3D view of the top Rotliegend reservoir showing the depth structure of the Groningen gasfield and the Slochteren-1 exploration well. The perspective is from the ESR. Field length and width are approximately 40 km and 30 km, respectively. Colour scale: red is at 2600 m and dark blue is at 3000 m below mean sea level.
Chapter 15 — Reserves and production history

1 Introduction

Figures 15.1 and 15.2 show oil and gas accumulations (pumped into 1244 fields) discovered so far within the SPB area. It is immediately apparent that the vast majority of the fields are concentrated in a relatively narrow east–west-trending corridor in the SPB. This chapter describes the history of the oil and gas fields within the SPB and considers two key questions:

1. What are the petroleum geological controls on the location of the oil and gas fields?
2. How have the discovery of these fields and the associated hydrocarbon volumes evolved over time?

The objective is to provide some insights into the history of exploration and production (E&P) in the SPB area and offer information on E&P opportunities for the future.

2 Information and data

2.1 Geological information

The general approach has been to use a synthesis of information and interpretations on the petroleum geology found elsewhere in this Atlas and combine that with the data on the known oil and gas fields (see Chapters 6–12, Figures 6.20, 7.20, 7.21, 8.18a, 9.11, 10.11 and 11.24). The descriptions of the hydrocarbon resources in each chapter have, to some extent, already given an explanation of why fields are where they are.

Chapter 13 defines six petroleum provinces in the SPB area, which are characterized by a unique source–rock type and age. In addition, 13 petroleum provinces have been delineated, each of which hosts one or more of the petroleum systems. The provinces are listed in Table 15.1.

Table 15.1 Petroleum provinces and their key characteristics.

<table>
<thead>
<tr>
<th>Petroleum system / province</th>
<th>Main reservoir(s)</th>
<th>Number of accumulations</th>
<th>Volume Gas (bcm)</th>
<th>Oil (m₃)</th>
<th>Example fields</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Devonian source</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I Baltic Basin</td>
<td>Carboniferous</td>
<td>68</td>
<td>10</td>
<td>0.9</td>
<td>62</td>
</tr>
<tr>
<td>Carboniferous &amp; Permian source</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II Anglo-Dutch and North German basins</td>
<td>Bottling, Zechstein, Triassic, Carboniferous</td>
<td>761</td>
<td>6878</td>
<td>4668</td>
<td>0.11</td>
</tr>
<tr>
<td>III NW Midlands and Cleveland Basin</td>
<td>Carboniferous, Zechstein</td>
<td>56</td>
<td>3.3</td>
<td>6.7</td>
<td>4.7</td>
</tr>
<tr>
<td>IV Thuringian and Sachsen-Anhaltian basins</td>
<td>Zechstein, Triassic</td>
<td>18</td>
<td>4.4</td>
<td>5.6</td>
<td>0.13</td>
</tr>
<tr>
<td>V Pomerania</td>
<td>Carboniferous, Bottling, Zechstein</td>
<td>35</td>
<td>16</td>
<td>2.2</td>
<td>6</td>
</tr>
<tr>
<td>VI Lower-Silesian Moravian and Bohemian</td>
<td>Bottling, Zechstein</td>
<td>175</td>
<td>181</td>
<td>82</td>
<td>27</td>
</tr>
<tr>
<td>VII Lublin Basin</td>
<td>Carboniferous</td>
<td>4</td>
<td>1.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>basin source</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VIII World Boom</td>
<td>Jurassic</td>
<td>19</td>
<td>0.12</td>
<td>3.3</td>
<td>2.1k</td>
</tr>
<tr>
<td>IX Tall End Graben</td>
<td>Carboniferous</td>
<td>22</td>
<td>141</td>
<td>70</td>
<td>456</td>
</tr>
<tr>
<td>X Dutch Central Lobe</td>
<td>Jurassic</td>
<td>14</td>
<td>2.7</td>
<td>32</td>
<td>2.1</td>
</tr>
<tr>
<td>XI West Netherlands and Broad Firths basin</td>
<td>Jurassic, Carboniferous</td>
<td>60</td>
<td>139</td>
<td>109</td>
<td>0</td>
</tr>
<tr>
<td>XII Lower Saxony and British Isles</td>
<td>Jurassic, Carboniferous</td>
<td>354</td>
<td>10</td>
<td>7.1</td>
<td>437</td>
</tr>
<tr>
<td>Shallow gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XIII Shallow gas</td>
<td>Carboniferous</td>
<td>7</td>
<td>13</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

* All information is up to date as of 15 th January 2007. Oil and gas reserves are treated separately, i.e. they have not been converted to Oil Equivalent units. Reserves are defined as unattributed recoverable reserves (proved and probable), according to today’s estimates. Reserves are not classified in detail according to one of the many existing country or company specific classification schemes in use, but beyond the scope of the Atlas to consider the subtle differences between the classifications, let alone try to standardise them. However, reserves are classified as Developing or Unattributed, depending on the development status of the field. A field that consists of pure primary or secondary accumulations is considered Developing, if at least one of the accumulations has been developed.

UK operators have given permission to use their field volume data under the following disclaimer: “UK ultimate recoverable reserves quoted are the opinion of the operator at the time of the request to publish, and do not necessarily reflect the views of any partners in the relevant joint venture.”

In Chapter 14, the vast set of exploration wells drilled in the SPB area has been presented and statistically converted to Oil Equivalent units. Reserves are defined as ultimately recoverable volumes (proven and probable), according to today’s estimates. Reserves are not classified in detail according to one of the many existing country or company specific classification schemes in use, but beyond the scope of the Atlas to consider the subtle differences between the classifications, let alone try to standardise them. However, reserves are classified as Developing or Unattributed, depending on the development status of the field. A field that consists of pure primary or secondary accumulations is considered Developing, if at least one of the accumulations has been developed.

