions as the main driving factors for TOC enrichment. Locally increased subsidence in salt-rim synclines gave rise to a very high TOC contents. This overall homogeneous depositional character and laterally traceable TOC-trends suggest that the deposition occurred in an extensive marine basin that was susceptible to stratification and enhanced preservation of organic matter.

The present-day distribution (Fig. 14.11) as well as the maturity of the Posidonia Shale Formation are strongly influenced by uplift and erosion. On the Mesozoic platform areas, i.e. the uplifted shoulders of the main Jurassic rift basins, most of the Lower Jurassic sediments were eroded (Fig. 14.3; Trabucho Alexandre & Wong, 2025, this volume). In addition, Late Cretaceous basin inversion resulted in uplift along the axes of the basins. Consequently, the onshore and the southern offshore region basin fills show a so-called burial anomaly. This means that the past burial depths and related temperatures were higher than those observed at present (e.g. Pluymaekers et al., 2012; Nelskamp et al., 2021). In regions affected by this burial anomaly, little to no hydrocarbon generation can be expected since the uplift, making them higher exploration risk areas.

The large Schoonebeek oil field was not sourced from the Posidonia Shale, but from Lower Cretaceous lacustrine source rocks of the Coevorden Formation. In the Netherlands, these algal, Type-I source rocks only occur in the onshore Lower Saxony Basin (Binot et al., 1991; NITG, 2000; Amberg et al., 2022). As the name 'Lower Saxony' indicates, the main extent of this basin is in Germany where the source rocks belong to the Bückeberg Formation (or Wealden Shale, e.g. Froidl et al., 2021).

Source rocks with similar characteristics to the Posidonia Shale Formation occur in the Lower Jurassic Aalburg and uppermost Triassic Sleen Formations. However, the limited geochemical analyses suggest significantly lower oil generation potential compared to the Posidonia Shale (Houben et al., 2017). Due to their similar geochemical footprint the contribution of these source rocks is unknown. The bituminous Clay Deep Member of the Lower Cretaceous Lutite Formation in the northern part of the Dutch Central Graben also has oil-generating potential. However, the areal and stratigraphic extent of this member is much smaller than those of the time equivalent, very productive, hot shales in the British, Danish and Norwegian sectors of the North Sea (e.g. Petersen et al., 2017;

Verreussel et al., 2018, 2025, this volume). Middle Jurassic coals, with relatively high Hydrogen/Carbon ratios, may also have contributed to the oil fields in the Danish offshore (Petersen & Hertle, 2018). The equivalent formations in the Dutch Central Graben area are the Middle and Upper Graben formations which contain coaly intervals with similar organic geochemical properties (Doornenbal & Stevenson, 2010).

Other oil-prone source rocks occur in the Permian Copershale- and Z2 Carbonate members. Despite numerous oil shows in Zechstein reservoirs, these source rocks have given rise to minor oil accumulations only locally (e.g. Stadskanaal, Gieterveen and E13-01). This is not only because of their limited thickness, but also because any oil expelled from these source rocks and originally trapped in Zechstein or Rotliegend reservoirs, has been subsequently flushed out by the abundant gas charge from the Westphalian below. The presence of H₂S in Zechstein gas reservoirs as well as high condensate content in Rotliegend gas is linked to the hydrocarbons generated from these Zechstein source rocks.

Carboniferous oil-prone source rocks occur in the basal Namurian organic-rich shales of the Geverik Member which has been studied for shale oil/gas potential (Van Bergen et al., 2013; Zijp et al., 2015). These basinal organic-rich shales have been encountered in deep wells (e.g. Winterswijk-1, Luttelgeest-1, Uithuizermeeden-2) in the Groningen area and in the southeastern Netherlands onshore (Geverik-1, Californie-GT-01). The Geverik Member can be up to 50 m thick and has TOC contents of up to 9% (Bouw & Lutgert, 2012). In much of the Netherlands the Geverik Member is post-mature for oil due to its great burial depth (>5 km; Fig. 14.26) and vitrinite reflectance values of over 2%. However, there are clear exceptions to this. In the Geverik-1 and Californie-GT-01 wells in Limburg the Geverik Member was encountered at depths of less than 1 km TVD and ~1.5 km TVD, respectively. However, vitrinite reflectance measurements show maturities above 2% in these areas. In the Limburg area the maturity of the Geverik Member is therefore controlled by its past burial, uplift and erosional history rather than the present burial depth (see also maturity map in Zijp et al., 2015). In the UK, the equivalent Bowland Shale is the source rock for the earliest oil discoveries, including the Hardstoft (1919) and Eakring (1939) discoveries (Kombrink et al., 2010) and has been investigated in the context of shale gas exploration (Andrews, 2013).

Based on regional paleogeographic reconstructions, source rocks for oil may also occur in Dinantian and Devonian deposits (Cameron & Ziegler, 1997). However, in most places the present-day (or maximum) burial depth will render them post-mature for oil and gas generation.

Hydrocarbon plays

A hydrocarbon play is used here to describe a region in which the oil or gas occurrences are controlled by the same set of geological circumstances. The term is widely used in the realm of exploration to categorize hydrocarbon resources. Proven gas and oil plays in the Netherlands range from Westphalian to Quaternary in age.

Devonian and lower Carboniferous plays are regarded as speculative because of their poor reservoir quality and the post-maturity of their source kitchens. The Namurian Epen Formation is prospective for (shale) gas, but this play has never been effectively explored.

The Rotliegend play is by far the most important gas play, with the Groningen field accounting for over 60% of the Dutch initial gas reserves. Excluding the Groningen field, approximately 65% of all the initial resources in the so-called 'small fields' are found in the Rotliegend as well. The cumulative amount of produced gas and the remaining economically producible Dutch gas resources amount to $3724 \times 10^9 \text{ m}^3$ (MEACP, 2022). Recoverable gas reserves for the Groningen field were reduced by 470 billion m^3 due to the premature cessation of production. Safety issues related to the induced seismicity in the depleting Groningen field prompted this closing-in (MEACP, 2018).

The most important oil play consists of the Jurassic and lower Cretaceous sands that were charged from the Jurassic Posidonia shale. Cumulative produced oil and economically producible remaining oil resources are reported to amount to 190.7 million Sm^3 (MEACP, 2022).

For oil, there is a marked variation in the recovery factors (e.g. 12% to 70% in the West Netherlands Basin and 35% for Schoonebeek), but for gas, the recovery factors generally vary between 70% and 90%, and in some cases are as high as 95% (e.g. as originally predicted for the Groningen field prior to the decision to close-in the field). For gas in tight or in very shallow reservoirs, or in reservoirs with low connectivity (e.g. in the Westphalian), recovery efficiencies are notably lower.

Westphalian play

The Westphalian is present throughout most of the Dutch subsurface and is locally up to 5.5 km thick (Huis in 't Veld & Den Hartog Jager, 2025, this volume). Gas fields producing from Westphalian sandstones occur in the eastern Netherlands and adjacent parts of Germany, as well as in the Cleaverbank Platform in the northwestern offshore and in the adjacent British sector (Figs 14.3, 14.12). Gas charge is derived from Westphalian coals, with on the Cleaverbank Platform also a minor contribution from Namurian source rocks (Gerling et al., 1999; Breunese et al., 2010; Besly, 2018). Traps are formed by tilted fault block

closures below the Base Permian Unconformity. Where Rotliegend sandstones directly overlie this unconformity, gas will migrate into the Rotliegend reservoir and the Westphalian sandstones only contain gas when the height of the trap (or gas column) exceeds the thickness of the Rotliegend, e.g. in the Groningen field. In the east of the Netherlands where no Rotliegend sandstones overlie the unconformity, the Zechstein salt forms a near perfect top seal for the Westphalian traps. On the Cleaverbank Platform the claystones and evaporites of the Silverpit Formation form the seal. Locally, intra-Westphalian shales and faults may also form seals (Figs 14.3, 14.12).

A key uncertainty for the Westphalian play is the presence of good reservoir sandstones within the traps at the level of the Base Permian Unconformity. Due to early Permian uplift and erosion, different rocks subcrop at this unconformity. A good understanding of facies distribution within the Westphalian and mapping of intra-Westphalian horizons is therefore a pre-requisite to pursue this play (Quirk, 1993; Quirk & Aitken, 1997). Fluvial sandstone reservoirs occur at distinct stratigraphic levels within the Westphalian, with the most important reservoir units occurring in the Tubbergen Formation. These Westphalian C-D (Bolshevik-Asturian) sandstones are gas-bearing in several fields. Approximately 65% of the total volume of gas produced from Carboniferous reservoirs is from on-shore fields, mainly in the east of the Netherlands. The largest of these is the Coevorden field, discovered in 1948 at a depth of ca. 2800 m. Since its discovery, approximately $20 \times 10^9 \text{ m}^3$ gas has been produced from the Carboniferous. In addition, $12 \times 10^9 \text{ m}^3$ has been produced from the Zechstein Carbonates and a minor 140 million m^3 from the Triassic (Production plan Coevorden, NAM, 2018). Other significant Carboniferous fields in the area are Dalen, Tubbergen and Hardenberg. The upper Carboniferous reservoir sands were derived from erosion of the rising Variscan mountain belt to the southeast. They wedge-out northwestward showing an overall decrease in reservoir potential in that direction. The typically sheet-like stacked sandstones have net-to-gross ratios as high as 50% (Kombrink et al., 2007). The uppermost Carboniferous (Westphalian D and Stephanian) comprises red beds, with low net-to-gross ratios of 10 to 20%. Porous conglomeratic sandstones occur, but their distribution is hard to predict. The reservoir architecture of the Westphalian sandstones and the faulted nature of the traps in the east of the Netherlands result in strong compartmentalization of the gas fields.

Offshore Carboniferous fields in the Cleaverbank Platform-area have contributed ca. 35% of the gas produced from Carboniferous reservoirs in the Netherlands. In this offshore area, gas-bearing fluvial channel sandstones occur

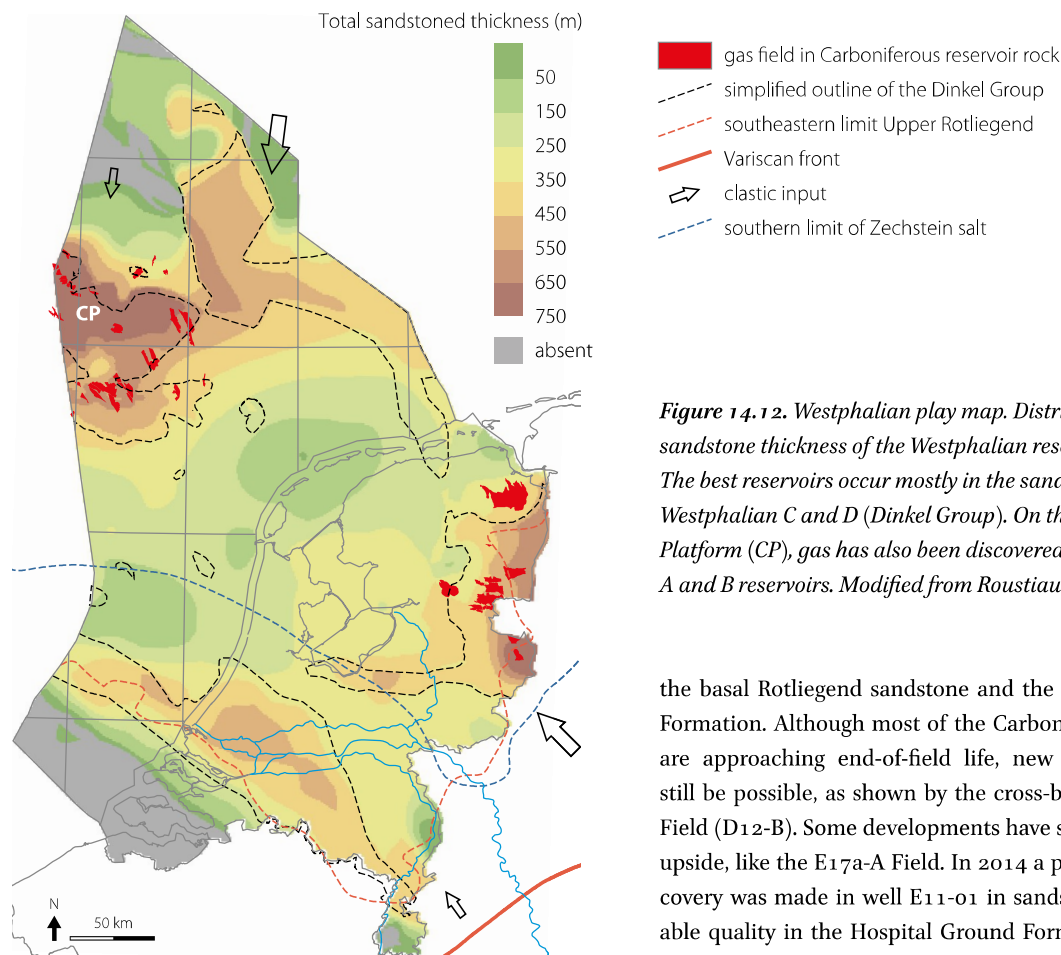


Figure 14.12. Westphalian play map. Distribution and net sandstone thickness of the Westphalian reservoir rocks. The best reservoirs occur mostly in the sandstone-prone Westphalian C and D (Dinkel Group). On the Cleaverbank Platform (CP), gas has also been discovered in Westphalian A and B reservoirs. Modified from Roustiau et al. (2022).

mainly in the Westphalian A and B (Botney Member of the Klaverbank Formation, Caister and Murdoch sandstones; Huis in 't Veld & Den Hartog Jager, 2025, this volume) and, as in the Dutch onshore, also in Westphalian C and D deposits (Hospital Ground and Step Graben formations). The fluvial systems that deposited these sands were sourced from the north (see Fig. 14.12) and their reservoir quality deteriorates towards the south. The sandy facies may extend further eastward to the Schill Grund High, at the southern margin of the Ringkøbing-Fyn High, although there are insufficient well data to substantiate this. The Westphalian A and B deposits generally have low net-to-gross ratios. The main fields are located in the northern K and southern D and E quadrants, at depths of around 3500 to 4000 m, north of the pinch-out of the Rotliegend sandstones, where the evaporite bearing Silverpit shales generally form an excellent seal. The largest Westphalian field is E17a-A, with an initial gas-in-place volume of ca. 1.8×10^9 m³ of which 1.0×10^9 m³ may be produced (Nephtune, 2021). The trend of Westphalian gas fields continues into the UK sector of the North Sea, with fields like Orca, Caister, Murdoch, Ketch and Schooner and several other discoveries (Mijnssen, 1997). The fields in E18, F16 and the northern K quadrant produce commingled gas from

the basal Rotliegend sandstone and the Hospital Ground Formation. Although most of the Carboniferous gas fields are approaching end-of-field life, new discoveries may still be possible, as shown by the cross-border Sillimanite Field (D12-B). Some developments have shown significant upside, like the E17a-A Field. In 2014 a promising gas discovery was made in well E11-01 in sandstones of reasonable quality in the Hospital Ground Formation. However, as for several other discoveries in the D9, E12, E13 blocks, development of E11-01 was judged to be uneconomic.

