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# Exploration activities in the Netherlands and North-West Europe since Groningen

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## Abstract

Once the great size of the Groningen Field was fully realized late in 1963, exploration in the southern North Sea was a natural development as the reservoir bedding dipped westward. The origin of that bedding was not certain, one possibility, dune sands, led immediately to a program of desert studies.

Licensing regulations for Netherlands waters were not finalized until 1967, offshore exploration beginning with the award of First Round licenses in March 1968. In the UK area, the Continental Shelf Act came into force in May 1964, paving the way for offshore seismic, the first well being spudded late in that year. The first two wells were drilled on the large Mid North Sea High; both were dry, the targeted Rotliegend sandstones being absent. Then followed a series of Rotliegend gas discoveries, large and small, west of Groningen, so that by the time exploration began in Netherlands waters the UK monopoly market was saturated and exploration companies were already looking north for other targets including possible oil.

The Rotliegend was targeted in the earliest wells of the UK central North Sea even though there had already been a series of intriguing oil shows in Chalk and Paleocene reservoirs in Danish and Norwegian waters. These were followed early in 1968 by the discovery of gas in Paleocene turbidites at Cod, near the UK-Norway median line. The first major discovery was Ekofisk in 1969, a billion-barrel Maastrichtian to Danian Chalk field. Forties (1970) confirmed the potential of the Paleocene sands as another billion barrel find, while the small Auk Field extended the oil-bearing stratigraphy down to the Permian. In 1971, discovery of the billion-barrel Brent field in a rotated fault block started a virtual 'stampede' to prove-up acreage awarded in the UK Fourth Round (1972) before the 50% statutory relinquishment became effective in 1978.

Although the geology of much of the North Sea was reasonably well known by the end of the 1970s, new oil and gas reservoirs continued to be discovered during the next two decades. Exploration proved the Atlantic coast of Norway to be a gas and gas-condensate area. The stratigraphic range of reservoirs extended down to the Carboniferous (gas) and Devonian (oil), while in the past decade, forays into the UK Atlantic Margin and offshore Ireland met with mixed success. During this hectic activity, Netherlands exploration confirmed a range of hydrocarbon-bearing reservoirs; Jurassic oil in the southern Central Graben, Jurassic-Cretaceous oil derived from a Liassic source mainly onshore and, of course, more gas from the Rotliegend. German exploration had mixed fortunes, with no commercial gas in the North Sea and high nitrogen content in Rotliegend gas in the east. Similarly in Poland, where several small Zechstein oil fields were discovered, the Rotliegend gas was nitrogen rich. The discovery of some 100 billion barrels of oil and oil equivalent beneath the waters of the North Sea since 1964 led to an enormous increase in geological knowledge, making it probably the best known area of comparable size in the World. The area had a varied history over the past 500 million years: plate-tectonic movement, faulting, igneous activity, climatic change, and deposition in a variety of continental and marine environments, leading to complex geometrical relationships between source rock, reservoir and seal, and to the reasons for diagenetic changes in the quality of the reservoir sequences. Led by increasingly sophisticated seismic, drilling and wireline logging, and coupled with academic research, the North Sea developed into a giant geological laboratory where ideas were tested and extended industry-wide.

*Keywords:* Rotliegend, Groningen, exploration history, North Sea.

## Introduction

Gas in a Rotliegend reservoir was discovered by NAM at Slochteren in 1959. It was not until 1961, however, that the full extent of the gas-bearing Rotliegend sandstones was confirmed when the Ten Boer-1 well (originally drilled 1955) was deepened to find the sandstone below what became known as the Ten Boer Claystone. The reserves of gas in the Groningen Field were originally calculated to be about $60 \times 10^9$ $m^3$; nearly thirty years later its ultimate reserves was quoted as forty times greater at $2409 \times 10^9$ $m^3$ (Knaap & Coenen, 1987), nine years after that it was $2750 \times 10^9$ $m^3$ (Breunese & Rispens, 1996), and today is $2900 \times 10^9$ $m^3$ (Verberg, this volume). But already in 1963, newly revised volumes indicated that the field was sufficiently large (around $1640 \times 10^9$ $m^3$) to alter the fuel economy of much of adjacent NW Europe from one based on coal and coal gas to that of subsurface natural gas; it was already recognized as being in the super-giant league. If one such field existed, maybe other similar-sized fields could be found elsewhere. Once NAM had acquired a production concession for the entire province, steps were taken in 1963 to extend exploration elsewhere.

Core studies by KSEPL geologist Eppo Oomkens indicated that the bulk of the Rotliegend bedding dipped westward towards the North Sea, on the other side of which in NE England, sandstones of similar age and facies cropped out. Before any offshore exploration could take place, however, the nations bordering the North Sea had to ratify the Continental Shelf Convention of 1958 whereby, among other provisions, each had jurisdiction for controlling mineral exploration and production beneath the sea floor to the 'median line' between their land masses and, along the Atlantic Margin, to the edge of the continental shelf (200 m bathymetric contour). In the UK, the Continental Shelf Act came into force in May 1964 and paved the way for licensing offshore acreage. Exploration in the Netherlands offshore did not commence until March 1968, when the government awarded the first round of licenses. Thus UK offshore exploration began four years earlier than in Netherlands waters.

## Post-Groningen exploration in the Southern Permian Basin

The Groningen cores implied that the depositional extension of the Rotliegend reservoir should lie to the west. The first two wells (38/29-1, 44/2-1) were drilled to the NW, on the largest structural high then known below the North Sea (now the Mid North Sea High); this Permian high had no Rotliegend reservoir and both wells were dry (Glennie, 1997a). The third well (53/10-1) found the Rotliegend reservoir but lay south of the effective cap rock of Zechstein salt, so it too was dry. The fourth well (48/6-1) discovered the West Sole field. By the end of 1968, twelve gas fields had been discovered (Fig. 1, Tables 1 & 2), including the Hewett field (reservoirs of Triassic Bunter and latest Permian Hewett sandstones), with combined reserves for the twelve in excess of $649 \times 10^9$ $m^3$ of gas. Britain at that time had a state-imposed monopoly market for gas, which was reaching saturation with little prospect of a rise in the price for any new gas discoveries, exploration was reduced to drilling 'obligation wells', and oil companies began to seek new areas in which to explore. As will be shown later, there were early encouraging signs of the presence of oil north of the Mid North Sea High. Exploration in the UK southern North Sea was to remain stagnant until 1981, when the Gas Council recognized that unless they stimulated further activity by offering to increase the price of gas, they would soon not be able to meet their contractual sales commitments.

Following Groningen, other gas discoveries in the Netherlands continued to be made on land. Offshore drilling in Netherlands waters (ignoring outsteps from land) began in 1968 and met with instant success, although not with Rotliegend reservoirs; Mobil found gas in Bunter and Zechstein reservoirs in block P6, while NAM had a Bunter discovery in Block L2 (Dronkert et al., 1996) (Fig. 1, Table 2); the Rotliegend target for these wells had shaled-out, so subsequent drilling was directed further south in the K and L quadrants. Rotliegend gas was found in L10 and K7 in 1969, and five more fields in each of 1970 and 1971. By the end of 1972 the offshore discoveries numbered 17 but the writer does not know the volume of gas and oil discovered. Discoveries continue to be made.

The Groningen discovery stimulated exploration not only in UK and Dutch waters (e.g. Heybroek et al, 1967; Heybroek, 1975), but also eastward in German (e.g. Schröder et al., 1991) and Polish (Pokorski, 1989) land areas. Offshore exploration in German waters proved to be disappointing, firstly because the Rotliegend reservoir had shaled-out into a desert-lake sequence over much of the area (Fig. 2) and, where present, the gas had an uneconomically high percentage of either nitrogen or carbon dioxide; indeed, the nitrogen content, in particular, increased eastward and had a down-grading effect on much of the gas

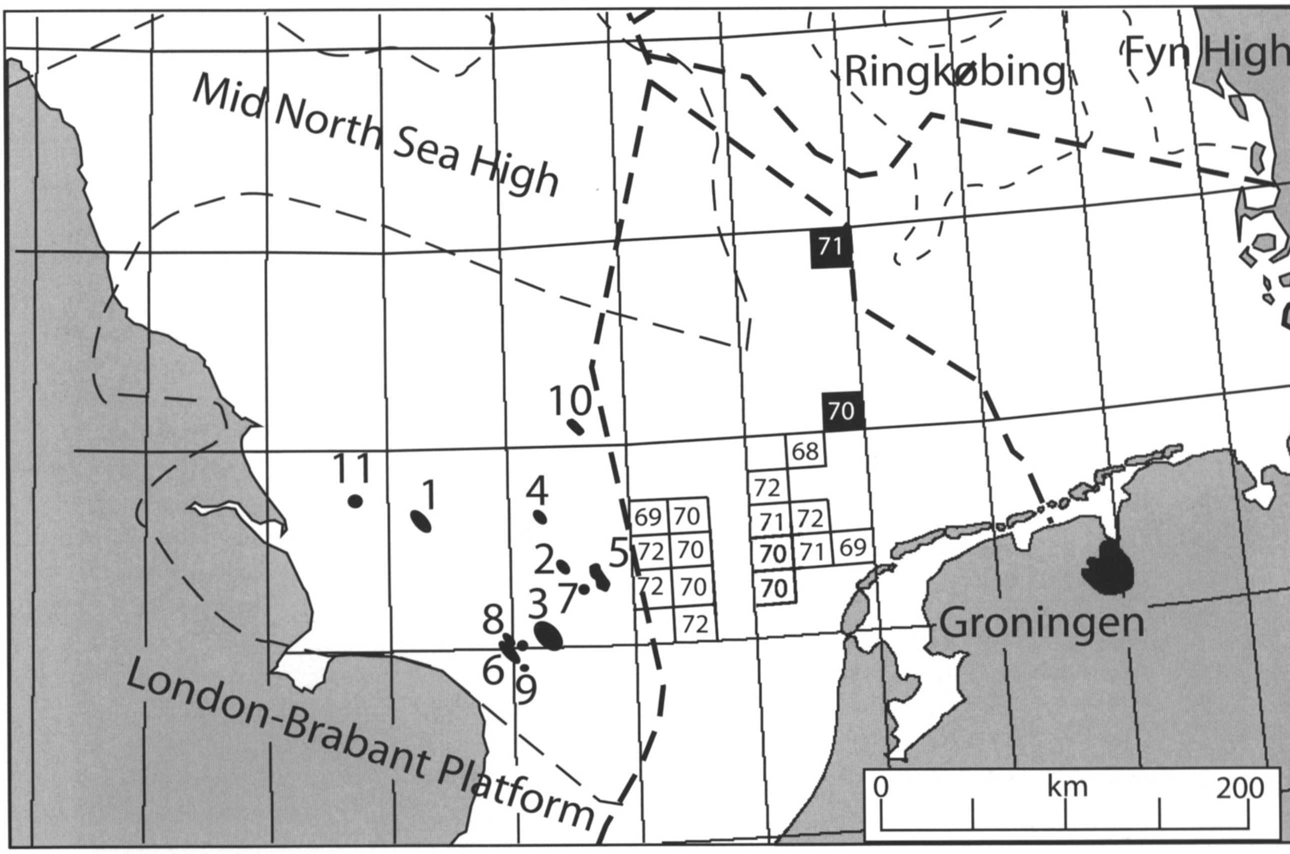


Fig. 1. The order and distribution of gasfield discoveries in the UK southern North Sea, 1965-1968, and the Netherlands offshore discoveries are given by year, 1968-1972. The latter are given only by year as their exact order is not known.

