Chapter 25

Geology of the Norwegian Continental Shelf

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25.1 Introduction

In the preceding chapters we have included only a few regional examples and case studies because of space limitations. The present chapter will, however, provide some examples. The North Sea and other parts of the Norwegian continental shelf contain several different petroleum provinces which can illustrate some of the general principles of petroleum geology and geophysics. The geological evolution of these sedimentary basins provides a necessary background to understand the distribution of source rocks and the timing of petroleum migration. The structural history of rifted basins, passive margins and also uplifted basins such as the Barents Sea is critical to the trapping of oil and gas. These basins are very well documented by seismic and well data. The Norwegian Petroleum Directorate also provide information about exploration and production on their web pages (http://www.npd.no).

The Norwegian continental shelf is unique with respect to the amount of information available about petroleum exploration and production and also geological and geophysical information and maps (http://www.npd.no/en/Topics/Geology/). You will there find updated information about exploration and production and also references to publications and reports. This is a supplement to this book. Furthermore, updated lithostratigraphic tables from the Norwegain Offshore are available from NPD (http://www.npd.no/en/Topics/Geology/Lithostratigraphy/).

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25.1.1 Regional Geological Setting

The Norwegian continental shelf comprises three main provinces (Figs. 25.1 and 25.2):

- North Sea
- Mid-Norwegian continental margin
- Western Barents Sea

Prior to continental break-up and the onset of seafloor spreading in the Norwegian-Greenland Sea (Fig. 25.3) these provinces were part of a much larger epicontinental sea lying between the continental masses of Fennoscandia, Svalbard and Greenland. Thus there are many similarities in the stratigraphy (Fig. 25.4) and geological evolution of the various provinces but also important differences – in particular during Cretaceous-Cenozoic times.

The sedimentary basins at the conjugate continental margins off Norway and Greenland and the adjacent shallow seas, the North Sea and the western Barents Sea, developed as a result of a series of post-Caledonian rift episodes until early Cenozoic time, when complete continental separation took place. The Norwegian Margin comprises the mainly rifted volcanic margin offshore mid-Norway (62–70°N) and the mainly sheared margin along the western Barents Sea and Svalbard (70–82°N) (Fig. 25.2). Physiographically, the Norwegian margin consists of a continental shelf and slope that vary considerably in width and morphology (Fig. 25.1).

25.1.2 Petroleum Exploration

When gas was found onshore in the Groningen Field in the Netherlands in 1958 it soon generated interest in the North Sea itself. However, it was difficult to say

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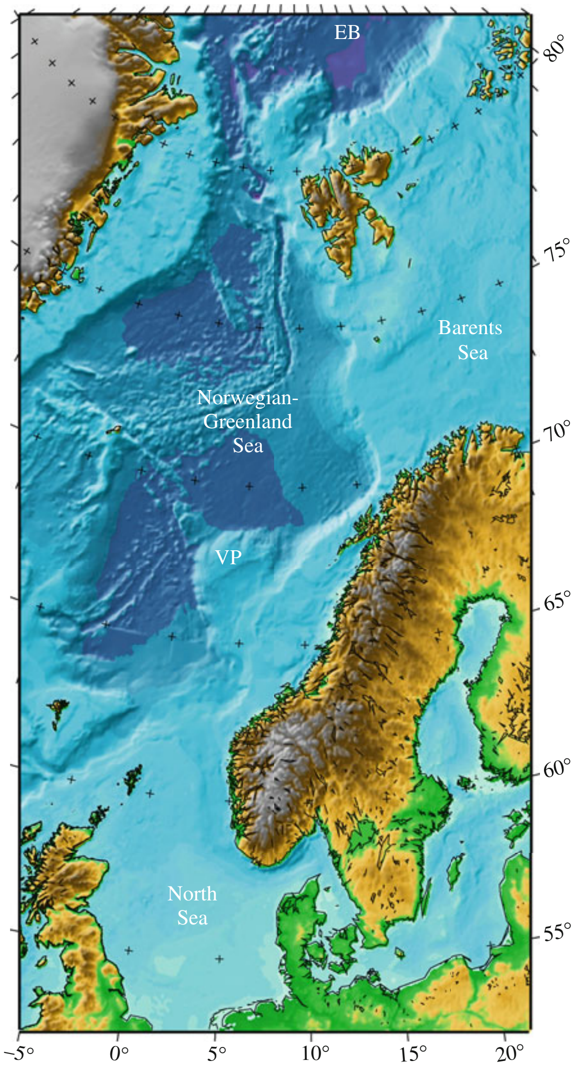

Fig. 25.1 Regional setting (bathymetry/topography) of the Norwegian Continental Shelf and adjacent areas. EB = Eurasia Basin, VP = Vøring Plateau

what lay off the Norwegian coast beneath the Quaternary sediments. Moraine material which had been recovered from the seabed during marine geological investigations in the 1950s contained clasts that almost without exception were basement rocks.

The pre-Quaternary geology of the Norwegian Continental Shelf was virtually unknown prior to the early 1960s, as there had been no seismic measurements and few other indications of what was beneath the cover of Quaternary, partly glacial, sediments. Before any seismic or borehole data were obtained in the North Sea, one had to extrapolate from the geology of the surrounding land areas. The Mesozoic rocks of northeast England and Denmark were assumed to continue beneath at least parts of the North Sea, and Carboniferous coal seams and Permian sediments were already well known in northeastern England. There were also a few indications that younger sedimentary rocks were present beyond the Norwegian coast. The moraines on Jæren contained small amounts of probably Cretaceous material, there were erratic blocks of Jurassic age on Froan and pieces of coal from Tun in Verran, off Trøndelag. Much farther north, the fairly thin Jurassic and Cretaceous sequences on Andøya had long been known. It was difficult, though, to know how much reliance could be placed on these scattered observations; not least, one had no idea of how thick such Mesozoic sediments would be.

It was difficult to know if the equivalents of the well known source rock, the Upper Jurassic Kimmeridge Clay extended into the Norwegian Shelf and if it was buried deeply enough for it to be mature.

A confirmation of the presence of thick sediment sequences on the shelf was obtained in seismic refraction studies in the Barents Sea and the central North Sea in the late 1950s, indicating accumulations in the order of several kilometres. Seismic refraction studies supported by potential field data in the Skagerrak, performed in 1963–1964, confirmed the presence of more than 3 km of sediments also in this area. The early seismic data that was shot in the North Sea had very poor quality and it was not until drilling on the Norwegian shelf commenced in 1966 that it was possible to have an informed opinion on the potential for oil and gas.

The Norwegian continental shelf, extending from the baseline to the limit approved by the UN Commission on the Limits of the Continental Shelf, amounts to 2.2 million km^2. About half of this acreage has bedrock in which petroleum may be found, and half of that has been opened for petroleum exploration. The first licences were awarded in 1965 and the first commercial discovery in the Norwegian part of the North Sea (block 2/4) was made in 1969. The motivation for this drilling was to test a possible Permian (Rotliegendes sandstone) reservoir. Instead, however, an unexpected discovery of hydrocarbons was made in a domal structure in Upper Cretaceous Chalk. Continued exploration on this play type resulted in a number of discoveries in the Ekofisk area of the central North Sea.

Large fields in the North Sea, such as Sleipner, Statfjord and Gullfaks, were discovered during the first 10 years after the Ekofisk Field was proven, and all four are still in production. Most of the other large

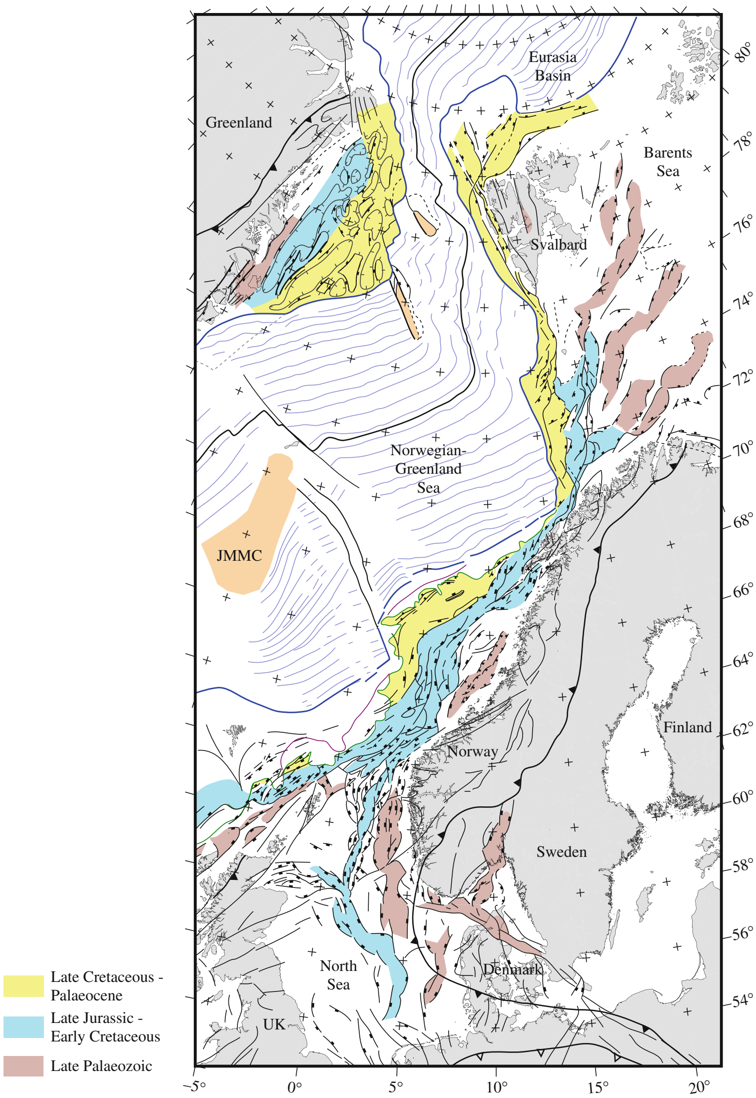

Fig. 25.2 Main structural elements of the Norwegian Continental Shelf and adjacent areas related to different rift phases affecting the NE Atlantic region (modified/updated from Faleide et al. 2008). For more details see close-up maps in Figs. 25.5, 25.10 and 25.14. JMMC = Jan Mayen microcontinent

fields on the shelf were found between 1979 and 1984 (see Sect. 25.2.3 for more details on the North Sea exploration history).

Following the exploration success in Norwegian waters south of 62°N, the areas to the north were opened for exploration in 1979. Results and experience gained from the North Sea were utilised when areas further north were opened, and areas with a similar geological setting to the northern North Sea were tested first (Haltenbanken offshore Mid-Norway and Tromsøflaket in the southwestern Barents Sea). The exploration histories of the areas north of 62° N are more complex, and even today important aspects of the petroleum geology remains enigmatic – partly due to geological complexities.

Large parts of the Norwegian continental shelf are now well explored. Better knowledge of the geology and advances in technology lead to a higher discovery rate, but the finds have mostly been small. Consequently, the growth in resources has been relatively low for the last 20 years. The largest discovery made in this period was Ormen Lange in the Norwegian Sea in 1997. Recent discoveries in the North Sea (Edvard Grieg and Johan Sverdrup) and

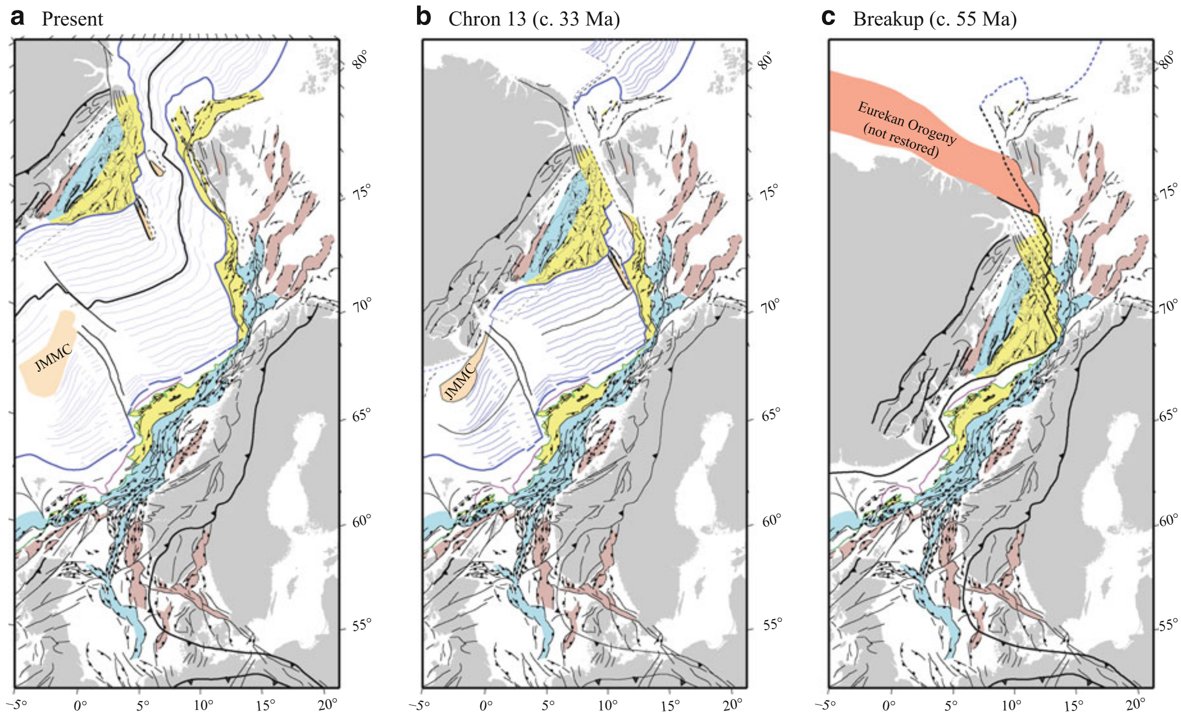

Fig. 25.3 Plate tectonic reconstructions of the NE Atlantic. (**a**) Present (same as Fig. 25.2), (**b**) Reconstruction to chron 13 (c.33 Ma) using the rotation pole of Gaina et al. 2009, (**c**) Reconstruction to time of breakup (c.55 Ma) based on unpublished work of Faleide et al.

Barents Sea (Johan Castberg and Gohta/Alta) have added considerable oil resources which will contribute to substantial production in years to come.

Technological advances have led to development of discoveries in areas of great water depth and far from shore. The technological advances have also made a higher proportion of the resources profitable to recover. On average, fields on the Norwegian shelf have a recovery factor of 46% for oil. This is high compared with oil provinces in other parts of the world. Continuous research and development of technology are required to raise this further.

Significant volumes remain to be found and produced on the Norwegian continental shelf. About 40–50% of the estimated oil and gas reserves have so far been produced. The reserves will depend on future oil and gas prices and on environmental restrictions. It may still be possible to make large discoveries in less explored areas, such as in deep waters in the Norwegian Sea, in the Barents Sea and in areas that are not yet open. Oil production reached its peak in 2000–2001, but gas production is still increasing. For more facts about the petroleum activity on the Norwegian shelf see http://www.npd.no/en/Publications/Resource-Reports/2014/.

25.2 North Sea

25.2.1 Structure

The North Sea is an example of an intracratonic basin; that is to say a basin which lies on continental crust. The prerequisite for forming major sedimentary basins on continental crust is that the crust (and mantle lithosphere) is thinned, resulting in subsidence to maintain isostatic equilibrium. The North Sea has been subjected to periods of stretching/thinning and subsidence during late Carboniferous, Permian-Early Triassic and Late Jurassic times. Each rift phase was followed by a thermal cooling stage, characterised by regional subsidence in the basin areas.

