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Structure and evolution of the continental margin off Norway and the Barents Sea

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The Norwegian Margin formed in response to early Cenozoic continental breakup and subsequent opening of the Norwegian-Greenland Sea. There is a well-defined margin segmentation and the various segments are characterized by distinct crustal properties, structural and magmatic styles, and post-opening history of vertical motions. The sedimentary basins at the conjugate continental margins off Norway and Greenland and in the western Barents Sea developed as a result of a series of post-Caledonian rift episodes until early Cenozoic time, when complete continental separation took place.

Introduction

The Norwegian continental margin comprises the mainly rifted volcanic margin offshore mid-Norway (62–70°N) and the mainly sheared margin along the western Barents Sea and Svalbard (70–82°) (Figures 1 and 2). Physiographically, the Norwegian margin consists of a continental shelf and slope that vary considerably in width and steepness. The two adjacent shallow seas, the North Sea and the Barents Sea were, prior to the formation of the deep NE Atlantic ocean in early Cenozoic time, part of a much larger epicontinental sea between the continental masses of Fennoscandia, Svalbard and Greenland. The conjugate continental margins off Norway and Greenland (Brekke, 2000; Skogseid et al., 2000; Hamann et al., 2005; Tsikalas et al., 2005a), and the Barents Sea (Faleide et al., 1993; Gudlaugsson et al., 1998), experienced a long history of post-Caledonian extension (since Devonian) until breakup in early Cenozoic time. The margins are part of the North Atlantic Volcanic Province (NAVP) (Saunders et al., 1997). The voluminous igneous activity during breakup has left a distinct imprint on the rifted margin segments in terms of extrusive and intrusive magmatism at various crustal levels.

In this paper we synthesize and describe the regional structural and stratigraphic framework of the continental margin off Norway and the Barents Sea, emphasising on margin segmentation, tectono-magmatic style, sediment distribution and possible structural inheritance. The compilation builds on a large amount of integrated seismic reflection, wide-angle refraction and potential field data, and published scientific papers.

Figure 1 Regional setting of the Norwegian continental margin, which formed in response to the Cenozoic opening of the Norwegian-Greenland Sea. Bathymetry/topography from the 1° × 1° elevation grid of Jakobsson et al. (2000). BF: Bjørnøya Fan, EGM: East Greenland Margin, GR: Greenland Ridge, HR: Hovgård Ridge, JMR: Jan Mayen Ridge, LVM: Lofoten-Vesterålen Margin, MM: Møre Margin, NSF: North Sea Fan, SF: Storfjorden Fan, VM: Vøring Margin, VP: Vøring Plateau, YP: Yermak Plateau.

Margin structure

The structural map (Figure 2) and a series of crustal transects (Figures 3 and 4) reveal an along-margin segmentation reflecting different geological provinces. The crustal thickness varies from 4–10 km in the oceanic Norway and Lofoten basins to about 30–32 km

near the coastline and in the western Barents Sea, and is primarily governed by multi-phase extensional deformation and breakup-related magmatism. The transition from oceanic to continental crust differs considerably between the rifted and sheared margin segments.

Mid-Norwegian margin

The mid-Norwegian margin comprises three main segments (Møre, Vøring and Lofoten-Vesterålen), each between 400–500 km long, separated by the East Jan Mayen Fracture Zone and Bivrost Lineament/transfer zone (Figures 1 and 2). A lower crustal body (LCB) characterized by high P-wave velocities, 7.3–7.6 km/s, believed to be of breakup-related magmatic origin is characteristic for the outer parts of the volcanic margin off mid-Norway (Mjelde et al., 2005a). The LCB is best developed on the Møre and Vøring margin segments where it forms the lower part of the thickened crust beneath the marginal highs, with continuity to the exceptionally thick oceanic crust to the west. To the east, it continues below the crust that was extended and thinned prior to breakup (Figure 3).

The formation of the mid-Norwegian margin comprises the following tectono-magmatic evolution (Eldholm et al., 2002): (1) lithospheric extension during a rift episode in the latest Cretaceous-Paleocene leading to plate breakup and separation, (2) central rift uplift and increased igneous activity during late rifting and a few m.y. after breakup, culminating with voluminous outpourings of basaltic lavas in the Early Eocene, and (3) change to normal accretionary magma volumes with subsequent continental margin subsidence and maturation (Middle Eocene-Present).