Table 1. The order and volumes of gas discovered in the UK southern North Sea, 1965-1968.
Although the precise order of discoveries is not known, in the first three years of exploration in the Netherlands offshore, ten fields were discovered, nine gas and one oil.
Within another two years those totals had increased to fifteen and two respectively, the volume of recoverable gas amounting to about 170 x $10^9$ $m^3$ (Breunese and Rispens, 1996).

Order of gasfield discoveries UK Southern North Sea 1965-1968

| Order of discovery | Field name | Date | Operator | Reserves $10^9$ $m^3$ |
|---|---|---|---|---|
| 1 | WEST SOLE | DEC 1965 | BP | 57 |
| 2 | VIKING B | DEC 1965 | CONOCO | 79 (total Viking) |
| 3 | LEMAN | APR 1966 | SHELL/ESSO | 316 |
| 4 | ANN | MAY 1966 | PHILLIPS | ? |
| 5 | INDEFATIGABLE | JUNE 1966 | AMOCO | 131 |
| 6 | HEWETT | OCT 1966<br>NOV 1966 | ARCO<br>MOBIL | 115* |
| 7 | INDE SW | JUNE 1967 | AMOCO | 2 |
| 8 | BIG DOTTY | SEP 1967 | ARCO | See Hewett* |
| 9 | CAMELOT N | NOV 1967 | MOBIL | 6 (INCL C, E & N) |
| 10 | CAISTER (BUNTER) | JAN 1968 | TOTAL | 11 |
| 11 | ROUGH | MAY 1968 | BRITISH GAS | 11 |
| 12 | DEBORAH | AUG 1968 | PHILLIPS | See Hewett* |
| | | | TOTAL | >649 |

Table 2. Important post-Groningen oil and gas discoveries in Netherlands, UK, Norwegian and Danish offshore areas, 1959-1997. Reservoir age and hydrocarbon type given in brackets.
Pc Paleocene, Eo Eocene, Ku Upper Cretaceous, Kl Lower Cretaceous, Ju Upper Jurassic Jm Middle Jurassic, Jl Lower Jurassic, Tr Triassic, B Bunter, Z Zechstein, R Rotliegend, C Carboniferous, D Devonian, Da Danian. o oil, g gas. [in Irish Sea], [IR Irish waters), *Atlantic continental shelf, Norway.

| Year | Netherlands | UK | Norway | Denmark |
|---|---|---|---|---|
| 1959 | Slochteren-1} | | | |
| 1962 | Annerveen (R, g) | | | |
| 1963 | Groningen} | | | |
| 1964 | | | | |
| 1965 | | West Sole (R,. g) | | |
| 1966 | | Leman, Inde, S.Viking (R, g) | | Kraka (Anne) (Ku, o+g) |
| | | Hewett (B, g) | | |
| 1967 | | Big Dotty (R, g) | Valhall (Ku,o) | |
| | | Camelot N (R, g). | | |
| 1968 | P6 (Z, Tr,g) | Caister (B, g) | Cod (Pc o) | Roar, Tyra (Ku, g) |
| | L2 (B, g) | Rough, Deborah (R, g) | | |
| 1969 | K7 (R, g) | Gordon (B, g) | Ekofisk (Ku, o) | S. Arne (Ku, o) |
| | L12 (R, g) | Montrose/Arbroath (Pc, o) | | |
| 1970 | F18 (Ju, o) | Forties (Pc, o) | Tor (Ku, o) | |
| | K7,K8, K11, K14(R,g) | | Ekofisk W (Ku, o) | |
| | L10, L13 (R, g) | | Eldfisk (Ku, o) | |
| 1971 | K11 (R, o) | Brent (Jm, o) | Frigg (Eo, g), | Dan (Ku, o/g) |
| | L7, L11 (R, g) | Auk (Z+R, o) | Bream (Jm, o) | Gorm (Ku,g) |
| | F3 (Ju, o) | Argyll (Z+R, o, abnd) | | |
| | | [Kinsale Hd, IR] (Kl, g) | | |
| 1972 | K13 (B, g) | Beryl, (Ju/Tr, o) | Edda (Ku, o) | |
| | K17 (R+Z, g) | | Albuskjell (Ku, o) | |
| | L4, L8 (R, o) | | Heimdal (Pc, g) | |
| 1973 | K10(R, g) | Piper (Ju, o) | Frigg O (Eo, g) | |
| 1974 | F3/2/6 (J, o) | Magnus (Ju, o) | Statfjord (Jm-l/Tru, o) | |
| | K4, K/15A (R, g) | Buchan (ORS, o) | Sleipner (Jm, g) | |
| | Rijn (Kl, o) | [Morcambe] (Tr, g) | Balder (Pc, o) | |
| 1975 | K15-FB (R, 25%CO2) | Britannia (Kl, g/c) | Valhall (Ku, o) | Svend (Ku, ?) |
| | | Scapa (Kl, o) | | |
| | | Brae (Ju, o) | | |
| | | Fulmar (Ju, o) | | |
| 1976 | Q8 (R, g) | Beatrice (Jm, o) | Ula (Ju, o) | |
| | | Machar (Da+Ku, o) | | |
| 1977 | L13 (R, g) | Captain (Kl, o) | Tommeliten (Ku, o+g) | Valdemar (Ku, o) |
| | | Clair (C/D, o) | | Skjold (Ku, o) |
| 1978 | | Gannet A (Pc, o) | Gullfaks (Jm, o) | |
| | | Clyde (Ju, o) | Hild (Jm, o) | |
| 1979 | Haven (Kl, o+g) | Gannet B (Pc, o+g) | Oseberg (Jm, o) | |
| | Helm (Kl, o) | | Snorre (Jl/Tr, o) | |
| | Helder (Kl, o) | | Troll (Jm, g+o) | |
| 1980 | Hoorn (Kl, o) | Brae, E (Ju, o+g) | Agat (Kl, g) | Harald (Ku+Jm, g+o) |
| | Kotter (Kl, o) | Carnoustie (Z, o) | Brage (Ju/Jm, o+g) | |
| | K10-B2 (B,o) | | | |
| 1981 | | Kittiwake (Ju, o) | *Midgard (Jm, g/c) | Rolf (Ku+Z, o) |
| | | Emerald (Jm, o) | Askeladd, Jm, g) | |
| 1982 | Logger (Kl, o) | Esmond (R, g) | | |
| | Rijn (Kl, o) | Everest (Pc, o+g) | | |
| 1983 | J, K & L (c+g) | Miller (Ju, o) | *Tyrihans (Jm, g+c) | Dagmar (Ku/Z, o) |
| | | Vulcan (R, g) | | |
| 1984 | | Markham (C, g) | *Draugen (Ju, o) | Elly (Ku+Ju, o) |
| | | | | Gert (Ju, o) |
| 1985 | G16 (?, g) | Murdoch (C, g) | *Heidrun (? o+g) | |
| | K9c (R, g) | | Smørbukk (Jl/Jm,o+g) | |
| 1986 | K6, g) | Schooner (C, g) | Albatross (Jl/Jm, g) | |
| | F14(J, o), F15 (?, g), | | | |
| 1987 | | Gryphon (Pc,Eo, o) | Tordis (?) | |
| 1988 | | Nelson (Pc, o) | Embla (D?,o) | |
| | | Shearwater (J, o+g) | | |
| 1989 | | Ganymede (R, g) | | |
| 1990 | | [Hamilton, Douglas] (Tr,o) | Trym (?) | |
| 1991 | | Elgin (Ju, o+g) | Vale (?) | |
| 1992 | | Foinaven (Pc, o) | | |
| | | [Lennox] (Tr, o+g) | | |
| 1993 | | Schiehallion (Pc, o) | | |
| 1995 | | | | Siri (Pc, o) |
| 1996 | | | | |
| 1997 | | Flora (R, o) | | |

