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Greenland – Norway separation: A geodynamic model for the North Atlantic

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Combining information from onshore and offshore Mid-Norway, we propose a structural model for the Scandinavian North Atlantic passive margin from Permo-Carboniferous through Present. We re-examine the role of post-Permo-Carboniferous normal faults and define an innermost boundary fault system forming the continentward limit of the rifted margin. Crustal-scale cross-sections of the Greenland-Norway passive margins show the asymmetric nature of crustal extension between the two conjugate margins. On both margins the upper plate/lower plate geometry and the dip of major extensional normal faults change across the broad width of the Jan Mayen Fracture Zone. South of this zone on the Møre Margin (Norway), the dip of the major faults is towards the west, defining a lower plate – tilted block margin. North of the transform on the Vøring-Trøndelag Margin (Norway), the major faults dip to the east, defining an upper plate or flexural margin. In the Norwegian passive margin, the transition occurs as a progressive change of vergence of normal faults between the northern Vøring-Trøndelag Platform area and the Møre Basin. The model shows continuous separation between the two conjugate margins of Greenland and Norway, starting with a very tight fit in Late Permian time. The rifting events between Late Permian and Late Cretaceous are associated with a broadly WSW-ENE- to W-E- oriented extension while Late Cretaceous to Early Tertiary extension directions are oriented NNW-SSE. These plate separation directions and the subsequent plate motion can be related to the important basin development within, and probably, to the structural evolution and geometry of, the conjugate passive margins.

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Introduction

The Norwegian North Atlantic rift system contains not only one of Europe's largest offshore hydrocarbon provinces, but also one of Europe's most investigated mountain belts, the Caledonian Orogen (Figs. 1 & 2). In this paper we combine data from both the onshore and offshore realms of this region and propose a conceptual model for the Scandinavian side of the North Atlantic rift system. The model takes into account a redefinition of the physical boundaries of the passive margin, a re-assessment of the crustal-scale structure of the conjugate Greenland-Norway margins, and a plate tectonic history that links rifting events and geometries from the Permian through to the Present. Changing the traditional boundaries of the passive margin necessarily affects calculations of the amount of extension an area has undergone, as well as interpretations of crustal structure in regional cross-sections that display both extended passive margin and unaffected craton. Our interpretation of the crustal-scale structure suggests predominantly asymmetric crustal extension and we discuss the implications of the margin structure and asymmetry on the regional evolution of the European North Atlantic passive margin.

Regional geology, and polyphase rifting

The continental crust in the Scandinavian Caledonides contains stacked nappes that resulted from thrusting and tectonic underplating of the exotic terranes from Laurentia/Iapetus and the imbrication of the W-subducting margin of Baltica in Paleozoic times (Gee et al. 1985, Stephens et al. 1985, Ziegler 1988a, Stephens & Gee 1989, Ziegler 1990, Rey et al. 1997). The collisional climax in Silurian-Early Devonian time was followed by a generalized collapse of the mountain belt and the probable break-off of the subducting slab. Subsequent geodynamic re-equilibration led to the development of intramontane, detrital Devonian basins (Steel et al. 1985, Osmundsen et al. 1998, Osmundsen & Andersen 2001). The present-day Caledonian thrust front (Fig. 2) of the overriding upper plate is the eroded remainder of an original thrust front located further to the east

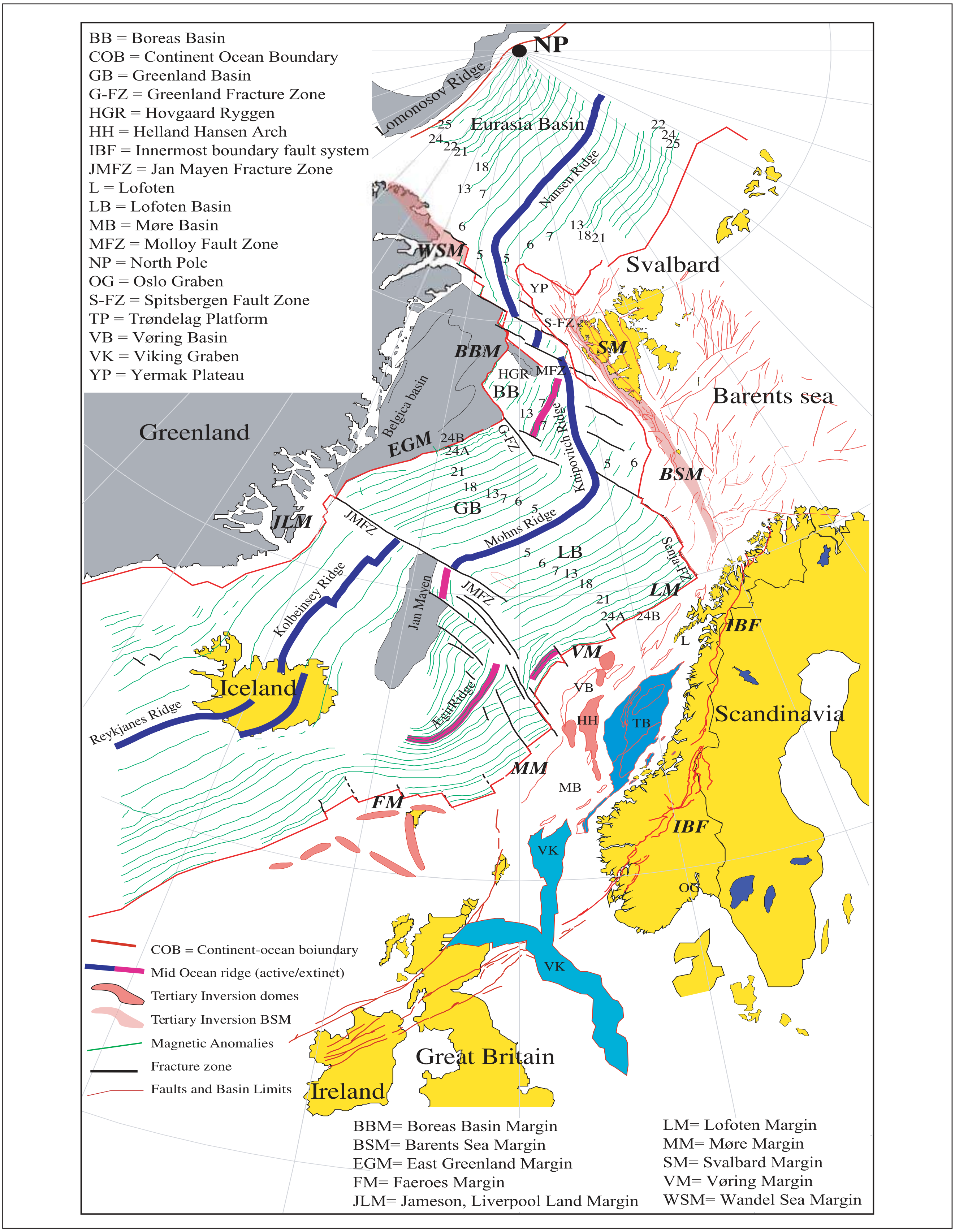


Fig. 1.Map of the North Atlantic Ocean with the Greenland and Norway conjugate margins. Major geographic areas and structural elements are shown: ocean basins, ocean ridges, main transform and fault systems, basins offshore Norway (modified from Blystad et al. 1995), and magnetic anomalies (from Skogseid et al. 2000). The different passive margin segments are highlighted. Tertiary inversion structures (domes) are shown for the Vøring and Færoes margins, and also for the Barents Sea, Svalbard and Wandel Sea margins. Note that the Jan Mayen Fracture Zone (JMFZ) incorporates a very broad zone along the western Vøring Basin margin.

(Hossack & Cooper 1986, Andréasson 1994, Garfunkel & Greiling 1998). While the mechanisms and causes of the mountain chain collapse (lithospheric root removal, slab breakoff, elastic rebound and gravitational body forces) and the transition to the purely extensional (rifting) regime are still debated (Andersen & Jamtveit 1990, Wilks & Cuthbert 1994, Hartz & Andresen 1997, Milnes et al. 1997, Marotta et al. 1998, Schott & Schmeling 1998, Koyi et al. 1999, Fossen 2000, Milnes & Koyi 2000), lithospheric 'root adjustment' following orogenic collapse probably left the mountain belt with a thinned lithosphere. The relict mountain belt was subsequently exposed to repeated rifting.

