VU Research Portal

Polyphase rift evolution of the Voring margin (Mid Norway): constraints from forward tectono-stratigraphic modelling.

Reemst, P.A.; Cloetingh, S.A.P.L.

published in

Tectonics

2000

DOI (link to publisher)

[10.1029/1999TC900025](https://doi.org/10.1029/1999TC900025)

[Link to publication in VU Research Portal](#)

citation for published version (APA)

Reemst, P. A., & Cloetingh, S. A. P. L. (2000). Polyphase rift evolution of the Voring margin (Mid Norway): constraints from forward tectono-stratigraphic modelling. *Tectonics*, 19(2), 225-240.
<https://doi.org/10.1029/1999TC900025>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

E-mail address:

vuresearchportal.ub@vu.nl

Polyphase rift evolution of the Vøring margin (mid-Norway): Constraints from forward tectonostratigraphic modeling

Paul Reemst¹ and Sierd Cloetingh

Tectonics/Structural Geology Group, Faculty of Earth Sciences, Vrije Universiteit, Amsterdam, Netherlands

Abstract. The mid-Norwegian Vøring margin bounding the northern Atlantic underwent several rift episodes after the Caledonian orogeny. Permo-Triassic extension concentrated at the eastern inner margin, followed by Jurassic-Cretaceous extension at the center of the margin. Finally, more westward, the last rift episode led to continental breakup in the earliest Eocene. Although the general architecture of the margin may be clear, the timing and distribution of particularly the oldest rift structures are poorly constrained. We use two-dimensional forward tectonostratigraphic modeling for better quantitative understanding of the tectonic evolution of the margin. Two regional profiles crossing the margin have been analyzed. Modeling of the two profiles integrates the basin shape and fill as well as the underlying crustal structure of the margin. The modeling allows us (1) to quantify the distribution and timing of extension of subsequent rift episodes, (2) to predict the basin and crustal architecture at deep levels, and (3) to test different interpretations of the seismic data. The level of lithospheric necking during basin formation is constrained by basement topography and Moho depth and lies within the middle crust (20 km). Furthermore, we investigate the migration of the rift axes and the elastic lithospheric strength during the different rift episodes. Locations of previous extension are not reactivated during renewed rifting. Instead, renewed rifting occurs preferentially in regions where the lithosphere has experienced less extension.

1. Introduction

The mid-Norwegian Vøring margin (Figure 1), at the edge of the European continent, forms the transition between the Fennoscandian mainland and the Atlantic Ocean. The margin records an almost 400 million year history of extensional basin evolution consisting of several distinct rift episodes [Ziegler, 1988; Skogseid *et al.*, 1992a], and the margin documents the most long-lived rift history of the world's present-day passive margins. Yet continental breakup between Greenland and Norway only occurred in the early Eocene after the most recent rift episode.

A large volume of seismic reflection and refraction data has greatly improved our knowledge of the crustal structure [Eldholm and Ewing, 1971; Eldholm and Mutter, 1986;

Planke *et al.*, 1991; Mutter *et al.*, 1984; Mutter and Zehnder, 1988; Skogseid and Eldholm, 1995; Digranes *et al.*, 1996] and basin fill of the margin [Boen *et al.*, 1984; Bukovics and Ziegler, 1985; Brekke and Riis, 1987; Dalland and Worsley, 1988; Skogseid and Eldholm, 1989; Brekke, 2000; Brekke *et al.*, 1999]. This large database makes the Vøring margin an excellent site to study the tectonic development and its relationships to the rift history of the larger northern Atlantic region.

In spite of the vast amount of data collected in the framework of recent petroleum exploration, different interpretations exist of the deep basin structure. Particular uncertainty exists on the base Cretaceous level in the deep Vøring Basin where well data do not reach into the deepest part of the basin and where sill intrusions hamper the interpretation of the seismic data. Despite a recently drilled well located at the Nyk High (profile 2) reaching into the Upper Cretaceous, geoscientists do still not agree on the base Cretaceous level in the deep adjacent basins [e.g. Blystad *et al.*, 1995; Skogseid and Eldholm, 1995; Skogseid *et al.*, 2000; Brekke, 2000; Brekke *et al.*, 1999]. This uncertainty affects interpretations of the tectonic history of the basin and is also transferred into reconstructions of the thermal history of the basin sediments.

In this paper, we integrate the basin evolution of the Vøring margin and the sub-basinal lithosphere in order to better constrain its Paleozoic until present-day tectonic history. Our approach addresses the tectonostratigraphic development of the basins across the margin and quantification of the amount of stretching during all subsequent rift episodes. For this purpose we carried out two-dimensional integrated modeling of both the crustal structure and basin stratigraphy along two regional profiles. Apart from studying the consequences of polyphase rifting of the margin, the modeling allows us to investigate quantitatively the implications of different structural and stratigraphic interpretations obtained from seismo-stratigraphy as well as the duration of the different rift episodes. In addition to uncertainties on the basin fill and shape, this also provides new constraints on the crustal structure and the thermomechanical evolution of the lithosphere.

Our results indicate that the maximum locus of extension migrates through time and that renewed rifting does not necessarily follow earlier rifts. Results of a recent study on the thermomechanical evolution of the south Alpine rifted margin [Bertotti *et al.*, 1997] show that the lithosphere on such locations is stronger than a nonextended lithosphere. The extension factors obtained provide new constraints on the development of the Vøring margin and consequently on

¹Now at Geologica, Stavanger, Norway.

Plate 1. Regional profiles showing basin configuration and crustal structure. Location is indicated in Figure 1. (a) Profile 1 (this study; B.T. Larsen, personal communication, 1990; and *Skogseid and Eldholm*, [1989]). (b) Profile 2: interpretation with a deep Cretaceous (DBC) Någrind Syncline (this study; B.T. Larsen personal communication, 1990; and *Blystad et al.*, [1995]). (c) Profile 2: alternative, shallow base Cretaceous (SBC) interpretation [*Skogseid and Eldholm*, 1995]. Expanding spread profiles (ESP) velocities and deep seismic reflection data [*Planke et al.*, 1991; *Skogseid et al.* 1992a; *Skogseid and Eldholm*, 1995] indicate the structure of the crust. HVB denotes high-velocity body ($7+ \text{ km s}^{-1}$) interpreted as magmatic underplate.

Figure 1. Structural elements, bathymetry, and location of regional profiles and wells on the Vøring margin. COB, continent ocean boundary; FSE, Faroe Shetland Escarpment; VE, Vøring Escarpment; SFZ, Senja Fracture Zone; JMFZ, Jan Mayen Fracture Zone. Inset shows location of the Vøring margin within the North Atlantic.

mechanical aspects of the breakup of the entire northern Atlantic region.

2. Tectonic Setting of the Vøring Margin

The Vøring margin underwent a protracted period of lithospheric extension after the Caledonian orogeny, starting during the Devonian with a phase of extensional collapse [Dewey, 1988] or, alternatively, regional extension [Fossen and Rykkelid, 1992]. Renewed, late Carboniferous to Triassic extension led to the formation of Permo-Triassic basins at the Trøndelag Platform (Plate 1) [Gabrielsen and Robinson, 1984; Bøen *et al.*, 1984; Bukovics *et al.*, 1984] and apparently continued into the Jurassic. Permo-Triassic extension probably also occurred at the Greenland conjugate margin [Larsen and Marcussen, 1992] and in the northern North Sea [Odinsen *et al.*, 2000, *ter Voorde et al.*, 2000]. The extent of the Permo-Triassic extension west of the Nordland Ridge is addressed by our models. Westward of the Nordland Ridge, Jurassic-Cretaceous extension was accompanied by major fault activity and resulted in the formation of the deep Cretaceous Vøring Basin, which encompasses several subbasins such as the Rås and Træna Basins [Bøen *et al.*, 1984; Bukovics *et al.*, 1984; Brekke and Riis, 1987; Skogseid and Eldholm, 1989; Blystad *et al.*, 1995]. The duration of this extension has been the subject of recent debate and is deliberated in section 5.