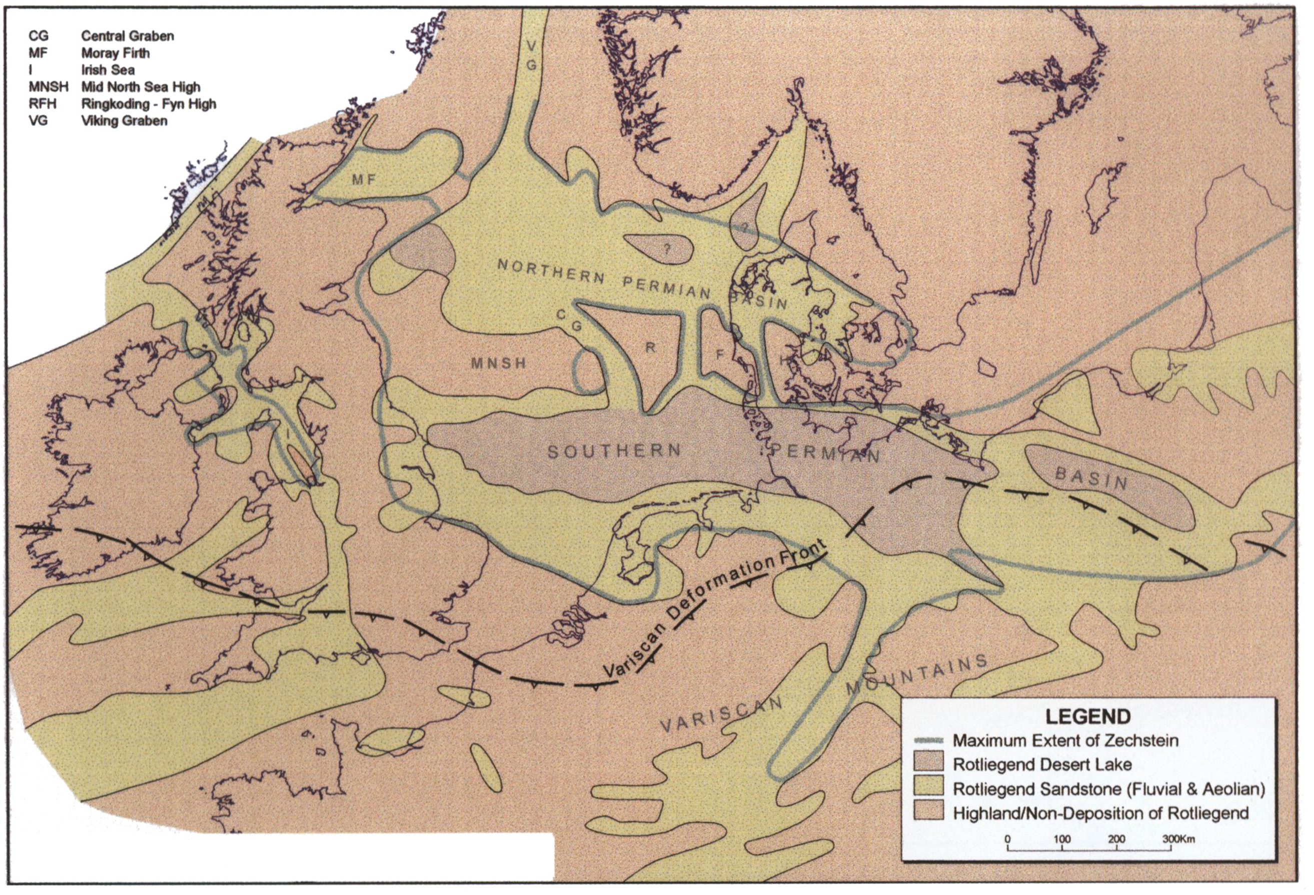


Fig. 2. The broad facies distribution of the Rotliegend in NW Europe and the maximum limit of the succeeding Zechstein, as recognized in 1999.

discovered in both Germany and parts of Poland, where its content locally exceeded 80% (Lockhorst, Gas Atlas, 1997); the economic value of the second largest Rotliegend gas field in western Europe, Salzwedel (~1700 × 109 m$^3$), just east of the former border between East and West Germany, was considerably reduced because of the locally very low calorific value of its gas. A saving grace, perhaps, was the discovery in both Germany and Poland of many small oil and gas fields with Zechstein reservoirs, the same horizon that was the target of 1959 exploration drilling in Ten Boer and the first Groningen well.

By the late 1960s, the general distribution and facies of the Rotliegend were known in the southern North Sea and the Netherlands (e.g. Glennie, 1972), and now to the Russo-Polish border. With the addition of the other formations of economic interest (Coal Measures, Zechstein and Bunter) these became considerably refined within what was to be known as the Southern Permian Basin (e.g. Ziegler, 1982, 1990, Van Wijhe, 1981, Van Wijhe and Bless, 1974; Van Wijhe et al. 1980; Glennie, 1986, 1997b, 1998; Peryt, 1989; Pokorski, 1989; Kiersnowski et al., 1995; Lockhorst, 1997; Fig 2, 3).

Because of the effects of global plate movements, the basin had shifted slowly northward from an equatorial location during Coal Measure (source rock) deposition to that of a trade-wind desert (dune and wadi reservoir rocks) in Rotliegend time. Basin subsidence seems to have been more rapid than basin infill, so the basin axis sank below the water table, thereby creating the Silverpit Lake with its essentially impervious sediments (seal to underlying Carboniferous reservoirs). Towards the end of the Permian period, the melting of icecaps over Gondwana led to a global rise in sea level and flooding of the basin by the Zechstein Sea, which, still in an essentially arid environment, gave rise to deposition of basin-margin carbonates (local reservoirs) and basin-center halites (almost perfect cap rock to the underlying Rotliegend). A return to terrestrial conditions during the Triassic resulted in a basin-center lacustrine environment (Bunter Shale), which was eventually replaced by those of fluvial and aeolian sands (Bunter Sandstone).

Regional and especially reservoir studies led to an increasing understanding of the composition and depositional environments of these economically important units (e.g. Van Veen, 1975, and Van Adrichem

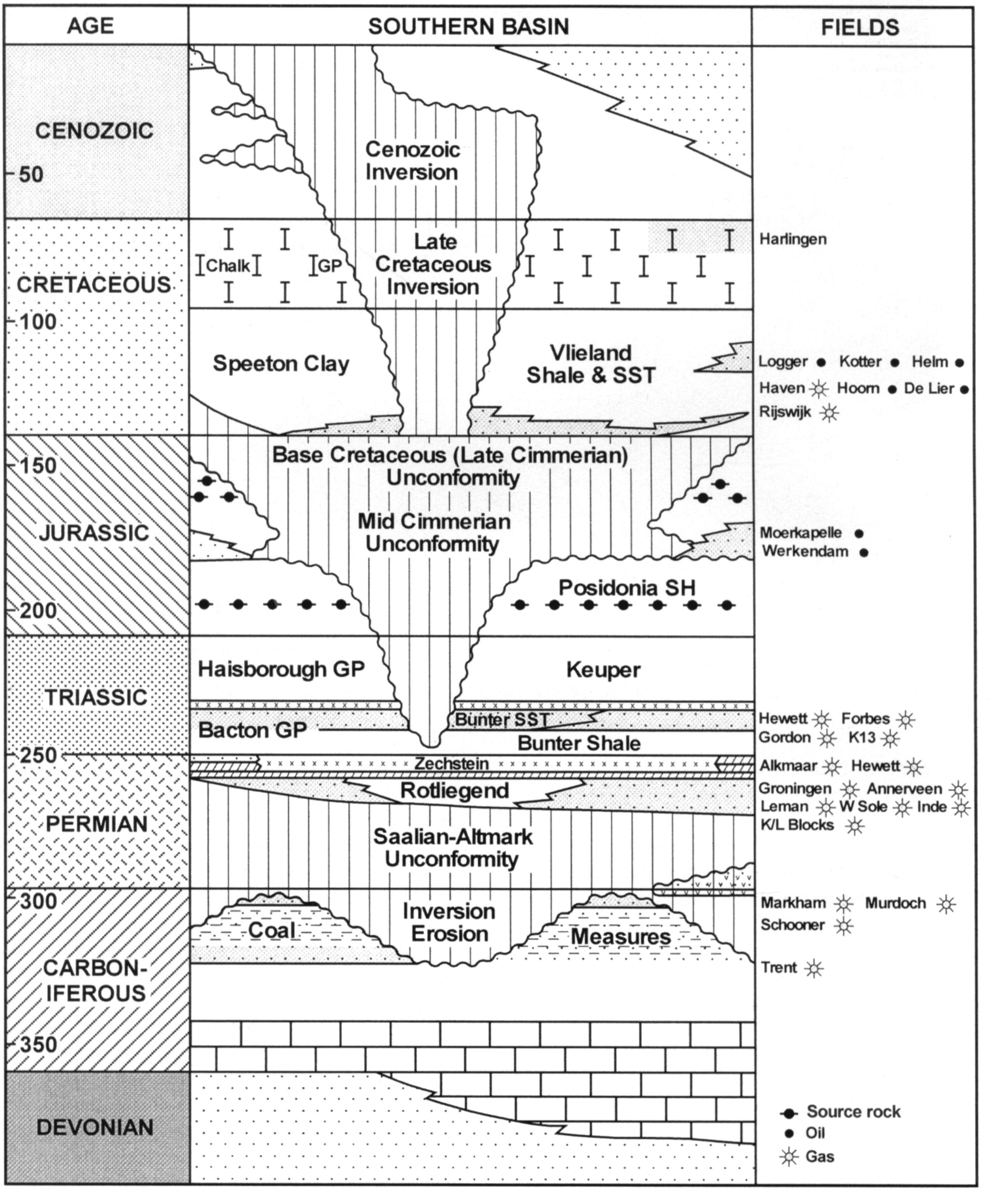


Fig. 3. Simplified stratigraphy of the southern North Sea in the UK and Netherlands sectors, together with some of the important gas and oil fields.

Boogaert, 1976 for the Rotliegend; Taylor, 1980, 1998, Van Adrichem Boogaert and Burghers, 1983 and Stromenger et al, 1996 for the Zechstein and Mader, 1982 for the Bunter). Early disappointments concerning the local quality of the reservoir led to the realization that a post-depositional history involving deep burial followed by uplift could lead to permeability loss through the formation of fibrous illite whiskers (e.g. Glennie et al., 1976; Oele et al., 1981; Gaupp et al. 1993).

In the Netherlands, land exploration for oil and gas (e.g. Rijswijk province; Bodenhausen & Ott, 1981) had continued unabated even after the discovery of this giant Groningen field. Following the *Yom Kippur* war of October 1973, oil was discovered in offshore areas (e.g. F3/2/6, Jurassic), and in Lower Cretaceous reservoirs at Rijn in 1974 (although not proven commercial until 1982), Haven, Helm and Helder in 1979, in Hoorn and Kotter in 1980, and in Logger (Goh, 1996) in 1982 (Table 2); oil was also found in 1980 in a Bunter reservoir in K10-B2 (Knapp & Coenen, 1987).

**Central & northern North Sea 1969 – 1999**

As already mentioned, in the early days of UK offshore exploration, Britain had a state-imposed monopoly market for all gas discovered. By the late 1960s, this market was reaching saturation as British Gas were trying to cope with building a nation-wide distribution system and to convert both domestic and commercial appliances from coal gas to natural gas, which had a higher calorific value (this had taken place in the Netherlands for Groningen gas already in the mid 1960s). With exploration in the southern North Sea slowing down, oil companies began to look elsewhere to employ their seismic and drill ships.

It was natural that Permian reservoirs should be targeted in the early wells drilled in the north.

