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Cretaceous evolution in the Norwegian Sea—a period characterized by tectonic quiescence

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Abstract

We interpret Cretaceous sedimentation in the Norwegian Sea, following the Jurassic rift episode and until the onset of Campanian rifting, to represent a post-rift thermal subsidence stage (ca. 140–80 Ma), i.e. a setting characterized by tectonic quiescence. This contrasts with previously published models, which emphasize the importance of tectonism in the Cretaceous evolution. The proposed model includes a significant tectonic relief and water depths in the Norwegian Sea, following Jurassic crustal stretching and associated tilting of major fault-blocks. Variation in sediment rate, type of sediment and thickness distribution, described to be indicative of Cretaceous tectonic events, are, in this paper, interpreted to reflect variations during infilling of the inherited Jurassic rift architecture, as well as responses to post-rift thermal subsidence, sediment loading and differential compaction during burial. The near perfect onlap of Cretaceous horizons along pre-existing fault scarps, later deformed by compaction, demonstrates the progressive post-rift sedimentary infill of deep-water basins by sedimentary bodies with a variety of depositional profiles. Cretaceous sediments in the Møre and Vøring Basins reached thickness (after compaction) of some 7–9 km, and this load produced a downward flexure of the lithosphere. Westward tilting of the Mid-Norway continental shelf area during the Cretaceous and onlap of post-rift sediments along basin margins, where the Cretaceous succession is relatively thin, demonstrate this. The infilling package of Lower Cretaceous sediments, which represents the immediate post-rift deposits, assume the wedge-shaped geometry of the remnant Jurassic rift topography and may display divergent reflector configurations induced by compaction. Early Cretaceous sedimentation rates, in major parts of the Norwegian Sea, are interpreted to be lower than the subsidence rate and accordingly Late Jurassic fault scarps remained significant features on the basin floor for a considerable time. The Early to Late Cretaceous transition saw a remarkable increase in sedimentation rate; the Cenomanian–Santonian rate was four-fold that of the average rate during the Early Cretaceous. The increased sediment supply outpaced subsidence and the topographic relief was levelled in the Santonian causing the different depocentres of Early Cretaceous time to merge into a wider depocentre. We interpret this as a mature stage of the post-rift development, when thermal equilibrium was obtained. The period of tectonic quiescence was terminated by a new rift episode, which was initiated in the Early Campanian and culminated with the final opening of the North Atlantic 55 Ma ago.
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Keywords: Cretaceous; Tectonics; Norwegian Sea

1. Introduction

Over the last decade, Cretaceous sediments have become increasingly important in exploration for hydrocarbons in the Norwegian Sea, offshore Mid-Norway (Fig. 1). Hence, understanding of how tectonic events have influenced sedimentation is vital for the prediction of reservoirs as well as the presence and maturation of source rocks in the area. The aim of this contribution is to explore the influence of tectonics on Cretaceous sedimentation in the Norwegian Sea as contrasting tectonic models have been published.

To study the post-Caledonian tectonic history of the Norwegian Sea, we should ideally be able to subdivide the sedimentary succession into a number of mega-sequences and to apply this subdivision in basin analysis as attempted by Reemst and Cloetingh (2000) and Walker, Berry, Bruce, Bystøl, and Snow (1997). Such mega-sequences should encompass sediments deposited during tectonic active periods (syn-tectonic sequences) and tectonic quiet periods (post-tectonic sequences). However, the only well established tectonic episodes in the Norwegian Sea for which syn- and post-tectonic sequences can be adequately resolved

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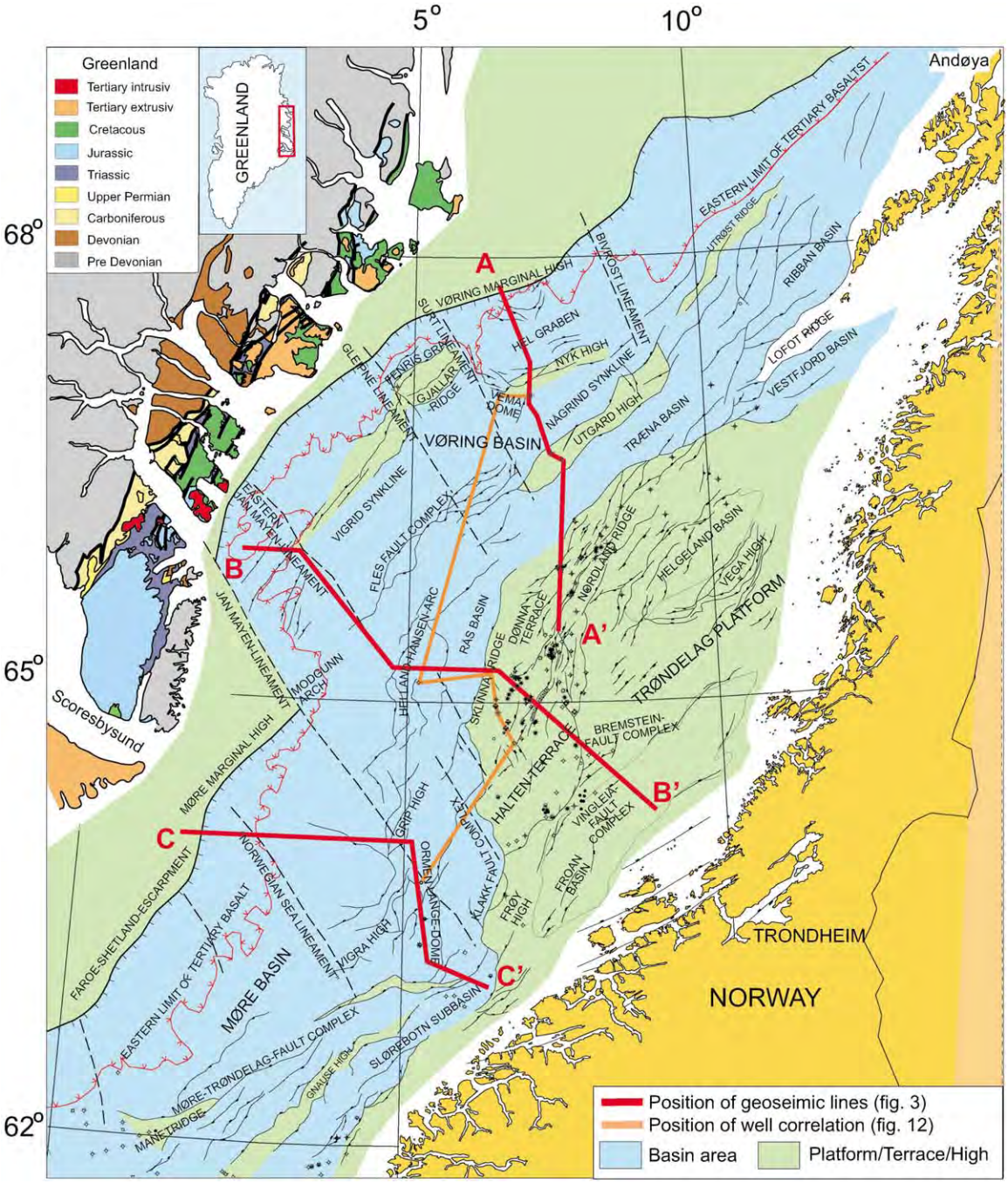

Fig. 1. Structural elements in the Norwegian Sea with the margin between 62°N and ca. 68°N, i.e. Bivrost Lineament representing the study area. A pre-drift reconstruction shows the position of East Greenland along the western margin of the Vøring and Møre Basins during the Cretaceous. The Island of Andøya, onshore Norway and associated with the Lofoten margin segment, is the only outcrop with Cretaceous sediments along the eastern basin margin.

on seismic, at least on platforms and terraces landward of the Vøring Basin (Fig. 1), are those related to the Jurassic and latest Cretaceous–Paleocene rift episodes (Fig. 2). To the west, beneath the Vøring and Møre Basins, Jurassic and older structures are difficult to identify due to the poor seismic data quality and the lack of wells penetrating deep into the Mesozoic sequence. Accordingly, there is a high degree of uncertainty with respect to the relative importance of post-Caledonian tectonic episodes (discussed in detail in Skogseid et al. (2000)).

The structural configuration of the Norwegian Sea continental margin between 62°N and ca. 68°N, i.e. Bivrost Lineament (Fig. 1), which represents the study area, is commonly interpreted to result from main rift episodes in the Early–Middle Devonian, Carboniferous, Late Permian–Early Triassic, Jurassic–earliest Cretaceous and latest Cretaceous–Paleocene (Blystad et al., 1995; Brekke, Sjulstad, Magnus, & Williams, 2001; Bukovics, Cartier, Shaw, & Ziegler, 1984; Doré et al., 1999; Gabrielsen, Odinsen, & Grunnaleite, 1999; Reemst & Cloetingh, 2000;

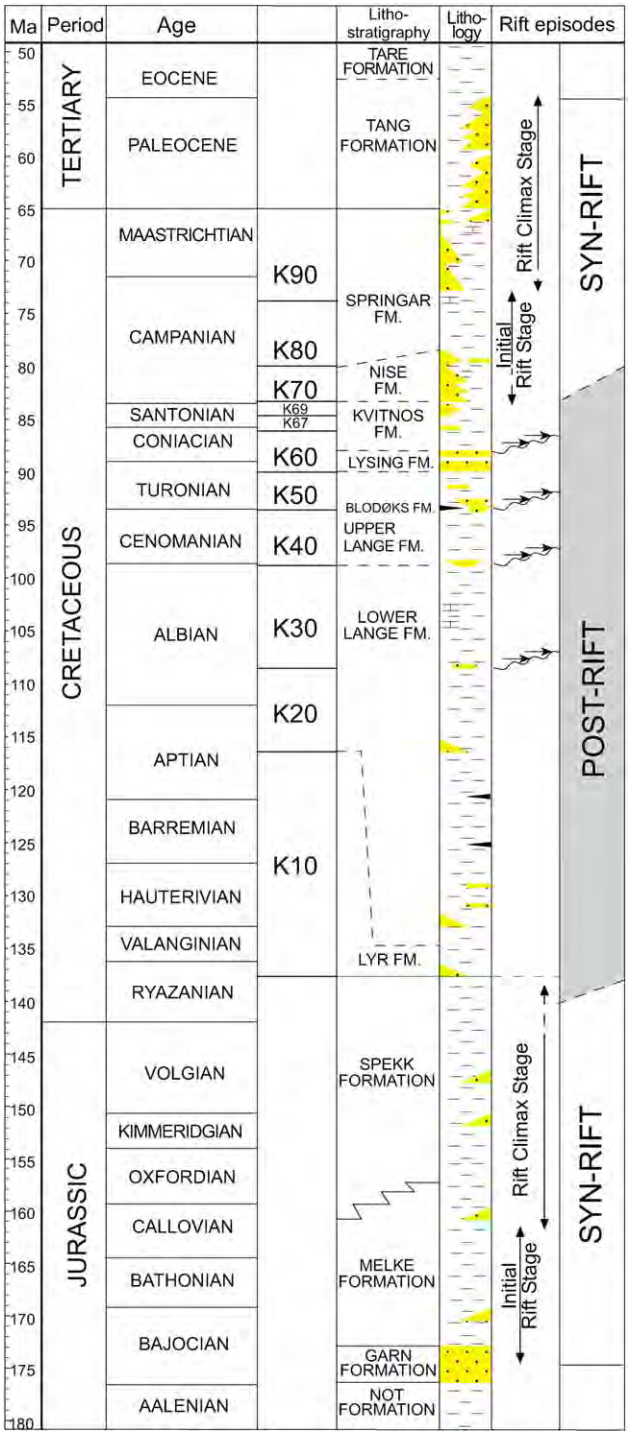

Fig. 2. Tectono-stratigraphic framework for the Norwegian Sea region.

Roberts et al., 1999; Ziegler, 1988). The Devonian to earliest Cretaceous extensional tectonics were related to continental rifting, whereas the last major rift episode in the latest Cretaceous to Paleocene represents a precursor to the final continental break-up and onset of sea-floor spreading in the North Atlantic.

An important Late Permian–Early Triassic rift episode is well established in the northern North Sea (Færseth, 1996; Roberts, Yielding, Kusznir, Walker, & Dorn-Lopez, 1995; Steel & Ryseth, 1990), and effects of this rift episode are also observed offshore Mid-Norway (Blystad et al., 1995; Brekke et al., 2001; Doré et al., 1999; Gabrielsen et al., 1999; Jongepier, Rui, & Grue, 1996; Schmidt, 1992). Jurassic rifting is documented over major parts of the North Atlantic domain, and in the Norwegian Sea structures related to Jurassic extension have been mapped on platforms and terraces which represent the eastern part of the study area (Blystad et al., 1995; Corfield, Sharp, Haeger, Dreyer, & Underhill, 2001).

In addition to major post-Caledonian rift episodes outlined above, several phases of tectonic activity have been invoked in the Cretaceous evolution of the Norwegian Sea (Bjørnseth et al., 1997; Blystad et al., 1995; Brekke, 2000; Brekke et al., 2001; Doré et al., 1999; Gabrielsen et al., 1999; Lundin & Doré, 1997; Roberts et al., 1999; Ziegler, 1988). Thickness variations across faults, wedge-shaped sedimentary bodies, influx of coarse clastics, onlap surfaces and the observation of the base Cretaceous reflection being offset by large faults have been regarded as indications of Cretaceous tectonic phases. We compare such observations described from the Norwegian Sea with analogues from other basins, to demonstrate that similar geometries and depositional profiles are reported from better known basins where the Cretaceous succession is included in the post-rift development (northern North Sea) (Bertram & Milton, 1989; Færseth et al., 1995; Gabrielsen, Kyrkjebø, Faleide, Fjeldskaar, & Kjennerud, 2001; Rattey & Hayward, 1993; Young, 1992). The intention of this paper is to demonstrate that features said to be indicative of Cretaceous tectonic phases can be explained without invoking tectonism, and that the time period between the Jurassic and the latest Cretaceous rift episodes was characterized by tectonic quiescence within the study area (Fig. 2).

