Paper I

From rifting to drifting: effects on the development of deep-water hydrocarbon reservoirs in a passive margin setting, Norwegian Sea

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The Cretaceous to Eocene deep-water hydrocarbon reservoirs in the Norwegian Sea were deposited during four main tectonic stages from continental rifting to oceanic drift: 1) Late Jurassic/Early Cretaceous continental rifting, 2) Early to Late Cretaceous post-rift subsidence, 3) Late Cretaceous/Paleocene continental rifting and 4) Post Paleocene oceanic drift –stage. The mode of deposition of reservoir rocks changed significantly between these stages, and the reservoir geometry, quality and the spatial reservoir distribution where controlled by three main factors: 1) sediment source area, 2) sediment transport system and 3) geometry of the receiving basin. The understanding of these factors and their effects on deep-water reservoir development to the tectonic development from rifting to drifting are vital when exploring deep-water hydrocarbon reservoirs in basins like the Norwegian Sea.

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Introduction

Prospective deep-water hydrocarbon reservoirs along the Atlantic margins developed during different tectonic stages beginning with continental rifting and ending with oceanic drift. Reservoirs in these deep-water settings vary in size, geometry and internal architecture related to controls operating during the development of the depositional systems. Several recent papers have classified turbidite systems and discussed the role of different processes controlling the resultant deposition (e.g. Reading & Richards 1994; Prather 2003; Steffens et al. 2003; Martinsen et al. 2005). The development of deep-water sedimentary systems is influenced by a number of factors, like grain-size and sand/mud ratios (Reading & Richards 1994), or the configuration of the receiving basin (Steffens et al. 2003). This paper describes and discusses the effects on the deep-marine reservoir development and the basin changes that are related to the Early Cretaceous to Eocene tectonic development in the Norwegian Sea.

Deep-water gravity flow deposits always seek the lowest topographic locations, and changes of basin topography had a major impact on depositional geometry and sediment distribution. In addition, changes in the tectonic regime influence the hinterland sediment source areas, the sediment transport pathways and the size and geometry of the depositional basin. An understanding of the depositional response to changes in the tectonic regime is thus vital for predicting reservoir deposition, both in terms of lithology, depositional geometries and spatial distribution of the reservoir.

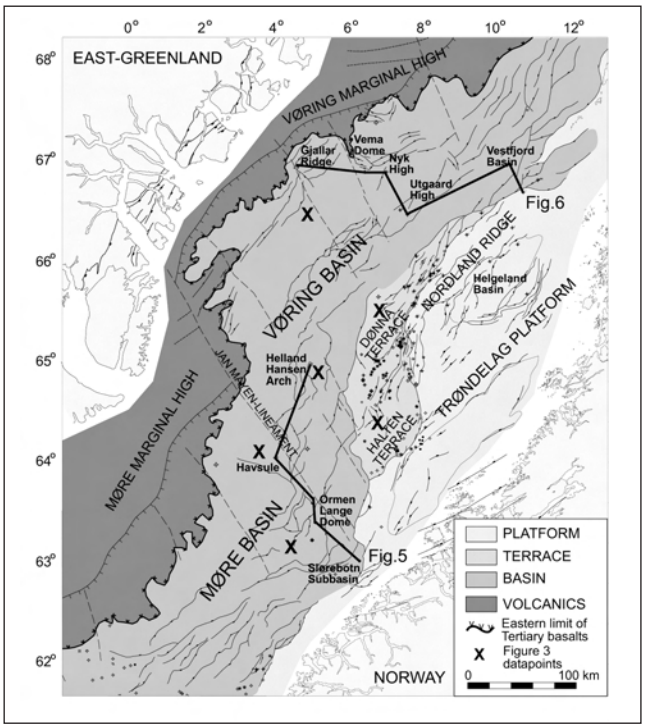

Fig. 1 Location map and main structural elements in the Norwegian Sea south of 68° N. A pre-drift reconstruction shows the position of East Greenland along the western margin of the Vøring Basin. Note location of well correlations in Figs. 5 & 6.

Deep-marine reservoirs in the Norwegian Sea have been in focus for exploration the last 10 years. One giant field (Ormen Lange; Gjelberg et al. 2001) and smaller discoveries (e.g. Nyk; Kittelsen et al. 1999) contain good-quality reservoir sandstones. Several wells have, however, failed to reveal the predicted reservoir, and the prediction of deep-water reservoir distribution is regarded as a key risk factor in future exploration of the Norwegian Sea. The prospective deep-water reservoirs in the Norwegian Sea are mainly of Cretaceous and Paleogene age, and were deposited during several distinct tectonic phases from continental rifting to oceanic drift. Understanding the sedimentary response to this tectonic development is regarded a key factor in improving the prediction of deep-water reservoir distribution in the Norwegian Sea.

Tectonostratigraphic Development

The present day Norwegian Sea is a NE-SW trending passive margin bounded to the west by a volcanic margin escarpment and to the east by the Norwegian mainland (Fig. 1). Main structural elements are the Møre and Vøring Basins in the west, Halten and Dønna Terraces and the Trøndelag Platform in the east (Blystad et al. 1995).

Several studies have been published that discuss the tectonic development during the Cretaceous to Paleogene of the Norwegian Sea (Blystad et al. 1995; Bjørnseth et al. 1997; Lundin & Doré 1997; Doré et al. 1999; Gabrielsen et al. 1999; Roberts et al. 1999; Brekke 2000; Mogensen et al. 2000; Brekke et al. 2001; Færseth & Lien 2002; Gernigon et al. 2003; Ren et al. 2003). These studies present partly variable timing and significance of the tectonic phases and events (see Færseth & Lien 2002), but the most recent papers agree on the timing and development of the main tectonic phases and events. These include Late Jurassic to earliest Cretaceous continental rifting and Late Cretaceous (Campanian) to Paleocene rift culminating in the Paleocene/Eocene continental separation in the North Atlantic region and Norwegian Sea (Skogseid et al. 2000; Færseth & Lien; 2002; Gernigon et al. 2003; Ren et al. 2003).

The regional Cretaceous to Paleogene stratigraphy and depositional history in the Norwegian Sea has been published in various degrees of detail; Swiecicki et al. (1997) present a broad tectonostratigraphic framework from the Devonian to the present in the Mid-Norway region. Brekke et al. (2001) present a broad overview of the North Atlantic geological development from the Paleozoic to the present. Vergara et al. (2001) discuss the distribution of Cretaceous and Paleocene deep-water reservoirs in the Norwegian Sea, with a focus on

