Extensional geometry of the Mid Norwegian Margin before Early Tertiary continental breakup

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Abstract

Interpretation of reflection seismic data integrated with existing crustal models provide an interpretation of the deeply buried Mesozoic extensional geometry of the Vøring and Møre margins in the Norwegian Sea. Whereas Late Paleozoic to Triassic basins are limited by high angle normal faults with NW and SE dips, the Late Jurassic–Early Cretaceous Vøring and Møre basins are characterised by low-angle normal faults that dip towards the NW. Between the Vøring and Møre basins, at the SE end of the Jan Mayen Fracture Zone, a synthetic transfer zone is interpreted. Geometrical models based on basin and fault geometries show that the rift system detached near the upper crust–lower crust transition in the study area. A simple geometrical forward model suggests that a substantial part of this stretching occurred during the Late Cretaceous–Paleocene, thinning the central and NW segments of the Late Jurassic–Early Cretaceous rift.

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1. Introduction

The Mid Norwegian passive margin is located in the North Atlantic Igneous Province (White & McKenzie, 1989). The margin formed by repeated extensional events that occurred in late Paleozoic–Triassic, Late Jurassic–Early Cretaceous and Late Cretaceous–Paleocene times (Blystad et al., 1995; Brekke, 2000; Bukovics & Ziegler, 1985; Doré et al., 1999; Ziegler, 1988). The last event culminated with the continental separation of North America and Eurasia and with the opening of the North Atlantic at the Paleocene–Eocene transition (Skogseid & Eldholm, 1989). Break-up was accompanied by intense igneous activity related to the presence of the Icelandic hot spot (Eldholm, Thiede, & Taylor, 1989; White & McKenzie, 1989; Skogseid, Pedersen, Eldholm & Larsen, 1992a). This long geodynamic evolution gave rise to the formation of different tectonic provinces in

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the geometries of the attenuated continental crust and the presence of a subcrustal high velocity body in the NW part of the margin (Mjelde et al., 2001; Mutter & Zehnder, 1988; Olafsson, Sundvor, Eldholm, & Grue, 1992; Planke, Skogseid, & Eldholm, 1991). Regardless of this amount of data, the extensional fault system of the Mid Norwegian Margin is poorly understood because it is obscured due to the considerable depth of the Cretaceous sedimentary basins and because of the presence, at shallow and mid crustal levels, of large volumes of volcanic sequences and igneous intrusions.

The main objectives of this work are: (1) To investigate the upper crustal structure of the Vøring Margin, the Møre Margin and of the segment of the margin between them at the southern end of the Jan Mayen Fracture Zone; (2) to determine the geometry of the pre-Late Cretaceous extensional fault system as well as the possible depth to the basal detachments; (3) to integrate the results in fully constrained crustal profiles and to calculate post-Early Jurassic crustal extension and stretching factors; and (4) to discriminate Late Jurassic–Early Cretaceous vs. Late Cretaceous–Paleocene rifting effects on the present-day geometry of the crust.

2. Late Paleozoic to Early Tertiary extensional evolution

The overall structure of the Vøring Margin (ca. 500 km wide) and the Møre Margin (ca. 300 km wide) separated by the Jan Mayen Lineament, consists of NE–SW trending basins bounded towards the NW by marginal highs (Fig. 1) (Blystad et al., 1995). The evolution of the Vøring and Møre margins since the end of the Caledonian Orogeny at Late Paleozoic times is summarised below.
Since Late Paleozoic to breakup at Paleocene–Eocene times, three main rifting events characterise the evolution of the Mid Norwegian Margin: (a) Late Paleozoic–Middle Triassic; (b) Late Jurassic–Early Cretaceous; and (c) Late Cretaceous–Paleocene. During Late Paleozoic took place transtensional deformation related with the extensional collapse of the Caledonian orogen that gave rise to the formation of Devonian basins at the Vøring and Møre Margins (Braathen et al., 2000; Gabrielsen, Odinsen, & Grunnaleite, 1999; Grønlie & Roberts, 1989; Hames & Andreassen, 1996). Subsequent rifting took place in the study area during Carboniferous, Permian and Middle Triassic times, forming basins mainly recognised in the Trøndelag Platform and SE of the Møre Margin (Brekke, 2000; Bukovics & Ziegler, 1985; Jongepier, Rui, & Grue, 1996; Skogseid, Pedersen, & Larsen, 1992b; Ziegler, 1988). A renewed extensional event at Late Jurassic–Early Cretaceous formed the Vøring and Møre basins (Brekke, 2000; Bukovics & Ziegler, 1985; Doré et al., 1999; Gabrielsen et al., 1999; Skogseid et al., 2000). The precise timing of this rifting event is controversial. Whereas in a number of works the duration of the rifting is extended to the Early Cretaceous (Doré et al., 1999; Skogseid et al., 2000) for other authors the rifting episode is Middle to Late Jurassic in age (Corfield & Sharp, 2000; Færseth & Lien, 2002). The youngest phase of extension occurred in Late Cretaceous–Paleocene times towards the NW of both the Vøring and Møre margins (Skogseid et al., 2000). However, evidence of Late Cretaceous–Paleocene normal faulting is restricted to the Vøring Basin (Brekke, 2000; Ren, Faleide, Eldholm, Skogseid, & Gradstein, 2003; Ren, Skogseid, & Eldholm, 1998). The recognised effect of the Late Cretaceous–Paleocene extension in the Mid Norwegian Margin is significant subsidence across a ca. 150 km wide zone landward of the continent-ocean boundary (Gabrielsen et al., 1999; Skogseid et al., 2000).