2. Published models for the Cretaceous evolution in the Norwegian Sea

The Mesozoic structural evolution and the mechanisms behind postulated tectonic events in the Norwegian Sea are widely debated topics. Published models of this region, which discuss the Cretaceous tectonic evolution, can be grouped into four main categories:

- *Extension* to create an orthogonal fault pattern of N–S to NE–SW striking normal faults (Blystad et al., 1995; Brekke & Riis, 1987; Bukovics et al., 1984; Doré et al., 1999; Gabrielsen et al., 1999; Knott, Burchell, Jolly, & Fraser, 1993; Lundin & Doré, 1997; Schmidt, 1992; Swiecicki, Gibbs, Farrow, & Coward, 1998).
- *Dextral* and/or *sinistral strike-slip movements* associated with NE–SW striking basement grains (Caselli, 1987; Gabrielsen & Robinson, 1984; Larsen, 1987; Price & Rattey, 1984).

- *Compression* to give localized folding and reverse reactivation of normal faults (Bjørnseth et al., 1997; Brekke, 2000; Gabrielsen et al., 1999).
- *Salt tectonics* to create dome-shaped structural features and faults mainly on the Halten Terrace (Jackson & Hastings, 1984; Withjack, Meisling, & Russel, 1989).

Most workers attribute Cretaceous structures within the study area to periods of crustal stretching and associated normal faulting. The highest frequency of normal faults within Cretaceous sediments can be mapped on platforms and terraces, which occupy the eastern part of the study area (Fig. 1). These faults are generally interpreted to have formed by crustal extension. As discussed below, however, we relate a majority of these faults to the mobility of underlying Triassic (Ladinian–Karnian) evaporites, and accordingly they are not a result of deep-seated Cretaceous crustal extension.

Several authors have postulated strike-slip movements along specific lineaments during the Cretaceous. Caselli (1987) described the total regional Late Jurassic to Cretaceous evolution offshore Mid-Norway to result from large-scale and deep-seated dextral strike-slip movements. Within the suggested structural setting, Caselli (1987) interpreted the Halten Terrace as a pull-apart basin associated with a releasing bend. However, in the Halten Terrace area, so-called flower/inversion structures (Caselli, 1987) have been interpreted as salt related features (Jackson & Hastings, 1984), and based on our mapping there are no restraining/releasing bend features along faults at high angle to the postulated strike-slip movements. Accordingly evidence of large-scale horizontal displacement in the structural evolution offshore Mid-Norway is not compelling.

A characteristic feature of the study area are major domes (Fig. 1) related to Tertiary compression (Doré & Lundin, 1996; Vågnes, Gabrielsen, & Haremo, 1998), which also resulted in significant Tertiary reverse reactivation of Mesozoic normal faults. Localized folding and reverse reactivation of faults at Cretaceous levels are interpreted as indicators of Late Cretaceous compressional tectonics in the Norwegian Sea (Bjørnseth et al., 1997; Brekke, 2000; Gabrielsen et al., 1999). The structures are generally expressed as monoclines associated with major normal faults, and can alternatively be interpreted as forced folds or fault-propagation folds related to the geometry of basement-involved faults (Corfield et al., 2001; Withjack et al., 1989).

In the contrasting models for the Cretaceous structural evolution of the Norwegian Sea, a number of tectonic phases are interpreted to have affected the area (Bjørnseth et al., 1997; Blystad et al., 1995; Brekke, 2000; Brekke, Dahlgren, Nyland, & Magnus, 1999; Brekke et al., 2001; Bugge, Tveiten, & Baeckstrøm, 2001; Caselli, 1987; Doré et al., 1999; Gabrielsen et al., 1999; Grønlie & Torsvik, 1989; Lundin & Doré, 1997; Pascoe, Hooper, Storhaug, & Harper, 1999; Price & Rattey, 1984; Skogseid et al., 2000). The large number of tectonic phases invoked, which spans most of the Cretaceous period, is partly a result of the lack of precision regarding timing of structural movements, especially to the west where well data are scarce and only available recently.

Lundin and Doré (1997) and Doré et al. (1999), argue that between the Jurassic and latest Cretaceous rift episodes (Fig. 2), deformation in the Norwegian Sea resulted primarily from two extensional events; the first in the Early Cretaceous (Neocomian) and the second in the mid-Cretaceous. As a result, a complex network of Jurassic and older basins was overprinted by a continuous chain of deep basins due to the northeastward propagation of Cretaceous rifting through the Rockall Trough, west Shetland/Fareoe Trough, central Møre Basin, eastern Vøring Basin, through the outboard of the Lofoten margin to the SW Barents Sea. Also Roberts et al. (1999) describe the tectono-stratigraphic evolution of the Norwegian Sea in terms of rift propagation. However, their model is based on merging of a southward propagating 'Arctic' rift and a northward propagating 'Atlantic' rift. The northward propagation of the Atlantic rift into the Bay of Biscay, the Rockall Trough and Faeroe Basin–Shetland Basin–Møre Basin completed the linkage to the Arctic rift in the Late Jurassic or earliest Cretaceous. Skogseid et al. (2000) proposed that the Rockall Trough became a failed rift in the Cretaceous, when sea-floor spreading progressed northward into the Labrador Sea. Hence, whereas Jurassic rifts most likely extend from the Rockall Trough, through the Shetland/Fareoe Trough, central Møre Basin, Vøring Basin to the SW Barents Sea, Cretaceous rifting may have been less influential in the Møre and Vøring Basins compared to areas further southwest.

Structures interpreted to result from Early Cretaceous tectonism are reported from basins located both southwest and northeast of the study area; to the southwest in the northwesternmost North Sea (Rattey & Hayward, 1993), the Faeroe–Shetland Trough (Dean, McLachlan, & Chambers, 1999) and to the northeast, west of Lofoten (Fig. 1) (Tsikalas, Faleide, & Eldholm, 2001) and in the Barents Sea (Faleide, Vågnes, & Gudlaugsson, 1993). Hence, these observations are compatible with Early Cretaceous extension focused on the present Atlantic margin. Observations favouring Cretaceous rifting along the margin have been assembled by Lundin and Doré (1997), and they state that evidence of Early Cretaceous faulting has not been reported in the Vøring and Møre Basins, which these authors attribute to poor seismic imaging due to the thick basin fill.

The thinning of crystalline crust, reaching a maximum beneath the central Møre Basin (Gabrielsen et al., 1999; Olafsson, Sundvor, Eldholm, & Grue, 1992; Skogseid et al., 2000), in combination with a NE–SW row of positive magnetic anomalies along the axis of thinning interpreted as a possible chain of seamounts of mafic composition (Lundin & Doré, 1997; Lundin & Rundhovde, 1993), were regarded

as indications of Early Cretaceous rifting in this basin (Doré et al., 1999). Alternatively, the anomalies represent highly magnetic basement blocks (Lundin & Doré, 1997), or these features as well as the crustal thinning are related to pre-Cretaceous rift episodes, interpreted to have affected the Møre Basin (Gabrielsen et al., 1999 and references therein). In summary, these observations do not represent compelling evidence of Early Cretaceous rifting in the Møre Basin, and it remains open to question whether a major Early Cretaceous extensional event is consistently identified along the margin to result in a continuous chain of Cretaceous rift basins, or if the Møre and Vøring Basins are areas which exhibit very modest and localized effects of Early Cretaceous tectonism as argued in this contribution.

3. Basin architecture and depositional geometries in the Cretaceous succession

The Cretaceous sedimentary succession in the Norwegian Sea outlines the large and overall saucer-shaped Møre and Vøring Basins (Fig. 1). Fig. 3 shows regional geoseismic profiles from platforms and terraces with condensed Cretaceous sequences to the east, across the Møre and Vøring Basins with the expanded Cretaceous sequences to the marginal highs to the west. Several wells have been drilled in the deep basins over the last years and have been evaluated in detail in this study, with respect to biostratigraphy and sedimentology and further used to support the seismic interpretation. The examples provided as figures are representative of Norsk Hydro's interpretation of available two- and three-dimensional surveys in the study area. The base of the Cretaceous which represents a key surface for structural analysis remains undrilled in the Vøring Basin, and alternative interpretations for this surface have been presented (Blystad et al., 1995; Brekke, 2000; Doré et al., 1999; Reemst & Cloetingh, 2000; Skogseid & Eldholm, 1989; Skogseid et al., 2000; Swieciki et al., 1998). Although there are uncertainties in the interpretation presented in our regional profiles (Fig. 3), the seismic horizons reveal the present geometry of post-Jurassic basins.

We interpret the shape of the base Cretaceous horizon beneath the Vøring and Møre Basins, to reflect underlying Jurassic fault-blocks similar to the terraces to the east (Fig. 3), although significantly modified by Tertiary compression especially in the Vøring Basin. Northeast of the study area, along the Lofoten segment of the margin (Fig. 1) where Cretaceous basins are shallow compared with the Vøring Basin; rotated fault-blocks bounded by basement-involved faults represent the typical expression of Jurassic rifting (Blystad et al., 1995; Tsikalas et al., 2001). Along the southeastern margin of the Møre Basin (ca. 63°N), a normal fault with a vertical offset of some 5–6 km at Jurassic levels separates the Slørebotn Subbasin (Fig. 1) from a narrow platform to the east. This basin margin fault has listric geometry with an intra-basement detachment to the west. A rotated Jurassic fault-block ca. 40 km wide, with crystalline basement capped by Middle Jurassic sediments on the crest, has been mapped below the Slørebotn Subbasin. Core data and the dipmeter log from well 6205/3-1R, which penetrated Cretaceous–Jurassic sediments in the immediate hangingwall of the fault, reveal a continued rotation of the hangingwall during Jurassic rifting and deposition of the syn-rift succession (Jongepier et al., 1996). Tilting was very gentle during a Bathonian–Oxfordian stage of rifting, but accelerated during the Kimmeridgian–Volgian rift climax stage to give a maximum tilt at the base of the syn-rift succession of ca. 50°. The latest Volgian–Early Cretaceous sediments, which onlap the tilted strata in the hangingwall, were deposited close to horizontal and represent passive infill of the relief created during Jurassic rifting (Jongepier et al., 1996).

In rift basins consisting of an array of rotated fault-blocks (half-grabens), these fault-blocks tend to have a decreasing basin floor elevation toward the rift axis (Nøttvedt, Gabrielsen, & Steel, 1995; Ravnås & Steel, 1998), as a result of background subsidence of the thinned crust (McKenzie, 1978). There is also a general trend in marine rift basins of a gradual increase in water depths as rifting progresses, reaching a peak during the rift climax stage, due to increased fault slip rates as extension localizes onto the major faults which outline the subbasins (Cowie, Gupta, & Dawers, 2000; Færseth, 1996; Færseth, Knudsen, Liljedahl, Midbøe, & Søderstrøm, 1997; Ravnås & Steel, 1998). From our observations, the initial Jurassic stretching affected a terrain that was close to or below sea level, in the eastern part of the study area, i.e. relatively near the margin of the rift basin (Fig. 1). Based on the considerations above, basin floor elevation is interpreted to be lower to the west and footwalls related to Jurassic rifting may have been completely submerged within the Møre and Vøring Basins, i.e. areas which we regard to have undergone maximum Jurassic extension (Skogseid et al., 2000). Consequently, rift-interior half-grabens which were located a considerable distance from the rift-margin hinterland, largely below deep waters and with the lack of rift-interior sources, are likely to be characterized by sediment-starved syn-rift successions. As argued below, we infer that there was maximum water depths of the order of kilometres in the Norwegian Sea following Jurassic crustal stretching and tilting of major fault-blocks. Hence, Jurassic syn-rift successions are likely to occupy a minor part of the half-grabens, and there was still significant relief and water depths at the Jurassic–Cretaceous transition. The near perfect onlap of the Cretaceous horizons, along pre-existing fault scarps, later deformed by compaction, is indicative of progressive sedimentary infill of a deep-water subbasins rather than a balance between sedimentation at constant base level and syn-depositional faulting along basin margins.

