Scandinavia's North Atlantic passive margin

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[1] The tectonics of the eastern passive margin of the North Atlantic are reexamined. The Scandinavian North Atlantic passive margin includes not only the offshore exploration and basin domain but also large portions of the onshore domains of the Scandinavian Caledonides. Combined information from structural geology, potential field data, regional geology, basin development, and geomorphology made it possible to propose a new definition of the passive margin. The rift shoulder is formed by linked faults defining the present rift flank. These faults are the extensional structures located furthest to the east onshore Norway/Sweden that can be linked to the rifting that led to the formation of the North Atlantic. This innermost boundary fault system (IBF) is formed by a set of normal west dipping crustal faults. It extends over a distance exceeding 2000 km from the North Sea, across the Caledonian mountain belt to the Barents Sea. The passive margin width, between the continent-ocean boundary and the IBF, ranges from 550 km in the south to over 700 km in mid-Norway to 165 km north of Lofoten. Rifting and faulting on the IBF started in Permo-Carboniferous, and a succession of rift phases eventually culminated in continental breakup and the formation of the North Atlantic. Basin development between Permian and Cretaceous was toward the future breakaway fault, but faulting was also active on land from Mesozoic to Present. Onshore-offshore crustal-scale cross sections show the geometry of the passive margin, the dip orientation of the major faults and the changes in crustal thickness. *INDEX TERMS:* 8015 Structural Geology: Local crustal structure; 8010 Structural Geology: Fractures and faults; 8105 Tectonophysics: Continental margins and sedimentary basins (1212); 8109 Tectonophysics: Continental tectonics—extensional (0905); 8110 Tectonophysics: Continental tectonics—general (0905); *KEYWORDS:* Norway, Sweden, North Atlantic, passive margin, onshore-offshore, extension, normal faults

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1. Introduction

[2] Beside being one of Europe's largest hydrocarbon provinces, Norway's North Atlantic margin is also the site of one of Europe's most investigated mountain belts, the Caledonian orogen. This twofold view of the margin has not only a scientific basis, a Mesozoic-Cenozoic rift margin with basin development offshore and a Paleozoic mountain belt with imbricate thrusts onshore, but also an economic one, hydrocarbon and mineral exploration linked to human habitation. Therefore the understanding of the genetic and geodynamic links between these two domains is important for the future scientific and socio-economic development of Norway. In this paper I will discuss and reassess the geographic/geologic extent of the passive margin that began developing in Permian, possibly already in late Carboniferous, following the Caledonian orogenic collapse and the Devonian intramontane basin development.

[3] For a long time the onshore-offshore transition has been considered the transition from a domain of mountain building processes to one of rift-related processes. The whole margin has been the locus of continued extension since the Permo-Carboniferous. It can be demonstrated that a large part of the onshore mountain belt is part of the extended continental crust that forms the passive margin of the North Atlantic. The position of the rift flank is given by the locus of its associated innermost boundary fault system (IBF). It is proposed here that this IBF runs along the topographic crest of the present mountain range for a distance over 2000 km from the North Sea Viking Graben and the Barents Sea. In the south it corresponds to the Lærdal-Gjende-Olestøl fault system and the Hardangerfjord fault zone with a splay formed by the Ryfylke Shear Zone; in central Norway/Sweden it is represented by the Kopperå Fault, the Røragen detachment and the Åre Fault system; farther north in the Nordland area this fault has hitherto no equivalent and a new fault segment is proposed here. North of Tromsø, in the Finnmark area, known, but unnamed, normal fault sets form the link to the Barents Sea domain

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(Figures 1 and 2a) and the IBF terminates against the Trollfjord-Komagelv fault. Through time, the locus of the highest stretching has moved progressively westward.

2. Regional Geology

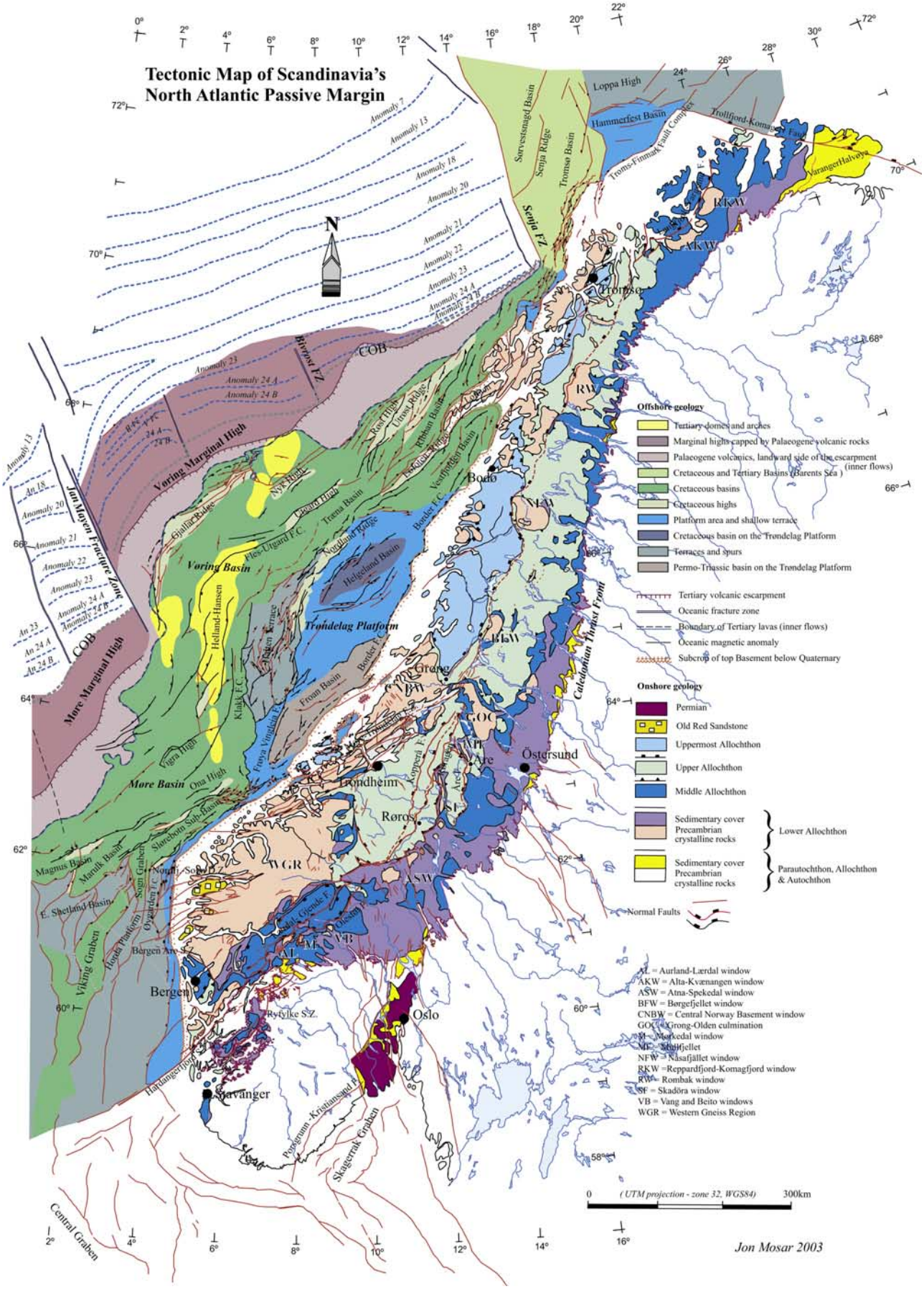
[4] On land in Norway and Sweden is the classic domain of the Caledonides, the mountain belt that formed as a result of the convergence of the North American plate with the west subducting margin of the Baltica plate that resulted in continent-continent collision. The stacked nappes comprise allochthonous continental and oceanic crust. They were the result of thrusting and tectonic underplating of the exotic terranes from Laurentia/Iapetus (microcontinents and island arcs) and imbrications of the Paleozoic passive margin of Baltica. The collisional climax was followed by a generalized collapse of the mountain belt [*Andersen*, 1998; *Fossen*, 1992] including the Scandian extensional events [*Osmundsen and Andersen*, 1994]. The development of intramontane, detrital Devonian basins [*Osmundsen et al.*, 1998; *Steel et al.*, 1985; *Steel*, 1976; *Ziegler*, 1996] followed the orogenic climax and is linked to the collapse of the mountain belt. The present-day thrust front of the overriding upper plate constitutes the remainder of the original thrust front which was farther to the east, and has been eroded [*Andréasson*, 1994; *Garfunkel and Greiling*, 1998; *Hossack and Cooper*, 1986] (Figure 1). The geodynamics causing the mountain chain collapse and the transition to the purely rift-related mechanisms are still debated [see, e.g., *Andersen and Jamtveit*, 1990; *Fossen*, 2000; *Hartz and Andresen*, 1997; *Koyi et al.*, 1999; *Milnes and Koyi*, 2000; *Milnes et al.*, 1997; *Mosar*, 2000; *Wilks and Cuthbert*, 1994]. This transition occurred during the late Devonian to Carboniferous. The rifting in a strict sense occurred from then on in a succession of phases. Norway's Atlantic margin is a classic passive margin that finally went from rifting to drifting in the early Tertiary (anomaly 24, around 53.9 Ma). Prior to, and during, the rift-drift transition the margin witnessed extensive volcanic activity and remains volcanically active today.

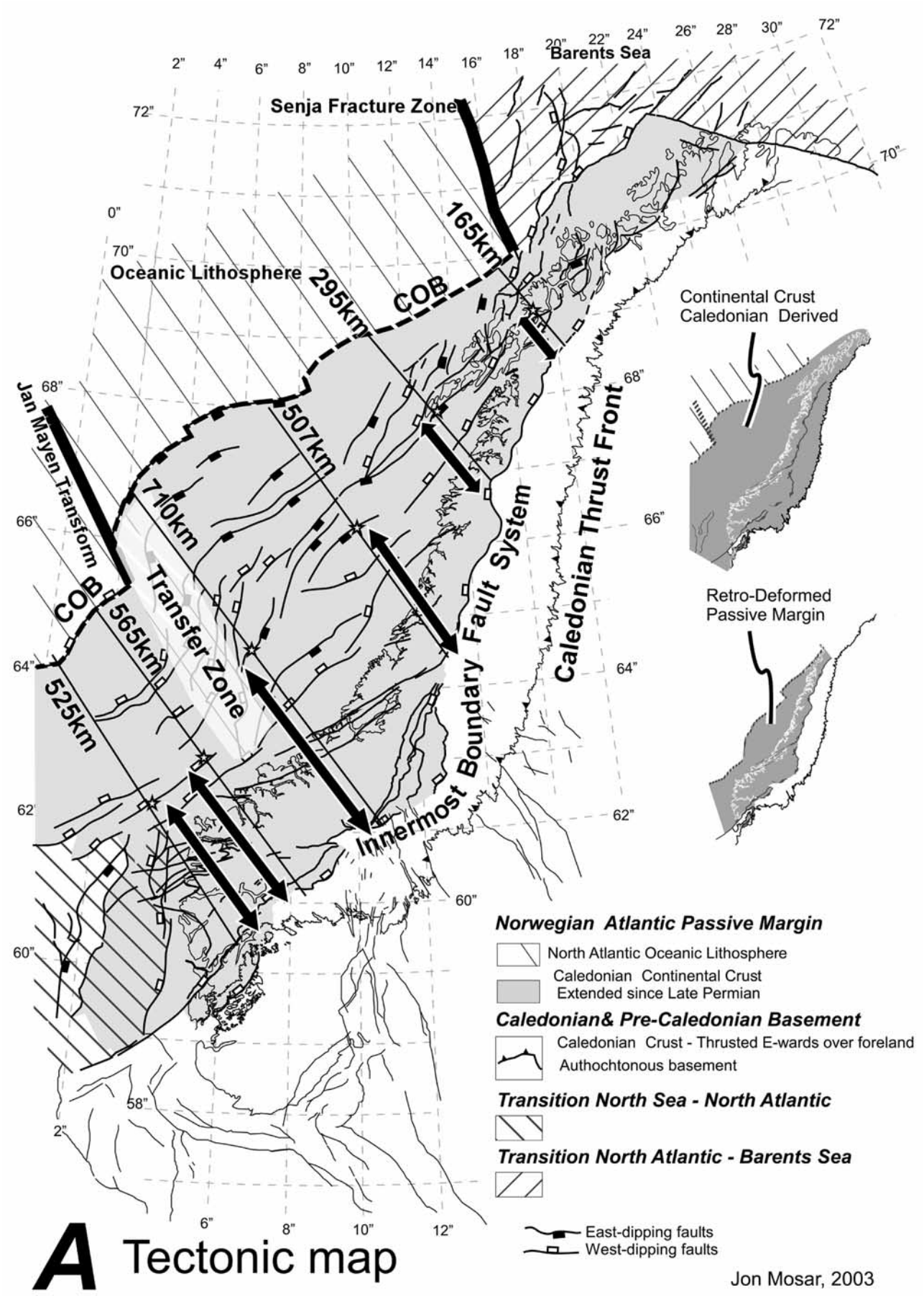
[5] Since the advent of petroleum exploration along the Norwegian coasts the offshore geology of the North Atlantic domains, including the mid-Norway shelf, has been extensively studied and discussed [*Blystad et al.*, 1995; *Fleet and Boldy*, 1999; *Nøttvedt*, 2000; *Parker*, 1993, and references therein]. To date, models for the development of the Norwegian Atlantic passive margin have mainly focused on the sedimentary cover sequence [*Brekke*, 2000; *Brekke et al.*, 2001; *Doré*, 1992b; *Doré et al.*, 1997; *Reemst and Cloetingh*, 2000; *Spencer et al.*, 1999; *Swiecicki et al.*, 1998; *Walker et al.*, 1997]. Basement structures offshore have been indirectly investigated through geophysical methods (potential field data, seismic reflection and refraction data). Three main structural domains can be identified between the transform margin of the Barents Sea to the north and the North Sea/Viking Graben to the south: (1) the Lofoton margin, (2) the Vøring Basin-Trøndelag Platform, and (3) the Møre Basin (Figure 1). The transition from continental crust to oceanic crust (the continent ocean boundary (COB)) has been located to the east of the oldest magnetic anomalies (24 A and B [see *Skogseid et al.*, 2000; *Torsvik et al.*, 2001a, 2001b, and references therein]). The transition from offshore to onshore/nearshore (the latter including areas with small sedimentary basins such as the Beistadfjorden basin in the Trondheim area [*Bøe and Bjerkli*, 1989; *Sommaruga and Bøe*, 2002]) has been considered the innermost part of the passive margin. The work presented here redefines this innermost margin position.