3. Seismic data and depth-conversion

The geometry of the Mid Norwegian Margin is mainly studied through the interpretation and depth conversion of multichannel seismic profiles forming one transect across the Vøring Margin and one transect across the Møre Margin. The Vøring Margin transect is composed from three seismic profiles that reach 9 s TWT of depth (12 km below sea-level after depth conversion) (Figs. 2 and 3). The transect runs NW from near the coastline through the Trøndelag Platform, the Nordland Ridge and the Træna Basin to the Utgard High. Then the transect follows a WNW direction across the Någrind Syncline, the southern termination of the Vema Dome, the Gjallar Ridge and the Vøring Marginal High (see Fig. 1 for location). The ages of the main reflectors of this transect are assigned according to completion logs from released oil exploration wells (Fig. 2). The age interpretation of older and undrilled strata in the Trøndelag Platform is extracted from Brekke (2000) and Bugge et al. (2002). The Møre Margin transect is made of two regional multichannel seismic profiles imaging from SE to NW the Størefot Subbasin, the Møre Basin and the Møre Marginal High (see Fig. 1 for location). The ages
of the main reflectors are assigned by the correlation with available oil exploration wells drilled in the platform areas and in the Cenozoic domes. The base of the Cretaceous corresponds to a strong seismic marker as reported in several publications (Blystad et al., 1995; Brekke, 2000; Bukovics & Ziegler, 1985; Gabrielsen et al., 1999).

A depth-conversion of the line drawings corresponding to the two transects is performed using seismic velocities extracted from well logs provided by Norsk Hydro and from published data. The utilised mean velocities for both the Vøring and Møre transects are 1.48 km/s for the water, 1.85 km/s for the Upper Pliocene and Quaternary and 2.20 km/s for the Tertiary. The pre-Tertiary in the Vøring Basin and the Cretaceous in the Møre Basin are depth converted using an interval velocity of 3.50 km/s. For the pre-Cretaceous sediments of the Trøndelag Platform, a mean velocity of 6.0 km/s is used based on velocity transects by Planke et al. (1991).

4. The geometry of the extensional basins

4.1. Vøring Margin

4.1.1. Trøndelag Platform

The Trøndelag Platform consists of a thick Late Paleozoic to Middle Triassic basin bounded by normal faults (Brekke, 2000; Bukovics & Ziegler, 1985). Five stratigraphic units are differentiated in the line drawing of Fig. 2 according to their relation with tectonic events. The lowest unit is of late Paleozoic to Middle Triassic age, is around 6 km thick and forms a rift basin bounded by major normal faults dipping towards the centre of the basin. The unit is interpreted in this work to slightly thicken towards the SE master fault and thus is interpreted to be, at least in part, of syn-rift character. However, Blystad et al. (1995) show in a nearby section a clear thickening of this lower unit towards the centre of the rift basin. The Middle Triassic to Jurassic unit shows a more uniform thickness across the Trøndelag Platform (a maximum of 1.5 km of thickness) with gradual thinning towards the SE margin. This unit overlies the Triassic normal fault in the SE side of the rift basin, whereas it is cut by the NW fault system. The Cretaceous unit is thin (a maximum thickness of 1 km) and shows a slight thickening in the centre of the basin where limited normal faulting occurred. The age of these faults is interpreted to be Late Jurassic since the lower Cretaceous strata onlap and overlie the faults. The Tertiary unit is very thin and uniform in thickness (approx. 0.6 km) whereas the Pliocene and Quaternary on top forms a 1.5 km thick prograding shelf succession dominating the bathymetry of the Trøndelag Platform. The depth to the top of the basement is difficult to determine with the available seismic data. The interpretation of the cross-section of Fig. 2 suggests that the sediments reach 6 s TWT below sea level. This depth can be underestimated since a deeper basin with the basement at approximately 8 s TWT depth (around 10 km of depth) has been documented using nearby seismic data (Osmundsen, Sommaruga, Skilbrei, & Olesen, 2002).

The structural pattern of the Trøndelag Platform is characterised by the two main fault zones bounding the Late Paleozoic to Middle Triassic rift basin. The SE fault zone is interpreted to be active during Late Paleozoic–Middle Triassic. The NW fault zone was also active during this time but experienced a later reactivation suggested by the presence of Triassic to lower Cretaceous sediments in the hangingwall and by the existence of upper Cretaceous beds overlying the fault. The seismic data does not allow to recognise if the lower Cretaceous strata are of syn-rift or post-rift character. Consequently, the fault reactivation is interpreted to occur in Late Jurassic and/or Early Cretaceous times.

4.1.2. Vøring Basin

The large-scale geometry of the Vøring Basin is slightly different N and S of the Surt Lineament. To the S of the Surt Lineament, the Vøring Basin is characterised by two major NE–SW depocentres (the Rás Basin and the Vigrid
Syncline) while to the N there are three depocentres with also a NE–SW direction (Træna Basin, Någrind Syncline and Vema Dome) (Brekke, 2000). The study transect images the Vøring Basin close to the transition between these two regions (see Fig. 1 for location). Along the study transect and below the Cenozoic succession, the pre-Tertiary is accumulated in the Træna Basin, the Någrind Syncline and the SW limit of the Vema Dome outlining gentle synclines at depth (Fig. 3). The depocentres are separated by basement highs: the Utgard High and the SE termination of the Nyk High. It must be noted that the precise location of the base of the Cretaceous in most of the Vøring Basin is not well known. This prevents an accurate interpretation of the timing of deformation and results in variable amounts of Cretaceous sediments depending on the preferred interpretation (Blystad et al., 1995; Brekke, 2000; Skogseid & Eldholm, 1989; Torne, Fernández, Wheeler, & Karpuz, 2003). Towards the SW of the study transect along the Rås Basin (Fig. 4), the base of the Cretaceous is interpreted as a prominent reflector which outlines tilted fault blocks in the Halten Terrace and in the Rås Basin at depth, in agreement with Osmundsen et al. (2002). The interpreted base of the Cretaceous is not offset by normal faults and the lower Cretaceous sediments onlap towards both sides of the Rås Basin and above the Jurassic structure in the Halten Terrace (Fig. 4). This interpretation suggests that the lower Cretaceous succession is of post-rift character and thus it favours a Middle to Late Jurassic timing for the deformation in this region (Færseth & Lien, 2002).