The type of sediment that will accumulate in any given basin is difficult to predict given the complexity of controls

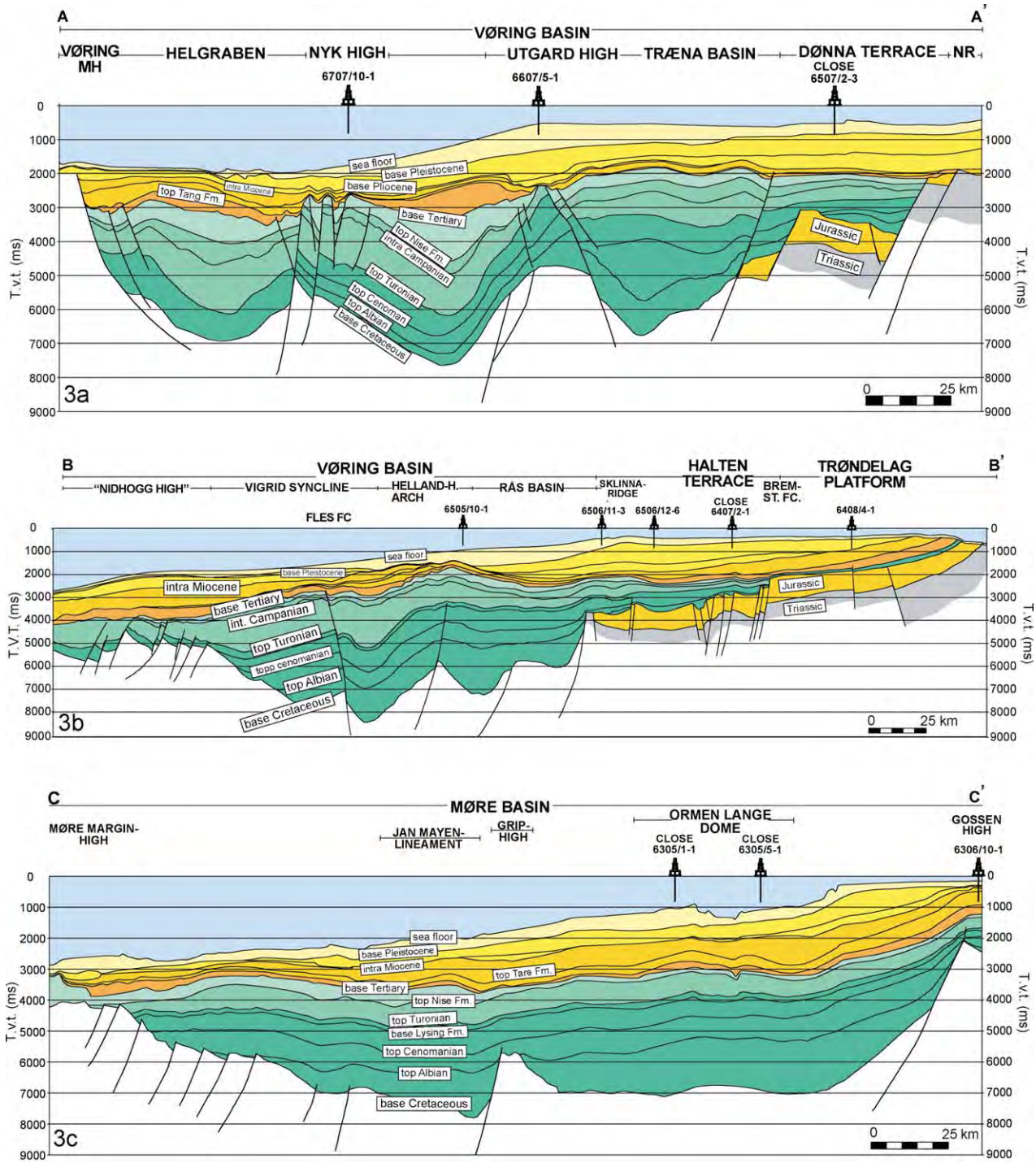

Fig. 3. Regional geoseismic profiles from structural highs with condensed Cretaceous sequences in the east, across the Vøring and Møre Basins with the expanded Cretaceous sequences to the marginal highs to the west. All wells drilled in the basins have been used to confirm the interpretation presented. The lowermost reflection in the deep basins is interpreted as a near base Cretaceous surface. The relief at this level is interpreted to reflect underlying Jurassic fault-blocks, although significantly modified by Tertiary compression. The load imposed by post-Jurassic sediments in the deep basins, produced a downward flexure of the lithosphere as demonstrated by the westward tilting of the Mid-Norway continental shelf area. See Fig. 1 for location of profiles.

on deposition, as summarized by Ravnås and Steel (1998). In this section we introduce factors, which we regard to be important with respect to sediment accumulation and depositional geometries in the Cretaceous succession. A characteristic feature of the Møre and Vøring Basins is the variation in sedimentation rate. Fig. 4 shows the cumulative Cretaceous sediment thickness (compacted) from key wells in the study area. To the west, where no wells have penetrated into Lower Cretaceous sediments, postulated and depth converted thicknesses from

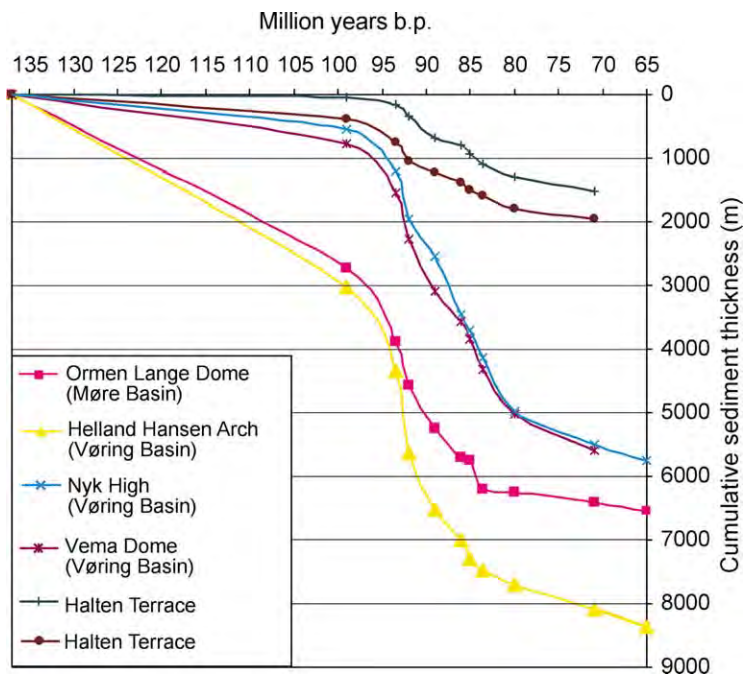

Fig. 4. Cumulative Cretaceous sediment thickness (compacted) from key wells in the study area. Postulated thickness from the seismic have been applied below terminations of the wells; 6305/1-1, 6505/10-1, 6707/10-1 and 6706/11-1. The Early to Late Cretaceous transition saw a remarkable increase in sediment accumulation rate reaching a maximum in the Cenomanian–Early Turonian.

the seismic have been applied. During the 35 million years from the Valanginian to the Albian, sediments accumulated very slowly. The present thickness of these compacted sediments indicates an average accumulation rate of 5 cm per 1000 years, but for specific intervals and areas (Rås Basin, Hel Graben, Någrind and Vigrid synclines) it was as low as 1.5 cm per 1000 years. In the following 20 million years (Cenomanian–Early Campanian), the average accumulation rate was 22 cm per 1000 years, i.e. on average a four-fold increase, but locally reaching a fifteen-fold increase. Sedimentation rate, facies and depositional systems are variably depending on a number of factors such as distance and connection to a hinterland with a sediment source, regional subsidence rates, climate, sediment source rock composition and position relative to sea level (Doglioni, Agostino, & Mariotti, 1998; Prosser, 1993; Ravnås & Steel, 1998). We interpret the mappable sedimentary units as well as the change in sedimentation pattern in terms of the interplay of factors mentioned above.

The Dønna and Halten terraces represented the eastern margin of the Vøring Basin proper during the Jurassic rifting (Figs. 1 and 3(a),(b)). The typical morphological expression of Jurassic extension in this part of the study area is tilted fault-blocks (Fig. 5), and as argued above we interpret the relief at base Cretaceous level further west (Fig. 3) to reflect the influence of similar Jurassic fault-blocks. Fig. 6 is an idealized section to illustrate the seismic expression of post-rift sedimentary infilling of half-grabens related to the Jurassic rifting. This conceptual section shows depositional geometries and features, which we propose to be typical of the Cretaceous sedimentary succession in the total study area. The Jurassic syn-rift sequence represents only a minor constituent of the half-graben fill, which is found to be typical of syn-rift sequences in many cases (Færseth & Ravnås, 1998; Mutter & Larsen, 1989; Prosser, 1993; Ravnås & Steel, 1998). The major part of the sediments, which constitutes the half-graben fill, represents the post-rift stage of basin evolution. The infilling package of the immediate post-rift sediments will assume the wedge-shaped geometry of the remnant rift topography. Ignoring the importance of this remnant topography in the creation of overall wedge-shaped geometries and the possibility of divergent reflector configurations induced by compaction, can lead to over-estimations of the duration of active faulting. This gives a different perspective on which characteristics are those distinctly associated with fault-controlled seismic sequences and are naturally important with respect to duration and timing of rifting (Prosser, 1993).

Cretaceous successions, which represent the infill of the interpreted base Cretaceous topography, show intervals with uniform thickness as well as intervals that are wedge-shaped. At the base or within wedge-shaped bodies, surfaces showing onlap towards fault block crests as well as fault scarps have been identified (Figs. 5–7):

Wedge-shaped successions. Wedge-shaped sedimentary bodies are generally restricted to the Lower Cretaceous succession (Figs. 3 and 7). Based on wells drilled on Jurassic fault-blocks to the east, Jurassic syn-rift successions

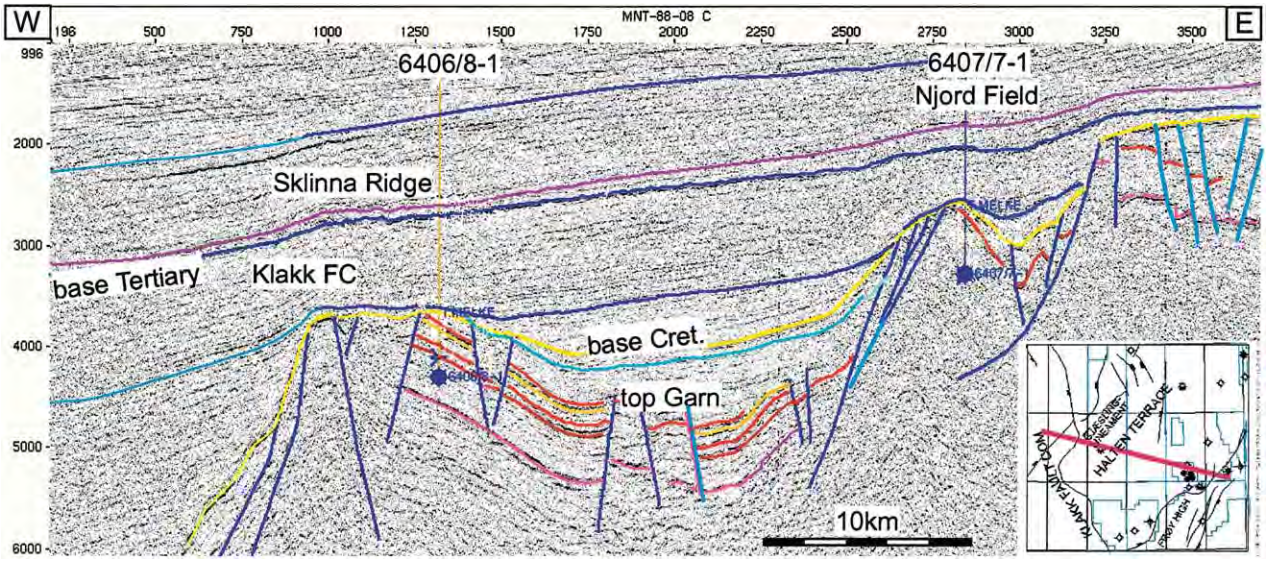

Fig. 5. Large tilted fault-blocks represent the main topographic expression following Jurassic rifting. The seismic section illustrates one of the Jurassic fault-block, the southern Halten Terrace in the eastern part of the study area. Cretaceous sediments have infilled the inherited topography and onlap the fault scarp. The loading of Cretaceous post-rift sediments to the west resulted in a westerly tilting of the Mid-Norway continental shelf area.

are typically shale-dominated and exhibit an increasing thickness down the dip slope of tilted fault-blocks (Figs. 5 and 6). As Cretaceous sediments were added to the basin fill, maximum thickness were deposited in the immediate hangingwall of the main fault and the continued compaction made room for additional sediments. As maximum accommodation space is available in down dip position, Cretaceous sediments infilling this space will be deposited with an increased thickness down dip to obtain a wedge-shape, and such units may display divergent reflections towards the major fault (Figs. 6 and 7).

Successions with uniform thickness. Regionally mappable units occur as intervals with a relatively uniform thickness within the Cenomanian–Santonian succession (Fig. 3) and are characterized by parallel reflections. We interpret this depositional pattern to reflect the infilling

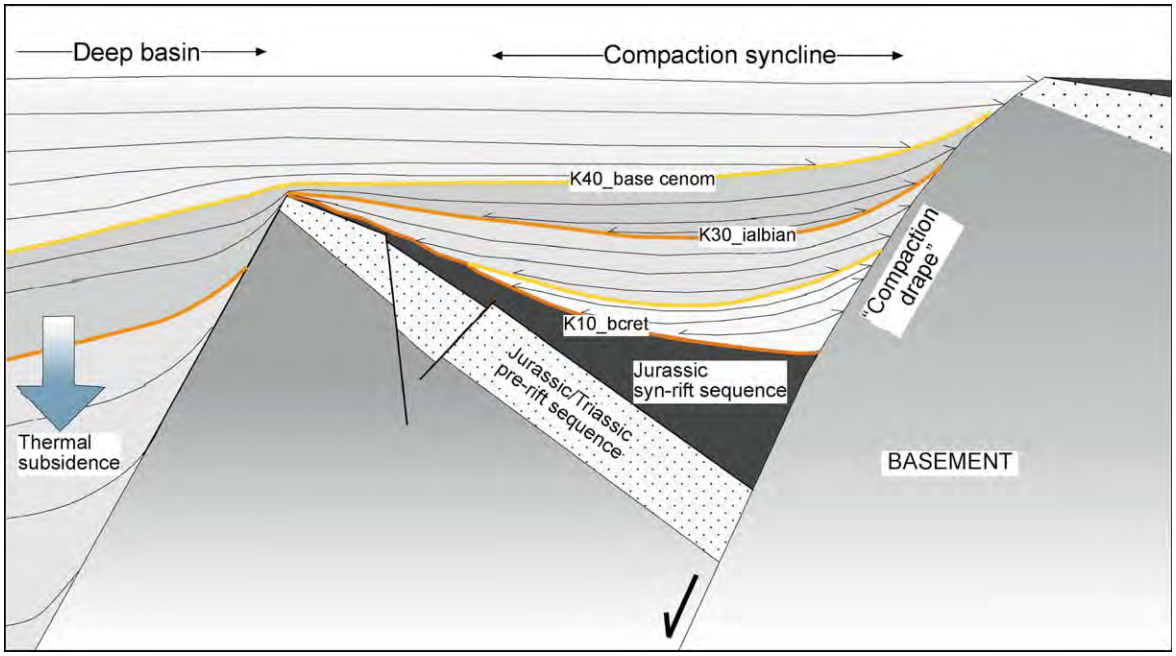

Fig. 6. Idealized section to illustrate the infill of a half-graben. The Jurassic syn-rift sequence represents only a minor constituent of the half-graben fill. Cretaceous depositional geometries and onlap patterns are interpreted to reflect the post-rift infilling of deep-water hangingwall subbasins following Jurassic extension and faulting. This conceptual section explains features typical of the Cretaceous sedimentary succession in the Norwegian Sea in terms of inherited relief, differential compaction during burial and varying supply of sediments.