3. The Passive Margin

[6] Rifting of continental crust leads to the formation of important rift-bounding normal faults. An upper/lower plate geometry may develop when rifting is asymmetric [*Lister et al.*, 1991; *Voggenreiter et al.*, 1988; *Wernicke and Tilke*, 1989]. Rift flanks develop as a combined result of mechanically and thermally induced uplift along the rift flank fault and may generate as much as several km uplift [*Burov and Cloetingh*, 1997; *Kooi and Cloetingh*, 1992; *van der Beek et al.*, 1994]. Continued rifting will in many instances lead to drifting thus separating two conjugate continental margins along the breakup fault. The subsequent formation of new oceanic crust/lithosphere and the formation of new magnetic anomalies helps determine the location of the continent ocean boundary (COB). In an ideal case, each margin has a main normal fault system that forms the limit to the undeformed hinterland. The rift flank is the geomorphologic expression of uplift along an important extensional fault and ultimately only indicates an important fault movement with an important morphotectonic expression, rather than the location of the innermost passive margin fault. This latter, if of lesser throw, may not have a very important associated topographic relief. During subsequent rifting events the location of the fault with the largest offset may change. Thus defining the innermost boundary fault (IBF) first requires an in-depth investigation of the chronology and tectonics of the passive margin considered. This is especially relevant in polyphase rift margins such as the Norwegian North Atlantic margin, where rift-related normal faults were active as early as late Carboniferous and

Figure 1. (opposite) Simplified onshore-offshore geological map of the Scandinavian North Atlantic passive margin. In the offshore domain the different major tectonosedimentary events are indicated (adapted and modified from *Blystad et al.* [1995], *Brekke et al.* [1999], *Gabrielsen et al.* [1999], *Mosar* [2000], and *Smethurst* [2000]). The dip direction of some of the major normal faults in the offshore, such as in the Nyk High, the Utgard High, and the Gjellar Ridge, are shown according to interpretation of confidential deep seismic surveys [*Osmundsen et al.*, 2002]). The faults have been color coded according to dip direction: red for west dipping and black for east dipping. The onshore tectonostratigraphic map is a simplified and modified version of the Scandinavian Caledonides tectonostratigraphic map by *Gee et al.* [1985]. Offshore magnetic anomalies are according to *Skogseid et al.* [2000]. Added and highlighted are the major normal fault systems relating to the Permian (possibly late Carboniferous) to Present extensional rift-related events discussed in this paper (map projection UTM, zone 32, WGS84).


Tectonic Map of Scandinavia's North Atlantic Passive Margin
Offshore geology
Tertiary domes and arches
Marginal highs capped by Palaeogene volcanic rocks
Palaeogene volcanics, landward side of the escarpment (inner flows)
Cretaceous and Tertiary Basins (Barents Sea)
Cretaceous basins
Cretaceous highs
Platform area and shallow terrace
Cretaceous basin on the Trøndelag Platform
Terraces and spurs
Permo-Triassic basin on the Trøndelag Platform
Tertiary volcanic escarpment
Oceanic fracture zone
Boundary of Tertiary lavas (inner flows)
Oceanic magnetic anomaly
Subcrop of top Basement below Quaternary
Onshore geology
Permian
Old Red Sandstone
Uppermost Allochthon
Upper Allochthon
Middle Allochthon
Sedimentary cover
Precambrian crystalline rocks
Lower Allochthon
Sedimentary cover
Precambrian crystalline rocks
Parautochthon, Allochthon & Autochthon
Normal Faults
AL = Aurland-Lærdal window
AKW = Alta-Kvænangen window
ASW = Atna-Spekedal window
BFW = Børgefjellet window
CNBW = Central Norway Basement window
GOC = Grong-Olden culmination
M = Mørkedal window
MF = Meråkfjellet
NFW = Nasafjället window
RKW = Reppardfjord-Komagfjord window
RW = Rombak window
SF = Skadöra window
VB = Vang and Beito windows
WGR = Western Gneiss Region
Tromsø
Bodø
Grong
Trondheim
Røros
Östersund
Bergen
Oslo
Stavanger
Lofoten
Vesterålen
Senja Ridge
Senja F.Z.
Tromsø Basin
Loppa High
Hammerfest Basin
Troms-Finmark Fault Complex
Trollfjord-Komagfjord Fault
Varanger Halvøya
Sarvesismaed Basin
Vøring Marginal High
Vøring Basin
Jan Mayen Fracture Zone
More Marginal High
More Basin
Trøndelag Platform
Helgeland Basin
Froan Basin
Caledonian Thrust Front
Central Graben
Skagerrak Graben
Magnus Basin
Marulk Basin
E. Shetland Basin
Viking Graben
Hardangerfjord
Rytylke S.Z.
Porsgrunn - Kristiansand F.
0 (UTM projection - zone 32, WGS84) 300km
Jon Mosar 2003


Barents Sea
Senja Fracture Zone
165km
295km
COB
Oceanic Lithosphere
507km
710km
565km
525km
Jan Mayen Transform
Transfer Zone
Innermost Boundary Fault System
Caledonian Thrust Front
Continental Crust
Caledonian Derived
Retro-Deformed
Passive Margin
Norwegian Atlantic Passive Margin
North Atlantic Oceanic Lithosphere
Caledonian Continental Crust
Extended since Late Permian
Caledonian& Pre-Caledonian Basement
Caledonian Crust - Thrusted E-wards over foreland
Authochtonous basement
Transition North Sea - North Atlantic
Transition North Atlantic - Barents Sea
East-dipping faults
West-dipping faults
A Tectonic map
Jon Mosar, 2003

Permian. The finite extensional width of the passive margin is then measured between the innermost boundary fault, the rift flank, separating the extended passive margin from the unaffected continent, and the outermost breakaway fault that forms the transition to oceanic lithosphere-continent ocean boundary (COB).

[7] In order to determine the innermost rift boundary fault (IBF) of the passive margin, information from a variety of data sets were combined. The major criteria to reassess the passive margin width include: geomorphic features (morphology, water/glacial divides, topographic crest), structural features (normal faults), uplift data and age data, geophysical data (basement topography maps from potential field data), Bouguer gravity, and regional structural geology. Results from age determinations and kinematics of extensional faults were also used. Other rift events that originated in Permian times, such as the Oslo Rift and the North Sea, are aborted rift systems that are not part of the North Atlantic passive margin development in a strict sense, and rifting never went to completion by forming a full-fledged oceanic realm. These rift events do play, however, an important role in the uplift history of Norway and in the shaping of the sediment source regions.

3.1. Normal Faults and Regional Tectonics

[8] Normal faults have mainly been described from offshore Norway in the substratum of the Trøndelag Platform, in the Vøring Basin, in the Møre Basin, as well as beneath the Lofoten and Utrøst Ridges [*Blystad et al.*, 1995; *Gabrielsen et al.*, 1999; *Osmundsen et al.*, 2002; *Tsikalas et al.*, 2001]. In recent years, growing evidence shows that the onshore portion, too, is affected by extensional, crustal-scale faulting and development of small basins (Figure 1) [*Andersen*, 1998; *Andersen et al.*, 1999; *Hurich et al.*, 1988; *Mosar*, 2000; *Sjöström and Bergman*, 1989; *Sjöström et al.*, 1991; *Wilks and Cuthbert*, 1994]. These onshore crustal-scale extensional events were, however, mostly ascribed to the collapse of the Caledonian orogeny (see discussion on polyphase faulting in section 4). These structures are best described in western and southern Norway [*Andersen*, 1998; *Dunlap and Fossen*, 1998; *Fossen*, 2000; *Fossen and Rykkelid*, 1992; *Hurich*, 1996], where they form the Lærdal-Gjende-Olestøl fault system (Figure 1). It has since become clear that these faults are extensional faults linked to rifting. They were active mainly in Permo-Triassic, but also during the Mesozoic [*Andersen et al.*, 1999; *Braathen*, 1999; *Eide et al.*, 1997, 1999; *Torsvik et al.*, 1997]. Jurassic-Cretaceous faulting also formed small spoon-shaped sedimentary half grabens such as that developed in Beitstadfjorden, in the innermost Trondheimsfjord, along the Verran Fault branch of the Møre-Trøndelag Fault Complex [*Bøe and Bjerkli*, 1989; *Sommaruga and Bøe*, 2002], or in the Andøy area north of the Lofoten [*Dalland*, 1975]. Similar extensional faults have been described throughout the Caledonides in Norway and Sweden and it is proposed here that the eastern most of them form the IBF and its associated faults. From south to north several different domains can be distinguished:

[9] One of the best studied areas is onshore western Norway the Western Gneiss region and its offshore continuation into the Møre Basin. The transition from unfaulted crust (rift-related faulting) in the east to rift-related faulting of the crust to the west, is formed by the Lærdal-Gjende-Olestøl fault system (Figure 1). This fault system extends SW into the Hardangerfjord Shear Zone [*Andersen et al.*, 1998] and continues offshore [*Færseth et al.*, 1995; *Smethurst*, 2000]. Farther inland to the southeast, the Ryfylke Shear Zone forms a splay of the main IBF system. On plate tectonic reconstructions of the Late Permian it can be shown that this latter fault most probably connects across the then closed or largely closed North Sea realm, to faults bounding the Midland Valley rift system farther to the southwest in Great Britain.

[10] In central Norway, the IBF system is composed from east to west by the Kopperå Fault, the Røragen detachment and the Åre Fault which is the innermost fault (Figure 1) [*Mosar*, 2000]. The faults have been described in the field [*Gee et al.*, 1994; *Sjöström and Bergman*, 1989; *Sjöström et al.*, 1991] and on seismic profiles [*Gee*, 1991; *Hurich and Roberts*, 1997; *Palm*, 1991; *Palm et al.*, 1991]. They appear to merge northward near the northern tip of the Møre Trøndelag Fault Complex [*Gabrielsen et al.*, 1999; *Grønlie and Roberts*, 1989; *Roberts*, 1998] in the vicinity of the Grong-Olden culmination [*Braathen et al.*, 2000].

[11] The continuation toward the north of the IBF has, hitherto, not been described, and no brittle structures, though very likely, have been reported yet in published literature. Farther north in the Ofoten-Lofoten area, ductile and brittle extensional shear zones have been documented. Thus east of Bodø in the Nasafjället window [*Essex and Gromet*, 2000] and in the Rombak massif of the Ofoten area [*Coker et al.*, 1995; *Rykkelid and Andresen*, 1994], ductile shear zones of Caledonian and Devonian age were active inside the orogenic wedge. East of Tromsø, in the north Lofoten area, the IBF connects to the Senja Fracture Zone which forms the continent-ocean transform that developed in the early Tertiary between the Barents Sea and the North Atlantic. North and east of Tromsø, into Finnmark, the transition onshore to the Barents Sea is formed by the Troms-Finnmark Fault Complex [*Siedlecka and Roberts*, 1996a]. The IBF is located farther inland and is represented by a series of large normal faults including the Langfjord-Vargsund fault [*Townsend*, 1987]. The IBF terminates to the NE against the Trollfjord-Komagelv normal Fault [*Siedlecka and Roberts*, 1996b], which forms the northeastern boundary to the Barents Sea (Figures 1 and 2a).

[12] Offshore, rifting that led to the formation of the Norwegian North Atlantic passive margin, is associated

Figure 2a. (opposite) Simplified tectonic map of the Scandinavian North Atlantic passive margin indicating the position of the innermost boundary fault system (IBF) and the structure/size of the passive margin. Only the major normal faults are shown. The present location of the Caledonian thrust front is also indicated. Margin width is indicated along six different transects. Shortening of 50% is indicated by large black arrows. Small inset maps show the extent of the Caledonian related crust and the possible size of the passive margin after restoration to a pre-Late Permian situation and admitting a 50% overall shortening of the margin.

with important detachments at depth and high-angle extensional faults near the surface. The main structural domains of the passive margin are separated by several major normal fault systems. These fault systems and related structural highs and half graben features are actively under investigation [*Blystad et al.*, 1995; *Brekke*, 2000; *Brekke et al.*, 1999, 2001; *Bukovics et al.*, 1984; *Doré et al.*, 1997; *Gabrielsen*, 1986; *Osmundsen et al.*, 2002; *Smora and Delirius*, 2001]. Also, while discussion concerning the dip directions of some major faults is ongoing, the main structural domains of the passive margin can be identified and are separated by several normal fault systems. The main normal faults in the Møre Basin are dipping to the west [*Brekke*, 2000; *Gabrielsen et al.*, 1999]. Along shore, the Sløre botn half graben forms the first sedimentary basin offshore western Norway. It has a well recognized fault system separating it from the onshore realm. The extension to the north-northeast, of the major half graben bounding fault, which runs east of the Froan Basin and Trøndelag Platform, is less well recognized and is termed here the Border Fault Complex (Figure 1). This major basin bounding fault continues north into the Vestfjorden Basin, east of the Lofoten High. It separates the onshore basement from Permo-Triassic (Froan Basin) and Permian to Jurassic basins of the Trøndelag Platform. Along the Nordland Ridge and the Bremstein fault complex, the Trøndelag Platform is separated from the Halten Terrace. The Klakk, Ytterholmen, and Revfjellet fault complexes form the eastern edge of the deep Vøring Basin [*Blystad et al.*, 1995; *Brekke*, 2000; *Osmundsen et al.*, 2002; *Pascoe et al.*, 1999; *Roberts and Yielding*, 1991; *Schmidt*, 1992; *Withjack and Callaway*, 2000; *Withjack et al.*, 1989; *Yielding and Roberts*, 1992]. The Lofoten Ridge and the Utrøst Ridge, in the north, are both bound by important normal faults on each side. Structural highs inside the Vøring Basin such as the Utgard High, the Nyk High, the Gjallar Ridge, but also the Vigra High in the Møre Basin are all associated with important extensional faults. Some of the major Tertiary inversion structures such as the Helland Hansen Dome, are also related to important normal faults [*Lundin and Doré*, 2002; *Mosar et al.*, 2002a; *Sanchez-Ferrer et al.*, 1999].