The Northern North Sea province is dominated by the Viking Graben, which continues into the Sogn Graben towards the north (Fig. 25.5). These grabens are flanked by the East Shetland Basin and the Tampen Spur to the west, and the Horda Platform to the east (Figs. 25.6 and 25.7). These are Jurassic-Cretaceous features, and the main crustal thinning took place in the late Middle to Late Jurassic, followed by thermal

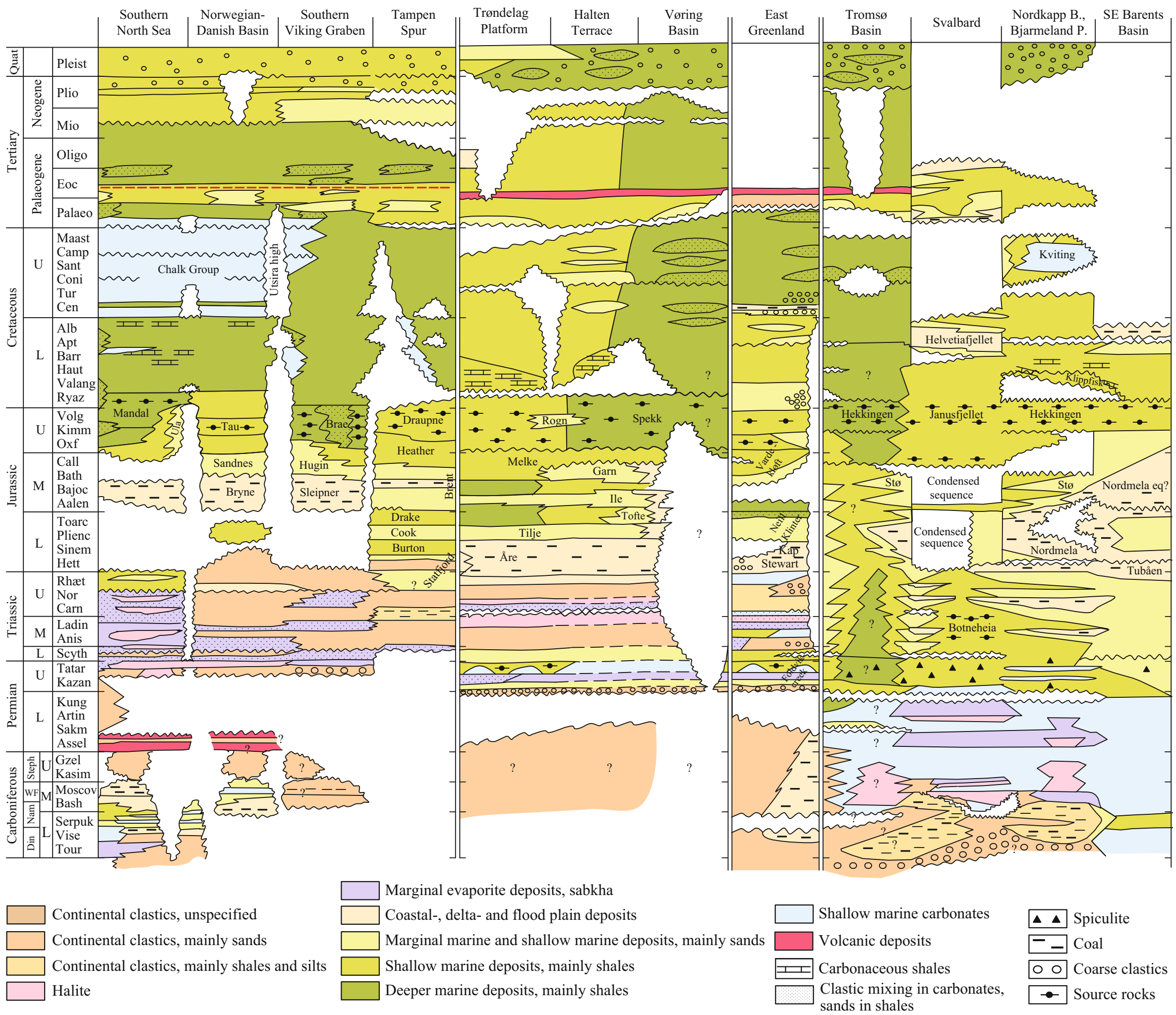

Fig. 25.4 Lithostratigraphic summary for the Norwegian Continental Shelf and adjacent areas (modified from Brekke et al. 2001)

subsidence and sediment loading in the Cretaceous. However, the Viking Graben and its margins are underlain by an older major rift basin of assumed Permian-Early Triassic age. The axis of this rift system is thought to lie beneath the present Horda Platform. It is bounded by the East Shetland Platform in the west and the Øygarden Fault Zone in the east. Structures within this area are characterised by large rotated fault blocks with sedimentary basins in asymmetric half-grabens associated with lithospheric extension and crustal thinning (Fig. 25.6). The area was presumably also strongly affected by post-orogenic (post-Caledonian) extension in Middle to Late Devonian times.

The Norwegian Central North Sea Province encompasses the northwestern part of the Central Graben (Figs. 25.5, 25.8 and 25.9), which is mainly a Jurassic-Cretaceous structure, and its northeastern margin. The strata of the Central Graben area were affected by halokinesis already in the Triassic, and major structuring accordingly occurred already in pre-Jurassic times. However, salt movements have locally continued into the Tertiary. Jurassic rifting and generation of large, rotated fault blocks resulted in extreme erosion in places. The complex structural pattern established during this stage was further complicated by Cretaceous inversion. The Norwegian-Danish Basin, east of the Central Graben, also contains

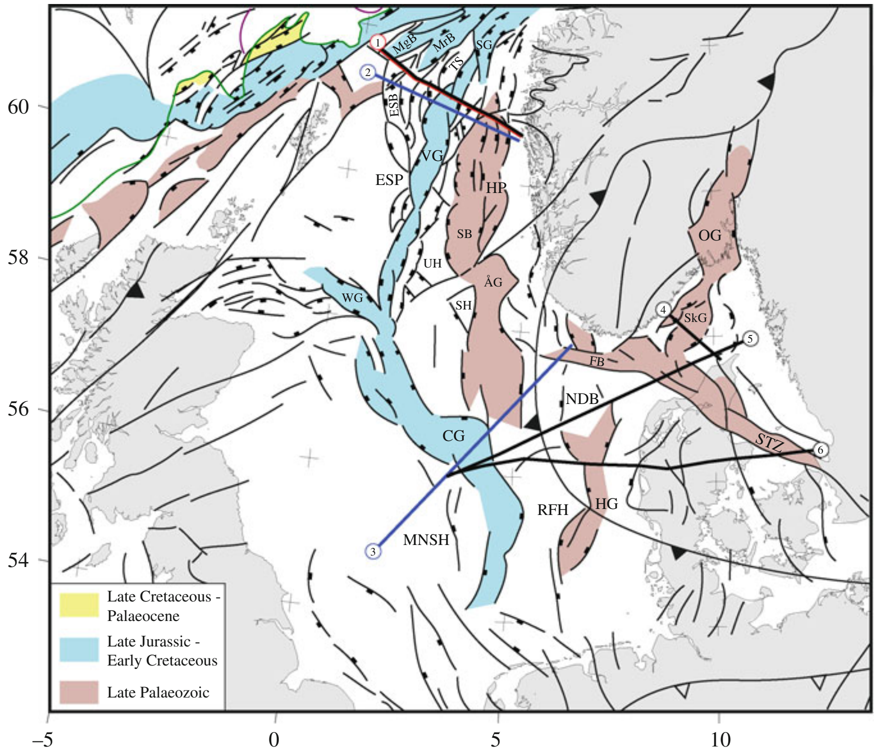

Fig. 25.5 Main structural elements in the North Sea and adjacent areas (close-up of Fig. 25.2 – modified/updated from Faleide et al. 2008). Location of interpreted regional profiles (*black*), crustal transects (*red*) and seismic examples (*blue*) shown in Figs. 25.4–25.9. CG = Central Graben, ESB = East Shetland Basin, ESP = East Shetland Platform, HG = Horn Graben, HP = Horda Platform, MgB = Magnus Basin, MNSH = Mid North Sea High, MrB = Marulk Basin, NDB = Norwegian-Danish Basin, OG = Oslo Graben, RFH = Ringkøbing-Fyn High, SB = Stord Basin, SG = Sogn Graben, SH = Sele High, SkG = Skagerrak Graben, STZ = Sorgenfrei-Tornquist Zone, TS = Tampen Spur, UH = Utsira High, VG = Viking Graben, WG = Witchground Graben, ÅG = Åsta Graben

many salt structures but has not been affected by significant rifting (Figs. 25.8 and 25.9).

The geometric shape of the sedimentary basin is influenced by the structure in the underlying rocks (basement) and by the thickness of the continental crust. Most of the North Sea is underlain by a Caledonian basement. Long-lived zones of weakness inherited from the Caledonian Orogeny played a role in the later evolution of the North Sea basin. The southeastern North Sea and Skagerrak are underlain by a Precambrian basement covered by a Lower Palaeozoic sedimentary succession. In the south the North Sea basin is bounded by the Hercynian (Variscan) mountain range which runs E-W through Germany, northern France and southwest England. The contraction occurred during the Carbonifererous-Permian. Uplift in this area resulted in vast amounts of sediment being deposited in the area to the north and this initiated the formation of the North Sea basin.

The offshore part of the Oslo Rift in the Skagerrak is characterised by NE-SW striking half-grabens (Fig. 25.9). Cross-sections across the Skagerrak show tilted half-grabens filled with down-faulted Upper Carboniferous-Lower Permian and Lower Palaeozoic strata that are unconformably overlain by Triassic sedimentary rocks. Although a thick succession of Lower Palaeozoic strata has been preserved in the Skagerrak Graben, a substantial part of this pre-rift unit has been eroded in the central part of the rift. From strata preserved in the onshore Oslo Graben we know that the Lower Palaeozoic succession consists mainly of Cambrian-Ordovician and Silurian platform series and Upper Silurian-lowermost Devonian clastic sedimentary rocks, with the latter being deposited in the Caledonian foreland basin. In the western part of the Skagerrak, the late Palaeozoic structures of the Oslo Rift link up with the Sorgenfrei-Tornquist Zone (also termed the Fennoscandian Border Zone in

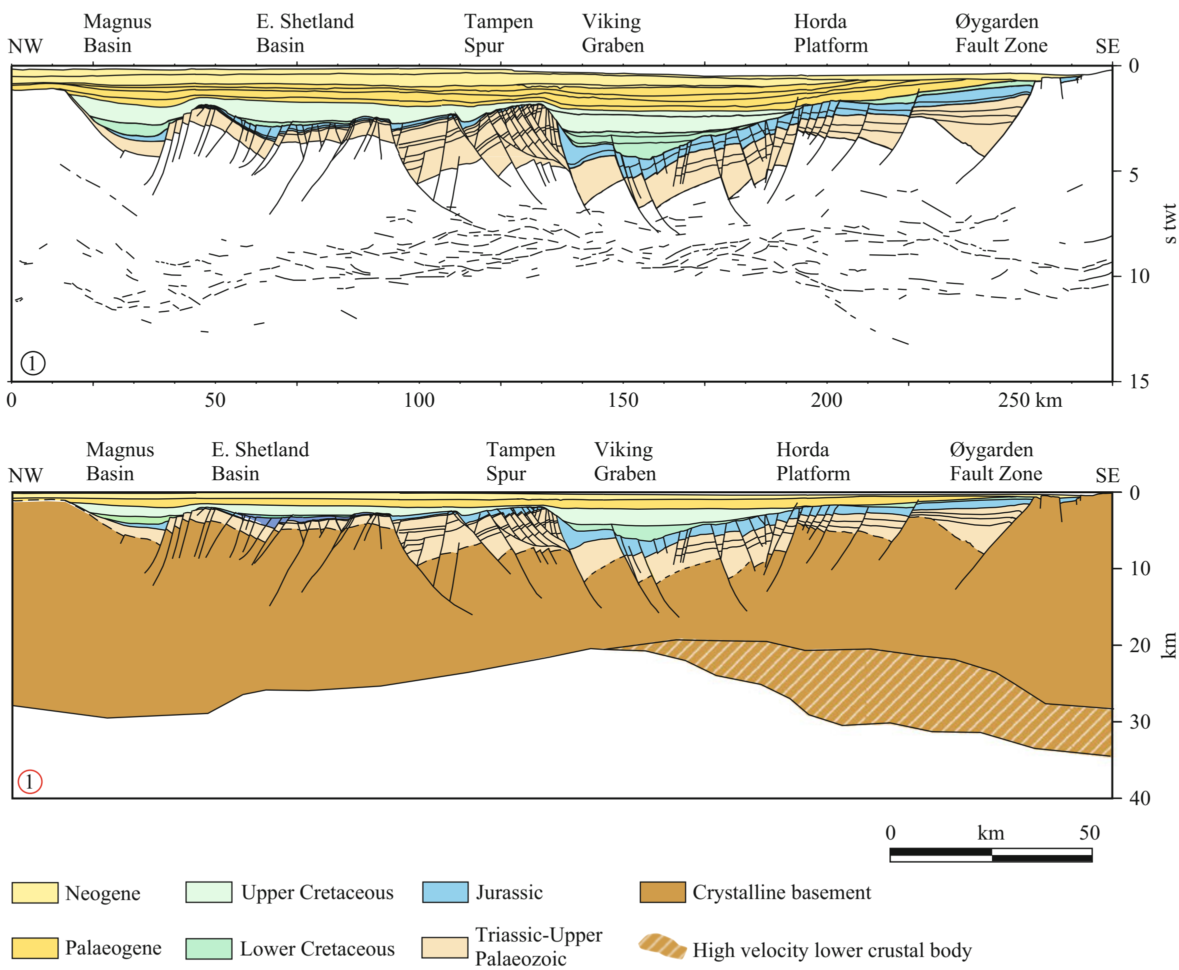

Fig. 25.6 Interpreted regional deep seismic line and crustal transect across the northern North Sea (modified from Christiansson et al. 2000). See Fig. 25.5 for location

Denmark). The Sorgenfrei-Tornquist Zone strikes in a NW-SE direction from the western Skagerrak across northern Jutland and the Kattegat into Scania (Fig. 25.2). If the effects of post-Permian structuring along the Sorgenfrei-Tornquist Zone are restored, late Palaeozoic rift structures similar to those seen in the Oslo Rift are observed. The major NW-SE trending faults are associated with dextral strike-slip movements during Late Carboniferous-Early Permian times.

25.2.2 Stratigraphy/Evolution

A stratigraphic summary for the North Sea is given in Fig. 25.4.

25.2.2.1 Devonian

The Caledonian Orogeny led to uplift and formation of a major mountain chain along western Scandinavia and Scotland, East Greenland and a southern branch into Poland. Thick red continental sediments, which in Britain are known as Old Red Sandstone, were deposited in Devonian time in response to the extensional collapse of the Caledonides. On the Norwegian mainland we have Devonian basins in western Norway (Hornelen, Håsteinen, Kvamshesten, Solund) which are filled with thick conglomeratic sediments. There are also Devonian deposits further north, for example on the island of Smøla. The Devonian sandstones of western Norway are metamorphosed and can not be reservoir rocks, but they are somewhat more porous in southern England.

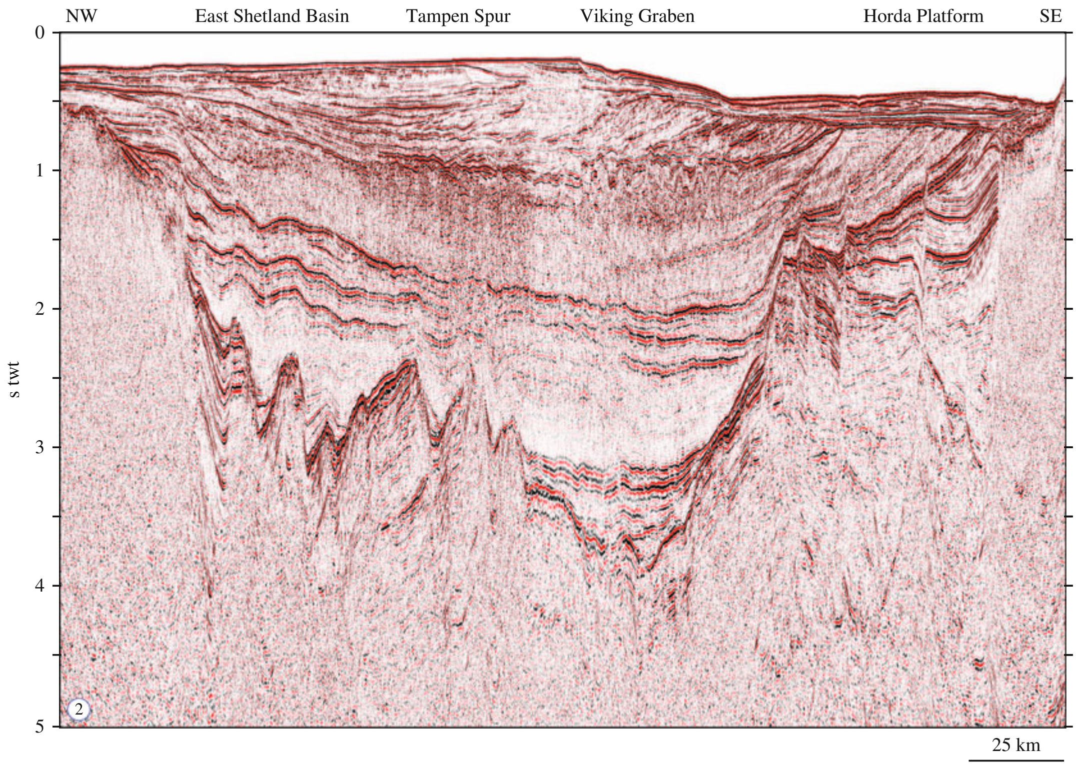

Fig. 25.7 Regional seismic line across the northern North Sea (courtesy Fugro and TGS). See Fig. 25.5 for location and Fig. 25.6 for stratigraphic information

Although Devonian sediments in the northern North Sea have been reached in only a few wells, there are reasons to believe that Devonian sediments are present regionally in the deeper parts of the pre-Triassic half-grabens beneath the Horda Platform, Viking Graben and East Shetland Basin. The presence of Upper Palaeozoic rocks, of both Devonian and Lower Permian age (Rotliegendes), has also been confirmed by drilling on the East Shetland Platform. Seismic data reveal large sedimentary basins beneath the platform, thought to contain Upper Palaeozoic (Devonian-Carboniferous) rocks. In this context it is important to note that oil is produced from Devonian sandstones in the Embla Field of the Central Graben.

The Caledonian plate movement changed from subduction to Late Devonian lateral (strike-slip) movement between Greenland and Fennoscandia, including along the Great Glen Fault. In Scotland this was marked by active volcanism, especially in the Midland Valley Rift.