The first signs that oil, rather than gas, might be present north of the mid North Sea High came in Danish waters in 1966 with the small Anne field, which had a reservoir of Upper Cretaceous Chalk rather than Rotliegend (not in production until 25 years later as the Kraka field; Table 2) and, a year later, the then uneconomic Valhall field (also oil) in Norwegian waters (on stream 1982); in both fields, the chalk reservoir had a relatively low permeability. These small discoveries were followed by one of gas condensate at Cod (Norway), this time in a Paleocene reservoir, and gas at Roar and Tyra (Denmark), again Chalk and uneconomic at the prevailing price of oil and gas. The first discovery of major interest was the Norwegian billion-barrel (237 × $10^9$ $m^3$) Ekofisk oilfield (Pekot & Gersib, 1987), which also had a Chalk reservoir; it quite outshone the small British Arbroath field with a Paleocene reservoir, which was discovered in the same month. Although the matrix permeability of the chalk in Ekofisk averaged only 1.0 mD, appraisal drilling showed that it had an effective permeability of up to 150 mD because of natural fractures caused by the underlying diapiric Zechstein salt.

Late in 1970, the giant Forties field was discovered in UK block 21/10, about 150 km NW of Cod, also with a Paleocene sandstone reservoir (Wills, 1991; Fig. 4, 5; Table 2). Appraisal drilling confirmed recoverable reserves of about 400 × $10^9$ $m^3$ of light oil and a reservoir permeability that ranged up to 4000 mD. Three months later, the stratigraphic range of oil discoveries was extended down to the Permian with the relatively small but highly productive (940 m3/day) Auk field; the Rotliegend now looked more promising within this new oil province. It was in the summer of 1971, however, that the northern North Sea was confirmed as an important hydrocarbon province with the discovery of Brent (block 211/29; 360 × $10^9$ $m^3$ of oil and 160 × $10^9$ gas) in Middle Jurassic sandstones within a rotated fault block (Bowen, 1975; Struijk & Green, 1991). Following the new (4th) round of licensing awards in 1972, the next six years was a time of hectic drilling to prove where oil was (or was not!) before a compulsory relinquishment of 50% of the acreage became effective. Many of these important early UK finds were in the East Shetland Basin (e.g. Beryl, Cormorant, Dunlin, Thistle, Ninian, Magnus) with rather fewer in the Central North Sea (e.g. Piper, Claymore, Britannia, Fulmar, Captain; Fig.4; Table 3, 4).

Following Brent, a string of oil and gas discoveries of similar type (Late Triassic to Middle Jurassic reservoirs in rotated fault blocks) were made in Norwegian waters (Heimdal, Balder, Statfjord, Sleipner, Gullfaks, Oseberg, Snorre; Fig.4, Table 4). The giant Troll field (1252 × $10^9$ $m^3$ recoverable gas overlying a thin oil column containing some 33 × 106 $m^3$ oil), discovered in 1979, has excellent porosity of some 34% and permeability up to tens of Darcies (Grey, 1987). On the Atlantic continental margin of mid-Norway, gas condensate was discovered in the Midgard field in 1981 (Ekern 1987). This was the first of a series of discoveries (Tyrihans, Draugen, Heidrun; Fig. 6, Table 4) that extended north as far as the SW Barents Sea (Campbell and Ormaasen, 1987) these northern areas proved to be gas or gas-condensate prone rather than of economicaly more valuable oil.

**Economic & technical controls on exploration & production**

The commerciality of the North Sea area, especially for the smaller fields, remained in doubt until the global price for oil quadrupled following the *Yom Kippur* war of 1973, thereby encouraging non-OPEC countries to establish their own sources of supply. The new economic environment, in which the price of oil

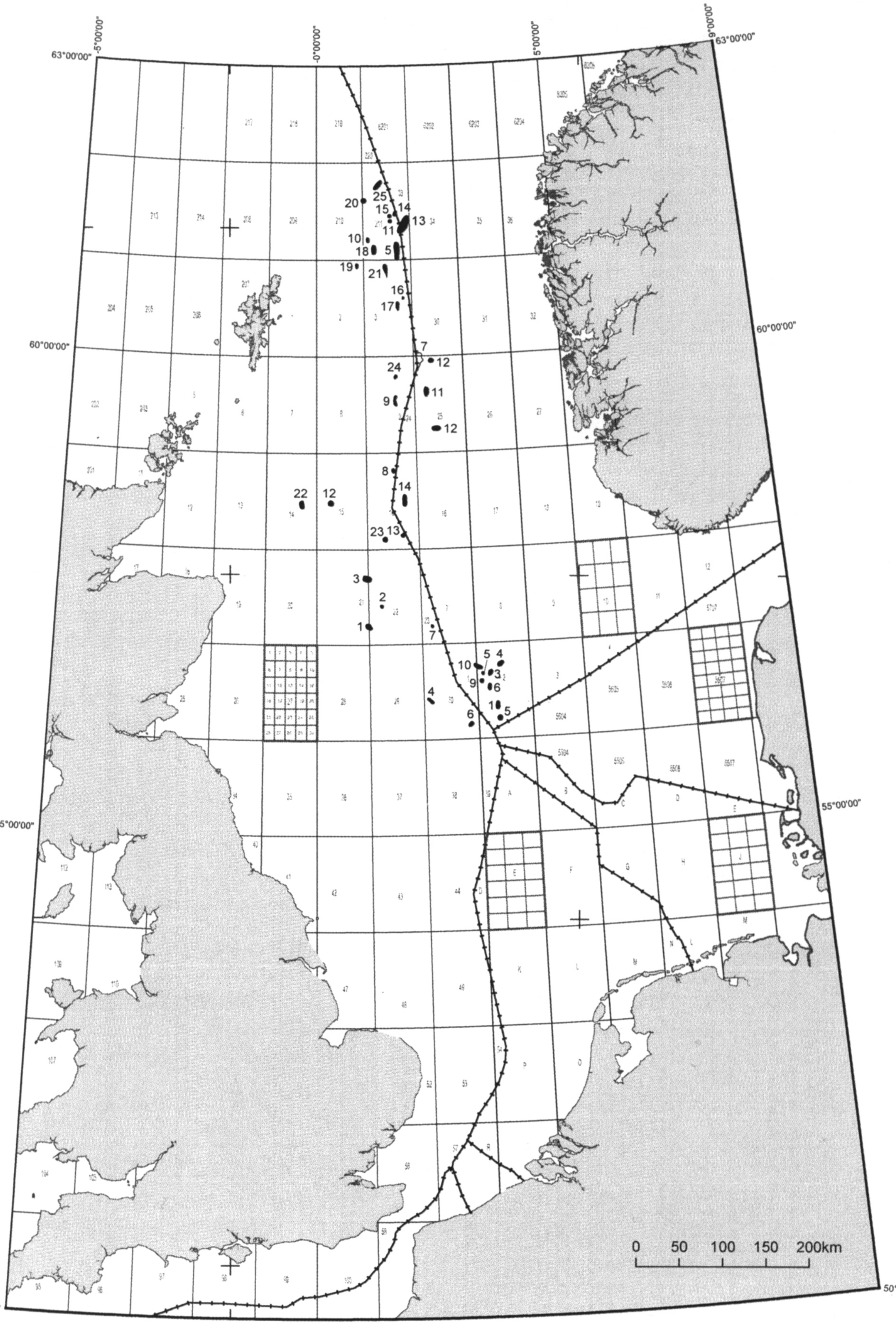


Fig. 4. The order and distribution of discoveries in the separate UK and Norwegian sectors of the central and northern North Sea, 1969-1974. Note the differences in block sizes and numbering in each national sector.

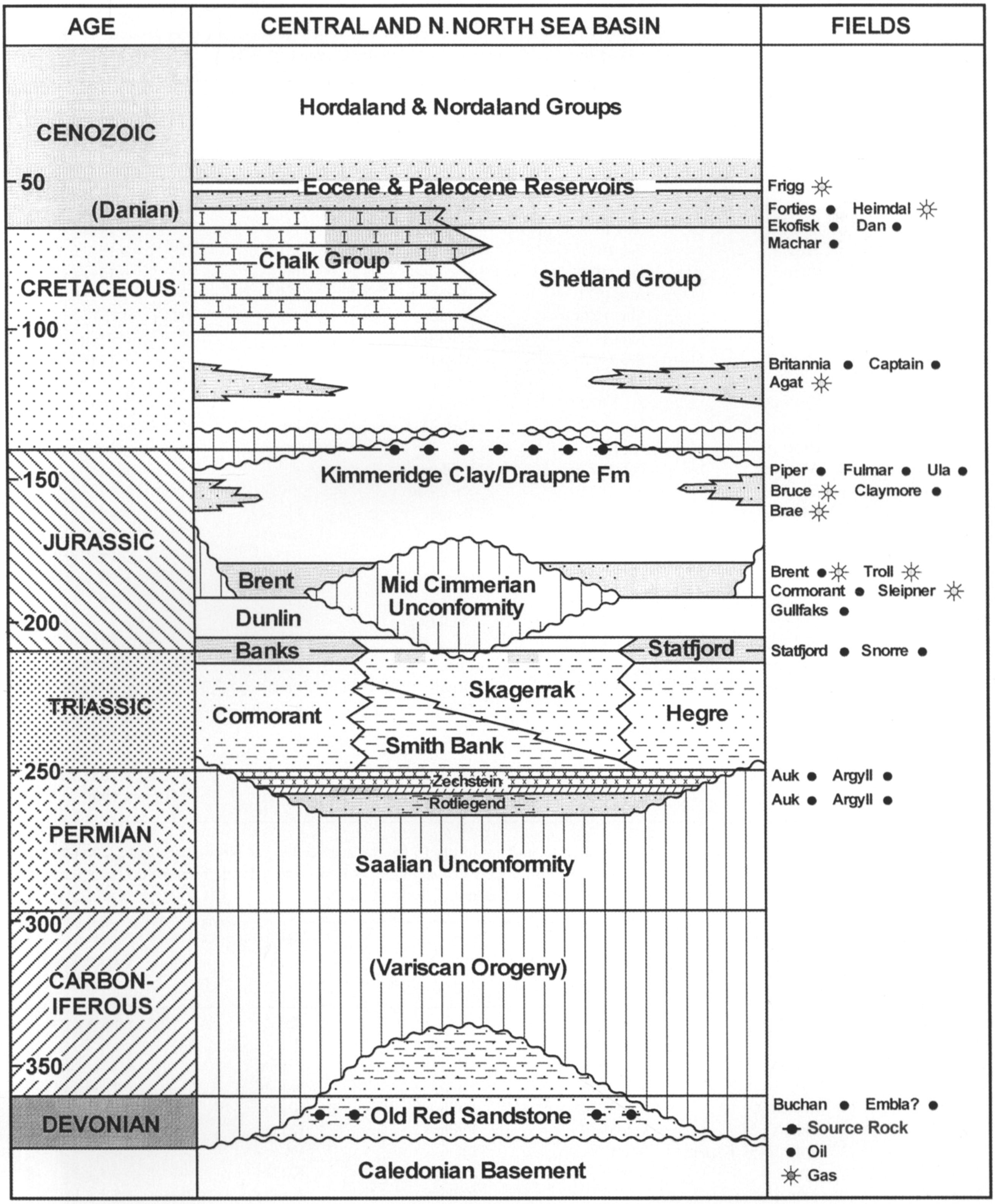


Fig. 5. Simplified stratgraphy of the central and northern North Sea. The Kimmeridge Clay/Draupne Formation is the dominant source rock. Reservoir ages for oil and gas fields range from Devonian to Paleogene via vertical migration and/or fault-related offset (see Fig. 8).