[13] The development of extensional basins over normal faults creates a variety of geometries such as half grabens with rollover structures, crestal grabens and antithetic faults [see also *Gabrielsen*, 1986]. The outermost extensional faults in the system are located along the Vøring and Møre marginal highs.

3.2. Geomorphic Features

[14] The Fennoscandian North Atlantic coastal mountain region with its 2000 km length, shows a strong first-order asymmetry: (1) ocean board is a rugged morphology deeply incised by alpine glaciers and rivers draining into the Atlantic, and (2) landward, toward the craton interior, the slopes are gentle, and the rivers rather linearly drain toward the east into the Gulf of Bothnia and into the Skagerrak (North Sea) [*Gjessing*, 1967; *Holtedahl*, 1953; *Lidmar-Bergstöm et al.*, 2000; *Peulvast*, 1985] (Figure 2b). The mountain range shows two culminations, one in southwest Norway in the Jotunheimen area and one in Nordland, east of the Lofoten (in Sweden and Norway). Both areas culminate at over 2000 m. The central part of the mountain range, in central Norway, is shallower with summits in the 1500–1700 m range. The water/drainage divide is roughly coincident with the eastern side of the highest topographic points (Figure 2b).

[15] Studies on the morphotectonics, morphological surfaces (paleic surface, peneplains, block fields), valley incision, tilting and saprolites, indicate that the Scandian mountain range has been subjected in many places, if not everywhere, to continued post-Paleozoic erosion and peneplanation [*Gjessing*, 1967; *Lidmar-Bergstöm*, 1995; *Lidmar-Bergstöm et al.*, 2000; *Riis*, 1996]. Predating the last glaciation and postdating the Paleozoic peneplanation, several erosional surfaces and/or remnants can be discriminated: Middle Jurassic, Late Cretaceous, Paleogene, late Pliocene, and Pleistocene [*Doré*, 1992a; *Lidmar-Bergstöm et al.*, 2000; *Riis*, 1996]. Erosion and uplift producing tilting are much more important along the western coastal margin of the mountain range than inland to the east. Total uplift is estimated in the various areas to be of several kilometers.

[16] The IBF shows a first-order relationship with the main topographic features. The proposed fault system (Figures 1 and 2b) runs along the western side of the highest elevations in Nordland and central Norway/Sweden (Åre) which coincides with the water divide. This is true also for the southern portion of the Lærdal-Gjende fault zone (SW of the Olestøl fault). To the west are the rugged topography and the deeply incised valleys, to the east the rather uniform slope gently dipping toward the Gulf of Bothnia. This general feature suffers a major exception in the Western Gneiss area. Indeed, to the west, at the northern tip of the Lærdal-Gjende fault between Jotunheimen and Rondane, the highest topography is located to the west of the IBF. Also, the rivers between the Vang and Beito window and the Atna-Spekedal window, which form Gudbrandsdalen, drain the eastern Jotunheimen area and almost form a catchment across the mountain range. This area forms, however, a topographic high that is located to the southwest of a NW-SE trending normal fault with a dip to the NE. This fault merges where the Lærdal-Gjende-Olestøl fault system, which is the southern portion of the IBF, is relayed to the north by the Kopperå Fault, the Røragen detachment and the Åre Fault system. This could possibly explain why topography here, west of the IBF, could be higher than to the east.

3.3. Geophysical Data

[17] In the offshore domain most of the major faults have been documented using seismic investigation techniques, both shallow and deep, but the deeper structures remain topics of discussion [*Blystad et al.*, 1995; *Gabrielsen et al.*, 1999; *Mosar*, 2000; *Osmundsen et al.*, 2002]. Only few deep seismic lines are available onshore, but they clearly reveal major normal faults cutting the whole crust in the Western Gneiss region and also in central Norway and in Sweden [*Andersen*, 1998; *Gee*, 1991; *Hurich*, 1996; *Hurich et al.*, 1989; *Hurich and Roberts*, 1997; *Palm*, 1991; *Palm et al.*, 1991]. A recent reinvestigation of a deep seismic profile in central Norway-Sweden [*Juhojuntti et al.*, 2001] has shown a weak thinning of the crust west of the present Caledonian thrust front in the Åre area in the Sweden-Norway border zone. This area is coincident with the IBF location proposed here. The analyses by *Juhojuntti et al.*

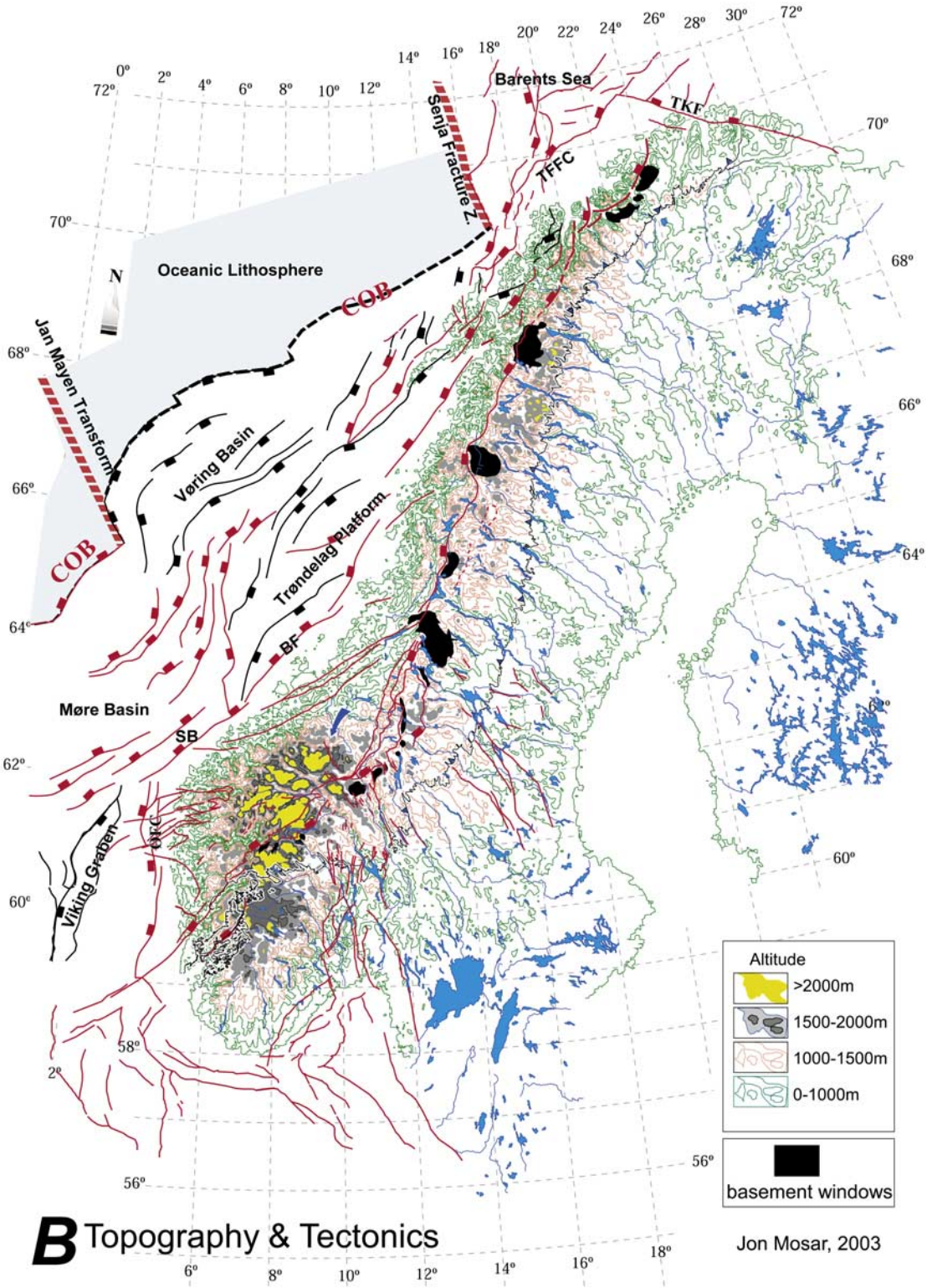


Figure 2b. Onshore morphotectonic map of the Scandinavian North Atlantic passive margin showing the main topographic features and their relation to the extensional structural features of the passive margin. The location of the westernmost basement windows (Caledonian thrusted basement) is also indicated. Notice the first-order asymmetry with gentle slopes to the east and more rugged topography to the west.

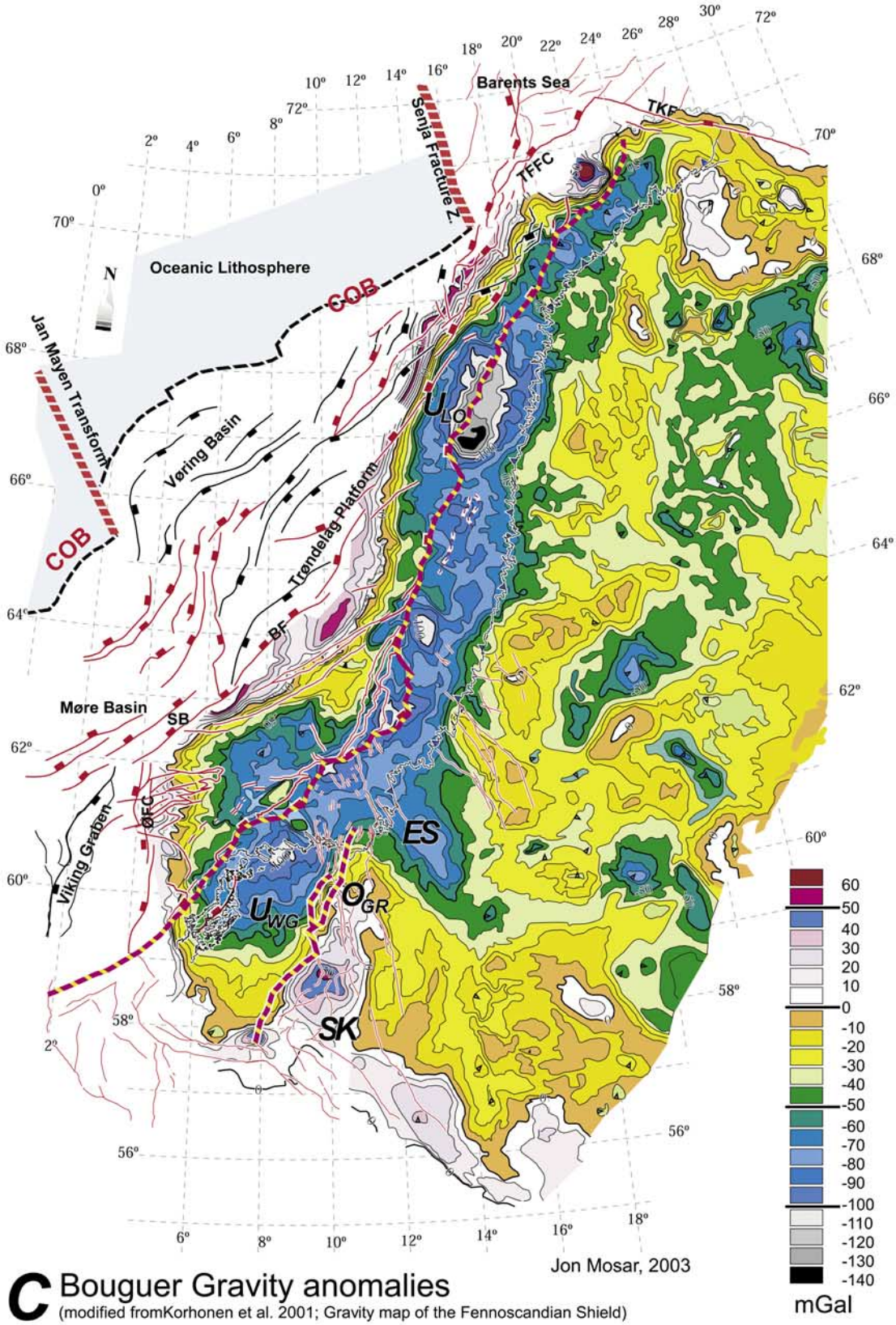


Figure 2c. Onshore Bouguer gravity anomaly map (terrain correction applied, modified from *Korhonen et al.* [1999]) of the Scandinavian North Atlantic passive margin with overlay of the major rift-related normal faults. Notice that the IBF is systematically located to the west of the main negative Bouguer anomaly (map projections UTM, zone 32, WGS84).

[2001] of the depth changes of the Moho from some 50 to 45 km show that this change is real. A thinning of the crust in a similar structural position, under the Hardanger-Lærdal-Gjende fault zone, has also been previously suggested [*Færseth et al.*, 1995; *Hurich*, 1996].

[18] Potential field data allow investigation of the deep structure of the basement/crust and lithospheric mantle. Bouguer gravity anomalies over Norway and Sweden (Figure 2c) show an important negative gravity anomaly (in excess of −100 mGal) that extends along the mountainous crest, onshore of the passive margin from the Western Gneiss region along the Norway/Swedish border to the north toward the Barents Sea [*Balling*, 1984; *Dyrelius*, 1985; *Korhonen et al.*, 1999; *Wolff*, 1984; *Kinck et al.*, 1993; *Olesen et al.*, 2002; *Poudjom Djomani et al.*, 1999; *Skilbrei et al.*, 2002]. The anomaly has been linked to a sub-Moho or base lithospheric structural heterogeneity implying a non negligible mass deficit. This deficit has been associated with deformation processes that have their origin in the deeper part of the lithosphere (mantle) [*Bannister et al.*, 1991].

[19] Using potential field data information, it is possible to derive a basement structure map of the Nordland area [*Olesen et al.*, 2002; *Skilbrei et al.*, 2001] which shows a consistent downdrop of several kilometers of the western block along an unknown fault whose surface trace runs west of the major basement windows and appears coincident with the IBF.