Where the Westphalian sandstones are gas-bearing, they mostly have fair to good porosities (average 9%, maximum 20%) and permeabilities (average 1-2 mD, locally >100 mD) and good initial production rates of about 1×10^6 m³/day or more can generally be achieved (Van Buggenum & Den Hartog Jager, 2007). However, their poor reservoir connectivity often results in limited connected volumes per well accompanied by rapidly declining flow rates, thus seriously hampering the economic viability of offshore Westphalian gas accumulations.

Rotliegend play

Even excluding the giant Groningen field, the Slochteren Formation of the Upper Rotliegend Group is volumetrically by far the most important gas reservoir in the Netherlands. The Rotliegend play consists of an ideal superposition of 1) the prolific Westphalian source rocks for gas, 2) the thick Slochteren sandstone reservoirs, and 3) the near-perfect seal of the Zechstein salt (Glennie & Provan, 1990; Grötsch & Gaupp, 2011). Most traps form simple asymmetrical tilt-block configurations (Fig. 14.13). The Slochteren reservoir sandstones are present in the classical Rotliegend play fairway which runs E-W from the Gronin-

gen field to the offshore K and L blocks. To the north the Slochteren sandstones shale-out into the Silverpit Formation. The southern boundary of the play is determined by the depositional limit of either the Slochteren reservoir or the Zechstein seal (Fig. 14.14). Two exceptions are the P6 and Q10 gas fields which are not sealed by Zechstein salt but by the distal Zechstein Fringe deposits. Although most gas in the Upper Rotliegend reservoirs was sourced from Westphalian coal measures (Van Wijhe et al., 1980; Glenne, 1998), in some areas (northern Netherlands, north-west offshore) the basal Namurian hot shales and/or the lower Carboniferous coals (e.g. Gerling et al., 1999) potentially contributed as well.

The sands in the Slochteren Formation were mainly derived from the Variscan Mountains to the south (Verdier, 1996; Geluk, 2007). They show marked differences in reservoir quality. Well-sorted and clean eolian sandstones form the best reservoirs, but there are also packages of up to tens of metres of mainly fluvial sandstones with locally conglomeratic intervals that are of fair reservoir quality. The sandstones of the Upper Slochteren Member shale out towards the north into the Ten Boer Member (Bouroullec & Geel, 2025, this volume). Depending on the amount of sand present, the Ten Boer Member acts either as a waste zone or as seal for the underlying Slochteren sandstones. Even where the Ten Boer is not a top seal, it forms a lateral seal where it is juxtaposed against Slochteren reservoirs across faults (Fig. 14.16). Its sealing potential improves with increasing shale content, which suggests that a sealing shale-gouge formed along the fault planes. In some gas accumulations, the gas-water contact extends even below the mapped spill point controlled by the Ten Boer Member lateral seal, indicating that faults in clean sandstones can also be sealing. It is therefore likely that factors other than shale gouge, such as cataclasis and/or diagenesis, also play a role in determining whether a fault is sealing (Leveille et al., 1997).

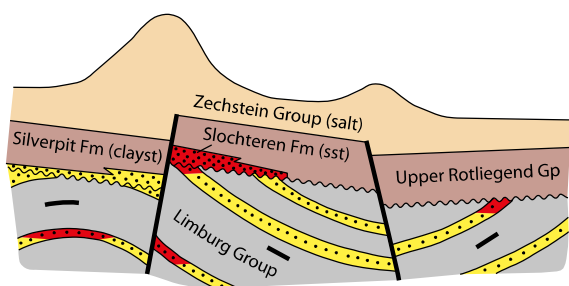


Figure 14.13. Hydrocarbon trapping styles in the Westphalian. Most gas (red) is found directly below the Base Permian Unconformity, where Slochteren sandstones are thin or absent. At intra-Westphalian levels only sub-commercial gas volumes have been encountered to date. Modified from De Jager and Geluk (2007).

Below the Silverpit shales, basal sandstones of the Lower Slochteren Member are locally present. Thickness variations of these sandstones are controlled by the paleotopography at the time of deposition. This paleotopography, was in turn controlled by faulting and the type of formation sub-cropping the Base Permian Unconformity. The shaly parts of the Westphalian A and B were less resistant to erosion than the sandy parts. The eroded shaley areas turned into lows where sand accumulated, while the more resistant areas formed ridges, on top of which little or no sand was deposited (Geluk & Mijnlief, 2001; Mijnlief & Geluk, 2011).

Most Rotliegend gas reserves occur in the northeast of the Netherlands and in the offshore K and L quadrants (Central Offshore Saddle, the southern sector of the Cleaverbank Platform and the northern sector of the Broad Fourteens Basin). This E-W belt of Rotliegend gas fields extends westward into the British Indefatigable and Sole Pit areas. Additional Rotliegend fields occur in the Vlieland Basin and the northwestern sector of the Central Netherlands Basin (Fig. 14.13).

The giant Groningen field in the northeastern onshore is by far the largest gas field (Roels, 2001; Verberg, 2001; Fig. 14.1). Other large accumulations are Annerveen, located directly south of the Groningen field (Veenhof, 1996) and the Ameland complex of fields located directly north of Groningen, below the Wadden Sea (Crouch et al., 1996). Both fields have a gas-initially-in-place (GIIP) volume of ca. $75 \times 10^9 \text{ m}^3$. It is noteworthy that the Ameland complex appears to be underfilled. Structural reconstruction shows that Late Cretaceous inversion enlarged the Ameland trap. Apparently, subsequent charge was insufficient to completely fill it.

Marked variations in the nitrogen contents in gas in the northeast of the Netherlands are attributed to variations in charge history. Traps that have access to recent gas charge are characterized by very low nitrogen contents (<5%). On the Friesland Platform, where charge modelling indicates that the last phase of gas charge occurred prior to Jurassic rifting, nitrogen levels were as high as 25%. Residual oil is often reported from cores cut in Slochteren sandstones. This is interpreted to indicate an early oil charge from intra Zechstein and/or Coppershale source rocks. The oil was later flushed out by excessive amounts of gas, filling the majority of trapping structures with gas down to spill point. The only live oil found so far in Slochteren sandstones is in Midlaren in northeast Drenthe, where a 120-m oil column was encountered below a gas cap. The oil is juxtaposed across a fault against Z2 Carbonate. The carbonates may have allowed leakage of gas but formed a lateral seal to oil.

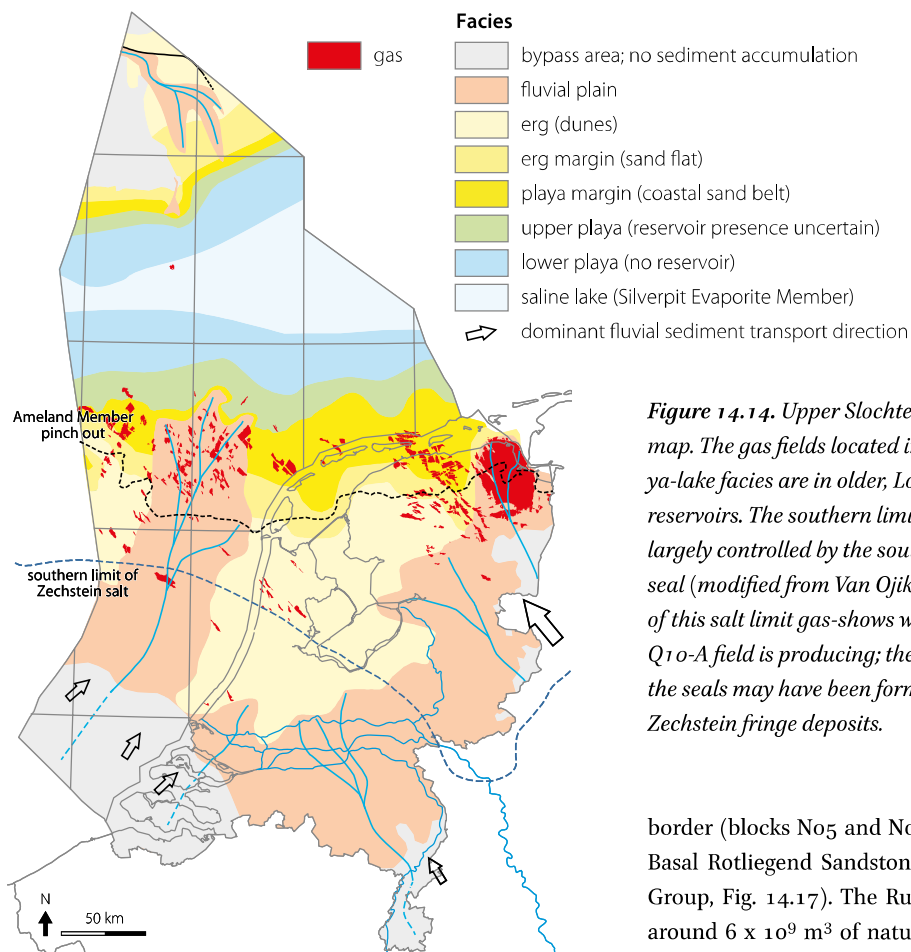


Figure 14.14. Upper Slochteren (Upper Rotliegend) play map. The gas fields located in the northern area of playa-lake facies are in older, Lower Slochteren sandstone reservoirs. The southern limit of Rotliegend gas fields is largely controlled by the southern extent of the Zechstein top seal (modified from Van Ojik et al., 2023). In four wells south of this salt limit gas-shows were encountered, but only the Q10-A field is producing; the other reservoirs are tight. Here, the seals may have been formed by clay layers within the Zechstein fringe deposits.

In the offshore K and L quadrants, K8-FA is the largest field with a GIIP of some $64 \times 10^9 \text{ m}^3$ (NAM, 2016b). In these offshore fields the traps are also simple tilt blocks with the overlying thick Zechstein evaporites forming the top seal. As the Ten Boer shales are much thinner than in the northeast Netherlands, there is less potential for an additional gas column height due to fault juxtaposition of the Ten Boer Member against Slochteren sands. Locally, where the Zechstein salt seal is breached by erosion, salt welding and/or by faulting, basal Triassic shales form an effective alternative top seal (e.g. in K15-FC and K15-FK). Variations in gas-water contacts across different field compartments, and gas columns below conventional spill points, indicate that sealing faults are also present in these offshore fields. This has also been observed in the western continuation of the Rotliegend play in the UK sector of the southern North Sea (Leveille et al., 1997).

In the northern K quadrant and adjacent areas, basal Slochteren sandstones (see Bouroullec & Geel, 2025, this volume), sealed by the overlying Silverpit Formation also contain commercial gas accumulations. The most significant is the Markham field in the J3/J6 area, straddling the UK-Netherlands border. The recent discoveries of the Ruby and Turkoois fields, both straddling the Dutch German

border (blocks No5 and No4), proved the potential of the Basal Rotliegend Sandstones Member (Upper Rotliegend Group, Fig. 14.17). The Ruby field is expected to contain around $6 \times 10^9 \text{ m}^3$ of natural gas. These basal sandstones were encountered in a number of legacy wells. Although they were gas bearing, the uncertainty of their presence, relatively high nitrogen content and a questionable seal quality make this a high-risk play (Corcoran & Lunn, 2014). The ability to discriminate these sands on modern 3D seismic data opened the play which is claimed to potentially contain over $30 \times 10^9 \text{ m}^3$ (Burgess et al., 2018; Fig. 14.17). According to the paleogeographical study of the Rotliegend by De Bruin et al. (2015), this basal reservoir sand may also be present along the northern margin of the Southern Permian Basin (northern A-, B- and F quadrants), but this play has not yet been tested.