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The historical discovery process of oil and gasfields may have been influenced by non-geological factors the fields and associated hydrocarbon volumes that have been discovered by exploration drilling. This chapter focusses on 3.2 Key elements of the exploration and production history

To help visualise the synthesis of information, maps have been generated for each petroleum province, and North German basins (Section 5.2.1). The pattern of exploration wells show the extent to which hydrocarbons in the SPB. This is specifically dealt with in the sections describing the Anglo-Dutch The deposition of the Zechstein halite cover has had a major influence on the migration and trapping main control on the distribution of the oil and gasfields; the reservoir-facies maps provide another determined groups of proven oil and gasfields within them. The source-rock distribution maps show the A common feature of the petroleum provinces is that they all have accumulations of oil or gas that have been proven by drilling. This chapter reviews the specific features of these provinces and the geographically co-located petroleum provinces.

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5.2 Carboniferous and Permian-sourced fields

5.2.1 Anglo-Dutch and North German basins

The Carboniferous, in particular the Westphalian Coal Measures, provides the principal source-rock interval in the Anglo-Dutch and North German basins. Distribution of these coals and their maturity largely dictates the distribution of hydrocarbons accumulations. To date, an estimated total of 700 km of recoverable gas have been discovered in reservoirs that are inferred to have been sourced by the Carboniferous petroleum system. Oil generated from Carboniferous source rocks is of minor importance in the area. The extent of this petroleum province and the hydrocarbon fields are shown in Figure 15.5. Details on the fields are given in Appendix 3.2.

Factors controlling the distribution of hydrocarbon fields

A major controlling factor is the presence of Upper Permian Zechstein evaporites, the principal seal to the Lower Permian Rotliegend and Zechstein reservoirs (pre-salt reservoirs). Zechstein salt also commonly prevents gas from migrating into Triassic and younger reservoirs (post-salt reservoirs). The majority of the fields in the Anglo-Dutch Basin (78% of all fields) contain reserves in Rotliegend reservoirs. Most of the fields (361 out of 407) are located beneath the Zechstein, where its thick evaporite successions from the primary seal. The rest of the fields (66) are located at the Zechstein Basin margin, where slope and lagoon/slope facies are found. The evaporites in these marginal Zechstein deposits apparently still provide an effective seal to the Rotliegend reservoirs. No Rotliegend fields are located in the so-called ‘Tribe’ Zechstein, where there are insufficient evaporites to form a seal and so gas has migrated to the next seal in places, the shales and evaporites of the Triassic Selkirk and Rot formations and the Lower Cretaceous Vaalrand Clastic Formation. A unique occurrence in the area is the Harlinge field, an Upper Cretaceous chalk reservoir beneath Triassic clays trapped by the Carboniferous.

Development of reservoir quality sandstones in the Rotliegend is another key factor controlling field distribution in the region. Aeolian sandstones are preserved in a delta belt around the southern part of the area and, to a more limited extent, around the northern margins, and pass basinward into contemporary non-reservoir plays-landward sands and evaporites.

Figures have been documented and no oil and gas fields have been discovered so far. The quality of the Malda Cardinham reservoirs depends mainly on the intensity of quartz cementation, which is dependent on its maximum depth of burial (Jokinen, 1998; Meijer et al., 2007). Small oilfields are also present in Flandrian and Mission limestones, mainly carbonate buildups that developed in marginal zones of the basin (Brambilla et al., 1992; Koeve et al., 1994).

Cumulative gas reserves (bars) Cumulative oil reserves (bars)

Cumulative gas reserves (m) Cumulative oil reserves (m)

Cumulative gas reserves (kbar) Cumulative oil reserves (kbar)

Cumulative gas reserves (m²) Cumulative oil reserves (m²)

Cumulative gas reserves (m³) Cumulative oil reserves (m³)

Cumulative gas reserves (kbar) Cumulative oil reserves (kbar)

Cumulative gas reserves (m²) Cumulative oil reserves (m²)

Cumulative gas reserves (m³) Cumulative oil reserves (m³)

Cumulative gas reserves (kbar) Cumulative oil reserves (kbar)

Cumulative gas reserves (m²) Cumulative oil reserves (m²)

Cumulative gas reserves (m³) Cumulative oil reserves (m³)

Cumulative gas reserves (kbar) Cumulative oil reserves (kbar)

Cumulative gas reserves (m²) Cumulative oil reserves (m²)

Cumulative gas reserves (m³) Cumulative oil reserves (m³)
Almost all gas-bearing reservoirs (45 out of 101) in the Zechstein are in the 22 and 23 subbasins are located in a relatively narrow band of platforms, grabens and slope facies located between the evaporite basins and the fringe facies. Stacked Zechstein and Rotliegend reservoirs are found in eight fields within the Anglo–Dutch and North German basins.

Post-salt producing reservoirs are more often located at either the fringes of the Zechstein Basin, such as the Triassic Jurassic and Cretaceous fields in the North Sea and adjacent waters, or in the German border region (Coevorden) and the northern edge of the Lower Saxony Basin in Germany. Carboniferous reservoirs sourced by the Zechstein require even larger migration paths than the Triassic. The D-1a-Fa field is one of the early discoveries of such a reservoir. Some 14% of all fields in the Anglo–Dutch and North German basins have Triassic reservoirs. Jurassic and younger reservoirs make up only 6% of the fields. In combination, these fields contain less than 10% of the total gas ultimate recovery in the region.

The distribution of Carboniferous fields is controlled by the presence of reservoir sands and a mudstone top seal (and the Proven Unconformity), or by internal seals within the Zechstein and Stephanian sections. The fields are located in three areas: the offshore Shielfield / Cullen Bank area, the Dutch–German border area, and the Zechstein Basin area. Carboniferous reservoirs discovered in the Dutch sector in the 1960s and 1970s followed the succession on the US side of the median line, and are related to intracratonic Westphalian reservoirs below the Proven Unconformity. These discoveries have been developed for a long time due to unconformity controls. A significant component of the gas found in the Shielfield / Cullen Bank area has been generated from Rovannah marine source rocks (Gerling et al., 1999c), which should extend the geographic area of exploration for Carboniferous reservoirs in the Zechstein Basin. The lack of sealing Zechstein evaporites and migration along fault-plane conduits in these areas relate to inverted basins such as the Dutch Central Graben, the East Midlands area and the Cleveland Basin (Chapter 6). The principal source rocks are Rovannah marine shales locally supplemented by late Devonian (Tournaisian) marine shales (Revland Shale Formation). Westphalian Coal Measures can constitute an additional source rock, for example through these shales are immature in the area, migration from the more deeply buried marine shales in the adjacent offshore Anglo-Dutch Basin can not be discounted.