The geometry of the Vøring Basin along the studied transect is determined by the three depocentres and their bounding highs. The Træna Basin close to the Trøndelag Platform constitutes the main pre-Tertiary depocentre where the sediments reach a maximum thickness of 7 km according to the seismic interpretation (Fig. 3). The NW limit of the Træna Basin is defined by SE-dipping Fles Fault Complex, which cuts Cretaceous deposits above the Utgard High (“A” in Fig. 3). Its SE limit is defined by an upper Cretaceous onlap relationship against a NW-dipping monoclinal flexure in the Nordland Ridge. The reflectors within the monocline appear to be truncated by an erosional surface in the contact with the upper Cretaceous (“B” in Fig. 3). This structure has been interpreted as a monoclinal roll-over related to a major SE-dipping normal fault system forming the Fles Fault Complex (Mosar, 2000; Osmundsen et al., 2002). These authors also propose SE-dipping normal faults located NW of the Någrind Syncline and NW of the Vema Dome, defining a fault system with dominant SE polarity in the Vøring Basin. However, the available seismic data does not provide evidences of deep SE normal faults along our studied transect. Furthermore, the structure towards the SW along the strike of the Nordland Ridge, consists of NW-dipping fault systems forming the Ytreholmen Fault Zone and the Revfallet Fault Complex (Blystad et al., 1995). These faults constitute a fairly continuous NW-dipping fault system bounding the SE flank of the Vøring Basin that is synthetic with the Klakk Fault Complex located towards the SW. Attached to this fault system, there is a Cretaceous depocentre that does not present shifts along its axial trace (see Figure 4 of Torne et al., 2003). Based on this along-strike structure, we interpret NW-dipping normal faults to continue towards the SE limit of the Træna Basin together with the conjugate fault system located in the Utgard High. Severe post-rift thermal subsidence may explain the NW flexure observed in the pre-Cretaceous sediments in the Nordland Ridge.

In the Någrind Syncline the pre-Tertiary sediments attain a maximum thickness of ca. 6 km along the study transect (Fig. 3). The thickness is maximum in the syncline axis and reduces towards the Utgard High (D-D’ profile in Blystad et al., 1995). However, no normal faults are interpreted SE of the syncline (Fig. 3). Towards the NW, the present Vema Dome overprints a pre-Tertiary basin up to 7 km thick. This basin is limited at depth towards the SE by a narrow and seismically transparent region interpreted as a basement high. The seismic data shows a deep (6–7 s TWT) and

Fig. 4. Geoseismic interpretation showing the Halten Terrace and Rås Basin. Note the prominent W-dipping Klakk Fault Complex separating the thick deposits of the Rås Basin from the thin Cretaceous sediments of the Halten Terrace. A wedge-shaped body below the base of the Cretaceous reflector in the hangingwall of the Klakk Fault Complex is interpreted as the syn-rift unit. The Cretaceous post-rift sediments onlap towards both sides of the basin and bypass the structural highs (black arrows), suggesting a passive infill of the structural paleorelief. Seismic data by courtesy of WesternGeco.
reflective unit that presents different thicknesses at both sides of this high (Fig. 5). Towards the NW of the high the reflective unit is thicker and reveals onlaps and internal erosional truncations suggesting a syntectonic infill. Towards the SE of the high the unit is thinner but is not affected by normal faults. According to our interpretation, the syntectonic thickening of the unit is due to the activity of a NW-dipping normal fault at depth (Fig. 5). This interpretation contrasts with a SE-dipping normal fault bounding the high towards the NW suggested by Osmundsen et al. (2002).

The Gjallar Ridge is located at the NW margin of the Vøring Basin and is formed by a set of Late Cretaceous–Paleocene low-angle and listric normal faults (Ren, 1996; Ren et al., 1998) dipping towards the NW and that flatten down-dip at ca. 6 km of depth (Fig. 6). The fault system involves cover rocks either Cretaceous in age (Gernigon, Ringenbach, Planke,Jonquet-Kolsta, & Le Gall, 2001) and possibly older (Torne et al., 2003). The fault system is unconformably overlaid by Eocene sediments (Hjelstuen, 2001).

The amount of extension accommodated by the SE border fault system of the Vøring Basin can only be confidently estimated in the Raås Basin with the available data. In this region the base of the Cretaceous and the geometry of the syn-rift are reasonably well determined. The heave is constrained in the hangingwall by the interpreted base of the syn-rift unit and in the footwall by the top of the basement in the W limit of the Halten Terrace (Fig. 4). According to this interpretation the Klakk Fault Complex accommodates 25 km of heave. This measurement reasonably coincides with the 30 km of heave estimated by Osmundsen et al. (2002) in the same region. To the SW of the Træna Basin the heave is estimated measuring the horizontal separation in a published regional profile. The Jurassic presents a heave of ca. 20 km N of the Nordland Ridge across the Dønna Terrace (Fig. 3, section a in Færseth & Lien, 2002).