reached a peak of over $35/barrel in 1981, ensured the development until almost the end of the century of many otherwise marginal fields. The global encouragement to protect national supplies of oil eventually led to over-production and a temporary fall in the price of oil to below $10/barrel at the beginning of 1986. Under these conditions the Stock Market collapse of 1987 resulted in the take-over of many weaker companies. The Gulf War of 1991 stiffened the price of oil, but overproduction led to another period

Table 3. The order, reservoir age and volumes of oil and gas in the 25 discoveries of the UK central and northern North Sea, 1969-1974. Paleocene, Eo Eocene, Ku Upper Cretaceous, Kl Lower Cretaceous, Ju Upper Jurassic Jm Middle Jurassic, Jl Lower Jurassic, Tr Triassic, Z Zechstein, R Rotliegend, C Carboniferous. o oil, g gas. * Includes Cormorant N, ** inludes Claymore C & N.

| Order of discovery | Field name | Date | Operator | Reservoir | Reserves o 106 $m^3$, g 109 $m^3$ |
|---|---|---|---|---|---|
| 1 | Gannet F | Mar. 1969 | Shell/Esso | Pc | o 0.2 |
| 2 | Arbroath | Dec 1969 | Amoco | Pc | o 16 |
| 3 | Forties | Nov 1970 | BP | Pc | o 398 |
| 4 | Auk | Feb 1971 | Shell/Esso | Z/R | o 15 |
| 5 | Brent | July 1971 | Shell/Esso | Jm | o 359, g 159 |
| 6 | Argyll | Aug 1971 | Hamilton | Z/R | 15 |
| 7 | Lomond | May 1972 | Amoco | T g | 13 |
| 8 | Kingfisher | June 1972 | Shell/Esso | J | o 9 + g 10 |
| 9 | Beryl A | Sep 1972 | Mobil | Ju/Tru | o 127 |
| | | | Phillips | Tru | |
| 10 | Cormorant S | Sep 1972 | Shell/Esso | Jm | o 100* |
| 11 | Deveron | Sep 1972 | Britoil | Jm | o 3 |
| 12 | Piper | Jan 1973 | Elf | Ju | o 156 |
| 13 | Maureen | Feb 1973 | Phillips | Pc | o 33 |
| 14 | Dunlin | July 1973 | Shell/Esso | Jm | o 54 |
| 15 | Thistle | July 1973 | Britoil | J | o 64 |
| 16 | Ellon | Aug 1973 | Total | Jm | o 6 |
| 17 | Dunbar | Nov 1973 | Total | J/Tr | o 19 |
| 18 | Hutton | Dec 1973 | Conoco | Jm | o 28 +g 17 |
| 19 | Heather | Dec 1973 | Unocal | Jm | o 16 |
| 20 | Osprey | Feb 1974 | Shell/Esso | Jm | o 8 |
| 21 | Ninian | Apr 1974 | Chevron | Jm | o 162 |
| 22 | Claymore | June 1974 | Elf | Cl/Ju/Z/C | o 93** |
| 23 | Andrew | June 1974 | Britoil | Pc/C | o 20+g 7 |
| 24 | Bruce | July 1974 | Hamilton | C/Jm/Jl | c 19 |
| 25 | Magnus | July 1974 | BP | Ju | o 102 |
| | | | | TOTAL | o 1832 + g 193 |

Table 4. The order, reservoir age and volumes of oil, condensate and gas in the 15 fields discovered in the Norwegian sector, 1969-1974. Pc Paleocene, Eo Eocene, Da Danian, Ku Upper Cretaceous, Kl Lower Cretaceous, Ju Upper Jurassic Jm Middle Jurassic, Jl Lower Jurassic, Tr Triassic, Z Zechstein, R Rotliegend, C Carboniferous. o oil, g gas, c condensate.

| Order of discovery | Field name | Date | Operator | Reservoir | Reserves o & c 106 $m^3$ g 109 $m^3$ |
|---|---|---|---|---|---|
| 1 | Valhall | 1967 | Amoco | Ku | o 38 + g |
| 2 | Cod | June 1968 | Phillips | Pc | g 8+c 3 |
| 3 | Ekofisk | Dec 1969 | Phillips | Ku/Da | o 237 + g 126 |
| 4 | Tor | Nov 1970 | Phillips | Ku/Da | o 18 + g 12 |
| 5 | Ekofisk W | Dec 1970 | Phillips | Ku/Da | c 10 + g 28 |
| 6 | Eldfisk | Dec 1970 | Phillips | Ku/Da | o 48 + g 39 |
| 7 | Frigg (N+UK) | July 1971 | Elf | Eo | g 191 |
| 8 | Edda | Sept 1972 | Phillips | Ku/Da | o 4 + g 2 |
| 9 | Albuskjell | Oct 1972 | Phillips | Ku/Da | c 8 + g 18 |
| 10 | Heimdal | Dec 1972 | Elf | Pc | g 36 |
| 11 | Frigg O (a +b) | Sept 1973 | Elf | Eo | g 13 |
| 12 | Balder | May 1974 | Esso | Pc | o 11-23 |
| 13 | Statfjord | Dec 1974 | Mobil | Jm/Jl/Tru | o 482 + g 88 |
| 14 | Sleipner V | Dec 1974 | Statoil | Jm | g 126 + c 45 |
| 15 | Hod | Dec 1974 | Amerada | Ku/Da | o 6 |
| | | | | TOTAL | o+c 862, g 496 |

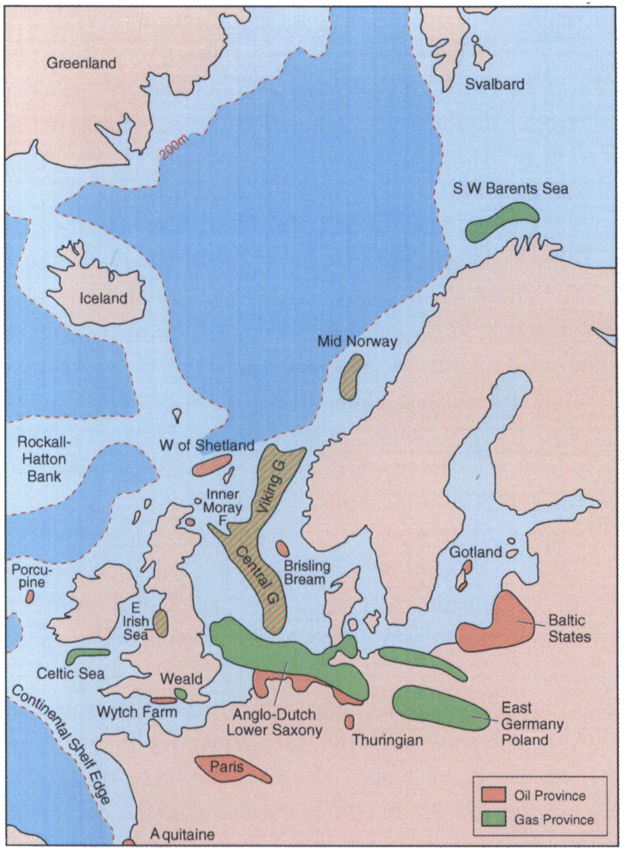


Fig. 6. Major post-Groningen oil and gas provinces of NW Europe. Modified from Glennie & Hurst, 1996.

of oil at $10/barrel in late 1998 – early 1999. Such low prices called for drastic cost-saving measures to be taken with platform development and day-to-day operations. Some uneconomic stand-alone fields became viable, however, when developed as clusters (e.g. Gannet; Armstrong et al., 1987), and by the use of sea-floor production manifolds, unmanned and floating platforms, and modified tankers for offshore oil storage.

The use of 3D seismic techniques, enabled by increases in the efficiency and power of computers, meant that subsurface geology could be mapped with much greater precision than ever before. First used for the development of fields already discovered, it soon proved to be economic even for exploration surveys. Indeed, Epting (1996) showed that in the NE Netherlands, a serious decline in the annual volume of discovered reserves during the 1970s and 1980s was reversed from 1990 onward (Grijpskerk-1) through the use of 3D seismic.

An important factor in improving the commerciality of fields with complex reservoirs was the use from the late 1980s onward of horizontal drilling. This technique prevented water-coning in thin oil legs and increased the bore-hole surface area in contact with reservoirs of low permeability, thereby attaining much greater well productivities. The coupling of 3D seismic and through-casing logging, led to the recognition of producible but unswept oil in older fields (e.g. Weber, 1999). A combination of both successes and failures had led by 1995 to the discovery of some 100 billion barrels ($16 \times 109$ $m^3$) of recoverable oil and oil equivalent (Spencer et al., 1996). This wealth of hydrocarbons was also accompanied by a wealth of new geological knowledge.