25.2.2.2 Carboniferous

Following the markedly dry climate which prevailed through Devonian time in the North Sea region, the Carboniferous period gradually became more humid. Northwest Europe moved northwards from the arid belt of the southern hemisphere into the humid equatorial belt. This provided the basis for all the coal deposits. There was also a marked transgression over large areas. The strike-slip movements along the Greenland/Fennoscandia plate boundary ceased at the transition from Devonian to Carboniferous, and ever since this has been an area of diverging plate movement and rift formation until final continental break-up and onset of seafloor spreading in earliest Eocene time. There was rifting in the Midland Valley of Scotland, continuing along the Forth Approahes into the Witch Ground Graben which was a volcanic centre in the North Sea. Black mud deposited in these graben structures forms source rocks for oil.

There was no rifting in England at that time and the Carboniferous Limestone was deposited as a shelf carbonate during the Early Carboniferous. North of the

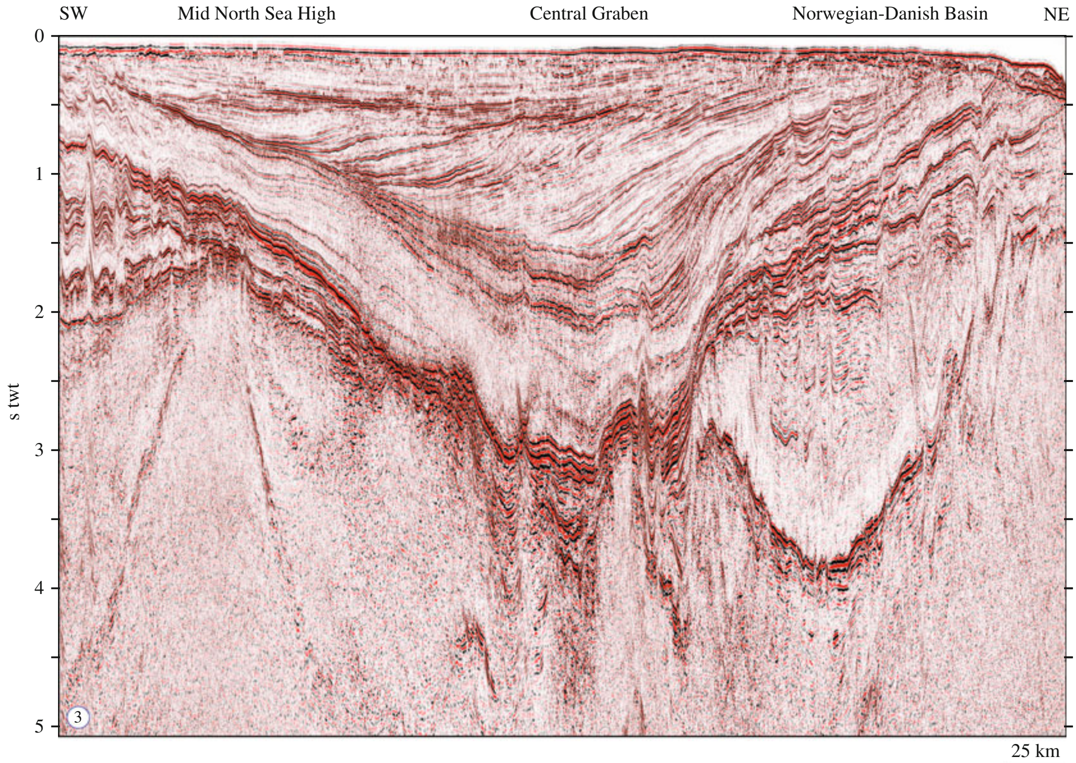

Fig. 25.8 Interpreted regional deep seismic line and crustal transect across the northern North Sea (modified from Christiansson et al. 2000). See Fig. 25.5 for location

carbonate platform and in much of the North Sea, deeper water shales predominated, with some carbonate. Sandstones are encountered higher up in the Lower Carboniferous and these can be important reservoir rocks in the southern North Sea (Fell Sandstone). At the Lower/Upper Carboniferous boundary is the Yoredale Formation, consisting of cyclic deposits of marine carbonates and shales, and fluvial sandstones. These have been interpreted as the result of eustatic changes in sea level due to glaciations in the southern hemisphere, but local tectonics and even sedimentation processes can also produce cyclicity.

The Hercynian (Variscan) mountain range formed along the subduction zone through Germany and northern France close to south England. It was uplifted as a marked topographic feature, and at its foot (the Variscan foredeep) major sedimentary units were deposited, derived from erosion in the mountains. Thick beds of coal developed from the swamp areas on the deltas. In Britain these sandy delta deposits are known as the Millstone Grit. Contemporary coal deposits are found in the southern North Sea and in the Netherlands, and it is these which provided the source of the gas in this region. Fluvial sandstones between the coal seams can be reservoirs both for oil and gas. Black marine shales were also deposited in the mid-Carboniferous in the southern part of the North Sea. In the Oslo Region there are thin sandstones and carbonate sediments of the Asker Group yielding Upper Carboniferous fossils, demonstrating a connection with the North Sea basin.

25.2.2.3 Permian

During the early Permian, uplift of the Hercynian (Variscan) mountain range continued and sedimentary basins developed in front of it in the southern North Sea and within subsided areas of the range itself. At the same time, northwest Europe was pushed farther northwards from the equator, into the dry belt of the northern hemisphere. The high mountain range to the south also contributed to severe aridity in the North Sea basin and most of northwest Europe. This region was then located in the middle of a large continent in a similar position to the dry areas to the north of the present Himalayas.

The latest Carboniferous-Permian extension in the North Sea region (Fig. 25.2) was linked to the Variscan fold belt by strike-slip movements on a series of NW-SE trending zones of weakness (among others the Sorgenfrei-Tornquist Zone). The rifting was associated with widespread and massive igneous activity. This is well known from the onshore part of the Oslo Rift (Oslo Graben) but similar rocks, both extrusives and intrusives, are present in the subsurface offshore (e.g. Skagerrak Graben, Sorgenfrei-Tornquist Zone, Central Graben; Fig. 25.9).

Sedimentation in the North Sea region was dominated by two E-W aligned basins separated by the Mid-North Sea and Ringkøbing–Fyn highs. The basins were infilled with Rotliegend continental sediments, most rapidly in the southern basin which was nearest the mountains and subsided fastest. Alluvial fans and aeolian dune sand accumulated most of the sediment supply from the south. These types of sediment are well-exposed in southwest England near Exmouth but also in northeast England, near Durham and Newcastle. In the North Sea basin the Upper Rotliegend contains an extensive, mostly aeolian, sandstone called the Auk Formation.

The climate behind the mountain range was dry, and a marine evaporite basin eventually developed, possibly with a narrow passage through the Viking Graben to the open ocean in the north to a seaway between Norway and Greenland. There was, however, an important connection eastwards through Poland. The deposition of the Zechstein salt commenced in the southern Permian basin and spread across most of the North Sea basin during Late Permian time but is absent in the northern North Sea. Sabkha deposits accumulated in areas marginal to the evaporite basins.

25.2.2.4 Triassic

Rifting continued into earliest Triassic time and the Triassic to Middle Jurassic succession reflects a pattern of repeated outbuilding of clastic wedges from the

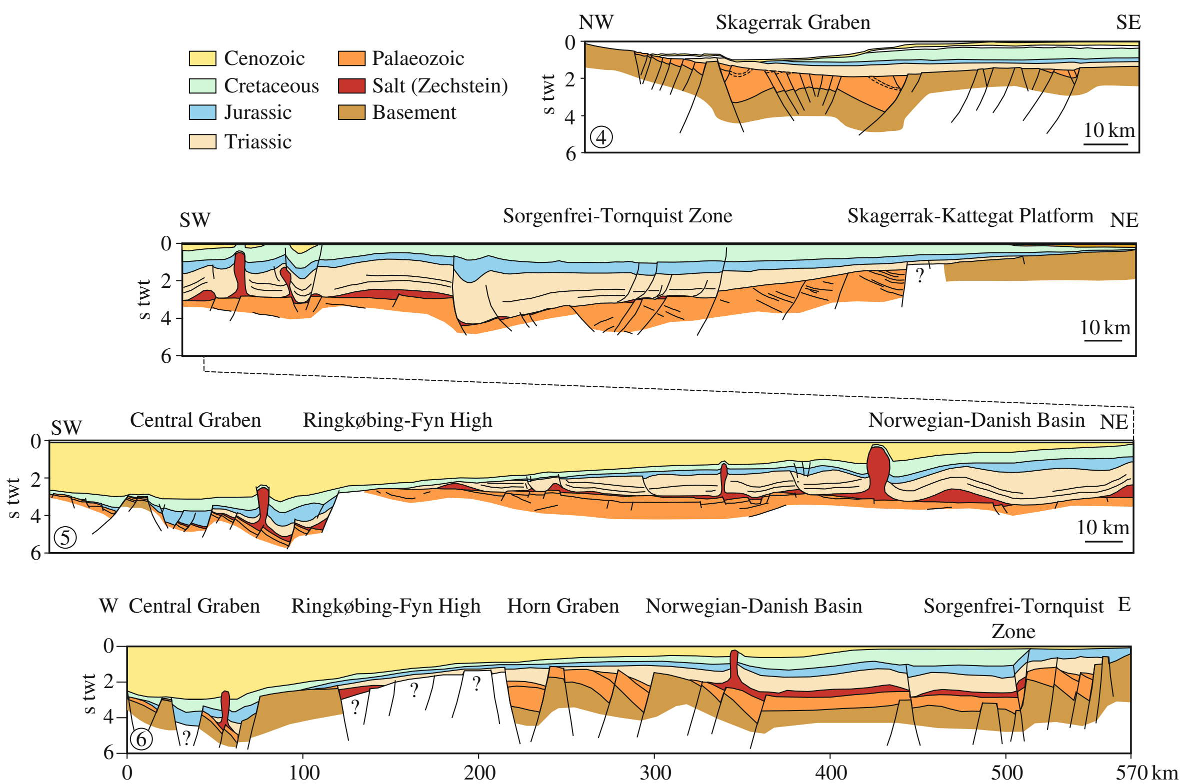

Fig. 25.9 Regional profiles across the SE North Sea, Skagerrak and Kattegat (modified from Heeremans and Faleide 2004). See Fig. 25.5 for location

Norwegian and East Shetland hinterlands within a generally evolving post-rift basin. There was still considerable sediment supply from the Variscan mountains to the south and there is also evidence of an uplift of Scandinavia. A broadly similar geometry of the megasequences in both continental Triassic and marine Jurassic successions was related to subsidence-rate variations. Differential subsidence across faults throughout Triassic time has also been reported. The Øygarden Fault Zone, forming the eastern margin of the Permo-Triassic basin, was active throughout most of the time interval. The sedimentation rate was in most cases high enough to keep up with the subsidence, resulting in a rather flat landscape with gently flowing rivers. If the sediment supply had been less, these rift basins would have been marine. Along the rift structure along the middle of the North Sea the thickness of the Triassic sediments may exceed 5 km. The underlying Permian salt started to form diapirs and Triassic sediment was eroded, or not deposited, at the top of the structures.

The climate in northwest Europe during the Triassic was still arid, and continental red beds continued to be predominant. In England these are referred to as the New Red Sandstone because they are similar to the Devonian continental sediments (Old Red Sandstone). The equivalent facies in Germany is the Bunter sandstone of Lower Triassic age. In south England east of Exmouth there are also good exposures of Triassic deposits with sandstones and conglomerates (Sherwood Sandstone Group) and mudstones (Mercia Mudstone Group). The Sherwood Sandstone is a very important groundwater reservoir in large areas of England. In Southern Norway north of Hamar, the Brumundal sandstone is an outlier of a more extensive cover of Permian red bed facies.

In the Upper Triassic we find carbonates (Muschelkalk) and salt deposits (Keuper salt) in the southern part of the North Sea. In the central and northern areas, however, continental clastic sedimentation continued right up to the end of the Triassic (Rhaetian). Sabkha environments fringed the evaporite basins and caliche, that is carbonate precipitation in soil profiles, is typical. Towards the end of the Triassic the climate became less arid with more normal fluvial sedimentation and gradually also marine sedimentation when the Statfjord Formation was deposited.

The Triassic fluvial sandstones may have variable sorting and reservoir quality depending upon facies and distance to basement sources. In the fluvial channel facies there may be well developed clay coatings on quartz grains, retarding quartz cementation. The clay coatings have probably formed in the vadose zone where surface water has filtered down to the groundwater table.

25.2.2.5 Jurassic

The transition from Triassic to Jurassic approximately coincides with a change from continental to shallow marine depositional environments. The climate also gradually became more humid in the Jurassic as northwest Europe was pushed northward out of the arid belt at about 30° N. A transgression in the Early Jurassic (Lias) led to the accumulation of black shales over large parts of NW Europe and they are exposed in Yorkshire in northeast England and Dorset in southern England. This is because a transgression over an uneven land surface results in a shallow sea with poor vertical circulation in the water. The Upper Lias (Toarcian) in particular contains good source rocks for oil and gas in southern parts of the North Sea. In Britain and much of the North Sea the Lias deposits consist of black shales with thin carbonate and sand beds. Iron-rich layers with siderite ($FeCO_3$) and chamosite (Fe-chlorite) are common. Beds rich in these two minerals were the basis for iron mines which were especially important during the industrial revolution in England, Germany and France.

In the northern part of the North Sea fluvial and partly marine sandstones of Lower Jurassic age (Lunde and Statfjord formations) are important reservoir rocks in the Viking Graben. The Statfjord Formation is succeeded by the Dunlin Group, which is a dark marine shale but normally without enough organic content to become a significant source rock. Then follows the Brent Group sandstone, a prograding delta sequence which forms the main reservoir rock in the northern North Sea. This sandstone was deposited in a delta that drained the central part of the North Sea towards the marine embayment to the north, between the Shetland and Horda platforms. It was sourced from an uplifted area in the south associated with Middle Jurassic (Bajocian-Bathonian) volcanic activity. The volcanic centre was located south of the Viking Graben and east of Scotland (Moray Firth). On the other side of the uplifted area, the sediments were transported southwards, exemplified in good coastal sections in Yorkshire.

The lower part of the Brent Group consists of upward-coarsening beds of mica-rich sandstones that represent prograding delta deposits, especially distributary mouth bars. This is the Etive and Rannoch formations. The middle part is the Ness Formation, comprised mostly of fluvial delta facies with channels, crevasse sand deposits, lagoonal deposits and coal beds. These delta top facies were deposited during a northward progradation of the Brent Delta. At the top of the Brent Group, the Tabert Formation is a generally well-sorted sandstone formed by the reworking of deltaic deposits during a transgression. The sediment supply from the south was no longer able to keep up with the basin subsidence, resulting in a gradual drowning of the Brent Delta. Each of these delta facies has its characteristic reservoir properties, which are a function both of primary sorting and mineralogy and subsequent diagenetic modification.

Nearly all samples from these deltaic reservoir rocks show evidence of meteoric water flushing and have well developed authigenic pore-filling kaolinite and partly dissolved feldspar (see Chap. 4). At burial depth >4 km (130°C) kaolinite have reacted with K-feldspar and is replaced by illite.

There is normally little clay coating on quartz in the Brent sandstones and quartz cementation may be extensive so that the porosity is reduced to 10-15% at 4 km depth.

In the Late Jurassic, volcanism was very much reduced and the areas within and surrounding the rift systems subsided in response to lower geothermal gradients. At the same time, normal faulting along the Viking Graben led to the rotation of basement blocks and their overlying sediments. The shoulders of the tilted fault blocks were exposed to erosion, removing Lower-Middle Jurassic and locally even Upper Triassic strata. The Late Jurassic (Oxfordian) transgression covered the Viking Graben with a thick drape of clayey sediments of the Heather Formation, while the coarser clastics (sand) were deposited as turbidites and in deltas along the basin margins. Some of the deltas appear to have been controlled by the same structures that have determined the location of the fjords in western Norway.

The uppermost Jurassic Kimmeridge Clay Formation is transgressive and often forms a several hundred metres thick rich source rock which on the Norwegian side is called the Draupne Formation. The rift topography produced numerous, locally overdeepened, basins with poor bottom water circulation. Only a relatively small proportion of the organic production was oxidised while the sedimentation rate was fairly high. The organic-rich shales of the Upper Jurassic are thus the prime source rock in the North Sea, and provided the main petroleum source in both the Statfjord and Ekofisk areas. The thickness of the Upper Jurassic sediments along the rift axis may reach 3,000 m. The deposition of organic-rich shales continued into the Early Cretaceous in some of the basins. The edges of the rotated blocks suffered erosion and a few were not buried until the Late Cretaceous. The majority of the faults die out before the Cretaceous but a few continue up into younger beds. The rifting resulted in rotated fault blocks containing sandstone reservoirs of Lower and Middle Jurassic age (sandstones of the Brent Group and Statfjord Formation). Small fan deltas developed along the rift and also deepwater sandstones including debris flows. Some of these are good reservoir rocks occuring within the Upper Jurassic source rocks (see Chap. 12).

Upper Jurassic sandstones deposited on submarine slopes are much less leached and have less kaolinite than the Brent sandstones. They may however contain grain-coating micro-quartz which retards quartz cementation, thus preserving porosity. This is linked to a siliceous sponge (*Rhaxella*), see Chap. 4.

In much of the North Sea basin Kimmeridge shale equivalents are immature but in the Upper Jurassic rift structures this source rock is buried to much greater depth corresponding to the oil window, and even gas window.