4.2. Møre Margin

The Møre Margin is mainly infilled by a thick Cretaceous succession, but lacks a bounding structural province.
equivalent to the Trøndelag Platform in the Vøring Margin (Fig. 7). The Cretaceous and Tertiary infill forms a gentle and broad syncline in which the SE flank dips towards the NW whereas the NW flank is nearly horizontal. The Cretaceous unit accumulated in a symmetrical basin and has a maximum thickness of up to 9 km in its centre, NW of the Møre–Trøndelag Fault Complex. The Late Pliocene and Quaternary clastic units show a gentle NW slope with a relatively narrow continental shelf (Fig. 7).

The base of the Cretaceous outlines an irregular geometry in the SE flank of the basin with narrow basement highs separating subbasins with ca. 20 km of width (Fig. 7). These highs are interpreted to be bounded by low angle normal faults (Graue, 1992; Jongepier et al., 1996; Smelror et al., 1994) which along the transect of Fig. 7 dip mainly towards the NW. The onlap of the lower Cretaceous sediments against the base of the Cretaceous suggests that the entire unit infills a previous rift topography (Færseth & Lien, 2002). Furthermore, along the studied transect the Cretaceous to the Quaternary sequence contains no normal faults with significant offsets (Figs. 7 and 8). The faults are interpreted to only affect the rocks below the base of
the Cretaceous and to be active during Late Jurassic. In seismic profiles along the Slørebotn Subbasin the normal faults reveal both NW and SE dips (Fig. 8), but along the Møre-Trøndelag Fault Complex (Fig. 7) and the Klakk Fault Complex (Fig. 8) the faults dip towards the NW and have the most significant throws.

The heave across the Møre Margin fault system is estimated using the cutoff of the base of the Cretaceous in the different faults interpreted along the section of Fig. 8. The amount of heave estimated reaches 30 km. This value is a minimum estimate since the top of the pre-rift unit would provide more elevated values. In the eastern Møre Basin up to 40 km of extension were accommodated by a single normal fault according to Osmundsen et al. (2002). The geometry of the faults is listric and shows relatively low angles at upper levels (15–20° after depth conversion) (Fig. 8). This fault geometry has previously been documented in the Gossa High to the NE (Brekke & Riis, 1987) and along the Magnus Basin and the Manet Ridge to the SW of the margin (Graue, 1992; Nelson & Lamy, 1987).

### 4.3. Vøring–Møre transfer zone

The Vøring and Møre basins are characterised by fault systems with a dominant NE–SW strike. The two fault systems are connected along a 270 km long zone following the W side of the Trøndelag Platform (Fig. 9). Along this province the faults show an intricate trend between NE–SW and N–S that suggests that the region consists on a transfer zone between the Voring and Møre basins. In the study of this transfer zone we analyse the base of the Cretaceous horizon (in depth) of the study area supplied by Norsk Hydro. From the depth map a slope map is constructed (Fig. 9a). The colour gradation of the map shows the steeper slopes in white and the gentler slopes in black. Comparison

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Fig. 9. (a) Slope map of the base-of-Cretaceous horizon with the location of the sections represented in (c). Light colours represent the steeper slopes and were interpreted as normal faults. (b) Map geometry of the main faults affecting the pre-Cretaceous in the Voring and Møre basins. (c) The cross-sections showing the base of Cretaceous geometry allow the heave and the lateral continuity of the faults to be interpreted. See text for further discussion.
to seismic profiles shows that the steeper slopes (white) generally correspond to normal faults.

The main characteristic of this large-scale fault system, comprising the structures of the Vøring and Møre basins and of the transfer zone, is that all major faults dip towards the NW and W. The major fault along the Vøring Basin is located NW of the Nordland Ridge (fault “a” in Fig. 9). Towards the NW of this border fault, an antithetic set of normal faults constitutes the Fles Fault Complex (Fig. 3). The major fault zone in the Møre Basin is located along the Møre–Trøndelag Fault Complex and continues with a N–S trend along the Klakk Fault Complex in the transfer zone (fault “b” in Fig. 9). The limit between the transfer zone and the Vøring Basin is constituted by a system of synthetic normal faults (fault “c” and nearby faults in Fig. 9), showing smaller horizontal displacements. Towards the NW of the border faults there is a system of synthetic intrarift faults, with shorter lateral extent and smaller heaves. In the transfer zone, some of the intrarift faults have an overlapping geometry in map view (Morley, 1988) and are isolated from one another at the scale of the map (soft-linked faults according to Walsh & Watterson, 1991). An example of soft-linked faults are faults “d” and “e” or faults “f” and “g” in Fig. 9. Other faults appear to be linked on the scale of the map (hard-linked faults); for example, faults “b” and “f” or faults “g” and “h” in Fig. 9.

The timing of the formation of the SE border faults of the Vøring and Møre basins is interpreted to be previous to the Cretaceous deposition according to the analysis of seismic data (Figs. 4, 7 and 8). Consequently, a Middle to Late Jurassic timing of deformation (Færseth & Lien, 2002) is preferred at least for the SE fault system of the Mid Norwegian Margin. According to the map of the base of the Cretaceous (Fig. 9), the total extension related to the described fault system is approximately constant in the Vøring Basin, in the transfer zone and in the Møre Basin. This constitutes the SE border of the Middle to Late Jurassic rift that defined the Trøndelag Platform. The map of the faults (Fig. 9a) suggests that in the transfer region developed an oblique accommodation zone as a consequence of the en echelon arrangement of the Vøring and Møre basins. In this interpretation, the marginal highs in the Vøring and Møre margins may correspond to the NW conjugate of this rift system. It must be emphasised, however, that this conjugate fault system of the rift basin is not well imaged in the studied transects. The Late Cretaceous–Paleocene rifting, which developed more intensely in the NW part of the Vøring and Møre margins (Skogseid et al., 2000), likely overprinted the geometry of the NW side of the Vøring and Møre rift systems.