[20] Present-day uplift in Fennoscandia has been measured using a combination of techniques including GPS, tide gauges, and precise leveling together with gravity. Presently active, postglacial rebound subsequent to the last deglaciation is in the order of 800 m in the center Baltic Sea and 400 m west of the Caledonian thrust front [*Dehls et al.*, 2000]. It can be shown [*Bakkelid*, 1992; *Fjeldskaar et al.*, 2000, and references therein] that the present uplift, with a maximum of 8 mm/yr located over the Golf of Bothnia, is mainly caused by isostatic adjustment following melting of the Late Weichselian ice. However, a significant part of residual uplift is located in the mountainous area of Norway. *Fjeldskaar et al.* [2000] attribute this latter uplift to the way in which the glacial isostatic uplift is overprinted by a weak tectonic uplift component; the weak tectonic component must then be active at present.

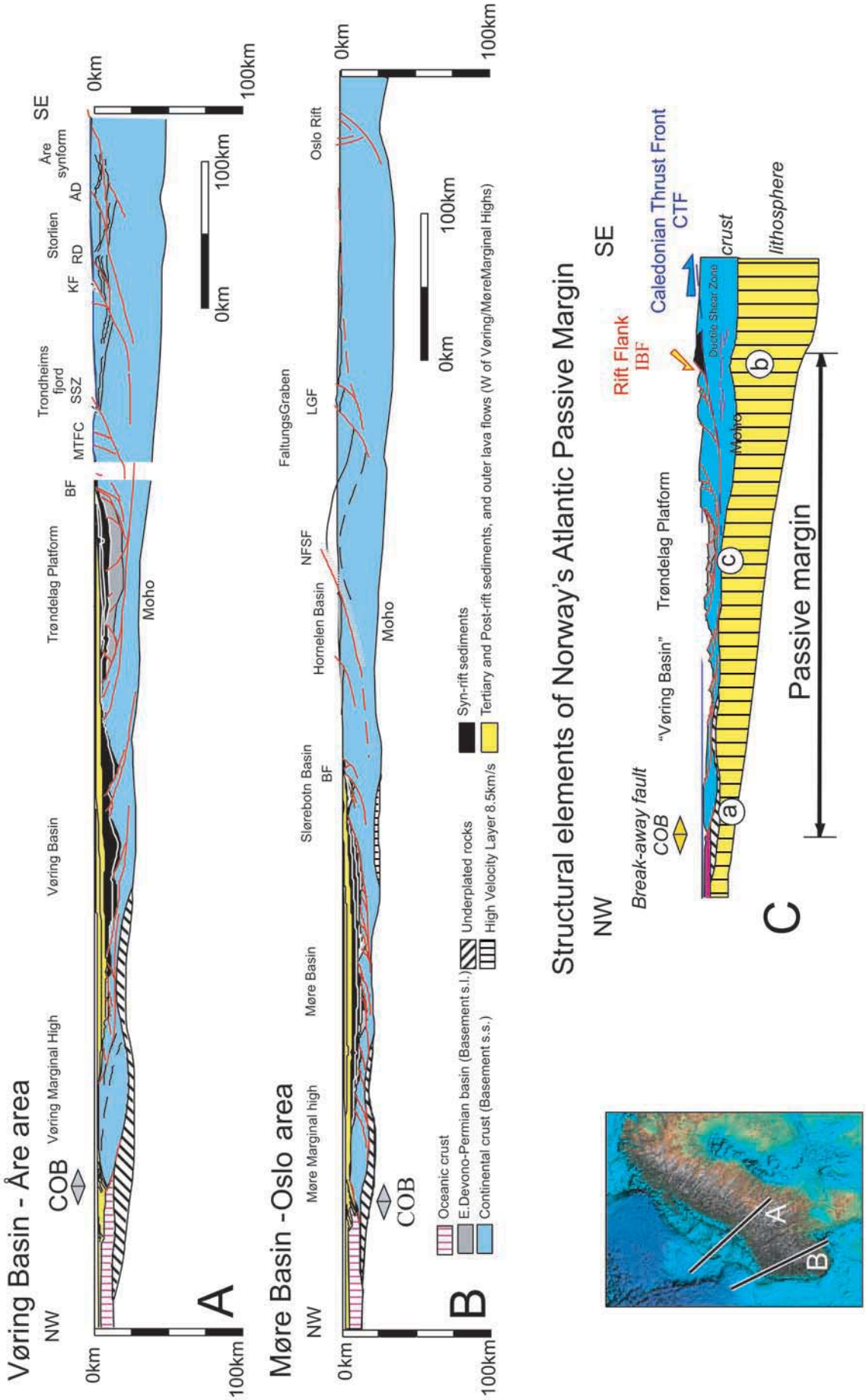
4. Polyphase Rift and Uplift History

[21] The present structure of the passive margin reflects the cumulative effect of several consecutive rifting events that controlled basin development, and climaxed in continental breakup, the opening of the North Atlantic and formation of new oceanic crust. These rifting events were coevel with Mesozoic uplift periods and preceded the important Tertiary uplift enhancing the present-day mountain topography.

[22] Prior to rifting in a strict sense, a syncollisional exhumation and postorogenic collapse dissected the imbricate thrust nappes of the Caledonides. This extensional faulting was active at different periods and at different depths, and has been documented from isotope ages, mineral assemblages, tectonics, and sedimentation history. Important extension (extensional collapse) occurred in Early Devonian (circa 410–405 Ma) at depths of ~10km, during and postdating the Scandian collisional climax [*Andersen*, 1998; *Boundy et al.*, 1996; *Braathen et al.*, 2000; *Dunlap and Fossen*, 1998; *Eide et al.*, 2002; *Essex and Gromet*, 2000; *Klein et al.*, 1999; *Terry et al.*, 2000; *Torsvik et al.*, 1997]. Simultaneously, and continuing into the Middle Devonian, continental sediments were deposited in transpressional/transtensional intramontane basins nested in the hanging walls of the Caledonian system [*Andersen et al.*, 1999; *Bøe et al.*, 1989; *Fossen*, 1992, 2000; *Osmundsen and Andersen*, 1994, 2001; *Steel*, 1976; *Ziegler*, 1988]. Some of these basins were deformed and metamorphosed to epizonal, lower greenschist facies conditions subsequent to deposition [*Bøe et al.*, 1989; *Sturt and Braathen*, 2001]. This, in turn, suggests that Early to Middle Devonian basins have been subjected to a postdepositional burial depth greater than 10 km. This is corroborated by data from fission track studies from offshore wells on the Horda Platform [*Andriessen and Bos*, 1986] which indicate removal of crustal material in excess of 13 km since 390 Ma (Middle Devonian). Similarly, the Silurian to Devonian foreland basin of the Caledonides, situated to the east and southeast of the present orogenic front, was filled with 2.5 to 4 km of sediments that were subsequently eroded [*Cederbom*, 2001; *Cederbom et al.*, 2000; *Larson et al.*, 1999]. No Carboniferous sediments are known from the Fennoscandian Caledonides, though they are known in Greenland indicating rifting started as early as Late Carbiniferous. Important, 2–5 km unroofing has been documented in western and southern Norway, following the extensional collapse of the mountain belt possibly as early as early Carboniferous [*Eide et al.*, 2002, 1999] and/or during Permo-Carboniferous times [*Dunlap and Fossen*, 1998].

[23] Rifting in a strict sense, related to the separation of Greenland and Norway (plate models and *Mosar et al.* [2002b, and references therein] and *Torsvik et al.* [2002, and references therein]), started in Permian, possibly in Late Carbiniferous, following the postorogenic collapse and the rapid early Carboniferous unroofing of the Caledonides and the associated formation and subsequent dismantling of the orogenic foredeep. The different rift-related uplift and subsidence events are best documented in the offshore part of the passive margin, even though considerable debate still exists as to the exact timing of all the important events. Onshore, and in the absence of sediments associated to the rifting, the different uplift/erosion events have been determined using paleomorphologic criteria, isotope dating and fission track studies.

[24] Offshore, the faults related to the different rifting events are ubiquitous and well known, and have been extensively studied and discussed [*Fleet and Boldy*, 1999; *Nøttvedt*, 2000; *Pascal and Gabrielsen*, 2001]. The generally accepted model involves multiphase rifting [*Brekke*, 2000; *Brekke et al.*, 1999; *Doré*, 1991, 1992b; *Doré et al.*, 1999; *Gabrielsen*, 1986; *Lundin and Doré*, 1997; *Skogseid and Eldholm*, 1995; *Skogseid et al.*, 1992b, 2000; *Torske and Prestvik*, 1991; *Vogt*, 1986a, 1986b]. The major rift events occurred in the Permian/Triassic, Late Jurassic/Early Cretaceous and Late Cretaceous/early Tertiary and the locus of rifting migrated westward with time [*Brekke*, 2000; *Reemst and Cloetingh*, 2000; *Spencer et al.*, 1999; *Swiecicki*


Vøring Basin - Åre area
NW
SE
0km
100km
COB
Vøring Marginal High
Vøring Basin
Trøndelag Platform
BF
MTFC
SSZ
Trondheims fjord
KF
RD
Storlien
AD
Åre synform
Moho
A
Møre Basin -Oslo area
Møre Marginal high
Møre Basin
Sløreboten Basin
Hornelen Basin
NFSF
FaltungsGraben
LGF
Oslo Rift
Oceanic crust
E.Devono-Permian basin (Basement s.l.)
Continental crust (Basement s.s.)
Underplated rocks
High Velocity Layer 8.5km/s
Syn-rift sediments
Tertiary and Post-rift sediments, and outer lava flows (W of Vøring/MøreMarginal Highs)
B
Structural elements of Norway's Atlantic Passive Margin
Break-away fault
COB
"Vøring Basin"
Trøndelag Platform
Rift Flank
IBF
Caledonian Thrust Front
CTF
Ductile Shear Zone
crust
lithosphere
Moho
a
b
c
Passive margin
C
A
B

et al., 1998; *Tsikalas et al.*, 2001; *Walker et al.*, 1997]. The major Permo-Triassic basin developed on the Trøndelag Platform and is separated from the onshore by the boundary fault (BF; Figures 1, 2, and 3). Farther west, the Late Jurassic rifting is characterized by the rotated fault blocks of the Halten Terrace and is also seen in the Slørebotn Subbasin. Smaller Jurassic basins, developing over listric normal faults are thought to form simultaneously farther west in the Vøring and Møre Basins but also onshore [*Bøe and Bjerkli*, 1989; *Sommaruga and Bøe*, 2002]. Important uplift, recognized on subsidence curves, has been documented during the latest Jurassic (around 140Ma). During the Cretaceous maximum subsidence occurred in the Vøring and Møre Basins. Alternatively, the Cretaceous sedimentation between 140 and 80 Ma is interpreted to represent a postrift thermal subsidence stage [*Færseth and Lien*, 2002]. Uplift at the edge of the Trøndelag Platform and the Halten Terrace indicate 1500m of footwall uplift due to elastic rebound [*Roberts and Yielding*, 1991; *Yielding and Roberts*, 1992], 0–5 km from south to north normal offset on Revfallet fault [*Pascoe et al.*, 1999], and basement cover decoupled faulting [*Blystad et al.*, 1995; *Brekke*, 2000; *Osmundsen et al.*, 2002; *Schmidt*, 1992; *Withjack and Callaway*, 2000; *Withjack et al.*, 1989]. Following the rift-drift transition in early Tertiary, inversion caused uplift centered around the areas of maximum Late Cretaceous to early Tertiary extension [*Mosar et al.*, 2002a].

[25] Onshore, it has been shown that some of the major normal faults in western Norway have Permian and younger ages. Thus recent dating on the Lærdal-Gjende-Olestøl fault system shows that movement on this latter fault system occurred in the Late Permian and in the Late Jurassic-Early Cretaceous [*Andersen et al.*, 1999; *Braathen et al.*, 1999; *Eide et al.*, 1997, 1999; *Torsvik et al.*, 1997, 1992] and had a brittle component. Farther to the NE, the Røragen-Koppera-Åre detachment system appears to be genetically linked with the Lærdal-Gjende-Olestøl fault system farther south. By analogy, it is suggested here that movements on the Åre-Røragen detachment system also occurred during the Permo-Mesozoic. Rift-related west dipping normal faults have been described in the Lofoten area. Some of these extensional faults are possibly of Permian age and are thought to affect the nappes and the basement [*Hames and Andresen*, 1996]. Along the mid-Norway coast, the Møre-Trøndelag Fault Complex forms a major high-strain shear zone [*Gabrielsen*, 1989; *Grønlie and Roberts*, 1989; *Séranne*, 1992]. Repeated reactivation recorded along this fault complex ranges from ductile movement in the Devonian period to brittle offsets in Late Cretaceous-early Tertiary time [*Torsvik et al.*, 1989]. Brittle faulting in the Lofoten has been attributed to Jurassic/Cretaceous and Tertiary phases [*Dalland*, 1975; *Klein et al.*, 1999; *Løseth and Tveten*, 1996]. Normal faults are also known in the Finnmark area [*Townsend*, 1987], but remain hitherto of unconstrained age.

[26] Studies on morphology, valley incision profiles, paleic surfaces, and saprolites reveal the existence of several paleosurfaces and relics of denudation/uplift between the Cambrian and the Present [*Doré*, 1992a; *Doré and Jensen*, 1996; *Gjessing*, 1967; *Lidmar-Bergstöm*, 1995, 1996; *Lidmar-Bergstöm et al.*, 2000, 1997; *Nesje et al.*, 1987; *Riis*, 1996]. Thus the primary sub-Cambrian peneplain and the subsequently developed Caledonian orogeny have been reworked by deep weathering and peneplained to a nearly flat surface in the Middle Jurassic. A Late Jurassic uplift event was probably limited to narrow zones along major normal faults. By mid-Cretaceous, Fennoscandia was transgressed and eventually buried by a sedimentary cover ($\ll$1000 m). Late Cretaceous and Paleogene uplift mainly affected SW Norway (800 m) and northern Fennoscandia (>1200 m) and led to the formation of a new peneplain and the erosion of possible Mesozoic sediments.