Also in the western sector of the Central Netherlands Basin, Rotliegend gas fields such as Bergen, Groet, Bergermeer, Schermer and Middellie have been brought to production (Van Lith, 1983). Even at significant depths, reasonable porosities ($>15\%$ at 4000 m) occur in the better reservoir levels of the Slochteren Formation. The main deterioration of reservoir potential is by early carbonate cementation or the late growth of fibrous illite. The latter is associated with deep paleo-burial, in particular within the inverted portion of the Broad Fourteens Basin. Growth of illite fibres in the pores has little effect on porosity but significantly reduces permeability. The presence of formation waters rich in ions of clay minerals is conducive

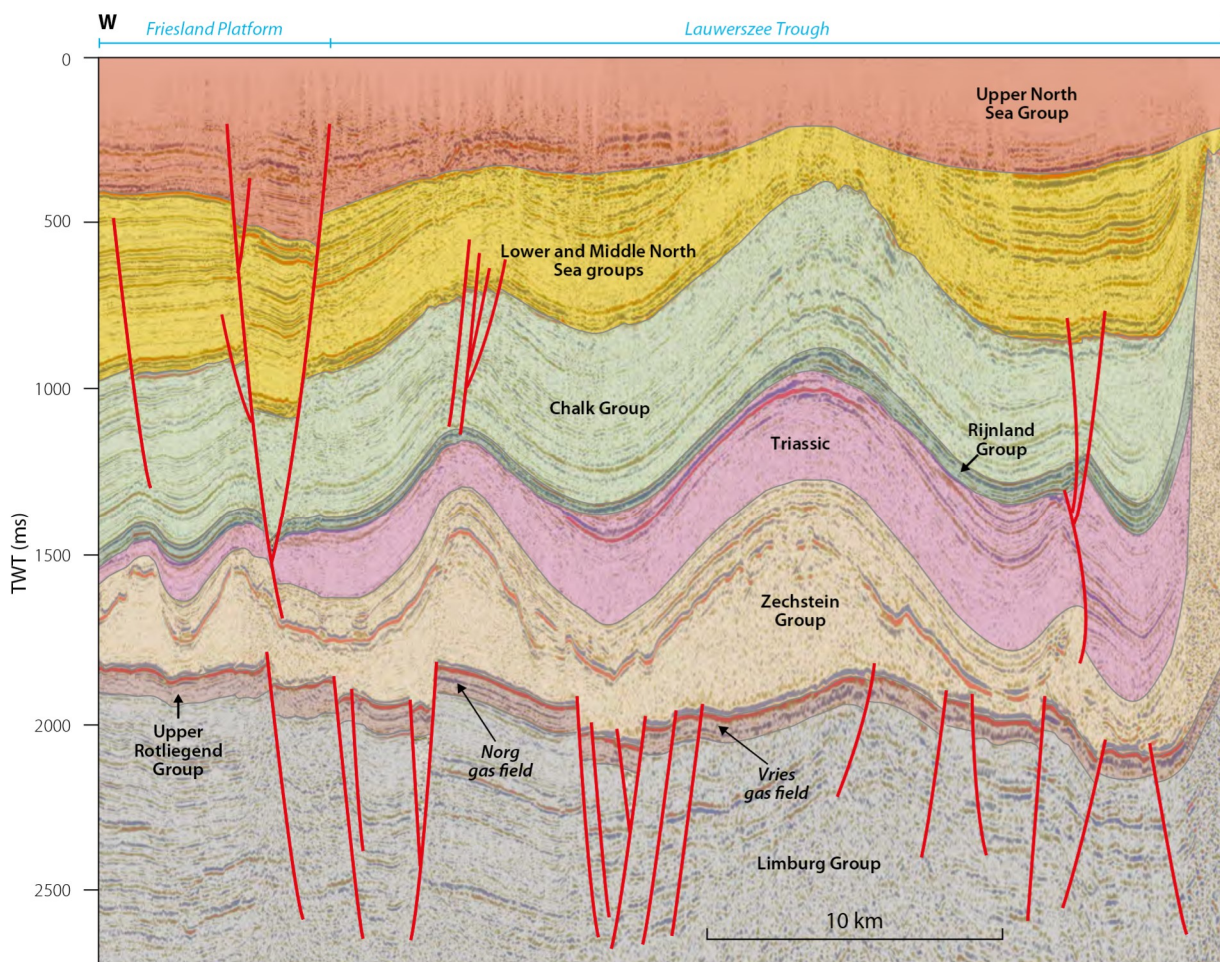


Figure 14.15. Seismic line in the northeast Netherlands (Friesland Platform to Lauwerszee Trough) showing the setting of the Norg en Vries gas fields in fault blocks in the Upper Rotliegend Group. For location see Fig. 14.1.

to illite diagenesis. This is likely to be the case where for example the Slochteren is juxtaposed against the shaly Westphalian (Gaupp et al., 1993). However, where the Slochteren was already gas-bearing prior to deep burial, growth of diagenetic illite has been inhibited. Therefore, to be able to predict reservoir quality, a good understanding of depositional trends, as well as of timing of trap formation, gas charge and temperature and burial history, is required. Low permeabilities and resultant uneconomic production rates are linked to depositional facies, such as in fine-grained, argillaceous wadi sands (Frikken, 1999).

Zechstein play

Gas fields producing from the Zechstein Group mostly occur in platform carbonates. These carbonates developed in marine settings along the Southern Permian Basin margin and are sealed by Zechstein salt and anhydrite (Van der Baan, 1990; Van de Sande et al., 1996; Geluk, 2007; Bouroullec & Geel, 2025, this volume). In addition, some minor clastics (so-called fringe sandstones) along the southern extremities of the basin, host a number of gas fields (Fig.

14.18). The traps are predominantly fault-dip closures, with some four-way dip closures. As with the Rotliegend play, gas charge to the Zechstein was from the Westphalian and Namurian. Contributions from Zechstein oil-prone source rocks have locally resulted in condensate-rich gas. Oil shows in the Zechstein have been recorded in numerous wells in the northeast of the Netherlands (e.g. fields Stadskanaal and Gieterveen). Analyses indicate that these shows are derived from intra-Zechstein source-rock intervals and from the Coppershale Member. In the northwestern offshore (E13-01) minor amounts of oil were encountered as well. The most likely source rock for this oil is the so-called Stinkkalk (or Stinkschiefer), which is the basinal equivalent of the Z2 Carbonate Member (De Jager & Geluk, 2007; Bouroullec & Geel, 2025, this volume). The best Zechstein reservoirs with porosities of ca. 14% occur in the Z2 Carbonate and, less frequently, in the Z3 Carbonate members. A single accumulation in the Z1 Carbonate Member (Q05-A) came on stream late 2004 (Geluk, 2000; MEA, 2006). The highest porosities occur in the shelf-edge facies that developed above the paleo-highs formed by the

underlying Z1 Anhydrite. Subaerial exposure of the platform occurred occasionally and karstification locally enhanced reservoir quality. The adjacent slope facies consists mainly of redeposited platform sediments. Small-scale reefs occur locally, but they are restricted to the Z1 Carbonate (Geluk, 2007). The basinal facies of the carbonates comprises fine-grained limestones and dolomites. The Zechstein carbonates experienced a complex diagenetic history, including cementation, leaching and dolomitization, which has resulted sometimes in strong lateral variations in their porosity and permeability. Especially in the tight slope- and basinal facies with porosities <4-5%, such as encountered in the Dalen, Emmen and Coevorden fields, economic gas production rates largely depend on the presence of fractures (Frikken, 1999).

The first offshore gas discovery, in 1968, was in Zechstein dolomites in block P6 (Van der Poel, 1989). Various additional wells in the P and Q quadrants and in the southernmost part of the K quadrant have subsequently tested gas, but gas is produced from a Zechstein reservoir below a larger Triassic gas accumulation only in block P6. One of the Zechstein fields in the onshore part of the Central Netherlands Basin is the Alkmaar field which is now used

for underground gas storage (Juez-Larré et al., 2025, this volume).

Along the northern margin of the Southern Permian Basin, in the area of the Elbow Spit and Mid-North Sea highs, the Zechstein also comprises slope and platform carbonates as proven by well Eo2-02. Although quite thin, carbonate build-ups in the Zechstein may have better reservoir quality further north. In this context the recent discovery of gas in the Pensacola prospect along the northern margin of the basin on the UK side is supportive (jpt.spe.org/shell-makes-gas-discovery-at-pensacola, 2023).

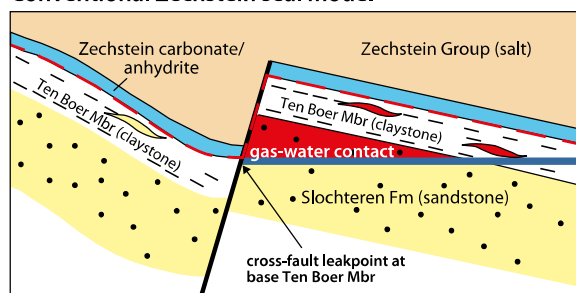
A special case is the gas accumulation discovered in 1985 by well G16-01 on the Schill Grund High, where a leached Z3 Carbonate and an overlying Upper Jurassic sandstone form a single composite reservoir above a Zechstein salt dome. The Lower Cretaceous Vlieland Claystone Formation provides the seal.

In the West Netherlands Basin, the four Zechstein cycles are developed as siliciclastic basin-margin facies ('fringe sandstones'- Fig. 14.18). The best reservoir was found in offshore block P10, where a sandstone interval reaches a thickness of ca. 125 m. Since no Zechstein evaporites are present here to provide a top seal, predominantly sub-commercial quantities of gas have been encountered in the area. An exception is the Zechstein reservoir unit of the Q10-A field that recently came on stream in combination with Rotliegend and Triassic sandstone reservoirs. Recent exploration activities for Zechstein reservoirs are limited to the Friesland area where several small fields, often associated with gas-bearing reservoir rocks in Rotliegend and/or Vlieland Sandstones were discovered.

Triassic plays

Triassic sandstones are widely distributed in the Netherlands and form the second most important gas reservoir, next to the Rotliegend sandstones. Producing Triassic fields occur in the east of the Netherlands, in the West Netherlands Basin and in the northern and western offshore (Fig. 14.19). The top seal is in most cases formed by Triassic shales. Where the Triassic is truncated by the Base Cretaceous Unconformity, Lower Cretaceous shales form the top seal. The Solling Claystone Member seals accumulations in the Main Buntsandstein (Spain & Conrad, 1997), whereas the clayey Muschelkalk and Keuper formations seal accumulations in the Röt. The gas was mainly sourced from Westphalian coal measures, and partly also from the basal Namurian hot shales (Fontaine et al., 1993; De Jager et al., 1996; De Jager & Geluk, 2007) and is trapped in a range of styles. In the northern sector of the Dutch subsurface, the underlying Zechstein salt forms a barrier that prevented Westphalian gas from reaching Triassic reservoirs. Only where this regional seal is breached by salt withdrawal or by faulting, could Westphalian gas

Conventional Zechstein seal model



Ten Boer seal model

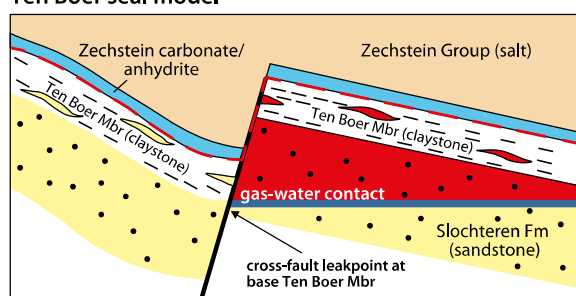


Figure 14.16. Ten Boer sealing concept. The regional top seal for the Rotliegend is the base of the Zechstein (red line in upper image). Where the Ten Boer Member is sufficiently shaly, it provides a seal in fault juxtaposition (red line in lower image), even though intra-Ten Boer Member sandstones may be gas-bearing, and on the same pressure gradient as the gas in the Slochteren sandstones. Modified from De Jager and Geluk (2007).

charge Triassic reservoirs. In the West Netherlands Basin, Zechstein salt is absent and the Triassic sandstones form the first well-sealed reservoir above the Westphalian. The Triassic sandstones were deposited in fluvial and eolian settings and were derived from the Variscan mountains towards the south. In the south, the Main Buntsandstein Subgroup forms a thick massive reservoir package. To the north this package splits into several thinner sandstone units, such as the sandstones of the Volpriehausen and Detfurth formations, which are separated by clay- and siltstones that form regional seals (Van Adrichem Boogaert & Kouwe, 1994; Ames & Farfan, 1996; Geluk, 2005; Bachmann et al., 2010; McKie & Kilhams, 2025, this volume).

The first Triassic discovery was the Coevorden field in 1948. This tilted fault block was found to be gas-bearing in the Main Buntsandstein Subgroup and in the Upper Triassic Muschelkalk, Keuper and Röt, as well as in the underlying upper Carboniferous. The Buntsandstein is also a proven gas reservoir in the eastern Netherlands. The Waneperveen and De Wijk fields (Gdula, 1983; Bruijn, 1996; Pipping et al., 2001) produce from reservoirs that are sealed by shales of the Lower Cretaceous Vlieland Claystone Formation. Reservoir characteristics are enhanced

as a result of leaching below the Base Cretaceous Unconformity. Even leached anhydritic shales of the Lower Triassic Rogenstein Formation are productive in these fields. Channel sands at the base of the Vlieland Sandstone Formation locally form part of the complex traps.