Extensional faulting and basin formation are demonstrated to have been active in the Late Devonian and Carboniferous on Norway and East Greenland (Braathen et al. 2002, Eide et al. 2002, Hartz et al. 2002, Osmundsen et al. 2002, 2003). The development of these basins was related to Devonian sinistral translation of Greenland-Laurentia relative to Baltica which led, in turn, to the formation of transtensional/transpressional basins and the collapse of the Arctic-North Atlantic Caledonides (Ziegler 1988b, a). Rifting sensu stricto started around Mid Carboniferous times, as seen in East Greenland, and was well underway by the Late Permian (see also Hartz et al. 2002). During this rifting process, the continental crust of Norway was repeatedly stretched and extended and a series of important basins was created above normal fault systems which may have rooted in the ductile zone of the middle crust (Mosar 2000). The successive rifting events eventually culminated with continental break-up and the opening of the North Atlantic Ocean in Tertiary time. Models for and general discussions of these rifting episodes can be found in e.g. Vogt (1986), Torske & Prestvik (1991), Parker (1993), Lundin & Doré (1997), Doré et al. (1999), Fleet & Boldy (1999), Brekke (2000), Nøttvedt (2000), Skogseid et al. (2000), Brekke et al. (2001).

Extensional faulting (Fig. 2) associated with the rift development was not restricted to what is now the offshore realm, but can also be seen on the Scandinavian mainland (Norton 1986, 1987, Gee 1988, Sjöström & Bergman 1989, Wilks & Cuthbert 1994, Færseth et al. 1995, Hartz & Andresen 1997, Braathen 1999). Post-Permian rift-related faults have been described in small, nearshore basins such as the Beitstadfjord Basin, north of Trondheim (Bøe & Bjerkli 1989, Sommaruga & Bøe 2003) as well as in Western Norway (Eide et al. 1997, Andersen 1998, Andersen et al. 1999).

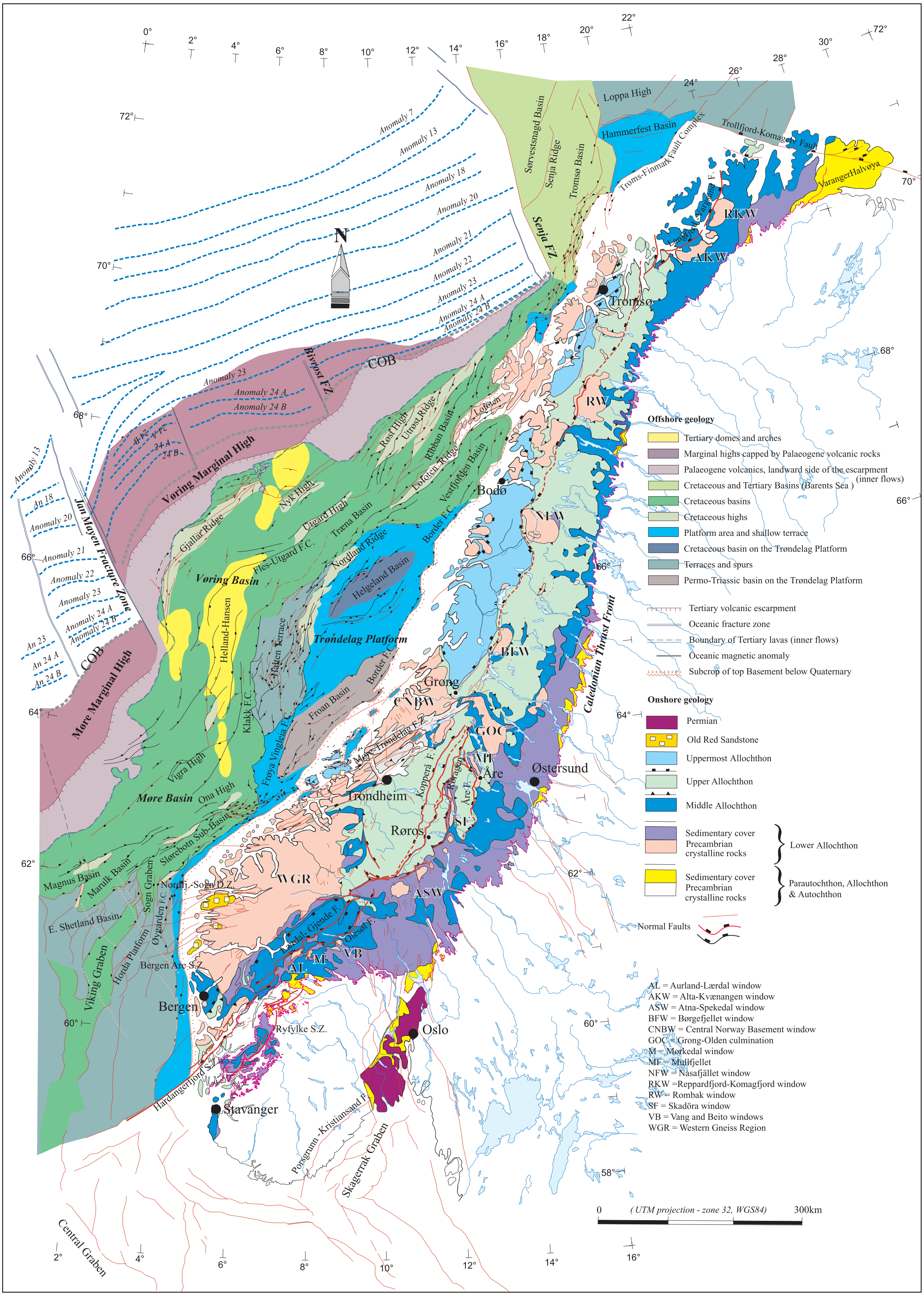
The passive margin: from Innermost Boundary Fault system to the Continent Ocean Boundary

The Scandinavian Atlantic passive margin extends from Svalbard to the intersection with the North Sea Grabens (Fig. 1 & 2). The structure of the Norwegian offshore portion can be subdivided into several distinct segments from SW to NE (Dalland et al. 1988, Doré et al. 1997, Lundin & Doré 1997, Brekke et al. 1999, Osmundsen et al. 2002): the Møre margin (Gabrielsen et al. 1999), the Vøring margin together with the Trøndelag Platform (Brekke 2000), the Lofoten margin (Tsikalas et al. 2001) and the Barents Sea - Svalbard margin (Eldholm et al. 1987, Faleide et al. 1991). In addition, a large portion of the onshore mountain belt, not traditionally considered as part of the passive margin, is included in our definition of the passive margin.

In the following we use passive margin to refer to the area that extends from the boundary for continent-ocean transition zone to the innermost continental fault system that can be related to rifting. This innermost normal fault is considered by some authors (Lister et al. 1986, Wernicke & Tilke 1989, Lister et al. 1991) as the detachment or break-away zone/fault and corresponds to the rift shoulder (Beaumont et al. 2000). In order to avoid ambiguities with the zone/fault along which sea-floor spreading occurs, often also referred to as a 'break-away zone/fault' (or final break-up), we choose here to refer to the innermost boundary fault system - IBF (Mosar et al. 2001, Mosar submitted).

The continent-ocean boundary (COB) corresponds to the transition from oceanic lithosphere to continental lithosphere. Rather than a discrete limit, this boundary forms a narrow band or zone of varying width. We identify here a new IBF system on the Norway margin, and use a rough new COB in the North Atlantic realm. The proposed IBF system (Mosar submitted) has been identified on the basis of map fault traces, topographic-geomorphic features, age determinations and kinematics of extensional faults and published seismic and potential field interpretations. The COB has been defined on the basis of the location of magnetic anomalies in the oceanic crust (Skogseid et al. 2000), new interpretations of potential field data, and information from seismic data (Figs. 1 & 2). Critically, the width of the passive margin and related issues of extension magnitude through time, are measured between the IBF and the COB. Essentially, by 'moving' the IBF from a nearshore (coastal) position to a continentward position, we alter the perspective geometries and crustal responses to the Late Carboniferous through Present rifted margin.