## Post-Groningen geological advances in NW Europe

Prior to the discovery of Groningen, the geology of the land areas of NW Europe was reasonably well known from rock exposures and from mining for coal in the UK, Netherlands, Germany and Poland. There had been a limited amount of drilling on land but, except in a most generalized way, the rocks penetrated were virtually unknown outside the oil industry. A few publications, however, later turned out to be exceedingly important (e.g. Visser, 1956; Visser & Sung, 1958; see also Heybroek, 1987) in the early days of North Sea exploration. Around 1960, our knowledge of the geology beneath the North Sea and along the Atlantic margin of NW Europe was a virtual blank. When exploration was considered within the southern North Sea, the hope of finding Rotliegend sediments received encouragement from the knowledge that rocks of similar age and facies were exposed in NE England ('Yellow Sands' of County Durham; Shotton, 1956). The present state of regional understanding of the Rotliegend depositional history owes much to exploration in Germany, including the former East Germany (e.g. Plein, 1995, Schneider et al., 1995, Glennie, 1997b) in addition to the cartographic framework compiled by Ziegler (1982, 1990). As already mentioned, many of these results are now summarized in the Gas Atlas of NW Europe (Lockhorst, 1997).

The first few wells rapidly established a general stratigraphy for the southern North Sea (Fig. 3). The Carboniferous was considered to be economic basement and was rarely penetrated by the drill for more than a few meters, perhaps because the first 15 m or so of the uppermost beds were generally oxidized to redness, and perhaps also because an early deep penetration (Signal's 1965 well 41/20-1; see Fig 3 in Glennie, 1997a and Fig. 4.8 in Besly, 1990) was a dry hole. Following the initial discoveries, there was of a lack of interest in southern North Sea gas in the UK sector, so additional deep penetrations were not made there until the early 1980s when the reservoir potential of the Carboniferous was tested successfully.

The geology of the North Sea's Southern Permian Basin is relatively simple (Figs 2 & 3). Some initially unexplained complexities occurred in former deep troughs (Central Graben and Sole Pit, Broad Fourteens and West Netherlands basins; Fig.7), now presumed to result from extensional tectonics, with local highs (Winterton, Texel-IJsselmeer) as footwall uplifts (Rijkers & Geluk, 1996). The Rotliegend in some apparently shallow structures had unexpectedly poor permeabilities, which were later shown to result from burial below about 3000 m followed by inversion uplift (e.g. Oele et al., 1981, Glennie & Boegner, 1981). Horizontal drilling and hydraulic fracturing are now used to overcome the problems that are associated with production from a tight reservoir (e.g. Crouch et al, 1996: Frikken, 1996).

In the central and northern North Sea the geology differed markedly from what had been experienced in the Southern Permian Basin. The wells drilled in the first few years established a stratigraphy that was broadly similar to that in the south; the Cenozoic was locally much thicker, the Carboniferous was almost absent, while the Devonian Old Red Sandstone was widespread above a relatively shallow Caledonian basement (Figs. 5 & 7). The most striking feature of the northern North Sea, however, was its structure. It was soon realized that this area was bisected by a major post-Hercynian graben system (P.A. Ziegler, 1975; W.H. Ziegler, 1975) whose later development affected sedimentation and preservation until early in the Cretaceous, when the graben axis began to form a roughly linear depocentre for younger sequences. The northern part of this (Central, Viking) graben system seemed to overlie the late Silurian Iapetus Suture (Harland & Gayer, 1972), which then trended southwestward between the Southern Uplands of Scotland and the English Lake District. The developing structural geometry was of major economic importance as it controlled the maturation of a widespread source rock (confirmed as the Kimmeridge Clay Formation only later in the decade) within the grabens and the entrapment of the oil and gas produced from it in overlying and flanking reservoirs ranging in age from Devonian to Cenozoic (Fig. 8).

## Some key Plate-Tectonic events that influenced North Sea Geology

As evidence accumulated, it became clear that throughout its history, the development of North Sea geology had been controlled to a large extent by the effects of plate-tectonic movements (a term not invented until the late 1960s!). These can be generalized as follows (see e.g. Torsvik et al., 1996, and summary cartoons fig. 2.2 of Glennie & Underhill, 1998):

1) Throughout the earlier Palaeozoic, Scotland formed part of Laurentia-Greenland and was separated from Baltica and a Central England-South Denmark micro-continent by the Iapetus Ocean; in the Tornquist Sea between England-Denmark and Baltica, marine source rocks of Cambrian age (Ara Fm.) later sourced the oil fields of Gotland and the Baltic states (Fig. 6). The Tornquist Sea closed at the end of the Ordovician. Closure of the Iapetus Ocean, resulted in the Caledonian Orogeny of Silurian age, and the Old Red Continent, which was then located south of the Devonian equator.
2) Closure of Proto-Tethys in southern Europe resulted in the Variscan Orogeny, in the northern fore-deep of which the mainly terrestrial Carboniferous source and reservoir rocks were deposited in an equatorial environment. Much of NW Europe was subjected to erosion (Saalian Unconformity; Fig. 3) during most of the earlier Permian as the area drifted into northern latitudes similar to those of the modern Sahara Desert.
3) Post-orogenic subsidence of the E-W trending Southern and Northern Permian Basins, and Moray Firth, was accompanied or followed shortly by the development of the roughly N-S trending Viking/Central graben system and others to both the east (e.g. Horn/Oslo) and west (Worcester Graben, East Irish Sea, North Channel). These grabens seemed to be associated with an aborted attempt to create an Atlantic Ocean, which was already evident as the likely route of the Zechstein transgression between Norway and Greenland (e.g. Doré & Gage, 1987; Taylor, 1998).
4) Crustal extension gave rise to early Mid-Jurassic volcanism at the intersection between the Moray Firth – Tornquist-Teysseyre fault systems and the Viking and Central Grabens, which resulted in erosion and non-deposition ('Mid-Cimmerian Unconformity'; Fig. 5) of a large surrounding area. Importantly, post-thermal subsidence accommodated deposition of Mid and Late Jurassic reservoir sequences especially over the Brent Province of the East Shetland Basin (Fig. 7) and over the Outer Moray Firth (Underhill & Partington, 1994; Underhill, 1998). Extension, but without further volcanism, continued until about the

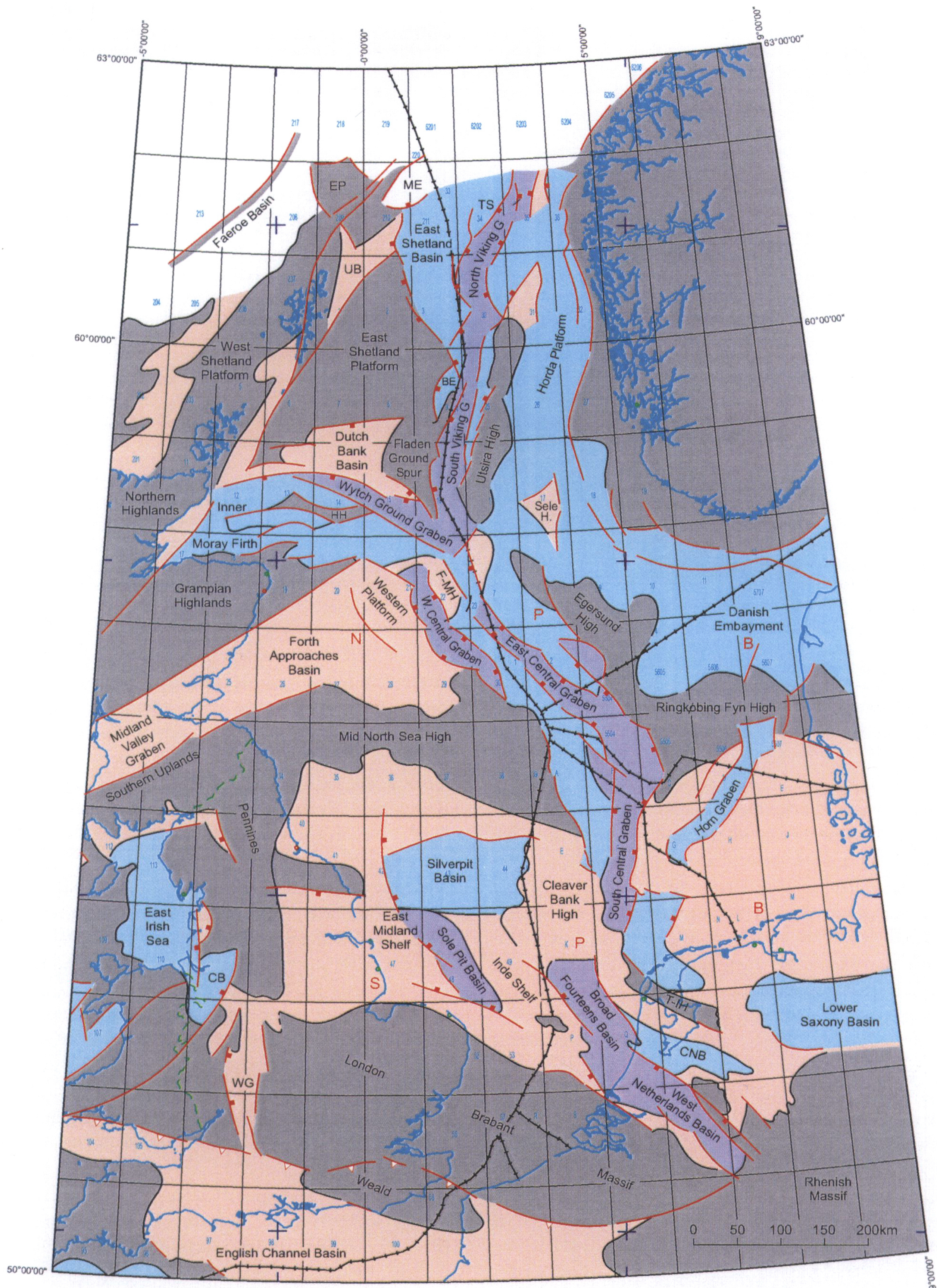


Fig. 7. Megatectonic map of the North Sea. Purple, deep depositional troughs, some now inverted; blue, intermediate basin depth; pink, shelves and shallow basins; grey, outcropping land and shallow sub-sea hights. BE Beryl Embayment; CB Cheshire Basin; CNB Central Netherlands Basin; EP Erland Basin; F-MH Forties-Montrose High; ME Magnus Embayment; NDP Northern Permian Basin; SPD Southern Permian Basin; T-IH Texel-IJsselmeer High; TS Tampen Spur; UB Unst Basin. Simplified from Glennie, 1990.