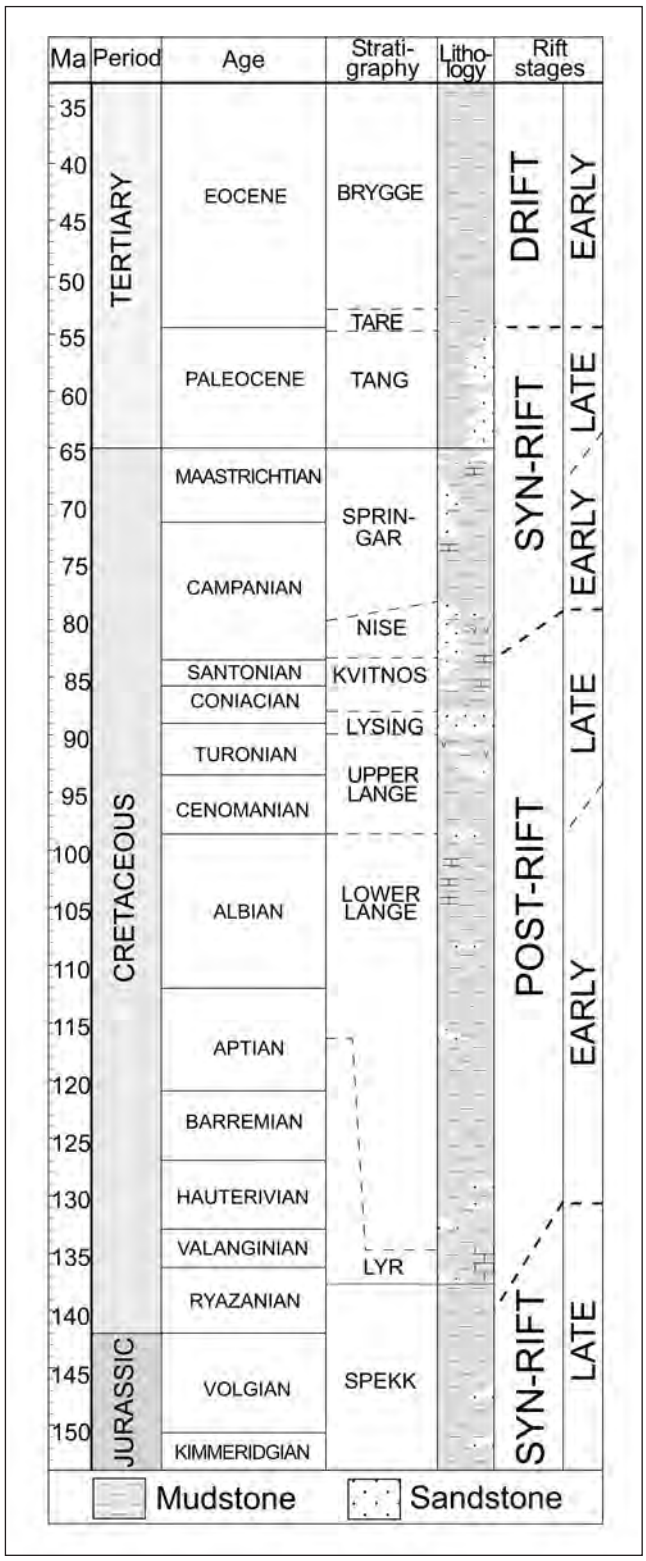

Fig. 2 Tectono-stratigraphic framework of the Upper Jurassic to Eocene succession for the Norwegian Sea region. Cretaceous sedimentation in the Norwegian Sea, following the Late Jurassic rift episode and until the onset of Campanian rifting is interpreted to represent a post-rift thermal subsidence stage. This stage can be subdivided into an early and late post-rift stage. The rift stage from the Campanian to the oceanic Drift stage at the transition Paleocene/Eocene is subdivided into an early and late rift-stage. Note the occurrence of sandstone reservoirs marked white stippled in the lithology column, mud is marked grey and dashed. The stratigraphic nomenclature is from Dalland (1988).

the description of selected sandstone reservoirs and their distribution. Here, I describe and combine the depositional response to the tectonic development and discuss the main factors that affect deep-water reservoir development and distribution within each tectonic stage.

The tectono-stratigraphic framework of the Late Jurassic to Eocene of the Norwegian Sea is presented in Figure 2. The main tectonic phases are the Late Jurassic/earliest Cretaceous continental rifting passing into a post-rift stage, followed by a new rift initiated in the Campanian, culminating in oceanic rifting and drifting at the Paleocene/Eocene transition. Sedimentation varies during the tectonic development both in terms of volume and rate (Figs. 2 and 3). Dramatic variations in the spatial distribution of sediment occur during each phase of tectonic development; this is illustrated in Figs. 4a-e. These variations and their fundamental controlling factors will be described and discussed below.

According to Færseth & Lien (2002) the Cretaceous evolution of the Norwegian Sea following the Late Jurassic/earliest Cretaceous rift episode, and lasting until the Late Cretaceous rifting, represent a post-rift thermal subsidence stage (Fig. 2). This stage can be divided into an early post-rift stage and a late post-rift stage related to changes in basin topography and reservoir development.

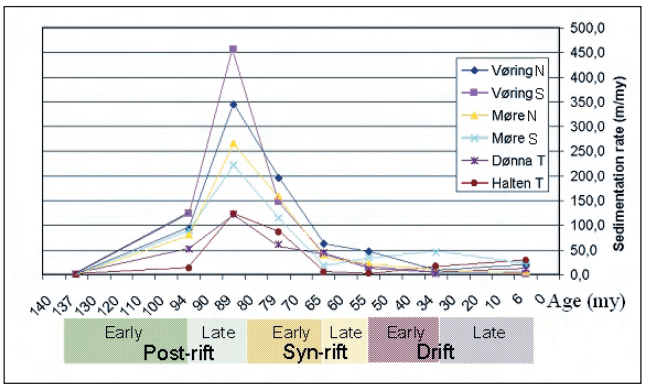

Fig. 3 Sedimentation rate (m/my) from several positions in the study area (see Fig. 1 for positions of measured sedimentation rate). The sedimentation rate varies between the different stages, but all areas follow the regional variations even though they are measured in different structural elements.

Early post-rift stage

Following the Late Jurassic-earliest Cretaceous rifting, the basins in the Norwegian Sea continued to subside during the Cretaceous due to a combination of thermal subsidence, lithospheric response to loading and compaction of underlying sediments during burial (Færseth & Lien 2002). Early Cretaceous sedimentation rates (Fig. 3) in major parts of the Norwegian Sea are interpreted to be lower than the subsidence rate. The relief at base Cretaceous level is inferred to reflect underlying Jurassic rift architecture characterized by large tilted fault-blocks. The Late Jurassic fault scarps remained as significant morphological escarpments on the basin floor and influenced sedimentation for a considerable time after cessation of the rifting (Fig. 4a). Accordingly, the Lower Cretaceous (early post-rift) sediments exhibit pronounced thickness variations across pre-existing rift topography (Fig. 4a). Sand-rich sediments deposited during the Early Cretaceous were mostly trapped in localized marginal basins like the thick sandy Lower Cretaceous succession on East Greenland (Larsen et al. 2001), the Slørebotn Sub-basin in the Møre Basin (Fig. 5) (Martinsen et al. 2005), and in sub-basins on the Trøndelag Platform (e.g. Helgeland Basin Fig. 4a). These depositional systems are characterised by thick aggradational successions of shallow- to deep-marine facies deposited in local half-grabens located along the basin margin (Larsen et al. 2001; Færseth & Lien 2002; Martinsen et al. 2005). In the deeper Møre and Vøring basins, mud deposition probably dominated during the early post-rift stage, however, no wells are drilled deep enough to supports this interpretation. The overall post-rift stage can in general be characterised as complex basin topography with sub-basins trapping the coarse sediments at the inner margin areas, and a subsiding deep, mud-prone outer basin.

Late post-rift stage

The increased sediment supply during the Cenomanian and Turonian (Fig. 3) outpaced the subsidence rate and the topographic relief from the Late Jurassic rift stage was levelled during the late post-rift stage. Accordingly, the different depocentres of Early Cretaceous time merged into a wider depocentre (Fig. 4b). The passive infill, high subsidence rate and subsequent sediment loading in the basin caused flexuring and associated tilting of the basin margins (Færseth & Lien 2002). Hence, the margins became shallow water, low-topography shelf areas (e.g. the Trøndelag Platform) with gentle slope transitions (e.g. the Halten Terrace) toward the deeper Møre and Vøring Basins. Local areas were exposed during relative sea-level falls caused by eustasy variations, or in combination with uplift caused by basin margin flexuring. The exposed sediment source areas at the basin margins included areas like the Nordland Ridge and the East Greenland margin (Larsen et al. 2001). Sandstones of the upper Lange and Lysing formations (Fig. 2) were deposited in the late post-rift stage, and are characterised by thin sheet-like units generally 20-50 m thick (Figs. 5 & 6, see also Vergara et al. 2001). Based on the basin topography (Fig. 4b) and facies development, the Halten and Dønna Terraces

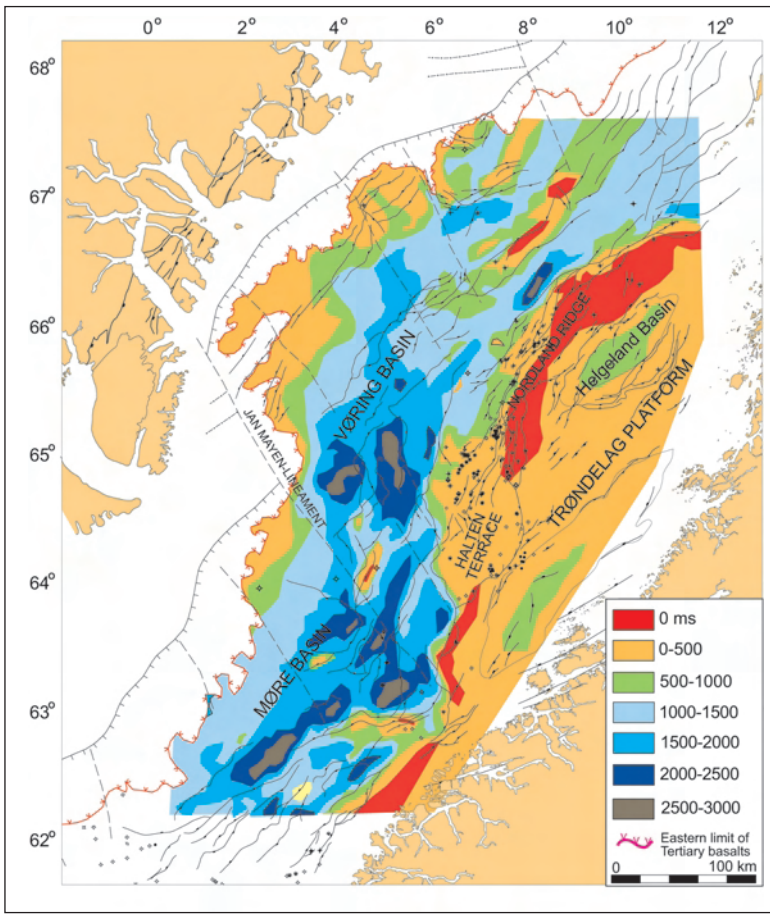

Fig. 4a Sediment thickness for the early post-rift stage (Lower Cretaceous succession) in milliseconds (ms) computed from regional seismic mapping. Note the large variation in sediment thickness from the platform to the basin, and within the basins