Finally, during the Late Cretaceous the last episode of lithospheric extension started and led to continental breakup during the earliest Eocene [Skogseid and Eldholm, 1989; Skogseid *et al.*, 1992a]. The late stage of the last rift episode was associated with igneous activity leading to the generation of large, subaerial, flood basalts within the North Atlantic Volcanic Province (Figure 1). This is the time when the Iceland Plume started to affect the NE Atlantic by filling the lithospheric relief (see Skogseid *et al.* [2000] for a discussion). The contemporaneous emplacement of magma at crustal levels during rifting resulted in the formation of anomalously thick oceanic crust and magmatic underplating of the thinned continental crust (Plate 1) [Planke *et al.*, 1991; Skogseid *et al.*, 1992a, b]. Consequently, the Vøring Marginal High was elevated above sea level during early Paleogene times and remained a sediment provenance area for the eastward Vøring Basin into the Eocene [Skogseid and Eldholm, 1989]. Since then, the Vøring margin gradually subsided and was covered by sediments in the Paleogene and Neogene from the uplifted Norwegian mainland [Riis and Fjeldskaar, 1992; Stuevold *et al.*, 1992; Reemst *et al.*, 1996; Stuevold and Eldholm, 1996; Rohrman and van der Beek, 1996].

3. Seismic Profiles

In our study, we used two depth-converted regional seismic profiles displaying the basin configuration and crustal structure across the Vøring margin (Plate 1). They extend from the Norwegian mainland to the oceanic crust and illustrate the division of the margin into the inner Trøndelag Platform, the Vøring Basin, and the Vøring Marginal High.

The Nordland Ridge separates the Trøndelag Platform from the Vøring Basin. Comparison of profiles 1 and 2 shows that the Nordland Ridge and associated faulting become less persistent to the north.

3.1. Profile 1

The Trøndelag Platform consists of a Permo-Triassic horst and graben terrain underlying a widely distributed sequence of Jurassic sediments of uniform thickness. The westward continuation of the Triassic and Jurassic horizons beyond the Nordland Ridge cannot be inferred from the seismic data directly in both profiles. Triassic sediments are presumed to be present under the Gjallar Ridge. Observed symmetric patterns along the axis of the Rås Basin suggest that the Jurassic sediments under the Dønna Terrace and west of the Rås Basin are of equal thickness.

The base Cretaceous horizon shows a significant basin relief across the margin which is well established at the Trøndelag Platform but has been inferred at the outer part of the margin without any well control. Particular uncertainty exists in the Fenris Graben, which has a Cretaceous age in our study but which according to Skogseid and Eldholm [1995] may be of Permo-Triassic or even older age. The graben shows also signs of Late Cretaceous inversion and is overlain by postrift Tertiary and Quaternary wedges.

3.2. Profile 2

Profile 2 has been interpreted differently by several academic and industrial geoscientists. Here we present two different interpretations: a so-called deep base Cretaceous (DBC) interpretation and a shallow base Cretaceous (SBC) interpretation. The differences between the SBC and DBC interpretations are the following:

1. The main difference is the position of the base Cretaceous horizon in the deep Vøring Basin. In the DBC interpretation the Vøring Basin consists of three Jurassic-Cretaceous subbasins: the Træna Basin, the Någrind Syncline, and the Hel Graben. According to Skogseid and Eldholm [1995] (SBC interpretation), the Någrind Syncline is of pre-Cretaceous age. In their interpretation the Cretaceous Træna Basin pinches out toward the Lofoten Islands, and extension shifts to the western Hel Graben where it continues northward and is cut off by Eocene oceanic crust [Skogseid *et al.*, 2000]. Analogous to the Jameson Land Basin on Greenland [Larsen and Marcussen, 1992], a Permo-Triassic or even Devonian age is assigned to the Någrind Syncline.

2. A second difference is the presence of Jurassic sediments between the Nordland Ridge and the Træna Basin (i.e. the northern extension of the Dønna Terrace).

3. A third difference is the inferred thickness of the Paleocene unit.

Geophysical data (Plates 1a and 1c) record a gradual crustal thinning across the margin landward of the continent-ocean boundary, punctuated by a pronounced reduction in crustal thickness beneath the Fenris Graben and the Rås Basin (profile 1) and beneath the Træna Basin and the Hel Graben (profile 2). The data also image voluminous extrusive complexes including seaward dipping reflectors, an

anomalously thick oceanic crust, and a high-velocity (>7 kms⁻¹) lower crustal body, interpreted as underplated magma [Skogseid and Eldholm, 1995].

4. Tectonostratigraphic Modeling of the Regional Profiles

4.1. Modeling Strategy

We use a two-dimensional pure shear forward model [Kooi *et al.*, 1992], modified after McKenzie [1978], including multiple stretching episodes of finite duration [Cochran, 1983; Jarvis and McKenzie, 1980] to analyze the polyphase rift evolution of the Vøring margin. It incorporates depth-dependent stretching [Royden and Keen, 1980] and lateral heat flow [Steckler, 1981].

The kinematics of stretching and the flexural isostatic response are controlled by the depth of necking [Braun and Beaumont, 1989; Kooi *et al.*, 1992] which describes the level around which the lithosphere is thinned during rifting. In this manner, fault-controlled synrift stratigraphy can be simulated without having to revert to unrealistically low flexural rigidities [Kooi *et al.*, 1992; Spadini *et al.*, 1995]. A constant necking level, slightly deeper than mid-crustal (Table 2), appears to be characteristic for all rift episodes. It has been obtained after testing for several values, constrained by Moho and basement relief, and is confirmed by dynamic models for rift evolution [e.g., Dunbar and Sawyer, 1989; Bassi *et al.*, 1993]. The necking level is measured from a reference sea level. This implies that in case of multiple rifting, also after a previous rift episode it remains within the middle crust because of the accumulated sediment pile on top of it. The flexural strength of the lithosphere is controlled by the 400°C isotherm compatible with reviews by van der Beek *et al.* [1994] and Burov and Diament [1995].

The model is run by dividing the lithosphere, with a constant prerift lateral thickness, into a number of 10 km wide boxes. Each box is assigned crustal (β) and subcrustal (δ) stretching factors for each episode. The thermal state and its

Table 2. Model Parameters Used in the Tectonostratigraphic Forward Model

Parameter	Symbol	Value
Initial lithospheric thickness, km	L	125
Initial crustal thickness, km	C	35
Coefficient of thermal expansion, °C ⁻¹	α	3.4×10^{-5}
Asthenospheric temperature, °C	T	1333
Thermal diffusivity, cm ² s ⁻¹	T	7.8
Necking level, km	z_{neck}	20
Isotherm describing EET, °C	T_{eet}	400
Surface density mantle rock, g cm ⁻³	ρ_m	3.30
Surface density crustal rock, g cm ⁻³	ρ_c	2.8
Water density, g cm ⁻³	ρ_w	1.03
Sediment grain density, g cm ⁻³	ρ_s	2.60
Sediment surface porosity,	ϕ_0	0.58
Compaction depth constant, km ⁻¹	c	0.41
Gravitational acceleration, m s ⁻²	g	9.8

EET, equivalent elastic thickness.

subsequent subsidence/uplift are calculated using a finite difference scheme. Optionally, variations in intraplate stress can be applied [Cloetingh *et al.*, 1985]. The basement subsidence is inverted to the corresponding stratigraphy by fill of sediments to a paleowater depth profile for each time step, taking compaction into account. A long-term sea level curve based on the work of Bond and Kominz [1984] has been applied. Paleowater depth estimates have been obtained from biostratigraphic information derived from drilling samples and seismic correlations [Eldholm *et al.*, 1989; Skogseid *et al.*, 1992a; Poole and Vorren, 1993; B.T. Larsen personal communication, 1991]. The stratigraphic horizons following the Harland *et al.* [1989] timescale and model parameters are displayed in Tables 1 and 2.