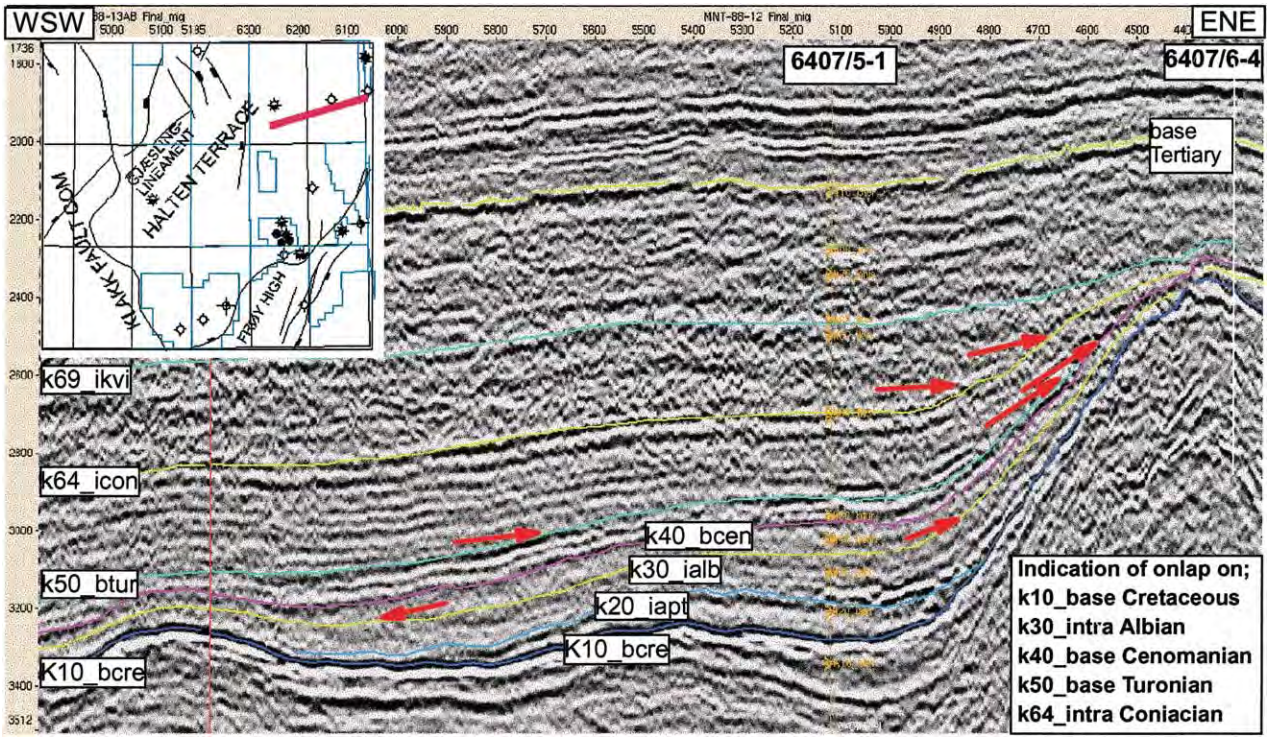

Fig. 7. Jurassic faulting resulted in a significant relief between the Trøndelag Platform and the Halten Terrace. The Cretaceous sediments which infilled the topography, onlap the pre-existing fault scarp and were subsequently deformed by compaction. Due to the continued compaction of clay-dominated sediments in the hangingwall, the fault plane continued to grow up through the overlying sediments subsequent to the deposition. This type of faulting, driven by compaction, can be very long-lived and is not an indication of crustal extension.

of earlier rift topography during periods which were characterized by relatively high sedimentation rate (Fig. 4). According to Prosser (1993), a late post-rift infill will be imaged on seismic reflection profiles as parallel reflectors that are of a more continuous nature than the early post-rift succession.

Onlap surfaces. Onlap surfaces are well displayed on the dip slope of individual half-grabens and also in the immediate hangingwall of major Jurassic faults, due to Cretaceous infilling of the remnant Jurassic rift topography (Figs. 6 and 7). We interpret the mapped onlap surfaces to represent time-periods characterized by sediment starvation and drape, dominantly by hemipelagic mudstones. During periods of minimum sedimentation rate, the available sediments in the sub-basins became subject to differential compaction, which created a topographic depression on the hangingwall floor close to major faults (Figs. 6 and 7). During a new period with increased sedimentation rate, sedimentary gravity flows entering the basin will follow and be deposited within such depressions and will onlap margins of the compactional syncline. The lateral boundary between submarine fans and pelagic draping sediments is generally hard to resolve seismically. Although seismic reflections may be seen to onlap a dipping seismic sequence boundary (Fig. 7), the time-equivalent section may still be resolved high on the dip slope if wells are available to give precise and detailed biostratigraphy.

4. Cretaceous evolution in the Norwegian Sea

The termination of the Jurassic rifting, with a transition to the thermal subsidence stage, appears to be in the latest Jurassic (intra-Volgian) as thin Late Volgian mud locally drape some of the eroded highs offshore Mid-Norway (Jongepier et al., 1996), which is also consistent with observations in the northern North Sea (Færseth et al., 1995; Rattey & Hayward, 1993). However, several authors have suggested tectonic models with greater emphasis on Cretaceous tectonism to the west (Doré et al., 1999 and references therein). Our interpretation is that during the Early Cretaceous the subsidence rate outpaced the sedimentation, at least in the distal parts of the Early Cretaceous deposystem, as the thermal subsidence has the highest rate during the first tens of million years and decreases asymptotically with time (McKenzie, 1978). Consequently, Late Jurassic fault scarps remained significant morphological escarpments on the basin floor and influenced sedimentation for a considerable time after the cessation of rifting. In the Late Cretaceous, increased sediment supply outpaced

the subsidence rate, and from seismic interpretation and well data, it appears that the topographic relief was levelled in the Santonian (Fig. 3).

4.1. Early Cretaceous evolution

The Early Cretaceous is here interpreted to involve amalgamation of subbasins, initially represented by large tilted Jurassic fault-blocks, and the smoothing of basin floors (Fig. 3). The pronounced thickness variation of Lower Cretaceous sediments, wedge-shaped sedimentary bodies and the observation that the base Cretaceous reflection is offset by large faults have been regarded as evidence of Early Cretaceous tectonism (Lundin & Doré, 1997 and references therein). Similar observations from the better known North Sea basin which borders the Møre Basin to the south (Gabrielsen et al., 2001; Figs. 6(a)–(c)) have, however, over the last decade been regarded as representative of a thermal subsidence stage with the infilling of a pronounced Jurassic rift topography (Bertram & Milton, 1989; Færseth et al., 1995; Gabrielsen et al., 2001; Rattey & Hayward, 1993; Young, 1992). Interpreting fault movement from thickness variations is difficult without prior knowledge of the paleobathymetry, and it is impossible to distinguish between syn-sedimentary fault movement and onlap to a pre-existing fault scarp from thickness variations alone (Bertram & Milton, 1989; Doglioni et al., 1998; Prosser, 1993).

The regional profiles across the Møre and Vøring Basins exhibit few major faults in the Cretaceous sediments (Fig. 3). Based on our interpretation, major faults affecting Cretaceous sediments in these basins can be attributed to the Campanian–Paleocene extensional episode as they generally display the same amount of offset from top Cretaceous and downwards (Fig. 3(a) and (b)). Faults which affect Cretaceous sediments are most frequent landward of the Vøring Basin, where Cretaceous sediments are relatively thin. Most of these faults are located within flexures/monoclines at Cretaceous levels, which represent the transition zones between regional-scale structural elements (Fig. 3). Within the transition zone between the Halten Terrace and the Trøndelag Platform, Triassic (Ladinian–Karnian) evaporites acted as a detachment between basement-involved faults of the Bremstein Fault Complex below the evaporites, and faults at a higher level which influenced Jurassic–Cretaceous sediments (Fig. 8 and 9). The faulting

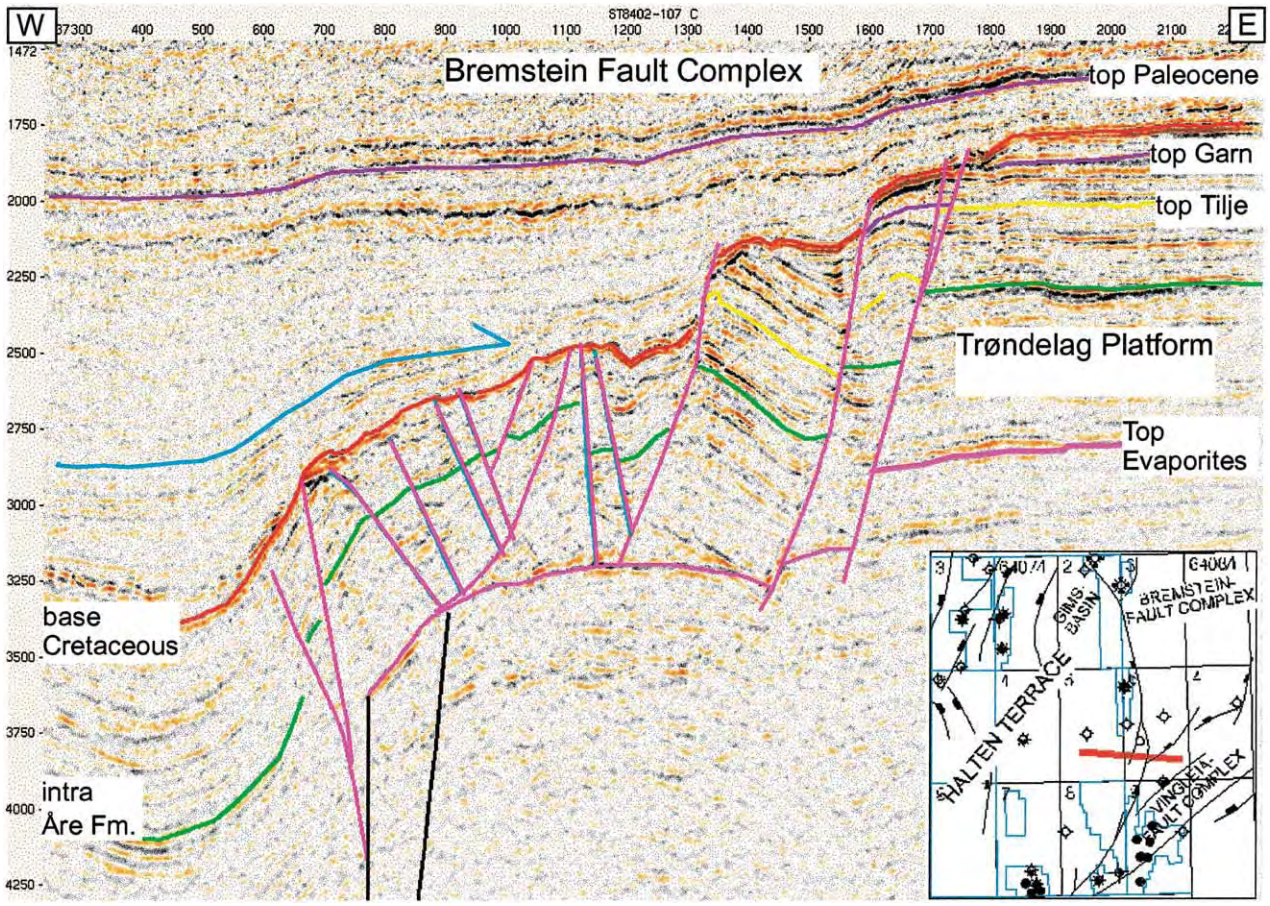

Fig. 8. Several onlap surfaces are associated with the transition zone between the Halten Terrace and the Trøndelag Platform. Along this particular zone, the Triassic evaporites acted as a detachment between basement-involved faults of the Bremstein Fault Complex below the salt and faults affecting the Jurassic–Cretaceous sediments. The lateral flow of Triassic salt contributes to the broad, asymmetric flexure, which became onlaped by Cretaceous sediments.

is interpreted to result from the lateral flow of the evaporites within this zone, which contributes to the broad asymmetric flexure with normal as well as reverse faults within sediments above the evaporites.

Normal faults with moderate throws, indicating earliest Cretaceous tectonic activity are observed on the Halten Terrace. Such faults are generally characterized by hangingwall syn-rift growth wedges, which display divergent internal reflections (Fig. 10). As these wedges are located directly above the base Cretaceous surface, we interpret that they represent localized effects of earliest Cretaceous extension. However, most of the faults on the Halten Terrace, which affect Early Cretaceous sediments, can be explained without invoking crustal stretching. In the northern part of the terrace, Early Cretaceous normal faults, which outline narrow grabens (Fig. 11), result from the withdrawal of the underlying Triassic evaporites with associated faulting in the overlying sediments. The westerly tilt of the Halten Terrace (Fig. 3(b)) related to subsidence in the Vøring Basin, apparently triggered some translation to the west and southwest of the post-salt sediments to result in initial rafting and associated normal faulting in Lower Cretaceous sediments especially in the northwestern part of the terrace area (Kristensen, 2002).

Early Cretaceous onlap surfaces typically occur in association with flexures/monoclines, which represent the transition zones between platforms, terraces and deep basins. The onlap surfaces are mapped towards the steep limb of the monoclines (Figs. 7 and 8), i.e. areas most likely to be influenced by effects of differential compaction, sediment loading and the regional tilting to the west due to lithospheric load. Hence, although several onlap surfaces have been identified in the eastern part of the study area, such observations do not represent evidence of associated tectonic phases.