The IBF. - A distinctive, linked fault system – the IBF – has been proposed to extend over a distance exceeding 2000 km from the Barents Sea to the North Sea and is located to the west of the present-day Caledonian thrust front (Figs. 2 & 3). The IBF runs from southwest to north and northeast across the topographic crest of the present mountain chain and separates a gently east-dipping domain to the east from more rugged topo-


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 = Mullfjellet
NFW = Nasafjället window
RKW =Reppardfjord-Komagfjord window
RW = Rombak window
SF = Skadöra window
VB = Vang and Beito windows
WGR = Western Gneiss Region
0
(UTM projection - zone 32, WGS84)
300km
N
Sørvestsnagd Basin
Senja Ridge
Tromsø Basin
Senja FZ
Loppa High
Hammerfest Basin
Troms-Finmark Fault Complex
Trollfjord-Komagelv Fault
VarangerHalvøya
Langfjord F.
RKW
AKW
Tromsø
RW
Bodø
NFW
BFW
Grong
CNBW
GOC
MF
Åre
Østersund
Caledonian Thrust Front
Trondheim
Kopperå F.
Røragen F.
Åre F.
Røros
SF
ASW
WGR
Møre-Trøndelag F.Z.
Nordfj.-Sogn D.Z.
Lærdal-Gjende F.
Olsen F.
VB
M
AL
Bergen Arc S.Z.
Bergen
Ryfylke S.Z.
Oslo
Hardangerfjord S.Z.
Stavanger
Porsgrunn -Kristiansand F.
Skagerrak Graben
Central Graben
Anomaly 7
Anomaly 13
Anomaly 18
Anomaly 20
Anomaly 21
Anomaly 22
Anomaly 23
Anomaly 24 A
Anomaly 24 B
Anomaly 23
Anomaly 24 A
Anomaly 24 B
24 A
24 B
Bivrøst FZ
COB
Vøring Marginal High
Jan Mayen Fracture Zone
Anomaly 13
An 18
Anomaly 20
Anomaly 21
Anomaly 22
Anomaly 23
Anomaly 24 A
Anomaly 24 B
An 23
An 24 A
An 24 B
COB
Møre Marginal High
Røst High
Utrøst Ridge
Ribban Basin
Lofoten
Lofoten Ridge
Vestfjorden Basin
Nyk High
Gjallar Ridge
Utgard High
Træna Basin
Fles-Utgard F.C.
Nordland Ridge
Border F.C.
Vøring Basin
Helgeland Basin
Helland-Hansen
Halten Terrace
Trøndelag Platform
Border F.C.
Klakk F.C.
Frøya Vingleia F.C.
Froan Basin
Vigra High
Møre Basin
Ona High
Slørebotn Sub-Basin
Magnus Basin
Marulk Basin
Sogn Graben
Øygarden F.C.
E. Shetland Basin
Horda Platform
Viking Graben
0°
2°
4°
6°
8°
10°
12°
14°
16°
18°
20°
22°
24°
26°
28°
30°
72°
70°
68°
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16°

graphy and glacial valleys to the west; as such, the IBF forms the innermost rift shoulder that separates the unextended craton from the rifted passive margin (Figs. 2 & 3). This position of the IBF at the surface corresponds at depth to a zone of slight crustal thinning (Dyrelius 1985, Hurich & Kristoffersen 1988, Hurich et al. 1989, Hurich & Roberts 1997, Andersen 1998) and to the important negative Bouguer gravity anomaly of Scandinavia (in excess of –100 mGal; Balling 1984, Kinck et al. 1993, Korhonen et al. 1999, Skilbrei et al. 2001, Olesen et al. 2002, Skilbrei et al. 2002). The IBF trace also lies directly to the west of a series of small basement massifs which are themselves located above the shallow décollement of the Caledonides (Fig. 2). The IBF, as defined here, is not a single fault, but a linked fault system that reactivated former reverse or normal ductile faults of probable Devonian-Carboniferous ages along the western slopes of these massifs. The IBF probably experienced several successive periods of extension since the late Carboniferous/Permian and was most likely active as recently as the Tertiary and possibly the Present.

The COB. - Along the North Atlantic volcanic margins, the COB, or transition zone between continental and oceanic lithosphere, is frequently associated with, but also masked by, magmatic rocks linked to the break-up process (Skogseid et al. 1992, Saunders et al. 1997, Eldholm et al. 2000, Berndt et al. 2001). The magmatic rocks developed along the marginal highs and are characterized by substantial amounts of intrusive rocks, as well as thick layers of seaward-dipping reflectors related to extrusive volcanic rocks. Volcanism was associated with the initial break-up of the NE Atlantic and important crustal thinning and magmatic underplating. Along the Lofoten, Barents Sea, Svalbard, Wandel Sea, Boreas Basin, and East Greenland margins we adopted a COB based on a combined interpretation of gravity and magnetic data and commercial seismic surveys; at the Møre and Vøring Marginal High, the COB trace closely follows that proposed by Skogseid et al. (2000). Along the Jameson, Liverpool Land and Færoes margins the COB more loosely follows the location of the oldest magnetic anomalies.

Fig. 2. Tectonostratigraphic map of the Atlantic Scandinavian passive margin. The post-Late Permo-Carboniferous normal faults onshore and offshore are emphasized. The IBF is defined in Western Norway by the Lærdal-Gjende-Olestøl (LGO) fault system, and in central Norway it includes the Åre and Kopperå faults and the Røragen detachment system and the northern tip of the Møre Trøndelag Fault Complex (Andersen 1998, Mosar 2000). The IBF is traced along the topographic culmination of the mountain chain and connects former ductile extensional faults located on the western slopes of basement windows: the Børgefjellet window, the Nasafjället window, and the Rombak window (Rykkelid & Andresen 1994, Essex & Gromet 2000). In the Nordland area, the IBF and equivalent faults are proposed to consist of fault segments defined by the topographic crest of the mountain chain, the location of the basement windows, and interpretations of potential field data indicating major basement offset in the structures (Olesen et al. 2002). To the north-northeast of Tromsø in the Finnmark area, a set of large normal faults including the Langfjord-Vargsund fault form the northernmost branch of the IBF, that terminates against the Trollfjord-Komagelv fault at the edge of the Barents Sea (Siedlecka & Roberts 1996b, a). Offshore map: from Blystad et al. 1995; Brekke et al. 1999, Gabrielsen et al. 1999; Smethurst, 2000, and data from NPD-Olje Direktorat. Scandinavian Caledonides tectonostratigraphic map: Sveriges geologiska undersökning Ser. Ba nr. 35; compiled by Gee et al. 1985. Onshore-Offshore map: modified from Mosar 2000, Offshore magnetic anomalies: from Skogseid et al. 2000.

Width of the passive margin

With the COB and IBF as primary markers, we can quantify the width of the passive margin along its extent (Figs 1 & 2). The smallest width of some 165 km is found along a section across the Lofoten area, while the broadest margin width of c. 710 km is measured along a section across the Vøring Basin into Sweden (Åre-Östersund). Some 550 km of extended margin are measured along a section through the Møre Basin and the Western Gneiss Region. These widths correspond to the finite extension of the margin since Permo-Carboniferous time and represent the cumulative effect of the successive rifting-stretching events from the Mid-Late Carboniferous to Present. In a simple, first-order, semi-quantitative attempt to measure the pre-rift margin width, we used a combined approach with plate tectonic reconstructions and line-length balancing of the top-to-basement surface. In agreement with other studies (Gabrielsen et al. 1999, Reemst & Cloetingh 2000, Skogseid et al. 2000) and discussion in Brekke et al. (2001), we estimated an average total extension in the order of 200% (β=2), which means that the margin doubled its width since the Permo-Carboniferous. Conversely, in Late Permian-Early Jurassic plate reconstructions, the COB can be restored considerably farther inboard from its present position, and a very tight fit between Greenland and Scandinavia can be achieved. This implies important shortening of the existing basins and may restore sediment source areas closer to depositional realms.