On the basis of inspection of the two regional profiles (Plate 1), subsidence analysis from well data [Reemst, 1995], and the tectonic history of the Vøring margin [Skogseid *et al.*, 1992a], we adopted the following stretching episodes in the models: a Permo-Triassic episode (290-235 Ma), a Late Jurassic-Early Cretaceous episode (170-95 Ma), and a Late Cretaceous-Early Tertiary episode (75-57 Ma). These episodes correspond to periods of fault activity creating horst and graben structures within the different regions, and they have been mapped from seismic data [Gabrielsen *et al.*, 1984; Blystad *et al.*, 1995]. The earliest extensional episode of Devonian age is not included. Instead, an initial crustal thickness of 35 km has been used, representing the average crustal thickness after extensional collapse of the Caledonian orogeny. For reasons discussed in section 4.2 we have divided the Late Jurassic-Early Cretaceous and Late Cretaceous-early Tertiary episodes into two phases with the transitions at 140 and 60 Ma, respectively.

For each of the three major episodes the amount of crustal and subcrustal stretching employed has been obtained by a trial and error procedure to obtain a best fit with the interpreted profiles. We have considered the underplate to be part of the crust, which, in terms of isostasy, is a reasonable assumption.

Table 1. Assigned Ages of Stratigraphic Units and Seismic Reflectors

Reflector	Age, Ma
Seafloor	0
Base Quaternary	2
Base Pliocene	5
Top Paleocene	57
Top Cretaceous	65
Cenomanian (mid-Cretaceous)	97
Base Cretaceous	145
Intra-Jurassic 1	185
Intra-Jurassic 2	195
Base Jurassic	208
Intra-Triassic 1	227
Intra-Triassic 2	233
Middle Triassic	235
Permian	245

Plate 2. Modeled cross sections of profile1 for different time steps. VMH, Vøring Marginal High.

4.2. Modeled Basin Evolution

The preferred models for the two transects are presented in the form of forward modeled paleostratigraphic cross sections for a number of time steps (Plates 2-4). The paleo-stratigraphic cross sections represent the evolution of the different basins across the margin through time.

4.2.1. Profile 1: Permo-Triassic - Early Jurassic. Maximum stretching is adopted beneath the Trøndelag Platform and beneath the Fenris Graben with uniformly distributed stretching in between. This is consistent with the observation of Permo-Triassic extension over a very wide region, including the conjugate East Greenland side of the rift system [Surlyk *et al.*, 1984; Larsen and Marcussen, 1992] and the North Sea [Gabrielsen *et al.*, 1990; Badley *et al.*, 1988; Færseth *et al.*, 1995]. At the same time, it is in good agreement with the relatively shallow level of the Moho in this area.

4.2.2. Profile 1: Middle Jurassic - Early Cretaceous. A broad Jurassic basin is modeled after stretching from 170 to 140 Ma, slowly tapering off toward the east and the west. This results in a unit of Jurassic and Early Cretaceous sediments in the Rås Basin, which we assume to exist on the basis of crustal structure, whereas at both flanks a thinner Jurassic layer is produced. Continued extension concentrates in the Rås Basin in the Early Cretaceous (140-95 Ma), separating the eastern located Trøndelag Platform from the deep Vøring Basin. West of the Rås Basin, the Gjallar Ridge develops as a high, separating the Rås Basin from the Fenris Graben. Subsequently, during Late Cretaceous times, a thick postrift sequence covers the rift basins and highs. A decreasing water depth reproduces the filling of a moderately deep basin during the Cretaceous.

In the modeled section the Nordland Ridge undergoes substantial postrift subsidence during the Cretaceous. Apparently, the distribution of the sediment load in the flexural model causes downbending of the Nordland Ridge during this phase. A relevant aspect of rift flank uplift is the detachment level of the faults bounding the rift [ter Voorde and Cloetingh, 1996] as well as erosion of the uplifted rift shoulder [van Balen *et al.*, 1995]. Whereas the model is based on a pure shear extension mode, the faults may continue into lower crustal levels and decouple the crust under the Trøndelag Platform from the crust underneath the Rås and Træna Basins. In such a scenario, footwall uplift of the Nordland Ridge may overrule the effect of lithospheric flexure during the postrift phase. Furthermore, erosion is governed by the input of a water depth profile which is adequate on margin-scale models. However, for detailed analysis of rift shoulders, dynamic erosion and sedimentation models have to be incorporated [e.g., Burov and Cloetingh, 1997].

4.2.3. Profile 1: Late Cretaceous - Eocene. In the first phase (75-60 Ma) we adopt depth-dependent stretching by increasing the sub-crustal stretching values to simulate the vertical motions associated with the arrival of the Iceland Plume [Skogseid *et al.*, 1992b; Lawver and Müller, 1994]. In the second phase (60-57 Ma), depth-dependent stretching of the lithosphere is employed to create oceanic lithosphere west of the continent ocean boundary (COB). For this purpose, the

subcrustal stretching factor has an infinite value [Parsons and Sclater, 1977]. Eastward of the COB, an increase of subcrustal stretching values is applied to model the isostatic uplift due to underplating.

Deep Paleocene water depths keep accommodation space available for the deposition of younger Tertiary sediments. The paleowater depth at the Trøndelag Platform is about 200 m more than the paleobathymetry estimates assumed by Poole and Vorren [1993].

At 60 Ma, owing to differential stretching to account for the arrival of the Iceland Plume in the region, thermally induced uplift at the Vøring Marginal High (VMH) occurs and leads to the deposition of only a thin Paleocene synrift sequence. Note that the Fenris Graben experiences uplift in the model, because of renewed thinning of already much thinned lithosphere. In addition to other controls [Brun and Nalpas, 1996], it can be considered as a mechanism to account for the observed inversion of the graben. Little subsidence occurs over the eastern part of the margin during this time, because the thermally induced uplift balances out the crustal thinning related subsidence. At breakup time (57 Ma) the model produces flexural as well as thermal uplift of the VMH.

4.2.4. Profile 1: Post breakup evolution. The next time step, until 5 Ma, shows the thermal contraction induced subsidence of the margin. The onset of glacial erosion over the shelf is modeled by an increase in bathymetry resulting in erosion of underlying sediments at the continental shelf. At the same time, sedimentation and subsidence continue at the outer part of the Vøring margin including the VMH. The last step in the stratigraphic model demonstrates the rapid progradation of the Pliocene-Pleistocene wedge by filling the earlier created accommodation space. This procedure results in deposition of a substantial but, with respect to the observations, too thin Pliocene wedge, especially at the Trøndelag Platform.