Almost all of the discovered fields are currently in production or under development, which indicates the mature stage of development of the region. Of the total gas produced, 42% has been from the Netherlands (19% offshore, 13% onshore), 37% has been from fields offshore UK and 21% has been from Germany. 5.2.2 East Midlands and Cleveland Basin

The UK onshore Carboniferous petroleum province spans two discrete areas within the Northwest European Carboniferous Basin, the East Midlands area and the Cleveland Basin (Chapter 6). The principal source rocks are Rovannah marine shales, locally supplemented by late Devonian (Tournaisian) marine shales (Revland Shale Formation). Westphalian Coal Measures can constitute an additional source rock, for example through these shales are immature in the area. Migration from the more deeply buried marine shales in the adjacent offshore Anglo-Dutch Basin can not be discounted. The area contains 41 fields and discoveries plus 25 gasfields and discoveries (Figure 15.7, 13 fields are not shown). Eighteen of the oilfields are currently producing, all of which occur in the East Midlands: nine gasfields are producing, four in the East Midlands and five in the Cleveland Basin. A full list of the fields, and the latest published production statistics are given in Appendix 3.3. Factors controlling the distribution of hydrocarbon fields

The East Midlands comprises several east–west–east–west trending Carboniferous sub-basins. Potential reservoir rocks are abundant in the Devonian to Carboniferous succession; however, the main oil reservoirs are Rovannah marine shales within the Middle and Upper Carboniferous. Zechstein evaporites within the lower and middle Carboniferous. The Zechstein evaporites within the lower and middle Carboniferous are potentially an important seal for Carboniferous gas reservoirs. The Zechstein reservoirs discovered in the Zechstein Basin are not a significant part of the total gas production in the UK.
The main reservoirs are Upper Permian (Zechstein) limestones, basal Permian sandstones (Rotliegend Yellow Sandstone Formation) and Namurian sandstones. Jurassic and Early Cretaceous migration of hydrocarbons from deeply buried Namurian shales was mainly towards the southern margin of the basin. Some re-migration may have taken place northwards towards the axis of the basin following Tertiary inversion. Although most of the discoveries made in the basin lie along the faulted southern margin, prospects along the northern faulted margin of the basin offer further potential.

**Exploration**

There have been 166 exploration wells aimed at predominantly Carboniferous plays in the East Midlands and the Cleveland Basin since 1919 ([Figure 15.8](#)). The first East Midlands oil discovery was made in 1919 by the Dinantian Hardstoft well ([Figure 15.7](#)) production from Carboniferous Limestone beds in an anticlinal trap. A major oil-exploration effort was made between 1938 and 1946, when 32 657 t of condensate had been produced by the end of 2007. The Hardstoft field continues to produce oil for about 25 years following its discovery in 1919. Development of the Eckington-Duke’s Wood field followed during the 1940s. Although the Farley’s Wood oilfield was discovered in 1943 it did not come onstream until 1945; however, it continued to produce to the present day. The Melton oilfield started production in 1946, 3 years after it was discovered. The Bottesford, Stainston, Combs Warren and Scratby North oilfields began production between 1985 and 1989. A further 11 oilfields were developed during the 1980s, all of which were onstream as of the end of 2007. The Eckington-Duke’s Wood field was the first to be developed in the Cleveland Basin. Production began in 1980 and continued until 1986. It was followed by the Lintonfield gasfield, which came onstream in 1971, but produced for only 3 years ([Stagg, 1983]). The Hatfield Moor gasfield had been in production from 1988 to the present day. The Caythorpe, Kirby Muxloe, Risby, Melton, Trurofield and Saltfleetby gasfields came onstream between 1992 and 1999, and the Pocklington and Emsworth gasfields began production in 2001 and 2002 respectively. All of these major recent developments remain onstream at present.

In the East Midlands, there are 11 oilfields which have seen production, 18 are currently producing and one oilfield (Reepham) is under development. Three gasfields have seen production (two in the Cleveland Basin) and nine fields (five in the Cleveland Basin) were producing gas at the end of 2005. The producing oilfields of the East Midlands had yielded 8.11 mln m³ oil by the end of 2005. Note that this figure includes production from six fields for which no estimate of ultimate recovery is known. The total gas production by the end of 2005 for the fields in the East Midlands and the Cleveland Basin is not known.

**Cleveland Basin**

The Jurassic to Early Cretaceous Cleveland Basin is an onshore component of the Anglo-Dutch Basin, specifically of the Solent Basin, located in north-east England. It was inverted during the Tertiary Alpine Orogeny, and it overlies a Carboniferous basin that was itself inverted by the end-Carboniferous Variscan inversion. The Carboniferous source rocks of the Cleveland Basin lie beyond the wet-gas window, although Permian gas-prone source rocks are largely absent due to pre-Pennine erosion from the basin, except at the Robin’s Hood Bay horsetail where a north-west–south-east-trending outcrop terminates nearby offshore.

The main reservoirs are Upper Permian (Zechstein) limestones, basal Permian sandstones (Rotliegend Yellow Sandstone Formation) and Namurian sandstones. Jurassic and Early Cretaceous migration of hydrocarbons from deeply buried Namurian shales was mainly towards the southern margin of the basin. Some re-migration may have taken place northwards towards the axis of the basin following Tertiary inversion. Although most of the discoveries made in the basin lie along the faulted southern margin, prospects along the northern faulted margin of the basin offer further potential.