4.4. Geometry of the normal fault system

Along parts of the Mid-Norwegian Margin there is no clear evidence of the geometry at depth of the Late Paleozoic–Early Triassic and Middle to Late Jurassic normal faults. However, seismic data from the Vøring Margin reveal a shallow listric geometry in agreement with previous works (Brekke & Riis, 1987; Bukovics & Ziegler, 1985; Mosar, 2000). In the western Møre Margin at about 15 km depth (Gabrielsen et al., 1999) horizontal reflections are interpreted as the basal detachment of the normal fault system. These observations allow us to estimate the depth of the detachment in the Vøring Margin using simple geometrical techniques (Chevron construction) based on the geometry of the top of the pre-rift unit and on the geometry of the related border faults (Williams & Vann, 1987).

The depth of detachment is firstly estimated in the well-constrained Permo-Triassic Froan Basin, S of the Trøndelag Platform (Blystad et al., 1995) (Fig. 10a). The master fault

![Fig. 10. Estimation of the depth of the detachment and the geometry of the master normal fault of the Froan Basin utilising several versions of the Chevron construction assuming vertical shear (Williams & Vann, 1987).](image-url)
of this basin dips towards the SE and accommodates 2 km of horizontal extension according to the section K-K’ of Blystad et al. (1995). The section K-K’ is converted to depth to construct a hangingwall roll-over profile using the geometry of the base of the Permo-Triassic unit (Fig. 10b). Two Chevron constructions (Williams & Vann, 1987) with conservation of both heave and displacement determine a depth to the detachment of 20 and 24 km, respectively, below the top of the Triassic (22–26 km of depth below the present-day sea level).

The detachment in the Voring Basin is difficult to determine since the geometry of the Jurassic pre-rift unit is not well constrained. We use instead the base of the Cretaceous as determined by 3D gravity modelling (Torne et al., 2003). Given that the Jurassic syn-rift is relatively thin (less than 1 s TWT thick) in neighbouring regions like the Rás Basin (Fig. 4), the existence of a thin syn-rift succession could also be possible in the Voring Basin. Consequently, the effect of not considering the thickness of the syn-rift unit in the Chevron construction along the Voring Basin results in a slightly and acceptable underestimation of the depth to the detachment. In the Vøring Basin the depth to the detachment is calculated along the Træna Basin to Någrind Syncline study transect (Fig. 3). Furthermore, the detachment is also calculated in the transfer zone, along the Rás Basin transect west of the Klakk Fault Complex (Fig. 4). Along the Rás Basin the geometry of the bordering fault system is better constrained since the base of the Cretaceous and the syn-rift sediments can be interpreted from the seismic data (Fig. 4).

Along the Trøna Basin to Någrind Syncline transect (Fig. 11) the roll-over profile is constructed using the present-day geometry of the section and the 25 km of heave interpreted in this work for the SE boundary fault system of the Voring Basin. An alternative profile is based on the unloading and decompaction (Sclater & Christie, 1980) of Cenozoic and Cretaceous sediments. The latter method provides a section with a geometry comparable to that of the basin before the deposition of the Cretaceous unit. The unloading of the units involves flexural isostatic adjustment of the section, assuming a relatively low value for the effective elastic thickness (15 km) and a Young’s modulus value of $7 \times 10^{10}$ N. The compensation of the section using flexural isostasy is based on Turcotte and Schubert (1982). Using the present-day Trøna Basin section, three different depths to the detachment are obtained according to the different methods (depths referred to the present-day sea level) (Fig. 11b): (1) 24 km of depth using an area balance.
(Hamblin, 1965) and the Chevron construction (Williams & Vann, 1987) (Fig. 11b, d1 and d2); (2) 21 km of depth using the Chevron construction with 30° of antithetic inclined shear (White, Jackson, & McKenzie, 1986) (Fig. 11b, d3); and (3) 17 km of depth using 60° of antithetic shear (Fig. 11b, d4). Using the unloaded section (Fig. 11c) and the same methods as with the present-day section, the depths to the detachment become shallower: (1) 19 km of depth (Fig. 11c, d1 and d2); (2) 16 km of depth (Fig. 11c, d3); and (3) 15 km of depth below present-day sea level (Fig. 11c, d4). Using the present-day Rås Basin section and only the Chevron construction, a detachment located at 18 km of depth below the sea level is found.

The results of this modelling provide geometrically estimated detachments for the boundary fault against the Trøndelag Platform at depths between 22 and 26 km. The detachments estimated for the boundary fault against the Vøring Basin are at depths between 15 and 24 km. These depths can be overestimated, since the extension of subsidiary faults affecting the hangingwall of the master faults is not taken into account in the geometrical models (Song & Cawood, 2001). The subsidiary normal faults are especially abundant in the Froan Basin and in the Træna Basin. The obtained detachment against the Trøndelag Platform is deeper than the detachment interpreted at 15 km of depth in the Møre Basin (Gabrielsen et al., 1999). However, the majority of the detachments estimated for the Vøring Basin are at a depth close to that observed in the adjacent Møre Basin, specially the detachments obtained with the unloaded section (Fig. 11c).