4.2.5. Profile 2: Permo-Triassic - Early Jurassic. In the DBC scenario (Plate 3), Permo-Triassic rifting concentrates on the Trøndelag Platform, whereas in the SBC scenario a second rift center is located beneath the Någrind Syncline (Plate 4). The geometry of the second basin is constrained by deep seismic reflection and refraction data providing control on the total sediment thickness and crustal structure (Plate 1).

4.2.6. Profile 2: Middle Jurassic - Early Cretaceous. In the DBC interpretation (Plate 1b) no pre-Cretaceous horizons have been identified beneath the Vøring Basin and on the Nordland Ridge. In contrast to profile 1, this leaves room for a scenario in which rifting concentrates in the Træna and Någrind Basins, accompanied by uplift of the Nordland Ridge, already during Jurassic times. Following this model, a deep Jurassic Træna Basin and Någrind Syncline develop. The Nordland Ridge becomes an elevated structure in already the earliest Cretaceous as a result of the 170-140 Ma rift episode, prohibiting the deposition of Jurassic sediments. The Nordland Ridge separates the two basins from the Trøndelag Platform where a shallow but broad Jurassic basin forms on top of the older Permo-Triassic structures. During continued extension in the Early Cretaceous (140-95 Ma) a further concentration of stretching in the Træna Basin and Någrind Syncline takes place, whereas the development of major

Plate 3. Modeled cross sections of profile 2 for different time steps following a deep base Cretaceous (DBC) interpretation of the Nâgrind Syncline.

Plate 4. Modeled cross sections of Profile 2 for different time steps following a shallow base Cretaceous (SBC) interpretation of the Nâgrind Syncline.

stretching in the Hel Graben is initiated. Subsequently, during the Late Cretaceous a postrift sequence covers the synrift basins and highs. In this model, like in profile 1, the postrift subsidence on the Nordland Ridge exceeds the value observed in the seismic section.

In the SBC model (Plate 4) the Late Jurassic extension is uniformly distributed over the profile, resulting in a Jurassic sequence that is about even in thickness over the whole section as in the seismic interpretation of Plate 1c. The main structuring of the margin between the Trøndelag Platform and the Vøring Basin, in this model, only occurs in the late Early Cretaceous (140–95 Ma). By middle Cretaceous times, two main Cretaceous basins have developed: the Træna Basin and the Hel Graben. In between, a broad area of minor subsidence exists across the Nâgrind Syncline. Simultaneously, the uplift of the Nordland Ridge occurs. A Late Cretaceous sequence covers the whole margin at 75 Ma. In the SBC scenario the modeled geometry on the Nordland Ridge better fits the observed profile owing to the later onset of the main phase of rifting. As also observed in the profile (Plate 1b), the modeled Early Cretaceous sediments are truncated and subsequently covered by Late Cretaceous sediments in vicinity of the ridge.

4.2.7. Profile 2: Late Cretaceous – Eocene. In both the DBC and SBC scenarios a small thermally induced uplift at the VMH occurs, because of differential stretching, and leads to deposition of a thin Paleocene synrift sequence at 60 Ma. Continued differential stretching leads to thermally and flexurally induced uplift and erosion of the VMH at 57 Ma. In the SBC scenario, two Paleocene depocenters are modeled: the Nâgrind Syncline and the Hel Graben. In the DBC scenario, however, a more even and thinner Paleocene unit is modeled. In both cases, uplift in the Hel Graben results from extension of already attenuated lithosphere. As mentioned in section 4.2.3., this may explain the observed inversion, i.e., the Vema Dome of *Skogseid and Eldholm* [1989] and *Stuevold et al.* [1992].

4.2.8. Profile 2: Post breakup evolution. The next time step, until 5 Ma, shows for both scenarios the thermal subsidence phase. Following the same procedure as that described for profile 1, the final step in the model shows a substantial but too thin Pliocene-Quaternary wedge. Filling to the present-day water depth results in the deposition of a thin Quaternary layer over the shelf. Apparently, the thermal subsidence in the postbreakup phase of the margin does not create enough accommodation space to allow deposition of the Miocene and Pliocene sediments. It has been shown that incorporation of a phase of intraplate compressive stress during the late Neogene can explain a considerable part of the necessary late stage margin subsidence [*Cloetingh et al.*, 1990; *Reemst*, 1995].

4.3. Stretching Distribution

4.3.1. Profile 1. The crustal stretching factors of the three individual rift episodes show a maximum of about 1.6 during the Permo-Triassic at the Trøndelag Platform, a maximum β of 2.7 during the Jurassic-Cretaceous episode at the Rås Basin, and a maximum β of 3.8 during the Cretaceous-Tertiary episode at the outer margin. This last number has

been corrected for underplating. To obtain a better estimate for the true amount of extension the thickness of the underplate is subtracted from the total crustal thickness. This corrected stretching value has a maximum underneath the Fenris Graben coinciding with the location where the underplate is thickest. The obtained stretching distribution shows a shift of maximum β peaks for each episode, reflecting a westward migration of the rift axis through time (Plate 5c). The cumulative crustal stretching factor (i.e., the total stretching up to a given time, obtained by multiplication of all foregoing stretching factors) is a measure of the total heat put into the model, including that to effectuate uplift above sea level during Cretaceous-Tertiary rifting and continental breakup. It reaches an infinite value in the oceanic domain.

4.3.2. Profile 2: DBC interpretation. Maximum Permo-Triassic stretching occurs at the Trøndelag Platform ($\beta=1.6$). During the Jurassic-Cretaceous extension episode the Træna Basin and Nâgrind Syncline yield maximum stretching values of 2.3 and 2.2, respectively. The model allows a major part of this extension to occur in the Late Jurassic, an interval not covered by seismic data. Beneath the western Hel Graben the major part of the Jurassic-Cretaceous extension occurs in the Early Cretaceous. Because the crust has been less thinned on this location during earlier phases, a relatively low Early Cretaceous β value causes more subsidence than that in the Nâgrind and Træna Basins. The stretching values employed during the last episode show a general westward increase but are low under the VMH where the crust is relatively thick. A corrected β value of 3.1 occurs where the underplate is thickest, i.e., at the Nyk High. As in profile 1, we recognize a westward migration of maximum stretching for the consecutive rift episodes (Plate 6c). The cumulative crustal stretching factors indicate three local maxima: beneath the Træna Basin ($\beta=3.9$), the Nâgrind Syncline ($\beta=5.3$), and at the Hel Graben ($\beta=4.1$). The cumulative subcrustal stretching increases toward the oceanic domain in the west.

4.3.3. Profile 2: SBC interpretation. In this scenario a maximum in Permo-Triassic stretching ($\beta=1.6$) at the Trøndelag Platform is accompanied by substantial stretching in the Nâgrind Syncline to account for the inferred thick pre-Jurassic strata at this location (Plate 7). Jurassic-Cretaceous rifting focuses in the Træna Basin ($\beta=1.6$) and the Hel Graben ($\beta=1.5$). The bulk part of this extension takes place during the Early Cretaceous rather than the Late Jurassic. In the Hel Graben a maximum in Cretaceous-Tertiary stretching occurs, which after correction for underplating amounts to a β value of 3.3. In general, a westward migration of maximum stretching can also be observed in this scenario although the pattern is slightly more complex as in the previous scenarios. During the first two rift episodes, two maxima occur with minor stretching in between, but they do not coincide. Apparently, renewed rifting preferably occurs at locations where minor stretching took place during a previous rift episode. The cumulative stretching values confirm the westward migration with a maximum of cumulative extension ($\beta_{\text{cum}}=4.6$), and the cumulative subcrustal stretching again increases toward the west.