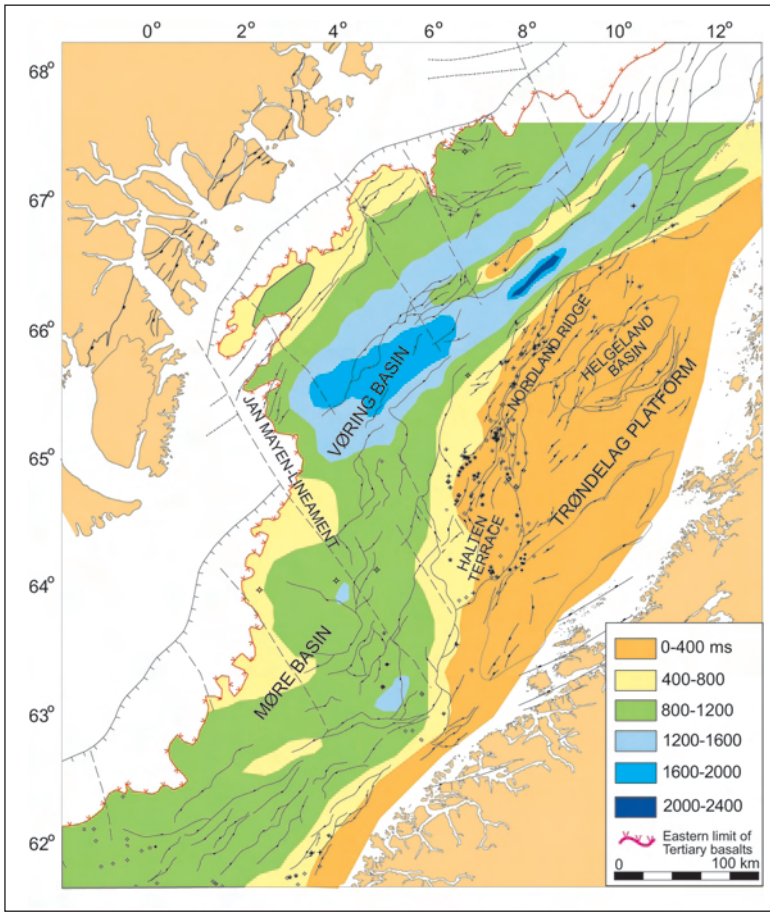

Fig. 4b Sediment thickness map of the late post-rift stage (Turonian succession) in milliseconds (ms) computed from regional seismic mapping. Note the relative uniform thickness across the area compared to Figure 4a.

are interpreted as regional slopes during the late post-rift stage, and the sandstone deposition on these slopes is controlled by subtle topography controlled by the differential compaction from underlying Jurassic structures (Færseth & Lien 2002; Martinsen et al. 2005). The increase in sedimentation rate at the Early to Late Cretaceous transition in the Møre and Vøring Basins (Fig. 3) coincided with the middle Albian-Turonian infill of the onshore East Greenland Jurassic rift topography (Whitham et al. 1999) and infill of the sub-basins at the eastern margin (e.g. the Helgeland Basin, Fig. 4b). This allowed for sediment transport across the shelves and slopes into basin areas. Provenance data (Fonneland et al. 2004) support a westerly source for the late, post-rift sediments as far into the basin as the Helland Hansen-Arch and Ormen Lange-Dome (Figs. 1, 4b & 5). High sedimentation rate and widespread sedimentation across a basin with gentle topography is interpreted to reflect the mature stage of the post-rift development. In the distal part of the basin the Lysing Formation sediments are heterolithic, very fine-grained (Fig. 5) and have limited reservoir potential.

Rift stage

The post-rift stage with tectonic quiescence was terminated by a new rift episode, which was initiated in the Campanian (Færseth & Lien 2002; Ren et al. 2003) and culminated with the final opening of the North Atlantic at 55 Ma (Brekke 2000; Skogseid et al. 2000; Lundin & Doré 2002). According to Færseth & Lien (2002) and Ren et al. (2003), the rift phase can be divided into an initial (or early) rift phase characterized by large-scale normal faulting and a late (or main) rift phase associated with continued extension, regional uplift, intrusive igneous activity and subsequent erosion.

The new rift activity was associated with a change from basin-wide deposition during the late post-rift stage (Fig. 4b), to deposition in progressively more localized basin lows (Figs. 4c & 4d). The thickness of the succeeding Campanian-Maastrichtian sequence varies across the Norwegian Sea (Fig. 4c), with large thicknesses in the Vøring Basin controlled by large-scale normal faulting. This thickness variation across the basin increases during the main rift stage (Fig. 4d) with a change to variable and increased thickness also in the Møre Basin.

The Late Cretaceous-Paleocene rift stage is associated with uplift of the regional hinterland (Skogseid et al. 2000), with an inferred subsequent increase in volume of sediment available for erosion. A major stratigraphic unconformity from the Santonian to Late Paleocene is present in the succession at Hold With Hope, onshore East Greenland (Kelly et al. 1998; Larsen et al. 2001)

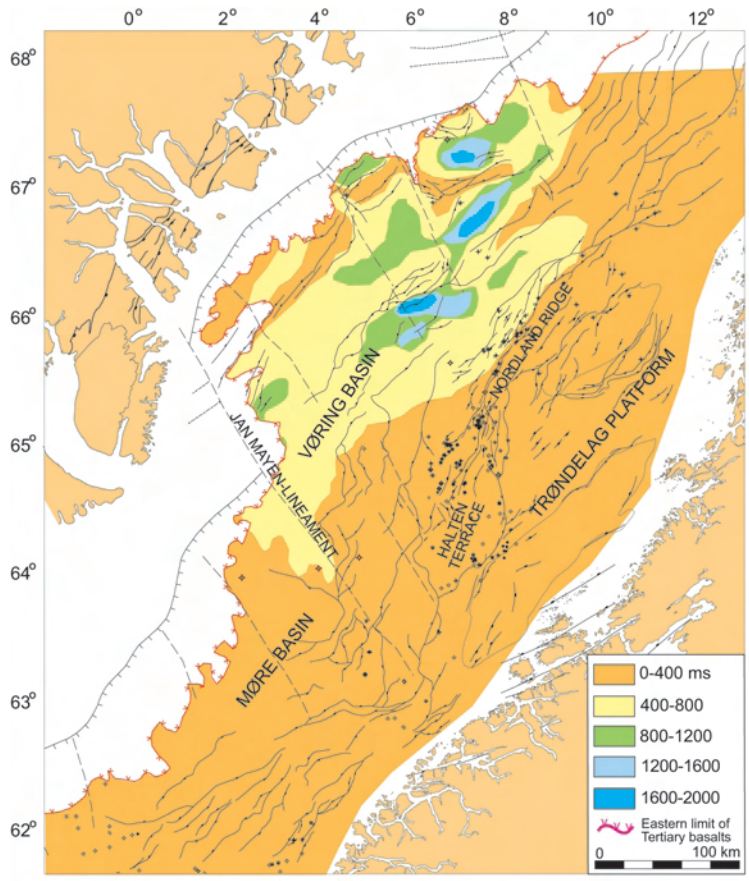

Fig. 4c Sediment thickness map of the early rift-stage (Campanian – Maastrichtian succession) in milliseconds (ms) computed from regional seismic mapping. Note the thick intervals in the Vøring Basin in this stage

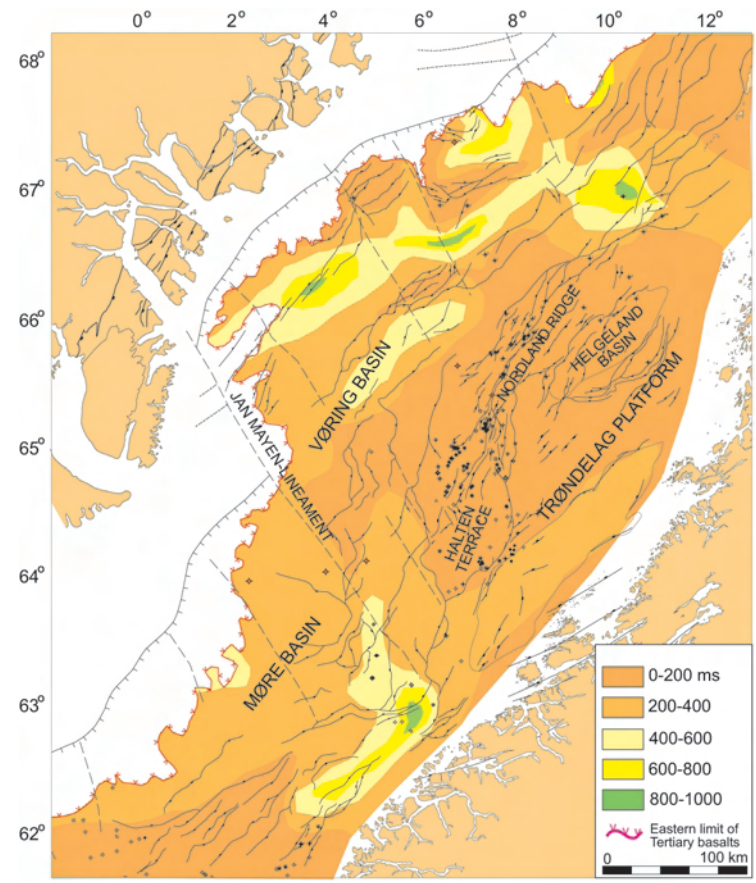

Fig. 4d Sediment thickness map of the late rift-stage (Paleocene succession) in milliseconds (ms) computed from regional seismic mapping. Note the localised thickness variation in the Vøring and Møre Basins.