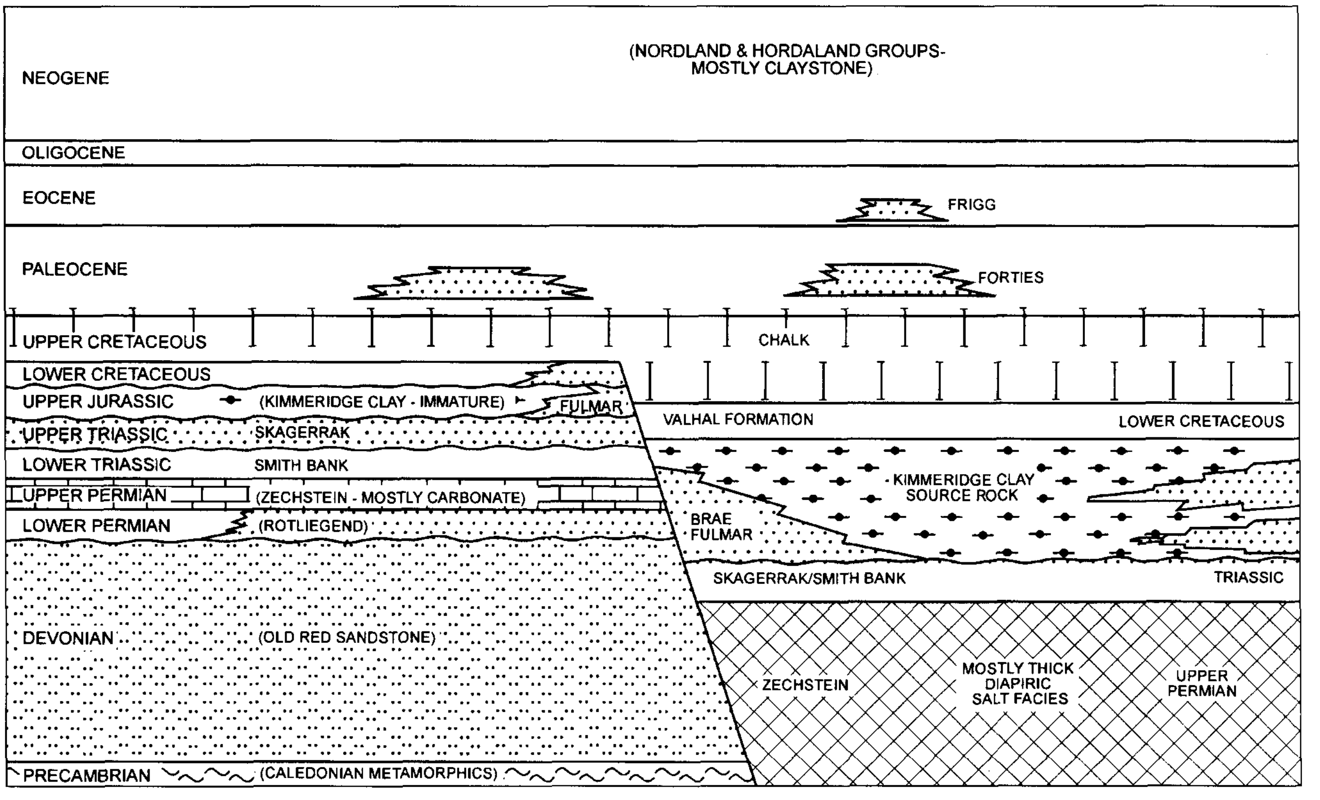


Fig. 8. Source-rock/reservoir geometry: Central Graben and South Viking Graben area's.

Jurassic-Cretaceous boundary, when deposition of the main Kimmeridgian-Ryazanian source rock ceased.

5. Post-extension thermal subsidence of up to 5000 m was centered over the axes of the North Sea graben system; this had the effect throughout the Cenozoic time span of bringing the Kimmeridge Clay (and other less important source rocks) to maturity for both oil and gas generation as different hydrocarbon kitchens were progressively buried.
6. In the Late Paleocene, volcanism and associated uplift of the western margin of Scotland heralded the start of active opening of the Atlantic Ocean. This uplift led to renewed erosion, the products of which were deposited as turbidite reservoir rocks (e.g., Forties, Frigg) within the Central Graben and, to a lesser extent, west of Shetland (e.g. Foinaven, Schiehallion; Fig.6; Table 2).

Much of the foregoing geological interpretation has depended on oil company seismic and well data. The later interpretations probably would have been less reliable and been reached more slowly without a strong interplay with academic research (e.g. considerable biostratigraphic, sedimentological and structural analysis, basic plate-tectonic concepts), derived in part from published literature. This interaction was also a natural outcome over the years of the movement of geoscientists between universities and industry, coupled with the award of research contracts and studentships, and the development of both short industry-oriented courses in petroleum-related topics and of specialized university degree courses. An example of a contracted university survey is the use of wide-angle seismic data in the recognition of sediments beneath the thick basalts east of the Faroe Islands (Richardson et al., 1999).

The scenes of greatest industry-wide scientific exchange, however, were the many conferences and their published proceedings. Arguably the most important of these events was the so-called Bloomsbury conference of 1974 in London (Woodland, 1975), at which academics were amazed at the amount and scientific quality of the data released by the oil companies; they realized that in many respects the industry was well ahead of them in understanding the geological development of NW Europe, in part because the seismic, cores, cuttings and wireline logs acquired during drilling provided vital three-dimensional information that is lacking in most surface exposures. The former leisurely pace of academic research was too slow for the oil industry where many interpretations require almost instant application; industry funding ensured more rapid university research.

In addition to the economic gain of oil and gas, our understanding of the geological development of NE

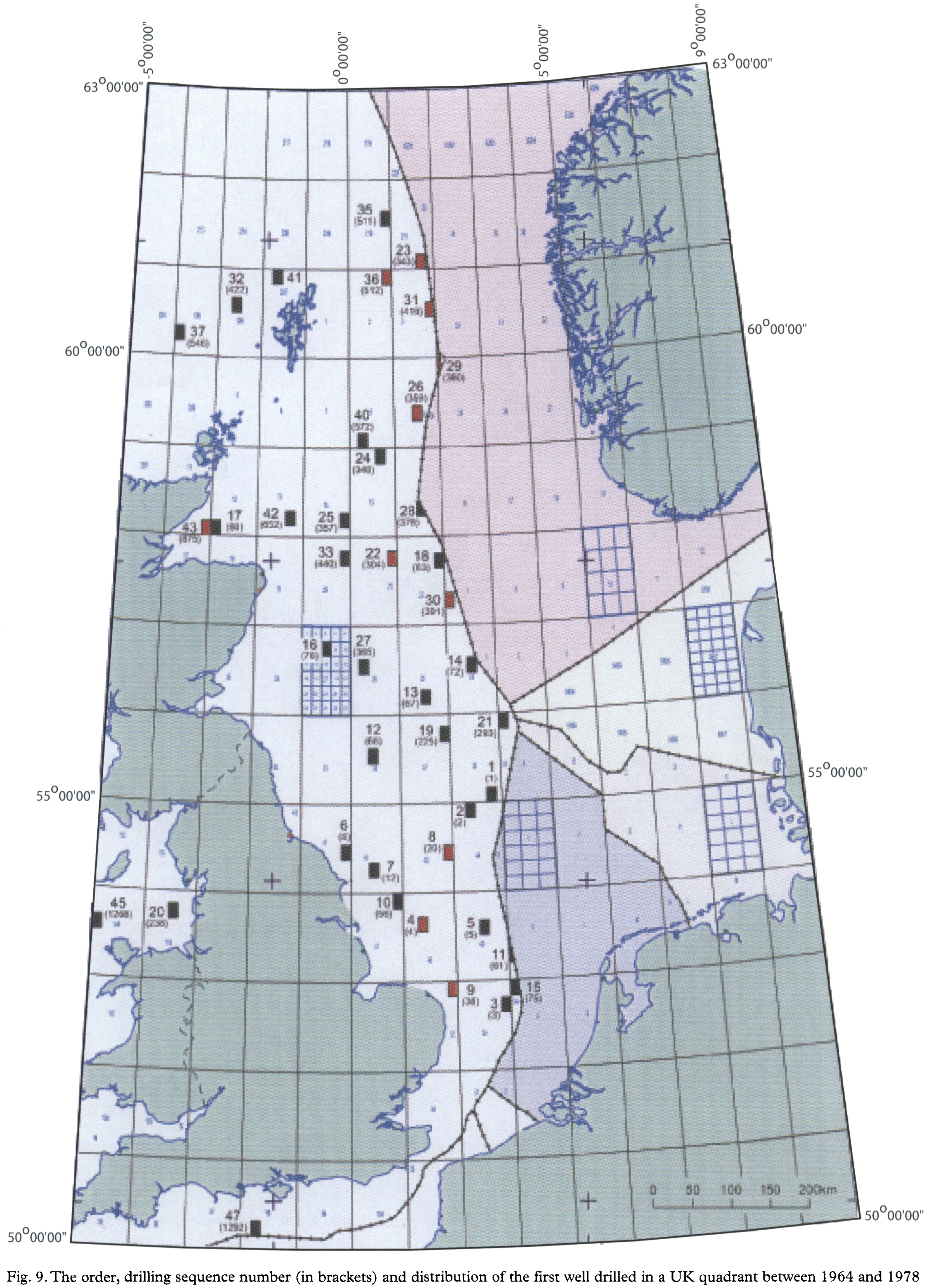


Fig. 9. The order, drilling sequence number (in brackets) and distribution of the first well drilled in a UK quadrant between 1964 and 1978 show the development of interest in different parts of the UK offshore. The red rectangles denote oil or gas discoveries. See also Table 5.