25.2.2.6 Cretaceous

The last phase of rifting in the North Sea in the Late Jurassic was followed by a major transgression, but the uplifted rift stuctures remained dry and were islands for most of the Early Cretaceous. There is a major unconformity between the Cretaceous and the Jurassic except in the deep parts of the rifts where there may have been continuous sedimentation (Figs. 25.6 and 25.7). The Base Cretaceous Unconformity is very well marked on most seismic sections from the North Sea. Fault activity diminished during the Cretaceous, and the Cretaceous subsidence was due primarily to crustal cooling after the Jurassic rifting. The transition from syn- to post-rift configuration was strongly diachronous, suggesting that the thermal state of the system was not homogeneous at the onset of the post-rift stage.

Three stages can be identified in the post-rift Cretaceous development of the northern North Sea: (1) The incipient post-rift stage (Ryazanian–latest Albian) was characterised by different degrees of subsidence. The major structural features inherited from the syn-rift basin (e.g. crests of rotated fault blocks, relay ramps and sub-platforms) had a strong influence on the basin configuration and hence the sediment distribution. (2) In the middle stage (Cenomanian–late Turonian) the internal basin relief became gradually drowned by sediments. This is typical for basins where sediment supply outpaces or balances subsidence, as was the case in the northern North Sea. Thus, the influence of the syn-rift basin topography became subordinate to the subsidence pattern determined by the crustal thinning profile, which in turn relied on thermal contraction and isostatic/elastic response to sediment loading. (3) The mature post-rift stage (early Coniacian–early Palaeocene) was characterised by the evolution into a wide, saucer-shaped basin where the syn-rift features were finally erased. Since thermal equilibrium was reached at this stage, subsidence ceased, and the pattern of basin filling became, to a larger degree, dependent on extra-basinal processes (see Chap. 12).

The Lower Cretaceous shales are black, but only locally do they form good source rocks. Conditions subsequently became more oxidising as bottom circulation improved. In the Early Cretaceous grey to reddish oxidised shales were also deposited, which become increasingly calcareous upwards. The Lower Cretaceous shales (Cromer Knoll Formation) are shallow to deep marine mudstones with little sand.

In the Late Cretaceous the sea attained its transgressive maximum and clastic sedimentation almost ceased across large areas of northwest Europe. Parts of Scandinavia were probably also covered by the Cretaceous sea. Sedimentation was dominated by planktonic carbonate algae (coccolithoporids) which formed a lime mud, the main component of Chalk, though it also includes some foraminifera and bryozoa. The main development of the Chalk was in the Campanian and Maastrichtian, but sedimentation continued up into the Danian of the Palaeocene, for the most part through resedimentation of earlier Chalk deposits which had been uplifted along the central highs. In the Viking Graben the carbonate content diminishes northwards and we do not have pure limestone (Chalk) facies like that in the southern and central part of the North Sea. Instead, shales predominate, though often with a significant carbonate content.

At the close of the Cretaceous and beginning of the Cenozoic, compressive movements were felt from the Alpine Orogeny to the south. Part of this movement was accommodated along diagonal fault zones, such as the Sorgenfrei-Tornquist Zone in Scania and the Kattegat. The Polish Basin and parts of the North Sea area were uplifted (inversion) and eroded.

25.2.2.7 Cenozoic

The early Cenozoic rifting, break-up and onset of seafloor spreading in the NE Atlantic gave rise to differential vertical movements also affecting the North Sea area. The sedimentary architecture and breaks are related to tectonic uplift of surrounding clastic source areas, thus the offshore sedimentary record provides the best age constraints on the Cenozoic exhumation of the adjacent onshore areas.

Major depocentres sourced from the uplifted Shetland Platform and areas along the incipient plate boundary in the NE Atlantic formed during Late Palaeocene-Early Eocene times. A local source area also existed in western Norway. Tectonic subsidence accelerated in Palaeocene time throughout the basin, with uplifted areas to the east and west sourcing prograding wedges, which resulted in large depocentres close to the basin margins. Subsidence rates outpaced sedimentation rates along the basin axis, and water depths in excess of 600 m are indicated. Uplift along the Sorgenfrei-Tornquist Zone caused erosion into top Chalk along the southeastern flank of the North Sea basin.

Prominent ash layers of earliest Eocene age are found throughout the entire North Sea and also further north. Onshore in Denmark the volcanoclastic sediments are known as “moler”. The extensive volcanism was related to the opening of the North Atlantic and both the Eocene and Oligocene mudstones are dominated by smectitic clays formed from the volcanic ash. These smectitic mudstones are characterised by seismic velocities that are low, even compared to the overlying Neogene sediments. Ash layers rich in volcanic glass (hyaloclastites or tuff) may, however, develop into hard layers due to diagenesis. They will then be characterised by high seismic velocities, particularly after burial to more than 2 km depth and quartz cementation, giving rise to strong seismic marker horizons (top Balder Formation).

In Eocene times progradation from the East Shetland Platform was dominant and major depocentres developed in the Viking Graben area, with deep water along the basin axis. The Palaeocene and Eocene submarine fans were built up with turbidite sands carried out into the central part of the North Sea with the Utsira High limiting their eastward extent. Parts of Fennoscandia were probably covered by sea during Middle-Late Eocene times.

At the Eocene-Oligocene transition, southern Norway became uplifted. This uplift, in combination with prograding units from both the east and west, gave rise to a shallow threshold in the northern North Sea, separating deeper waters to the south and north. The uplift and shallowing continued into Miocene time when a widespread hiatus formed in the northern North Sea, as revealed by biostratigraphic data. Miocene outbuilding from the north into the southeastern North Sea was massive (Fig. 25.8). Coastal progradation of the Utsira Formation in the northern North Sea reflects Late Miocene-Early Pliocene uplift and erosion of mainland Norway. This relatively thick sandstone is a good aquifer and is used for injection of CO_2 in the Sleipner Field. It was still relatively warm in the Early Pliocene, compared to the Late Pliocene when mountain glaciation started to develop.

The Late Pliocene-Early Pleistocene basin configuration was dominated by the progradation of thick clastic wedges in response to uplift and glacial erosion of eastern source areas (Figs. 25.7 and 25.8). Considerable uplift of the eastern basin flank is documented by the strong angular relationship and tilting of the complete Cenozoic succession below the mid-Pleistocene angular unconformity. The Plio-Pleistocene sediments are partly glacial and partly marine representing reworked glacial sediments and are typically poorly sorted. Such sediments compact readily because of the poor sorting of glacial and glaciomarine sediments and periods of glacial advances may have contributed to the compaction.

The ice sheets advanced repeatedly out onto the shelf, but often deposited much of their debris load relatively near to land. Only during relatively short periods did the glaciers cover most of the North Sea basin. When major ice sheets developed on the Baltic Shield much of the ice flowed southwards along the valleys to the Oslo region and deepened the Oslofjord. The ice flow continued along the south coast of Norway and eroded a trough in the Tertiary and Mesozoic sediments. This is up to 700 m deep and continues up along western Norway. Thick Pleistocene sedimentary fans were deposited at the slope in front of the bathymetric trough.

Periods of ice loading resulted in a tectonic tilting of much of the shelf, particularly in the inner part. This has in some cases influenced oil migration and resulted in tilted OWC (e.g. in the Troll Field). Ice loading has also caused compaction so that Quaternary moraines and glaciomarine sediments have become overconsolidated.

At most places on the shelf the Holocene (the last 10,000 years) is represented by only a thin layer of silty sediment, chiefly reworked from Quaternary or older sediments exposed on topographic highs or along the margins of the North Sea. Very little "new" sediment has been supplied from land during the Holocene. This is because the fjords act as very efficient sediment traps, collecting the sediment from the rivers. Because fjords are deep but have shallow thresholds, not much clastic sediment reaches the shelf. On the seafloor there are in many areas frequent depressions which are typically a few tens of metres across and several metres deep. These are called pockmarks and have formed by fluid, generally gas, seeping from deeper layers to emerge at the seafloor.

The Cenozoic sedimentation was relatively rapid and the clayey sediments had little time to compact sufficiently to reduce the water content. Some beds therefore display plastic folding and diapir structures due to the under-compacted clays, especially in the Eocene. Polygonal faults are also common in these mudstones. They form a network which are from several hundred metres to 1 km across.

25.2.3 Exploration History and Petroleum Provinces/Systems

Exploration has been taking place in the North Sea for over 40 years and most of the large Norwegian fields are situated here. This is a mature part of the continental shelf and most of the plays are confirmed. The Norwegian part of the North Sea can be divided into two petroleum provinces characterised by different petroleum systems/plays: (1) the Central Graben area, and (2) the northern North Sea (Fig. 25.5).

The most important source rocks in the North Sea are shales in the Upper Jurassic. Thick beds of shale rich in organic matter were deposited over most of the North Sea area in Late Jurassic time. In the Norwegian sector, these belong to the Draupne Formation in the Viking Group or the Mandal Formation in the Tyne Group. Middle Jurassic coal is another important source rock, mainly for gas. In the southern part of the Norwegian sector, this coal is found in the Bryne Formation in the Vestland Group. In the northern part of the North Sea, these coal seams are found in the Brent Group. Source rocks may possibly be found in Carboniferous or older strata in the southern part of the North Sea, but these have so far not been confirmed.

25.2.3.1 Central Graben

In the Central Graben area rifting took place during Permian-Early Triassic and Middle-Late Jurassic times, and Zechstein salt was deposited north of the Mid North Sea High (Figs. 25.8 and 25.9). When this area was first drilled, the target was the Permian sandstones beneath the salt. It was by accident that oil was discovered in the Upper Cretaceous rocks (Chalk). Ekofisk was the first field to be discovered, but now there is a string of fields with Upper Cretaceous reservoirs, both on the Norwegian side and in the Danish Sector.

There are other sandstone reservoirs too, such as those of Upper Jurassic age in the Ula and Gyda fields. This lead is found south of the Brent delta, which excluded the Brent Group from forming reservoir rocks there. The area was uplifted and Middle Jurassic sediments are mostly absent. Later, oil has been found in Upper Palaeozoic reservoir rocks which had been the original prospecting target in the area. In the Embla Field the reservoir rock is a sandstone believed to be of Devonian age.

The Ekofisk Field, found in 1969, was the first large oilfield in Europe. The Chalk in the Ekofisk reservoir is of the same type as we have onshore in Denmark and eastern England in stratigraphic levels approaching the Cretaceous/Cenozoic boundary (Maastrichtian and Danian). Chalk lithologies had previously been assumed to be far too fine-grained to be reservoir rocks, and Ekofisk was the first large oilfield of this type. The Austin Chalk in Texas is one of the few other occurrences where Chalk forms a reservoir rock, but the fields there are fairly small by comparison.

Chalk is comprised of microscopic (0.001–0.005 mm) skeletons of planktonic algae which floated in the surface waters. After they died they sank to the seafloor to accumulate as a calcareous ooze. First when the scanning electron microscope (SEM) was developed was it possible to study these algae. The coccolithoporid skeleton consists of calcite, which makes the sediment more stable during diagenesis. We do not find as much solution and reprecipitation as would have been the case if the fossils had been aragonitic. There was uplift and some erosion of the Chalk in the Danian (earliest Cenozoic) with a degree of resedimentation of Chalk beds along the slopes of the shallower areas, i.e. slumping. These redeposited Chalk sediments have proved to be the ones with the best reservoir characteristics.

The Chalk beds were then buried by Palaeocene and Eocene clays which sealed the Chalk and prevented the freshwater circulation which we otherwise often find in carbonate rocks along continental shelves. These clays have high contents of expanding clay minerals (smectite) and form a layer with very low permeability, so that porewater could not be forced out quickly enough with respect to the subsidence rate. The effective stresses and hence compaction have therefore been strongly reduced, and this is an important factor explaining why the porosity can still be as high as 30–35%. Both mechanical compaction and chemical pressure solution are reduced by the overpressure. The Ekofisk reservoir lies at over 3 km depth and without overpressure there would not have been such good porosity. In the shallower Valhall reservoir the effective stresses are even lower.

The Ekofisk structure is a dome-shaped anticlinal which has formed in response to an underlying salt diapir (Upper Permian). The structure covers c.50 km^2 and has a closure height of 244 m. The oil column is 306 m in thickness, which means there is oil below the structure's lowest point (spill point). This situation requires an additional diagenetic trap, i.e. low permeability coupled with the capillary forces in the Chalk hinder the oil from seeping out laterally from below the structural trap. The porosity within the reservoir rock varies from 30 to 35% to tighter layers with 0–20%. However, in addition to this primary porosity there is a secondary porosity provided by fissures. Fissures are particularly important in connecting the small pores, so that the permeability increases to circa one to a few millidarcy. Without the fissuring the permeability would be much lower and it would have been impossible to produce the reservoir. The fissures are probably related to the horizontal tension which developed when the beds were bent upwards above the salt structure, so that the cracks are mostly vertical. The high overpressure also aids the fissuring process. The source rock for the hydrocarbons at Ekofisk is the underlying Kimmeridge Clay which attains its optimal maturity at this depth.

Gas injection and water injection have been important for maintaining reservoir pressure and preventing the fissures from closing. The reservoir rock has also been deliberately fissured by hydrofracturing, to increase the permeability. The platform at Ekofisk has sunk several metres during production, and the subsidence has continued despite the pressure being maintained with water injection. According to the laws of soil- and rock-mechanics the subsidence should cease when the effective stresses are not increasing, but here there has probably also been a chemical compaction which is not simply a function of effective stresses. This may be due to water substituting for the oil during production. The injected sea water contains high concentrations of sulphate and also Mg^{++} which were not present in the porewater of the reservoir. This led to increased compaction (water-weakening) and also changed the surface properties and wettability. These factors helped to increase the recovery from the Ekofisk Field. There are several satellite fields, including Cod, Albuskjell, Tor, Eldfisk, West Ekofisk and Edda.

25.2.3.2 Northern North Sea

The northern North Sea contains the majority of the giant fields discovered so far in the Norwegian continental shelf. The area is, however, still under intensive exploration, and the existing infrastructure makes even relatively small and complex traps interesting. The province is extensively drilled, particularly along the margins of the basin, and a whole series of trap types have been investigated. The most common trap type is provided by rotated fault blocks along both margins of the Viking Graben (Figs. 25.6 and 25.7), generated during Bathonian-Ryazian extension. The reservoirs are commonly found within sandstones of the Rhaetian-Sinemurian Statfjord Formation, in the Aalenian-Bathonian Brent Group, and locally in the Pliensbachian-Toarcian Cook Formation of the Dunlin Group. Sealing faults are frequently important for this trap type. Also Upper Jurassic (Bathonian-Kimmeridgian) sandstones provide good reservoirs, perhaps particularly in the platform areas, where fault block rotation is moderate (e.g. the Troll Field), and in mixed structural-stratigraphic traps along fault-block crests. Post-rift marine sands (Cretaceous and Cenozoic) add to the prospectivity of the northern North Sea. Indeed, the Cenozoic marine sands of the Frigg type were the major target of early exploration activity.

In the northern North Sea there are no Permian salt deposits, but there are large thicknesses of Permian and Triassic sediments at depth (Fig. 25.6). The large oil fields in the northern part of the North Sea have Brent Group sandstones, and often also Statfjord Formation sandstones, as reservoir rocks. This applies to Statfjord, Gullfaks, Vigdis, Visund, Snorre and Oseberg. The traps consist of rotated fault blocks formed during rifting in the Late Jurassic. They stood as islands in the sea, and much of the Upper Jurassic and Lower Cretaceous is absent through non-deposition or erosion. At the top of the Gullfaks structure we only find a thin shale from the Upper Cretaceous, and the structure probably remained above sea level until then.

The source rock is the Kimmeridge Clay from the Upper Jurassic (Draupne Formation), and the oil has migrated up to the top of the fault blocks, but stratigraphically downwards from Upper to Middle or Lower Jurassic. In the Snorre Field the erosion at the top of the rotated fault blocks has reached right down to sandstones in the Upper Triassic (Lunde Formation) which is the reservoir rock together with the Statfjord Formation. The Statfjord Field was discovered in 1974 and was the first giant oil field on the Norwegian shelf after Ekofisk. The field lies in blocks 33/9 and 13/12, and extends into the British Sector. The Statfjord Field is large, estimated to contain about 575 mill. tons oil and $85 \cdot 10^9\ m^3$ gas and NLG. Since the sand has such high porosity and permeability, the production rate was very high (330,000 barrels a day in 1997). Most of the oil and gas has now been produced. Statfjord is located on part of the platform-like Tampen Spur which is situated north of the Viking Graben and east of the East Shetland Basin (Figs. 25.6 and 25.7). The

Tampen Spur is one of several fault blocks which subsided and rotated along low-angle faults in Middle to Upper Jurassic time. The reservoir rocks consist of the Statfjord Formation (Lower Jurassic) and the Brent Group (Middle Jurassic).