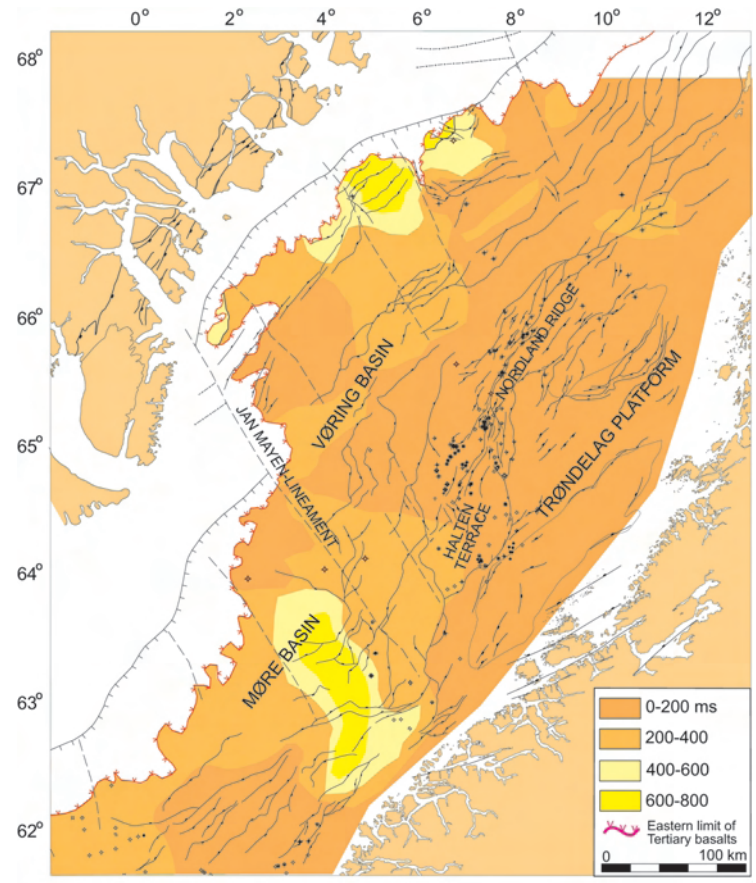

Fig. 4e Sediment thickness map of the early drift-stage (Eocene succession) in milliseconds (ms) computed from regional seismic mapping. Note the relatively uniform thickness from the platform to the basins, but increased thickness in the northwestern Vøring Basin.

where Upper Paleocene fluvial sediments overlie deep-water Santonian shale.

The drainage of the hinterland is interpreted to follow older zones of weakness such as those that define the present-day fjords and major lineaments, transporting sediments into the deeper basin. A similar model was suggested by Witham et al. (1999) and by Brekke et al. (2001). In the model by Witham et al (1999), coarse clastic sediments were focused by the NW-SE trending lineaments and transported from East Greenland across a narrow, Late Cretaceous shelf, into the deeper Vøring Basin in the east where they were deposited as sand-rich, deep-marine fans in a thick (>1000m) succession (Fig. 6). In addition to the unconformity on East Greenland, a major hiatus between the Early Maastrichtian and Late Paleocene is observed in wells on structural highs in the Vøring Basin (Fig. 6) (Vergara 2001; Færseth & Lien 2002; Ren et al. 2003). The Early to Late Paleocene erosion of the structural highs in the Vøring Basin is probably related to a combination of local tectonics (tilting of fault-blocks) and to regional uplift associated with the arrival of the Iceland mantle plume in the Paleocene, which induced thermal and dynamic regional uplift (Skogseid et al. 2000; Ren et al. 2003). A major stratigraphic unconformity between Lower/Middle Maastrichtian and Upper Paleocene sediments is observed at the eastern basin margin from the Møre Margin to the Halten Terrace and Trøndelag Platform (Brekke et al. 1999; Gjelberg et al. 2001). A complete succession is deposited and preserved in the central basins (e.g. Ormen Lange wells, Fig. 5) (Gjelberg et al. 2001). The unconformity at the Norwegian margin is suggested to be related to basin-margin uplift and associated rotation related to rifting in the North Atlantic (Riis 1996). Thick Upper Maastrichtian to Paleocene sedimentary wedges prograded into the basin from the margins, represented by the up to 100m thick sand-rich Ormen Lange fan and the 700m thick sand-rich Vestfjorden fan (Figs. 5 & 6) (Brekke et al. 1999; Martinsen et al. 1999; Gjelberg et al. 2001; Martinsen et al. 2005). Provenance studies support an East Greenland source for the Campanian and Maastrictian sandstones deposited in the Vøring Basin (Morton & Grant 1998; Fonneland et al. 2004), and a Norwegian mainland source for the Maastrichtian and Paleocene sandstones in the eastern Møre Basin (Ormen Lange) and in the Vestfjord Basin (Fonneland et al. 2004).

The wells on the structural highs in the Vøring Basin (Gjallar Ridge, Vema Dome and Nyk High), and along the eastern basin margin, have a thin succession of Upper Paleocene strata deposited unconformably on the Early Paleocene hiatus (Fig. 6). The strata are interpreted to have been deposited in an upper bathyal environment, as a transgressive succession during drowning of the highs.

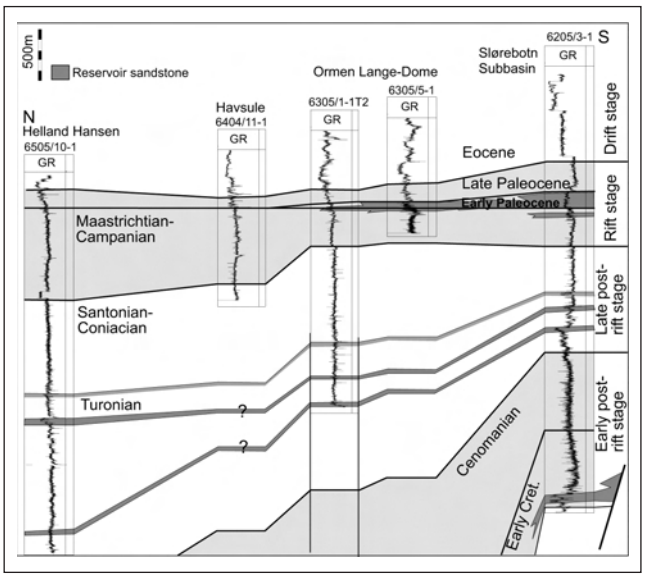

Fig. 5 Well correlation illustrating the Cretaceous to Eocene lithology and depositional geometries in the central southern Vøring Basin, across the Møre Basin and to the Møre Margin (see location of line in Fig. 1). The succession is mud dominated with few thin sandstones marked dark grey.

Drift stage

The early drift stage starts with the opening of the North-East Atlantic Ocean at the Paleocene-Eocene transition, and onset of sea-floor spreading between Norway and Greenland with associated volcanism and thermal subsidence (Eldholm et al. 1989, Skogseid et al. 2000). The Vøring and Møre basins underwent rapid subsidence following crustal separation (Bukovics & Ziegler 1984) with associated igneous activity and subaerial volcanism.

The Eocene epoch reflects the early passive margin history characterised by differential subsidence, which is caused by thermal cooling and contraction of the lithosphere, and by sediment loading and compaction.

The early drift sediment thickness increases westward towards the spreading axis (Fig. 4e), and there is a dramatic change in basin development compared with the late rift stage (Fig. 4d). The oceanic drift stage marks the termination of the western sediment source with subsidence in the west and the Norwegian mainland as the remaining main sediment source. The Eocene succession in the Norwegian Sea is dominated by mud (Figs. 5 & 6). Well 6704/12-1 on the Gjallar Ridge drilled a thick Eocene succession (Fig. 4e) and penetrated 330m of Eocene shale (Fig. 6). Tuffs observed in the wells are mainly of Late Paleocene age and related to the volcanism just prior to the sea-floor spreading. In the Møre Basin, the Eocene succession thickens toward the west (Fig. 4e) where the deposits are mud dominated (Fig. 5) but sandstones are penetrated by a few wells in the Northern North Sea (Martinsen et al. 1999).