In the West Netherlands Basin, exploration for Triassic gas accumulations only effectively started in 1982. The typical trap in this play consists of a Late Jurassic horst block in which the reservoir is sealed vertically by Upper Triassic evaporitic shales and laterally by Upper Triassic to Lower Jurassic shales (Fig. 14.20; De Jager et al., 1996). Lateral seal risks exist where fault-throws are so large that Triassic sandstones are juxtaposed against the Jurassic Delfland sequence (Delft Sandstone Member). Gas discoveries line up along the southwestern border of the West Netherlands Basin on a WNW-ESE trending structural trend consisting of tilted fault blocks or inverted flower structures. The best reservoirs occur along its southwestern margin, with excellent gas production rates of several million cubic metres per day being reached in some fields. Towards the north, reservoir quality deteriorates rapidly due to erosion of the best reservoir section in the upper part of the Main Buntsandstein Subgroup, in combination

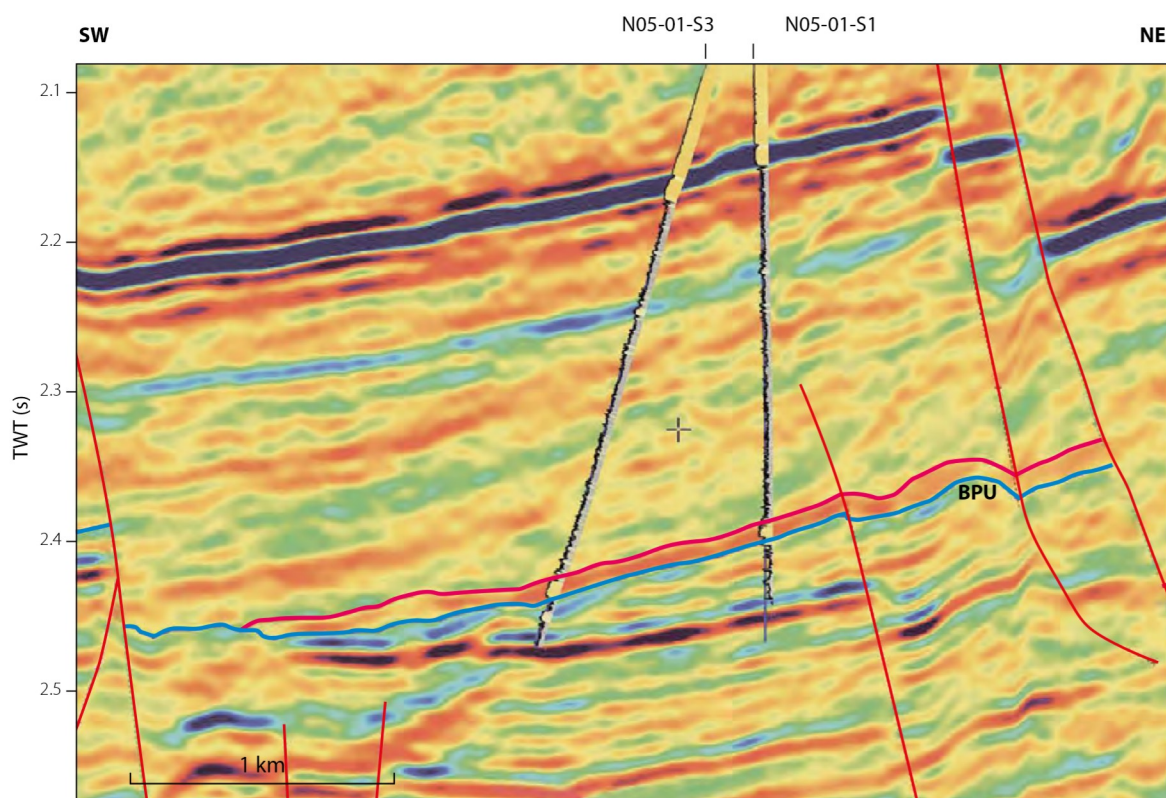


Figure 14.17. Seismic time section (freely available at www.nlog.nl) showing the overall setting and the tilt-block trap style of the Ruby field, a basal Slochteren clastics (Upper Rotliegend Group) gas discovery made in 2017. Gamma-ray logs of N05-01-S1 and N05-01-S3 show that this thin basal sandstone unit (yellow in the log) directly overlies the Base Permian Unconformity (BPU; in light blue). A high acoustic impedance contrast is associated with these reservoir sandstones (modified from Burgess et al., 2018 and Doornenbal et al., 2019).

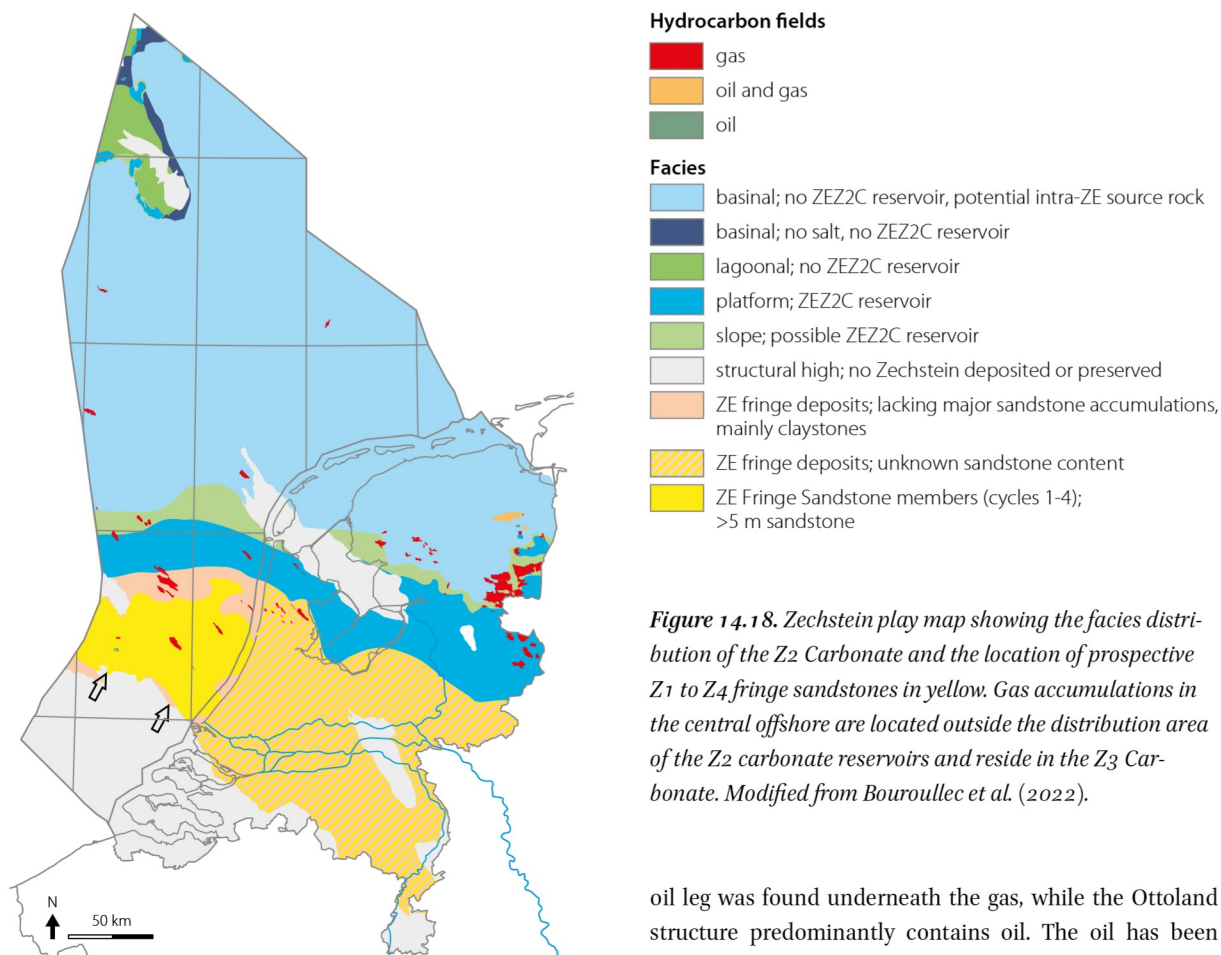


Figure 14.18. Zechstein play map showing the facies distribution of the Z2 Carbonate and the location of prospective Z1 to Z4 fringe sandstones in yellow. Gas accumulations in the central offshore are located outside the distribution area of the Z2 carbonate reservoirs and reside in the Z3 Carbonate. Modified from Bouroullec et al. (2022).

with a general increase in pre-inversion burial. This deep burial in inverted basins caused diagenetic reduction of porosity and permeability as can be seen in a number of fields in blocks Po2 and P12 (Van Hulten, 2009). Furthermore, because of tectonic inversion during the Late Cretaceous, traps in the central and northern part of the West Netherlands Basin changed their structural configuration or were even destroyed, while new ones formed. At the same time, following uplift and declining heat flow most of the Carboniferous and the Jurassic source rocks stopped generating hydrocarbons in this part of the basin (De Jager et al., 1996). A timing problem thus exists for new traps that formed during tectonic inversion. In the southern part of the West Netherlands Basin, where no or very little inversion occurred, gas generation continues to the present day.

In the Jurassic basins in the South (West Netherlands Basin, Central Netherlands Basin and Broad Fourteens Basin) gas-bearing Triassic sandstone reservoirs occur along the WNW-ESE structural trend. Although the Triassic play in the West Netherlands Basin is largely a gas play, in several accumulations (e.g. Papekop, Pernis West, Spijkenisse Oost, Waalwijk, Zuid Botlek, Oud Beijerland-Noord, Q16-Maasmond and offshore in the P10/P11 blocks) an

oil leg was found underneath the gas, while the Ottoland structure predominantly contains oil. The oil has been matched to the source rocks of the Lower Jurassic Posidonia Shale, with probably some contribution from the Lower Jurassic Aalburg and uppermost Triassic Sleen formations, and possibly also from Carboniferous rocks (De Jager et al., 1996). This oil migrated across faults into the Triassic reservoirs from younger source rocks in adjoining down-thrown blocks. Where the Posidonia Shale has not been downfaulted to below the Triassic reservoir, as is the case for some oil-bearing structures, it is very unlikely that it could have charged these traps. In those cases, the oil is most probably entirely sourced from the Aalburg and Sleen Formations (Van Balen et al., 2000).

In the northern offshore, sandstones of the Volpriehausen and Detfurth formations are reservoirs for gas fields located in the northern Vlieland Basin, Terschelling Basin, Schill Grund High and southern Dutch Central Graben area. In 1992, the L5-FA field was the first sizeable Triassic field to come on stream in the northern offshore. This field lies on the NE-SW structural trend that dominates the Southern Central Graben and the Terschelling Basin. In these blocks most traps are related to halokinesis of the underlying Zechstein salt, and occur in turtleback anticlines, against salt walls or as fault-dip closures (Fig. 14.21; see also Bouroullec & Ten Veen, 2025, this volume). Examples of these trap types are the economic accumulations in L2, F15 (Fontaine et al., 1993) and G14, G16, and G17.

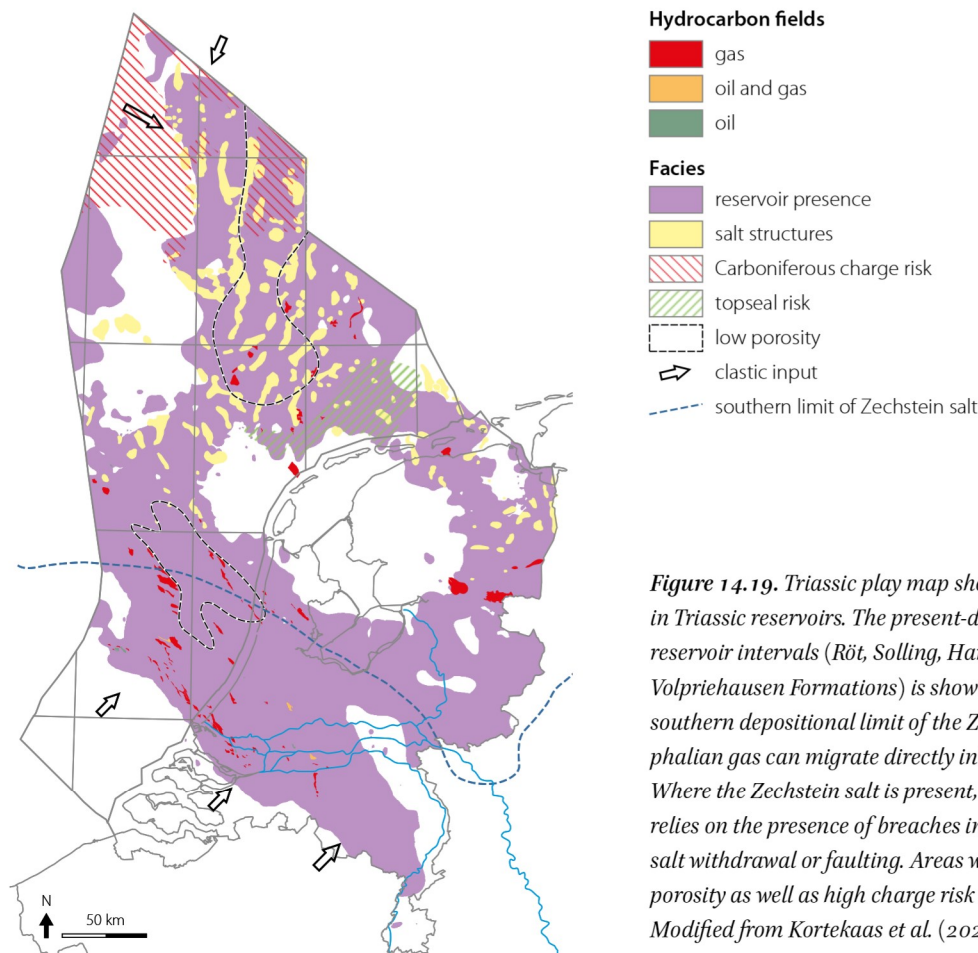


Figure 14.19. Triassic play map showing gas and oil fields in Triassic reservoirs. The present-day distribution of the reservoir intervals (Röt, Solling, Hardegsen, Detfurth and Volpriehausen Formations) is shown in purple. South of the southern depositional limit of the Zechstein salt, Westphalian gas can migrate directly into Triassic reservoirs. Where the Zechstein salt is present, charge into the Triassic relies on the presence of breaches in the Zechstein due to salt withdrawal or faulting. Areas with weak top seal, low porosity as well as high charge risk are indicated on the map. Modified from Kortekaas et al. (2022).