4.2. Cenomanian–Santonian evolution

Published accounts give the overall impression that effects of tectonism became more pronounced in the Late Cretaceous as compared to the Early Cretaceous, and that renewed tectonic activity affected the deep basins from the earliest Cenomanian (Bjørnseth et al., 1997; Brekke, 2000; Brekke et al., 2001; Doré et al., 1999; Gabrielsen et al., 1999; Lundin and Doré, 1997). Doré et al., 1999 argue that an extensional event affected the Norwegian Sea, either as a separate mid-Cretaceous event or as a long-duration Late Cretaceous tectonic event. However, as stated by Skogseid et al. (2000) and concluded in this study, no distinct rift structures or basins of this age are identified within the study area.

The Cenomanian–Santonian is generally a shale- and siltstone-dominated sequence (Fig. 12) and only relatively

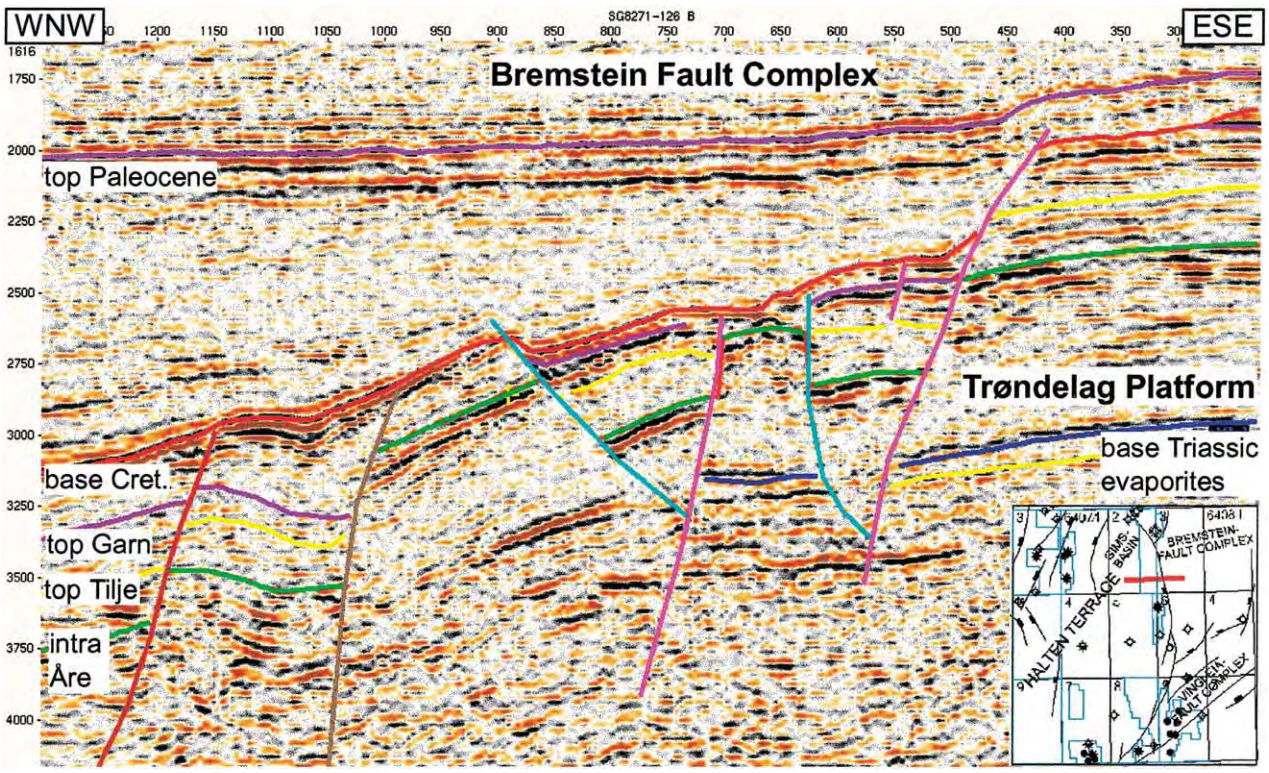

Fig. 9. During the Cretaceous the morphological steps created due to Jurassic extension and normal faulting were infilled by sediments. In the seismic section, the Cretaceous succession exhibits reflections, which converge to the ESE, i.e. towards the fault plane, and is not indicative of crustal extension. The faulting of Cretaceous sediments is interpreted to be driven by compaction, and due to the continued compaction of clay-dominated sediments in the hangingwall, the fault plane continued to grow up through the overlying sediments subsequent to the deposition.

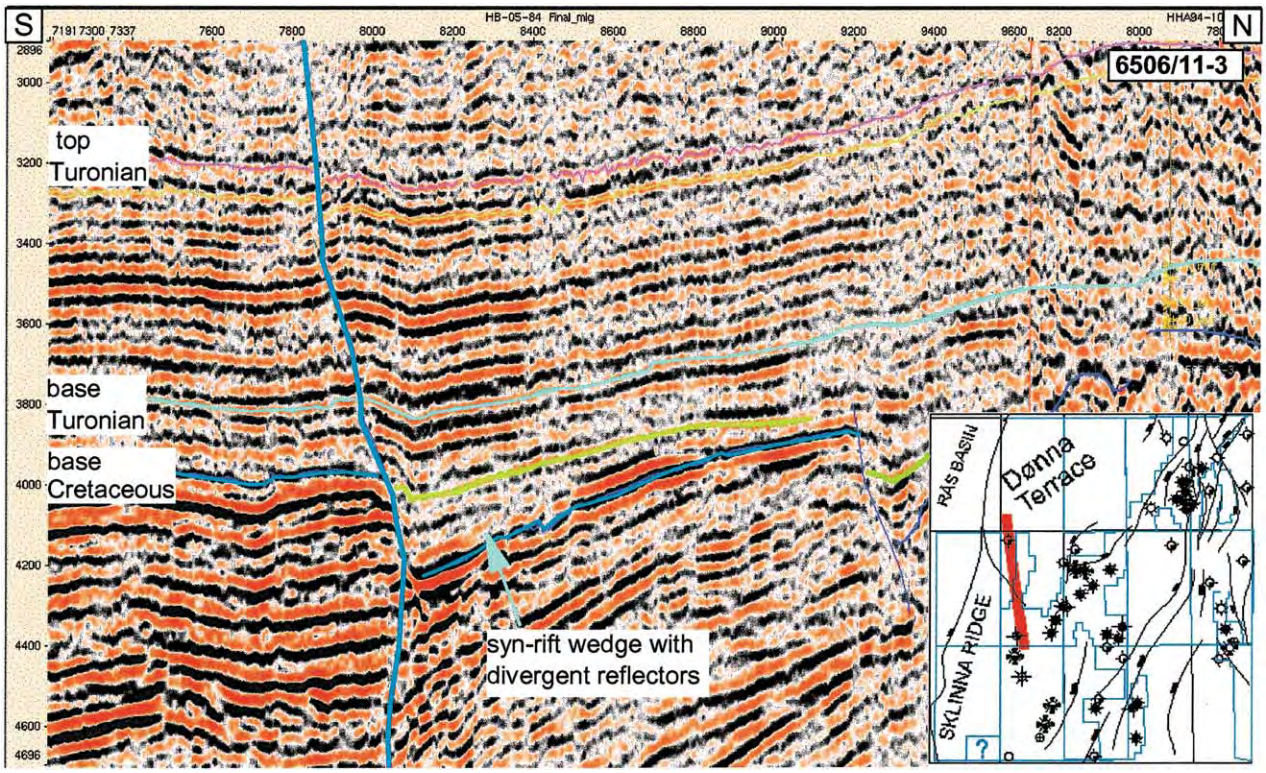

Fig. 10. The seismic section shows a normal fault with moderate throw on the Halten Terrace. The fault exhibits a hangingwall syn-rift growth wedge with divergent internal reflections. As the wedge is located directly above the base Cretaceous surface, it is interpreted to result from localized earliest Cretaceous extension and reactivation of a Jurassic fault.

thin sandstone units have been recorded in wells penetrating this interval. From seismic (Fig. 3) and wells (Fig. 4) an increased sedimentation rate in the Vøring and Møre Basins has been demonstrated. With respect to the increased influx of sediments into the western Vøring Basin, it is noteworthy that on NE Greenland, which at this stage of development was located in the proximity of the western margin of the Vøring Basin (Fig. 1), fault activity is said to have ceased following a Middle Albian extensional phase (Whitham, Price, Koraini, & Kelly, 1999), i.e. increased sedimentation rate was associated with a tectonically quiet period. On East Greenland, the Early Cretaceous was a period of extensive erosion and reworking of Middle–Upper Jurassic sandstones and the erosional products were transported and deposited in the north–south oriented and fault-bounded Jurassic rift basins (Larsen, Nedkvitne, & Olaussen, 2001). It was probably not until the middle Albian–Turonian that the Jurassic onshore rift topography was peneplaned, opening for transverse sediment transport across the Greenland shelf and the increased influx of sediment into basinal areas to the east (Whitham et al., 1999).

As for the Early Cretaceous, the Mid-Norway continental shelf area was subject to westward tilting during the Late Cretaceous (Figs. 3 and 5), which resulted in thinning and onlap of sequences to the east (Figs. 7–9). Whereas the Lower Cretaceous sediments exhibit a dramatic basinward increase in thickness due to the differential relief at the interpreted base Cretaceous level, the Upper Cretaceous succession shows an overall continuous increase in thickness towards the basin axis (Fig. 3). Hence, through the Cenomanian–Santonian the different depocentres of Early Cretaceous time, including the Halten and Dønna terraces merged into a wider depocentre. We interpret this as a mature stage of the post-rift development, when thermal equilibrium was obtained. From seismic interpretation and well data, an easily correlatable and silty Santonian interval with a uniform thickness of ca. 300 m extends across the Norwegian Sea from the western Vøring Basin to Møre Basin and onto the Halten Terrace (Fig. 12). This implies that a relatively flat basin-floor existed across the entire study area, i.e. the pre-existing topography was filled by sediments, and the structural elements inherited from earlier rifting were now levelled.

The Fles Fault Complex, subdividing the Vøring Basin (Fig. 1), is said to have played an important role in the Late Cretaceous tectonic development of the Vøring Basin, and several phases of reactivation have been attributed to this complex (Bjørnseth et al., 1997; Brekke, 2000; Doré et al., 1999; Lundin & Doré, 1997). Our seismic interpretation suggests, however, that faults of the Fles Fault Complex which affect the Upper Cretaceous succession generally exhibit comparable offset also at top Cretaceous level and

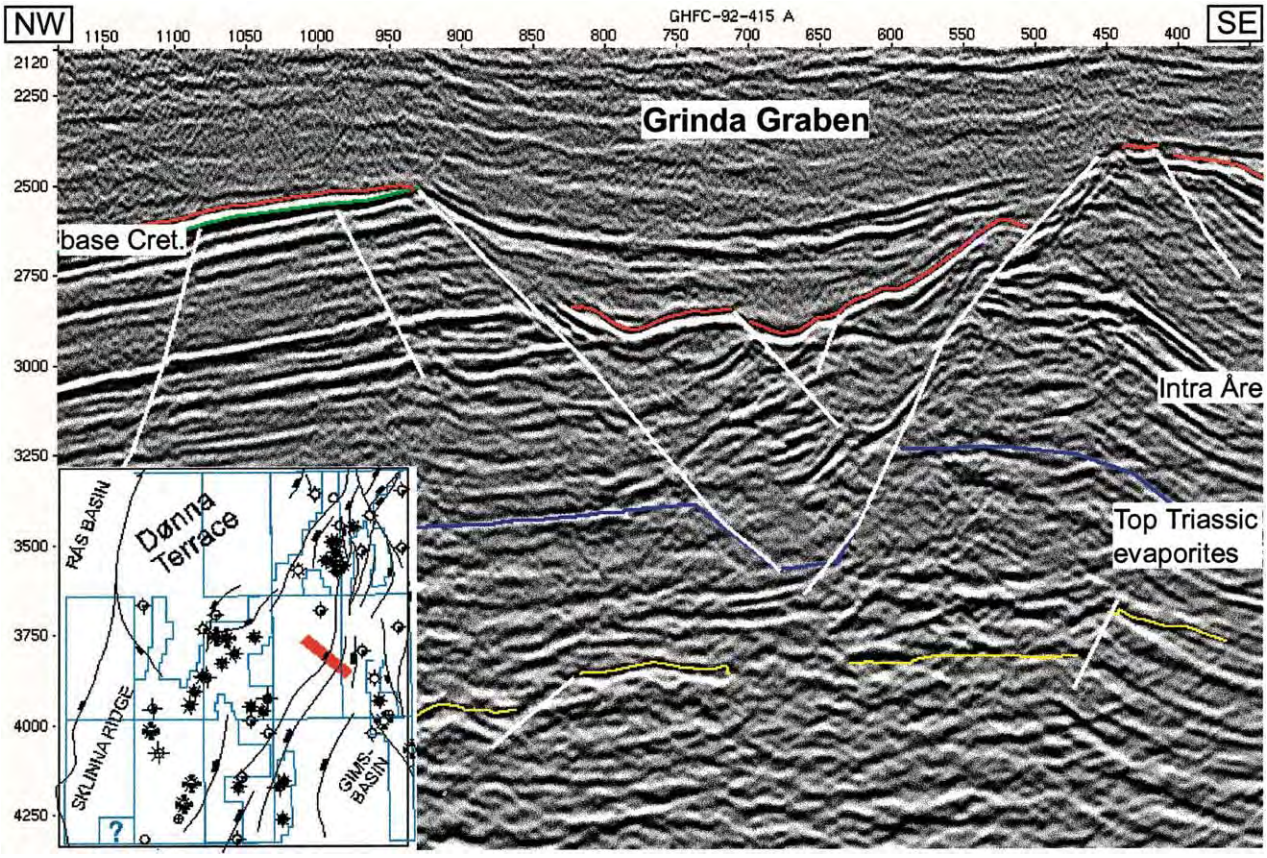

Fig. 11. A majority of the faults affecting Mesozoic sediments on the Halten Terrace are associated with mobile Triassic evaporites. The seismic section shows normal faults which outline the narrow Grinda Graben (see inset), which can be explained in terms of Early Cretaceous salt withdrawal and associated faulting in the overlying sediments, i.e. normal faulting without any crustal extension. The evaporites acted as a detachment level between Jurassic–Cretaceous faults and normal faults below the evaporates, which are interpreted to result from Late Permian–Early Triassic extension.

that the main fault activity can be attributed to the Campanian–Paleocene rift episode and the subsequent Tertiary compression with reverse reactivation of faults.