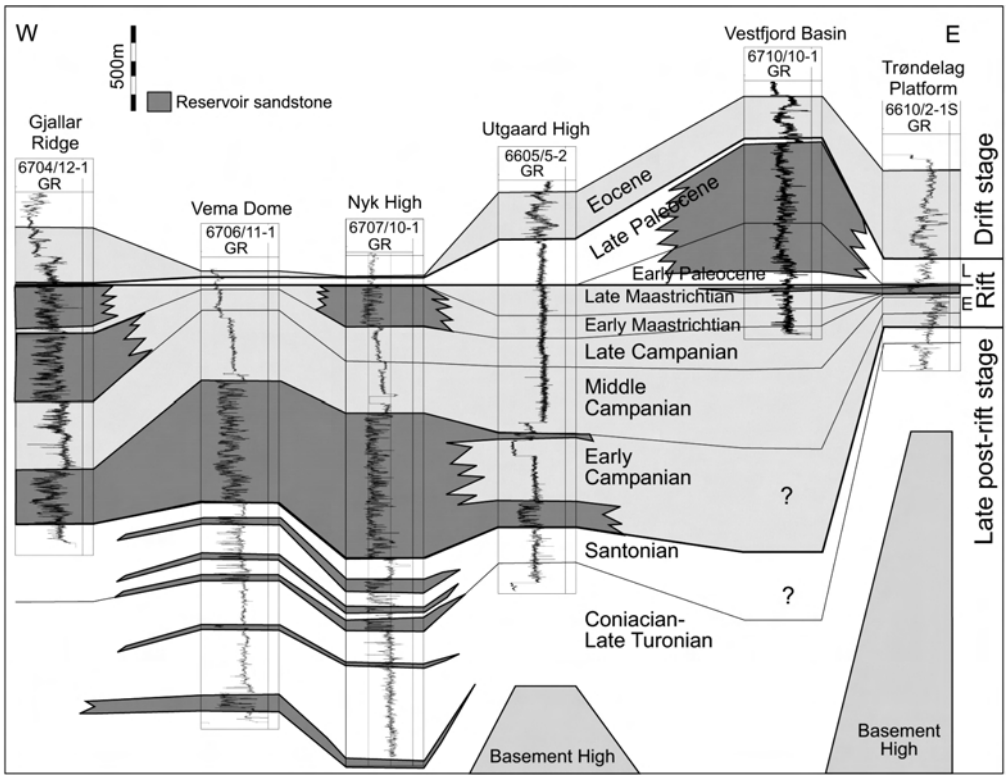

Fig. 6 Well correlation illustrating the Upper Cretaceous to Eocene lithology and depositional geometries in the Vøring Basin, across the Utgard High and to the Vestfjord Basin and Trøndelag Platform (see location of line in Fig. 1). Note the thick sandstone units (dark grey colour) present in the Vøring Basin (Gjallar Ridge, Vema Dome, Nyk High and the Vestfjord Basin. These are interpreted to be deposited during the early and late rift stage.

In general, the Eocene is dominated by pelagic to hemipelagic, mud prone deep-water sedimentation and slope processes, which include gravitational deformation and random low-density turbidity currents. Regional progradational and aggradational strata built up on the eastern shelf or slope where sea-level fluctuations allowed reservoirs to form in fluvial through deep-water depositional environments. A Late Neogene regional uplift of the inner shelf and the adjacent landmass associated with erosion by glacial processes induced a westward progradation of a huge Pliocene-Pleistocene wedge (Stuevold et al. 1992).

Factors controlling the changes in deep-water reservoir development

Within each stage in the tectonic evolution, several processes control the deep-water deposition. These processes do not act individually, but influence each other. Three main factors are proposed to control deep-water deposition in the Norwegian Sea: 1) sediment source area, 2) transport systems and 3) geometry of the receiving basin. Between the different depositional stages, changes in dominance of these factors control the geometry, quality and the spatial distribution of reservoirs. An understanding of these factors and their influence during the depositional stages is vital in exploration for deep-water reservoirs in basins like the Norwegian Sea.

Early post-rift stage

The depositional environment characteristic of the early, post-rift stage is shown in Figure 7. The predicted lack of widely distributed coarse clastics in the Møre and Vøring Basins is related to the limited sediment source potential and the lack of efficient transport pathways caused by the complex basin topography.

In the early post-rift stage the sediment sources were exposed local highs that were progressively transgressed. In the deeper basin the local highs were relatively rapidly transgressed and the sediment source potential was limited. Parts of these highs consisted of relatively high net/gross Triassic to Jurassic sediments, and provided excellent sand sources but with limited sediment volume potential however, the inner basin margins significant reservoirs are present (East Greenland; Larsen et al. 2001, Helgeland Basin; Fig. 7). These are located close to the larger hinterland source areas, and have short transport distances, and the basin topography from the rifting trapped the sediments in the local sub-basins (Fig. 7). The relatively high topographic relief and short transport distance may have caused texturally immature sediments to accummulate. The local and limited sediment source areas combined with complex transport routes and localised depocentres are the main controls of reservoir development in the early post-rift stage (Fig. 7). Limited reservoir potential is therefore to be expected in the central parts of the Norwegian Sea.

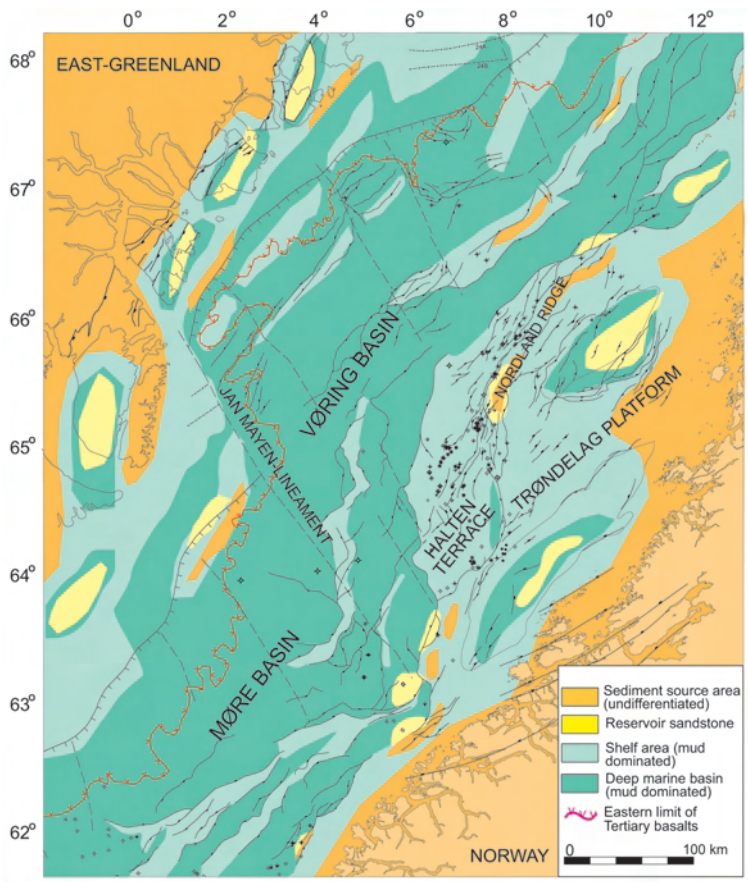

Fig. 7 Paleogeographic map illustrating the early post-rift stage. Note the complex topography with reservoir deposition in the inner marginal subbasins.

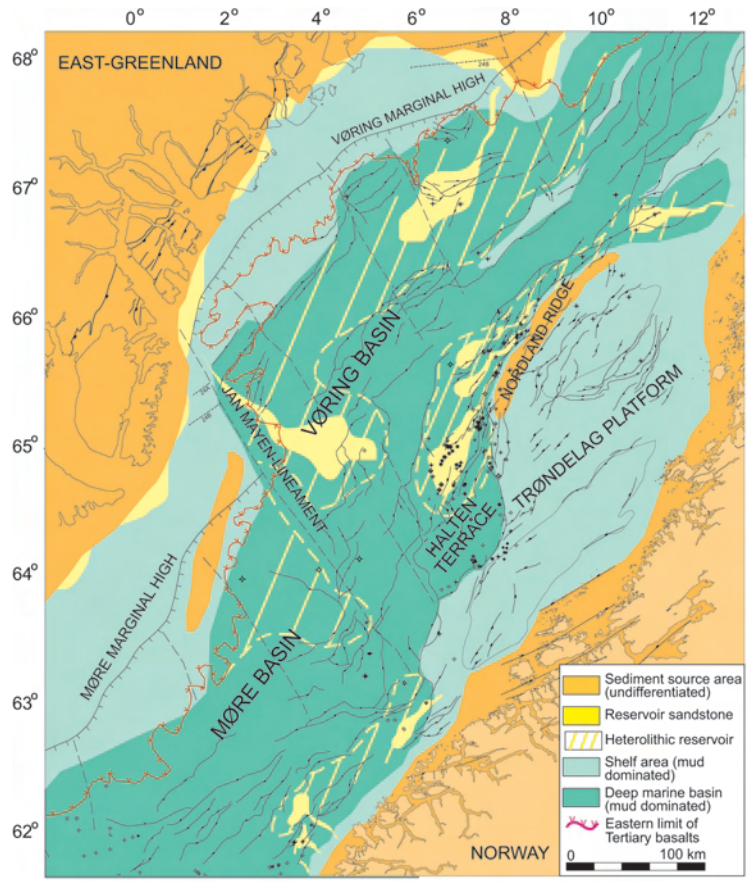

Fig. 8 Paleogeographic map illustrating the late post-rift stage. Note the gentle and low topography with reservoir deposition in the central parts of the basin.