The Statfjord Formation is comprised of fluvial sandstones which are replaced towards the top by shallow marine deposits. The Dunlin Shale succeeds the Statfjord Formation, and has enough organic material to be a source rock even if its contribution is very modest compared to the Kimmeridge Clay (Draupne Formation). During the Middle Jurassic there was considerable volcanic activity in the central part of the North Sea (Rattray Formation). This volcanism and the high geothermal gradients caused this area to be uplifted. The Triassic and Permian sandstones were then eroded and the sediments were for the most part transported northwards in a fluvial system which debouched in the Brent delta. The delta built out across almost the entire area between west Norway and Shetland, and sediment was also supplied from these areas to the delta. A several hundred metre thick series called the Brent Group was deposited, consisting of five formations that represent different facies. First the Broom Formation was deposited, mostly on the British side, and the Oseberg Formation on the Norwegian side. These were deposited as local fans related to faults along the sides of the initial rift. The Rannoch Formation consists of a mica-bearing sandstone which represents an upwards-coarsening sequence – from “offshore” to “shoreface” – and represents the actual progradation of the Brent delta. The mica settled out of suspension outside the fluvial channels. The Etive Formation consists of sandstones deposited on the delta front above wave base and is therefore better sorted. The Ness Formation represents the fluvial delta-top facies. Here there are meandering fluvial channels and crevasse splays. The clay and mica contents are higher in the levée and overbank deposits. The Ness Formation represents the maximum northward extent of the delta. The Tarbert Formation is much better sorted, having been deposited as marine delta-front sediments while the delta was being transgressed by the sea. The sediment supply from the Mid-North Sea High was reduced as this area was gradually transgressed and sediment supply to the delta could then no longer keep pace with the subsidence. Part of the Ness Formation was probably eroded and redeposited as marine sediments as part of the Tarbert Formation.

The reservoir properties are a function of these depositional conditions, both on account of primary sorting and because diagenetic changes are usually determined by the primary mineralogical composition and sorting. The sandstones of the Brent Group are generally immature with a high content of feldspar and mica indicating a basement source and a relatively short transport into the prograding Brent delta. This implies that all sandstone bodies where flushed intensively by freshwater shortly after deposition. Nearly every sample of Brent Sandstone therefore contains abundant evidence of feldspar leaching and pore-filling authigenic kaolinite. Carbonate-cemented beds are often associated with marine environments with aragonitic fossils which have dissolved and formed cement.

The Brent delta was transgressed by the mudstones of the Heather Formation towards the end of the Late Jurassic. The main source rock for the area is the Upper Jurassic Kimmeridge Clay. It was deposited over a large part of the North Sea basin and also onshore present Britain. In the northern North Sea it is referred to as the Draupne Formation and the Mandal Formation in the Norwegian Central Graben. It may be more than 500 m thick along the rotated fault blocks which emerged as islands. The irregular bottom topography in the basin gave poor circulation and stagnant conditions with the deposition of a good source rock. The crests of many of the blocks were so heavily eroded during rotation that most of the Jurassic sequence is missing from them.

Shale at less than 3.5 km depth on the shallower parts of the structures is not sufficiently mature to have generated oil or gas in significant quantity. Where the Kimmeridge Clay is downfaulted deeply enough along the listric faults, oil has migrated up into the tectonically overlying but stratigraphically underlying Statfjord and Brent Groups. Most of the oil comes from the area north of the Snorre Field where the source rock (Draupne Formation) is buried to 4–5 km, but there is also some from the areas south of Gullfaks. Such areas that have generated a lot of oil are called kitchen areas.

In the Troll Field the reservoir rock is of Upper Jurassic age and contains mostly gas formed in the deepest parts of the basin ($>$4.5 km).

The oil began to migrate into the reservoir during early to mid-Tertiary times, when the source rock (Kimmeridge Clay) began to be mature. The oil/water contact in the Statfjord Formation and the Brent Group is at different levels which relate to two different pressure cells. The reservoir lies at 2.5–3 km depth and the sandstones have little quartz cement, such that loose sand is often recovered instead of solid core samples. There is also a danger of some sand coming up during oil production.

During recent years, increasing focus has been set on the prospectivity of sands in the post-rift sequences, and some discoveries in different settings have been made (e.g. the Agat and Grane fields). The greatest exploration success during recent years is the Edvard Grieg and Johan Sverdrup oil discoveries in southern parts of the Utsira High (see Chap. 26 for more details).

Some of the reservoirs in the northern North Sea leak oil or gas, and the gas in particular is seen in seismic reflection data. The leakages are probably the result of pressure having built up to the point where the cap rock has fractured, as at Gullfaks (block 34/10). This means that some of the oil has migrated up through the Cretaceous shale cap rock and into the Cenozoic succession. Parts of this oil and gas have accumulated in Palaeocene and Eocene sandstones that were deposited as turbidites emanating from the Shetland Platform to the west. After deposition, the eastern side towards the Norwegian coast was uplifted, imparting a gentle westward dip to the top of these sandstone beds. They now form traps, as in the Frigg Field where the reservoir is Eocene turbidite sands. Heimdal, Balder and Grane fields also contain Palaeocene and Eocene sandstones, which are good reservoir rocks. Eocene clays rich in smectite make good cap rocks. These clays are lightly compacted, have low seismic velocities and often form small diapirs. During the Palaeocene a lot of sediment was supplied from the west, but these beds also dip westwards and rarely have closure towards the east.

In the northern North Sea a gas field (Peon) is found in the Quaternary glacial sediments only about 160 m below the seafloor. This shows that compacted glacial sediments may serve as a cap rock and be capable of trapping gas.

25.3 Mid-Norwegian Shelf/Margin

25.3.1 Structure

Along strike the mid-Norwegian margin comprises three main segments (Møre, Vøring and Lofoten-Vesterålen), each 400–500 km long, separated by the East Jan Mayen Fracture Zone and Bivrost Lineament/Transfer Zone (Fig. 25.10).

The Møre Margin is characterised by a narrow shelf and a wide/gentle slope, underlain by the wide and deep Møre Basin with its thick Cretaceous fill (Figs. 25.11 and 25.12). The inner flank of the Møre Basin is steeply dipping basinward and the crystalline crust thins rapidly from >25 km to <10 km. The sedimentary succession is thickest along the western part of the basin, 15–16 km, decreasing landwards to 12–13 km. The Møre Basin comprises sub-basins separated by intrabasinal highs formed during Late Jurassic-Early Cretaceous rifting. Most of the structural relief was filled in by mid-Cretaceous time. Sill intrusions are widespread within the Cretaceous succession in central and western parts of the Møre Basin, and lava flows cover the western part. Seaward of the Faeroe-Shetland Escarpment, at the Møre Marginal High, thickening of the crystalline crust and shallowing of the pre-Cretaceous sediments and top crystalline basement occur near the continent-ocean transition.

The ~500 km wide Vøring Margin comprises, from southeast to northwest, the Trøndelag Platform, the Halten and Dønna terraces, the Vøring Basin and the Vøring Marginal High (Figs. 25.10, 25.11, 25.12 and 25.13). The Trøndelag Platform has been largely stable since Jurassic time and includes deep basins filled by Triassic and Upper Palaeozoic sediments. The Vøring Basin can be divided into a series of sub-basins and highs, mainly reflecting differential vertical movements during the Late Jurassic–Early Cretaceous basin evolution.

The Vøring Plateau is a distinct bathymetric feature (Fig. 25.1), and includes the Vøring Marginal High and the Vøring Escarpment. The Vøring Marginal High consists of an outer part of anomalously thick oceanic crust, and a landward part of stretched continental crust, covered by thick Early Eocene basalts and underplated by mafic intrusions.

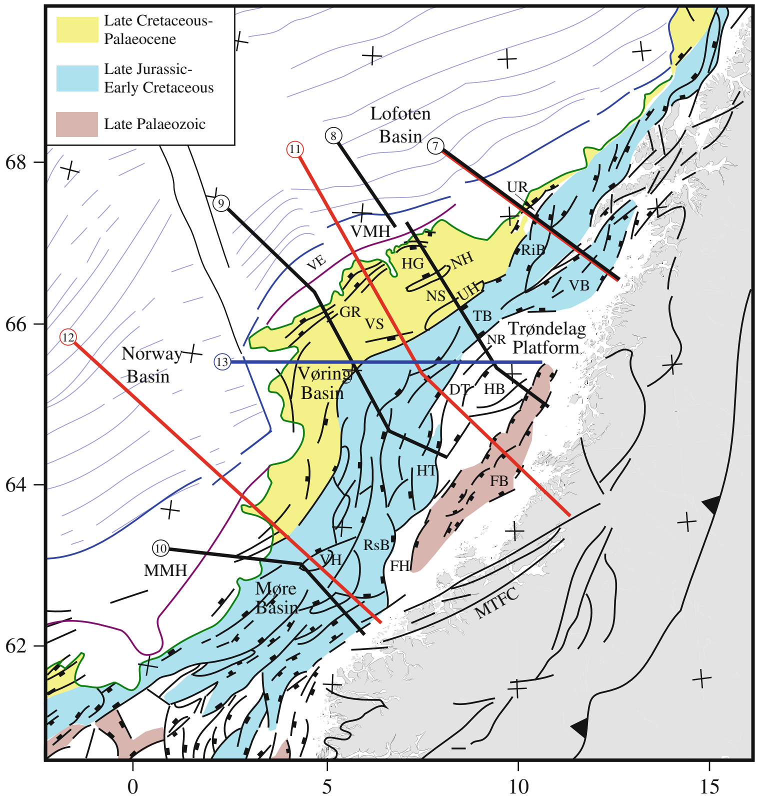

Fig. 25.10 Main structural elements of the mid-Norwegian Margin and adjacent areas (close-up of Fig. 25.2 – modified/updated from Faleide et al. 2008). Location of interpreted regional profiles (*black*), crustal transects (*red*) and seismic examples (*blue*) shown in Figs. 25.11, 25.12 and 25.13. DT = Dønna Terrace, FB = Froan Basin, FH = Frøya High, GR = Gjallar Ridge, HT = Halten Terrace, HB = Helgeland Basin, HG = Hel Graben, MMH = Møre Marginal High, MTFC = Møre-Trøndelag Fault Complex, NH = Nyk High, NR = Nordland Ridge, NS = Någrind Syncline, RiB = Ribban Basin, RsB = Rås Basin, TB = Træna Basin, UH = Utgard High, UR = Utrøst Ridge, VE = Vøring Escarpment, VH = Vigra High, VB = Vestfjorden Basin, VMH = Vøring Marginal High, VS = Vigrid Syncline

The Bivrost Lineament separates the Vøring and Lofoten-Vesterålen margins, marking the northern termination of the Vøring Plateau and the Vøring Marginal High, as well as the Vøring Escarpment. The Bivrost Transfer Zone is a major boundary in terms of margin physiography, structure, break-up magmatism and lithosphere stretching; break-up related magmatism is more voluminous south of it while the less magmatic Lofoten-Vesterålen margin was more susceptible to initial post-opening subsidence.

The Lofoten-Vesterålen margin is characterised by a narrow shelf and steep slope (Figs. 25.10, 25.11 and 25.12). The sedimentary basins underneath the shelf are narrower and shallower than on the Vøring and Møre margins. Typically they form asymmetric half-graben structures with changes in polarity bounded by a series of basement highs along the shelf edge. Beneath the slope, break-up-related lavas mask a sedimentary basin whose detailed mapping is hampered by poor seismic imaging. The continental crust on the Lofoten-Vesterålen margin appears to have experienced only moderate pre-break-up extension, contrasting with the greatly extended crust in the Vøring Basin farther south.

25.3.2 Stratigraphy/Evolution

A stratigraphic summary for the Mid-Norwegian Shelf/Margin is shown in Fig. 25.4. The pre-opening, structural margin framework is dominated by the NE Atlantic-Arctic Late Jurassic–Early Cretaceous rift episode responsible for the development of major

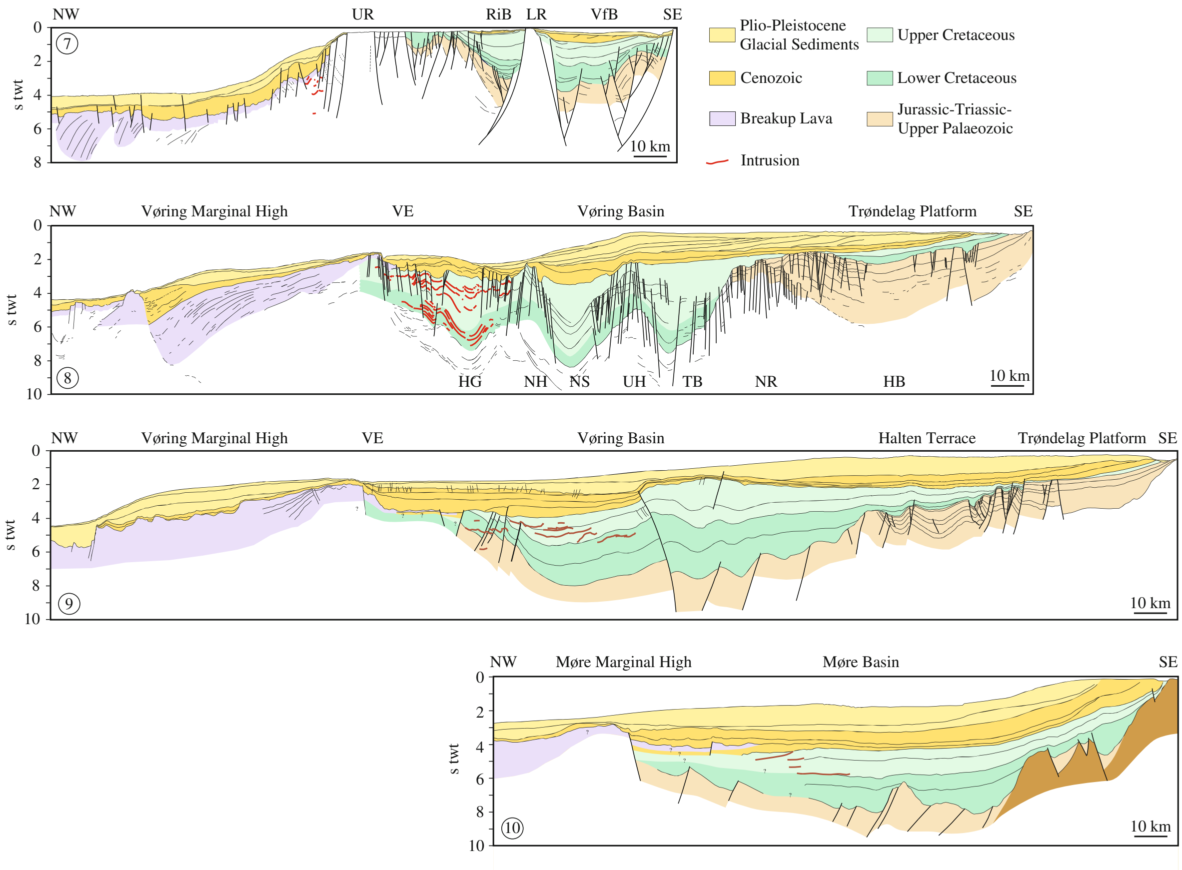

Fig. 25.11 Regional profiles across the Mid-Norwegian Margin (profiles 7–8 modified from Blystad et al. 1995, and profiles 9–10 modified from Tsikalas et al. 2005). See Fig. 25.10 for location and abbreviations

Cretaceous basins such as the Møre and Vøring basins off mid-Norway, and the deep basins in the SW Barents Sea (Fig. 25.3). Prior to that, Late Palaeozoic rift basins formed between Norway and Greenland and in the western Barents Sea along the NE-SW Caledonian trend. It has been suggested that the main Late Palaeozoic–Early Mesozoic rift episodes took place in mid-Carboniferous, Carboniferous–Permian and Permian–Early Triassic times. Sediment packages associated with these movements are poorly resolved, mainly because of overprint by younger tectonism and burial by thick sedimentary strata.

On the mid-Norwegian margin, the Trøndelag Platform (Froan Basin) and Vestfjorden Basin record significant fault activity in Permian–Early Triassic time. Permian–Triassic extension is generally poorly dated, but is best constrained onshore East Greenland where a major phase of normal faulting culminated in the mid-Permian and further block faulting took place in the Early Triassic. The later Triassic basin evolution was characterised by regional subsidence and deposition of large sediment volumes. The Lower-Middle Jurassic strata (mainly sandstones) reflect shallow marine deposition prior to the onset of the next major rift phase.

A shift in the extensional stress field vector to NW-SE is recorded by the prominent NE Atlantic-Arctic late Middle Jurassic–earliest Cretaceous rift episode, an event associated with northward propagation of Atlantic rifting. Considerable crustal extension and thinning led to the development of major Cretaceous basins off mid-Norway (Møre and Vøring basins) and East Greenland, and in the SW Barents Sea (Harstad, Tromsø, Bjørnøya and Sørvestsnaget basins). These basins underwent rapid differential subsidence and segmentation into sub-basins and highs.

By mid-Cretaceous time, most of the structural relief within the Møre and Vøring basins had been filled in and thick Upper Cretaceous strata, mainly fine-grained clastics, were deposited in wide basins.