Asymmetric rift geometry of the conjugate Norway-Greenland margins

The development and the geometry of rifts has been extensively discussed in recent years (e.g. Wernicke 1985, Lister et al. 1991, Ziegler 1996, Ziegler et al. 1998). In our analysis of the rifting in the North Atlantic, we use a model with an asymmetric rift geometry (Fig. 3) with correspondingly clear differences in the development of the conjugate margins (Voggenreiter et al. 1988, Lister et al. 1991, Stampfli et al. 2001, Ziegler et al. 2001). The rift geometry controls the development

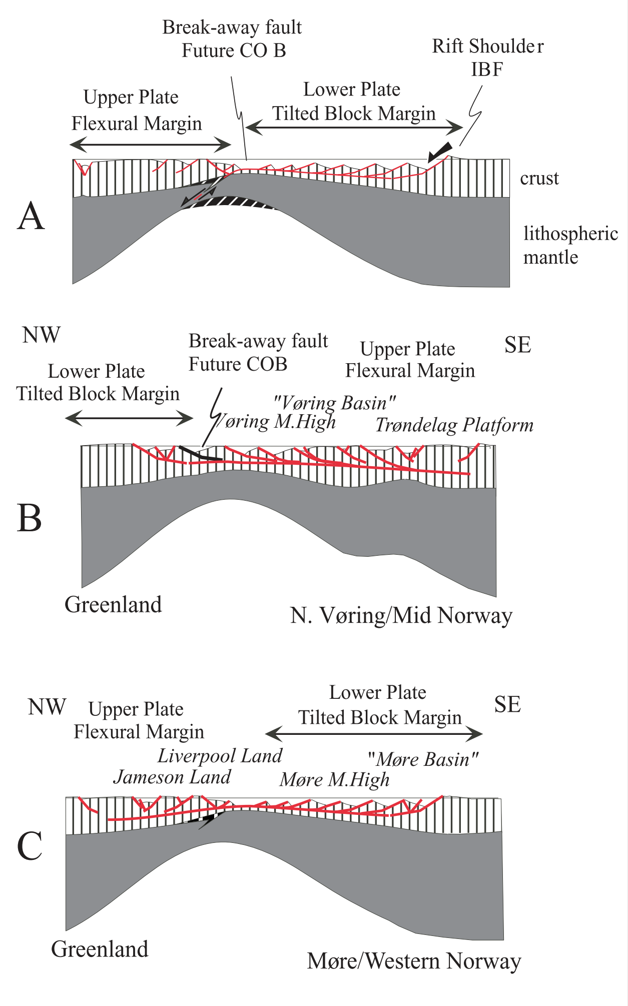

Figure 3: A. Geometry and terminology of an asymmetric rift system just prior to sea-floor spreading. B,C. Asymmetric margin geometry as discussed in this paper for sections north and south of the Jan Mayen Fracture Zone and Jan Mayen Lineament. Models are tentative reconstructions for a geometry prior to break-up and sea-floor spreading, possibly in the Jurassic-Cretaceous.

of an upper plate, or flexural margin, and a lower plate, or tilted-block margin. In an initial stage of rifting, the brittle upper crust of both the upper and lower plates is extended over a ductile basal layer along a series of listric normal faults; this configuration facilitates development of tilted blocks and half-graben structures. As rifting progresses, the lower and upper plate continue to extend and are ultimately separated during final break-away. The lower crust and the lithospheric mantle behave in a ductile manner, generating heterogeneous stretching and boudinage (Malavieille & Taboada 1991, Brun & Beslier 1996, Gartrell 1997). In such a scenario, detachment faults need not necessarily cut through the entire lithosphere. Models of the compressional strength of passive margins with an upper-plate geometry versus a lower-plate geometry (Ziegler et al. 1998, Ziegler et al. 2001) show that the upper-plate margin is weaker than the lower-plate margin.

The development of extensional normal faults in a combined upper- and lower-plate setting creates a variety of geometries (Gabrielsen 1986) such as half-grabens with roll-over structures, crestal grabens and antithetic faults, ramp-flat geometries, forced folds, and linked fault systems. In order to determine the regional structure and geometry of the major fault systems and to determine the primary, large-scale dip-directions since Permian time, we built upon the many published studies on Mid Norway's offshore domain (Bukovics & Ziegler 1985, Roberts & Yielding 1991, Yielding & Roberts 1992, Blystad et al. 1995, Grunnaleite & Gabrielsen 1995, Jongepier et al. 1996, Bjørnseth et al. 1997, Grevemeyer et al. 1997, Lundin & Doré 1997, Doré et al. 1999, Pascoe et al. 1999, Sanchez-Ferrer et al. 1999, Brekke 2000, Osmundsen et al. 2002, and references therein). Additional constraints on regional normal fault systems, their orientations and related geometries were provided from new interpretations of a high-quality, long-offset seismic reflection survey recorded to 14 seconds two-way time in the Norwegian Sea area (Osmundsen et al. 2002). In Scandinavia's North Atlantic passive margin these geometries are, to an important extent, linked to older, major Paleozoic detachment faults and basement core-complexes (Braathen et al. 2002, Osmundsen et al. 2003).

Structural provinces north and south of the Jan Mayen Fracture Zone

At a crustal scale, two large provinces with different geometries and different dip directions of major fault systems are found north and south of the Jan Mayen Fracture Zone (JMFZ) and the Jan Mayen Lineament (JML) (Fig. 1). In the oceanic realm, the JMFZ separates the extinct Ægir Ridge system (Grevemeyer et al. 1997) and the Kolbeinsey Ridge to the south from the Mohns Ridge system to the north (Fig. 1). Towards the north, the Mohns Ridge extends into the oblique-transform ridge system of the Knipovitch Ridge (Vogt 1986, Thiede et al. 1990, Vogt et al. 1998).

In the prolongation of the JMFZ, the JML forms the 'soft link' or transition zone between the Møre and Vøring Basins (Figs. 1 & 2 and discussion in Lundin & Doré 2002, Mosar et al. 2002). To the south of the JMFZ and JML are the Færoe and Møre margins on the Norwegian side, and Jan Mayen and Liverpool Land - Jameson Land areas of the Greenland margin. To the N, on the Greenland side, are the extended offshore margin of East Greenland and the Boreas Basin margin, and on the Scandinavian side, the Vøring and Lofoten margins.

In the Norway margin this transition or 'soft link' zone is located between the Frøya High and the Modgunn Arch and runs over the Helland-Hansen Arch and the