**Chapter 15 — Reservoirs and production history**

**Development history**

The Eckington-Duke’s Wood field continued to produce oil for about 25 years following its discovery in 1919. Development of the Eckington-Duke’s Wood field followed during the 1940s. Although the Farley’s Wood oilfield was discovered in 1943 it did not come onstream until 1945; however, it continued to produce to the present day. The Melton oilfield started production in 1946, 3 years after it was discovered. The Bottesford, Stainston, Combs Warren and Scratby North oilfields began production between 1985 and 1989. A further 11 oilfields were developed during the 1980s, all of which were onstream as of the end of 2007. The Eckington-Duke’s Wood field was the first to be developed in the Cleveland Basin. Production began in 1980 and continued until 1986. It was followed by the Lintonfield gasfield, which came onstream in 1971, but produced for only 3 years ([Stagg, 1983]). The Hatfield Moor gasfield had been in production from 1988 to the present day. The Caythorpe, Kirby Muxloe, Risby, Melton, Trurofield and Saltfleetby gasfields came onstream between 1992 and 1999, and the Pocklington and Emsworth gasfields began production in 2001 and 2002 respectively. All of these major recent developments remain onstream at present.

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**Field characteristics and volumes**

The locations of oil and gas accumulations/fields is shown in [Figure 15.9](#) and the main field attributes are listed in [Appendix 3.4](#) (from: Earin et al., 1998b; Pake & Raich, 1996; Schwerdt et al., 2000; Paternak et al., 1998; Bleichert et al., 2000, 2002). [Figure 15.10](#) shows the produced oil and gas volumes in fields discovered in the Thringstone and Sub-Permian basins ([Miller et al., 1993; Earin et al., 1998b; Paternak et al., 1994, 1998]). Some of the gasfields in the Thringstone Basin also contain condensate, of which 32 857 t had been produced by the end of 2007.
The Thuringian Basin is located in central Germany. It is bounded to the north by the Thuringian Forest and to the south by the Mountains in the north. The Sub-Hercynian Basin is a small depression to the north of the Harz Mountains. Both basins are part of a large embayment that started to develop during the Werra and by the Harz Mountains in the north. The Sub-Hercynian Basin is a small depression to the north of the Thuringian and Sub-Hercynian basins. The next discoveries were made at the Mühlhausen gasfield in January 1981; the Daszewo N gasfield has an Upper Carboniferous reservoir with reserves of 1.4 bcm (the field is well-known for the huge fire that burned for more than a month from December 1980 to January 1981); the Boszów-1 gasfield was discovered in 1988 in the borehole. The research shows that oil generation had started in the Late Jurassic although the main phase took place in the Cretaceous. The exploration curve shows that oil accumulation started in the Late Jurassic although the main phase took place in the Cretaceous. In particular, algae and cyanobacteria were formed to form a huge biomass that played an important role in the coalification of the region, which led to many areas of the Thuringian and Sub-Hercynian basins. After a period of time, a new exploration program started in 1981 when modern high-resolution 3-D seismic surveys, which had not previously been used, were carried out on Stassfurt Carbonate target, (Bella et al., 1988) within both the Thuringian and Sub-Hercynian basins. Potential oil-platform hydrocarbon traps were identified in both basins (Bella et al., 1988; Pinkal et al., 1989). In 1986, prospects were tested at the Stassfurt Z2 well in the Stassfurt Carbonate basin and at Spritzen Z2 in the Thuringian Basin; however, neither known hydrocarbons nor economic amounts. The typical curve shows the two main discovery phases. The first relatively large discovery was made during the early stage of exploration and the second discovery phase correlates with the main drilling phase. Systematic studies of the Polish Landau structural units were started in 1955 by the Petroleum Geological Survey in collaboration with the Polish Geological Institute. The first deep borehole was drilled in 1935 (Brzeźnica, depth 950 m) and reached the Upper Triassic. New boreholes were drilled throughout the following years and the present number of deep drillings (more than 1000 m) stands at 374. During that period the main exploration activity took place in the area of the Fore-Sudetic Monocline. The first oil discovery in the Polish Lowlands was made in 1916 (at the Bydgoszcz-1 well) in carbonates of the Zechstein Main Dolomite Formation at a depth of about 1800 m. The initial output was more than 100 t/day. About 130 000 t of oil was produced from the field. In 1964, the first gasfield was discovered in Rosowice (Ca2) of Pomerania. This is largely due to the thermal history of the region, which led to many areas of the Polish Lowlands. The scientific basis for exploration was the available geophysical (gravimetric) and geological expertise and the information that was available in German and Polish publications. The first drill sites were planned in the Bajoj region (Klodawa-1) where geophysical surveys indicated the presence of a salt diapir. Drilling started in 1964 and salt was encountered at a depth of 125 m; however, the suspected oil accumulations in the area around the salt diapir were not confirmed.

### 5.2.4 Pomerania

Carboniferous-sourced fields

**Figure 15.11a** gives an overview of the Pomerania petroleum province. The region of Pomerania in the north-eastern Polish Lowlands was considered to have hydrocarbon potential from the 1970s as it was analogous to the Hanover region in Germany where many oilfields had been discovered. In Pomerania, deposits, immediately after World War II, the Petroleum Institute in Szczecin started to explore for hydrocarbons in the Polish Lowlands, and on the 3rd January 1946 the oil company “North” was founded. A significant increase in resources in the Pomerania region took place from 1970 to 1980 (Appendix 3.5a), which is clearly shown on the creaming curve (Figure 15.12). Oilfields were quickly developed in the region and about 50 oil fields were exploited (Table 15.1). Gas in the region normally contains 50 to 80% methane. Not all gasfields were developed and only half of the reserves was produced. The last 25 years of exploration has resulted in very few significant successes.

Zeolite-sourced fields

**Figure 15.12** gives an overview of the Zeolite-sourced petroleum province. The discovery history is summarised in **Figure 15.12**. Details on the fields are given in Appendix 3.5b. The petroleum system of Zeolite deposits in the Pomerania region is focused on the Main Dolomite carbonates (Ca2). The Zeolite deposits in Poland are mainly evaporites subordinated into four cycle types (Chapter 8). The first cycle (Pomerania, Pomerania) starts with the development of the Zeolite Limestones (Ca2) and the Werra (Cretaceous) and the Harz Mountains (Pliocene-Miocene).