The most pronounced Late Cretaceous structural development offshore Mid-Norway has in publications been associated with growth of the Gjallar Ridge and the development of a regional onlap surface against the southeastern flank of the ridge. The Gjallar Ridge is a huge domal-shaped structure located at the northwestern margin of the Vøring Basin (Fig. 1), covered by a thin Cretaceous succession compared to basins located to the southeast (Berndt, 2002; Brekke et al., 2001). The structure has been interpreted as a rollover above a deep-seated, SE-dipping fault with a ramp-flat-ramp geometry (Bjørnseth et al., 1997) and as draping above underlying basement block (Brekke et al., 2001).

A regional onlap surface has been identified against the southeastern flank of the Gjallar Ridge, and following Bjørnseth et al. (1997) the onlap surface was associated with the first Late Cretaceous tectonic event recognized throughout the Vøring Basin. These authors suggested an Early Cenomanian age for this tectonic event and according to Doré et al. (1999) the unconformity was dated as Cenomanian from a shallow core (Hansen, Bakke, & Fanavoll, 1992) in the Ribban Basin (Fig. 1), northeast of the study area. More recent, deep wells drilled on the Nyk High, well 6707/10-1 (TD ~ 5050 m) and Vema Dome, well 6706/11-1 (TD ~ 5300 m) demonstrate that the top Cenomanian surface is below termination of these wells, i.e. significantly deeper than interpreted by previous authors. In our interpretation, the onlap surface on the southeast flank of the Gjallar Ridge represents a Late Turonian surface, which is consistent with the redating published by Brekke et al. (2001). As effects of sediment loading and compaction during burial were at a maximum in the deepest parts of the adjoining basins to the southeast, the flanks of these basins are likely to be onlapped by younger sediments up the dip slope of the Gjallar Ridge.

5. Campanian–Paleocene rift episode

The Campanian–Paleocene rift episode lasted some 25–27 Ma (Fig. 2) and led to continental separation in the North Atlantic region and Norwegian Sea. Extensional faults related to this rift episode, occur as a set of northwest-dipping faults and strongly rotated fault blocks at Upper Cretaceous–Early Tertiary levels in the western Vøring

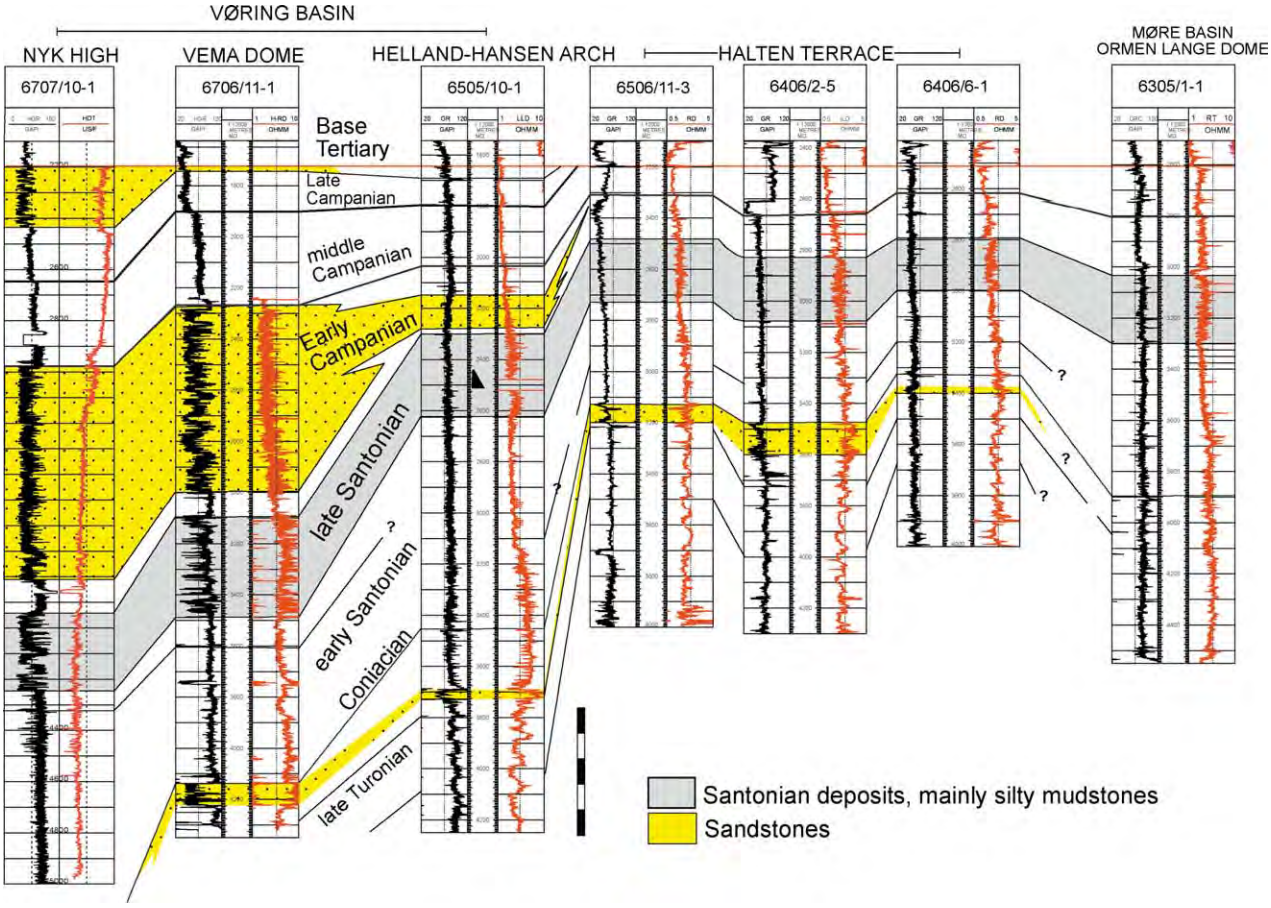

Fig. 12. The well correlation illustrates the uniform thickness of a Santonian interval in the Vøring and Møre Basins and on the Halten Terrace. This correlation illustrates that the topographic relief, inherited from the Jurassic extensional episode and associated normal faulting, was levelled in the Santonian. Note the thick Early Campanian succession to the west, in wells drilled on the Nyk High and Vema Dome. See Fig. 1 for location.

Basin (Fig. 13). Based on seismic data and available wells, we interpret that rifting was initiated in the Early Campanian, around 82–80 Ma (Fig. 2), which is consistent with the interpretation of Tsikalas et al. (2001) along the Lofoten margin segment, northeast of the study area (Fig. 1). Other workers have suggested a Maastrichtian or earliest Paleocene rift initiation (Brekke et al., 1999; Roberts, Lundin, & Kusznir, 1997; Skogseid et al., 2000; Walker et al., 1997). The Lower Campanian sequence deposited during the initial rift stage varies dramatically in thickness, from more than 800 m thick sandstone on the Nyk High (Kittelsen, Hollingsworth, Marten, & Hansen, 1999), to about 200 m thick mudstone succession in the southeastern Vøring and Møre Basins and less than 200 m on the Halten Terrace (Fig. 12). This demonstrates that subbasins located nearest the sediment source area to the west were able to trap most of the coarse material delivered from the hinterland. The transition to the rift climax stage (Fig. 2) resulted in deepening of hangingwalls and was associated with sediment starvation and deposition of a mud-dominated Middle Campanian sequence in the Norwegian Sea (Fig. 12).

In the eastern part of the study area, faults of the Vingleia, Bremstein and Revfallet Fault Complexes (Fig. 1) controlled the final separation of the Halten and Dønna terraces from the Trøndelag Platform. During this late stage of development, the southern part of the Nordland Ridge, in the footwall of the Revfallet Fault Complex (Fig. 1), was subjected to significant uplift that destroyed the Late Jurassic peneplain in that area. Smaller faults, which are most frequent on the northern part of the Halten Terrace, exhibit offset at top Upper Cretaceous and are interpreted to reflect fault activity into the earliest Tertiary (Fig. 14). Hence, renewed fault activity recorded in the eastern part of the study area, appears to be coeval with deformation within the Vøring and Møre Basins and indicates that crustal extension associated with the Campanian–Paleocene rift episode affected also the eastern part of the study area.

6. The onshore–offshore link

Available onshore observations, summarized in this section and which may be relevant to the study area, indicate that influence of Cretaceous tectonism was modest along the basin margins. The Island of Andøya (Fig. 1), associated with the Lofoten margin segment, represents

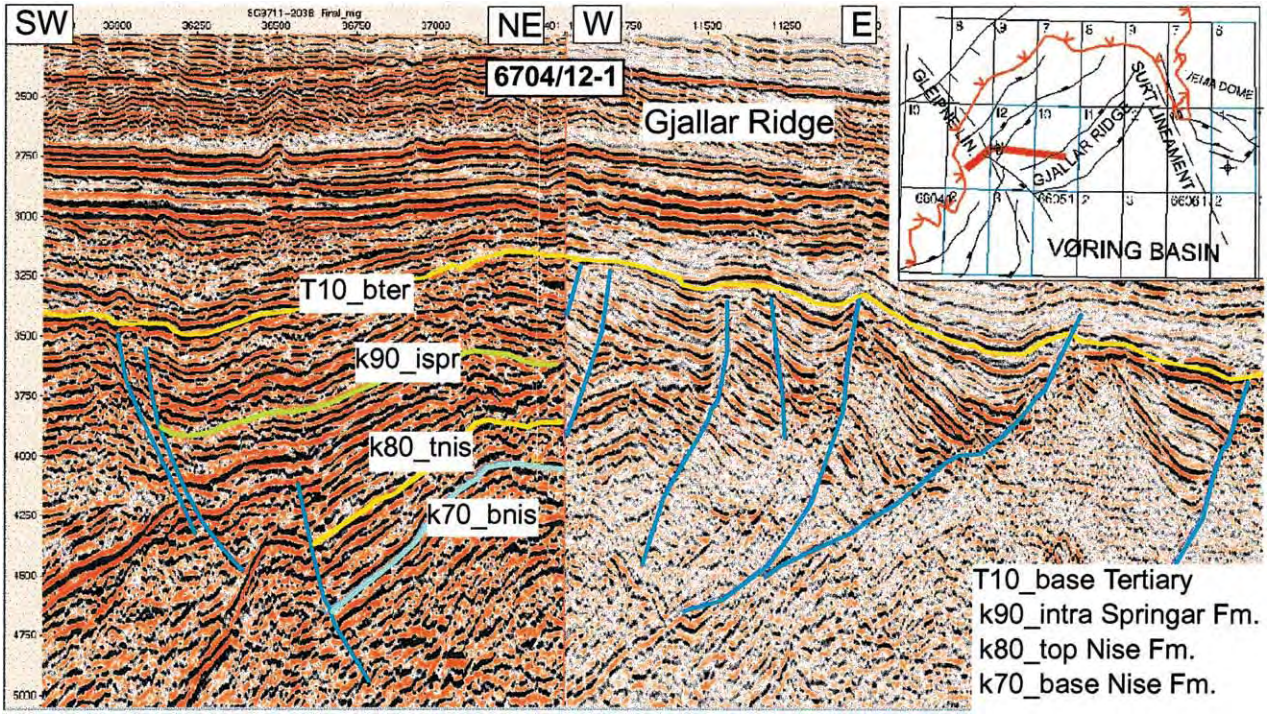

Fig. 13. The Gjallar Ridge located at the western margin of the Vøring Basin, is suggested to represent uplift in the footwall of large, deep-seated and northwesterly throwing normal faults related to a Campanian–Paleocene extensional episode. The normal faults mapped over the Gjallar Ridge and the associated rift-wedges, indicate Early Campanian initiation of the extensional episode. During the Eocene–Oligocene, the ridge was further accentuated by compression. See Fig. 2 for age of reflectors.