Plate 5. Comparison of observed and modeled cross sections of profile 1 and the stretching distribution yielded from tectonostratigraphic modeling. (a) Interpreted profile 1. (b) Modeled profile 1. (c) Crustal stretching factors of individual rift episodes. (d) Cumulative crustal stretching distribution. (e) Cumulative sub-crustal stretching distribution.

4.4. Elastic Strength Calculations

In our model, the strength of the lithosphere, represented by its equivalent elastic thickness (EET), is defined by the 400°C isotherm [Watts *et al.*, 1982; Burov and Diament, 1995]. Following the thermal calculations of the finite difference scheme that we employed, values of the EET are made for each time step. This allows us to compare the lithospheric strength (in terms of its EET) at different locations across the margin during time (Figure 2). Minimum EET values are obtained in the center of a rift basin during extension. For example, during the first rift episode, rifting concentrates on the Trøndelag Platform, resulting in a reduced lithospheric strength. During the second rift episode, rifting does not occur where lithospheric strength is lowest but at a more western location. Inspection of Figure 2 shows that for each episode, renewed rifting does not coincide with the previous location

of rifting where the strength of the lithosphere is lowest. Instead, the new rift axis migrates to a new location.

4.5. Crustal Structure

Comparison of the modeled crust geometry with the crustal structure derived from seismic reflection and refraction data shows that in profile 1 (Plate 8) the modeled basement largely coincides with basement estimates inferred from other studies [Skogseid *et al.*, 1992a; Planke *et al.*, 1991; Skogseid and Eldholm, 1995]. In general, the modeled Moho fits the geophysical data. Discrepancies occur under the Vigrid Syncline and in the continent-ocean transition zone. In both areas the modeled Moho is at a shallower level than that in the geophysical interpretation. It should be noted that the data points are not located on the profile itself but are projected from a distance, giving rise to uncertainty of the exact depth.

Plate 6. Comparison of observed and modeled cross sections of profile 2 for the deep base Cretaceous (DBC) scenario and the stretching distribution yielded from tectonostratigraphic modeling. (a) Interpreted profile 1. (b) Modeled profile 1. (c) Crustal stretching factors of individual rift episodes. (d) Cumulative crustal stretching distribution. (e) Cumulative sub-crustal stretching distribution.

On the basis of reflection data only, it may be argued that a too thick pre-Cretaceous section has been modeled beneath the Vigrid Syncline. The modeled basement, however, indicates that incorporation of such a sediment pile meets the inferred basement relief [Skogseid *et al.* 1992a].

The modeled basement following the DBC interpretation (Plate 8b) coincides to a large extent with the reflection and refraction data. Also, the modeled Moho roughly agrees with the geophysical data. Deviations occur underneath the Nordland Ridge, where the modeled Moho is too deep, and at the Någrind Syncline, where it is shallower than that suggested by the data.

In the SBC case (Plate 8c), the comparison of the modeled Moho with the observations is slightly better whereas, at the

same time, the fit of the modeled basement with the seismic basement is worse. This may indicate that a thick pile of Devonian-Permian strata, as interpreted by Skogseid and Eldholm [1995] but not included in the models, does exist beneath the Træna Basin and the Någrind Syncline (see Plate 1c).

Deviations of the modeled crustal structure from the observations may arise from uncertainties in the model parameters. A particularly important parameter in fitting the crustal geometry is the level of necking. The observed crustal structure, showing both substantial basement and Moho topography, supports necking level within the middle crust.

Plate 7. Comparison of observed and modeled cross sections of profile 2 for the shallow base Cretaceous (SBC) scenario and the stretching distribution yielded from tectonostratigraphic modeling. (a) Interpreted profile 1. (b) Modeled profile 1. (c) Crustal stretching factors of individual

Figure 2. Equivalent elastic thickness (EET) values for different locations along the Vøring margin at the end of the consecutive rift episodes. Locations across profile 1 are the following: Vøring Marginal High (VMH), Fenris Graben (FG), Vigrid Syncline (VS), Rås Basin (RB), and Trøndelag Platform (TP). Locations across profile 2 are the following: VMH, Hel Graben (HG), Någrind Syncline (NS), Træna Basin (TB) and TP. End of Permo-Triassic rift is 245 Ma, end of Jurassic-Cretaceous rift is 95 Ma, and end of Cretaceous-Tertiary rift is 57 Ma. (a) Profile 1. (b) Profile 2, DBC scenario. (c) Profile 2, SBC scenario.

Testing of different necking values revealed that a necking level of 20 km produces a best fit with the general basin fill and crustal structure. A comparable midcrustal necking depth has been inferred from previous modeling studies along other segments of the Norwegian margin [Reemst *et al.*, 1994; van der Beek, 1995; Odinsen *et al.*, 2000].

5. Discussion and Conclusions

Different evolutionary scenarios of the margin have been modeled and provided additional information in areas where a seismostratigraphic framework is lacking. Generally, the modeling results show a good agreement between the large-scale basin shape and sedimentary architecture and the interpreted seismic data, but locally deviations from the basin stratigraphy and crustal structure occur. While the large-scale basin structure and fill can be considered as robust, the results are complicated by uncertainties in the model parameters (e.g., paleowater depth and compaction) and simplifications made, intrinsic to tectonic modeling studies. Our modeling study has a number of implications of key importance for the evolution of the Vøring margin and rifted continental margins in general.

5.1 Timing, Extent, and Magnitude of the Different Rift Episodes

It appears that substantial pre-Cretaceous crustal stretching has affected the Vøring Basin. Our model results indicate that Permo-Triassic rifting played a substantial role on the whole Vøring margin and not only at the Trøndelag Platform, where it can be observed on seismic reflection data. The modeled profiles provide the extent and magnitude of this rift episode and the accompanying basin shape also in areas beyond seismic resolution.

The length and magnitude of the Jurassic-Cretaceous rift episode are best modeled using a stretching event lasting into middle Cretaceous times (95 Ma) rather than being restricted to the Late Jurassic and earliest Cretaceous as in the adjacent North Sea rift system [Gabrielsen *et al.*, 1990]. Alternatively, a separate “middle Cretaceous” rift episode has been suggested by Blystad *et al.* [1995] and Lundin and Doré [1997]. In line with Skogseid *et al.* [2000], we argue that there is no distinct rift structure or basin of this age identified, and we prefer one Jurassic-Cretaceous rift episode extending into the middle Cretaceous.

In the Rås Basin (profile 1), substantial Late Jurassic

Plate 8. Modeled basin configuration and crustal structure and comparison with geophysical data and interpretations along the profiles. (a) Profile 1. (b) Profile 2, deep base Cretaceous (DBC) scenario. (c) Profile 2, shallow base Cretaceous (SBC) scenario. Seismic reflection and refraction data show basement, Moho, and shape of the underplated high velocity body ($>7 \text{ km s}^{-1}$) [Planke *et al.*, 1991; Skogseid *et al.* 1992a; Skogseid and Eldholm, 1995].

extension, based on rift axis symmetry, produces a reasonable fit of both stratigraphy and crustal structure to the available data. Permo-Triassic extension in the Fenris Graben is consistent with the interpreted crustal structure and Mesozoic-Cenozoic stratigraphy in this region.