Late post-rift stage

During the late post-rift stage (Fig. 8) continuous regional subsidence and eustatic sea-level rise flooded the basin highs and transgressed the hinterland source areas. The sediment source areas changed from being dominant local, intra-basinal structural highs to areas located at the basin margins. These were periodically elevated and exposed to erosion by a combination of eustatic sea-level falls and by regional flexure and tilting caused by sediment loading in the deeper Vøring and Møre basins (Færseth & Lien 2002). Despite the lack of a major tectonic rift event during the late post-rift stage, the basin geometry and topography changed due to regional thermal subsidence and the progressive infilling of sediments into a broad "steer head" basin. This changed the depositional reservoir geometries from constrained to sheet-like, i.e. they were less constrained by the basin rift topography. Although no major topography constrained the transport of sediments, and sand was transported widely and to the central basin floors (i.e. the Helland-Hansen Arch, Fig.8), the geometries of the reservoirs were partly controlled by differential compaction across underlying structures (Martinsen et al. 2005). Coarse clastic sediment volume was constrained by the relatively limited source area at the narrow basin margin zone, and the magnitude and duration of the relative sea-level falls. Because of the low relief topography, reservoir sands cannot be excluded in any parts of the entire basin. However, significant sand volumes were probably related to intra-slope depocentres areas linked to a close sediment source (i.e. the Dønna Terrace, Fig. 8).

The large increase in sedimentation rate during the late post-rift stage (Fig. 3) is enigmatic, and not fully understood. The change may have been induced by a combination of variations in factors like sediment source, basin geometry and possibly climatic changes. Although evolution of the climate is uncertain, the overall climate was warm and eustatic sealevel high during mid-Cretaceous times. This should not in itself have increased the sedimentation rate significantly from the Early Cretaceous. However, the progressively cooler climate in the latest Cretaceous could have partly contributed to a reduction in sedimentation rate into the Campanian and Maastrichtian (Fig. 3). Another contributing factor was the infill of the inner marginal basins during the early post-rift phase providing sediment bypass across the shelves in the late post-rift stage. This, in combination with basin margin uplift related to the sediment loading-induced flexure, increased the sediment supply to the basin from the early- to late post-rift. The depositional basin during the late post-rift stage was narrow (150-200 km pre-Late Cretaceous continental rift-extension), had relatively shallow-water conditions compared to the early post-rift stage, developed deltaic systems on the basin shelves (Larsen et al. 2001), and had the potential to deliver huge amounts of silt and muddy sediment into the central parts of the Møre and Vøring basins (Figs. 5 & 6). The reduction in sedimentation rate from the late post-rift into the rift stage can be interpreted as a combination of cooler climate in association with a more complex basin topography. This is discussed further below.

Rift stage

The depositional environment of the rift stage is divided into two periods, early syn-rift stage (Fig. 9) and late syn-rift stage (Fig. 10). The main factors influencing reservoir deposition in the rift stage are related to the change to a larger hinterland sediment source area, increased supply of sandy sediment, variably connected sediment transport pathways, and increasingly localised depocentres.

The western hinterland was strongly influenced by the activity of the Iceland plume (Skogseid et al. 2000), which was located in north-western Greenland and moved slowly towards the south and southeast during the Late Cretaceous (Lavwer & Muller 1994). Regional uplift associated with the plume activity (Skogseid et al. 2000) increased the drainage area for sediments transported eastward, and the large volumes of coarse sediment deposited in the Vøring Basin during the rift stage probably reflect the activity of the Iceland Hotspot. Activity of the Iceland Plume may have pulsated, as has been suggested, during the Early Paleocene (Lundin & Dore 2002). Periods of high plume activity have been correlated with variations in sedimentation rate both in the North Sea and in the Faeroe-Shetland Basin (White & Lowell 1997). The substantial thickness of Lower Campanian sandstone deposited in the Vøring Basin (Figs. 6 & 9) suggests an Early Campanian (or slightly younger) uplift of the hinterland source area. This suggested Early Campanian uplift was probably related to hotspot activity, coinciding with the inferred initiation of the early rift stage in the Vøring Basin. Termination of the deposition of the Lower Campaninan sandstones is marked by a rapid transition to a regionally developed Middle Campanian mudstone unit in the Vøring Basin (Fig. 6) which may be related to a period of thermal subsidence of the Iceland Plume and consequent drowning of the sediment source area. Note however that routing of coarse clastics into the Vøring Basin during the Middle Campanian may also be explained by progressively increased rift activity. Increased faulting and block rotation into the main rift extension stage increased the basin topography, thus causing sediments derived from the western hinterland to become trapped in marginal sub-basins. In the latter interpretation, sandstones of Middle Campanian age are assumed to be deposited in sub-basins closer to the western source area.

Further onset of reservoir deposition in the Vøring Basin

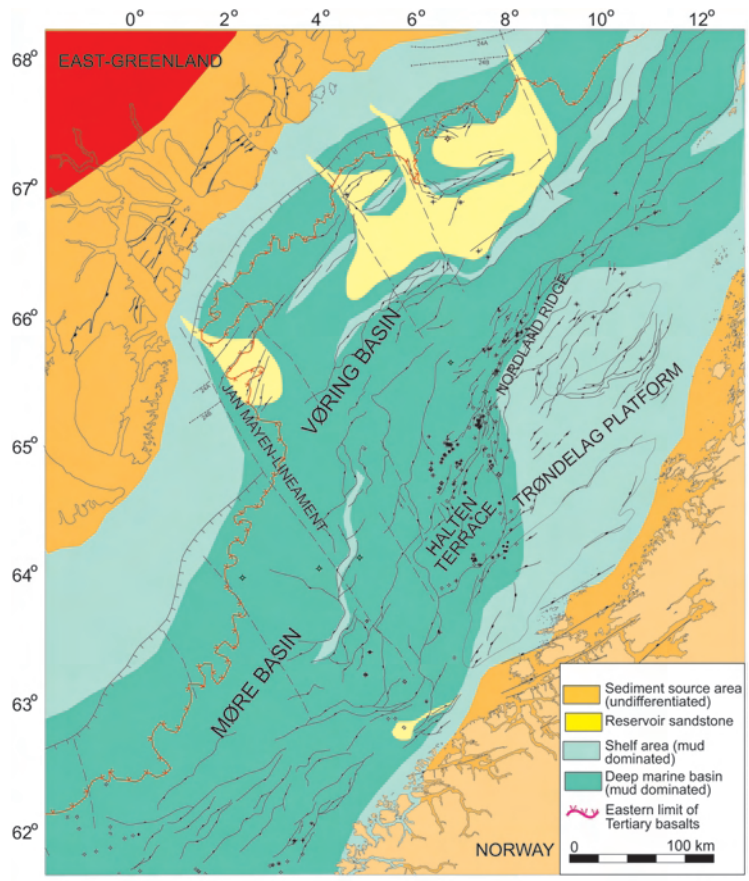

Fig. 9 Paleogeographic map illustrating the early rift stage. Note the large deep-marine fan systems developing in the northwestern Vøring Basin and the associated uplift of the western hinterland (marked red on East Greenland). No significant reservoir was sourced from the Norwegian hinterland during this stage.

during the latest Campanian and into the Early Maastrichtian (i.e. in the Gjallar Ridge, Fig. 6), occurred as the sedimentation rate overcame the subsidence rate, following progradation of deep-water systems to the east. Although the rift extension in the basin continued, associated rift-margin uplift occurred (possibly related to the hotspot activity) and affected sediment deposition in the basin. During rift-margin uplift, the hinterland source area increased and the inner marginal sub-basins filled up, became successively uplifted and forced sediment to prograde into the basin to the east.

Uplift and associated erosion at the basin margins continued through the Early Paleocene, marked by the development of a regional basin-margin unconformity. Regional subsidence started during the Late Paleocene and is recorded by Late Paleocene mud draping at the Early Paleocene unconformity along both basin margins. This indicates that the regional relative subsidence in the Norwegian Sea started just before the continent-continent separation, not just after the separation. This can be interpreted as subsidence related to increased extension prior to the onset of ocean spreading.

The interaction between tectonic uplift and extensional subsidence controlled the reservoir distribution during the rift stage. The sedimentary record indicates a continuous uplift of the Greenland margin from at least Early Campanian to Early Paleocene. The regional uplift begun to affect the Norwegian margin later, probably from Late Maastrichtian onwards, causing regional regression and deposition of a thick upper-omst Maastrictian to Lower Paleocene sandstone succession in the Ormen Lange area and in the Vestfjord Basin (Fig. 10).