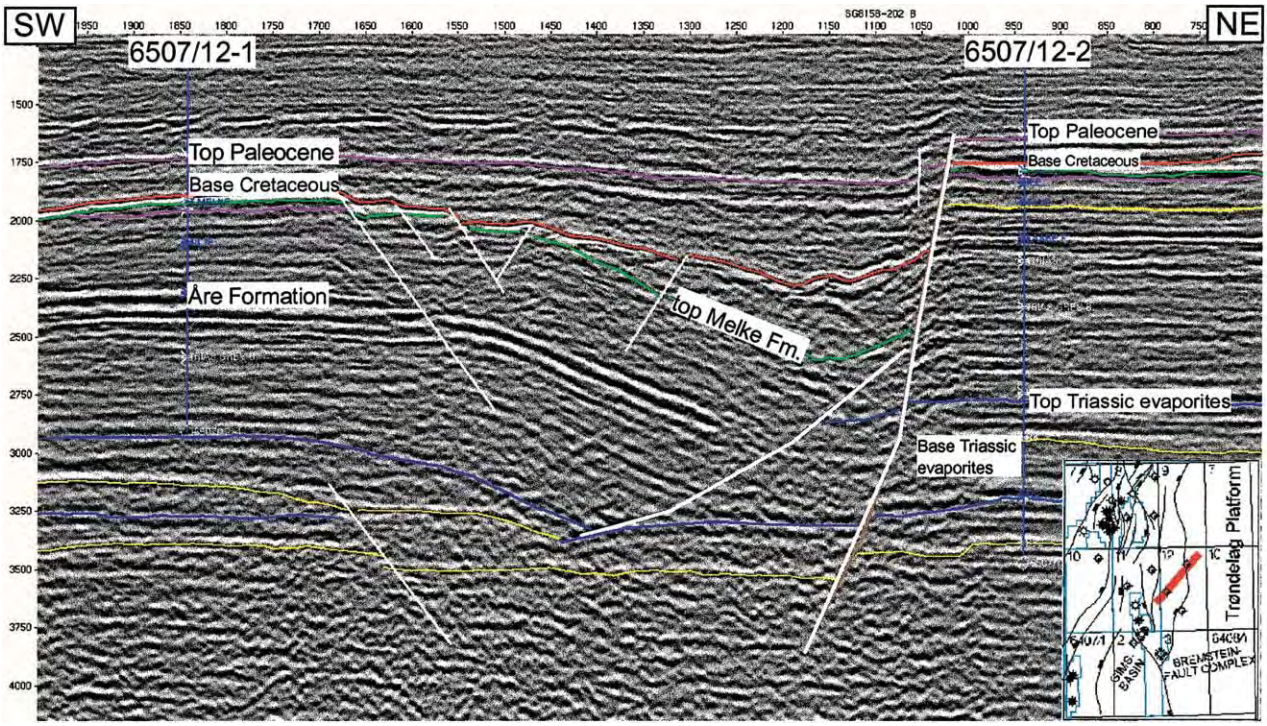

Fig. 14. A normal fault, which represents the boundary between the Trøndelag Platform and the Halten Terrace, offset Early Tertiary sediments (Tang and Tare formations, see Fig. 2). The fault throw is equal at Tertiary and Triassic levels. This late fault activity appears to be coeval with faulting in the Vøring and Møre Basins, which result from Campanian–Paleocene crustal stretching.

the only exposure of Cretaceous sediments onshore Norway. The sediments are located within a small, NNE–SSW striking and fault-bounded area. Preserved fine-grained marine Cretaceous sediments with a total thickness exceeding 500 m are of Valanginian–Aptian age. Dalland (1981) interpreted the outcrop areas on Andøya as the western flank of a rift basin situated below Andfjord to the east of Andøya. The rift basin was primarily a result of Late Jurassic (Kimmeridgian–Ryazanian) extension, but according to Dalland (1981) some faulting seems to have taken place in the area during deposition of the Lower Cretaceous muddy sequence, probably mainly within Aptian time.

East Greenland (north of 72°N), with a pre-drift position approximately 100–150 km northwest of the Gjallar Ridge (Fig. 1), contains well-exposed Cretaceous sediments. Skogseid et al. (2000) suggest that the present NE Greenland margin is part of a larger Cretaceous basin including also the Hel Graben in the northern Vøring Basin (Fig. 1), the Harstad Basin off northern Norway and the Tromsø Basin in SW Barents Sea. An obliquely cutting line of Tertiary continental break-up, are now separating these basins (Fig. 1). A number of normal fault systems can be traced for several hundred kilometres in NE Greenland. The faults strike N–S to NNE–SSW and they generally dip to the east to define westward-tilted fault blocks (Surlyk, 1977). These faults result from a rift episode, which was initiated in the Late Bajocian, culminated in the Late Jurassic with formation of strongly tilted fault blocks and faded out in the earliest Cretaceous (Surlyk & Noe-Nygaard, 2001).

The Cretaceous succession of NE Greenland is more than 2 km thick and consists of siliciclastic, mainly marine sediments which overlie the degraded rift topography of the Jurassic–earliest Cretaceous rift episode (Kelly, Whitham, Koraini, & Price, 1998; Larsen et al., 2001). The Cretaceous succession is bounded by two major angular unconformities; an unconformity at the base which was formed following the main rift episode, with Late Hauterivian sediments above Jurassic and older strata (Kelly et al., 1998; Larsen et al., 2001), and an erosional unconformity at the top which is suggested to be of Paleocene age. In addition, four unconformities are interpreted within the Cretaceous succession (Larsen et al., 2001) and said to be of Late Barremian, Early Aptian, Late Aptian and Late–Early Albian age. As Aptian deposits rest with an erosional, angular unconformity on faulted Valanginian or older rocks, Surlyk, Clemmensen, and Larsen (1981) postulated a pre-Aptian phase of extension and associated block faulting. Kelly et al. (1998) suggest a Barremian–mid Albian age for this extensional phase, whereas Whitham et al. (1999) claim that this time period was characterized by at least two tectonic phases; a Late Barremian–Early Aptian extension, followed by a new phase of normal faulting, which took place between Early Albian and late Middle Albian. It is, however, noteworthy that the total extension associated with the fault period (Barremian–late Middle Albian) is very modest and estimated to give a total $\beta = 1.03$ (Whitham et al., 1999).

Surlyk and Noe-Nygaard (2001) describe the Cretaceous succession on East Greenland as post-rift sediments deposited during thermal subsidence following Jurassic–earliest Cretaceous rifting and punctuated by several possibly rift-related fault events. The interpreted Cretaceous extensional phases on East Greenland are generally related to deposition of breccias, conglomerates and sandstones. However, at least some of these deposits represent downslope sliding and slumping along discrete detachment planes (Surlyk & Noe-Nygaard, 2001), i.e. they are result of gravity collapse and not associated with rift-related faulting. Based on these arguments as well as the scattered nature of Cretaceous outcrops and lack of seismic profiles, Surlyk and Noe-Nygaard (2001) state that it is difficult to evaluate if the faults affecting Cretaceous sediments are related to true extensional events. Also Witham et al. (1999) conclude that Cretaceous rift events in East Greenland are not well constrained and accordingly, the extent to which fault events and their timing can be extrapolated regionally, i.e. to offshore areas is equivocal.

It has been suggested that the tectonic movements continued through the Late Cretaceous, reaching a climax in the Cenomanian and the Middle Turonian (Surlyk et al., 1981), whereas Whitham et al. (1999) state that following Middle Albian extension, fault activity in NE Greenland ceased. Most of the faults affecting Upper Cretaceous sediments and attributed to Late Cretaceous extensional events, are NE–SW striking Paleogene faults which cross-cut Cretaceous sediments as well as the overlying basalts (Kelly et al., 1998; Larsen et al., 2001).

7. Discussion

In the Norwegian Sea, onlap surfaces, thickness variations across faults, wedge-shaped sedimentary bodies, variations in sedimentation rate and influx of coarse clastics have been regarded as indications of Cretaceous tectonic events. Such indications, combined with uncertainties regarding the timing of interpreted tectonic events result in contrasting tectonic models and the overall impression that the Norwegian Sea was tectonically active during the Cretaceous. Our interpretation contrasts with the suggested tectonic models and emphasizes a general lack of Cretaceous tectonic activity. Below is a discussion of features which in published literature have been regarded as indications of Cretaceous tectonism in the Norwegian Sea.

Onlap surfaces. In the study area, onlap surfaces, which have been interpreted to reflect Cretaceous tectonism, occur as regional surfaces along basin margins and at the transition between major structural elements inboard of the deep Vøring Basin (Fig. 8). On a smaller scale, onlap surfaces are well displayed on the dip slope of individual half-grabens and also in the immediate hangingwall of

major faults of Jurassic origin (Figs. 5–7). None of the unconformities recorded and interpreted as indications of tectonic activity have been demonstrated to truncate underlying Cretaceous strata, even in crustal areas, which should be expected if they were related to Cretaceous extensional phases with rotational tilt and footwall uplift of major fault-blocks.

In considerations of Cretaceous tectonism based on regional onlap surfaces, the flexural response of the lithosphere to loading may represent an important aspect. The load imposed by the huge volume of Cretaceous sediments produced a downward flexure of the lithosphere, demonstrated by the westward tilting of the Mid-Norway continental shelf area (Fig. 3). As a response to the loading, basin margin areas to the east may have acted as a peripheral bulge likely to be onlapped by Cretaceous sediments. The flexure profile of the lithosphere to a specific surface load, on a long time scale, will be influenced by factors such as flexural rigidity and elastic thickness (Masek, Isacks, Gubbels, & Fielding, 1994; Walcott, 1972). The lithospheric thinning and heating due to Jurassic extension in the Norwegian Sea, followed by post-rift Cretaceous loading may have resulted in flexuring of a progressively colder and more rigid substrate. As a consequence, long-wavelength effects of Cretaceous thermal contraction and sediment loading were superimposed on the inherited short-wavelength topography from the Jurassic rifting. Owing to the wavelength associated with the flexural rigidity of the lithosphere, the isostatic response to the load is more regional than the load itself and induces uplift of the flanks of deep sedimentary basins (Small & Anderson, 1995). Hence, seismic onlap in the pelagic parts of the basins, towards margins characterized by a relatively thin cover of Cretaceous sediments, may indicate periods of starvation and condensation combined with a change in the slope on the basin flanks consistent with long wavelength thermal flexuring.

Thickness variations across faults. Thickness variations of Cretaceous sediments across normal faults are frequently equated with rift events in studies from the Norwegian Sea. However, in most cases the palaeobathymetry is ignored in such considerations, which may lead to totally unjustified conclusions with respect to the influence of crustal stretching. In general, subsidence greatly exceeds sediment supply during a rift episode and hangingwall syn-rift sequences are often thin as the potential for starvation is high due to rapid drowning of basins. Landward of the Vøring Basin on the Halten and Dønna terraces (Fig. 1), the Spekk Formation, which constitutes the rift climax sequence (Late Oxfordian–Volgian), represents only a minor part of the half-graben fill.

As pointed out by Prosser (1993), many interpretations of reflection data appear to overestimate the proportion of basin fill that was deposited as fault movement occurred. In many cases the syn-rift sequence is found to be a minor constituent of the half-graben fill whereas a major part of the overall wedge-shaped body represents the post-rift stage of basin evolution with a passive infilling of pre-existing relief. Also Bertram and Milton (1989), stated that the infilling of a bathymetrically deep half-graben by post-rift sediments would mimic the tapering wedge of a syn-rift sequence. Due to the continuous compaction of Cretaceous sediments in hangingwalls, Jurassic fault planes continued to grow up through the overlying sediments which cause upturn of reflectors and compaction induced faulting (Figs. 6 and 7). This type of 'drape-slip' faulting (Bertram & Milton, 1989), driven by compaction, is not an indication of crustal extension but is commonly associated with the thermal subsidence stage (Færseth et al., 1995; Gabrielsen et al., 2001).

Wedge-shaped sedimentary bodies. During a rift period, faulting actively controls sedimentation. During the rift climax stage, sedimentation is likely to be outpaced by subsidence and differential relief will be created across fault scarps. On a seismic section the rift climax sediments are characterized by the development of divergent forms related to continued tilting of the hangingwall during deposition. The infilling package that represents the immediate post-rift sediments will, however, assume the wedge-shaped geometry of the remnant rift topography, and may also display divergent reflector configurations induced by compaction.

The Lower Cretaceous succession which infills the interpreted base Cretaceous relief in the study area generally thickens down-slope to define wedge-shaped bodies (Fig. 3), which could give the impression of accompanying fault movements. In contrast to true wedge-shaped, syn-rift units, the Cretaceous sediments are interpreted to thin up the scarp of major normal faults (Figs. 3, 7). Hence, in our view, wedge-shaped Cretaceous geometries in the study area, in most cases evolved through onlapping reflectors infilling pre-existing bathymetry.

Variations in sedimentation rate. The increased rate of subsidence during the Jurassic rift climax stage and the immediate post-rift stage resulted in an increase in accommodation space, possibly termination of established sediment transport systems by major faults and accordingly a reduction in sediment flux to the basin centres. The relative sea level, size of drainage catchments and the distance of hinterland area to successive subbasins determine the extent to which individual half-grabens receive sediment from a rift margin drainage. The increased rate of sediment accumulation in the Late Cretaceous as compared to the Early Cretaceous (Fig. 4) may reflect that larger volumes of sediments entered the interior part of the basin by a smoothing of the basin topography and establishment of sediment transport systems from the hinterland to the deeper basins. This is suggested for the Albian–Turonian, when transverse depositional systems were established, and became important especially along the western margin of the Vøring and Møre Basins.

Influx of coarse clastics. A commonly held view in published literature seems to be that exposure of new

sediment source areas due to rifting will be reflected in basin stratigraphy by influx of coarser sediments. Following this, the presence of coarse clastics is often interpreted as an indication of a tectonic event. However, the distance of hinterland area to successive subbasins determines the extent to which individual half-grabens receive sediment from a rift-margin drainage or are dependent on supply from rift-interior sediment sources. During a rift episode, subbasins located nearest the hinterlands generally tend to trap most of the coarse material delivered by the rift-margin depositional systems. Subbasins located far from hinterlands and where subsidence greatly exceeded sediment supply during the rift stage, are likely to become very starved in coarse clastics. According to Blair (1988) and Prosser (1993), rifting will be associated with sediment that is generally fine grained, and it will only be at some time after the cessation of rifting that large volumes of coarser sediments are introduced into the basin. Observations from the North Sea (Færseth & Ravnås, 1998; Ravnås & Steel, 1998) as well as on terraces inboard of the Vøring Basin demonstrate that sequences deposited during the rift climax stage are thin, and that they constitute only a minor part of the basin fill receiving a limited amount of coarse clastics.

7.1. Influence of Jurassic rift architecture

Cretaceous sediment dispersal and geometries are in this study interpreted to be strongly related to the Jurassic rift architecture. Accordingly, the basin floor relief and palaeowater depths at the end of Jurassic rifting are important parameters with respect to Cretaceous sedimentation. Structures related to the Jurassic extensional episode are recognized along the eastern margin of the Vøring and Møre Basins, and also on East Greenland, which in a pre-drift position was located along the western margin of these basins (Fig. 1). It is not known whether Jurassic rifting affected the entire region from Mid-Norway to East Greenland, or if two or more rifts existed. In the interpretation of Skogseid et al. (2000), relatively narrow N–S to NE–SW striking pre-Cretaceous rift segments are located in the Møre and Vøring Basins below the deepest base Cretaceous surface. A 45–70 km wide zone of pronounced crustal thinning is located beneath the Cretaceous Rås Basin (Fig. 1), which also has the most elevated Moho. Farther north, two relatively narrow pre-Cretaceous rift arms are interpreted to underlie the Træna Basin and the Hel Graben, respectively. The Hel Graben and Rås Basin are associated with the strongest negative residual gravity anomalies in the study area (Berndt, 2002). This type of relationship between narrow rifts and broad overlying basins associated with thermal subsidence, results in the typical 'steer's head' geometry of sedimentary basins (Dewey, 1982; McKenzie, 1978; White & McKenzie, 1988).