A different interpretation of the seismic data resulted in two distinct model scenarios for profile 2: a deep base Cretaceous (DBC) and a shallow base Cretaceous (SBC) scenario. The DBC scenario is modeled analogue to profile 1 and encompasses substantial Late Jurassic extension in the Någrind and Træna Basins. In the SBC scenario, pre-Cretaceous extension already occurs during Permo-Triassic rifting in the Någrind Syncline and, to a lesser extent, in the Træna Basin. According to the SBC interpretation (Plate 1c), the thin Jurassic sequence beneath the Någrind and Træna Basins does not allow significant Jurassic extension. Thus extension is applied in the Permo-Triassic in order to account for the observed crustal thickness. Comparison of the modeled and observed basements, suggests a deep Cretaceous Någrind Syncline (DBC scenario), whereas the modeled

Moho better fits with a shallow Cretaceous Någrind Syncline (SBC scenario). On the basis of the present model results, neither scenarios can be excluded. However, recent commercial drilling has penetrated through a thick Late Cretaceous sequence on the Nyk High, and these results, although not open to the public in detail, seem to be in favor of a deep position of the base Cretaceous horizon [Brekke, 2000; Kittelsen *et al.*, 1999].

Our stretching values for the latest Cretaceous-Tertiary rift episode are higher than those calculated by one-dimensional subsidence analysis [Skogseid, 1994] and the flexural cantilever model [Walker *et al.*, 1997; Roberts *et al.*, 1997]. Whereas the former used Airy isostasy, the latter assumes unrealistically low (<2) EET values, both underestimating the strength of the lithosphere during and after rifting. Furthermore, both Walker *et al.* [1997] and Roberts *et al.* [1997] recognized that their own approach ignores underplating and does not include two-layer stretching to account for temperature anomalies as those of the Iceland Plume. As this can lead to large discrepancies

between stretching factors obtained from backstripping and forward modeling, the novel aspects included in our modeling are of key importance in modeling volcanic rifted margins.

5.2. Stretching Mechanics and Rift Migration

Uncertainty in the level of necking during the subsequent rift episodes affects the depths of the calculated Moho and basement. The shape of the interpreted Moho and basement, both showing a pronounced relief, indicates that necking of the lithosphere probably occurred around a midcrustal level.

The kinematically imposed level of necking has been interpreted in different ways. Kooi *et al.* [1992] related the necking level to a level of maximum lithospheric strength. Weissel and Karner [1989] related the kinematic level to a lower crustal detachment. A level corresponding to a transition zone between brittle and ductile deformation has been proposed by van der Beek *et al.* [1994]. Spadini *et al.* [1995] argue that a deep crustal necking depth corresponds to a lower crust being "squeezed" out between two strong lithospheric layers. Cloetingh *et al.* [1995] compiled an overview of kinematic parameters obtained for various rifted basins in different tectonic settings and discussed their correlation with prerift rheology. Most of these data have been inferred from basins undergoing one phase of crustal extension. Multiple episodes of lithospheric stretching makes the relationship between necking level and lithospheric strength and prerift rheology more complex. More work combining kinematic modeling and dynamic models of lithospheric extension [e.g., Bassi, 1995] is required to better

understand the role of necking during polyphase rifting and its relation to lithospheric strength.

The most striking aspect of the Vøring margin, i.e., the succession of several rift episodes, is incorporated into our models. An important result of our analysis is the migration of the locus of maximum extension through time. The strength of the lithosphere is significantly reduced at such locations during rifting, exemplified by lower EET values. However, an apparent increase in lithospheric strength must have occurred at these locations before the onset of a renewed episode of rifting. This notion is supported by a detailed study on the thermomechanical evolution of the south Alpine rifted margin [Bertotti *et al.*, 1997] incorporating a well-constrained rheological layering of the crust and mantle. As pointed out by these authors, after thermal relaxation, thinned parts of the margin are stronger as they have a higher proportion of strong mantle versus crustal material compared with nonthinned segments, even for slow rifts at passive margins. These findings corroborate our results which indicate that at the Vøring margin, renewed rifting preferentially occurs in apparently weak nonextended lithosphere rather than on the location of stronger lithosphere at previous rift axes.

Acknowledgments. Statoil is thanked for financial support and for providing data. Bjørn T. Larsen and Jakob Skogseid helped with the compilation of the profiles. Henk Kooi, Jakob Skogseid, Roy Gabrielsen, and Lars Jensen gave useful comments on earlier versions of the manuscript. Vladimir Lyakhovsky, Harald Brekke, and one anonymous reviewer gave useful comments. Netherlands Research School of Sedimentary Geology (NSG) publication 990210.

References

- Badley, M.E., J.D. Proce, C. Rambech-Dahl, and T. Agdenstein, The structural evolution of the northern Viking Graben and its bearing upon extensional modes of basin formation, *J. Geol. Soc. London*, **145**, 455-472, 1988.
- Bassi, G., Relative importance of strain rate and rheology for the mode of continental extension, *Geophys. J. Int.*, **122**, 195-210, 1995.
- Bassi, G., C.E. Keen, and P. Potter, Contrasting styles of rifting: Models and examples from the eastern Canadian margin, *Tectonics*, **12**, 639-655, 1993.
- Bertotti, G., M. ter Voorde, S. Cloetingh, and V. Picotti, Thermomechanical evolution of the south Alpine rifted margin (north Italy): Constraints on the strength of passive continental margins, *Earth Planet. Sci. Lett.*, **146**, 181-193, 1997.
- Blystad, P., H. Brekke, R.B. Færseth, B.T. Larsen, J. Skogseid, and B. Tørudbakken, Structural elements of the Norwegian Continental Shelf. II, The Norwegian Sea Region, *Norw. Petrol. Dir. Bull.*, **6**, 45 pp., 1995.
- Bøen, F., S. Eggen, and J. Vollset, Structures and basins of the margin from 62-69°N and their structural development, in *Petroleum Geology of the North European Margin*, edited by A.M. Spencer *et al.*, pp. 3-28, Graham and Trotman, Norwell, Mass., 1984.
- Bond, G.C., and M.A. Kominz, Construction of tectonic subsidence curves for the early Paleozoic miogeosyncline, southern Canadian Rocky Mountains: Implications for subsidence mechanisms, age of breakup and crustal thinning, *Geol. Soc. Am. Bull.*, **95**, 155-173, 1984.
- Braun, J., and C. Beaumont, A physical explanation of the relationship between flank uplifts and the breakup unconformity at rifted continental margins, *Geology*, **17**, 760-764, 1989.
- Brekke, H., The tectonic evolution of the Norwegian Sea Continental Margin with emphasis on the Vøring and Møre basins, *Geol. Soc. Spec. Publ.*, **167**, 327-378, 2000.
- Brekke, H., and F. Riis, Tectonics and basin evolution of the Norwegian shelf between 62°N and 72°N, *Nor. Geol. Tidsskr.*, **67**, 295-322, 1987.
- Brekke, H., S. Dahlgren, B. Nyland, and C. Magnus, The prospectivity of the Vøring and Møre basins on the Norwegian Sea continental margin, in *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*, edited by A.J. Fleet and S.A.R. Boldy, pp. 261-274, Geol. Soc. London, London, 1999.
- Brun, J.-P., and T. Nalpas, Graben inversion in nature and experiments, *Tectonics*, **15**, 677-687, 1996.
- Bukovics, C., and P.A. Ziegler, Tectonic development of the Mid-Norway continental margin, *Mar. Pet. Geol.*, **2**, 2-22, 1985.
- Bukovics, C., E.G. Cartier, N.D. Shaw and P.A. Ziegler, Structure and development of the Mid-Norway continental margin, in *Petroleum Geology of the North European Margin*, edited by A.M. Spencer *et al.*, pp. 407-423, Graham and Trotman, Norwell, Mass., 1984.
- Burov, E., and S. Cloetingh, Erosion and rift dynamics: new thermomechanical aspects of post-rift evolution of extensional basins, *Earth Planet. Sci. Lett.*, **150**, 7-26, 1997.
- Burov, E.B., and M. Diament, The effective elastic thickness (T_e) of continental lithosphere: What does it really mean? *J. Geophys. Res.*, **100**, 3905-3927, 1995.
- Cloetingh, S., H. McQueen, and K. Lambeck, On a tectonic mechanism for regional sea level variations, *Earth Planet. Sci. Lett.*, **75**, 157-166, 1985.
- Cloetingh, S., F. Gradstein, H. Kooi, A.C. Grant, and M. Kaminski, Did plate reorganisation cause rapid late Neogene subsidence around the Atlantic? *J. Geol. Soc. London*, **147**, 495-506, 1990.
- Cloetingh, S., J.D. van Wees, P.A. van der Beek, and G. Spadini, Role of pre-rift rheology in kinematics of extensional basin formation: Constraints from thermomechanical models of Mediterranean and intracratonic basins, *Mar. Pet. Geol.*, **12**, 793-807, 1995.
- Cochran, J.R., Effects of finite rifting times on the development of sedimentary basins, *Earth Planet. Sci. Lett.*, **66**, 289-302, 1983.
- Dalland, A., D. Worsley, and K. Ofstad (Eds.), A lithostratigraphic scheme for the Mesozoic and Cenozoic succession offshore mid- and northern Norway, *Norw. Petrol. Dir. Bull.*, **4**, 65 pp., 1988.
- Dewey, J.F., Extensional collapse of orogens, *Tectonics*, **7**, 1123-1139, 1988.
- Digranes, P., R. Mjelde, S. Kodaira, H. Shimamura, T. Kanazawa, H. Shiobara, and E.W. Berg, Modeling shear waves in OBS data from the Vøring Basin (Northern Norway) by 2-D ray-tracing, *Pure. Appl. Geophys.*, **147**, 611-629, 1996.
- Dunbar, J.A., and D.S. Sawyer, How preexisting