During the rift stage, the locations of reservoir deposition on a regional scale were controlled by the width of the basin-margin shelves (Figs. 9 & 10). This is related to the proximity of the sediment source and short transport distances. The change from unconfined late post-rift reservoir geometries (Fig. 8) to the increasingly confined sedimentation during the rift-stage (Figs. 9 & 10) is interpreted to be a response to the newly-created basin-floor topography during the progressively extensional rifting.

On a semi-regional scale, the individually evolving rift-blocks controlled the locations and geometries of the reservoirs. During the initial rift stage, reservoir units were located along the western basin margin which had a narrow shelf with their boundaries defined by large faultblocks (Fig. 9). During the main rift stage (Fig. 10) the reservoir geometries along the western margin were constrained into smaller, localized depocentres, bounded

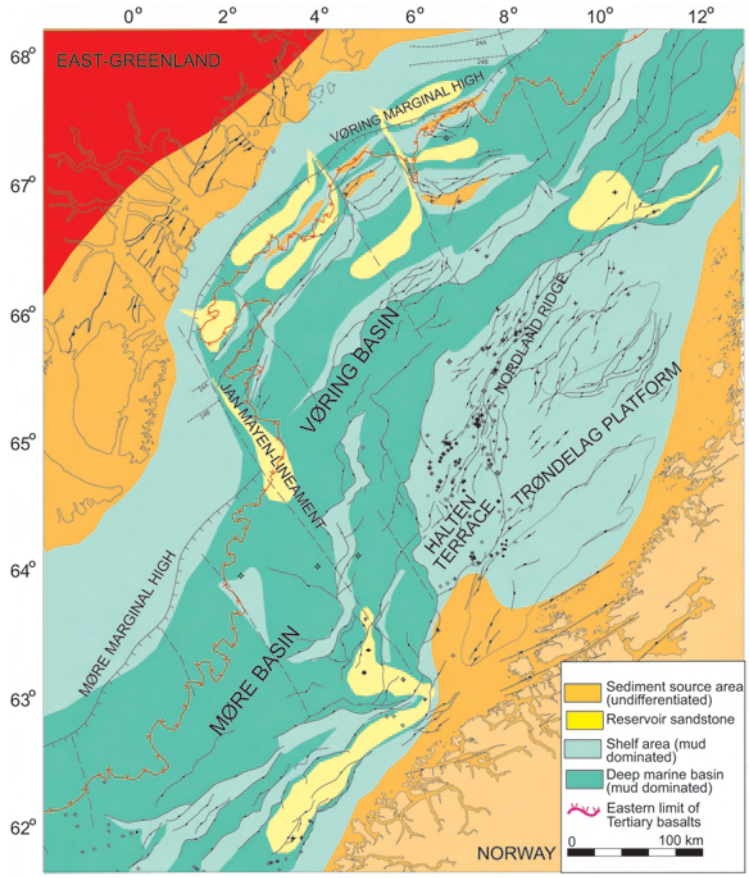

Fig. 10 Paleogeographic map illustrating the late rift stage. Note the uplift of the Norwegian hinterland (marked red) and the associated deposition of the thick deep-marine fan systems in the Ormen Lange area (south) and the Vestfjord Basin (north). At this stage, the basin topography and sediment transport routes became progressively more complex. Note also the correlation between the distribution of the narrow shelves and reservoir deposition.

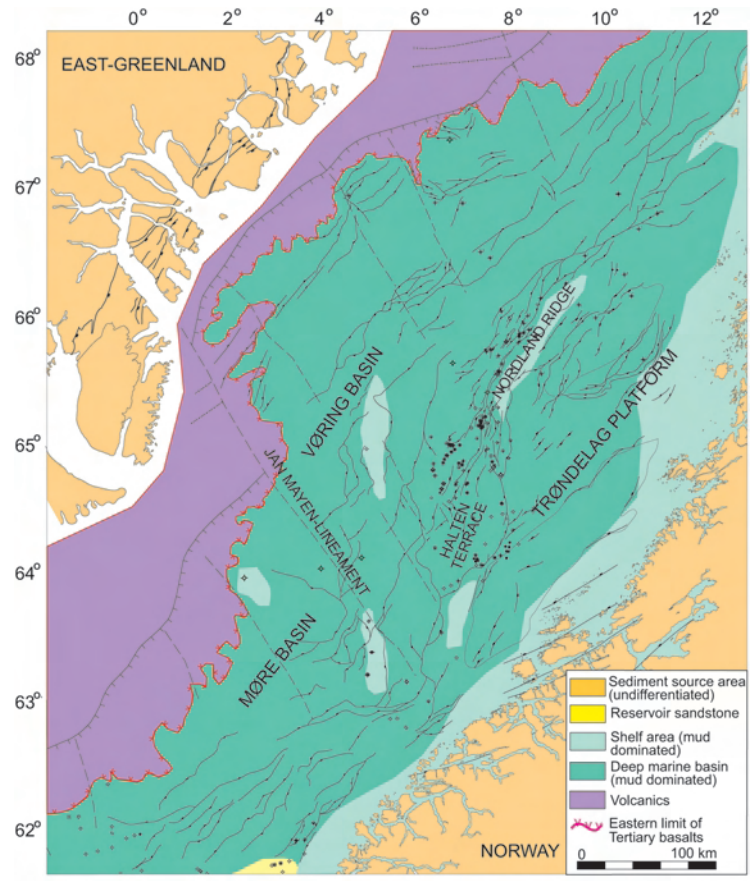

Fig. 11 Paleogeographic map illustrating the early drift stage. Oceanic rifting terminated the western sediment source, and a volcanic margin developed in the west. Regional subsidence transgressed the highs and the eastern hinterland, and subsequent deposition in the basin was dominated by mud.

by the evolving half-grabens. Along the eastern margin, the extension is of a lesser magnitude, depocentres are broader and their location is inferred to be controlled by subsidence related to reactivation of older structures, as in the case of the Ormen Lange deep-water system (Gjelberg et al. 2001).

Early drift stage

The dominant change in basin configuration from the rift to drift stage is the change from basin-margin uplift and continental extension-related fault-block rotation, to regional subsidence with consequent relative sea-level rise. The main change in the balance of driving factors from rift to drift is related to the change in sediment source. After the continent-continent separation, the western margin became inactive as a sediment source for coarse clastics to the Norwegian margin (Fig. 11). Regional subsidence drowned the intra-basinal highs (e.g. the Gjallar Ridge Fig. 6), and any potential sands coming into the basin had to be derived from the Norwegian hinterland. Regional subsidence also affected the Norwegian hinterland and its basin margin, causing marine transgression and depositing deep-marine muds that onlapped the Early Paleocene unconformity. The overall subsidence and lack of a coarseclastic sediment source explain the lack of sandstone penetrated by wells in this stratigraphic interval in the Norwegian Sea. The potential for discovering Eocene reservoirs in the Norwegian Sea is regarded as low.

Conclusions

Prospective deep-water reservoirs in the Norwegian Sea are deposited during a tectonic evolution from continental rifting to oceanic drift, where the reservoir quality, geometry and spatial distribution vary with each tectonic stage. Three fundamental factors control sedimentation:

1) The variation in the sediment source (drainage) area seems to have exerted a major control over the overall volume of sand deposited. Thick aggradational sandy successions were deposited in the rift-stage during hinterland uplift, while a lack of sand deposition dominates the drift stage when the source area was drowned. The sediment source area was mainly controlled by a complex interaction of relative tectonic subsidence or uplift induced by rift extension, variation in hot-spot activity or basin-margin flexural uplift related to sediment loading. In addition, variations in the eustatic sea-level and in climatic conditions may have had an additional significant control.

2) Variation in the complexity of the sediment transport routes from source to basin had a major control over the location of reservoir intervals. Thick sand successions were deposited along the inner basin margin, and mud in the basin centre during the early post-rift and late rift stages. In contrast, sands were transported to the basin centre during the late post-rift stage when the transport routes across the basin margin shelf were simple. The complexity in the sediment transport route varies according to the tectonic stage and is controlled by the relation between subsidence and sedimentation rate.

3) The receiving basin geometry and topography were major controls on the geometry and quality of the reservoirs. Thick, aggrading, localised sand-rich deposits dominate during the rift stage, while thinner, widely-distributed sheet-like sand- to mud-rich deposits dominate during the late post-rift stage. Basin geometry and topography changed between the tectonic stages and were controlled by the rift-extension rate and by the relationship between the subsidence and sedimentation rates. An understanding of these fundamental factors active during basin development is vital to facilitate robust prediction of deep-water reservoirs in the Norwegian Sea.

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References

Bjørnseth, H.M., Grant, S.M., Hansen, E.K., Hossack, J.R., Roberts, D.G. & Thompson, M. 1997: Structural evolution of the Møre Basin, during the Late Cretaceous and Paleocene. *Journal of the Geological Society of London 154*, 559-563.

Blystad, P., Brekke, H., Færseth, R.B., Larsen, B.T., Skogseid, J. & Tørudbakken, B. 1995: Structural elements of the Norwegian continental shelf. Part II: The Norwegian Sea Region. *Norwegian Petroleum Directorate Bulletin, 8.* 45 pp.