[27] The Tertiary uplift and subsidence, though undoubtedly documented from offshore sediments, are still a matter of intense debate. Both the timing (two main episodes in early Tertiary and Neogene) and the location of the major uplifts are still loosely constrained, not to mention the mechanisms explaining the uplift [*Japsen and Chalmers*, 2000; *Olesen et al.*, 2002]. Neogene uplift, though important, is restricted to south Norway and the Troms/Lofoten area [*Dehls et al.*, 2000; *Riis*, 1996], and its onset postdates major volcanism and continental breakup by 25 Ma and predates Pliocene glaciations [*Rohrman et al.*, 1995]. These different uplift events are corroborated both by analysis of subsidence offshore and by fission track studies onshore. Cooling events deduced from fission track studies occur in the Late Paleozoic-Triassic, the Late Jurassic (around 140 Ma), and the Cretaceous (around 90 Ma) [*Rohrman et al.*, 1995]. A final uplift starts in the Neogene. Unlike these studies, which show a dome-like uplift with a steep western flank, a study in progress along the mid-Norway section [*Redfield*, 2000] shows movement of blocks/compartments along discrete faults. Uplift in the innermost (western) block between the Kopperå detachment and the Åre detachment occurred in the Cretaceous after 100 Ma. Although no

Figure 3. (opposite) Simplified crustal-scale cross sections of the Scandinavian North Atlantic passive margin. The cross sections are synthetic sections combining information from various published sources as well as new interpretations. The sections show the geometrical relationship of the major normal extensional faults to the crustal structure. (a) Section across mid-Norway from the Vøring Marginal High to Åre/Østersund (Sweden) modified from *Mosar* [2000]. (b) Section from the Møre marginal high across the Faltungs Graben in the western Gneiss Region into the Oslo Graben. (c) Simplified section of the Scandinavian North Atlantic Passive margin showing the main structural features and timing/location of the different "rifting" events: (1) major Permo-Triassic fault movement forming the Froan Basin and including the Jurassic events in the Trøndelag Platform and the Halten Terasse; (2) Cretaceous deepening of the Møre and Vøring Basins; (3) rift-drift transition of early Tertiary and onset of the North Atlantic oceanic crust formation; and (4) Tertiary(?) to possible Present extension in the crust/lithosphere linked with rejuvenated fault motion on the IBF. Area a, underplated material; area b, Present location of negative Bouguer gravity anomaly and crustal thinning; area c, Permo-Triassic basins and possibly Devonian basins. AD, Åre Detachment; BF, border fault; KF, Kopperå Fault; LGF, Lørdal-Gjenda Fault; MTFC, Møre-Trøndelag Fault Complex; NFSF, Nordfjord-Sogn Fault; RD, Røragen Detachment; SSZ, Stadland shear zone.

sediments remain from the eastern foreland basin of the Caledonides in Sweden, fission track data indicate a cumulated 2–4 km section of missing (eroded) Late Paleozoic to Late Cretaceous sediments [*Cederbom*, 2001; *Cederbom et al.*, 2000; *Larson et al.*, 1999]. This is also in agreement with estimates of 3–4 km of post-Permian erosion in the Oslo rift area [*Rohrman et al.*, 1994]. Similarly, studies from organic maturation of coal from samples nearshore mid-Norway and from boulders originating from the Beistadfjorden Jurassic Basin in the Trondheim area indicate a maximum burial in excess of 2.3 km [*Weisz*, 1992]. This is consistent with uplift and erosion figures from other areas and studies.

[28] Presently active, postglacial rebound subsequent to the last deglaciation is around of 800 m in the center of Baltic Sea and reduces to 400 m west of the Caledonian thrust front [*Dehls et al.*, 2000; *Fjeldskaar et al.*, 2000]. Active faulting is also documented by earthquake data. Thus NW-SE directed compressional (thrusting) and extensional (normal) faulting and strike-slip faulting is still active at present-day (see *Bungum et al.* [1991] for location and detailed discussion).

5. Continent-Ocean Boundary

[29] The continent-ocean boundary (COB) corresponds to the transition zone from continental lithosphere to oceanic lithosphere. This transition zone is frequently associated with, but also masked by, magmatic extrusives along the North Atlantic volcanic margins [*Berndt et al.*, 2001; *Eldholm et al.*, 2000, 1989; *Skogseid et al.*, 1992a]. These magmatic events have been associated with excess magma production prior to the rift-drift transition. They have also been linked to the influence of the Iceland hot spot [*Skogseid et al.*, 2000], although new thermomechanical models of rift margins show that no hot spot influence is required to explain the large volumes of melt generated [*Anderson*, 2000; *van Wijk et al.*, 2001]. The COB is located in the transition zone between the oldest magnetic anomaly and the first continental crust. Offshore Norway this correlates to anomaly 24 and the main break-off fault which is located to the W-NW of the Møre and Vøring marginal highs. The precise position of the COB and the structure and nature of the substratum in the Vøring and Møre marginal highs [*Mjelde et al.*, 2001; *Ren et al.*, 1998; *Skogseid and Eldholm*, 1987; *Tsikalas et al.*, 2001] remain matters of debate and are difficult to resolve given the problems with the resolution and penetration of the seismic surveys. Mainly on the basis of magnetic anomaly data from the oceanic crust but also on gravimetric information and information from seismic data, it is possible to trace the COB along the edge of the European continent in the northern Atlantic (Figure 1). To the north of the Lofoten, along the SW edge of the Barents Sea shelf, the COB merges with the Senja Fracture Zone and forms the link between the passive margin and the transform boundary forming the SE part of the DeGeer shear zone separating the Barents Sea/Svalbard from Greenland (Figure 1).

6. Interpretation: Passive Margin Redefined

[30] Combining information from the previously discussed data and interpretations, it is proposed here that the innermost normal boundary fault system (IBF) coincides with today's location of the rift flank. This rift flank is associated with rift development and passive margin formation along the eastern North Atlantic margin, in Norway and Sweden, since Permian, possibly since late Carboniferous. The IBF runs from the North Sea (Viking/Central Graben) over a distance of 2000 km into the shelf of the Barents Sea, where it terminates at the Trollfjord-Komagelv Fault Zone. Southwest of the Central Graben, the IBF can be correlated with the Midland Valley Graben faults which form an extensional fault system, also active since the late Permian. The SW segment of the IBF is formed by the Hardangerfjord Shear Zone, possibly the Ryfylke Shear Zone and the Lærdal-Gjende-Olestøl fault system. Their equivalents in central Norway-Sweden are the Kopperå Fault, the Røragen detachment and the Åre Fault system, which merge to the north with the northern tip of the Møre-Trøndelag Fault Complex. In Nordland, extensional faults that can be linked to the IBF have, to date, not been described, although extensional faults on the western side of the basement windows of Børgefjellet, Nasafjället, and Rombak are known. The single trace of the IBF proposed in this area is based on the location of the basement windows, its position west of the topographic culmination and the negative gravity high. North of Tromsø, in the Finnmark area, the IBF is formed partly by the Langfjord-Vargsund fault and runs northwest of the Alta-Kvænangen and Reppardfjord-Komagfjord windows. West of Tromsø a series of minor faults links the IBF to the Senja Fracture Zone.

[31] The location of the IBF is coincident, as discussed before, with a series of structural features. In a number of areas the IBF is coincident with normal faults described previously in the literature. These faults have mainly been described as ductile extensional faults of Devonian age. The strongest correlation, also described in southern and central Norway by *Andersen et al.* [1999], is the relationship with the basement windows: Aurland-Lærdal; Mørkedal; Vang and Beito; Atna-Spekedal; Skadöra, Mullfjellet; Grong-Olden culmination; Børgefjellet; Nasafjället; Rombak; Alta-Kvænangen; and Reppardfjord-Komagfjord windows. The IBF consistently develops on the western side of these windows. Tectonically speaking, these windows are formed by shallow parautochthonous slivers of basement detached over shallow décollements and thrust onto the Caledonian foreland during the formation of the mountain belt. Thus the IBF reactivates former ductile faults in an extensional context. Similar normal, rift-related faults that reactivate inherited ductile faults/thrusts over basements are described in mid-Norway with the Høybakken and Kollstraumen detachment zones [*Braathen et al.*, 2000, 2002; *Eide et al.*, 2002]. It is further relevant to notice that the innermost boundary fault system is systematically located west of the present-day Caledonian thrust front.

[32] The IBF also shows an intimate link to the present topography. Overall, the IBF is located to the west of the topographic crest and hence also to the west of the shallow slopes inclined toward the east and the Golf of Bothnia. This type of feature is consistent with a rift flank developing over a large normal fault whose offset generates uplift (possibly due to elastic rebound) on the "lower plate" or footwall portion. In the transition zone from the Hardan-

gerfjord Shear Zone/Lærdal-Gjende-Olestøl fault system to the Kopperå Fault-Røragen detachment-Åre Fault system, this relationship is more complicated. The uplifted footwall is not located uniquely to the east of the IBF but also to the south of a branch oriented N-S.

[33] The age of IBF and locus of the "most important" normal fault during the different "rifting events" are largely unknown. Further research has to reveal their existence and their detailed timing. To date, it has been proven that portions of the IBF such as the Lærdal-Gjende fault and other normal rift-related faults were active in Permian and Jurassic/Cretaceous. By extrapolation and because of structural analogies it is suggested that all the faults associated with the IBF have been active since the Late Permian, if not continuously than repeatedly at various periods. Also, by extending the observation and documented Mesozoic brittle faulting from the IBF in western, central south, and mid-Norway, it is proposed that brittle overprints are most likely to be discovered elsewhere along the IBF in North Norway and thus confirm the existence and location of the IBF as proposed here.

[34] In the offshore domain, the different subsidence/uplift events are closely associated with important movements on normal faults. In the onshore realm, the various uplift events tend to be associated with domes and continuous widespread uplift, rather than uplift associated with or along discrete faults/fault systems. The strong asymmetry of uplift curves shown by *Rohrmann* [1995] and *Rohrman et al.* [1995] for the fission track data in southern and western Norway (tight isolines along the coast and wide spaced curves on the eastern side of the "dome"), and also the results from *Redfield* [2000] in mid-Norway, are, however, indicative of uplift along discrete boundaries [see also *Andersen et al.*, 1999]. These boundaries are in good agreement with the loci of the major normal rift faults discussed here along the IBF.

[35] Discussions on the different causes for uplift are linked to the different periods and tectonic features: for example, the Neogene domal uplift is thought to be caused by asthenospheric diapirism [*Rohrman and van der Beek*, 1996]. This uplift is often associated to two domal structures in southern and in northern Norway. Detailed topographic profiles, and results from fission track data seem to indicate that at least the northern "dome" is not a smooth domal feature, but rather an asymmetric structure [*Hendriks and Andriessen*, 2002]. It is suggested here that this is also applicable to the southern "dome" which may be a structure bound by major normal faults (IBF to the west and Porsgrunn-Kristiansand Fault to the east at the transition to the Oslo rift and the Skagerrak). Similarly, the whole of the passive margin can be subdivided into discrete blocks with discontinuous boundaries, rather than a few "domal" features with smooth edge. The boundaries of these discrete blocks are normal faults that were active at different periods since the Permian and possibly since the late Carboniferous. Some of them reactivate Middle Paleozoic ductile faults (both reverse and normal) related to the Caledonian orogenesis [*Osmundsen et al.*, 2002].

[36] The potential field data and especially gravity, as well as the morphology and topography features, give important information on the deep structures and the mechanisms that generated them. The large negative gravity anomaly that runs along the whole of the Scandinavian Atlantic margin is located directly under the proposed IBF. Gravity anomalies are the result of a cumulative effect of different causes which may include changes in the nature of the rocks (e.g., allochtonous basement windows versus autochthonous basement windows, topography, fault offset, and crustal/lithospheric structures [*Olesen et al.*, 2002]). The first-order expression of the negative gravity anomaly is topography. This is corroborated by the fact that the highest mountains follow the negative gravity anomaly trend and coincide with the water divide. Thinning observed from seismic studies in the crust is at the exact location of the gravity anomaly maximum in the mid-Norway-Sweden area and in the south central Norway. This hints to a possible link between faulting and topography. On top, two features, one at the base of the crust indicating the thinning of the crust and one at the base of the lithosphere indicating lithospheric thinning, probably are combined in the present regional negative gravity anomaly. These two features most likely have different wavelengths/amplitudes and different asymmetries and may therefore be difficult to link directly to the fault geometry observed at the surface and may not be present all along the margin [*Olesen et al.*, 2002; *Skilbrei et al.*, 2002]. This is in agreement with results from analogue modeling of rift and passive margin development [*Brun and Beslier*, 1996; *Gartrell*, 1997; *Mulegeta and Ghebread*, 2001]. Further, the crust is affected by at least two different directions of extension (North Atlantic, North Sea, and possibly Skagerak-Oslo Graben) which, when superposed, may create interference patterns leading to complex structures [*Færseth*, 1996].

[37] In the case of the Fennoscandian passive margin, even after removing the influence of, e.g., basement windows and the uplift related to the "Neogene" domes, there is still an important negative gravity anomaly stretching along the whole passive margin and the present rift flank or IBF. It is therefore not unreasonable to assume that the IBF may have been active in the Tertiary and possibly into the present. The corollary of this would be to admit that below the IBF, active, present-day thinning of the crust/lithosphere (incipient rifting?) is taking place. The present-day activity might be corroborated by the observation of residual present uplift located in the mountainous area of Norway [*Fjeldskaar et al.*, 2000] and attributed to a weak tectonic overprint of the glacial isostatic uplift. However, these hypotheses should be carefully tested since other explanations, like an Iceland plume outlier, can be invoked to explain the negative gravity anomaly not least of which a possible outlier of the Iceland hot spot plume [*Skogseid et al.*, 2000]. The negative gravity anomaly can be the expression of an older feature that developed during the Permo-Mesozoic, especially the Permian to Early Mesozoic when rifting and fault movements were most important.

7. Conclusions: Perspectives

[38] A number of direct and indirect geological and geophysical evidences converge to support the existence of a 2000 km long innermost boundary fault system (IBF) that runs through the heart of the Swedish-Norwegian mountain range, from the North Sea Central Graben to the Barents Sea. This fault system corresponds to the location

of a series of linked faults defining the present rift flank and hence the innermost portion of the Scandinavian North Atlantic passive margin. The extended continental crust between this IBF and the COB suffered a polyphase history of extension since the Permian, and possibly since the late Carboniferous, that culminated with the separation of Greenland and Europe, the formation of the North Atlantic Ocean, and, subsequently, the establishment of the Present geomorphologic and tectonic features.