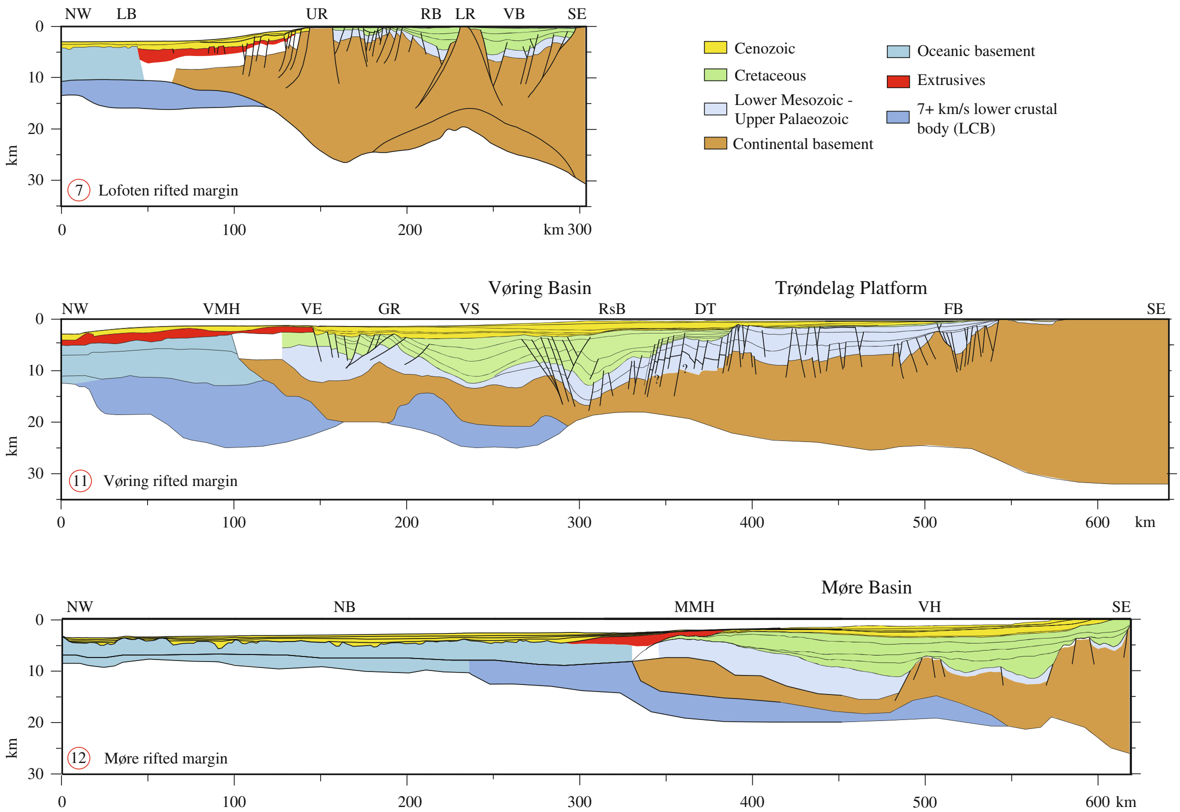

Fig. 25.12 Regional crustal transects across the Mid-Norwegian Margin (modified/updated from Faleide et al. 2008). See Fig. 25.10 for location and abbreviations

Pulses of coarse clastic input with an East Greenland provenance appeared in the Vøring Basin from early Cenomanian to at least early Campanian times.

Break-up in the NE Atlantic was preceded by prominent Late Cretaceous–Palaeocene rifting. At the onset of this rifting, the area between NW Europe and Greenland was an epicontinental sea covering a region in which the crust had been extensively weakened by previous rift episodes. The main period of brittle faulting occurred in Campanian time followed by smaller-scale activity towards break-up. The Campanian rifting resulted in low-angle detachment structures that updome thick Cretaceous sequences and sole out at medium-to-deep intracrustal levels on the Vøring and Lofoten-Vesterålen margins.

Late Cretaceous–Palaeocene rifting at the Vøring Margin covers a ~150 km wide area bounded on the east by the Fles Fault Complex and the Utgard High (Fig. 25.10). Along the outer Møre and Lofoten-Vesterålen margins, most of the Late Cretaceous–Palaeocene deformation is masked by the lavas, but the structures appear to continue seawards underneath the break-up lavas. On the Møre and Vøring margins, the Palaeocene epoch was characterised by relatively deep water conditions. Depocentres in the western Møre and Vøring basins were sourced from the uplifted rift zone in the west. The northwestern corner of southern Norway was also uplifted and eroded, and the sediments were mainly deposited in the NE North Sea and SE Møre Basin.

Final lithospheric break-up at the Norwegian margin occurred near the Palaeocene–Eocene transition at ~55 Ma. It culminated in a 3–6 m.y. period of massive magmatic activity during break-up and the onset of early seafloor spreading. At the outer margin (e.g. Møre and Vøring margins), the lavas form characteristic seaward-dipping reflector sequences (Fig. 25.11) that drilling has demonstrated to be subaerially and/or neritically erupted basalts. These have become diagnostic features of volcanic margins. During the main igneous episode at the Palaeocene–Eocene transition, sills were intruded into the thick Cretaceous successions throughout the NE Atlantic margin, including the Vøring and Møre basins. Magma intrusion into organic-rich sedimentary rocks led to formation of large volumes of greenhouse gases that were vented to the atmosphere in explosive gas eruptions forming several thousand hydrothermal vent complexes along the Norwegian margin.

The mid-Norwegian margin experienced regional subsidence and modest sedimentation since Middle Eocene time and developed into a passive rifted margin bordering the oceanic Norwegian-Greenland Sea. Mid-Cenozoic compressional deformation (including domes/anticlines, reverse faults and broad-scale inversion) is well documented on the Vøring margin, but its timing and significance are debated. The main phase of deformation is clearly Miocene in age but some of the structures were probably initiated earlier in Late Eocene–Oligocene times.

There is increasing evidence on the Norwegian margin for Late Miocene outbuilding on the inner shelf (Molo Formation) indicating a regional, moderate uplift of Fennoscandia. Over the entire shelf there is a distinct unconformity, which changes on the slope to a downlap surface for huge prograding wedges (Fig. 25.13) of sandy/silty muds sourced on the mainland areas around the NE Atlantic and the shelf. This horizon marks the transition to glacial sediment deposition during the Northern Hemisphere glaciations since about 2.6 Ma. Latest Pliocene sedimentation is interspersed with ice-rafted debris signifying regional cooling and formation of glaciers. Large Plio-Pleistocene depocentres formed fans in front of bathymetric troughs scoured by ice streams eroding the shelf. The Naust formation consist of mostly glacial sediments which offshore Mid-Norway may reach a thickness of more than 1,000 m.

25.3.3 *Exploration History and Petroleum Provinces/Systems*

The mid-Norwegian continental shelf was opened for exploration in 1980, when a limited number of blocks on Haltenbanken were announced in the fifth licencing round, and it has had fields in production since 1993. These are situated within the major fault complexes which separate the platform area to the east from the deep Cretaceous basins in the west, and along the margin of the Trøndelag Platform (the Halten and Dønna terraces) (Figs. 25.10 and 25.11). In recent years blocks have also been awarded in greater water depths within the deep Vøring and Møre basins.

25.3.3.1 Haltenbanken

The Haltenbanken area (Halten and Dønna terraces) has good source rocks and reservoir rocks, and also structural traps (Fig. 25.11). On the eastern side of the main fault (the Klakk Fault), water has drained

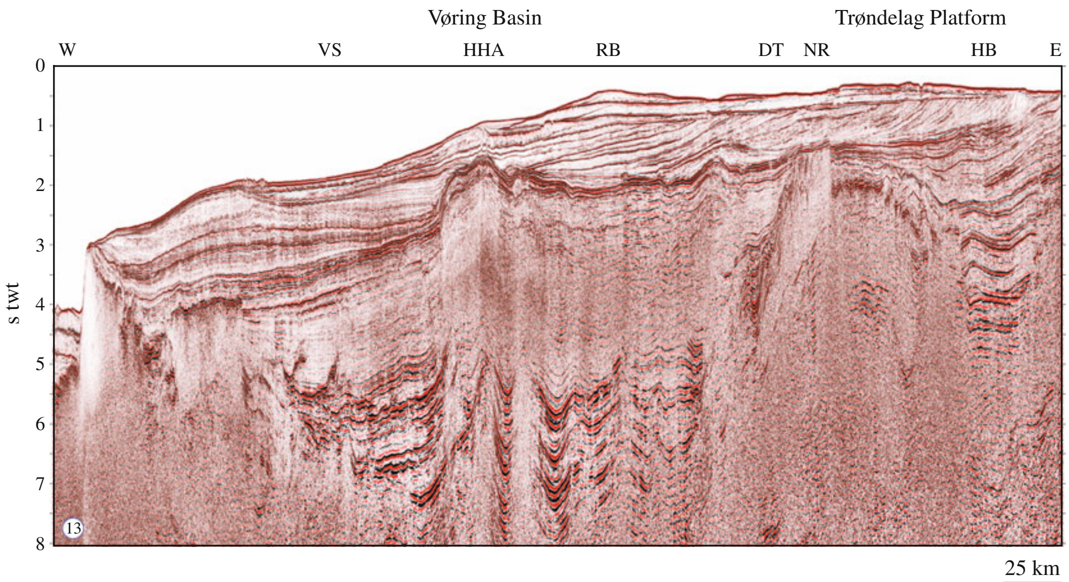

Fig. 25.13 Regional seismic line across the Mid-Norwegian Margin (courtesy Fugro and TGS). See Fig. 25.10 for location and abbreviations and Fig. 25.11 for stratigraphic information

eastwards through the Jurassic sandstones up to the coast so that pressure has not built up much above hydrostatic pressure; this has been an important factor in hindering leakage. The main problem in the area is that many of the reservoirs are very deep and oil can have escaped due to overpressure. Typical trap types drilled so far on the mid-Norwegian continental shelf are rotated fault blocks of Jurassic age in the horst-and-graben terrane of the Halten Terrace, and complex fault blocks within the major fault zones. Here too the source rock formed during rifting in the Late Jurassic. It is called the Spekk Formation, which approximately equates with the Draupne Formation in the North Sea and the Kimmeridge Formation in England. In the Early Jurassic Åre Formation there are coal beds, which may be the source for the gas and possibly some of the oil.

The most important reservoir rocks are of Early and Middle Jurassic age, with alternating sandstones and shales from the Åre, Tilje, Tofte, Ile and Garn formations (Fig. 25.4). The fields in the east, for example Heidrun Field, are not so very deep, but in the Smørbukk Field the reservoir rocks lie at more than 4 km. Also here it was block rotation during rifting which created the majority of the structures.

West of the Smørbukk Field there is a large fault, and to the west of that there is high overpressure in the Jurassic sandstones. Several wells have been drilled here that show signs of there having once been oil present, and that it has leaked out. This is presumably due to the high pressure having reached fracture pressure. In the Kristin Field, however, some of the oil is still in place. The Lavrans and Kristin fields lie at more than 5 km, where the temperature can reach 170–180°C. Here the porosity and permeability in the reservoir rocks are critical, and it is the degree of quartz cementation which essentially determines whether there is sufficient porosity to produce petroleum. The sand grains are coated with chlorite in much of the Tilje Formation, and in places also in the Garn Formation. This hinders quartz precipitation and thus helps maintain the relatively high porosities (20–25%) despite the great burial depth. Where the chlorite is absent and the sand is pure quartz, as in other parts of the Garn Formation, the porosity is quite low (<10–12%). Precipitation of illite from kaolinite and K-feldspar has in many cases reduced the permeabillity significantly at a depth of >3.8-4.0 km. Some of the sandstones contain however dominantly plagioclase, and illitisation of kaolinite is then prevented (See Chap. 4). These compositional differences may reflect source areas both from the east and from the west (Greenland).

The Draugen Field has Upper Jurassic sandstone reservoirs and is fairly shallow, just 1.5 km. The source rock in this area is not mature and the oil found at Draugen has actually had a relatively long migration path from deeper-lying areas to the west.

The subsidence and sedimentation rates were high during the Quaternary, providing a sequence about 1 km thick (Fig. 25.13). This is considerably greater than in most of the North Sea. Thus neither the reservoir nor source rocks have been deeply buried for a geologically long period. This has left the source rocks somewhat immature for their depth, but also means that the reservoir rocks have less quartz cement.

25.3.3.2 Vøring and Møre Basins

This area was first opened for exploration at the end of the 1990s, with great expectation because of the large structures that could be seen on the regional seismic. Inversion structures (mainly huge, gentle anticlines with wavelengths in the order of tens of kilometres) are common in the deep Cretaceous basins, and provide traps of considerable size. These were generated during Tertiary inversion.

The geology proved to be very different from the North Sea and Haltenbanken. There had been considerable magmatic activity associated with the break-up between Norway and Greenland and the initiation of seafloor spreading. Tertiary lavas had flowed out across great tracts of land and intrusive dykes and sills penetrated the Cretaceous sediments. There was some concern that this could have raised the temperature so much that all the oil had become gas. However, it was found that this heating had been quite local and had had little overall effect.

More significant was the extreme thickness of the Cretaceous sequence, up to 6–7 km. This meant that the Upper Jurassic source rocks had already matured by the mid-Cretaceous. This was before the reservoir rocks, of Upper Cretaceous and Lower Tertiary age, had even been deposited, and before the structures we now see (e.g. Ormen Lange Dome, Helland Hansen Arch, Gjallar Ridge) had formed. It thus appears that the structures have only trapped some of the gas formed at depth from the oil. Gas has been found in several prospect in the western Vøring Basin, in Upper

Cretaceous sandstones. One of these gas discoveries is now under development (Aasta Hansteen). It has been possible to map the distribution of sands from amplitude analysis of the seismic data.

The large Ormen Lange gas field was proven in 1997. It is located at water depths of 800–1,100 m in the eastern Møre Basin within the Storegga Slide area. The gas is found in Palaeocene and uppermost Cretaceous reservoir rocks (sandstones).

25.4 Barents Sea

25.4.1 Structure

The Barents Sea covers the northwestern corner of the Eurasian continental shelf. It is bounded by young passive margins to the west and north that developed in response to the Cenozoic opening of the Norwegian-Greenland Sea and the Eurasia Basin, respectively (Figs. 25.1 and 25.2).

The western Barents Sea is underlain by large thicknesses of Upper Palaeozoic to Cenozoic rocks constituting three distinct regions (Figs. 25.14, 25.15 and 25.16). (1) The Svalbard Platform is covered by a relatively flat-lying succession of Upper Palaeozoic and Mesozoic, mainly Triassic, sediments. (2) A basin province between the Svalbard Platform and the Norwegian coast is characterised by a number of sub-basins and highs with an increasingly accentuated structural relief westwards. Jurassic-Cretaceous, and in the west Palaeocene-Eocene, sediments are preserved in the basins. (3) The continental margin consists of three main segments: (a) a southern sheared margin along the Senja Fracture Zone; (b) a central rifted complex southwest of Bjørnøya associated with volcanism and (c) a northern, initially sheared and later rifted margin along the Hornsund Fault Zone. The continent-ocean transition occurs over a narrow zone along the line of Early Tertiary break-up and the margin is covered by a thick Upper Cenozoic sedimentary wedge.

The post-Caledonian geological history of the western Barents Sea is dominated by three major rift phases, Late Devonian?-Carboniferous, Middle Jurassic-Early Cretaceous, and Early Tertiary, each comprising several tectonic pulses. During Late Palaeozoic times most of the Barents Sea was affected by crustal extension. The later extension is characterised by a general westward migration of the rifting, the formation of well-defined rifts and pull-apart basins in the southwest, and the development of a belt of strike-slip faults in the north. Apart from epeirogenic movements which produced the present day elevation differences, the Svalbard Platform and the eastern part of the regional basin have been largely stable since Late Palaeozoic times.

25.4.2 Stratigraphy/Evolution

The Barents Sea is underlain by a thick succession of Palaeozoic to Cenozoic strata showing both lateral and vertical variations in thickness and facies – characterised by Upper Palaeozoic mixed carbonates, evaporites and clastics, overlain by Mesozoic-Cenozoic clastic sedimentary rocks (Fig. 25.4). Direct information on the nature of the crystalline crust beneath the Barents Sea sedimentary basins is scarce, but the available, mostly indirect, evidence indicates that the basement underlying much of its western part was metamorphosed during the Caledonian Orogeny and that the structural grain within the Caledonian basement may have influenced later structural development. The Caledonian crystalline basement has a NE-SW grain and was folded during Silurian time.

25.4.2.1 Upper Palaeozoic

Within the Caledonian domain Devonian molasse sediments were deposited in intermontane basins undergoing extensional collapse. A Devonian tectonic regime comprising both extensional and compressional events is so far only known on Svalbard, located on the northwestern corner of the Barents Shelf. Here, thick Devonian strata are found in a north-south trending graben structure and the graben fill is discordantly overlain by Carboniferous strata (Fig. 25.17).