- weaknesses control the style of continental breakup, *J. Geophys. Res.*, **94**, 7278-7292, 1989.
- Eldholm, O., and J. Ewing, Marine geophysical survey in the southwestern Barents Sea, *J. Geophys. Res.*, **76**, 3832-3841, 1971.
- Eldholm, O., and J.C. Mutter, Basin structure of the Norwegian margin from analysis of digitally recorded sonobuoys, *J. Geophys. Res.*, **91**, 3763-3783, 1986.
- Eldholm, O., J. Thiede, and E. Taylor, Evolution of the Vøring Volcanic Margin, *Proc. Ocean Drill. Program Sci. Results*, **104**, 1033-1065, 1989.
- Færseth, R.B., R.H. Gabrielsen, and C.A. Hurich, Influence of basement structure of the North Sea basin, offshore southwest Norway, *Nor. Geol. Tidsskr.*, **75**, 105-119, 1995.
- Fossen, H., and E. Rykkeli, Post-collisional extension of the Caledonide orogen in Scandinavia: structural expressions and tectonic significance, *Geology*, **20**, 737-740, 1992.
- Gabrielsen, R.H., and C. Robinson, Tectonic inhomogeneities of the Kristiansund-Bodo Fault Complex, offshore mid-Norway, in *Petroleum Geology of the North European Margin* edited by A.M. Spencer et al., pp. 397-406, Graham and Trotman, Norwell, Mass., 1984.
- Gabrielsen, R.H., R. Færseth, G. Hamar, and H.C. Rønnevik, Nomenclature of the main structural features on the Norwegian Continental Shelf north of 62nd parallel, in *Petroleum Geology of the North European Margin*, edited by A.M. Spencer, et al., pp. 41-60, Graham and Trotman, Norwell, Mass., 1984.
- Gabrielsen, R.H., R.B. Færseth, R.J. Steel, S. Idil, and O.S. Kløvjan, Architectural styles of basin fill in the northern Viking Graben, in *Tectonic Evolution of the North Sea Rifts*, edited by D. Blundell and A.D. Gibbs, pp. 158-179, Clarendon, Oxford, England, 1990.
- Harland, W.B., R.L. Armstrong, A.V. Cox, L.E. Craig, A.G. Smith, and D.G. Smith, *A Geological Time Scale*, Cambridge Univ. Press, New York, 1989.
- Jarvis, G.T., and D.P. McKenzie, Sedimentary basin formation with finite extension rates, *Earth Planet. Sci. Lett.*, **48**, 42-52, 1980.
- Kittelsen, J.E., R.R. Hollingsworth, R.F. Marten, and E.K. Hansen, The first deep-water well in Norway and its implications for the Cretaceous play, Vøring Basin, in *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*, edited by A.J. Fleet and S.A.R. Boldy, pp. 275-280, Geol. Soc. London, London, 1999.
- Kooi, H., S. Cloetingh, and J. Burrus, Lithospheric necking and regional isostasy at extensional basins, 2, Stress-induced vertical motions and relative sea level changes, *J. Geophys. Res.*, **97**, 17,573-17,591, 1992.
- Larsen, H.C., and C. Marcussen, Sill-intrusions, flood basalt emplacement and deep crustal structure of the Scoresby Sund region, East Greenland, in *Magmatism and the Causes of Continental Breakup*, edited by B.C. Storey, T. Alabaster, and R.J. Pankhurst, *Geol. Soc. Spec. Publ.*, **68**, 365-386, 1992.
- Lawver, L.A., and R.D. Muller, Iceland hotspot track, *Geology*, **22**, 311-314, 1994.
- Lundin, E.R., and A.G. Doré, A tectonic model for the Norwegian passive margin with implications for the NE Atlantic: Early Cretaceous to break-up, *J. Geol. Soc. London*, **154**, 545-550, 1997.
- McKenzie, D.P., Some remarks on the development of sedimentary basins, *Earth Planet. Sci. Lett.*, **40**, 25-32, 1978.
- Mutter, J.C., and C.M. Zehnder, Deep crustal structure and magmatic processes: The inception of seafloor spreading in the Norwegian-Greenland Sea, in *Early Tertiary Volcanism and the Opening of the NE Atlantic*, edited by A.C. Morton and L.M. Parton, *Geol. Soc. Spec. Publ.*, **39**, 35-48, 1988.
- Mutter, J.C., M. Talwani, and P.L. Stoffa, Evidence for a thick oceanic crust adjacent to the Norwegian margin, *J. Geophys. Res.*, **89**, 483-502, 1984.
- Odinsen, T., P. Reemst, P. van der Beek, R.H. Gabrielsen, and J. I. Faleide, Permo-Triassic and Jurassic extension in the northern North Sea: Results from tectonostratigraphic forward modeling, *Geol. Soc. Spec. Publ.*, **167**, 83-104, 2000.
- Parsons, B., and J.G. Sclater, An analysis of the variation of ocean floor bathymetry and heat flow with age, *J. Geophys. Res.*, **82**, 803-828, 1977.
- Planke, S., J. Skogseid, and O. Eldholm, Crustal structure off Norway, 62 to 70 north, *Tectonophysics*, **189**, 91-107, 1991.
- Poole, D.A.R., and T.O. Vorren, Miocene to Quaternary paleoenvironments and uplift history on the mid Norwegian shelf, *Mar. Geol.*, **115**, 173-205, 1993.
- Reemst, P., Tectonic modelling of rifted continental margins: Basin evolution and tectono-agnatic development of the Norwegian and NW Australian margin, Ph.D. thesis, 183 pp., Vrije Univ., Amsterdam, 1995.
- Reemst, P., S. Cloetingh, and S. Fanavoll, Tectonostratigraphic modeling of Cenozoic uplift and erosion in the southwestern Barents Sea, *Mar. Pet. Geol.*, **11**, 478-490, 1994.
- Reemst, P., J. Skogseid, and B.T. Larsen, Base Pliocene velocity inversion on the eastern Vøring Margin: Causes and implications, in *Impact of Glaciations on Basin Evolution: Data and Models from the Norwegian Margin and Adjacent Areas*, *Global Planet. Change*, vol. 12, edited by A. Solheim et al., pp. 201-212, Elsevier, New York, 1996.
- Riis, F., and W. Fjeldskaar, On the magnitude of the late Tertiary and Quaternary erosion and its significance for the uplift of Scandinavia and the Barents Sea, in *Structural and Tectonic Modeling and its Application to Petroleum Geology*, edited by L.M. Larsen et al., *Norw. Petrol. Soc. Spec. Publ.*, **1**, pp. 163-185, Elsevier, New York, 1992.