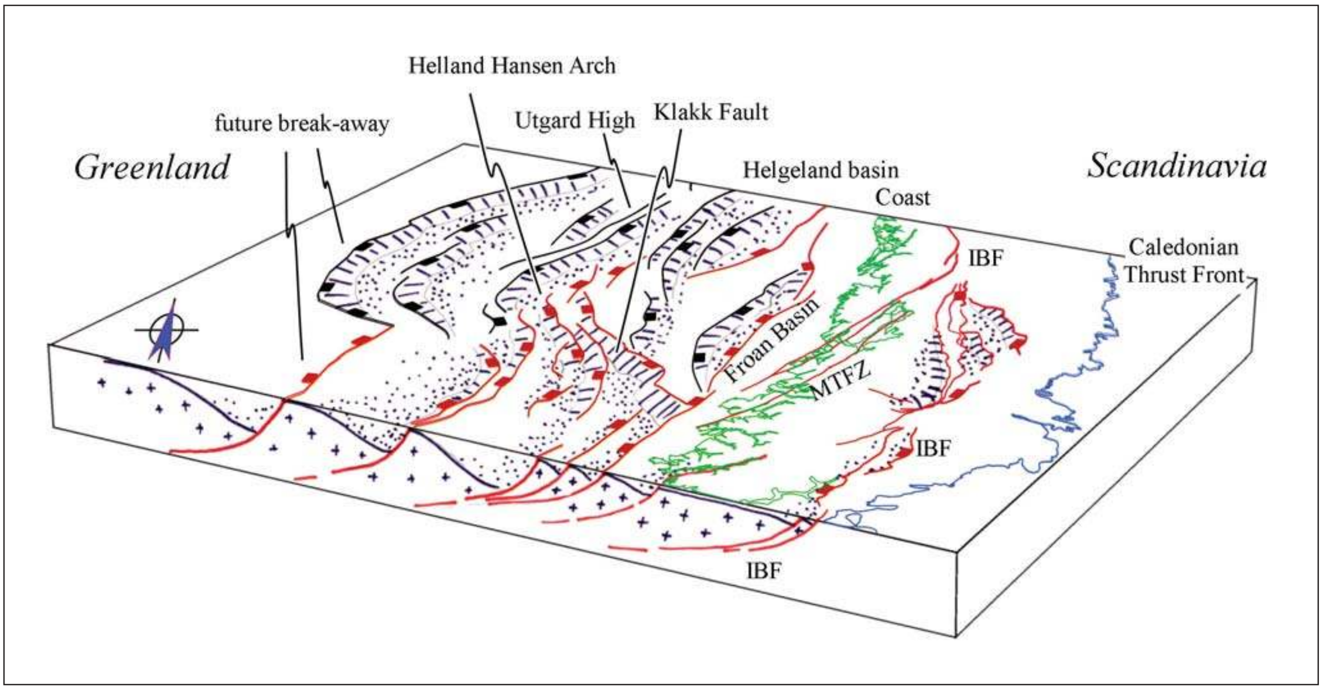

Fig. 4. Tentative 3D rendering of the transition/transfer zone from lower plate geometry and tilted block margin to upper plate geometry and flexural margin between the Møre-South Vøring Basins and the Central Vøring Basin. Faults are the same as in map of figure 2. Red faults are west-dipping, black faults are east-dipping; IBF is innermost boundary fault system. No structures are shown west of the future break-up zone on the conjugate Greenland margin. West of the Gjellar Ridge the major fault dips to the east below the sudsidiary west-dipping faults of the Gjallar Ridge according to interpretation from (Osmundsen et al. 2002).

Ormen Lange Dome (Lundin & Doré 2002, Mosar et al. 2002; Figs. 2 & 4). Transfer geometries such as convergent, divergent and synthetic, normal-fault systems (Morley 1995), are a common feature along passive margins. Thus the Ormen Lange Dome and the South Helland-Hansen Arch show predominantly NW- and W-dipping normal faults along their eastern parts, whereas the North Helland-Hansen Arch shows E-dipping normal faults along its western edge (Fig. 2 & 4; Bukovics et al. 1984, Bukovics & Ziegler 1985, Blystad et al. 1995, Grunnaleite & Gabrielsen 1995, Sanchez-Ferrer et al. 1999, Brekke 2000, Osmundsen et al. 2002). The transition from south to north forms a convergent step-over zone, especially visible in the geometries of the normal faults bounding the deep Cretaceous basin underlying the Helland-Hansen Arch.

Crustal-scale cross sections and changing fault geometries

Crustal-scale cross sections on the Mid-Norway Atlantic margin, and across the ocean into Greenland, highlight the important changes in the dip direction of the major extensional faults on both conjugate margins (Figs. 5 & 6). Interpretations of the offshore setting are based on work by Osmundsen et al. (2002) as well as work from published geoseismic profiles which are based on seismic reflection data (Blystad et al. 1995), seismic refraction data (Planke et al. 1991, Mjelde et al. 1993, Planke & Eldholm 1994, Mjelde et al. 1996, Mjelde et al. 1997, Mjelde et al. 1998), and geophysical modeling (Skogseid 1994, Skogseid & Eldholm 1995, Olesen et al. 1997, Digranes et al. 1998). Interpretations onshore are based on available deep seismic surveys and interpretations of the crustal structure (Dyrelius 1985, Hurich & Kristoffersen 1988, Hurich et al. 1989, Palm 1991, Palm et al. 1991, Hurich 1996, Hurich & Roberts 1997, Andersen 1998, Mosar 2000, submitted). Below we discuss these sections across the margin, on which the change of fault geometry is evident, mainly from dominantly W-dipping in the south to E-dipping in the north. The importance of the JMFZ and JML as a linking- or transition-zone is emphasized in this series of figures.

South of the JMFZ, the architecture of the Norwegian margin is dominated by W-dipping crustal faults. Similarly, the structure of Jameson Land and Liverpool Land is characterized by an important extensional fault system dipping to the west (Fig. 6B). The Jameson Land Basin develops over an important crustal-scale normal fault dipping to the west. Seismic investigations further southwest along the volcanic margin show similar, W-dipping faults (Larsen & Saunders 1998). The extent to which basement underlies the Jan Mayen microcontinent remains unknown, but its subsurface structure appears to show dominantly W-dipping normal faults (Gudlaugsson et al. 1988, Kuvaas & Kodaira 1997, Planke & Alvestad 1999), a crustal root at a depth of 20 km, and crustal thickness of 10 km. Seismic studies

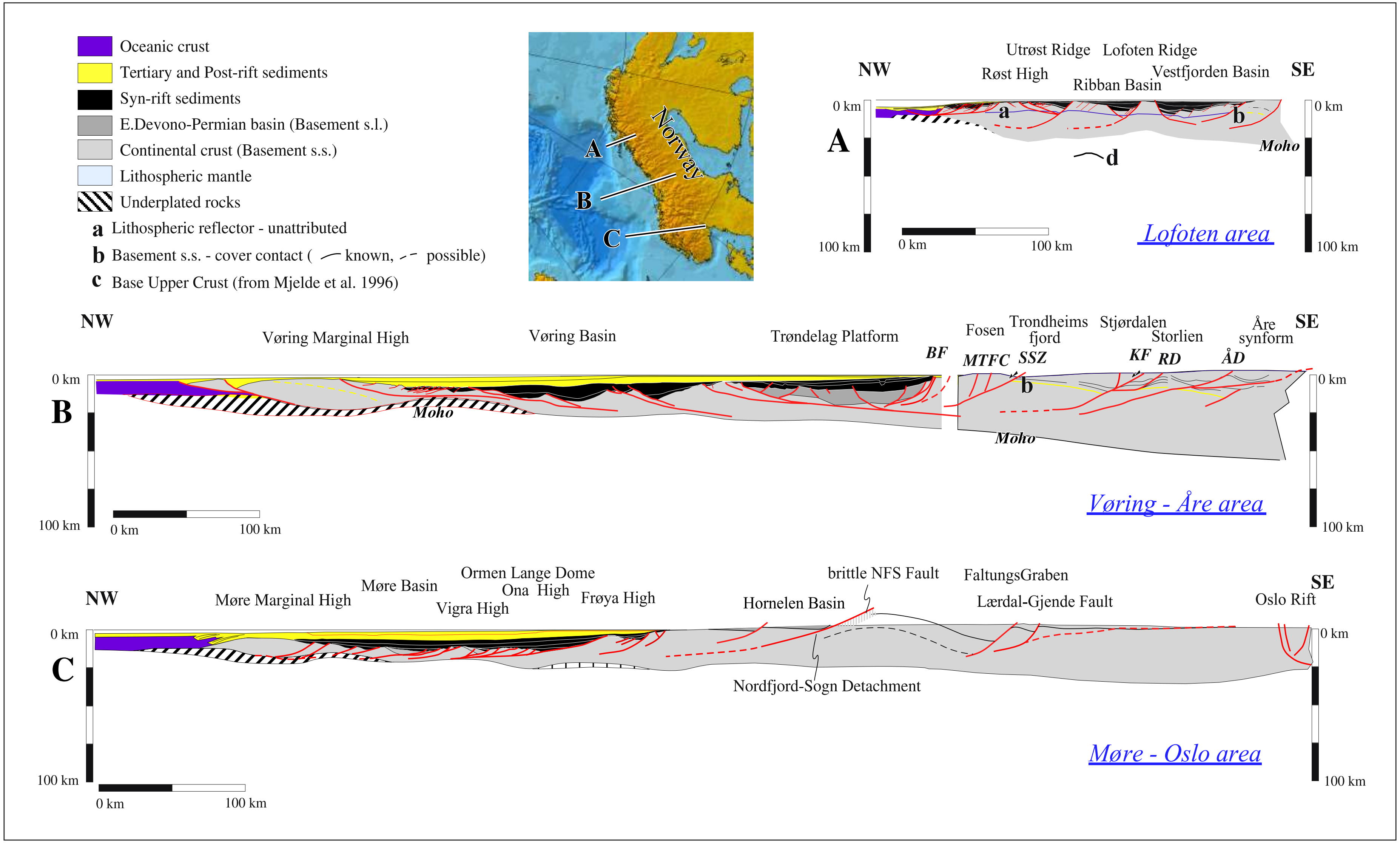

Fig. 5. Crustal-scale cross-section across the Scandinavia North Atlantic passive margin. Onshore-offshore links are shown together with upper/lower plate geometry and the changing asymmetry from north to south. A. in the Lofoten section no unique well defined asymmetry is recognizable. B. The Mid-Norway-Vøring section shows an upper plate geometry with the important extensional faults dipping to the east. C. The Western Norway-Møre section shows a lower plate - tilted block geometry with all the major extensional faults dipping to the west. The offset on the normal faults can be determined from seismic profiles in the offshore domain and can be in the km range; in the onshore portion the displacment on these faults is difficult assess and remains uncertain, but is also expected in the km range. Profiles A and B based on Mosar (2000), submitted and Osmundsen et al. (2002), profile C based on compilation from Osmundsen et al. (2002) and Olafsson et al. (1992), Blystad et al. (1995), Gabrielsen et al. (1999) for the offshore; Blystad et al. (1995), Hurich (1996), Andersen (1998), Fossen et al. (2000)for the onshore. AD = Åre Detachment; KF = Kopperå Fault; MTFC = Møre-Trøndelag Fault Complex; RD = Røragen Detachment; SSZ = Stadland shear zone.