### History

**Exploration**

The exploration history of the Thuringian and Sub-Hercynian basins is shown in **Figure 15.10**. The creaming curve for these basins is based on data presented in Appendix 3.4. Following an oil and gas inflow in the potash mine at Volbrom in 1910, hydrocarbon exploration took place in several phases within the Thuringian and Sub-Hercynian basins. The next discoveries were made at the Wilhelmsburg gasfield in the Thuringian Basin and the small Eleonora saltfield in the Sub-Hercynian Basin. After World War II, there was extensive drilling from the mid-1940s to mid-1960s and from the late 1960s to early 1970s. The most recent exploration phase started at the end of the 1970s and continued into the 1980s based on new geological concepts regarding the location of the Stassfurt Carbonate barrier zone. After a period of inactivity, a new exploration program started in 1981 with modern high-resolution 3-D seismic surveys, which had not previously been used, were carried out on Stassfurt Carbonate target, (Bella et al., 1988) within both the Thuringian and Sub-Hercynian basins. Potential oil-platform hydrocarbon traps were identified in both basins (Bella et al., 1988; Pinkal et al., 1989). In 1986, prospects were tested at the Stassfurt Z2 well in the Stassfurt Carbonate basin and at Spritzen Z2 in the Thuringian Basin; however, neither known hydrocarbons nor economic amounts. The typical curve shows the two main discovery phases. The first relatively large discovery was made during the early stage of exploration and the second discovery phase correlates with the main drilling phase. Systematic studies of the Polish Landau structural units were started in 1955 by the Petroleum Geological Survey in collaboration with the Polish Geological Institute. The first deep borehole was drilled in 1935 (Brzeźnica, depth 950 m) and reached the Upper Triassic. New boreholes were drilled throughout the following years and the present number of deep drillings (more than 1000 m) stands at 374. During that period the main exploration activity took place in the area of the Fore-Sudetic Monocline. The first oil discovery in the Polish Lowlands was made in 1916 (at the Bydgoszcz-1 well) in carbonates of the Zechstein Main Dolomite Formation at a depth of about 1800 m. The initial output was more than 100 t/day. About 130 000 t of oil was produced from the field. In 1964, the first gasfield was discovered in Rosowice (Ca2) of Pomerania. This is largely due to the thermal history of the region, which led to many areas of the Polish Lowlands. The scientific basis for exploration was the available geophysical (gravimetric) and geological expertise and the information that was available in German and Polish publications. The first drill sites were planned in the Bajoj region (Klodawa-1) where geophysical surveys indicated the presence of a salt diapir. Drilling started in 1964 and salt was encountered at a depth of 125 m; however, the suspected oil accumulations in the area around the salt diapir were not confirmed.

**Development and production**

Most of the oil and gas accumulations have been developed. Today, only four fields at Wülzburg, Langensalza, Kirchheilingen SW and Fahner Höhe are still producing gas. Three fields at Kirchheilingen, Langensalza, Kirchheilingen SW and Fahner Höhe are still producing gas. Three fields at Kirchheilingen, Langensalza, Kirchheilingen SW and Fahner Höhe are still producing gas. Three fields at Kirchheilingen, Langensalza, Kirchheilingen SW and Fahner Höhe are still producing gas. Three fields at Kirchheilingen, Langensalza, Kirchheilingen SW and Fahner Höhe are still producing gas. Three fields at Kirchheilingen, Langensalza, Kirchheilingen SW and Fahner Höhe are still producing gas. Three fields at Kirchheilingen, Langensalza, Kirchheilingen SW and Fahner Höhe are still producing gas.
Field characteristics

In the Fore-Sudetic Monocline, the largest gasfields were discovered between the late 1960s and late 1980s (e.g. Bogatynia; Olsztyn (14.4 km²); Bninno (5.5 km²); Brzostow (2.79 km²); Tarnobrzeg (2.45 km²); Wałcz (15.9 km²); Zakroczym (22.3 km²); Żelędy (24.5 km²); Pniewy (4.5 km²); and Rudin (6.18 km²). Gasfields such as Bogatynia-Szczecin or Wałcz are characteristic of the Fore-Sudetic-Schlesische Limestone reservoirs (Sedziwko et al., 1995; Kierzkowski, 1995; Figure 15.13a). Figure 15.13a shows the Rotliegend and the Rotliegend-Schlesische Limestone (Ca1) gasfields in the Fore-Sudetic Monocline (after Buniak, 2008). The map shows gasfields in production, developed and exhausted, and demonstrates the discovery history and the diverse gas-tap origins. The gasfields are clearly defined in groups with tectonic, palaeogeographical or mixed gas traps.

There are no Rotliegend gasfields in western Poland, apart from those in the Poznań region. Similarly, in eastern Germany there are no Rotliegend gasfields other than the exhausted gasfield at Riedenburg in eastern Brandenburg and gasfields in Mecklenburg-Vorpommern, where the gas is associated with the Zechstein Rau-Dolomit-stairs (Purtanek, 2008).

3.2.5 Fore-Sudetic Monocline and Brandenburg

Carboniferous-sourced fields

Source

The Carboniferous is the source rock for hydrocarbons (natural gas) in the area of the Fore-Sudetic Monocline. The monocline corresponds to the folded and tilted Carboniferous rocks of the south-western Polish Variscan Elements, which extended into eastern Germany. The Variscan Elements consist of Lower Carboniferous (Tournaisian to Visean and lower Namurian) thick siliciclastic and carbonate rocks with high organic content. The younger collared Westphalian to Stephanian strata are absent or occur in restricted areas as erosional remnants of the former sedimentary cover. Older hydrocarbon sources in the Variscan Elements area are hypothetical. However, in places, the high helium content of the total gas volume suggests deeper gas sources (Kurczewski, 1999).