Salt walls in the Terschelling Basin and southern Dutch Central Graben seal-off separate pressure cells that contain Triassic reservoirs (Crepieux et al., 1998). In some of these cells, reservoir pressures equal the minimum horizontal stress, thus causing the seal to be breached. Deeper culminations in these pressure cells may be protected against seal failure.

Sandstones of the Triassic middle Solling Sandstone Member form an exceptional reservoir in the L9 area. Well L09-07, drilled in 1992, found this hitherto unknown reservoir to be gas-bearing (Geluk, 2005; De Jager, 2012). Subsequent development drilling of the L09-FD, FF and FI complex of fields established total recoverable gas reserves of ca. $31 \times 10^9 \text{ m}^3$ (NAM, 2014) in the so-called 'Fat Sand' reservoir. The 'Fat Sand' is up to 125 m thick and has a net-to-gross ratio of close to 100% with average permeabilities in the Darcy range. Gas production rates from this extremely prolific reservoir are typically several million cubic metres per day per well. To the north, in block L6, the same reservoir is salt-plugged. The unusually large thickness of the Solling Sandstone in part of block L9 implies a unique depositional setting. Extensive core coverage indicates that the reservoir mainly consists of eolian sandstones, with locally some water-laid sediments.

Well- and seismic data show that the reservoir package is wedge-shaped and thickens into a listric normal fault that detaches onto the top of the Zechstein salt, adjacent to a salt wall (De Jager, 2012). The eolian sandstones are clearly preserved in a syn-depositional half-graben, the development of which appears to be related to Early Triassic extension. This development has proven to be rather local, and no further discoveries of these 'Fat Sands' have been made since the discoveries in L9 (De Jager, 2012).

Salt plugging of reservoirs is a serious risk to the Triassic play in the northern offshore (Purvis & Okkerman, 1996). Salt-plugged reservoirs have been encountered near salt walls and along fault planes and are often characterized by a phase reversal of the seismic response at top reservoir. Careful study of seismic amplitudes may indicate whether good reservoirs are present or not.

Because of the economics-driven focus on near-field exploration, recent Triassic discoveries are concentrated around known fields. Most discoveries are in the onshore part of the West Netherlands Basin in the Rotterdam area and offshore in the P10-P11 and G16 clusters. All discoveries are limited in volume (between 0.5 and $2.5 \times 10^9 \text{ m}^3$). To date, no Triassic discoveries have been made on the Cleaverbank Platform area. Because of deep erosion, the

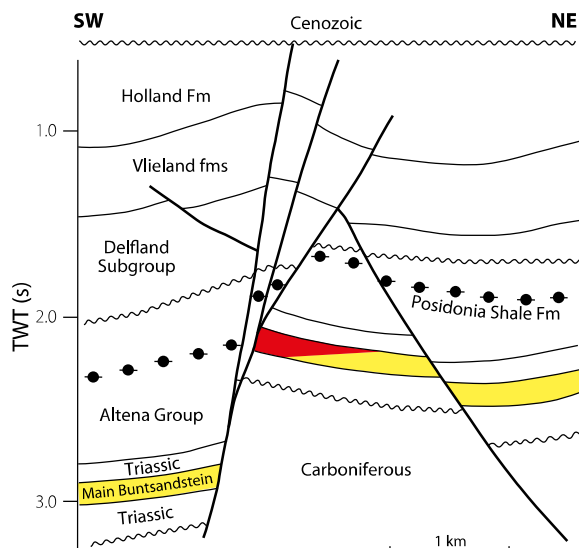


Figure 14.20. Example of a trap in the Triassic of the West Netherlands Basin (Wassenaar Deep gas field). The Main Buntsandstein reservoirs (yellow) have younger Triassic shales as top seal and are laterally sealed by Lower Jurassic shales. Modified from De Jager and Geluk (2007).

Triassic is in many places truncated by the Base Cretaceous Unconformity. Associated leaching has resulted in excellent reservoirs, with average porosities as high as 27%. The lack of exploration success in the Cleaverbank Platform area is attributed to the absence of charge through windows in the thick sealing claystones and evaporites of the Rotliegend and Zechstein. Kortekaas et al. (2022) suggested a northern provenance of reservoir sands

in the Step Graben to the west of the Central Graben. This resembles the locally sourced fluvial deposits in the North German Basin as described by Olivarius et al. (2017). Charge for any trapping structures in the Cleaverbank Platform area may come from Namurian shales or Carboniferous coals, which are likely to be present at depth and in the gas window (Schroot et al., 2006; De Bruin et al., 2015; Ter Borgh et al., 2018). Migration paths may be along faults, through windows in the salt seal or, as recently demonstrated, along volcanic dykes (Underhill, 2009; Kortekaas et al., 2018). Given the attractive trapping configuration, migration is the main risk due to the presence of extensive Zechstein salt layers. Kortekaas et al. (2018) have identified 42 leads in their regional study. However, none of these has been drilled yet.

Upper Jurassic and Lower Cretaceous plays

Upper Jurassic and Lower Cretaceous oil plays are restricted to the Cimmerian rift basins, such as the Dutch Central Graben, Broad Fourteens, Lower Saxony and West- and Central Netherlands basins. The reservoirs occur in clastic syn-rift and early post-rift deposits and show rapid facies changes ranging from continental to marine. There is also a great variation in trap styles. These plays are much more oil-prone than the other Dutch plays. This is mainly because of oil charge from the Lower Jurassic Posidonia Shale, which is only present in the extensional Late Jurassic-Early Cretaceous rift basins (Fig. 14.11). Most of the gas present is derived from the Westphalian, and in the Dutch Central Graben also from Jurassic coal-bearing sequences and/or deeper Jurassic shales of the Aalburg Formation.

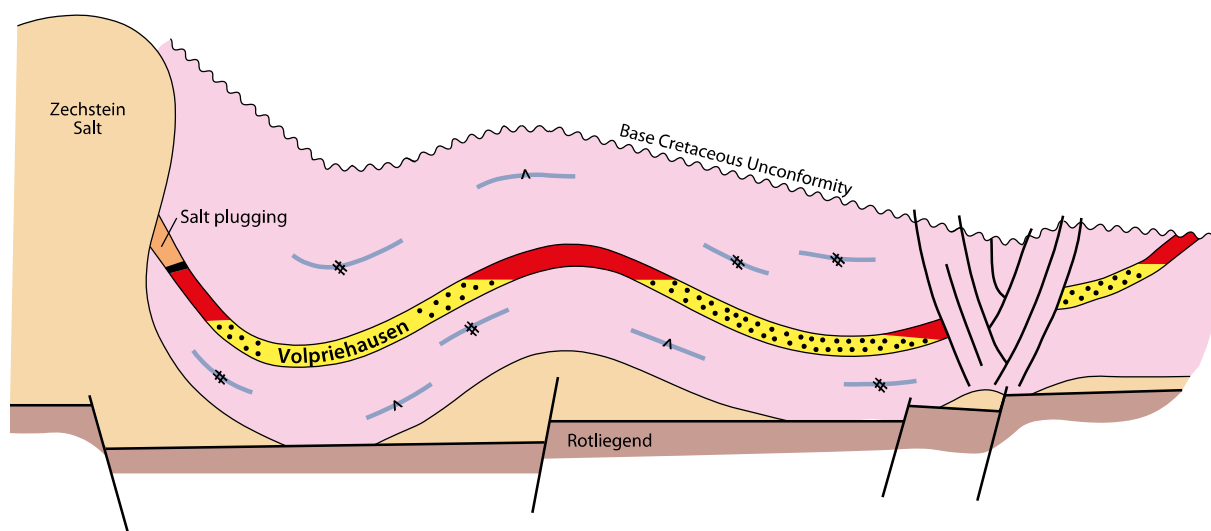


Figure 14.21. Trapping styles in the Triassic of the northern offshore. Most gas (red) is trapped in four-way dip-closed structures above salt swells or in turtle-back structures. Where the Triassic is truncated at the Base Cretaceous Unconformity, Lower Cretaceous marine shales may provide the seal. Salt-plugged reservoirs may provide lateral stratigraphic seals. Modified from De Jager and Geluk (2007).

In the east of the Netherlands, the Schoonebeek field has produced a total of ca. 250 million barrels ($40 \times 10^6 \text{ m}^3$) of oil from the Lower Cretaceous Bentheim Sandstone. The accumulation at a depth of ca. 800 m is exceptional, as it is sourced from lacustrine algal Type-I source rocks of Early Cretaceous age (Coevorden Formation). These source rocks have a limited distribution in the Netherlands but extend into the Lower Saxony Basin in Germany (Binot et al., 1991). The relatively low gravity of the oil of 25° API reflects the low maturity of the source rocks. Geochemical data indicate that the oil is an early expulsion product, without any sign of biodegradation. The field was discovered in 1943 and produced conventionally from 1947 until 1996. In 2011 the western part of the field was re-developed with a low-pressure gravity-assisted steam flood. The eastern part of the field is permanently abandoned (De Keijzer et al., 2009).

Gas fields at the level of the Lower Cretaceous Vlieland sandstones on the Friesland Platform in the northeast Netherlands are, amongst others, Tietjerksteradeel, Waneperveen, Leeuwarden, Harlingen (Van den Bosch, 1983) and De Wijk. Additional discoveries have been made in the intermediate areas where Vermilion drilled several gas-bearing structures such as Vinkega, De Hoeve, Langezwaag and Diever. The main difficulty of this play is to predict the presence of the Vlieland Sandstone, the distribution of which is somewhat erratic and cannot readily

be interpreted from the seismic data. Many of these fields have stacked reservoirs in which the Rotliegend, Zechstein and Vlieland Sandstone are all hydrocarbon bearing.

In the West Netherlands Basin, an intensive drilling programme in the 1950s led to the discovery of the Rijswijk, Pijnacker, De Lier, IJsselmonde, Wassenaar, Zoetermeer and Moerkapelle oil fields. Exploration from the late 1970s to early 1990s resulted in further discoveries, both onshore (Berkel, Barendrecht, Rotterdam, Pernis and Pernis West) and offshore (P8, P9, P11, P12, P15, and Q13). Rotterdam is the largest field, with initial reserves of ca. 90 million barrels ($14 \times 10^6 \text{ m}^3$). Both gas and oil are present in sandstones of the Upper Jurassic to Lower Cretaceous syn-rift and Lower Cretaceous post-rift deposits (Bodenhausen & Ott, 1981). Many of the older fields have been abandoned or closed-in over the last few years, and currently oil production is only from Rotterdam and the offshore fields Q13a-Amstel and the P15-Rijn. The best reservoirs are the post-rift Rijswijk, Berkel and IJsselmonde sandstones that were deposited as coastal barrier complexes overlying the Late Cimmerian Unconformity (Den Hartog Jager, 1996). Additional reservoirs are the younger De Lier and Holland Greensand sandstones as well as the older synrift Delfland Subgroup. Many of the reservoirs have oil columns with a gas cap, with the younger reservoirs generally containing more gas (De Jager et al., 1996). The presence of gas is often a downgrading factor, as it reduces the potential oil volumes in the traps, while the gas volumes are insufficient to justify development as gas fields.

Some of the fields contain very heavy oil with API gravities of 13° to 20° , resulting in low recovery factors (e.g. Moerkapelle and Wassenaar). The low API gravity is the result of biodegradation at the onset of the Cenozoic. Because of tectonic inversion, reservoirs were then at or near the surface, where bacteria had access to fresh meteoric waters (De Jager et al., 1996).

Traps are mainly four-way dip-closures along anticlinal trends that formed in response to the Late Cretaceous and early Cenozoic inversion along the southwestern basin margin (Fig. 14.22; Racero-Baena & Drake, 1996). Further north, in the more strongly inverted sectors of the West Netherlands and Central Netherlands basins, the target reservoirs have been eroded. Although the rapid facies variations within the Upper Jurassic and Lower Cretaceous suggest a potential for stratigraphic traps, these have yet to be encountered.