Brekke, H., Dahlgren, S., Nyland, B. & Magnus, C. 1999. The prospectivity of the Vøring and Møre basins on the Norwegian Sea continental margin. *In* Fleet, A.J. & Boldy, S.A. (eds.): *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference,* 41-61.

Brekke, H. 2000: The tectonic evolution of the Norwegian Sea Continental margin with emphasis on the Vøring and Møre Basins. *In* Nøttvedt, A. et al. (eds.): *Dynamics of the Norwegian Margin.* Geological Society of London Special Publication 167, 327-378.

Brekke, H., Sjulstad, H.I., Magnus, C. & Williams, R.W. 2001: Sedimentary environments offshore Norway - an overview. *In* Martinsen, O. J. & Dreyer, T. (eds.): *Sedimentary Environments Offshore Norway - Palaeozoic to Recent.* NPF Special Publication 10, 7-37.

Bukovics, C., Cartier, E.G., Shaw, N.D. & Ziegler, P.A. 1984: Structure and development of the mid-Norway Continental Margin. In Spencer, A.M. (ed.): *Petroleum Geology of the North European Margin.* Norwegian Petroleum Society, 407-423.

Dalland A., Worsely, D. & Ofstad K. 1988: A lithostratigraphic scheme for the Mesozoic and Cenozoic succession, offshore Mid- and Northern Norway. *Norwegian Petroleum Directorate Bulletin 4,* 1-65.

Doré, A.G., Lundin, E.R., Jensen, L.N., Birkeland, Ø., Eliassen, P.E. & Fichler, C. 1999: Principal tectonic events in the evolution of the northwest European Atlantic margin. *In* Fleet, A.J. & Boldy, S.A. (eds.): *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference,* 41-62.

Eldholm,O., Thiede, J. & Taylor, E. 1989: Evolution of the Vøring volcanic margin. In: Eldholm, Thiede, J. and Taylor, E. (eds.): *Proceedings of the Ocean Drilling Program, Scientific Results 104,* 1033-1065.

Fonneland, H.C., Lien T., Martinsen, O.J., Pedersen, R.B. & Ko_ler, J. 2004: Detrital zircon ages: a key to understanding the deposition of deep marine sandstones in the Norwegian Sea. *Sedimentary Geology 164,* 147-159.

Færseth, R. and Lien, T. 2002: Cretaceous evolution in the Norwegian Sea - a period of tectonic quiescence. *Marine and Petroleum Geology 19,* 1005-1027.

Gabrielsen, R.H., Odinsen, T. & Grunnaleite, I. 1999: Structuring of the Northern Viking Graben and the Møre Basin: the influence of basement structural grain, and the particular role of the Møre-Trøndelag Fault Complex. *Marine and Petroleum Geology 16,* 443-465.

Gernigon, L., Ringenbach, J.C., Planke, S., Le Gall, B. & Jonquet-Kolstø, H. 2003: Extension, crustal structure and magmatism at the outer Vøring Basin, Norwegian margin. *Journal of the Geological Society, London 160,* 197-208.

Gjelberg, J.G., Enoksen, T., Kjærnes, P., Mangerud, G., Martinsen, O.J., Roe, E. & Vågenes, E. 2001: The Maastrichtian and Danian depositional setting along the eastern margin of the Møre Basin (mid-Norwegian Shelf): implications for reservoir development of the Ormen Lange Field. *In* Martinsen, O.J. & Dreyer, T. (eds.): *Sedimentary Environments Offshore Norway – Palaeozoic to Recent.* NPF Special Publication 10, 421-440.

Kelly, S.R.A., Whitham, A.G., Koraini, A.M. & Price, S.R. 1998: Lithostratigraphy of the Cretaceous (Barremian-Santonian) Hold with Hope Group, NE Greenland. *Journal of the Geological Society, London 155,* 993-1008.

Kittelsen, J.E., Hollingsworth, R.R., Marten, R.F. & Hansen, E.K. 1999: The first deepwater well in Norway and its implications for the Cretaceous play, Vøring Basin. *In* Fleet, A.J. & Boldy, S.A. (eds.): *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference,* Geological Society, London, 275-280.

Larsen, M., Nedkvitne, T. & Olaussen, S. 2001: Lower Cretaceous (Barremian-Albian) deltaic and shallow marine sandstones in North-East Greenland - sedimentology, sequence stratigraphy and regional implications. *In* Martinsen, O.J. & Dreyer, T. (eds.): *Sedimentary Environments Offshore Norway – Palaeozoic to Recent.* NPF Special Publication 10. 259-278.

Lavwer, L.A., & Muller, R.D. 1994: Iceland hotspot track. Geology, 22, 311-314.

Lundin, E.R. & Doré, A.G. 1997: A tectonic model for the Norwegian passive margin with implications for the NE Atlantic: Early Cretaceous to break-up. *Journal of the Geological Society, London, 154,* 545- 550.

Lundin, E. & Doré, A.G. 2002: Mid-Cenozoic post-breakup deformation in the 'passive' margins bordering the Norwegian-Greenland Sea. *Marine and Petroleum Geology 19,* 79-93.

Martinsen, O.J., Bøen, F., Charnock, M.A., Mangerud, G. & Nøttvedt, A. 1999: Cenozoic development of the Norwegian margin 60-640N: sequences and sedimentary response to variable basin physiography and tectonic setting. *In* Fleet, A.J. & Boldy, S.A.R. (eds): *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference,* Geological Society, London, 293-304.

Martinsen, O.J., Lien, T. & Jackson, C. 2005: Cretaceous and Palaeogene turbidite systems in the North Sea and Norwegian Sea basins: source, staging area and basin physiography controls on reservoir development. *In* Dorè, A.G. & Vining, B.A. (eds): *Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference,* Geological Society, London, 1147-1164.

Mogensen, T.E., Nyby, R., Karpuz, R. & Haremo, P. 2000: Late Cretaceous and Tertiary structural evolution of the northeastern part of the Vøring Basin, Norwegian Sea. *In* Nøttvedt, A. et al. (eds.): *Dynamics of the Norwegian Margin.* Geological Society, London, Special Publication,167, 379-396.

Morton, A.C. & Grant, S. 1998: Cretaceous depositional systems in the Norwegian Sea: Heavy mineral constraints. *American Association of Petroleum Geologists 82,* 274-290.

Prather, B.E. 2003: Controls on reservoir distribution, architecture and stratigraphic trapping in slope settings. *Marine and Petroleum Geology 20,* 529-546.

Reading, H.G. & Richards, M. 1994: Turbidite Systems in Deep-Water Basin Margins Classified by Grain-Size and Feeder System. *American Association of Petroleum Geologists Bulletin 78,* 792-822.

Ren, S., Faleide, J.I., Eldholm, O., Skogseid, J. & Gradstein, F. 2003: Late Cretaceous – Paleocene tectonic development of the NW Vøring Basin. *Marine and Petroleum Geology 20,* 177-206.

Riis, F. 1996: Quantification of Cenozoic vertical movements of Scandinavia by correlation of morphological surfaces with offshore data. *Global and Planetary Change 12,* 331-357.

Roberts, D.G., Thompson, M., Mitchener, B., Hossack, J., Carmichael, S. & Bjørnseth, H. M. 1999: Palaeozoic to Tertiary rift and basin dynamics: mid-Norway to the Bay of Biscay- a new context for hydrocarbon prospectivity in deep water frontier. *In* Fleet, A.J. & Boldy, S.A. (eds.): *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference,* 7-40.

Skogseid, J., Planke, S., Faleide, J.I., Pedersen, T., Eldholm, O. & Neverdal, F. 2000: NE Atlantic continental rifting and volcanic margin formation. *In* Nøttvedt, A. et al. (eds.): *Dynamics of the Norwegian Margin.* Geological Society, London, Special Publication 167, 295-326.

Steffens, G.S., Biegert, E.K., Sumner, H.S. & Bird, D. 2003: Quantitative bathymetric analyses of selected deepwater siliciclastic margins: receiving basin configurations for deepwater fan systems. *Marine and Petroleum Geology 20,* 547-562.

Stuevold, L.M., Skogseid, J. & Eldholm, O. 1992: Post-Cretaceous uplift events on the Vøring continental margin. *Geology 20,* 919-922.

Swiecicki, T., Gibbs, G.E., Farrow, G.E. & Coward, M.P. 1997: A tectonostratigraphic framework for the Mid-Norway region. *Marine and Petroleum Geology 15,* 245-258.

Vergara, L., Wreglesworth, I., Trayfoot, M. & Richardsen, G. 2001: The distribution of Cretaceous and Paleocene deep-water reservoirs in the Norwegian Sea basins. *Petroleum Geoscience 7,* 395-408.

White, N., & Lovell, B. 1997: Measuring the pulse of a plume with the sedimentary record. *Nature 387,* 888-891.

Whitham, A.G., Price, S.P., Koraini, A.M. & Kelly, S.R.A. 1999: Cretaceous (post-Valanginian) sedimentation and rift events in NE Greenland. *In* Fleet, A.J. & Boldy, S.A. (eds.): *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference,* 325-336.