5. Integration of extensional structure in crustal-scale sections

The upper crustal transects across the Vøring and Møre margins (Fig. 1) are combined with crustal profiles along the same transects constructed by 2D modelling (Figs. 12a and 13). The 2D modelling technique integrates heat flow, gravity, elevation and geoid data which permits to determine the thermal structure of the lithosphere and its density distribution at depth, under the assumptions of local isostasy and steady-state thermal regime. The modelling is performed using a finite element code, which solves simultaneously the geopotential, lithostatic and heat transport equations (Zeyen & Fernández, 1994). The crustal structure across the Vøring Margin is first constrained from available seismic data, from published ocean bottom seismograph (OBS) data (Mjelde et al., 2001) and expanded spread and wide aperture CDP profiling data (Mutter & Zehnder, 1988; Zehnder, Mutter, & Buhl, 1990). In the Trøndelag Platform and the offshore section of the profile, we use seismic results from Planke et al. (1991) and Korja, Korja, Luosto, & Heikkinen (1993), respectively. For the Vøring Marginal High and Vøring Basin, we use the crustal structure obtained from a combined 3D seismic and gravity
The work of Torne et al. (2003) also allows the geometry of the base of the Cretaceous in the Vøring Basin to be determined. The deeper crustal levels of the Møre Margin are constrained using OBS data provided by Norsk Hydro and deep seismic data from Olafsson et al. (1992). The obtained crustal models are compared with geophysical observations along the same transect showing a general good agreement.

The present-day thickness of the crust along the Vøring Margin thins towards the oceanic domain in a staircase geometry (Fig. 12). Major steps in the Moho topography approximately coincide with boundaries of major tectonic units at upper crustal levels. The first step is located underneath the SE boundary of the Trøndelag Platform. The thickness of the crust below the Trøndelag Platform is about 30 km. The second step roughly coincides with the SE boundary of the Vøring Basin. The lower crust thins to zero along this step, and the upper crust below the Vøring Basin thins from about 25 km against the SE flank to 15 km below the Vøring Marginal High. The thickness of the crystalline basement plus the pre-Cretaceous sediments is relatively small reaching minimum values of about 7–8 km across the southern end of the Vema Dome. The thickness of the crystalline basement plus the pre-Cretaceous sediments increases again towards the Vøring Marginal High although the entire crust shows its minimum thickness as it approaches the oceanic domain (Fig. 12). The Møre Margin crust (Fig. 13) shows a similar pattern but lacking the Trøndelag Platform equivalent. The first step is located approximately below the SE boundary of the Møre Basin and throughout this step the thickness of the lower crust reduces to zero. Along this transect the minimum pre-Cretaceous crustal thickness is located below the inner lava flows SE of the Færoe-Shetland Escarpment, and increases again towards the Møre Marginal High to thin to zero towards the oceanic domain. Along this marginal high, the total crustal thickness is reduced to about 10 km (Fig. 13). The combination of the crustal models across the Vøring and Møre margins with the proposed geometries of the fault system and the interpreted depths of the basal detachment is used to constrain the extensional geometry of the Mid-Norwegian crust.

In the Trøndelag Platform the normal faults of the Permo-Triassic basins have relatively steep dips (50–70°) in their upper 10 km. The estimated geometry of the Froan Basin master fault (Fig. 10) is used to constrain the geometry at depth of the master fault of the Trøndelag Platform along the study transect (Fig. 12b). The depths calculated for the detachment in the Froan Basin coincide reasonably well with the boundary between the upper crust and the lower crust in the Trøndelag Platform as shown in Fig. 12b. No significant Permo-Triassic extension is found SE of this master fault, but Permo-Triassic basins are documented on the conjugate Greenland Margin (Stemmerik, Dam, Noe-Nygåard, Piasecki, & Surlyk, 1998). We
therefore infer that this master fault and detachment faced towards the centre of the rift system.

The detachments estimated for the Vøring Basin using the Chevron constructions range between 15 and 24 km of depth. Excluding these two extreme values the estimated depths are grouped around 20 km of depth below sea level (Fig. 11), which is close to the base of the upper crust underneath the Træna Basin. Hence in the present interpretation the SE border fault of the Vøring Basin flattens near the base of the upper crust at 20 km depth, and follows this interface to the NW below the Vøring Basin (Fig. 12c). The geometry of this master fault is completed using the fault geometry obtained from the Chevron construction that better fits the detachment located at 20 km of depth (Fig. 11). The fault shows a geometry with three gentle segments showing different dips. Its shallower segment dips 13° towards the NW. This fault is consistent with the formation of two basins separated by a structural high (Fig. 12c).

In the SE Møre Basin, the close spacing of a set of listric normal faults and the poorly known geometry of the NW part of the basin prevents a confident geometric estimate to the depth of the detachment. However, the very low dip and position of the faults strongly suggest a subhorizontal detachment located near the base of the upper crust (Fig. 13). Such a detachment would be 20 km deep at the basin depocentre and around 16 km deep towards the NW (Fig. 13). This interpretation is in close agreement with previous models suggested for this region (Gabrielsen et al., 1999; Nelson & Lamy, 1987).

In our model the extensional detachment is located near the upper–lower crust boundary, although a location within the lower crust during Middle to Late Jurassic could also be possible. This model is similar to the crustal configuration interpreted in the Northern North Sea, where the lower crust acted as a weak zone in which the major extensional detachment sole out (Odinsen, Christiansson, Gabrielsen, Faleide, & Berge, 2000).

6. Stretching determination

The geometry of the upper crust in the Vøring Margin (NW of the Nordland Ridge) and in the Møre Margin are used to calculate the accumulated stretching since the Early Jurassic; this includes the Middle to Late Jurassic and Late Cretaceous–Paleocene rifting events (Fig. 14). We use only the upper crust in order to minimise errors derived from the differential stretching between upper and lower crust. The stretching estimation is performed along the two transects by comparing the present-day length of the pre-Cretaceous upper crust (including crystalline basement and pre-Cretaceous sediments) with the length of an undeformed crustal block with uniform thickness and equivalent area (Fig. 14). The thickness of the undeformed crustal block corresponds to the estimated thickness of the crust before the Middle to Late Jurassic rifting. The calculation is made assuming: (a) an extension direction approximately parallel to the transects; (b) an efficient decoupling between upper and lower crustal levels; and (c) a constant volume of upper crustal material through the consecutive extensional episodes. According to the last assumption, the Middle to Late Jurassic syn-rift geometry should not be considered in the area balance, since the syn-rift sediments can constitute new material added during the extension. Consequently, the resultant values of extension will be slightly underestimated.