The Upper Jurassic and Lower Cretaceous oil and gas plays of the Broad Fourteens Basin are essentially the same as in the West Netherlands Basin, with the same source rocks and reservoir sandstones. All known trapped hydrocarbons are located along the northeastern margin of the inverted basin in Q1 (Helm, Hoorn, Helder, Haven and Halfweg fields; Roelofsen & De Boer, 1991) and in K18 and

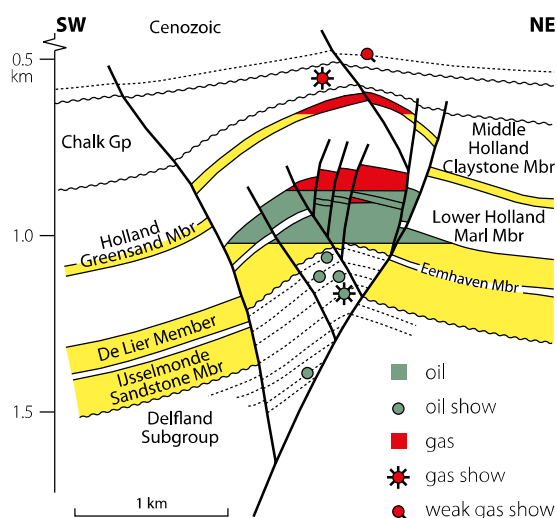


Figure 14.22. Example of a hydrocarbon trap in the Upper Jurassic and Lower Cretaceous in the West Netherlands (IJsselmonde-Ridderkerk field). Several stacked reservoirs are present, the shallower of which contain more gas and the deeper more oil. The complex anticlinal structure is a so-called 'flower structure' formed during strike-slip faulting related to inversion of the West Netherlands Basin and the Broad Fourteens Basin. Modified from De Jager and Geluk (2007).

L16 (Kotter and Logger fields; De Jong & Laker, 1992; Goh, 1993). These oil fields have ceased production. In the inverted areas of the Broad Fourteens Basin, as in the West Netherlands Basin, there is a timing problem regarding hydrocarbon generation and trap formation. In these areas, the Carboniferous source rocks became mature in the Late Jurassic or the Cretaceous, prior to the main phase of trap formation, which is Late Cretaceous or even younger.

In the Dutch Central Graben, several oil discoveries were made in Upper Jurassic and Lower Cretaceous sandstones (Wong et al., 1989; Wong, 1991). The largest field is F3-FB, where several sandstones in the Upper Jurassic Central Graben Group contain light oil/condensate (ca. 50° API) and gas. The volume of oil initially in place in this field is ca. 100 million barrels ($16 \times 10^6 \text{ m}^3$). Other oil accumulations are in F3-FA, F14-FA, F17-FA, F17-FB, F18-FA, L1-FB, L2-FA and L5-FA. Of these only F3-FA was developed as a gas-condensate producer. Gas caps are present in F3-FB and F18-FA. Most of these hydrocarbons have been generated by the Posidonia Shale, with minor contributions from the Aalborg and Sleen formations and from coals in the Central Graben Group.

The traps in the graben occur either in either four-way dip-closures in salt-related turtle-back structures (F3-FB, Fig. 14.23) or in tilted fault blocks. The southern sector of the graben has been more strongly inverted, resulting in greater structural complexity and compartmentalization of the traps. Reservoir distribution is another complicating factor in that the syn-tectonic sedimentary sequences have been deposited in fluvial, deltaic and lagoonal environments. This is especially the case in the southern part of the graben, where the sand-to-shale ratios vary greatly, and where individual sands seem to have a limited lateral extent.

In the Terschelling Basin only one small gas discovery has been made in block L6. This lack of success is attributed mainly to a lack of lateral and top seals. Gas charge may be limited as well, as migration paths from the Westphalian through the Zechstein evaporites are tortuous at best. Coals within the Central Graben Group are not very extensive but may nevertheless have contributed some gas charge. In the Wadden Sea area of the Vlieland Basin, the large Zuidwal field produces gas from the Vlieland Sandstone Formation in a drape structure over an Upper Jurassic volcanic complex (Perrot & Van der Poel, 1987; Hergreen et al., 1991).

Upper Cretaceous chalk play

The Chalk Group forms the reservoir in several major oil fields in the Norwegian and Danish sectors of the North Sea (e.g. Ekofisk, Dan, Gorm and Skjold). In the Netherlands, the first and so far only economic oil accumulation in the chalk is the Hanze field, which was discovered

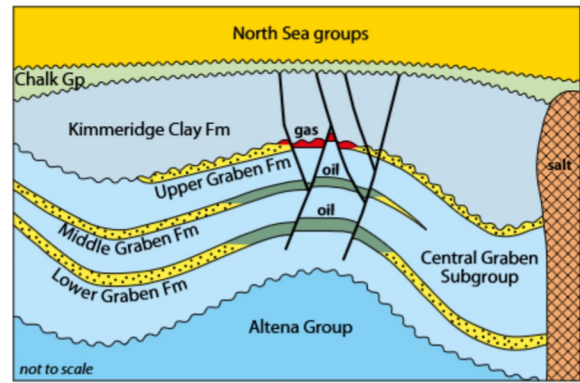


Figure 14.23. The F3-FB field in the northern part of the Dutch Central Graben. The three main Upper Jurassic sandstone reservoirs are stacked four-way dip-closed turtle-back structures. The reservoirs are compartmentalized by the faults and have different hydrocarbon-water contacts. Modified from De Jager and Geluk (2007).

in 1996 in offshore block F2 in the north of the Dutch Central Graben. The Ommelanden and Ekofisk formations constitute the reservoirs. This field is the largest producing oil field in the offshore Netherlands with a STOIP of $20.5 \times 10^6 \text{ m}^3$ (Dominik et al., 2000; Dana Petroleum, 2014). The success of the Hanze field initiated an increased interest in the chalk play (Van der Molen, 2004; Van der Molen et al., 2005; Guasti et al., 2009, 2010). In several structurally valid tests, oil shows have been encountered in the chalk, in particular in the Dutch Central Graben area. This includes the F17-Rembrandt and F17-Vermeer oil accumulations discovered in 2012 (Van Lochem, 2018) as well as the Fo6b-Snellius and Fo6b-Zulu oil accumulations (both discovered in 2014). So far none of these discoveries has come on stream. In most of these cases the oil is likely to have been derived from the Posidonia Shale. The Upper Maastrichtian and Danian parts of the Chalk Group in general have a fair reservoir quality for oil and gas reservoirs, due to the presence of fractures in the very fine-grained chalk. These fracture networks resulted from diapirism in the underlying Zechstein salt pushing the chalk upwards thus forming domal structures.

The only onshore gas field that has produced from the Chalk Group is the Harlingen field (Van den Bosch, 1983), but due to severe production-induced subsidence, it ceased production in 2008. Subsidence significantly exceeded predictions in both rate and amount (23 cm since the start of production in 1988). Strong subsidence is assumed to be the result of pore collapse and pressure solution within very porous layers of the reservoir (De Waal et al., 2016). In the West Netherlands Basin, gas has been tested from the Maastrichtian and Danian parts of the Chalk Group in the IJsselmonde structure. In the De Wijk field, chalk is assumed to be gas bearing as well (NAM, 2016a).

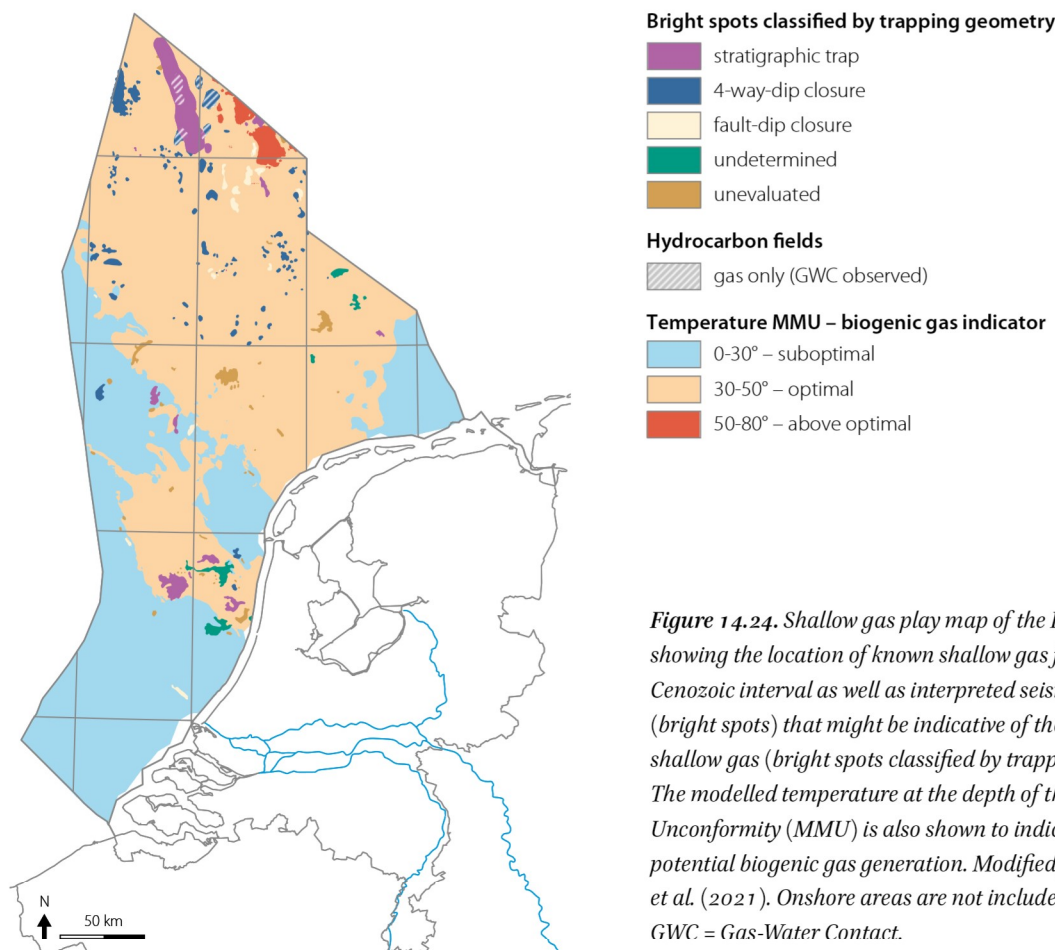


Figure 14.24. Shallow gas play map of the Dutch offshore showing the location of known shallow gas fields in the Cenozoic interval as well as interpreted seismic anomalies (bright spots) that might be indicative of the presence of shallow gas (bright spots classified by trapping geometry). The modelled temperature at the depth of the Mid Miocene Unconformity (MMU) is also shown to indicate zones of potential biogenic gas generation. Modified from Ecclestone et al. (2021). Onshore areas are not included in this study. GWC = Gas-Water Contact.

The Upper Maastrichtian and Danian parts of the Chalk Group in general have a fair reservoir quality for oil and gas due to the presence of fractures in the very fine-grained chalk. These fracture networks resulted from diapirism of the underlying Zechstein salt pushing the chalk upwards and forming domal structures. Although the reservoir characteristics of the Chalk Group are generally only poor to fair, they are comparable to those of the chalk in the Danish and Norwegian sectors of the North Sea. The lack of success in the chalk in the Netherlands is possibly related to the relatively shallow depth of burial and to a limited charge. The shallow burial has resulted in a reduced sealing capacity of the Paleogene above the somewhat overpressured chalk reservoirs, causing leaky traps.

Cenozoic plays (shallow gas)

The main Cenozoic gas accumulations occur offshore in the A and B quadrants at depths of 300 to 800 m in Plio-Pleistocene sediments of the westward prograding Eridanos shelf-edge delta system. Because of the shallow depth this offshore play is often pragmatically referred to as 'shallow gas play' (Fig. 14.24). Strong amplitude anomalies or bright spots and deeper velocity pull-downs on seismic profiles clearly indicate the presence of gas in subtle

four-way dip structures with a structural relief of only a few tens of metres. Structures are often situated above underlying diapirs, either due to Cenozoic salt rise or differential compaction (see also Bouroullec & Ten Veen, 2025, this volume). The more porous silty-sandy layers form the reservoirs while intercalated clays provide the necessary sealing capacity. Many of the shallow gas accumulations seem to be associated with gas chimneys, suggesting that leakage has taken place (Schroot & Schüttenhelm, 2003; Schroot et al., 2005; Ten Veen et al., 2014) from a deep thermogenic gas source, while gas composition and isotopes indicate a mostly biogenic source. De Bruin et al. (2022) argued that in some cases these gas chimneys may be artefacts of transmission and attenuation of the seismic signal below the shallow accumulations rather than indicating actual leakage.

The Plio-Pleistocene gas-bearing silts- and sandstones had long been recognized on seismic and had been encountered in wells drilled to deeper objectives. Eight shallow gas accumulations were discovered in the late eighties-early nineties. Although potentially economic production rates were tested from the silty sands in the topsets of prograding shelf-edge delta deposits in 1987 (well A18-02-S2), development was still slow for a number

of reasons. Pipeline infrastructure did not yet reach these remote fields, sand production from these unconsolidated sands posed a technical challenge, and the need for early compression formed an economic hurdle. It thus took some twenty years before the first shallow-gas discovery (A12-FA) came on stream in 2007. The A12-FA field ranks amongst the better producing gas fields in the Netherlands with production rates around 3 million Nm³/day from six wells. Currently production also comes from A18-A, B13-A and Fo2-Pliocene, while A15-A, B10-A and B16-A are expected to be developed in the near future. For B17-A development seems not viable. The reduction of pore volume by production-induced reservoir compaction has had a positive impact on the reservoir pressure and therefore recovery. The potentially negative effect of compaction on reservoir quality, i.e. reduction in permeability, is negligible (Van den Boogaard & Hoetz, 2012).