Lower to lower Upper Carboniferous strata, mainly clastics, were deposited in extensional basins ranging from wide downwarps to narrow grabens. A 300 km wide rift zone, extending at least 600 km in a northeasterly direction (Fig. 25.14), was formed mainly during mid-Carboniferous times. The rift zone was a direct continuation of the northeast Atlantic rift between Greenland and Norway, but a subordinate tectonic link to the Arctic rift was also established. The overall structure of the rift zone is a fan-shaped array of rift basins and intrabasinal highs with

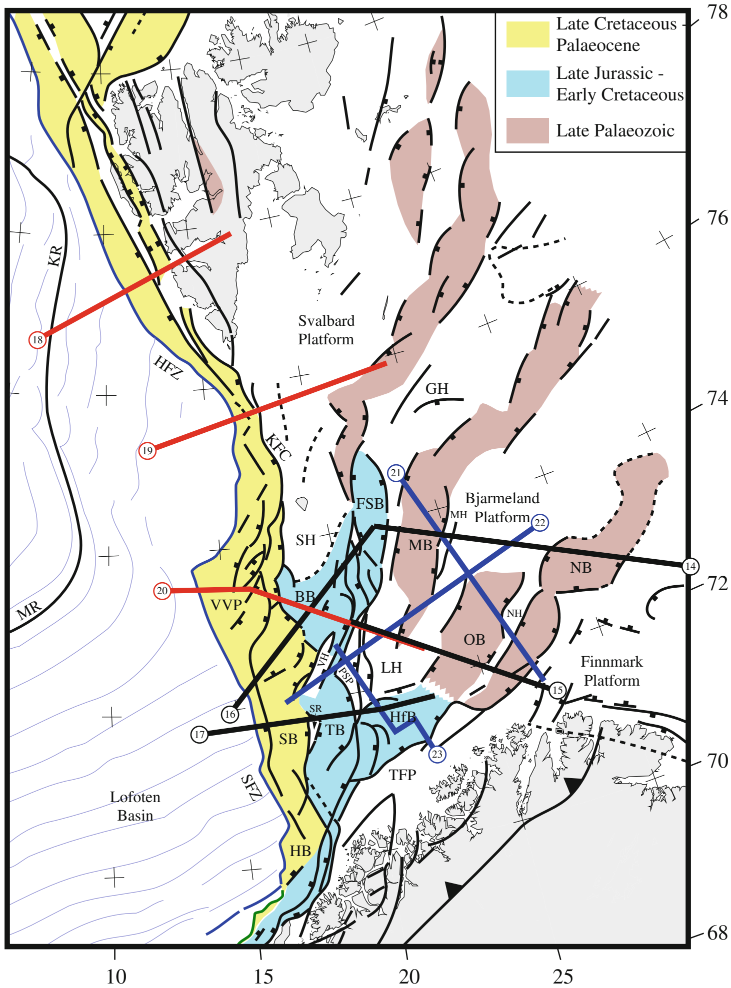

Fig. 25.14 Main structural elements in the western Barents Sea and adjacent areas (close-up of Fig. 25.2 – modified/updated from Faleide et al. 2008). Location of interpreted regional profiles (*black*), crustal transects (*red*) and seismic examples (*blue*) shown in Figs. 25.15, 25.16, 25.17, 25.18 and 25.19. BB = Bjørnøya Basin, FSB = Fingerdjupet Sub-basin, GH = Gardarbanken High, HB = Harstad Basin, HfB = Hammerfest Basin, HFZ = Hornsund Fault Zone, KFC = Knølegga Fault Complex, KR = Knipovich Ridge, LH = Loppa High, MB = Maud Basin, MH = Mercurius High, MR = Mohns Ridge, NB = Nordkapp Basin, NH = Nordsel High, OB = Ottar Basin, PSP = Polheim Sub-platform, SB = Sørvestsnaget Basin, SFZ = Senja Fracture Zone, SH = Stappen High, SR = Senja Ridge, TB = Tromsø Basin, TFP = Troms-Finnmark Platform, VH = Veslemøy High, VVP = Vestbakken Volcanic Province

orientations ranging from northeasterly in the main rift zone to northerly at the present western continental margin. The structural style is one of interconnected and segmented basins characterised by half-graben geometries.

The Carboniferous rift phase resulted in the formation of several interconnected extensional basins filled with syn-rift deposits and separated by fault-bounded highs. Structural trends striking northeast to north dominate in most of the southwestern Barents Sea (Fig. 25.14) where the Tromsø, Bjørnøya, Nordkapp, Fingerdjupet, Maud and Ottar basins have been interpreted as rift basins formed at this time (Figs. 25.15, 25.18, 25.19 and 25.20). Fault movements ceased in the eastern areas towards the end of the Carboniferous and the structural relief was gradually infilled and blanketed by a platform succession of Late Carboniferous-Permian age. The lower part of this succession passes upwards from cyclical dolomites and evaporites to massive limestones. It includes a widespread evaporite layer of latest Carboniferous-earliest Permian age mapped

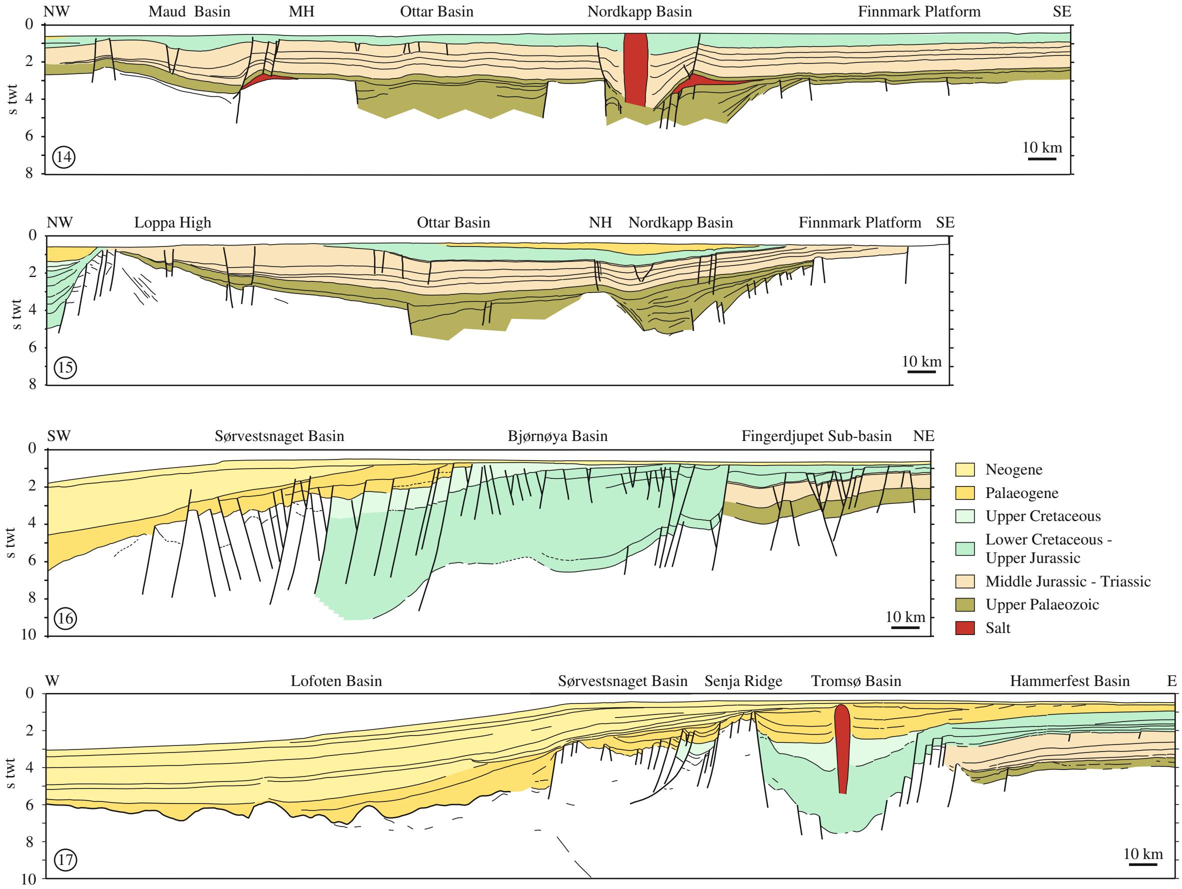

Fig. 25.15 Regional profiles across the western Barents Sea (modified from Faleide et al. 1993, Breivik et al. 1995). See Fig. 25.14 for location and abbreviations

regionally in the SW Barents Sea (also on the NE Greenland shelf/margin).

The thickness of the salt layer in the Nordkapp Basin (Fig. 25.18), which is inferred to have reached 4–5 km locally, implies that a substantial fault-generated depression was in place or developed during early Late Carboniferous times. Not all of this thickness corresponds to a fault-defined relief, however, because salt was also deposited in the basin during the subsequent phase of differential thermal subsidence. Still, a considerable fault-bounded basin must have existed.

From Bashkirian to Artinskian/Early Kungurian times, carbonate deposition took place on a broad shelf. Carbonate build-ups were common at basin margins and intrabasinal highs controlled by underlying older structures. Following Gzelian-Asselian/Sakmarian deposition of basinal evaporites and growth of marginal carbonate build-ups, a regional shallow-water carbonate platform was established during Sakmarian-Artinskian times. Carbonate sedimentation occurred in the entire region until late Early Permian time when clastic deposition started to dominate the area (Fig. 25.4). The change to platform type sedimentation marked the initial development of a regional sag basin which continued to subside in the Late Permian during the deposition of cherty limestones and shales.

The western part of the rift system was affected by renewed faulting, uplift and erosion in Permian-Early Triassic times. Normal faulting along the western margin of the Loppa High (Figs. 25.19 and 25.20) as well as the uplift, tilting and erosional truncation of the high itself are of sufficient magnitude to indicate a significant Permian-Early Triassic rift phase affecting the N-S structural trend. Evidence of fault movements

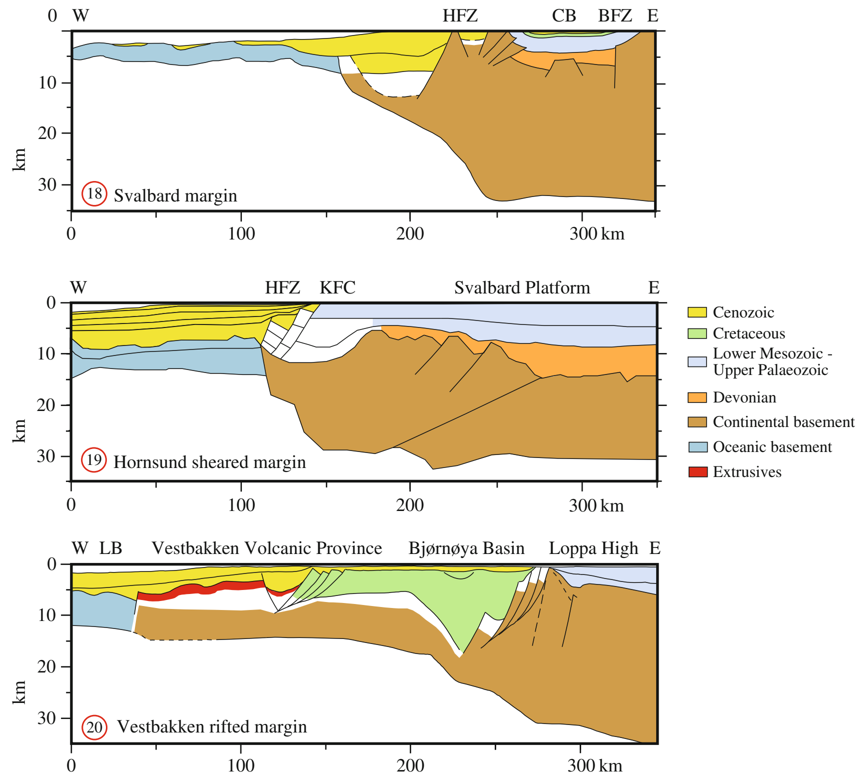

Fig. 25.16 Regional crustal transects across the western Barents Sea-Svalbard margin (modified/updated from Faleide et al. 2008). See Fig. 25.14 for location and abbreviations

is found as far north as the Fingerdjupet Sub-basin. The erosional surface associated with this rift phase extends from the Loppa High to the Stappen High, and Permian tectonic activity is known to have occurred on Bjørnøya and on the Sørkapp High in the southern part of Spitsbergen. Therefore the rift phase probably affected a narrow northerly trending zone along the entire present western margin.

25.4.2.2 Mesozoic

In Early Triassic time a regional deepwater basin covered much of the Barents Sea. During the relatively short Triassic period large amounts of clastic sediments were deposited. The Uralian highland to the east was an important sediment source. Sediments were also shed into the Barents Sea from the Baltic Shield and from other local source areas. Differential loading triggered salt diapirism in the Nordkapp Basin (Fig. 25.18) and possibly later also in other salt basins in the SW Barents Sea.

The Triassic strata are dominated by shales and sandstones, the vertical and lateral distribution of which is complex. There seems to be an increased content of coarse clastic rocks in the younger intervals. A similar increase is also observed in an easterly and a southerly direction towards the main sediment source area. Marine conditions prevailed in Late Permian and Early Triassic times followed by a shallowing and partial exposure of some areas. The continental regime prevailed in large areas in Middle Triassic time and the northward and westward prograding deltaic system continued to infill the regional basin.

In the central and northern basin areas marine conditions existed throughout the Middle Triassic. A good Middle Triassic source rock is known from Svalbard and this is probably present in large parts of the western Barents Sea. In the Late Triassic the shoreline was moved back to the southern and eastern borders of the SE Barents Sea basin. The Triassic ended with regression and erosion. Late Triassic sediments were also derived from other source areas, mainly in the northwest.

The Lower-Middle Jurassic interval is dominated by sandstones throughout the Barents Sea. These

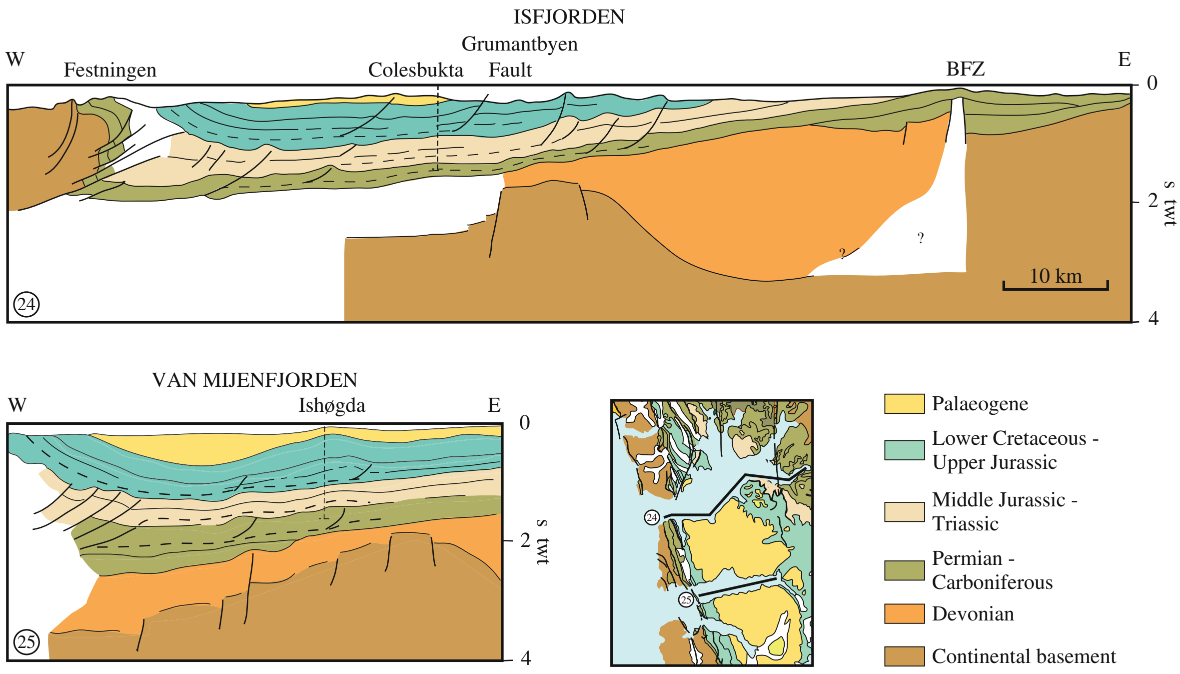

Fig. 25.17 Svalbard geology in seismic lines from fjords (modified from Faleide et al. unpublished)

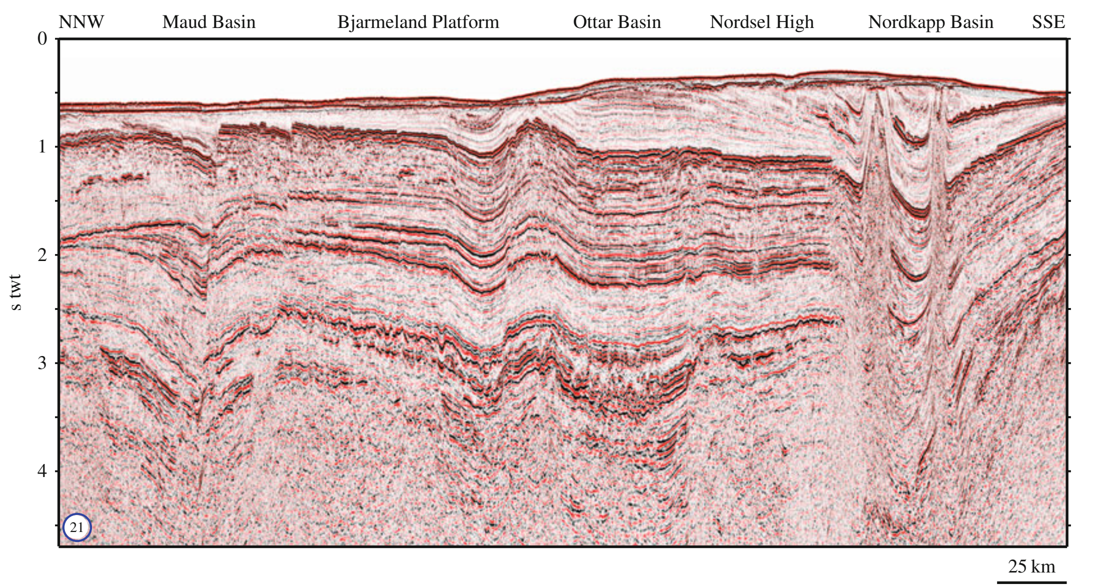

Fig. 25.18 Regional seismic line across the SW Barents Sea (Nordkapp Basin – Bjarmeland Platform – Maud Basin) (courtesy Fugro and TGS). See Fig. 25.14 for location and Fig. 25.15 for stratigraphic information

sandstones form the main reservoir in the SW Barents Sea (Hammerfest Basin; Fig. 25.20). They probably also covered the Loppa High and Finnmark Platform but were partly eroded during later tectonic activity. The late Middle Jurassic sequence boundary marks the onset of rifting in the southwestern Barents Sea, whereas unconformities within the Upper Jurassic sequence reflect interplay between continued faulting