[39] The IBF is not a single, continuous fault but rather a succession of overlapping fault strands. They are the innermost tectonic expression of the passive margin and form a discrete boundary between the rift area and the craton. The margin width, between the COB and the IBF changes from some 525–570 km in the Møre Basin to a maximum of 710 km in the Vøring Basin-Åre section and decreases to some 165 km in the Tromsø area near the Senja Fracture zone. Tentative preextension reconstructions, in agreement with published data mainly from the offshore realm, indicate a total finite extension in the order of 200%, thus doubling the margin width between the initiation of rifting in Permo-Carboniferous and Present.

[40] The offshore, but also the onshore, uplift/rift events clearly indicate that important extension associated with normal faults, occurred during repeated periods since Permian. Some of the major periods associated with normal faults are the Permo-Triassic, the Jurassic, the Late Jurassic-Early Cretaceous, the Middle Late Cretaceous, and the early Tertiary. Data from diverse sources, as discussed above, indicate that important uplift of the onshore area, especially during Tertiary but also in the Jurassic and Cretaceous, can also be linked to fault movement. It is suggested here that the onshore mountain range can be subdivided into different blocks/regions separated by discrete fault systems. The crust behaves as separate blocks that all have individual uplift/extension histories, rather than reacting as a continuous bending or doming medium. It is suggested here that the IBF was active in Permian for the first time (possibly even in latest Carboniferous) and was subsequently reactivated in Late Jurassic-Early Cretaceous and possibly again as recently as Tertiary.

[41] The large negative gravity anomaly that runs along the whole of the Scandinavian Atlantic margin is located under the IBF. This opens the speculation as to the significance of the associated mass deficit at depth, the consequences on the surface and the genetic link with IBF. The thinning of the crust/lithosphere and the timing discussed previously point toward a possibly Tertiary extension causing uplift. It can even be speculated that active present-day extension along a rejuvenated IBF is occurring. Thus the differential uplift, not generated by the glacial isostatically induced reequilibration, should be visible across the innermost edge of the passive margin. Such a proposal can be tested using modern techniques such as synthetic aperture radar interferometry. Discriminating between glacial rebound-induced uplift of the passive margin and uplift linked to other tectonic causes will be one of the future challenges along the Scandinavian passive margin.

[42] The new definition of the Fennoscandian North Atlantic passive margin proposed here raises a number of new questions related to the rift formation processes. Why is the IBF still forming the present rift escarpment, what are the mechanisms involved, and how is the geomorphology related to the tectonic structures and the processes operating in the crust and the lithosphere?

[43] One of the processes is, of course, escarpment retreat which occurs because the top of the escarpment coincides with the drainage divide [*Beaumont et al.*, 2000; *van Balen et al.*, 1995]. Continued back tilting of the escarpment helps maintain both the escarpment top as drainage divide and the escarpment gradient during retreat. Lasting tilting is due to flexural unloading and uplift in response to erosion. This mechanism of flexural unloading linked to lithospheric necking is favored to explain why rift flank uplifts persist for more than 100 Myr (that is longer then the time required for the lithosphere to cool and subside from a warm synrift state [*Beaumont et al.*, 2000; *Braun and Beaumont*, 1989]), as is the case in the Norwegian North Atlantic passive margin. However, when combined with the IBF on land, one should really consider escarpment retreat combined with repeated reactivation of preexisting faults. The combined effect could lead to rejuvenation of the escarpment morphology and may prove to help explain the present-day situation.

[44] The proposed location of the IBF on the passive margin, farther inland than hitherto suggested, will strongly influence future analyses of the rift evolution and prior models should be reassessed. Models of lithospheric-scale evolution (heat fluxes, stretching) must take into account the increased margin width with its onshore portion. In addition depths to the Moho and the base of the lithosphere must be reassessed. The chronology of the rift events must be reassessed in the light on the new onshore section of the passive margin. It already appears that extensional faulting is active in many places on the passive margin and that the locus of the major depositional centers and studies of sediment transport and provenance must be viewed with an active uplifting and receding passive margin flank. The new IBF further provides a testable model to integrate uplift information based on information, e.g., obtained from AFT, geomorphology, and geophysics.

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References

Andersen, T. B., Extensional tectonics in the Caledonides of southern Norway, an overview, *Tectonophysics*, *285*, 333–351, 1998.

Andersen, T. B., and B. Jamtveit, Uplift of deep crust during orogenic extensional collapse: A model based on field observations in the Sogn-Sunnfjord region of W. Norway, *Tectonics*, *9*, 1097–1111, 1990.

Andersen, T. B., H. N. Berry, D. R. Lux, and A. Andresen, The tectonic significance of pre-Scandian $^{40}Ar/^{39}Ar$ phengite cooling ages in the Caledonides of western Norway, *J. Geol. Soc. London*, *155*, 297–309, 1998.

Andersen, T. B., T. H. Torsvik, E. A. Eide, P. T. Osmundsen, and J. I. Faleide, Permian and Mesozoic extensional faulting within the Caledonides of central south Norway, *J. Geol. Soc. London*, *156*, 1073–1080, 1999.

Anderson, D. L., The thermal state of upper mantle: No role for mantle plumes, *Geophys. Res. Lett.*, *27*(22), 3623–3626, 2000.

Andréasson, P.-G., The Baltoscandian margin in Neoproterozoic-early Palaeozoic times. Some constraints on terrane derivation and accretion in the Arctic Scandinavian Caledonides, *Tectonophysics*, *231*, 1–32, 1994.

Andriessen, P. A. M., and A. Bos, Post-Caledonian thermal evolution and crustal uplift in the Eidfjord area, western Norway, *Nor. Geol. Tidsskr.*, *66*, 243–250, 1986.

Bakkelid, S., Mapping the rate of crustal uplift in Norway: Parameters, methods and results, *Nor. Geol. Tidsskr.*, *72*(3), 239–246, 1992.

Balling, N., Gravity and isostasy in the Baltic shield, in *First EGT Workshop: The Northern Segment*, edited by D. A. Galson and S. Mueller, pp. 53–68, Eur. Sci. Found., Strasbourg, France, 1984.

Bannister, S. C., B. O. Ruud, and E. S. Husebye, Tomographic estimates of sub-Moho seismic velocities in Fennoscandia and structural implication, *Tectonophysics*, *189*, 37–53, 1991.

Beaumont, C., H. Kooi, and S. Willett, Coupled tectonic-surface process models with applications to rifted margins and collisional orogens, in *Geomorphology and Global Tectonics*, edited by M. A. Summerfield, pp. 29–55, John Wiley, Hoboken, N. J., 2000.

Berndt, C., S. Planke, E. Alvestad, F. Tsikalas, and T. Rasmussen, Seismic volcanostratigraphy of the Norwegian Margin: Constraints on tectonomagmatic break-up processes, *J. Geol. Soc. London*, *158*, 413–426, 2001.

Blystad, P., H. Brekke, R. B. Færseth, B. T. Larsen, J. Skogseid, and B. Tørudbakken, Structural elements of the Norwegian continental shelf. part II: The Norwegian Sea region, *NPD, Norw. Pet. Dir. Bull.*, *8*, 1–45, 1995.

Bøe, R., and K. Bjerkli, Mesozoic sedimentary rocks in Edøyfjorden and Beitstadfjorden, central Norway: Implications for the structural history of the Møre-Trøndelag fault zone, *Mar. Geol.*, *87*, 287–299, 1989.

Bøe, R., K. Atakan, and B. A. Sturt, Deformation of Devonian rocks on Hitra and Smøla, central Norway, *Norges Geol. Unders. Bull.*, *414*, 1–19, 1989.

Boundy, T. M., E. J. Essene, C. M. Hall, H. Austrheim, and A. N. Halliday, Rapid exhumation of lower crust during continent-continent collision and late extension: Evidence from $^{40}Ar/^{39}Ar$ incremental heating of hornblendes and muscovites, Caledonian orogen, western Norway, *Geol. Soc. Am. Bull.*, *108*, 1425–1437, 1996.

Braathen, A., Kinematics of post-Caledonian polyphase brittle faulting in the Sunnfjord region, western Norway, *Tectonophysics*, *302*, 99–121, 1999.

Braathen, A., H. D. Maher Jr., T. E. Haabet, S. E. Kristensen, B. O. Tørubakken, and D. Worsley, Caledonian thrusting on Bjørnøya: Implications for Paleozoic and Mesozoic tectonism of the western Barents Shelf, *Nor. Geol. Tidsskr.*, *79*, 57–68, 1999.

Braathen, A., Ø. Nordgulen, P.-T. Osmundsen, T. B. Andersen, A. Solli, and D. Roberts, Devonian, orogen-parallel, opposed extension in the central Norwegian Caledonides, *Geology*, *28*(7), 615–618, 2000.

Braathen, A., P.-T. Osmundsen, Ø. Nordgulen, D. Roberts, and G. B. Meyer, Orogen-parallel extension of the Caledonides in northern central Norway: An overview, *Norw. J. Geol.*, *82*(4), 225–242, 2002.

Braun, J., and C. Beaumont, A physical explanation of the relation between flank uplifts and the breakup unconformity at rifted continental margins, *Geology*, *17*(8), 760–764, 1989.

Brekke, H., The tectonic evolution of the Norwegian Sea continental margin with emphasis on the Vøring and Møre Basins, in *Dynamics of the Norwegian Margin*, edited by A. Nottvedt, *Geol. Soc. Spec. Publ.*, *167*, 327–378, 2000.

Brekke, H., S. Dahlgren, B. Nyland, and C. Magnus, The prospective of the Vøring and Møre basins on the Norwegian Sea continental margin, in *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference Held at the Barbican Centre, London, 26–29 October 1997*, edited by A. J. Fleet and S. A. R. Boldy, pp. 261–274, Geol. Soc., London, 1999.

Brekke, H., H. I. Sjulstad, C. Magnus, and R. W. Williams, Sedimentary environments offshore Norway—An overview, in *Sedimentary Environments Offshore Norway: Paleaozoic to Recent*, edited by O. J. Martinsen and T. Dreyer, pp. 7–37, Elsevier Sci., New York, 2001.

Brun, J. P., and M. O. Beslier, Mantle exhumation at passive margins, *Earth Planet. Sci. Lett.*, *142*, 161–174, 1996.

Bukovics, C., E. G. Cartier, P. A. Shaw, and P. A. Ziegler, Structure and development of the mid-Norway continental margin, in *Petroleum Geology of the North European Margin*, edited by N. P. Society, pp. 407–423, Graham and Trotman, Norwell, Mass., 1984.

Bungum, H., A. Alsaker, L. B. Kvamme, and R. A. Hansen, Seismicity and seismotectonics of Norway and nearby continental shelf areas, *J. Geophys. Res.*, *96*, 2249–2265, 1991.

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.

Cederbom, C., Phanerozoic, pre-Cretaceous thermotectonic events in southern Sweden revealed by fission track thermochronology, *Earth Planet. Sci. Lett.*, *188*, 199–209, 2001.

Cederbom, C., S. Å Larson, E.-L. Tullborg, and J.-P. Stiberg, Fission track thermochronology applied to Phanerozoic thermotectonic events in central and southern Sweden, *Tectonophysics*, *316*, 153–167, 2000.

Coker, J. E., M. G. Steltenpohl, A. Andresen, and M. J. Kunk, An $^{40}Ar/^{39}Ar$ thermochronology of the Ofoten-Troms region: Implications for terrane amalgamation and extensional collapse of the northern Scandinavian Caledonides, *Tectonics*, *14*, 435–447, 1995.

Dalland, A., Mesozoic rocks of Andøy, northern Norway, *Norges Geol. Unders. Bull.*, *316*, 271–287, 1975.

Dehls, J. F., O. Olesen, H. Bungum, E. Hicks, C. Lindholm, and F. Riis, Neotectonic map: Norway and surrounding areas, Geol. Surv. of Norw., Trondheim, 2000.

Doré, A. G., The structural foundation and evolution of Mesozoic seaways between Europe and the Arctic, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *87*, 441–492, 1991.

Doré, A. G., The base Tertiary surface of southern Norway and the northern North Sea, *Nor. Geol. Tidsskr.*, *72*, 259–265, 1992a.

Doré, A. G., Synoptic paleogeography of the Northeast Atlantic Seaway: Late Permian to Cretaceous, in *Basins on the Atlantic Seaboard: Petroleum Geology, Sedimentology and Basin Evolution*, edited by J. Parnell, *Geol. Soc. Spec. Publ.*, *62*, 421–446, 1992b.

Doré, A. G., and L. N. Jensen, The impact of late Cenozoic uplift and erosion on hydrocarbon exploration: Offshore Norway and some other uplifted basins, *Global Planet. Change*, *12*, 415–436, 1996.

Doré, A. G., E. R. Lundin, Ø. Birkeland, P. E. Eliassen, and L. N. Jensen, The NE Atlantic Margin: Implications of late Mesozoic and Cenozoic events for hydrocardon prospectivity, *Pet.m Geosci.*, *3*, 117–131, 1997.

Doré, A. G., E. R. Lundin, Ø. Birkeland, P. E. Eliassen, and L. N. Jensen, Principal tectonic events in the evolution of the northwest European Atlantic margin, in *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference Held at the Barbican Centre, London, 26–29 October 1997*, edited by A. J. Fleet and S. A. R. Boldy, pp. 41–61, Geol. Soc., London, 1999.

Dunlap, W. J., and H. Fossen, Early Paleozoic orogenic collapse, tectonics stability, and late Paleozoic continental rifting revealed through thermochronology of K-feldspars, southern Norway, *Tectonics*, *17*, 604–620, 1998.

Dyrelius, D., A geophysical perspective of the Scandinavian Caledonides, in *The Caledonide Orogen: Scandinavia and Related Areas*, edited by D. G. Gee and B. A. Sturt, pp. 185–194, John Wiley, Hoboken, N. J., 1985.

Eide, E. A., T. H. Torsvik, and T. B. Andersen, Absolute dating of brittle fault movements: Late Permian and late Jurassic extensional fault breccias in western Norway, *Terra Nova*, *9*, 135–139, 1997.

Eide, E. A., T. H. Torsvik, T. B. Andersen, and N. O. Arnaud, Early Carboniferous unroofing in Western Norway: A tale of alkali feldspar thermochronology, *J. Geol.*, *107*, 353–374, 1999.