Gas in onshore Cenozoic sediments is of minor importance and is mostly associated with gas accumulations in traps with stacked reservoirs. Examples of these settings are the IJsselmonde structure in the West Netherlands Basin and the De Wijk field in Drenthe. In the IJsselmonde field small amounts of gas have been tested from the Eocene Oosteind Member, which lies some 30 m above the base of the Lower North Sea Group and has average porosities ranging from 34 to 39%. The De Wijk Member produced over a short period of time but was shut in due to sand and clay influx. In the De Wijk field the gas trapped in the tuffaceous sediments of the De Wijk Member is associated with underlying accumulations in the Liessel Member, Lower Cretaceous and Triassic reservoirs. Although the deeper parts of the gas field have been developed, the reservoir compaction of the unconsolidated De Wijk Member was very high and the consequent subsidence was such that production had to cease after only a small fraction of the GIIP had been produced. Recently production from the De Wijk Member was resumed in combination with the injection of nitrogen. This should drive the natural gas towards the production wells and at the same time keep the pressure from depleting (enhanced gas recovery). This way of producing has been successfully tested in an earlier phase in the underlying reservoirs of the De Wijk field (NAM, 2016a).

Gas compositions

The composition of the hydrocarbon and non-hydrocarbon components of natural gas are influenced by both the source rock and by secondary processes (e.g. mixing, migration fractionation, secondary cracking, biodegradation, water washing). Several studies have evaluated the gas composition of the Dutch on- and offshore (Lokhorst,

1997; De Jager & Geluk, 2007; Doornenbal & Stevenson, 2010). More recent studies have updated these compilations with newly released data and interpretations with respect to potential gas sources and secondary processes (Verweij et al., 2018).

Hydrocarbon gas

The main differences in hydrocarbon-gas composition are linked to the mixing of gasses expelled from different source rocks as well as to differences in source rock maturity. The gas-dryness ratio (C₁/C₂₊) of the Carboniferous, Rotliegend and Triassic reservoirs, as well as that of the Jurassic and Cretaceous reservoirs in the Vlieland Basin, Friesland Platform and Terschelling Basin, varies between 10 and 50. This mostly reflects variations in the maturity of the upper Carboniferous coals that sourced the gas. The most prominent exception is in the northern part of the Cleaverbank Platform, where the gas-dryness ratio suggests a much higher source-rock maturity than is measured on local, unaltered coal samples. This may be related to the local presence of igneous intrusions in the area, to longer migration distances or to the contribution of a more mature, deeper source rock such as lower Carboniferous coals. Some of the gas in the Zechstein reservoirs shows differences compared to other reservoirs, in isotopic composition as well as in the dryness ratio. This is most likely caused by secondary processes such as thermogenic sulphate reduction (TSR), as well as by source mixing. Low gas-dryness ratio of gas in Triassic reservoirs in the West Netherlands Basin indicates mixing of gas sourced from the Carboniferous with younger oil-associated gas. Similarly, the percentage of C₂₊ components in gas from Jurassic and Cretaceous reservoirs in the West Netherlands Basin, Broad Fourteens Basin and Dutch Central Graben is also high and related to oil-associated gas. This oil-associated gas is probably sourced from the Lower Jurassic Posidonia Shale Formation or from Upper Jurassic coals (De Jager et al., 1996).

Important non-hydrocarbon components in gas accumulations in the Netherlands, are nitrogen (N₂), carbon dioxide (CO₂) and hydrogen sulphide (H₂S). While N₂ and CO₂ mainly influence the calorific value of the gas, H₂S poses serious safety and health risks during drilling as well as during production, and significantly increases development costs.

Nitrogen

In Dutch gas accumulations nitrogen is the most abundant non-hydrocarbon component. The nitrogen content is highly variable and ranges from less than 1% to – locally – more than 85%. These ranges are also apparent on the larger scale of the Southern Permian Basin/Central Euro-

pean Basin System (Lokhorst, 1997; Gras & Clayton, 1998; Gerling et al., 1999; Krooss et al., 2005, 2008; Pletsch et al., 2010; Kotarba & Nagao, 2015). In general, sources of nitrogen in natural gas accumulations include atmospheric nitrogen, organic nitrogen in organic matter, such as peat, lignite, coal, anthracite, and dispersed organic matter in clastic and carbonate rocks, inorganic nitrogen (ammonium) in mineral phases of sedimentary and metamorphic rocks, inorganic nitrogen in nitrate salts (KNO_3 ; NaNO_3), and even the deep mantle (Littke et al., 1995; Krooss et al., 2005; Jurisch et al., 2012; Hoefs, 2015). Main potential sources of N_2 in the Netherlands include:

1. Organic sources: Westphalian coal measures, of which the most important coal-bearing source rock is the Maurits Formation, are the principal source rocks for Dutch hydrocarbon accumulations and are considered also to be the main source for nitrogen. The present-day distribution and thickness of these formations varies laterally due to uplift and erosion related to the Variscan Orogeny (Fig. 14.9a) and the depositional facies of the Westphalian A and B show regional variations as well. Additional sources of nitrogen are dispersed organic matter in Namurian and Westphalian shales and secondary sources include coals of the Dinantian Yoredale Formation (in the northern offshore), Zechstein source rock intervals (Copper Shale, ZEZ2C), as well as younger gas-prone source rocks, such as coals in the Mesozoic Delfland Subgroup and Central Graben Group, as well as the oil-prone Jurassic source rocks;
2. Inorganic sources include release of inorganic nitrogen from clay minerals in Namurian and Westphalian shales through ammonium-potassium exchange, from inorganic-nitrogen bearing minerals present in volcanic rocks in the Lower Rotliegend Group (extending from the Ems Low in Germany into the Lower Saxony Basin in the northeastern Netherlands) and from volcanoclastics in the Upper Rotliegend (Fig. 4 in Gaupp & Okkerman, 2011);
3. Magmatic sources: potential magmatic sources are listed by Van Bergen & Sissingh (2007) and Paleogene sources are described by Hernandez Casado & Underhill (2013), Underhill (2009), Wall et al. (2010). Magmatism is further discussed in Van Bergen et al. (2025, this volume).

Gas accumulations in Upper Rotliegend and Carboniferous reservoirs with a N_2 content exceeding 10% occur in the Province of Friesland, in the Lauwerszee Trough, in Groningen and the adjacent part of the offshore Schill Grund Platform (including Ameland wells and the H16-01 well). The maximum N_2 content in the Lauwerszee Trough is less than on the Groningen and Friesland Platforms. Both nitrogen and hydrocarbons in the Groningen gas field

probably originates from Westphalian sources in basins surrounding the Groningen field, while in the Lauwerszee Trough area the charge from Westphalian sources is local.

N_2 -rich gas accumulations containing more than 15% N_2 occur in the northeastern onshore part of the Friesland Platform (Upper Rotliegend, Rijnland Group, De Wijk Member), in Zechstein 2 carbonates in the onshore Lower Saxony Basin, and in the northwestern offshore in the D & E quadrants of the Cleaverbank Platform, Step Graben (and locally in K17-02, P02-03 in the Broad Fourteens Basin). The N_2 -rich gases in the Upper Rotliegend and Rijnland Groups in the Friesland Platform are probably related to timing and/or distance of migration. The other N_2 -rich gas accumulations seem to be related to specific local conditions, such as:

1. Rapid and intense heating of organic and inorganic nitrogen sources due to magmatic activity, especially in Step Graben and on the Cleaverbank Platform. Of special interest in this respect is the possible influence of deep-seated Paleogene dikes.
2. Intra-Zechstein processes, including Thermogenic Sulfate Reduction in the Lower Saxony Basin and the Broad Fourteens Basin, which explain why N_2 rich gases in Zechstein 2 carbonates also contain H_2S .
3. Intra-reservoir conditions in the De Wijk Member, related to the mineral composition of tuffites in combination with the possible influence of fluid flow and microbial activity at the shallow burial depth of this North Sea Supergroup unit.

Low to very low N_2 contents have been measured in gas samples from the central and western onshore and the southern offshore parts of the Netherlands (Roer Valley Graben, West Netherlands Basin, Indefatigable Platform and southernmost part of the Broad Fourteens Basin), as well as from the southern part of the Cleaverbank Platform (K, Jo3, Jo6 blocks) and Central Offshore Platform. This suggests that low N_2 contents may be related to recent gas charge from low maturity source rocks. However, low nitrogen content also occurs in combination with relatively dry and possibly more mature hydrocarbon gases. Alternatively, the nitrogen content might also be related to facies characteristics of the source rock, in combination with varying maturity.

Hydrogen sulphide

Many Zechstein gas accumulations in the eastern Netherlands as well as in the Broad Fourteens Basin and Friesland Platform contain hydrogen sulphide resulting in so-called sour gas. The H_2S content of these sour gas fields is commonly below 5 Mol% but can reach up to more than 30 Mol% (e.g. Vlagtwedde: 45 Mol%).

The most common sources of sulphur in the Dutch subsurface are:

1. Dissolved sulphate in formation water, originating from anhydrite in the Zechstein and Upper Germanic Triassic;
2. Accumulations of oil and wet gas, and their associated sources. For oil, the sources include Type II source rocks, such as Zechstein Copper Shale and ZEZ2C (Stinkkalk/Stinkschiefer), Jurassic source rocks and Namurian Geverik Shale. For wet gas, the main sources considered here are the Westphalian coals and organic matter rich Carboniferous shales;
3. Carbonate reservoirs (carbonates of the Zechstein and Upper Germanic Triassic groups, Dinantian carbonates, Cretaceous Chalk Group).

H₂S is mainly generated by Thermochemical Sulphate Reduction (TSR), which strongly accelerates at temperatures above ca. 120°C (Orr, 1977). Consequently, significant quantities of sour gas occur mainly where the reservoir is buried sufficiently deep, and where some of the above-mentioned sulphur sources are present. However, the complex interplay of all controls on TSR and other H₂S-generating processes, such as generation from carbonate source rocks and biochemical sulphate reduction, hampers accurate prediction of H₂S concentrations in undrilled prospects (Mittag-Brendel, 2000; Krooss et al., 2008).

Carbon dioxide

Carbon dioxide occurs naturally in the subsurface, often in large volumes (e.g. Barnes et al., 1978; Wycherley et al., 1999; Baines & Worden, 2004; Pearce et al., 2004). A large number of possible sources of CO₂ have been identified worldwide (Wycherley et al., 1999; Baines & Worden, 2004). The large spatial variation in CO₂ content in natural gas accumulations in the on- and offshore Netherlands results from several factors, such as different organic and inorganic sources for CO₂, high solubility of CO₂ in formation fluids and its high reactivity. CO₂ percentages in Dutch gas accumulations range up to 77%, with a large spatial variation. Sweet gas with CO₂ <1% occurs in about half of the wells. High to very high CO₂ contents of 10-20% and >20%, have been encountered at 7 and 10 well locations, respectively.

Both organic and inorganic sources of CO₂ have been identified in Dutch gas accumulations; gas accumulations may contain a mixture of both sources:

1. Organic source: especially during early maturation both gas and oil-prone source rocks generate CO₂. Given the widespread occurrence of especially gas-prone source rocks, organic CO₂ is an important contributor. Gas

samples containing CO₂ of organic origin are from different structural settings and stratigraphic units. Average CO₂ contents vary between 0.77 and 3.34 Mol%.

2. Inorganic source:

- a. CO₂ in gas accumulations in Zechstein carbonates (wells Geesbrug-1, Q02-03, Den Velde-2, -03 and Middelie-302) originated locally from dissolution of the carbonate rock. The high CO₂ content in well Geesbrug-1 may be due to the presence of H₂S and related carbonate dissolution by acidic fluids (Lokhorst, 1997; Gras & Clayton, 1998; Liu et al., 2014).
- b. Gas accumulations with more than 20% CO₂ are spatially related to Early Jurassic-Early Cretaceous rift-related magmatism and Paleogene magmatism. The high heat flow might have increased CO₂ generation from inorganic carbonate sources, with a possible contribution of direct CO₂ outgassing from the magmatic source;

Mixed organic-inorganic origin of CO₂ occurs where an organic origin is predominant, such as on the Cleaverbank Platform (in Upper Rotliegend reservoirs), while a predominantly inorganic origin is spatially related to the presence of igneous intrusions (Broad Fourteens and West Netherlands basins).

Future potential

The Dutch government's policy is to gradually transform to a CO₂ free energy system by 2050. As long as natural gas is needed domestic production is preferred over import. For that reason offshore production will be stimulated, but at the same time new exploration licences onshore will no longer be granted, no new licences for production from the Wadden Sea area will be issued and shale gas exploration and production will not be permitted anymore.