In the Vøring Margin, Jurassic extension occurred mainly NW of the Trøndelag Platform. Hence, the upper crustal thickness measured at the Nordland Ridge, in the footwall of the Jurassic rift, is used as the initial upper crustal thickness. This thickness is 20 km. After area balance, the amount of Middle to Late Jurassic extension is 110 km resulting in a mean ß factor value of 1.6 and reaching a maximum of 2.5 in the Vema Dome (Fig. 14).

According to Skogseid et al. (2000) the crust of the Møre Margin that is not affected by Jurassic extension is located on the SE side of the basin edge, near the coastline. In a first approach, 28 km of upper crust is measured near the coastline and is considered as the thickness of the upper crust before Jurassic rifting (Fig. 14). The total extension using 28 km of initial thickness is 180 km, resulting in a mean ß factor of 2.2. However, according to Gabrielsen et al.
and an average β factor of 1.7 (Fig. 14). Using 20 km of initial thickness used in the Vøring Margin. The new results provide a more conservative amount of extension of 140 km and an average β factor of 1.7 (Fig. 14). Using 20 km of initial thickness, a maximum β factor of 2.9 is attained below the inner lava flows, to the NW of the margin close to the continent-ocean boundary.

The accuracy of the stretching determination using an area balance method largely depends on two factors. The first factor is the assumed thickness of the upper crust before the Middle to Late Jurassic extension. An overestimation of this initial thickness implies that a part of the estimated extension corresponds to older rift events. In contrast, an underestimation of the initial thickness implies that a greater amount of post-Middle Jurassic extension has to be expected. A thick pre-Cretaceous body (approximately 4 km) has been interpreted below the Gjallar Ridge (Torne et al., 2003). Torne et al. (2003) also indicate that this body could correspond to Triassic and Jurassic sediments. This implies that the pre-Jurassic extension can be significant NW of the Vøring Basin and thus, the initial upper crust could be thinner than estimated. Consequently, the post-Middle Jurassic extension determined for the Vøring Basin can be regarded a maximum value. The pre-Cretaceous sediments NW of the Møre Margin are around 5 km thick according to the crustal model of Fig. 13. Therefore, the obtained value of post-Early Jurassic extension for the Møre Margin is also a maximum estimate. The second factor is the loss or gain of volume in the upper crust related with the emplacement of the igneous material near the continent-ocean transition. The high velocity body interpreted as underplated material can contain significant portions of the upper crust (Mjelde et al., 2001, 2002; Raum et al., 2002) and part of the present-day upper crust can correspond to the igneous intrusions (Mjelde et al., 2001). The first case implies an area loss and thus, an overestimated extension. The second case implies an area gain and an underestimated extension. Loses and gains of volume are difficult to estimate and do not necessarily cancel each other. However, they mainly occur in the region close to the continent-ocean transition and thus, only significant modifications of the upper crustal volume along this region can seriously modify the stretching estimations. In this work such modifications are considered unlikely.

The amounts of extension presented here are only slightly lower than other previously published values taking into account that we only use the upper crust (Reemst & Cloetingh, 2000; Skogseid et al., 2000). Post-Early Jurassic stretching factors of 1.7 for the Vøring Margin and of 1.9 for the Møre Margin have been determined by Skogseid et al. (2000), based on backstripping analysis and crustal geometry. These β factors result in 160 and 150 km of accumulated horizontal extension for the Vøring and Møre margins, respectively. Reemst and Cloetingh (2000) have provided β factors for different rifting events in the Vøring Basin using also backstripping analysis and considering different geometries for the Cretaceous infill. Their model with a thick Cretaceous geometry (similar to our interpretation) gives a mean post-Early Jurassic β factor of around 1.8.

7. Middle to Late Jurassic rifting vs. Late Cretaceous–Paleocene rifting

In order to discriminate amounts of extension for different rifting periods we construct a simple geometric model to reproduce the geometry of the decompacted Cretaceous of the Vøring Basin as well as the thinning of the upper crust in this region (Fig. 15). In this model we assume: (a) an initial upper crust of 20 km of thickness; (b) an extension produced along normal faults interpreted in the seismic data and detached at the base of the upper crust; and (c) a deformation produced in the hangingwall of the faults by vertical shear, allowing a reasonable area conservation after faulting.

The model is extended along three normal faults interpreted to be active only during Middle to Late Jurassic extension. The first of these faults is the SE border fault of the Vøring Basin, which accommodates 25 km of heave and forms the Træna Basin-Någrind Syncline pair (Fig. 12). The second is the observed normal fault of the Nyk High with 5 km of extension, forming the depocenter of the present-day
Vema Dome (Fig. 12). The third fault, not shown in Fig. 12 is a fault interpreted NW of the Gjallar Ridge and dipping towards the SE that fits the crustal geometry of the Gjallar Ridge and Vema Dome regions (Fig. 15). Along this inferred fault, a heave of 15 km is tentatively estimated in order to produce crustal thinning along the Gjallar Ridge region, as has been predicted by backstripping analysis (Reemst & Cloetingh, 2000; Skogseid et al., 2000). This fault would form the NW border of the Jurassic rift and produces additional thinning below the Vema Dome, where a significant Cretaceous depocentre is documented.