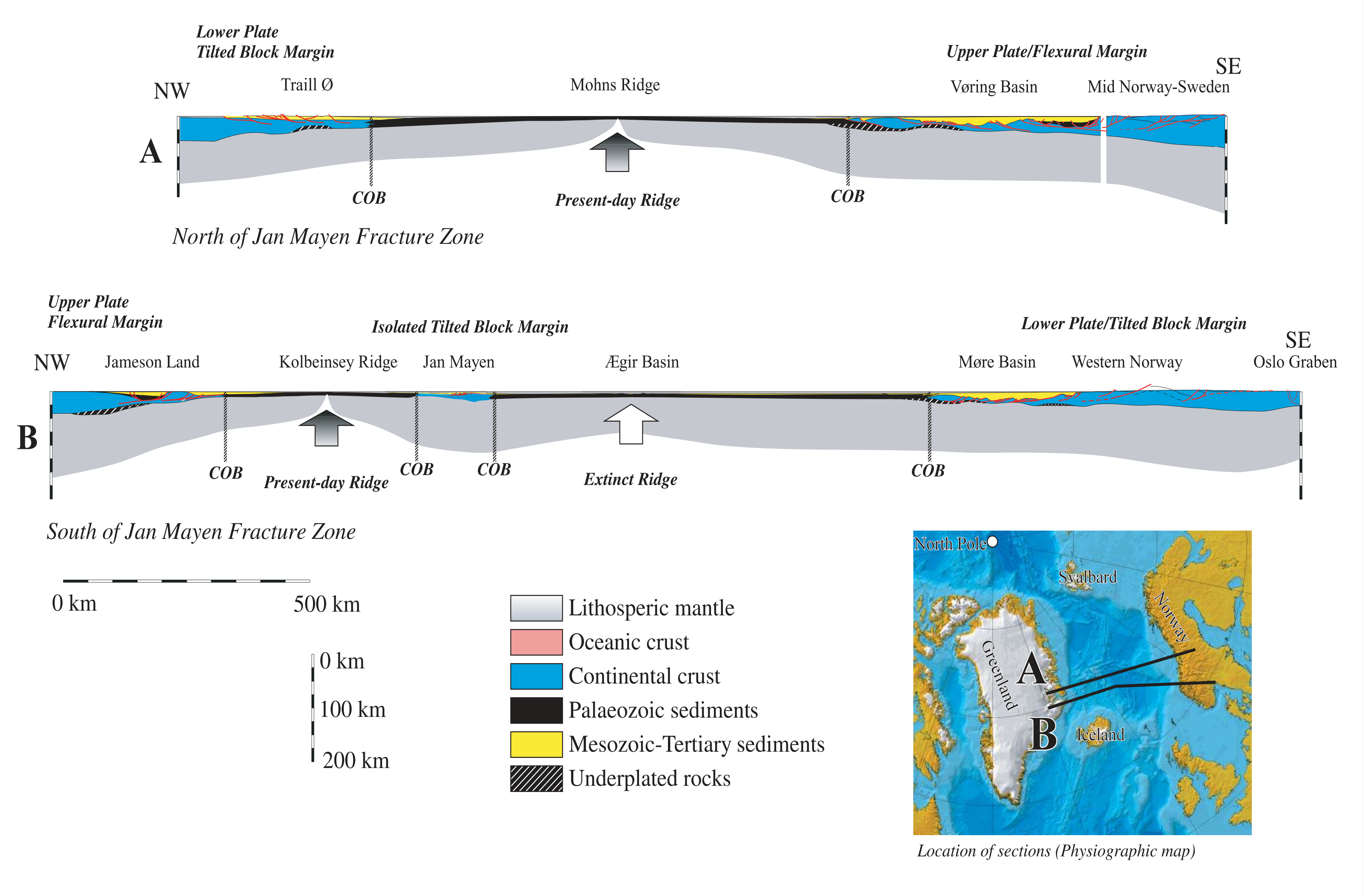

Fig. 6. Simplified cross sections through the conjugate passive margins of Norway and Greenland showing the transition from onshore to the offshore portion of the passive margins. Faults on Greenland are recognized from surface structures, as well as geophysical studies of the subsurface structure (Larsen & Marcussen 1992, Weigel 1995, Fechner & Jokat 1996, Mandler & Jokat 1998). Note the asymmetry in fault dip and margin geometry as well as the change in the dip of the major normal faults between the sections north and south of the JMFZ. The Ægir Ridge system went extinct around 25 ma (anomaly 7), and the Jan Mayen micro-continent pertained to the upper plate and was separated from Greenland after anomaly 7.

from the Møre Basin show that normal faults, over which half-graben basins develop, are the dominant structural features. The dip of the major normal faults is clearly towards the west. The Møre-Færoe-Shetland escarpment forms the transition to the outermost crustal block of the Norwegian margin, the Møre Marginal High. The Lærdal-Gjende-Olestøl fault (LGO) in the Western Gneiss Region, comprises a NW-dipping set of rift-related faults (Fig. 2 & 5C). The W-dipping crustal faults nearshore dip steeply in upper crustal levels and gently at depth where they continue into the offshore continental crust (Færseth et al. 1995, Milnes et al. 1997, Christiansson et al. 2000, Odinsen et al. 2000, Smethurst 2000).

The geometry of the East Greenland margin, north of the JMFZ, is dominated by extensional normal faults dipping to the east and related to development of important basins since the Permian (Surlyk 1991, Whitham et al. 1999; Fig. 6A). Deep geophysical studies show a basin geometry in agreement with major E-dipping faults (Whitham et al. 1999, Schlindwein & Jokat 2000). Along strike, major basin-bounding faults form relay ramp structures such as in the Hold with Hope area (Peacock et al. 2000).

Offshore Mid Norway, in the northern Vøring Basin and in the center and at the western edge of the Trøndelag Platform, the major faults are E-dipping (Fig. 5B; Osmundsen et al. 2002). The Trøndelag Platform is separated from the onshore domain by an important W-dipping normal fault system, here referred to as the Border Fault Complex. The onshore Mid Norway/Sweden area is also affected by extensional, crustal-scale faulting, and the development of small basins. The major rift-related faults in this onshore region are dipping to the west. Similarly, further north, additional normal, W-dipping faults are observed in the onshore basement (Fig. 2, 4 & 5A).

This series of cross-sections suggests that: 1) Norway's North Atlantic passive margin developed as an asymmetric passive margin, 2) the asymmetry of the passive margin in the Møre Basin and Western Gneiss Region is of lower-plate or tilted-block margin type, 3) the central Vøring Basin-Trøndelag Platform and Mid Norway domain exhibit an upper-plate or flexural margin geometry, 4) in the northern Vøring Basin, major normal faults dip to the east, whilst in the Møre Basin and southern Vøring Basin they dip to the west (see also Mosar et al. 2002, Mosar submitted). This geometry indicates a shift from an upper-plate to a lower-plate geometry between the northern Vøring and the Møre Basins. Furthermore, the Færoe-Shetland area to the south of the Møre Basin and to the northwest of the Shetland Platform could also be a potential candidate for an upper plate geometry: the major normal faults in the area are E-dipping as indicated from shallow and deep seismic profiles, though W-dipping faults also exist (Duindam & van Hoorn 1987, Gibbs 1987, Grant et al. 1999, Smallwood et al. 2001).