The Møre Margin is characterized by a narrow shelf and a wide/gentle slope (Figure 1), underlain by the wide and deep Møre Basin (Figure 2) comprising a thick Cretaceous fill (Figure 3). The inner flank of the Møre Basin is steeply dipping basinward and the crystalline crust thins rapidly from >25 km to <10 km (Figure 3; profile 1). The sedimentary succession is the thickest along the western part of the basin; 15–16 km, decreasing to 12–13 km landwards. The deep Møre Basin comprises sub-basins separated by intrabasinal highs formed during Late Jurassic-Early Cretaceous rifting. Most of the structural relief was filled in by mid-Cretaceous time. Sill intrusions are widespread within the Cretaceous succession in central and western parts of the Møre Basin, and lava flows are covering the western part of the basin. A 2–5 km thick LCB with >7 km/s P-wave velocity is present under most of the Møre Basin. This body has been interpreted as breakup-related magmatic underplating (Olafsson et al., 1992; Raum, 2000). Seaward of the Faeroe-Shetland Escarpment, at the Møre Marginal High (Figures 2 and 3), thickening of the crystalline crust and shallowing of the pre-Cretaceous sediments and top crystalline basement occur near the continent-ocean transition (COT) (Breivik et al., 2006).

The ~500 km wide Vøring Margin comprises, from southeast to northwest, the Trøndelag Platform, the Halten and Dønna terraces, the Vøring Basin and the Vøring Marginal High (Figures 2 and 3). The Trøndelag Platform has been largely stable since Jurassic time and includes deep basins filled by Triassic and Upper Paleozoic sediments (Figure 3; profiles 2–4). Wide-angle seismic refraction profiles and deep MCS profiles constrain the Moho depth from ~30–32 km close to mainland Norway to ~25 km on large parts of the platform. The Vøring Basin can be divided into a series of sub-basins and highs (Figure 3), mainly reflecting differential vertical movements during the Late Jurassic–Early Cretaceous basin evolution. Moho is undulating at 20–25 km depth beneath the deep basin (Figure 3; profiles 2–4). In most parts of the area the velocity of the lower crust is very high, 7.3–7.6 km/s in a lower crustal body (LCB) created by magmatic underplating (Mjelde et al., 2003, 2005a).

Figure 2 Regional structural map showing structural elements related to different rift phases affecting the NE Atlantic region. Location of margin transects in Figures 3 and 4 also shown. BB: Bjørnøya Basin, BL: Bivrost Lineament, EJMFBZ: East Jan Mayen Fracture Zone, GR: Greenland Ridge, HFZ: Hornsund Fault Zone, HR: Hovgård Ridge, JMR: Jan Mayen Ridge, MB: Møre Basin, MMH: Møre Marginal High, SB: Sørvestsnaget Basin, SFZ: Senja Fracture Zone, TB: Tromsø Basin, TP: Trøndelag Platform, VB: Vøring Basin, VMH: Vøring Marginal High, VVP: Vestbakken Volcanic Province, WJMFZ: West Jan Mayen Fracture Zone.

Alternative interpretations of the LCB, including inherited high pressure granulite/eclogite rocks, melted continental crust or serpentinised mantle rocks, were discussed by Gernigon et al. (2004). The thickness of the body varies considerably laterally within the area, from absence to about 8–9 km. These strong lateral variations might be caused by variations in the pre-breakup structure and/or spatial variations in the magma distribution process.

The Vøring Plateau is a distinct bathymetric feature (Figure 1), and includes the Vøring Marginal High and the Vøring Escarpment (Figures 2 and 3). The Vøring Marginal High consists of an outer part of anomalously thick oceanic crust and a landward part of stretched continental crust covered by thick Early Eocene basalts and underplated by mafic intrusions. Densely spaced OBS data reveal a ~25-km-wide COT zone beneath the inner parts of seaward

Figure 3 Crustal transects across the rifted continental margin off mid-Norway. Location of profiles in Figure 2. For references see text. DT: Dønna Terrace, GR: Gjallar Ridge, HT: Halten Terrace, HG: Hel Graben, JH: Jennegga High, LB: Lofoten Basin, LR: Lofoten Ridge, MMH: Møre Marginal High, NB: Norway Basin, NH: Nyk High, NS: Någrind Syncline, RB: Ribban Basin, RsB: Rås Basin, TrB: Trøna Basin, TP: Trøndelag Platform, UH: Utgard High, UR: Utrøst Ridge, VB: Vestfjorden Basin, VE: Vøring Escarpment, VH: Vigra High, VMH: Vøring Marginal High, VS: Vigrid Syncline.

dipping reflector (SDR) sequences (Mjelde et al., 2005b). Landward of the COT, seismic velocities of ~ 6.0 km/s in the top of the main crustal layer are conformable with granitic basement, whereas corresponding velocities seaward of the COT (~ 6.9 km/s) indicate gabbroic, oceanic crust. The COT is characterized by intermediate, ~ 6.5 km/s, velocities, interpreted as heavily intruded continental crust that is underlain by a high-velocity LCB (Figure 3).