Eide, E. A., P. T. Osmundsen, G. B. Meyer, M. A. Kendrick, and F. Corfu, The Nesna Shear Zone, north-central Norway: An $^{40}Ar/^{39}Ar$ record of Early Devonian-Early Carboniferous ductile extension and unroofing, *Norw. J. Geol.*, *82*(4), 317–340, 2002.

Eldholm, O., J. Thiede, and E. Taylor, Evolution of the Vøring volcanic margin, *Proc. Ocean Drill. Program Sci. Results*, *104*, 1033–1065, 1989.

Eldholm, O., T. P. Gladczenko, J. Skogseid, and S. Planke, Atlantic volcanic margins: A comparative study, in *Dynamics of the Norwegian Margin*, edited by A. Nottvedt, *Geol. Soc. Spec. Publ.*, *167*, 411–428, 2000.

Essex, R. E., and P. L. Gromet, U-Pb dating of prograde and retrograde titanite growth during the Scandian Orogeny, *Geology*, *28*(5), 419–422, 2000.

Færseth, R. B., Interaction of Permo-Triassic and Jurassic extensional fault-blocks during the development of the northern North Sea, *J. Geol. Soc. London*, *153*, 931–944, 1996.

Færseth, R. B., and T. Lien, Cretaceous evolution in the Norwegian Sea—A period characterized by tectonic quiescence, *Mar. Pet. Geol.*, *19*(8), 1005–1027, 2002.

Færseth, R. B., R. H. Gabrielsen, and C. A. Hurich, Influence of basement in structuring of the North Sea basin, offshore southwest Norway, *Nor. Geol. Tidsskr.*, *75*, 105–119, 1995.

Fjeldskaar, W., C. Lindholm, J. F. Dehls, and I. Fjeldskaar, Postglacial uplift, neotectonics and seismicity in Fennoscandia, *Quat. Sci. Rev.*, *19*, 1413–1422, 2000.

Fleet, A. J., and S. A. R. Boldy (Eds.), *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference Held at the Barbican Centre, London, 26–29 October 1997*, 1398 pp., Geol. Soc., London, 1999.

Fossen, H., The role of extensional tectonics in the Caledonides of south Norway, *J. Struct. Geol.*, *14*, 1033–1046, 1992.

Fossen, H., Extensional tectonics in the Caledonides: Synorogenic or post-orogenic, *Tectonics*, *19*, 213–224, 2000.

Fossen, H., and E. Rykkelid, Postcollisional extension of the Caledonide orogen in Scandinavia: Structural expressions and tectonic significance, *Geology*, *20*(8), 737–740, 1992.

Gabrielsen, R. H., Structural elements in graben systems and their influence on hydrocarbon trap types, in *Habitat of Hydrocarbons on the Norwegian Continental Shelf*, edited by N. P. Society, pp. 55–60, Graham and Trotman, Norwell, Mass., 1986.

Gabrielsen, R. H., Reactivation of faults on the norwegian continental shelf and its implications for earthquake occurrence, in *Earthquakes at North-Atlantic Passive Margins: Neotectonics and Postglacial Rebound*, edited by S. Gregersen and P. W. Basham, pp. 67–90, Kluwer Acad., Norwell, Mass., 1989.

Gabrielsen, R. H., T. Odinsen, and I. Grunnaleite, Structuring of the northern Viking Graben and the Møre Basin: The influence of basement structural grain, and the particular role of the Møre-Trøndelag Fault Complex, *Mar. Pet. Geol.*, *16*(5), 443–465, 1999.

Garfunkel, Z., and R. O. Greiling, A thin orogenic wedge upon thick foreland lithosphere and the missing foreland basin, *Geol. Rundsch.*, *87*, 314–325, 1998.

Gartrell, A. P., Evolution of rift basins and low-Angle detachments in multilayer analog models, *Geology*, *25*(7), 615–618, 1997.

Gee, D. G., The Scandinavian Caledonides: Basement involvement in Scandian thrusting, *Geol. Fören. Stockholm Förh.*, *113*(2/3), 259–260, 1991.

Gee, D. G., J.-C. Guezou, D. Roberts, and F. C. Wolff, The central-southern part of the Scandinavian Caledonides, in *The Caledonide Orogen-Scandinavia and Related Areas*, edited by D. G. Gee and B. A. Sturt, pp. 109–133, John Wiley, Hoboken, N. J., 1985.

Gee, D. G., M. Lobkowwicz, and S. Singh, Late Caledonian extension in the Scandinavian Caledonides: The Røragen detachment revisited, *Tectonophysics*, *231*, 139–155, 1994.

Gjessing, J., Norway's paleic surface, *Nor. Geol. Tidsskr.*, *21*, 69–132, 1967.

Grønlie, A., and D. Roberts, Resurgent strike-slip duplex development along the Hitra-Snåsa and Verran Faults, Møre-Trøndelag Fault Zone, central Norway, *J. Struct. Geol.*, *11*, 295–305, 1989.

Hames, W. E., and A. Andresen, Timing of Paleozoic orogeny and extension in the continental shelf of north-central Norway as indicated by laser $^{40}Ar/^{39}Ar$ muscovite dating, *Geology*, *24*(11), 1005–1008, 1996.

Hartz, E. H., and A. Andresen, From collision to collapse: Complex strain permutations in the hinterland of the Scandinavian Caledonides, *J. Geophys. Res.*, *102*(B11), 24,697–24,711, 1997.

Hendriks, B. W. H., and P. A. M. Andriessen, Pattern and timing of the post-Caledonian denudation of northern Scandinavia constrained by apatite fission track thermochronology, in *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration*, edited by A. G. Dore et al., *Geol. Soc. Spec. Publ.*, *196*, 117–137, 2002.

Holtedahl, O., On the oblique uplift of some northern lands, *Norges Geol. Unders. Bull.*, *T14*, 132–139, 1953.

Hossack, J. R., and M. A. Cooper, Collision tectonics in the Scandinavian Caledonides, *Collision Tectonics*, edited by M. P. Coward and A. C. Ries, *Geol. Soc. Spec. Publ.*, *19*, 287–304, 1986.

Hurich, C. A., Kinematic evolution of the lower plate during intracontinental subduction: An example from the Scandinavian Caledonides, *Tectonics*, *15*, 1248–1263, 1996.

Hurich, C. A., and D. Roberts, A seismic reflection profile from Størdalen to Outer Fosen, central Norway: A note on the principal results, *Norges Geol. Unders. Bull.*, *433*, 18–19, 1997.

Hurich, C. A., H. Palm, D. Dyrelius, Y. Kristoffersen, F. C. Wolff, and D. Roberts, Activation of Precambrian basement in the Scandinavian Caledonides: Views from seismic reflection data, *Norges Geol. Unders. Spec. Publ.*, *3*, 66–69, 1988.

Hurich, C. A., H. Palm, D. Dyrelius, and Y. Kristoffersen, Deformation of the Baltic continental crust during Caledonide intracontinental subduction: Views from seismic reflection data, *Geology*, *17*(5), 423–425, 1989.

Japsen, P., and J. A. Chalmers, Neogene uplift and tectonics around the North Atlantic: Overview, *Global Planet. Change*, *24*, 165–173, 2000.

Juhojuntti, N., C. Juhlin, and D. Dyrelius, Crustal reflectivity underneath the central Scandinavian Caledonides, *Tectonophysics*, *334*, 191–210, 2001.

Kinck, J. J., E. S. Husebye, and F. R. Larsson, The Moho depth distribution in Fennoscandia and the regional tectonic evolution from Archean to Permian times, *Precambrian Res.*, *64*, 23–51, 1993.

Klein, A. C., M. G. Steltenpohl, W. E. Hames, and A. Andresen, Ductile and brittle extension in the southern Lofoten archipelago, north Norway: Implications for differences in tectonic style along an ancient collisional margin, *Am. J. Sci.*, *299*, 69–89, 1999.

Kooi, H., and S. Cloetingh, Lithospheric necking and regional isostasy at extensional basins: 2. Stress-induced vertical motion and relative sea level changes, *J. Geophys. Res.*, *97*(B12), 17,573–17,591, 1992.

Korhonen, J. V., et al., Preliminary magnetic and gravity anomaly maps of the Fennoscandian shield 1:10 000 000, *Geol. Surv. Finland Spec. Pap.*, *27*, 173–179, 1999.

Koyi, H., A. G. Milnes, H. Schmeling, C. J. Talbot, C. Juhlin, and H. Zeyen, Numerical models of ductile rebound of crustal roots beneath mountain belts, *Geophys. J. Int.*, *139*, 556–562, 1999.

Larson, S. Å., E.-L. Tiullborg, C. Cederbom, and J.-P. Stiberg, Sveconorvegian and Caledonian foreland basins in the Baltic Shield revealed by fission-track thermochronology, *Terra Nova*, *11*, 210–215, 1999.

Lidmar-Bergstöm, K., Relief and saprolites through time on the Baltic Shield, *Geomorphology*, *12*, 45–61, 1995.

Lidmar-Bergstöm, K., Longterm morphotectonic evolution in Sweden, *Geomorphology*, *16*, 33–59, 1996.

Lidmar-Bergstöm, K., S. Olsson, and M. Olvmo, Palaeosurfaces and associated saprolites in southern Sweden, in *Paleosurfaces: Recognition, Reconstruction and Paleoenvironmental Interpretation*, edited by M. Widdowson, *Geol. Soc. Spec. Publ.*, *120*, 95–124, 1997.

Lidmar-Bergstöm, K., C. D. Ollier, and J. R. Sulebak, Landforms and uplift history of southern Norway, *Global Planet. Change*, *24*, 211–231, 2000.

Lister, G. S., M. A. Etheridge, and P. A. Symonds, Detachment models for the formation of passive continental margins, *Tectonics*, *10*, 1038–1064, 1991.

Løseth, H., and E. Tveten, Post-Caledonian structural evolution of the Lofoten and Vesterålen offshore and onshore areas, *Nor. Geol. Tidsskr.*, *76*, 215–230, 1996.

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.

Lundin, E. R., and A. G. Doré, Mid-Cenozoic post-breakup deformation in the 'passive' margins bordering the Norwegian-Greenland Sea, *Mar. Pet. Geol.*, *19*(1), 79–93, 2002.

Milnes, A. G., and H. A. Koyi, Ductile rebound of an orogenic root: Case study and numerical model of gravity tectonics in the Western Gneiss Complex, Caledonides, S. Norway, *Terra Nova*, *12*(1), 1–7, 2000.

Milnes, A. G., O. P. Wennberg, Ø. Skår, and A. G. Koestler, Contraction, extension and timing in the South Norwegian Caledonides: The Sognefjord transect, in *Orogeny Through Time*, edited by J.-P. Burg and M. Ford, *Geol. Soc. Spec. Publ.*, *121*, 123–148, 1997.

Mjelde, R., P. Digranes, M. Van Schaack, H. Shimamura, H. Shiobara, S. Kodaira, O. Mæss, N. Sørenes, and E. Vågnes, Crustal structure of the outer Vøring plateau, offshore Norway, from ocean bottom seismic and gravity data, *J. Geophys. Res.*, *106*(B4), 6769–6791, 2001.

Mosar, J., Depth of the extensional faulting on the mid-Norway Atlantic passive margin, *Norges Geol. Unders. Bull.*, *437*, 33–41, 2000.

Mosar, J., G. Lewis, and T. H. Torsvik, North Atlantic sea-floor spreading rates: Implications for the Tertiary development of inversion structures of the Norwegian-Greenland Sea, *J. Geol. Soc. London*, *159*, 503–515, 2002a.

Mosar, J., P. T. Osmundsen, A. Sommaruga, T. H. Torsvik, and E. Eide, Greenland - Norway separation: A new geodynamic model for the North Atlantic, *Norw. J. Geol.*, *82*(4), 281–298, 2002b.

Mulegeta, G., and W. Ghebread, Modeling heterogeneous stretching during episodic or steady rifting of continental lithosphere, *Geology*, *29*(10), 895–898, 2001.

Nesje, A., E. Anda, N. Rye, R. Lien, P. A. Hole, and L. H. Blikra, The veritical extent of the Late Weichsekian ice sheet in the Nordfjord-Møre area, western Norway, *Nor. Geol. Tidsskr.*, *67*(2), 125–141, 1987.

Nøttvedt, A., (Ed.), *Dynamics of the Norwegian Margin*, *Geol. Soc. Spec. Publ.*, *167*, 472 pp., 2000.

Olesen, O., E. R. Lundin, Ø. Nordgulen, P. T. Osmundsen, J. R. Skilbrei, M. A. Smethurst, A. Solli, T. Bugge, and C. Fichler, Bridging the gap between the onshore and offshore geology in the Nordland area, northern Norway, *Norw. J. Geol.*, *82*(4), 243–262, 2002.

Osmundsen, P. T., and T. B. Andersen, Caledonian compressional and late-orogenic extensional deformation in the Staveneset area, Sunnfjord, western Norway, *J. Struct. Geol.*, *16*, 1385–1401, 1994.

Osmundsen, P. T., and T. B. Andersen, The middle Devonian basins of western Norway: Sedimentary response to large-scale transtensional tectonics?, *Tectonophysics*, *332*, 51–68, 2001.

Osmundsen, P. T., T. B. Andersen, S. Markussen, and A. K. Svendby, Tectonics and sedimentation in the hangingwall of a major extensional detachment: The Devonian Kvamshesten Basin, western Norway, *Basin Res.*, *10*, 213–224, 1998.

Osmundsen, P. T., A. Sommaruga, J. R. Skilbrei, and O. Olesen, Deep structure of the Norwegian Sea area, North Atlantic margin, *Norw. J. Geol.*, *82*(4), 205–224, 2002.

Palm, H., Seismic images of Caledonian structures in Jämtland and Tröndelag, *Geol. Fören. Stockholm Förh.*, *113*(2/3), 263, 1991.

Palm, H., D. G. Gee, D. Dyrelius, and L. Björklund, A reflection seismic image of Caledonian structure in central Sweden, *Sver. Geol. Unders., Ser. Ca*, *75*, 1–36, 1991.

Parker, J. R., (Ed.), *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*, 1542 pp., Geol. Soc., London, 1993.

Pascal, C., and R. H. Gabrielsen, Numerical modeling of Cenozoic stress patterns in the mid-Norwegian margin and northern North Sea, *Tectonics*, *20*, 585–599, 2001.