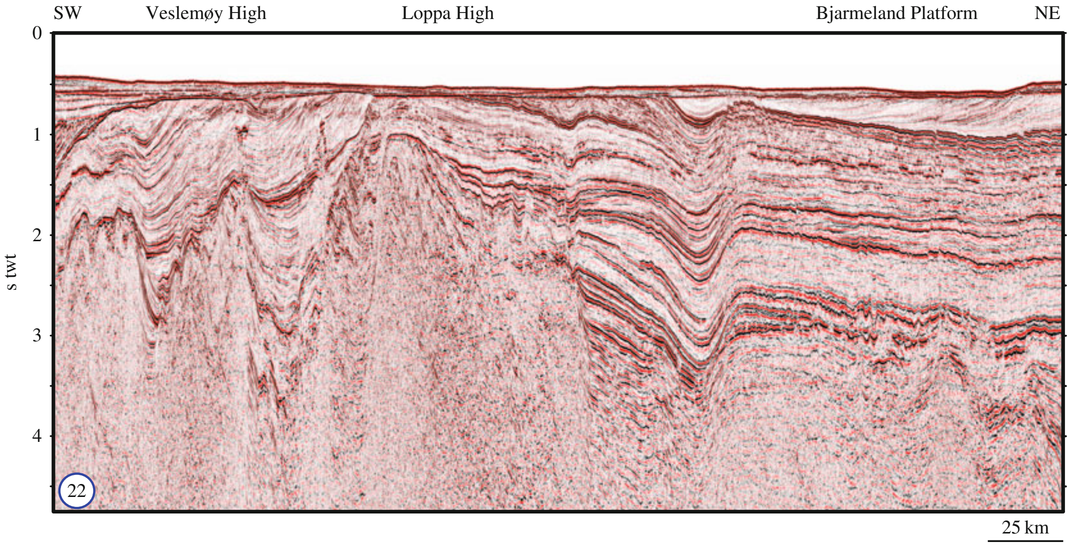

Fig. 25.19 Regional seismic line across the SW Barents Sea (Bjarmeland Platform – Loppa High – Veslemøy High) (courtesy Fugro and TGS). See Fig. 25.14 for location and Fig. 25.15 for stratigraphic information

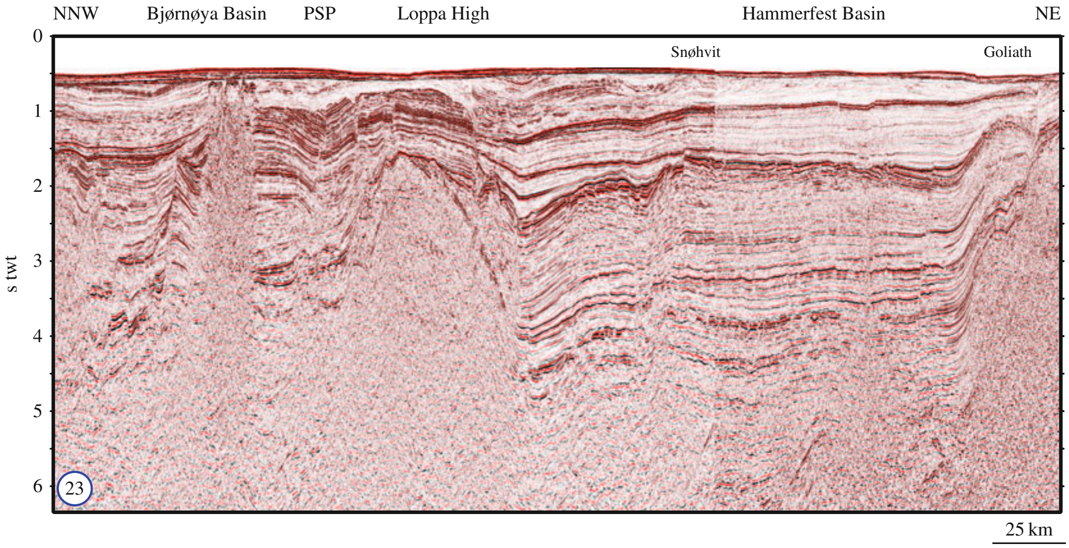

Fig. 25.20 Regional seismic line across the SW Barents Sea (Hammerfest Basin – Loppa High – Bjørnøya Basin) (courtesy Fugro and TGS). See Fig. 25.14 for location and Fig. 25.15 for stratigraphic information

and sea-level changes. The sequence is so thin that it is generally impossible to resolve these unconformities on the seismic data. The shales and claystones contain thin interbedded marine dolomitic limestone and rare siltstones or sandstones toward the basin flanks, reflecting relatively deep and quiet marine environments.

The Late Jurassic-earliest Cretaceous structuring in the SW Barents Sea was characterised by regional extension accompanied by strike-slip adjustments along old structural lineaments, developing the Bjørnøya, Tromsø and Harstad basins as prominent rift basins (Fig. 25.15). The evolution of these basins was closely linked to important tectonic phases/events in the North Atlantic-Arctic region. Rifting continued in Early Cretaceous time and an important phase of Aptian faulting is documented in the SW Barents Sea. Several phases of Late Mesozoic and Early Cenozoic rifting gave rise to very deep basins in the SW Barents Sea. A tentative Middle Jurassic horizon corresponding to the top of the shallow marine sandstones, also marking the onset of late Mesozoic rifting, can be followed from the seafloor down to 9 s twt (16–17 km) over a relatively short distance (Fig. 25.15).

The Lower Cretaceous comprises three sedimentary units from Valanginian to Cenomanian. Shales and claystones dominate, with thin interbeds of silt, limestone and dolomite. These strata make up the main basin fill in the deep SW Barents Sea basins and they dominate the regional subcrop pattern. The marine environments throughout the deposition of these units were dominated by distal conditions with periodic restricted bottom circulation.

In Early Cretaceous time the northern Barents Sea was characterised by widespread magmatism without any signs of faulting. Extrusives and intrusives (sills and dykes) belonging to a regional Large Igneous Province (LIP) in the Arctic are documented from both onshore (Svalbard and Franz Josef Land) and offshore areas in the northern Barents Sea. The magmatism was most extensive during Barremian?-Aptian times but both older and younger dates have been reported. The present distribution in the northern Barents Sea is modified by later uplift and erosion. The Early Cretaceous magmatism within the Arctic LIP had important palaeogeographic implications. It caused regional uplift and the Neocomian in the north and east was characterised by southward sediment progradation. This depositional regime is difficult to document in the western Barents Sea due to later uplift and erosion. The magmatism and regional uplift was related to rifting and break-up in the Amerasia (Canada) Basin and the formation of the Alpha Ridge.

Little or no Upper Cretaceous sediments were deposited in the Barents Sea except in the SW Barents Sea which continued to subside in response to faulting in a pull-apart setting. The Wandel Sea Basin is a NE Greenland equivalent where Late Cretaceous strike-slip faulting and pull-apart basin formation is well documented (Figs. 25.2 and 25.3). The Upper Cretaceous succession varies in thickness and completeness. In the Tromsø Basin a 1,200 m shale succession has been drilled while seismic data indicate that the sequence reaches 2,000–3,000 m in rim synclines in the central basin. Whereas the Tromsø and Sørvestsnaget basins were depocentres through most of this period, areas further east were either transgressed only during maximum sea-level and/or display only condensed sections.

25.4.2.3 Cenozoic

The Cenozoic structuring was related to the two-stage opening of the Norwegian-Greenland Sea and the formation of the predominantly sheared western Barents Sea continental margin (Fig. 25.3). Continental break-up and onset of seafloor spreading were preceded by a phase of rapid late Palaeocene subsidence. The Palaeogene succession rests unconformably on the Cretaceous and this depositional break at the Cretaceous-Tertiary transition (Maastrichtian-Danian) occurs throughout the southwestern Barents Sea.

The western Barents Sea-Svalbard margin developed from a megashear zone which linked the Norwegian-Greenland Sea and the Eurasia Basin during the Eocene opening. The first-order crustal structure along the margin and its tectonic development is mainly the result of three controlling parameters: (1) the pre-break-up structure, (2) the geometry of the plate boundary at opening and (3) the direction of relative plate motion. The interplay between these parameters gave rise to striking differences in the structural development of the different margin segments of sheared and/or rifted nature. The continent-ocean boundary is clear along the sheared Senja margin. The central rifted margin segment southwest of Bjørnøya was associated with magmatism in the Vestbakken Volcanic Province both during break-up at the Palaeocene-Eocene transition and later in the Oligocene. In the north, strike-slip movements between Svalbard and Greenland gave rise to compressional (transpressional) deformation within the Spitsbergen Fold and Thrust Belt (Fig. 25.17). Compressional deformation is also observed in the Barents Sea east of Svalbard, showing that stress related to transpression at the plate boundary west of Svalbard was transferred over large distances. Domal structures observed in the eastern Barents Sea may be related to this compressional regime.

The opening of the Greenland Sea was complex, involving jumps in the location of the spreading axis and the splitting off of microcontinents. Since earliest Oligocene time (magnetic chron 13) Greenland moved with North America in a more westerly direction relative to Eurasia (Fig. 25.3). This gave rise to extension, break-up and onset of seafloor spreading also in the northern Greenland Sea west of Svalbard, and a deep-water gateway between the North Atlantic and Arctic was finally established sometime in the Miocene. This had major implications for the palaeo-oceanography and climate in the region.

The late Cenozoic evolution was characterised by subsidence and burial of the margins by thick sediments in a clastic wedge derived from the uplifted Barents Sea area. Late Cenozoic uplift and erosion of the Barents Sea has removed most of the Cenozoic sediments, and even older strata. The subcrop pattern is dominated by Mesozoic units. The erosion seems to have been most extensive in the western Barents Sea, especially in the northwestern part including Svalbard where more than 3,000 m of sedimentary strata have been removed. In the SW Barents Sea the erosion estimates are in the range 1,000–1,500 m. In the eastern Barents Sea, little work has so far been done on Cenozoic uplift and erosion, however, erosion has been calculated to be between 250 and 1,000 m. High seismic velocities at the top of the bedrock in the NW Barents Sea, decreasing south- and eastwards, reflect the pattern of differential uplift and erosion. The Neogene and Quaternary, resting unconformably on Palaeogene and Mesozoic rocks, thickens dramatically in the huge sedimentary wedge at the margin. The glacial sediments are dated as Late Pliocene to Pleistocene/Holocene in age.

25.4.3 Exploration History and Petroleum Provinces/Systems

More than three decades of research and petroleum exploration in the Barents Sea have revealed a deep and complex sedimentary basin system affected by a variety of geological processes. A large petroleum potential has been proven including multiple source and reservoir intervals. However, there are still many uncertainties and problems linked to understanding the prospectivity of the Barents Sea. Areas in the southern Barents Sea were opened for exploration in 1980 and the first discovery was made in 1981.

A great variety of traps (fault and salt structures, stratigraphic pinchout) and sealing mechanisms exist in the Barents Sea area, and several different play models have proven hydrocarbon accumulations. The early discoveries were dominated by gas and gas condensate accumulations (e.g. Snøhvit Field), but several oil discoveries have been made recently in the SW Barents Sea (see below). Potential reservoirs are distributed across several stratigraphic levels from Devonian to Tertiary and comprise both sandstone and carbonate lithologies. Jurassic sandstones are the main proven reservoir but hydrocarbons have also been found in sandstones of Triassic and Cretaceous age. Several proven and potential source rock units are present in the Barents Sea. The most important are the Upper Jurassic and Triassic organic-rich (anoxic) shales. Lower Cretaceous, Permian and Carboniferous shales, as well as Lower Permian evaporites and Lower Jurassic coals, also have source potential.

About 25 discoveries have been made in the Barents Sea, most of them in the Hammerfest Basin (Fig. 25.20) where their reservoirs are in sandstones, mainly Jurassic, as in the Snøhvit Field. Deeper discoveries have also been made, such as in Triassic sandstones in 7122/7-1 (Goliath Field) and 7125/4-1 (Nucula Field). Oil and gas have also been found in Triassic sandstones in the Nordkapp Basin, which is dominated by salt tectonics (Fig. 25.18). Gas and oil have been found in carbonates of Carboniferous to Permian age on the Finnmark Platform. Recently, several oil discoveries have been made in the SW Barents Sea at or close to the Loppa High (Johan Castberg and Gohta/Alta).

The most significant exploration problem in the Western Barents Sea relates to the severe uplift and erosion of the area that took place during the Cenozoic. The quantity of sediments removed, and the timing of this removal, are still a matter of debate, but it is agreed that the uplift and erosion have had important implications for oil and gas exploration in the Barents Sea. Residual oil columns found beneath gas fields in the Hammerfest Basin indicate that the structures were once filled, or partially filled, with oil. The removal of up to 2 km of sedimentary overburden from the area has had critical consequences for these accumulations: exsolution of gas from the oil, and expansion of the gas due to the decrease in pressure, resulted in expulsion of most of the oil from the traps. Seal breaching and spillage probably also occurred as a result of the uplift and tilting. A further consequence of these late movements was the cooling of the source rocks in the area, which effectively caused most hydrocarbon generation to cease.

The Neogene uplift and erosion has had important consequences for Barents Sea petroleum systems – different from other basins at the Norwegian Continental Shelf.

Much of the North Sea basin and Haltenbanken offshore mid-Norway have been dominated by continued subsidence and sedimentation. Permian and Jurassic rifting resulted in uplift and erosion but most of the sedimentary sequences making up the basin fill are now at their maximum burial depth. This simplifies the reconstruction of the burial history also with respect to temperature and time for modelling of source rock maturation and migration. Similar time-temperature integrals may be used to model diagenetic processes like quartz cementation in reservoir rocks to predict reservoir quality. Particularly at Haltenbanken up to 1.5 km of Plio-Pleistocene basin subsidence and sedimentation imply that reservoirs now at 4 km burial depth were at 2.5 km depth 1.5–3.0 million years ago. The limited time at elevated temperature (>100°C) resulted in limited quartz cement compared to sandstones with less recent subsidence. In the Northern North Sea Quaternary uplift has affected the eastern parts including the Troll Field and has also caused late tilting of some of the sequences thus influencing petroleum migration and the fluid contacts.

In the western part of the Barents Sea late Neogene uplift and erosion may total 1.5–2 km. The timing of maximum burial depth and temperature is then more difficult to estimate with respect to maturation, migration and sometime remigration of oil and gas into traps. Maturation of source rocks is not only a function of the maximum burial temperature but of the time exposed to temperatures above 90–100°C.

Sandstones undergo diagenesis and quartz cementation both during subsidence and uplift as an exponential function of temperature when it is above about 80°C. Chemical compaction due to quartz cementation and porosity loss will therefore continue also during uplift. If the rock volume is reduced the shrinkage results in a reduction in differential stresses during tectonic deformation. In the parts of the Barents Sea where the uplift and erosion has been more than 1.5–2.0 km the maximum temperature may have exceeded 70–80°C and Jurassic or Cretaceous rocks are quartz cemented to some degree. This also means that the temperature has pasteurised the reservoir rocks with respect to bacteria. Oil migrating into such reservoir rocks will not easily be biodegraded. An example to illustrate this may be the Wisting discovery where normal unbiodegraded oil is found at very shallow depth, 2–300 m below the seafloor.

During glaciations maximum ice loadings of up to 2 km or more could add up to 10–20 MPa to the total overburden stress depending on the sea level. Overpresssured water below the ice would reduce the effective stress transmitted to the seafloor, but increase the pore pressure in the rocks below the seafloor. This means that more gas will be dissolved in the porewater of the underlying sedimentary rocks, and in reservoirs more gas could also dissolve in the oil phase.

During interglacial periods with no ice load, reduced pressure will cause gas to bubble out of the porewater and appear as shallow gas. It is important to distinguish between shallow biogenic gas produced by bacterial processes and thermogenic gas formed from maturation of source rocks at greater depth. This may be shallow gas due to upwards migration and also due to erosion of the overburden.

The Quaternary cover of glacial sediments may be hard and well compacted by the ice load and could in some cases also serve as a cap for oil and gas. The timing for trapping of petroleum would however have been very short (from the last glaciation). Because of their poor sorting of clay, silt and sand glacial sediments compact very effectively at moderate effective stresses (see Chap. 11). In the northern North Sea the Peon field is an example where the reservoir is only at about 200–300 m depth in Pleistocene glacial sediments which have been compacted by glacial loading.

The late uplift of the Barents Sea basin and proximal parts of the Norwegian offshore basins may have caused leakage of petroleum reservoir. The many prolific onshore basins in the world show however that not all traps for oil and gas have leaked during uplift and erosion.

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