- Roberts, A.M., E.R. Lundin, and N.J. Kusznir, Subsidence of the Vøring Basin and the influence of the Atlantic continental margin, *J. Geol. Soc. London*, **154**, 551-558, 1997.
- Rohrman, M., and P. van der Beek, Cenozoic postrift domal uplift of North Atlantic margins: An asthenospheric diapirism model, *Geology*, **24**, 901-904, 1996.
- Royden, L., and C.E. Keen, Rifting process and thermal evolution of the continental margin of eastern Canada determined from subsidence curves, *Earth Planet. Sci. Lett.*, **51**, 343-361, 1980.
- Skogseid, J., Dimensions of the Late Cretaceous-Paleocene Northeast Atlantic rift derived from Cenozoic subsidence, *Tectonophysics*, **189**, 91-107, 1994.
- Skogseid, J., and O. Eldholm, Vøring Plateau continental margin: Seismic interpretation, stratigraphy, and vertical movements, *Proc. Ocean Drill. Program Sci. Results*, **104**, 993-1030, 1989.
- Skogseid, J., and O. Eldholm, Rifted continental margin off mid-Norway, in *Rifted Ocean-Continent Boundaries*, edited by E. Banda, M. Torné, and M. Talwani, *NATO ASI Ser.*, **463**, 147-153, 1995.
- Skogseid, J., T. Pedersen, and V.B. Larsen, Vøring Basin: Subsidence and tectonic evolution, in *Structural and Tectonic Modeling and its Application to Petroleum Geology*, edited by R.M. Larsen et al., pp. 55-82, *NPF Spec. Publ.*, **1**, Elsevier, New York, 1992a.
- Skogseid, J., T. Pedersen, O. Eldholm, and B.T. Larsen, Tectonism and magmatism during NE Atlantic continental break-up: The Vøring Margin, in *Magmatism and the Causes of Continental Break-up*, edited by B.C. Storey, B.C. Alabaster, and R.J. Pankhurst, *Geol. Soc. Spec. Publ.*, **68**, 305-320, 1992b.
- Skogseid, J., S. Planke, J.I. Faleide, T. Pedersen, O. Eldholm, and F. Neverdal, NE Atlantic continental rifting and volcanic margin formation, *Geol. Soc. Spec. Publ.*, **167**, 295-326, 2000.
- Spadini, G., S. Cloetingh, and G. Bertotti, Thermo-mechanical modeling of the Tyrrhenian Sea: Lithospheric necking and kinematics of rifting, *Tectonics*, **14**, 629-644, 1995.
- Steckler, M.S., The thermal and mechanical evolution of Atlantic-type continental margins, Ph.D. thesis, 261 pp., Columbia Univ., Palisades, N.Y., 1981.
- Stuevold, L.M., and O. Eldholm, Cenozoic uplift of Fennoscandia inferred from a study of the mid-Norwegian margin, in *Impact of Glaciations on Basin Evolution: Data and Models from the Norwegian Margin and Adjacent Areas*, *Global Planet. Change*, vol. 12, edited by A. Solheim et al., 359-386, Elsevier, New York, 1996.
- Stuevold, L.M., J. Skogseid, and O. Eldholm, Post-Cretaceous uplift events on the Vøring continental margin, *Geology*, **20**, 919-922, 1992.
- Surlyk, F., S. Piasecki, F. Rolle, L. Stemmerik, E. Thompson, and P. Wrang, The Permian basin of east Greenland, in *Petroleum Geology of the North European Margin*, edited by A.M. Spencer et al., pp. 305-315, Graham and Trotman, Norwell, Mass., 1984.
- ter Voorde M., and S. Cloetingh, Numerical modelling of extension in faulted crust: Effects of localized and regional deformation on basins stratigraphy, in *Modern Developments in Structural Interpretation, Validation and Modelling*, edited by P.G. Buchanan, and D.A. Nieuwland, *Geol. Soc. Spec. Publ.*, **99**, 283-296, 1996.
- ter Voorde, M., R.B. Færseth, R.H. Gabrielsen, and S.A.P.L. Cloetingh, Repeated lithospheric extension in the northern Viking Graben: A coupled or a decoupled rheology, *Geol. Soc. Spec. Publ.*, **167**, 59-82, 2000.
- van Balen, R.T., P.A. van der Beek, and S.A.P.L. Cloetingh, The effect of rift shoulder erosion on stratal patterns at passive margins: Implications for sequence stratigraphy, *Earth Planet. Sci. Lett.*, **134**, 527-544, 1995.
- van der Beek, P.A., Tectonic evolution of continental rifts: Influences from numerical modeling and fission track thermochronology, Ph.D. thesis, Vrije Univ., Amsterdam, 1995.
- van der Beek, P.A., S. Cloetingh, and P.A.M. Andriessen, Mechanisms of extensional basin formation and vertical motions at rift flanks: Constraints from tectonic modelling and fission-track thermochronology, *Earth Planet. Sci. Lett.*, **121**, 417-433, 1994.
- Walker, I.M., K.A. Berry, J.R. Bruce, L. Bysto, and J.H. Snow, Structural modelling of regional depth profiles in the Vøring Basin: Implications for the structural and stratigraphic development of the Norwegian passive margin, *J. Geol. Soc. London*, **154**, 537-544, 1997.
- Watts, A.B., G.D. Karner, and M.S. Steckler, Lithospheric flexure and the evolution of sedimentary basins, *Philos. Trans. R. Soc. London, Ser. A*, **305**, 249-281, 1982.

- Weissel, J.K., and G.D. Karner, Flexural uplift of rift flanks due to mechanical unloading of the lithosphere during extension, *J. Geophys. Res.*, **94**, 13,919-13,950, 1989.
- Ziegler, P.A., Evolution of the Arctic-North Atlantic and the western Tethys. *Mem. Am. Assoc. Pet. Geol.*, **53**, 198 pp., 1988.

S.Cloetingh, Faculty of Earth Sciences, Vrije Universiteit, De Boelelaan 1085, 1081 HV Amsterdam, Netherlands.

P. Reemst, Geologica A.S., P.O. Box 8034, N-4068 Stavanger, Norway.(pre@geologica.no)

(Received June 2, 1997;
revised January 26, 1999;
accepted March 18, 1999.)