On the Halten and Dønna terraces, the base of the Jurassic syn-rift sequence can be mapped with reasonable confidence, and the pre- to syn-rift transition is a mid Jurassic (intra-Bajocian) reflector (Corfield et al., 2001). This rift initiation is consistent with observations from the northern North Sea (Færseth, 1996; Færseth & Ravnås, 1998) and in both areas Oxfordian–Volgian was the period of maximum crustal extension rate (Fig. 2), which created maximum topographic relief. During the initial stage of the Jurassic rift episode, the Trøndelag Platform together with the Halten and Dønna terraces acted as one giant fault-block along the eastern margin of the Vøring and Møre Basins, i.e. the Halten Terrace stayed close to the same elevation as the Trøndelag Platform relative to basins to the west. In the Late Jurassic and earliest Cretaceous, the Sklinna Ridge, which occupies the western edge of the Halten Terrace, was at the same elevation as other highs along the eastern margin of the Vøring and Møre Basins, i.e. the Nordland Ridge, the Frøy High and further south also the Manet Ridge (Fig. 1). The main subsidence of the western part of the terraces relative to the Trøndelag Platform, due to a westerly tilt (Figs. 3(b) and 5), took place in the Cretaceous as a result of lithospheric thermal subsidence and loading of sediments in the Vøring and Møre Basins.

All the elevated areas, east of the Møre–Vøring Basin proper, were deeply eroded during the Late Jurassic–earliest Cretaceous, leaving crystalline basement at relatively shallow depths, either subcropping uppermost Jurassic or Cretaceous units. The deep erosion attests to pronounced Jurassic uplift in the footwall of major basement-involved faults along the E–SE margin of the basins, which was accentuated by isostatic adjustments in the Early Cretaceous. From reconstructions, Jurassic footwall uplift must be in the order of 1.0–2.0 km in areas like the Nordland Ridge, Sklinna Ridge, Frøy High and Manet Ridge. Roberts and Yielding (1991) estimated an uplift of ca. 1.5 km due to elastic rebound and isostatic adjustments in the footwall of the Bremstein Fault Complex (Fig. 1), following Late Jurassic crustal stretching and normal faulting. The proportion of footwall uplift to hangingwall subsidence depends on the local sediment loading, but is generally in the order of 20–30% (Jackson & McKenzie, 1983; Jackson & White, 1989). Applying this ratio and the observed/modelled footwall uplifts, the maximum vertical offset on Jurassic faults must be of the order of 5–7 km, which is consistent with the interpretation across major faults along the eastern margin of the basins (Figs. 3, 5 and 7).

Due to the large hangingwall subsidence during the Late Jurassic rift climax stage, fault-blocks were submerged under a considerable depth of water at the end of rifting. Estimates of Early Cretaceous water depths in the deepest parts of the basins are not available due to lack of well data. However, drilled Upper Cretaceous sediments are interpreted to be deposited under deep-marine conditions, although these sediments were deposited when basins were partly infilled. Within half-grabens in the northwesternmost part of the North Sea (Magnus province), fault scarp relief of 2000 m is interpreted to have existed at the end of Jurassic rifting (Prosser, 1993), which is consistent with modelled Early Cretaceous palaeobathymetries

(Young, 1992). Along the southern margin of the Møre Basin, the progressive Cretaceous infill of deep-water (ca. 2000 m) basins has been suggested (Jongepier et al., 1996; Nelson & Lamy, 1987; Rattey & Hayward, 1993).

7.2. Cretaceous evolution in the Norwegian Sea

From our observations, we argue that the Cretaceous evolution following the Jurassic rift episode and until the Campanian rifting (ca. 140–80 Ma), represents a post-rift thermal subsidence stage across the Møre and Vøring Basins and that no major faulting during this period is recorded. The lack of evidence of Early Cretaceous faulting in the Vøring and Møre Basins has also been emphasized by other workers (Doré et al., 1999; Lundin & Doré, 1997), but was attributed to poor seismic imaging due to the thick basin fill. It remains a fact, however, that published accounts of Early Cretaceous rifting off Mid-Norway are often circumstantial, and as discussed above such indications allow alternative interpretations.

The features discussed above and interpreted as indications of tectonic events in published literature, have generally been related to Early Cretaceous rift propagation in the Atlantic margin. The rift propagation is interpreted to define a broad zone of extension and subsidence, postulated to extend from the southwestern Rockall Trough, through the central Møre Basin, eastern Vøring Basin and to the western Barents Sea (Doré et al., 1999; Roberts et al., 1999). Along the Lofoten margin segment (Fig. 1), Early Cretaceous synrift sedimentary expansion is postulated (Doré et al., 1999 and references therein). Tsikalas et al. (2001), in contrast to Doré et al. (1999), were not able to make a distinction between Late Jurassic and Early Cretaceous rifting along this margin segment. They state that Late Jurassic rifting is the dominant extensional episode, but due to thickening of Early Cretaceous sequences across faults they interpreted that rifting continued sometime into the Cretaceous.

Southeast of the study area in the Faeroe–Shetland Trough, expansion of Cretaceous sequences and deposition of coarse clastics have been associated with Neocomian rifting (Dean et al., 1999). Further northeast, in the northwesternmost North Sea (Magnus province), Hauterivian fault-controlled unconformities and associated depositional systems are described (Rattey & Hayward, 1993). Volgian–Valanginian activity is also proposed for the major NE-trending fault bounding the Manet Ridge (Fig. 1) (Graue, 1992). It is noteworthy, however, that Nelson and Lamy (1987) and Young (1992) interpret thick Cretaceous successions in half-grabens at the North Sea–Møre Basin transition, as passive infilling of remnant Jurassic rift topography. This notion is supported by wells drilled in the Slørebotn Subbasin close to the southeastern margin of the Møre Basin (Fig. 1). Well 6205/3-1R which reached a total depth of more than 5200 m, penetrated and partly cored Early Cretaceous–Late Jurassic sediments in the immediate hangingwall of the Møre Basin margin fault, and accordingly provides excellent data for the reconstruction of fault-block rotation, and thereby to constrain the duration of active Jurassic faulting. By combining seismic interpretation and dip magnitudes from the dipmeter log and core measurements, Jongepier et al. (1996) conclude that Jurassic extension, reached a rift climax stage during the Kimmeridgian–middle Volgian, whereas latest Volgian–Cretaceous sedimentation was characterized by passive infill and progressive onlap of the relief created during Jurassic rifting. Like Gabrielsen et al. (1999), we interpret topographic highs further west in the Møre Basin, below the mapped base Cretaceous horizon, to represent crustal parts of highly rotated Jurassic fault-blocks where magnetic basement is capped by relatively thin pre-Cretaceous sediments. The heave associated with the Møre Basin margin fault which is ca. 15 km, indicates that assuming regularly spaced Jurassic faults of similar magnitude further west would imply that the Møre Basin accommodated significant Jurassic extension.

Considering Cretaceous tectonism offshore Mid-Norway and the possibility of variations along strike, NW–SE oriented transfer zones may represent important elements as they result in a well- defined along-strike margin segmentation (Fig. 1). Some of the transfer zones appear to have had a long history of activity and correlate with major basement inhomogeneities (Blystad et al., 1995; Doré & Lundin, 1996; Doré et al., 1999; Gabrielsen et al., 1999). Transfer zones are observed over most of the margin as termination and offset of structural features, changes in fault pattern, and they may have acted as the persistent barriers to rift propagation (Tsikalas et al., 2001). Hence, the Jurassic rift basins, which result from rift propagation through the Rockall Trough, Shetland/Fareoe Trough, central Møre Basin, Vøring Basin to the SW Barents Sea (Doré et al., 1999; Roberts et al., 1999), may have experienced varying degree of Cretaceous extension.

Doré et al. (1999) highlight the distinction between E–W extension by Jurassic times, and the change to NW–SE extension in the Early Cretaceous, a notion which was based on the assumption that rift axis and normal faults developed perpendicular to the least principal stress (Lundin & Doré, 1997). However, in areas characterized by pre-existing structural grain, it is not obvious that the principal stress orientation can be deducted from fault orientation (Higgins & Harris, 1997; Morley, 1995). Based on observations in the northern North Sea, Færseth et al. (1997) argued that the extension remained NW–SE directed throughout the Jurassic (Late Bajocian–middle Volgian) rift episode, to reactivate both N–S and NE–SW oriented basement grain. Clifton, Schlische, Withjack, and Ackermann (2000) based on experiments, supported the model of Færseth et al. (1997) and stated that the two fault-populations were compatible with a consistent NW–SE extension. In the northern North Sea, there was, however, an increased influence of NE–SW striking basement shear zones, i.e. orthogonal to the least principal stress, as the crustal stretching accelerated during the Late Jurassic rift climax

stage. NE–SW striking normal faults are observed to cut across N–S trending faults which were active during an earlier stage of the Jurassic rift episode. Major NE–SW striking faults are abundant at the North Sea–Møre Basin transition, not merely as a result of proximity to the Atlantic margin, but to reflect the influence of the prominent NE–SW basement grain represented by the long-lived Møre–Trøndelag Fault Complex (Fig. 1). The model derived from North Sea data, appears to be compatible with our observations in the eastern part of the study area where normal faults, which strike N–S and NE–SW, were coeval and interpreted to result from Jurassic NW–SE extension.

As argued by Doré et al. (1999), Jurassic and Cretaceous rifting may represent separate events, however, in contrast to these authors our interpretation would imply a consistent NW–SE extension by the Jurassic time and into the Early Cretaceous. As a corollary, localized Ryazanian–earliest Valanginian reactivation of Jurassic normal faults in the study area may represent effects of a waning rift episode, which climaxed during the Late Jurassic. Whereas it is general consensus that major Jurassic rifting in the North Sea terminated during the Volgian, some of the rift basins associated with the northeastern propagation of Jurassic rifting in the Atlantic margin may have experienced prolonged crustal stretching into earliest Cretaceous, suggesting that termination of active stretching was not synchronous throughout the rift system. Hence, effects of Cretaceous tectonic activity may be variable along the NE–SW striking Jurassic zone of extension, and in our interpretation the Møre and Vøring Basins represent areas almost devoid of rifting in the time period between the Jurassic and the latest Cretaceous–Paleocene extensional episodes.

8. Conclusions

We argue that the Cretaceous evolution following the Jurassic rift episode and lasting until Campanian rifting (ca. 140–80 Ma), represents a post-rift thermal subsidence stage across the Møre and Vøring Basins and that no major faulting during this period is recorded. This contrast with suggested tectonic models for the shelf area offshore Mid-Norway and also with published observations southwest and northeast of the study area, interpreted as indications of Cretaceous tectonic events. NW–SE oriented transfer zones result in a well-defined along-strike margin segmentation in the Norwegian Sea and may have acted as barriers to Cretaceous rift propagation. Consequently, Jurassic rift segments, which propagated through the Rockall Trough, Shetland/Fareoe Trough, central Møre Basin, Vøring Basin to the SW Barents Sea, may have experienced varying degree of Cretaceous extension, and in our interpretation the Møre and Vøring Basins represent areas almost devoid of rifting during the time period under consideration.

Beneath the Vøring and Møre Basins, the relief at base Cretaceous level is inferred to reflect an underlying Jurassic rift architecture characterized by large tilted fault-blocks, which is the typical structural expression of Jurassic rifting observed inboard of the Vøring Basin, along the south-eastern margin of the Møre Basin as well as along the Lofoten margin segment, northeast of the study area. The tectonic relief may have caused water depths of the order of several kilometres in the deepest basins at the end of the Jurassic rifting. The near perfect onlap of the Cretaceous horizons along the pre-existing fault scarps, later deformed by compaction, is interpreted to reflect progressive sedimentary infill of deep-water basins.

The basins continued to subside during the Cretaceous due to a combination of thermal subsidence, lithospheric response to loading and compaction of underlying sediments during burial. This allowed the deposition of large thickness of Cretaceous post-rift sediments, and may explain a number of observations which in published literature are regarded as indicative of tectonic events:

- Expansion of Cretaceous sediments across normal faults and influx of coarser sediments are frequently equated with rift events. However, syn-rift sequences deposited during a rift climax stage, within the interior part of a rift basin, are generally thin and they are starved of coarse clastics.
- Interpreting fault movement from thickness variations across faults ignoring the palaeobathymetry may lead to unjustified conclusions with respect to the influence of crustal stretching as well as the duration of rifting.
- Post-rift sediments constitute a major part of the half-graben fill and assume the wedge-shaped geometry of the remnant rift topography with the possibility of displaying divergent reflector configurations induced by compaction.
- Differential compaction above the asymmetrical base to subbasins (half-grabens) caused upturn of reflectors and compaction induced faulting, generally associated with the thermal subsidence stage and such faulting can be very long-lived.

The Early to Late Cretaceous transition saw a remarkable increase in sedimentation rate; the Cenomanian–Santonian rate was four-fold that of the average rate during Early Cretaceous. The increased rate of sediment accumulation in the Late Cretaceous may reflect that larger volumes of sediments entered the interior part of the basin by a smoothing of the basin topography, and establishment of sediment transport systems from the hinterland to the deeper basins. The increased sediment supply outpaced subsidence and the topographic relief was levelled in the Santonian causing the different depocentres of Early Cretaceous time to merge into a wider depocentre. We interpret this as a mature stage of the post-rift development, when thermal equilibrium was obtained. The period of tectonic quiescence was terminated by a new rift episode, which was initiated in

the Early Campanian and culminated with the final opening of the North Atlantic 55 Ma ago.

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