Generation

Carboniferous sediments in the major part of south-west Poland attained thermal maturity prior to the Late Permian (Puppea et al., 2005). There is a significant difference in maturity development between the top of the Variscan succession and the lower part of the Permian to Mesozoic section. Puppea et al. (2005) estimated that the maturity profiles are not dependent on terrace dipping or thrust sheets (i.e. rapid burial processes), but resulted from Late Carboniferous heat flow in the external zone of the Variscan orogen. The heat flow varied laterally, although it was relatively high (Kaczmarchewicz et al., 1986; Specht & Kellner, 1987). Puppea et al. (2005) also noted the impact of Lower Permian volcanic traps on the thermal maturity of the Carboniferous succession beneath, as well as by ignition of hot fluids related to the volcanic activity. This maturity was high enough to generate hydrocarbons. A second stage of hydrocarbon generation (mainly dry gas) took place during later Triassic and Jurassic times due to burial of Carboniferous strata during subsidence and the development of the Mesozoic sedimentary cover.

A special attribute of the gas produced is the nitrogen content derived from organic matter and NH4 fixed during the burial of Carboniferous strata during subsidence and the development of the Mesozoic sedimentary cover. This maturity was high enough to generate hydrocarbons. A second stage of hydrocarbon generation (mainly dry gas) took place during later Triassic and Jurassic times due to burial of Carboniferous strata during subsidence and the development of the Mesozoic sedimentary cover.

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Analysis of gas production

The reservoir curves shown in Figure 15.14 provide details on the exploitation and discovery history of the Fore-Sudetic Monocline gasfields (Kurczewski, 1981; 1999; Polish Geological Institute, 1993). However, the left side of the curve does not explain the pure Rotliegend gas recovery from the Fore-Sudetic Monocline area. The curves show the progressive decline of gas recovery from the late 1970s to late 1980s. They also clearly show the gradual decline in gas production in the area, although the recent Rotliegend tight-gas discovery may result in a change in this trend.

Permian (Zechstein)-sourced fields

Field characteristics and volumes

The locations of oil and gas accumulations/fields are shown in Figure 15.13b and the main field attributes are listed in Appendix 3.5.9 (after Kierzkowski, 1999; Purtanek, 2008) Table 15.1 shows the produced volumes of oil and gas from fields in the Fore-Sudetic Monocline and Brandenburg. Some of these gasfields may also contain condensate.
Both the Pore-Sudetic Monocline and the neighboring Brandenburg region are located to south-west of the Halidian Trough and developed similarly during Permian times when the most distinctive structural elements in terms of basin palaeogeography were the Brandenburg-Wolzyn-Pogorzela series of palaeokarst. These highs were formed by Carboniferous to Permian volcanic rocks and subdivide Lower Carboniferous and possibly Devonian sedimentary rocks. The highs had a major influence on deposition of the Zeitenian Weas and Stauffert cycles as they were the places where the mostly sulphate platforms of the Weas and carbonate platforms of the Main Dolomite were formed. The Main Dolomite hosts many oil and gas fields, and is both a source rock (in addition to the basal and slope facies, the platform facies of the Main Dolomite are regarded as source rocks in the region) and reservoir. The oil that accumulated in the Main Dolomite is asphaltene-free, and gas is partly autolythic, syngenetic with oil, and partly asphaltic, source rocks being localized in deeper parts of the Zeitenian and older Carboniferous reservoirs. The oil and gas are commonly accumulated in structural, combined and stratigraphic traps. The seals are formed by Zeitenian evaporites.

History

Explanatory

The exploration history of the region is shown in Figure 15.14. The first oil deposit in the Pore-Sudetic Monocline, and in the entire Polish Lowland area, was discovered in 1961, in the Rybnik-1 well. This discovery had a considerable influence on the intense exploration that followed in the Pore-Sudetic area (Degowin, et al., 1978). Exploration was based on the concept that these were new discovery prospects in practically every structural uplift of the Main Dolomite as long as the potential traps had sufficient capacity (Karwowski, 1990). A total of 36 oil and gas fields have so far been found in the Pore-Sudetic area and 24 oil and gas deposits in Brandenburg. A full list of discoveries is given in Appendix 3.4.

The largest deposit in the area, and in Poland, is the Ruchomecko-Ruczews oil and gas deposit (Section 3.4 in Chapter 8); its discovery well reflects the exploration history in the Pore-Sudetic area. The earliest exploration was the 2-D seismic surveys that were not interconnected between 1958 and 1992 (Karwowski, 1990b). Those of the structures identified by those surveys were drilled between 1992 and 1994, and in the Mostno-1 well gas inflow was obtained. Oil and gas were found in the Ruchomecko-1 well and oil inflow was obtained in the Ruczes-1 well. Subsequent 3-D seismic analysis proved the presence of a single oil and gas accumulation, which allowed the location of subsequent wells to be optimised (Karwowski, 1990).

Development and production

Most of the oil and gas discoveries have been developed. There are 14 fields in the Pore-Sudetic Basin producing oil and gas, 11 of which have been developed during the last two decades. The first of oil deposit discovered in the Pore-Sudetic Basin (Rybnik-1) is still producing.

5.2.6 Lublin Basin

Figure 15.15 gives an overview of the Lublin Basin petroleum province. The fields discovered are listed in Appendix 3.7 and the discovery history is summarized in Figure 15.16.

Hydrocarbon accumulations discovered in Carboniferous deposits of the Lublin Basin occur within north-west–north-east-trending anticlinal structures along the basin axis (Chapter 6, Figure 6.4). Namurian and Westphalian sandstones, especially geophysical complexes D, H, I and L, have the highest north-west–south-east-trending anticlinal structures along the basin axis (Chapter 6, Figure 6.4).

According to Grodecki (2005), the potential oil and gas source rocks are the Visean and Namurian shales and thick-bedded sandstones (Chapter 6, Figures 6.3, 6.4, 6.10) and local limestone (the Husine, Trópczy and Bukowie formations), Westphalian A and B deposits (Lublin Basin) can also be considered as potential gas-type source rocks, whereas the Westphalian C and D deposits (Rusovce Formation) do not have any source-rock potential. The degree of organic-matter alteration generally increases northwards and north-westwards with increase in burial depth (Chapter 6, Figure 6.10).