Pascoe, R., R. Hooper, K. Storhaug, and H. Harper, Evolution of extensional styles at the southern termination of the Nordland ridge, mid-Norway: A response to variations in coupling above Triassic salt, in *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference Held at the Barbican Centre, London, 26–29 October 1997*, edited by A. J. Fleet and S. A. R. Boldy, pp. 83–90, Geol. Soc., London, 1999.

Peulvast, J.-P., Post-orogenic morphotectonic evolution of the Scandinavian Caledonides during the Mesozoic and Cenozoic, in *The Caledonide Orogen: Scandinavia and Related Areas*, edited by D. G. Gee and B. A. Sturt, pp. 979–995, John Wiley, Hoboken, N. J., 1985.

Poudjom Djomani, Y. H., J. D. Fairhead, and W. L. Griffin, The flexural rigidity of Fennoscandia: Reflection of the tectonothermal age of the lithospheric mantle, *Earth Planet. Sci. Lett.*, *174*, 139–154, 1999.

Redfield, T., Fracture lineaments, Cenozoic(?) faults, and Mesozoic extensional tectonics of the Møre Trøndelag region, central Norway, report, 21 pp., Norges Geol. Unders., Trondheim, 2000.

Reemst, P., and S. Cloetingh, Polyphase rift evolution of the Vøring margin (mid-Norway): Constraints from forward tectonstratigraphic modeling, *Tectonics*, *19*, 225–240, 2000.

Ren, S., J. Skogseid, and O. Eldholm, Late Cretaceous_Paleocene Extension on the Vøring Volcanic Margin, *Mar. Geophys. Res.*, *20*, 343–369, 1998.

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

Roberts, A. M., and G. Yielding, Deformation around basin-margin faults in the North Sea/mid-Norway rift, in *The Geometry of Normal Faults*, edited by A. M. Roberts, G. Yielding, and B. Freeman, *Geol. Soc. Spec. Publ.*, *56*, 61–78, 1991.

Roberts, D., High-strain zones from meso- to macro-scale at different structural levels, central Norwegian Caledonides, *J. Struct. Geol.*, *20*, 111–119, 1998.

Rohrman, M., Thermal evolution of the Fennscandian region from fission track thermochronology: An intergrated approach, Ph.D. thesis, Vrije Univ., Amsterdam, 1995.

Rohrman, M., and P. van der Beek, Cenozoic postrift domal uplift of North Atlantic margins: An asthenospheric diapirism model, *Geology*, *24*(10), 901–904, 1996.

Rohrman, M., P. van der Beek, and P. Andriessen, Syn-rift thermal structure and post-rift evolution of the Oslo Rift (southeast Norway): New constraints from fission track thermochronology, *Earth Planet. Sci. Lett.*, *127*, 39–54, 1994.

Rohrman, M., P. van der Beek, P. Andriessen, and S. Cloetingh, Meso-Cenozoic morphotectonic evolution of southern Norway: Neogene domal uplift inferrred from apatite fission track thermochronology, *Tectonics*, *14*, 704–718, 1995.

Rykkelid, E., and A. Andresen, Late Caledonian extension in the Ofoten area, northern Norway, *Tectonophysics*, *231*, 157–169, 1994.

Sanchez-Ferrer, F., S. D. James, B. Lak, and A. M. Evans, Techniques used in the exploration of turbidite reservoirs in a frontier setting: Helland Hansen license, Vøring Basin, offshore mid-Norway, in *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference Held at the Barbican Centre, London, 26–29 October 1997*, edited by A. J. Fleet and S. A. R. Boldy, pp. 281–292, Geol. Soc., London, 1999.

Schmidt, W. J., Structure of the mid-Norway Heidrun Field and its regional implications, in *Structural and Tectonic Modelling and Its Application to Petroleum Geology*, edited by R. M. Larsen et al., pp. 289–304, Elsevier Sci., New York, 1992.

Séranne, M., Late Paleozoic kinematics of the Møre-Trøndelag Fault zone and adjacent areas, central Norway, *Nor. Geol. Tidsskr.*, *72*, 141–158, 1992.

Siedlecka, A., and D. Roberts, The bedrock geology of Varanger Peninsula, Finnmark, Norway: An excursion guide, *Norges Geol. Unders. Spec. Publ., 5*, 45 pp., 1996a.

Siedlecka, A., and D. Roberts, Finnmark Fylke, Berggrunnsgeologi, Norges Geol. Unders., Trondheim, 1996b.

Sjöström, H., and S. Bergman, Asymetric extension and Devonian (?) normal faulting; examples from the Caledonides of eastern Trøndelag and western Jämtlandns, *Geol. Fören. Stockholm Förh.*, *111*(4), 407–410, 1989.

Sjöström, H., S. Bergman, and D. Sokoutis, Nappe geometry, basement structure and normal faulting in the central Scandinavina Caledonides: Kinematic implications, *Geol. Fören. Stockholm Förh.*, *113*(273), 265–269, 1991.

Skilbrei, J. R., O. Kihle, O. Olesen, J. Gellein, A. Sindre, D. Solheim, and B. Nyland, Gravity anomaly map of Norway and adjacent ocean areas, Geol. Surv. of Norway, Trondheim, 2001.

Skilbrei, J. R., O. Olesen, P. T. Osmundsen, O. Kihle, S. Aaro, and E. Fjellanger, A study of basement structures and onshore-offshore correlations in central Norway, *Norw. J. Geol.*, *82*(4), 263–280, 2002.

Skogseid, J., and O. Eldholm, Early Cenozoic crust at the norwegian continental margin and the conjugate Jan Mayen Ridge, *J. Geophys. Res.*, *92*(B11), 1471–1491, 1987.

Skogseid, J., and O. Eldholm, Rifted continental margin off mid-Norway, in *Rifted Ocean-Continent Boundaries*, *NATO ASI Ser., Ser. C*, vol. 463, edited by E. Banda, M. Torné, and M. Talwani, pp. 147–153, Kluwer Acad., Norwell, Mass., 1995.

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, T. Alabaster, and R. J. Pankhurst, *Geol. Soc. Spec. Publ., 68*, 305–320, 1992a.

Skogseid, J., T. Pedersen, and B. T. Larsen, Vøring Basin: Subsidence and tectonic evolution, in *Structural and Tectonic Modelling and Its Application to Petroleum Geology*, edited by R. M. Larsen et al., *Norw. Pet. Soc. Spec. Publ.*, *1*, 55–82, 1992b.

Skogseid, J., S. Planke, J. I. Faleide, T. Pedersen, O. Eldholm, and F. Neverdal, NE Atlantic continental rifting and volcanic margin formation, in *Dynamics of the Norwegian Margin*, edited by A. Nottvedt, *Geol. Soc. Spec. Publ.*, *167*, 295–326, 2000.

Smethurst, M. A., Land-offshore tectonic links in western Norway and the northern North Sea, *J. Geol. Soc. London*, *157*, 769–781, 2000.

Smora, J., and S. Delirius, The coupling relationship between the Viagra High and the Møring Virginal High, *J. Interior Geology*, *69*(2), 53–69, 2001.

Sommaruga, A., and R. Bøe, Geometry and subcrop maps of shallow basins along mid-Norway, *Mar. Pet. Geol.*, *19*(8), 1029–1042, 2002.

Spencer, A. M., Ø. Birkeland, G. Ø. Knag, and R. Fredsted, Petroleum systems of the Atlantic margin of northwest Europe, in *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference Held at the Barbican Centre, London, 26–29 October 1997*, edited by A. J. Fleet and S. A. R. Boldy, pp. 231–246, Geol. Soc., London, 1999.

Steel, R., A. Siedlecka, and D. Roberts, The Old Red Sandstone basins of Norway and their deformation: An overview, in *The Caledonide Orogen: Scandinavia and Related Areas*, edited by D. G. Gee and B. A. Sturt, pp. 293–315, John Wiley, Hoboken, N. J., 1985.

Steel, R. J., Devonian basins of western Norway: Sedimentary response to tectonism and to varying tectonic context, *Tectonophysics*, *36*, 207–224, 1976.

Sturt, B. A., and A. Braathen, Deformation and metamorphism of Devonian rocks in the outer Solund area, western Norway: Implications for models of Devonian deformation, *Int. J. Earth Sci.*, *90*, 270–286, 2001.

Swiecicki, T., P. B. Gibbs, G. E. Farrow, and M. P. Coward, A tectonostratigraphic framework for the mid-Norway region, *Mar. Pet. Geol.*, *15*(3), 245–276, 1998.

Terry, M. P., P. Robinson, M. A. Hamilton, and M. J. Jercinovic, Monazite geochronology of UHP and HP metamorphism, deformation, and exhumation, Nordøyane, Western Gneiss Region, Norway, *Am. Mineral.*, *85*, 1651–1664, 2000.

Torske, T., and T. Prestvik, Mesozoic detachment faulting between Greenland and Norway: Inferences from Jan Mayen fracture zone system and associated alkalic volcanic rocks, *Geology*, *19*(5), 481–484, 1991.

Torsvik, T. H., B. A. Sturt, D. M. Ramsay, A. Grønlie, D. Roberts, M. A. Smethurst, K. Atakan, R. Bøe, and H. J. Walderhaug, Palaeomagnetism, magnetic fabric and structural style of the Hornelen Old Red Sandstone, Western Norway, in *Paleomagnetic Rotations and Continental Deformation*, edited by C. Kissel and C. Laj, pp. 431–457, Kluwer Acad., Norwell, Mass., 1989.

Torsvik, T. H., B. A. Sturt, E. Swensson, T. B. Andersen, and J. F. Dewey, Palaeomagnetic dating of fault rocks: Evidence for Permian and Mesozoic movements and brittle deformation along the extensional Dalsfjord Fault, western Norway, *Geophys. J. Int.*, *109*, 565–580, 1992.

Torsvik, T. H., T. B. Andersen, E. A. Eide, and H. J. Walderhaug, The age and tectonic significance of dolerite dykes in western Norway, *J. Geol. Soc. London*, *154*, 961–973, 1997.

Torsvik, T. H., J. Mosar, and E. A. Eide, Cretaceous-Tertiary geodynamics: A North Atlantic exercise, *Geophys. J. Int.*, *146*, 850–866, 2001a.

Torsvik, T. H., R. Van der Voo, J. G. Meert, J. Mosar, and H. J. Walderhaug, Reconstructions of continents around the North Atlantic at about the 60th parallel, *Earth Planet. Sci. Lett.*, *187*, 55–69, 2001b.

Torsvik, T. H., D. Carlos, J. Mosar, L. R. M. Cocks, and T. Malme, Global reconstructions and North Atlantic palaeogeography 440 Ma to Recent, in *BATLAS-Mid Norway Plate Reconstruction Atlas With Global and North Atlantic Perspectives*, edited by E. Eide, pp. 18–39, Geol. Surv. of Norway, Trondheim, 2002.

Townsend, C., The inner shelf of North Cape, Norway and its implications for the Barents Shelf-Finnmark Caledonide boundary, *Nor. Geol. Tidsskr.*, *67*(2), 151–153, 1987.

Tsikalas, F., J. I. Faleide, and O. Eldholm, Lateral variations in the tectonometamorphic style along the Lofoten-Vesterålen volcanic margin off Norway, *Mar. Pet. Geol.*, *18*, 807–832, 2001.

van Balen, R. T., P. A. van der Beek, and S. 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., S. Cloetingh, and P. 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.

van Wijk, J. W., R. S. Huismans, M. ter Voorde, and S. A. P. L. Cloetingh, Melt generation at volcanic continental margins: No need for mantle plumes?, *Geophys. Res. Lett.*, *28*(20), 3995–3998, 2001.

Voggenreiter, W., H. Hötzl, and J. Mechie, Low-angle detachment origin for the Red Sea Rift System?, *Tectonophysics*, *150*, 51–75, 1988.

Vogt, P. R., Geophysical and geochemical signatures and plate tectonics, in *The Nordic Seas*, edited by B. G. Hurdle, pp. 413–663, Springer-Verlag, New York, 1986a.

Vogt, P. R., Seafloor topography, sediments, and paleoenvironments (Chapter 10), in *The Nordic Seas*, edited by B. G. Hurdle, pp. 237–412, Springer-Verlag, New York, 1986b.

Walker, I. M., K. A. Berry, J. R. Bruce, L. Bystøl, 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.

Weisz, G., An investigation of Jurassic coals from Haltenbanken and Beistadfjorden. A comparison of composition and maturity, Diploma thesis, Univ. of Trondheim, Trondheim, 1992.

Wernicke, B., and P. G. Tilke, Extensional tectonic framework of the U.S. central Atlantic passive margin, *AAPG Mem.*, *46*, 7–21, 1989.

Wilks, W. J., and S. J. Cuthbert, The evolution of the Hornelen Basin detachment system, western Norway: Implications for the style of late orogenic extension in the southern Scandinavian Caledonides, *Tectonophysics*, *238*, 1–30, 1994.

Withjack, M. O., and S. Callaway, Active mormal faulting beneath a salt layer: An experimental study of deformation patterns in the cover sequence, *AAPG Bull.*, *84*(5), 627–651, 2000.

Withjack, M. O., K. E. Meisling, and L. R. Russell, Forced folding and basement-detached normal faulting in the Haltenbanken area, offshore Norway, *AAPG Mem.*, *46*, 567–575, 1989.

Wolff, F. C., Regional geophysics of the central Norwegian Caledonides, *Norges Geol. Unders. Bull.*, *397*, 1–27, 1984.

Yielding, G., and A. M. Roberts, Footwall uplift during normal faulting - implications for structural geometries in the North Sea, in *Structural and Tectonic Modelling and Its Application to Petroleum Geology*, edited by R. M. Larsen et al., pp. 289–304, Elsevier Sci., New York, 1992.

Ziegler, P. A., Post-Hercynian plate reorganisation in the Tethys and Arctic - North Atlantic domains, in *Triassic-Jurassic Rifting*, *Dev. Geotectonics*, vol. 22, edited by W. Manspeizer, pp. 711–755, Elsevier Sci., New York, 1988.

Ziegler, P. A., Geodynamic processes governing development of rifted basins, in *Geodynamic Evolution of Sedimentary Basins*, edited by F. Roure et al., pp. 19–67, Technip, Paris, 1996.

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