Proven plays

The Netherlands clearly is a mature hydrocarbon province. With most of the current licences covered with 3D seismic data and with many wells drilled, the main prospective fairways have already been well explored. Yet, new discoveries continue to be made, although there are indications of a reduced exploration efficiency or 'creaming' (Fig. 14.25). From 1970 to 2000 the average discovery rate was 2×10^9 m³ per well, but from 2000 to 2020 this rate decreased to only 0.8×10^9 m³ per well. The exact reason needs to be examined. It may be due either to risk-averse exploration with a focus on near-field developments or to the exhaustion of the prospect portfolio. Note that there is also a remarkable change in exploration activities from 32 wells per year in the period 1970-1997, via 9 wells per year

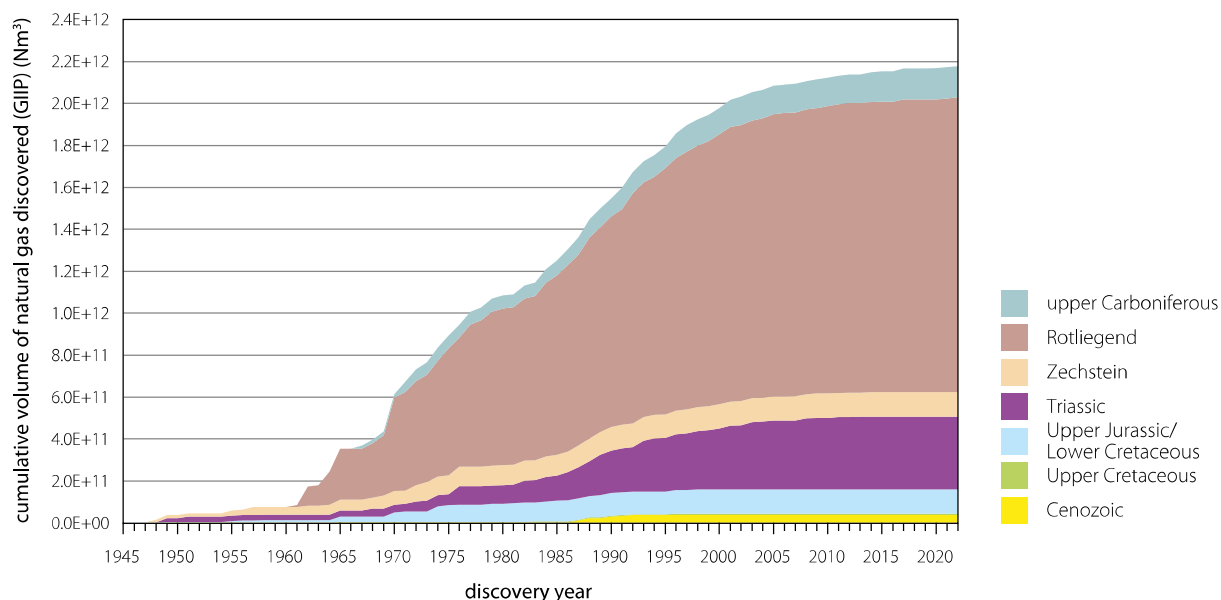


Figure 14.25. Creaming curve of gas resources of the small fields (excluding Groningen). Note that the contribution of the Upper Cretaceous is minor. Source: TNO – Geological Survey of the Netherlands.

from 1997-2015, decreasing to only 2-5 wells per year in the period 2015-2022 (Fig. 14.6).

The steady pace of new discoveries over the last two decades of the 20th century certainly partly resulted from the application of 3D seismic technology, which has revealed traps that hitherto were unnoticed. More recently advances in seismic processing, such as pre-stack depth migration, have further improved the accuracy of predictive subsurface models. In addition, geological concepts continue to be improved, resulting in the identification of new play opportunities and trapping styles. The future potential for new gas discoveries in the Netherlands, based on identified prospects in proven plays, as reported by the Ministry of Economic Affairs and Climate Policy (MEACP, 2022), is estimated to be approximately $80 \times 10^9 \text{ m}^3$ of gas. Based on a scenario with four exploration wells per year and subsequent field development, a total production of $56 \times 10^9 \text{ m}^3$ could potentially be realized in the next 25 years. These future reserves represent the addition of risked volumes of identified prospects in proven plays. These numbers do not include the unidentified potential that may result from identification of new plays and prospects, for example through the application of new technologies or extensions to proven play areas.

In a densely explored area such as the Netherlands, ongoing exploration continues to lead to new geological insights. The great variety of structural styles and potential reservoir-seal pairs only improves the chances that unidentified plays and prospects can be recognized. New technological developments are likely to provide increased accuracy to the predictions and a better understanding of

play and prospect risks. A break-through to improve gas production from tight reservoirs may not only allow the exploitation of many accumulations that are currently uneconomic but will also broaden the scope for exploration. Similarly, a break-through in permeability prediction (e.g. from seismic data) would result in the de-risking of prospects that are currently considered high risk. And, last but not least, higher gas prices, lower economic thresholds or cheaper drilling- and production technologies may render presently non-commercial accumulations economic in the future.

New or speculative plays

In most of the Netherlands the Devonian occurs at depths greater than 5 or 6 km and is a speculative target at best. Dinantian carbonates on the northern flank of the London-Brabant Massif and in well Winterswijk-1 in the east of the Netherlands have been found tight and water-bearing. Nevertheless, some potential remains in karstified and fractured platform-edge carbonates sealed by Namurian shales that may contain source rocks (Van Hulten & Poty, 2008; Jaarsma et al., 2013). In the P blocks exploration activities focus on this play, but no wells have been drilled yet. The 53/14a-2 exploration well just across the median line in UK waters with a similar Dinantian target was disappointing.

Wells in northern Belgium have indicated good porosities and Darcy scale permeabilities in karstified Dinantian carbonates near Loenhout, east of Antwerp. The Loenhout gas storage project was developed in this carbonate reservoir. The same Dinantian carbonates are the target

of a successful geothermal project in Mol (Belgium) and of a short-lived geothermal project near Venlo (Limburg). Though these Dinantian carbonates are directly overlain by the organic-rich Geverik Member, this has not given rise to any gas accumulations. Even though, the Geverik Member was a potential exploration target for shale-gas.

In the northern offshore, Viséan-Namurian sandstones of reservoir-quality are assumed to be present and Viséan-Namurian coals and shales are considered promising source rocks to charge these reservoirs in the northern part of the Dutch Central Graben and the adjacent Step Graben. The presence of a deep, mature Paleozoic source rock is supported by hydrocarbon shows and vitrinite reflectance data. In the southern E and F quadrants, charge may also occur laterally from upper Carboniferous Westphalian coals (Ter Borgh et al., 2018). Intra-Westphalian gas accumulations must rely on intra-formational seals and on lateral seals by favourable juxtaposition across faults. This concept is proven by a small and uneconomic gas discovery in block Q13. Also elsewhere in the Netherlands, intra-Westphalian shales occasionally seal small gas columns. Although no regional Westphalian seals have been identified, the 'marine bands,' which form laterally extensive but thin shale intervals, could prove to be effective as intra-formational seals.

The recent discovery of the Ruby and Turkoois fields straddling the Dutch German border (block No5 and No4, Fig. 14.17) proved the potential of the Basal Rotliegend Sandstone Member (Upper Rotliegend Group) in that area. This play certainly needs more appraisal drilling, but this discovery also focussed attention on possible gas accumulations in Rotliegend sandstones along the northern margin of the Southern Permian Basin in the A and B quadrants (De Bruin et al., 2015). Prospectivity in that area relies on finding structurally valid and well-sealed traps. A risk is the absence of Westphalian source rocks. However, Namurian organic-rich shales and Viséan coals (if present) display source-rock quality in nearby German and British wells.

Elsewhere, remaining Rotliegend potential is likely to be present in down-faulted traps relying on laterally sealing faults as was proven in the north of the Netherlands onshore (Corona, 2005). A technological break-through in the production of gas from tight reservoirs (permeability <1 mD) would open up additional potential, although as with the anticipated production of shale gas the economics may not be favourable.

Two potential Zechstein hydrocarbon objectives were proposed by Geluk (2000). Firstly, Z1 reefs, which could be present along the Dutch Central Graben, on the Mid-North Sea High and in the eastern Netherlands, as well as above topographic base-Zechstein highs elsewhere. Secondly,

Z2 carbonates in slump and mass-flow deposits in the western offshore, in front of a carbonate platform that existed in the southern K and L quadrants. Furthermore, Z2 off-platform highs may occur in this area. The recent Pensacola gas discovery in Zechstein Carbonates in the UK part of the Southern North Sea may open up this play. For successful exploration of these plays, 3D seismic interpretation and high-resolution sequence stratigraphy form a prerequisite.

Above the Zechstein salt, the Triassic is in many places intricately structured, and several potential reservoir objectives are present. New prospects may be present in the A and B quadrants formed by fluvial reservoir rocks in local depocentres with local sourcing from the north. These hydrocarbons would have to come from the lower Carboniferous coals of the Elleboog and Yoredale formations or the Namurian shales.

Several oil discoveries in the Upper Jurassic and Lower Cretaceous of the Dutch Central Graben are sub-economic because of compartmentalization related to the presence of sealing faults in combination with a complex depositional reservoir architecture. Improved understanding of their depositional setting may lead to a better assessment of risks and to improved prediction of reservoirs, thus creating possibilities for development of these accumulations.

Finally, the shallow gas play has proven to be a valid gas play, but still many areas need further exploration to get a better grip on its presence and the gas saturations.

Unconventional gas or shale gas

The shale gas rush in the USA which started around 2005, quickly spread to other parts of the world, including the Netherlands. The first exploration licence that explicitly targeted shale gas in the Netherlands was applied for in 2009. Shale gas occurs in tight, organic-rich (low permeability) rocks which are of regional or sub-regional extent and, if gas-bearing do not have a well-defined hydrocarbon-water contact. Targets in the Netherlands were the Namurian Geverik Member in the Carboniferous, the Epen Formation and the Jurassic Posidonia shales (Van Bergen et al., 2013; Zijp et al., 2015, Fig. 14.26).

The Geverik member is a relatively thin (15-25 m) siliceous and bituminous, carbonate-rich black shale with a high TOC of 8-9% (Van Balen et al., 2000; Bouw & Lutgert, 2012; Zijp et al., 2015). In the Netherlands this source rock was penetrated by 12 wells, but it is assumed to underlie large parts of the country. The main source of information on this source rock interval is well Geverik-1 which was cored over more than 1200 metres and included the entire Geverik Member. Due to its depth of burial its resource potential is assumed to be mainly restricted to the southern

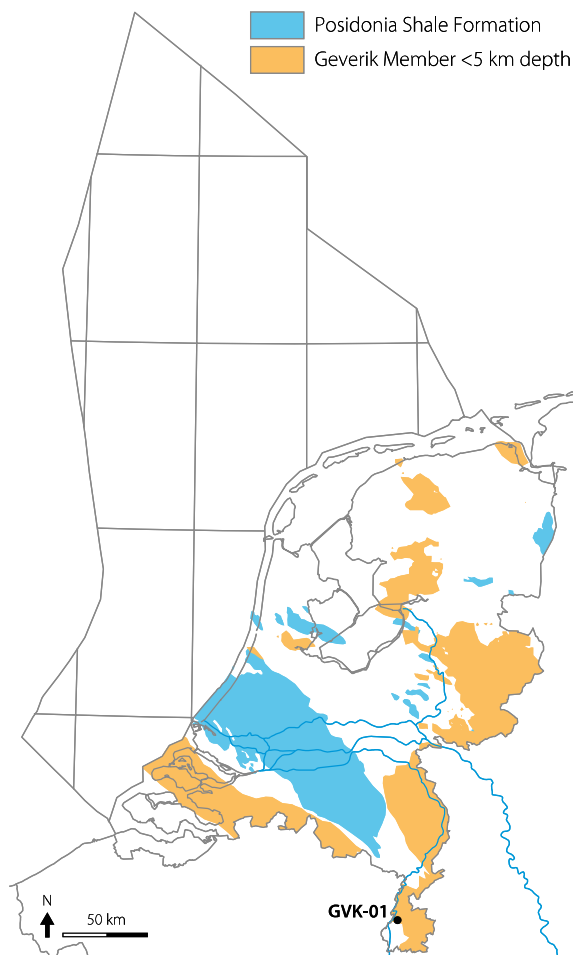


Figure 14.26. Onshore areas with shale gas/oil exploration potential for the Lower Jurassic Posidonia Shale Formation and the Namurian Geverik Member. For the Geverik Member only the distribution at a depth of less than 5000 m is shown as deeper burial is considered not to be prospective. Offshore shale gas production is assumed not to be prospective for economic reasons (from www.nlog.nl).

unavoidable. Despite these techno-economic challenges, a number of licences to explore for shale gas were applied for. In 2018, based on public opposition the Dutch government decided that exploration for shale gas was not permitted (Kamerstukken 32849 and 33529 nr. 126) and to this day the shale gas play is yet unproven as no exploration well has been spudded.

Acknowledgements

This paper is an updated version of the chapter published by de Jager and Geluk in 2007. We regret that Mark Geluk passed away in 2018. We hereby gratefully acknowledge his contribution to the development of the play concepts presented here. These concepts are based on the work by several generations of geoscientists. Comments on this manuscript by Bert Manders and Evert van de Graaff are gratefully acknowledged.

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.28164023>.

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margin of the Carboniferous Basin where burial depths are less than 5000 m (Fig. 14.26).

The Jurassic Posidonia shale (Toarcian, 182-180 Ma) is the main oil source rock in the Netherlands. The formation has been through drilled over 100 times, both on and offshore, but never as the primary target of a well. For that reason, few samples and measurements are available. Extensive outcrop analogue and well sampling studies have shown variable potential (e.g. Song et al., 2015; Ter Heege et al., 2015; Houben et al., 2016, 2018).

Shale gas resource estimates are poorly constrained due to the lack of data. Regional studies (Zijp, 2012, 2017; Zijp et al., 2017) have estimated recoverable reserves of 200 up to 500 x 10⁹ m³. Herber & De Jager (2010) estimated a mere 10-20 x 10⁹ m³ for the Geverik Member as surface constraints were likely to prevent drilling a large number of wells.

Development of unconventional reservoirs requires the drilling of a many closely spaced, preferably horizontal wells to drain the tight rocks. Ultimate recovery per well is significantly lower than from conventional gas fields (at least 20-50 times, Herber & De Jager, 2010). Moreover, in most cases large scale hydraulic fracturing operations are

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