Asymmetric rifting and development of upper/lower plate margins has previously been proposed for various portions of the conjugate margin in the North and Central Atlantic, such as the Galicia-Flemish Cap margin (Boillot et al. 1989, Sibuet 1992) south of Charlie-Gibbs fracture zone and the Bay of Biscay rift. Other examples were documented between Nova Scotia and Morocco (Favre & Stampfli 1992), the Tarfaya Basin-Baltimore Canyon Trough, the Senegal Basin-Carolina Trough, and the Blake Plateau Basin-Guinea Basin (Lister et al. 1991). Similarly, alternating upper/lower plate margin geometries have been proposed for the conjugate margins of Greenland and Norway, south and north of the JMFZ (Torske & Prestvik 1991). However, unlike the model we suggest, these latter authors propose a model with a main crustal detachment dipping to the east, south of the JMFZ, and dipping to the west, north of the JMFZ. The analysis of Torske et al. (1991) was based on rather shallow seismic data and on the occurrence and possible causes of volcanism on both margins. In this study, we had the benefit of high-quality, deep-seismic data sets to constrain the deep geometries.

Polyphase extensional faulting and passive margin development

Starting in Late Carboniferous, the area between Greenland and Norway was affected by a series of rift events (Ziegler 1982, 1988a, 1989, Doré 1991, Doré et al. 1997, Roberts et al. 1999, Brekke et al. 2001). Repeated stretching of the continental crust left the Norway passive margin with a locally strongly thinned crust and the lithospheric mantle may have been close to the base of the sedimentary basins which contain sediments in excess of 8-10 km; very deep basins of this sort can be typical for lower plate margins (Skogseid 1994, Skogseid & Eldholm 1995, Mjelde et al. 1997, Mjelde et al. 1998). Other sections of the stretched margin like the Trøndelag Platform and the onshore domain of Norway show more moderate crustal thinning.

Offshore and nearshore

During the Permo-Triassic, basin development was concentrated in nearshore areas such as in the Trøndelag Platform (Brekke et al. 2001, Bugge et al. 2002) and along the Greenland coast (Doré 1992b, Stemmerik et al. 2000) and was possibly superimposed on important Paleozoic (Devono-Carboniferous?) basins (Bukovics et al. 1984, Braathen et al. 2002, Osmundsen et al. 2002). Jurassic rifting seems to have been widespread (onshore and offshore), but the important, deep Meso-

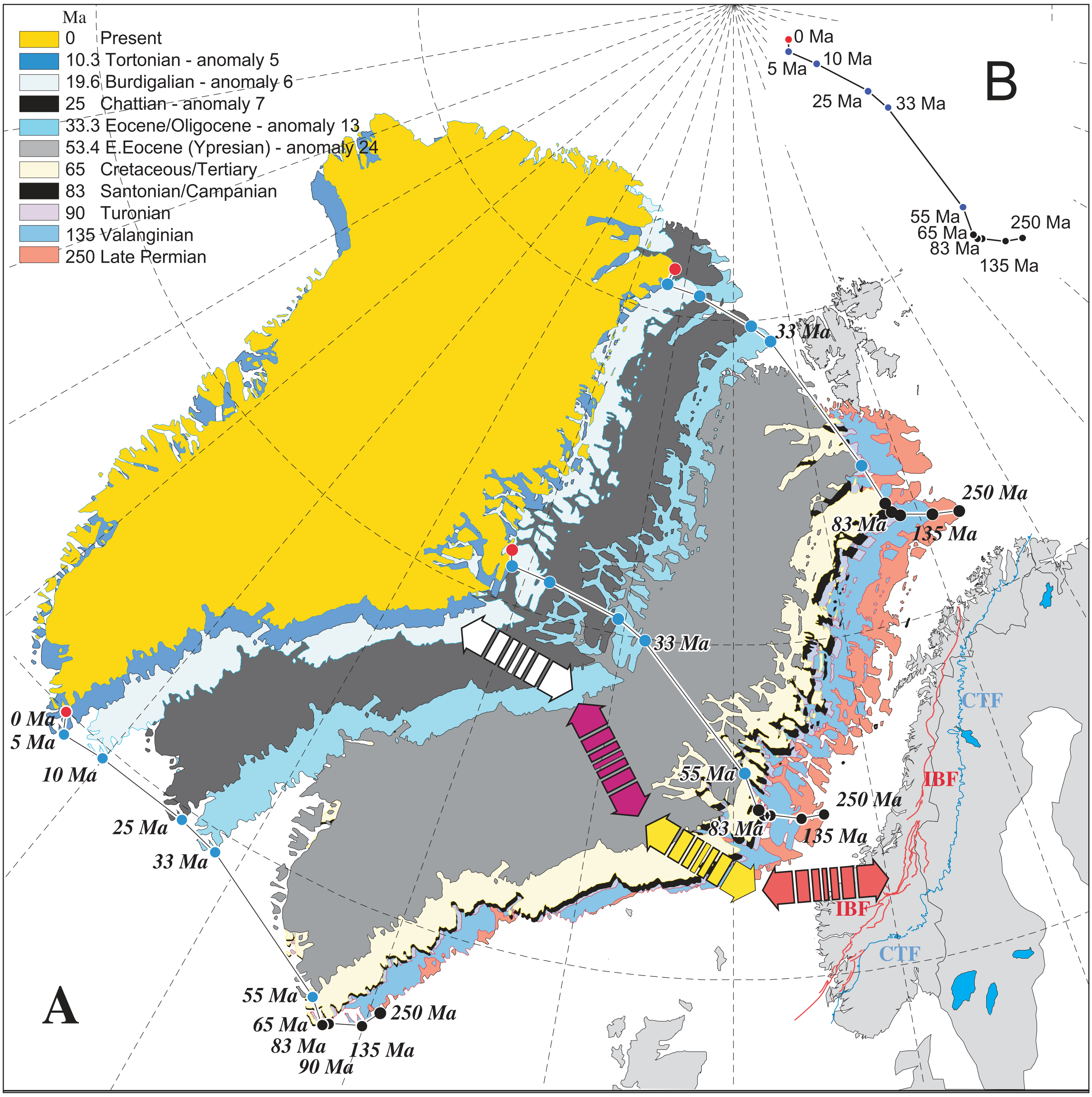

Fig. 7A. Plate reconstructions for Greenland versus Europe according to revised rotation poles in Torsvik et al. (2001b) with Europe fixed. A. To highlight opening directions, the successive positions of Greenland are shown, and the dots and connecting lines show the trajectory of three distinct points on Greenland. The large arrows qualitatively indicate the main different successive opening directions. A very tight fit is achieved for the earliest Permian fit implying that the margin on the Scandinavian side must be shortened by some 50%. A further consequence of this type of tight fit is an important overlap of NE Greenland and the Barents Sea implying important subsequent extension in these domains and detaching Svalbard from the European plate (see Torsvik et al. 2001b) for detailed discussion). B. Displacement path of point on Jameson Land (same as central path in A) with age attribution for each successive opening stage.

zoic basins formed to the west of the Permian basins (Ziegler 1988a, Doré et al. 1999, Brekke 2000). The Middle Jurassic to Early Cretaceous is another important period of rifting, that was followed by Middle Cretaceous rifting (Brekke et al. 2001). During these events the zone of highest crustal attenuation moved further westward and maximum subsidence occurred during the Early and Late Cretaceous in the Vøring and Møre Basins. The last important rifting event is of Late Cretaceous-Early Tertiary age (Doré et al. 1999, Brekke et al. 2001) and preceded crustal separation prior to break-up. The exact position of this break-up is obscured in the Vøring and Møre Basins by basalt flows but is clearly developed along the Barents Sea margin, and in the West Shetland trough. The rift-drift transition occurred in the Early Eocene just prior to anomaly 24B. During the Late Eocene-Early Oligocene and in the Miocene, compressional structures developed in response to the build-up of stresses in the elongations of the Iceland and Jan Mayen Fault zones (Doré & Lundin 1996, Vågnes et al. 1998, Lundin & Doré 2002, Mosar et al. 2002). The migration of the locus of maximum subsidence and the associated development of accommodation space is towards the future break-up location, that is westward on the Norwegian margin. Until the Tertiary, successive rift periods failed to proceed to crustal separation. The successive aborted rifts left the passive margin with an unequally stretched or 'boudinaged' continental crust and deep sedimentary basins. This evolution may be supported by numerical modeling on basin migration which suggests that successive rift basins are abandoned due to 'strain hardening', forcing the development of new rifts in the rheologically weaker, neighboring, unstretched crust (van Wijk & Cloetingh 2002); this appears to apply especially in areas with low lithospheric extension rates.