To date, hydrocarbon fields have been discovered in the Rynkówce, Sędzisz, Stężyca and Wilga regions (Chapter 6, Figures 6.10). The main facies attribute, reservoir parameters and resources are shown in Appendix 3.7. There are eight producing wells in the Stężyca field (Chapter 6, Figure 6.28d); the Stężyca-7 well produces about 21 t/day of oil and gas, Stężyca-3a well produces 17.73 m³/day of oil and Stężyca-5k well produces 107 Mcf/day, thus, well in the Wilga (Wilga-2) field currently produces about 1 MBCM of high methane gas and ten barrels of light crude oil per day.
The Lower Cretaceous Wealden Beds provide a third reservoir, as proven by numerous oil and gas shows (including the Shalfleet and Ashdown discoveries); however, substantial reservoirs have yet to be found in the Lower Cretaceous succession.

Hydrocarbon migration has occurred from the basin centre outwards to its northern and southern margins. Faults in the basin were likely to have provided migration pathways that resulted in multiple reservoir horizons with hydrocarbons at shallower and deeper levels in areas strongly affected by Tertiary inversion (Bolster & Pullen, 1990).

**Exploration**

Some 150 exploration wells have been drilled into Jurassic-source plays in the Weald Basin (Figure 15.17). The majority of these wells were drilled on Jurassic targets, although over 30% of the exploration wells were drilled to test the Cretaceous section.

The earliest reports of gas in the area were from wells drilled for water in 1836 and 1875 (Dawson, 1898; Pearson, 1903; Adcock, 1963). Water wells drilled in 1895 to 1896 at Heathfield found gas that was used to fuel gaslights at its railway station, which was the UK’s first-ever gas production. Early exploration of the Weald Basin during the 1930s to 1960s was based mainly on surface mapping, when no significant wells were drilled. The majority of these wells were drilled on Jurassic targets, although just over 10% of the exploration wells were drilled on Tertiary targets (Table 15.1). Gas production at Albury began in 1994. The producing oilfields of the Weald Basin had yielded 2.32 bcm of hydrocarbons and about 25% have led to commercial discoveries (Appendix 3.9).

**Development**

Dramatic growth in the gas industry began in the late 1980s to improve oil recovery from the tight chalk layers containing the bulk of the oil discoveries within the area of the petroleum system. A prime example of this development was the Balan field, which started production in 1987. The production strategy for the field consisted of natural depletion by means of deviated wells. The recovery factor was then estimated at 7%, but the horizontal wells and water injection allowed further development such that by 2008 the recovery factor was estimated to be five times greater than in 1987. The field provides a good example of how technological development can impact on a field within a relatively short time.

Mærsk Ola og Gas AS has developed a simplified and cost-efficient wellhead platform to improve the development of satellite fields, known as the STAR (Subsea Tied to Langskip) platform. STAR consists of a leg-supported caisson accommodating up to ten well conductors. The use of the STAR Platform leads to considerable cost savings compared to the expense of conventional steel-jacket construction and installation.

The main infrastructure was expanded in 2003 by a gas pipeline from Tys to the P03-FB platform in the Dutch sector. From there, gas is conveyed through the RINAT pipeline to the Netherlands. The pipeline started operating in 2004. To improve the efficiency of oil displacement, the Balan field has been developed with long horizontal wells arranged in a pattern of alternate production and injection wells with parallel trajectories.

5.3.3 Dutch Central Graben

**Field characteristics and volumes**

Figure 15.21 shows the fields that have been discovered in the area of the Dutch Central Graben and are considered to have been sourced by the Jurassic Prokinesis Shale. The main field attributes are listed in Appendix 3.10. Table 15.1 shows the volumes related to these discoveries.

**History**

Exploration

A total of 48 exploration wells have been targeted at Posidonia Shale sourced plays in the Dutch Central Graben (Figure 15.22). The majority of these wells have been drilled in the Upper Jurassic to Lower Cretaceous targets. The remainder were drilled on Chalk Group targets, mostly above salt domes.

Figure 15.22 shows the crowning curve for the Upper Jurassic / Lower Cretaceous plays. The curve is dominated by two relatively large discoveries. The largest, P03-FB, was discovered in 1974 during an early stage of offshore exploration in the Netherlands that started in 1968. The other major discovery was made in the early 1980s, but no large discoveries have been made since then.

Exploration of the Chalk play has not been very successful so far: out of almost 20 attempts, there has been only one commercial discovery at the F1-Maine field, the southward extension of several similar fields in the Danish sector. However, oil shows have been observed in many cases indicating that petroleum migration into these structures has occurred.

**Development**

Only three of the 12 discoveries have been developed (Appendix 3.10). This is due to heavy faulting and compartmentalization in the southern part of the Dutch Central Graben. Moreover, there is no oil evacuation pipeline system in the area. The developed ‘sill’ fields P03-FB and P2-Faroze also produce gas. This reflects the typical composition of the hydrocarbons generated by the Posidonia Shale in this area. The gas is evacuated through the RINAT pipeline from the P03-FB platform. The oil is heavily biodegraded and then transported by ship. The only gasfield developed so far is L06-A. The gas is evacuated via a subsea completion and pipeline to block G17, entering the NTT pipeline.
Field characteristics and volumes

Figure 15.23 shows the fields that have been discovered in the area of the West Netherlands and Broad Fourteens basins. The oil is considered to have been sourced by the Jurassic Posidonia Shale. The main field attributes are listed in Appendix 3.11. Table 15.3 shows the volumes related to discoveries in the basins that are sourced by the Posidonia Shale. The total STIEP was estimated in 1994 at 130 mln m³ (Ravena-Boers & Drake, 1996). The reserves are significantly lower due to asmenor volumes and/or poor reservoir-quality resulting in low recovery.

Early exploration was typically focused on Cretaceous reservoirs, either in sandstones of the marine Yoldia Sandstone Formation and/or the terrestrial Delfsdal Subgroup. Reservoir distribution is due to the complex interplay of neotectonics, changes as a function of sea-level fluctuations, and tectonics (De Harting Jager, 1990). Fields found with these reservoirs are inevitably 4-6 dip closures or faulted dip closures. Only oil has accumulated in the Delfsdal Sandstone reservoirs. The sealing potential of the intra-Delfsdal seals for gas proved to be insufficient. Gas caps (gas from Cretaceous sources or associated gas) are found in the reservoirs of the Yoldia Formation under the strong regional seal of the Yoldia-Claystone Formation. After the early 1980s, exploration resulted only in the discovery of small oilfields with hardly any economic value.