This model reproduces quite well the geometry of the basins after 45 km of Middle to Late Jurassic fault displacement, but not the geometry of the entire upper crust. The geometry of the base of the model is flat given that isostatic compensation is not applied to the model. Furthermore, the resultant upper crust is thicker than the present-day one, a difference which increases towards the Voring Marginal High (Fig. 15). Different processes of thinning can affect the geometry of the upper crust: (1) a greater amount of Jurassic extension; (2) extension produced by pre-Jurassic rifting events; (3) brittle extension produced by post-Jurassic rifting events; and (4) mechanisms of ductile deformation at lower crustal levels.

A greater Middle to Late Jurassic extension cannot be completely ruled-out, since the 45 km of stretching interpreted here reproduce well the geometry of the base of the Cretaceous but the model does not consider the geometry of the Middle to Late Jurassic syn-rift. Also the Permo-Triassic rift could contribute in part to have previously thinned the crust. This could occur especially in the region of the Voring Marginal High, where a thick unit of pre-Cretaceous sediments (including Permo-Triassic and Jurassic) has been interpreted (Torne et al., 2003). However, according to Skogseid et al. (1992b, 2000) the major part of post-Middle Jurassic stretching corresponds to the Late Cretaceous–Paleocene rifting. This rifting episode produced thinning in the Voring Margin along a region 200 km wide, from the continent-ocean boundary to the Utgard High (Skogseid et al., 2000). The extent of this documented extension agrees well with our determined misfit of upper crustal thickness (Fig. 15). Thus, Late Cretaceous–Paleocene extension might have a significant contribution in upper crustal extension from the central Voring Basin to the continent-ocean boundary. Possible signs of ductile deformation that could contribute to the stretching of the crust are sigmoidal geometries interpreted underneath the Gjallar Ridge (Gernigon et al., 2001). Ductile deformation has also been inferred in the same location based on strong thickness variations detected in lower crustal layers (Mjelde et al., 2001).

The timing of the disappearance of the lower crust below the Cretaceous depocentres in the Voring and More margins is more difficult to determine with our data. The obtained geometry of the crust before the Late Cretaceous–Paleocene rifting event is compared with the crustal geometry of the Northern North Sea based on interpretation of deep seismic reflection data (Christiansson et al., 2000; Odinsen et al., 2000) (Fig. 16a). In the North Sea the crustal geometry is the result of two main rifting events occurred at late Paleozoic–Triassic and Late Jurassic times (Badley, Price, Rambech, Dahl, & Agdestein, 1988). After these extensional events, the Northern North Sea shows a very reduced, if any, lower crust below the centre of the Viking Graben, whereas the pre-Cretaceous upper crust (including crystalline basement, Permo-Triassic syn-rift and Triassic post-rift) has...
a thickness that ranges between 20 and 12 km. These thicknesses are similar to the thicknesses of the presented geometric model of the Vøring Basin after 45 km of horizontal extension. With these 45 km of extension, the lower crust could have been largely removed in the Vøring Basin if the proportions between the upper crustal and lower crustal thinning were similar than in the North Sea. The simplified structural map of Fig. 16b shows the axis of the Late Cretaceous–Paleocene rifting event overprinting a former basin configuration along the Mid Norwegian Margin leaving unaffected the Northern North Sea and thus preserving the Jurassic structure.

8. Conclusions

Our studies indicate that the Vøring and Møre margins experienced a similar amount of post-Early Jurassic extension before the continental break up. Middle to Late Jurassic extension took place in both the Vøring and Møre margins along a set of NW-dipping normal faults, which are interpreted to display a listric geometry at depth. This rifting event is interpreted to be associated with a very thin syn-rift deposition and followed by important post-rift Cretaceous infilling of the Vøring and Møre basins. The Middle to Late Jurassic extensional systems SE of the Vøring and Møre basins have the same polarity and may constitute the SE flank of the combined rift. These extensional systems are linked through a proposed N–S trending transfer zone at the SE continuation of the Jan Mayen Fracture Zone. This synthetic transfer zone formed in response to the inherited offset between the two SE border faults of the Vøring and Møre basins and is parallel to the W border of the Halten Terrace and Trendelag Platform.

Using the geometry of the Vøring and Møre basins and of their master faults we constructed simple geometric models to calculate possible depths to the basal detachment of the late Paleozoic–Triassic and Middle to Late Jurassic extensional fault systems. In the Trendelag Platform the obtained detachments are located at 22 and 26 km of depth. In the SE side of the Vøring Basin the estimated depths of the detachments are located between 15 and 24 km, with the preferred values around 20 km. In the Møre Margin, the low dip of the normal faults at shallow levels suggests that they become subhorizontal few km below the base of the Cretaceous. The geometry of the normal faults and the geometry of the crust favour an extensional detachment located at around 15 km of depth in agreement with previous estimations (Gabrielsen et al., 1999).

The integration of the structure with crustal models in both the Vøring and Møre margins suggests that the calculated depths for the basal detachment of the late Paleozoic–Triassic and Middle to Late Jurassic fault systems mostly coincide with the depth to base of the present upper crust SE of the transects. The detachment towards the NW is interpreted to follow the boundary between upper and lower crust. Using these combined crustal sections we construct an area balanced model to determine the upper crustal stretching. Values of 110 and 140 km of post-Early Jurassic horizontal extension are estimated for the Vøring and Møre margins, respectively. These values represent upper crustal mean stretching factors of 1.6 for the Vøring Basin and of 1.7 for the Møre Basin. The stretching factors for the entire crust are sensibly higher due to the geometry of the extremely thinned lower crust.

A forward geometric, area-balanced model of the upper crustal deformation suggests that significant part of the total post-Early Jurassic extension contributes to stretch the central NW Vøring and Møre basins during Late Cretaceous–Paleocene. This stretching event, possibly overprinted the NW flank of the Middle to Late Jurassic rift system.

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References