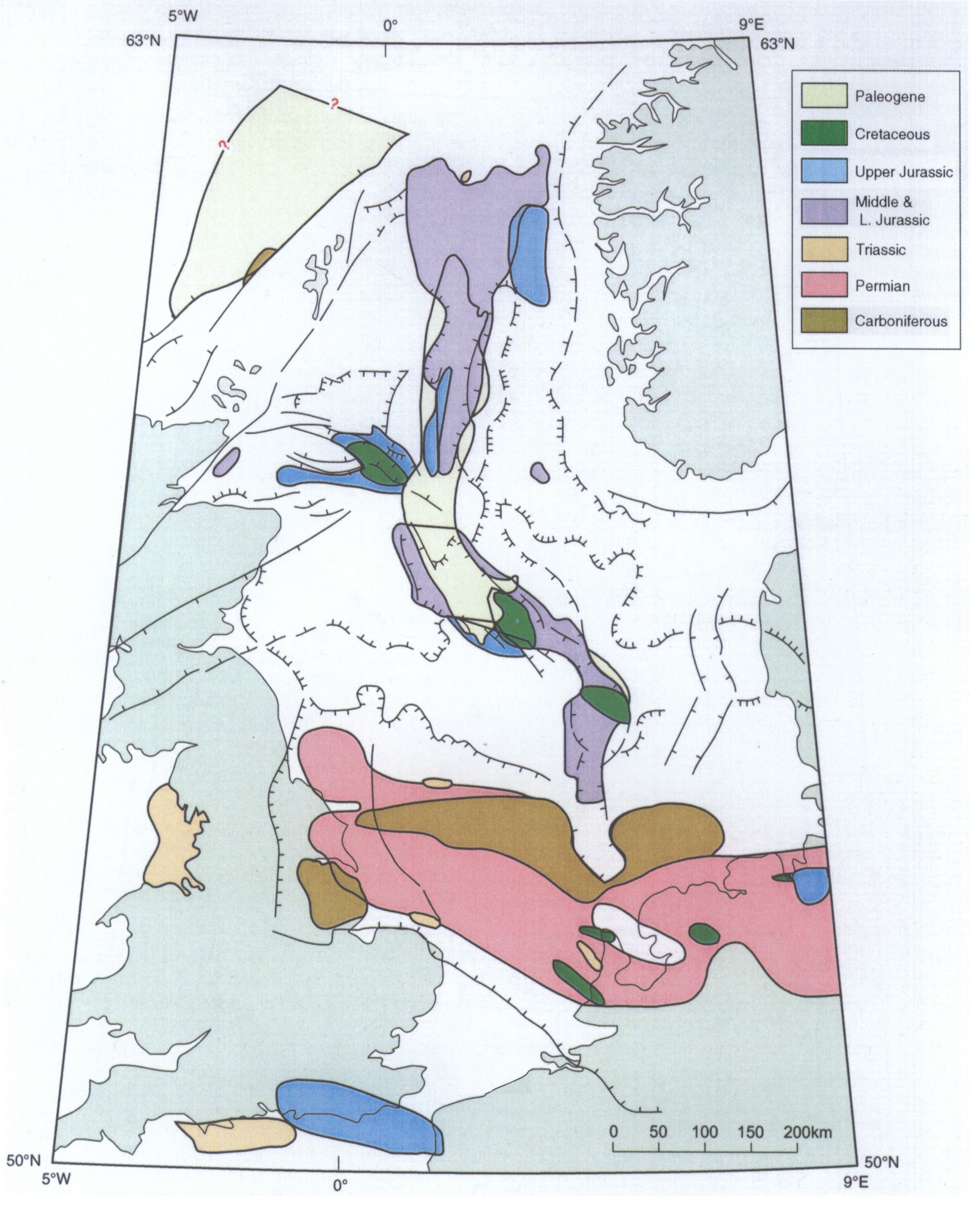


Fig. 10. Hydrocarbon Play map of the North Sea and adjacent areas. (Modified from Pegrum & Spencer, 1990, Parsley, 1990, Glennie, 1986 1996 & Johnson & Fisher, 1998).

Europe has increased enormously during the years of exploration since 1959. From a blank geological map of the North Sea area framed by regional land geology in 1965, we now have a fairly detailed subsurface stratigraphic and mega-tectonic framework (Figs. 3, 5 & 7), that matches outcrop areas on a broad scale; this becomes much more detailed where involved with the needs of field development.

From an exploration point of view, the outcome of the events outlined above can be seen in the distribution of a variety of 'play areas' (Fig. 9) depicting the likely locations of hydrocarbon-filled reservoir rocks of varying facies and age (see also Parsley, 1990; Pegrum & Spencer, 1990; Johnson & Fisher, 1998). The disparity in success between recent drilling using the play-map concept of figure 9 (about 1 in 2) and earlier wildcat drilling based on the first well drilled in each UK quadrant (about 1 in 5; Fig. 10; Table 5) shows how far the industry has progressed over the past 40 years.

Table 5. The order (left-hand column), well-sequence number and year, where known, of the first well drilled in each quadrant of the UK continental shelf, and fields discovered. The few discoveries in the tabulation illustrates the relative stratigraphic and structural uncertainty encountered during wildcat drilling. The quadrants of those numbers marked with an asterisk in the order column fall west of the map Fig. 4.

| | WELL No | SEQUENCE No | YEAR | COMPANY | OUTCOME | ONSTREAM |
|---|---|---|---|---|---|---|
| 36 | 2/5-1 | (512) | 1973 | Union | Heather | 1978 |
| 31 | 3/15-1 | (419) | 1973 | Total | Ellon | 1995 |
| 40 | 8/27a-1 | (572) | 1974 | Shell | D/A | |
| 26 | 9/23-1 | (359) | 1971 | Shell | show (Forth?) | |
| 29 | 10/1-1 | (380) | 1972 | Total | Frigg | 1977 |
| 43 | 11/30-1 | (875) | 1976 | Mesa | Beatrice | 1981 |
| 17 | 12/26-1 | (80) | 1967 | Hamilton | D/A | |
| 42 | 13/24-1 | (652) | 1974 | Amoco | D/A | |
| 25 | 14/25-1 | (357) | | Shell | D/A | |
| 24 | 15/4-1 | (348) | | Shell | D/A | |
| 28 | 16/23-1 | (378) | | Conoco | D/A | |
| 33 | 20/10-1 | (440) | 1974 | BP | D/A | |
| 22 | 21/10-1 | (304) | 1970 | BP | Forties | 1975 |
| 18 | 22/11-1 | (83) | 1968 | Gulf | SE Forties 'undiscovery' | |
| 30 | 23/21-1 | (391) | 1972 | Amoco | Lomond | 1993 |
| 16 | 27/3-1 | (76) | 1967 | Amoco | D/A | |
| 27 | 28/12-1 | (365) | 1971 | Burmah | D/A | |
| 13 | 29/23-1 | (67) | 1967 | Burmah | D/A | |
| 14 | 30/18-1 | (72) | | Hamilton | D/A show (Orion) | |
| 12 | 36/13-1 | (68) | 1967 | Arpet | D/A | |
| 19 | 37/10-1 | (225) | | Amoco | D/A | |
| 1 | 38/29-1 | (1) | 1964 | Gulf | D/A | |
| 21 | 39/1-1 | (293) | 1970 | Texaco | D/A | |
| 6 | 41/20-1 | (8) | 1966 | Signal | D/A | |
| 7 | 42/23-1 | (12) | 1966 | Burmah | D/A | |
| 8 | 43/20-1 | (20) | 1969 | Rycade | Gordon | 1985 |
| 2 | 44/2-1 | (2) | 1964 | Shell | D/A | |
| 10 | 47/5-1 | (56) | | Phillips | D/A | |
| 4 | 48/6-1 | (4) | 1965 | BP | West Sole | 1967 |
| 5 | 49/13-1 | (5) | 1966 | Gulf | show | |
| 11 | 50/26-1 | (61) | | Amoseas | D/A | |
| 9 | 52/5-1 | (38) | 1967 | Phillips | Hewett extension | |
| 3 | 53/10-1 | (3) | 1965 | Gulf | D/A | |
| 15 | 54/1-1 | (75) | | Conoco/NCB | D/A | |
| 46* | 72/10-1 | (1290) | | BNOC | D/A | |
| 49* | 86/18-1 | (1340) | | BNOC | D/A | |
| 48* | 87/12-1 | (1331) | | BP | D/A | |
| 39* | 93/2-1 | (567) | | BP | D/A | |
| 47 | 98/22-1 | (1292) | | BG | D/A | |
| 34* | 102/28-1 | (507) | | Shell | D/A | |
| 44* | 103/18-1 | (924) | | Shell | D/A | |
| 38* | 106/24-1 | (554) | | Arpet | D/A | |
| 45 | 107/21-1 | (1268) | | HC.GB | D/A | |
| 20 | 110/8-1 | (238) | 1969 | Gulf | next well Morcambe 'undiscovery' | |
| 37 | 205/21-1 | (546) | | Shell | show | |
| 32 | 206/12-1 | (422) | | Esso | D/A (SW of Clair) | |
| 41 | 207/2-1 | (620) | | Shell | D/A | |
| 35 | 210/15-1 | (511) | 1973 | Phillips | ?Wendy | |
| 23 | 211/29-1 | (343) | 1971 | Shell | Brent | 1976 |

## Conclusions

The discovery of the supergiant Groningen gas field in 1959 was the spur for active exploration in the North Sea and other land and marine areas of NW Europe. Early exploration concentrated on gas of Carboniferous origin in Rotliegend reservoirs; this activity extended to the search for oil and gas of Jurassic origin in reservoirs ranging in age from Cambrian to Cenozoic. In the first 30 years of this activity, the oil industry located ultimate recoverable reserves of some 100 billion barrels ($16 \times 109$ $m^3$) of oil and oil equivalent beneath the waters of the North Sea with more along the Atlantic Margin continental shelf and below the land surface of other parts of NW Europe. Continuing discoveries indicate that, despite some pessimism, more is likely to be found in future decades.

From an initial state of no knowledge of sub-sea geology, the industry has now reached the stage where the North Sea area for its size has the best known three-dimensional geology in the world. Much of the pre-Hercynian land area surrounding the North Sea acted as a source of sediment for the younger sub-sea formations but lacks these North Sea rock units. Thus North Sea stratigraphy helps to fill the gap in the younger history of the surrounding land area. Conversely, our early understanding of North Sea history would have been much more limited if those same land areas had not been studied carefully during the previous two centuries or so. The North Sea area has had a very varied history over the past 500 million years (plate-tectonic movement, igneous activity, climatic change, and deposition in a variety of continental and marine environments), leading to complex geometrical relationships between hydrocarbon source rock, reservoir and seal, and to the reasons for diagenetic changes in the quality of the reservoir sequences.

Led by increasingly sophisticated seismic, drilling and wireline logging, and now coupled with academic research, the North Sea has developed into a giant geological laboratory where ideas have been tested and extended industry-wide. The interchange of ideas presented at industry-sponsored and other conferences and in their ensuing publications has greatly improved our understanding of the geological history of NW Europe in general and the North Sea in particular.

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