It was later realized that oil could be trapped in Triassic reservoirs, when these had been uplifted during the Late Cretaceous inversion, in a structurally higher position than the Posidonia Shale in the downtown blocks (see Chapter 13, Section 3.1). The first discovery in this sub-play was the Poppensfield field in 1986. Figure 15.23 shows that exploration on Triassic prospects took place predominantly on the fringes of the basin due to reservoir deterioration as a result of deep pre-inversion burial in the basin centre.

The play area was thought to occur between the main basin-boundary faults. However, as a result of a series of failures when exploring the Triassic truncation trap play in the south-west of block P12, a commitment well was eventually targeted at a high-risk prospect in the north-west corner of the block. The main risks were changing, the absence of an oil source rock, and uncertainty as to reservoir connectivity, and a seal risk due to the potential presence of a (Triassic) shale seal on the unconformity. The discovery of the P12-6a Roper field proved the possibility of long-distance migration of oil from source to reservoir through a complex pathway of some 20-30 km.

Development

Most of the 43 discoveries have been developed (Appendix 3.11). Most of the developed discoveries have Cretaceous reservoirs, which prove to have the best reservoir quality and thus recoverable resources. The developed Triassic discoveries are limited to the southern margin of the West Netherlands Basin because permeability was preserved due to shallower burial relative to the basin centre.

Most of the developed oilfields have been abandoned or are near the end of production. A number of plans have been submitted recently for undeveloped fields on stream, as for example at the Poppensfield and O13-Fa fields. Redevelopment of abandoned oilfields is also being considered as for example at the Rijp oilfield.

5.3.4 West Netherlands and Broad Fourteens basins

Field characteristics and volumes

Figure 15.23 shows the fields that have been discovered in the area of the West Netherlands and Broad Fourteens basins. The oil is considered to have been sourced by the Jurassic Posidonia Shale. The main field attributes are listed in Appendix 3.11. Table 15.3 shows the volumes related to discoveries in the basins that are sourced by the Posidonia Shale. The total STIEP was estimated in 1994 at 130 mln m³ (Ravena-Boers & Drake, 1996). The reserves are significantly lower due to asmenor volumes and/or poor reservoir-quality resulting in low recovery.

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in Germany are Rühle (discovered 1949), Bramberge (discovered 1958) and Georgsdorf (discovered 1979). Figure 15.26: Creaming curve for the Lower Saxony Basin and Dogger Troughs petroleum province. Fields charged by the Posidonia Shale Formation (= Brabant). Plate Appendix 3.12. The Mittelplate-1 well was drilled in 1980 in what is now the biggest field in the Lower Saxony Basin. Production started in 2008 and there is still much to be learned about the production behaviour of these shallow accumulations.

5.4 Shallow-gas source

Chapter 5 gives an overview of the gas accumulations at shallow depth. There are many indications of these shallow-gas accumulations on seismic data, but many have also been penetrated during drilling and are considered to be a drilling hazard.

In terms of commercial development, the shallow-gas play is currently restricted to the northern Dutch sector in quadrants A and B (Figure 15.25 and Section 9 in Chapter 12). The fields are listed in Appendix 3.13. The number of wells drilled at shallow gas is too small to allow a creaming curve to be constructed. Production from these fields started in 2008 and there is still much to be learned about the production behaviour of these shallow accumulations.

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Several oilfields in north-west Germany are located in rim-synclines (Dogger Troughs), notably at Mittelplate (see Section 6.3.4 in Chapter 10). The Mittelplate-1 well was drilled in 1980 in what is now the largest oilfield in Germany. Even by international standards it can be considered to be a large oilfield. Annual production in 2005 was 2.4 million m³ and the estimated initial reserves could amount to more than 60 million m³ of oil. The oilgas field formed a structural trap at the eastern flank of the Hassel salt dome and its drape Middle Jurassic reservoir sandstones pinched-out on the flank of the salt dome. Short-distance hydrocarbons migration from the Lower Jurassic Posidonia Shale into the overlying reservoirs occurred from the deeper subsiding rim-synclines into the structural trap at the flank of the salt dome. On a broader scale, the field is located in the Jade West Holstein Trough, a diapiric structure of predominately north-north-east trending Permian salt domes. Diachronous movements started during the Triassic resulting in the formation of thick, mainly Jurassic sedimentary sequences within the primary rim-synclines of the West Holstein and East Holstein troughs. The latter trough contains the abandoned oilfields at Schöneweide and Schöneweide-Sse. Production from the larger offshore area started in 1984 and, over a period of 16 years, produced about 3.0 million m³ of oil and 0.052 billion m³ of gas from Middle Jurassic sandstones. The importance of the Jurassic troughs is linked to their thick Lower Posidonia Shale source rocks. In addition to the rim-synclines described above, there are either Jurassic troughs on the Pommern Platform that are related to salt terrains. This includes the Gilbern Trough, which displays a similar strike to the Holstein troughs. One of the larger oilfields in Germany, Blankendeich, is located in the northern part of this trough. Since its discovery in 1964, this field has produced about 15 million m³ of oil and 0.3 billion m³ of gas from the Dogger IIa sandstones. The Gilbern Trough also contains a number of smaller oilfields such as Verheug, which was discovered 1962 on the flank of a salt dome. Oil was produced from Lower and Middle Jurassic sandstones, which in 2001 was in the order of 25,000 m³, with cumulative production of 3.1 million m³.

Development Appendix 3.12. Data from the unexplored discoveries in this petroleum province. All of the producing fields with the exception of Mittelplate are located onshore, where a comprehensive infrastructure facilitates the evacuation of oil and gas. Mittelplate was discovered in 1980, although production only started in 1987 due largely to its location in the North Sea tidal flat area at the southern boundary of a National Park. NAM is planning to revive the Schöneweide oilfield using horizontal drilling and low-pressure steam injection. About 100 to 150 million m³ (about 100 to 190 million m³) are expected to be produced over a 25-year period starting in 2009/2010.