Onshore

Rift development and sedimentary basin formation in nearshore to offshore areas cannot be separated from simultaneous rifting in the onshore domain which produced uplift and extension. Active uplift and repeated movement on rift-related faults since the Devonian is indirectly implied on the Norway margin by the lack of sedimentary units much younger than latest Devonian age (Eide et al. submitted). Quantitative information on the amount and timing of uplift events on the onshore Norway-Sweden side of the passive margin derives from fission-track data and study of morphology-paleosurfaces. The different uplift events are corroborated by analysis of subsidence offshore.

Fission-track data from the Caledonides in Sweden indicate a cumulative 2 km section of missing (eroded) Late Paleozoic to Late Cretaceous sediments from what was a western foreland basin (Cederbom et al. 2000). The existence of a foreland basin is corroborated by models from Garfunkel & Greiling (1998). The former presence of a sedimentary section agrees with estimates of 3-4 km of post-Permian erosion in the Oslo rift area (Rohrman et al. 1994). Cooling events deduced from fission-track studies for the Norway-Sweden side of the passive margin indicate uplift in the Late Paleozoic-Triassic, the Late Jurassic (around 140 Ma) and the Cretaceous (at around 90 Ma; Rohrman et al. 1995). A final uplift period started in the Neogene (Riis 1996, Rohrman & van der Beek 1996). Studies on morphology-paleosurfaces-saprolites in Sweden also reveal the existence of several palaeosurfaces and relics of denudation/uplift between the Cambrian and the Late Tertiary (Doré 1992a, Lidmar-Bergstöm 1995, Doré & Jensen 1996, Lidmar-Bergstöm 1996, Riis 1996, Lidmar-Bergstöm et al. 1997). In summary, the onshore portion of the passive margin was probably buried in many areas during the Mesozoic and possibly the Tertiary (see also Brekke et al. 2001).

Plate-tectonic reconstructions

Plate tectonic reconstructions provide an independent tool to understand the dynamic evolution, including the basin development, of the investigated North Atlantic continental margin. Based on recent reviews of palaomagnetic poles (Torsvik et al. 2001a, Torsvik et al. 2001b), palaeomagnetic anomalies and rotation poles (Roest & Srivastava 1989, Gaina et al. 2002), and the ages of post-breakup magnetic sea-floor anomalies in the North Atlantic (Cande & Kent 1995, Skogseid et al. 2000) for Eurasia, Greenland and North America, a series of reconstructions from Late Permian to Present is presented in figure 9. The reconstructions highlight the pre- and syn-rift positions of the plates and primary trajectories of plate motions.

The initial pre-rift position of Europe, Greenland and North America is based on a classic Bullard fit (Bullard et al. 1965) which was slightly modified to achieve a better (tighter) fit of Greenland and Norway in Permian time. This position is consistent with information on the overall post-Early Permian extension/shortening (a 50% narrower pre-rift margin) observed on the Norway-East Greenland margins (Torsvik et al. 2001b). From Late Permian (250 Ma) to late Early Cretaceous (100-90 Ma) the opening direction between the present-day Norwegian shelf and East Greenland was W-directed, oblique to the present coastline. During the Late Cretaceous, the opening followed a more NE-NNE-direction, perpendicular to the margin's present coastline (Fig. 9). This change, which is also reflected in an important change of absolute plate directions around 85 Ma (Torsvik et al. 2001a), coincides with a period of important basin infill and high sedimentation rates (Coniacian-Santonian). The onset of seafloor spreading occurred at or just prior to anomaly 24 (24r : 53.347-55.904 Ma, Cande & Kent 1995, Mosar et al. 2002) which is the oldest normal polarity chron identified in the NE Atlantic (Talwani & Eldholm 1977, Hagevang et al. 1983). Most, if not all, of the extension on the passive margins of the Greenland and Lofoten seas, was achieved at that time. Extension of the continental crust continued into Tertiary in the Jan Mayen area, and the Boreas Basin - Barents Sea domains. A time of lowest spreading rates during Oligocene (30-25 Ma) coincides with the major changes in post-breakup plate motion and is coeval with ridge jumps as well as the final separation of Svalbard (Europe plate) and Greenland (North America plate).

Conclusions

Examination of the Mid-Norway onshore and offshore geology has allowed us to suggest a structural model for the evolution of the Norwegian North Atlantic passive margin. The rift processes that led to the formation of the North Atlantic and the formation of the Greenland and Norway conjugate passive margins started probably in late Carboniferous, building on an inherited geometry and structure of the Caledonian orogen and the Devono-Carboniferous, transtensional, intramontane basins. The polyphase rift history created a stretched continental crust between the COB and the IBF, or rift shoulder. The IBF system determines the boundary between rifted passive margin and unextended shield. This implies that the passive margin is much wider than previously assumed. The IBF was repeatedly active since Permo-Carboniferous times in conjunction with episodic uplift of the onshore portion of the margin. The passive margin is divided into several major domains separated by discrete faults/fault systems such as the IBF, the MTFC or the Klakk Fault Complex, that were probably repeatedly active during the successive rifting events.

The rifted margins on Greenland and Norway show a structural asymmetry, which can be described in terms of upper-plate geometry or flexural margin versus lower-plate geometry or tilted-block margin. In the central part of the Vøring Basin, the major normal faults dip to the east with a large roll-over structure east of the Nordland Ridge which may be interpreted as an upper-plate geometry. The conjugate margin portion in Greenland shows evidence of a tilted-block margin with the major faults also dipping to the east and consistent with a lower-plate geometry. Across the broad JMFZ, the conjugate passive margins change polarity. The transition is gradual between the central portion of the Vøring Basin and the Møre Basin. The southern Vøring Basin and the area of the Helland-Hansen Dome could form a relay structure (soft link) between the two basins. The Møre Margin shows W-dipping normal faults which are consistent with a lower-plate geometry containing tilted blocks. West-dipping faults are observed in Jan Mayen and on the Greenland margin, which would be indicative of an upper plate flexural margin.

The asymmetric structure of the Scandinavian passive margin and the changing polarities we suggest along its extent may have profound implications for the tectonic and dynamic development of the margin. Upper plate margins could have a lower compressional strength than lower plate margins (Ziegler et al. 1998, Mosar et al. 2002). The upper plate margins are therefore more likely to develop features such as inversion structures. The plate tectonic reconstructions for the Mesozoic evolution of the North Atlantic domain show important changes, not only in plate motion direction, but also in plate velocity, which can be correlated with important events in basin development and related dynamics.

The development of the different major offshore basins is intimately associated with uplift history of the mainland-onshore portion of the passive margin. This onshore portion functions as a long-lasting sediment source to the deep basins which develop mainly offshore. Most of the sediments sourced from the Scandinavian side of the margin and presently found in the basins of the Trøndelag Platform, in the Lofoten area and in the Møre and Vøring Basins would appear to have derived from the eroding rift shoulder, seaward (west) of the IBF. The rift-shoulder created by the IBF is a long-lasting drainage divide that appears to have been active at different periods since Permo-Carboniferous until Recent.

The structural and plate tectonic model presented here redefines many of the previously accepted definitions of the Norwegian North Atlantic passive margin. Its implications will help re-assess the geohistory of the rifting. The IBF highlights the co-eval onshore uplift history and basin formation and its importance for provenance studies and source areas. Lithospheric-scale modeling will have to take into account the onshore portion of the margin, but also the asymmetric nature of the extended continental crust. The plate dynamics will have to be more intimately linked to the evolution of the margin, the basin development and the formation of inversion structures.

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