The Bivrost Lineament separates the Vøring and Lofoten-Vesterålen margins, marking the northern termination of the Vøring Plateau and the Vøring Marginal High, as well as the Vøring Escarpment (Figure 2) (e.g., Olesen et al., 2002). The Bivrost transfer zone is a major boundary in terms of margin physiography, structure, breakup magmatism, and lithosphere stretching; breakup-related magmatism is more voluminous south of it and the less magmatic Lofoten-Vesterålen margin was more susceptible to initial post-opening subsidence (Tsikalas et al., 2005b).

The Lofoten-Vesterålen margin is characterized by a narrow shelf and steep slope (Figure 1). The sedimentary basins underneath the shelf are narrower and shallower than on the Vøring and Møre margins (Figure 3, profiles 5–6). Typically they form asymmetric half-graben structures with changes in polarity bounded by a series of basement highs along the shelf edge. Beneath the slope, breakup-related lavas mask a sedimentary basin whose detailed mapping is hampered by poor seismic imaging (Tsikalas et al., 2001). Deep seismic profiles show ~ 30 km Moho depth in the coastal areas and a distinct thinning beneath the Lofoten Islands (Figure 3; profiles 5 and 6). The latter has been related to the development of a core complex in the middle to lower crust in the Lofoten Islands region, which has been exhumed along detachments during large-scale extension (e.g., Mjelde et al., 1993; Steltenpohl et al., 2004; Tsikalas et al., 2005b). The continental crust on the Lofoten-Vesterålen margin appears to have experienced only moderate pre-breakup extension, contrasting the greatly extended crust in the Vøring Basin farther south (Figure 3).

Western Barents Sea-Svalbard margin

Late Cretaceous–Paleocene rifting and subsequent breakup and initial seafloor spreading in the Norwegian–Greenland Sea was linked to the Arctic Eurasia Basin by the regional De Geer Zone megashear system. The western Barents Sea-Svalbard margin developed along this zone and is composed of two large shear segments and a central rifted margin segment SW of Bjørnøya associated with volcanism (Figure 2). Each segment is characterized by distinct crustal properties, structural and magmatic styles, and history of vertical motion (Figure 4), mainly as a result of three controlling parameters (Faleide et al., 1991): (1) the pre-breakup structure, (2) the geometry of the plate boundary at opening and (3) the direction of relative plate motion. The COT is confined within a narrow zone (10–20 km) along the sheared margin segments (Breivik et al., 1999), but is more obscure and partly masked by volcanics at the rifted margin segments.

The Senja Fracture Zone (SFZ), or Senja Shear Margin, marks the southern segment of the predominantly sheared margin along the western Barents Sea (Figure 2). Landward of the SFZ, the margin bounds a basinal province in which as much as 18–20 km of sedimentary strata cover a highly attenuated crystalline crust (Figure 4; profile 7).

The Vestbakken Volcanic Province (VVP) is located at a rifted margin segment southwest of Bjørnøya, linking sheared margin segments to the south and north (Figure 2). An east-stepping of the Eocene dextral shear margin (releasing bend) gave rise to basin formation in a pull-apart setting. The VVP structures are mainly extensional, but transpress-

Figure 4 Crustal transects across the mainly sheared western Barents Sea-Svalbard margin. Location of profiles in Figure 2. For references see text. BB: Bjørnøya Basin, BFZ: Billefjorden Fault Zone, HfB: Hammerfest Basin, HFZ: Hornsund Fault Zone, HR: Hovgård Ridge, LB: Lofoten Basin, MD: Molloy Deep, RFZ: Raudfjorden Fault Zone, SB: Sørvestsnaget Basin, SFZ: Senja Fracture Zone, SR: Senja Ridge, TB: Tromsø Basin, VVP: Vestbakken Volcanic Province.

sional structures are observed locally. Prominent volcanoes as well as sill intrusions are observed at the outer margin (Faleide et al., 1988). Repeated tectonic activity in a pull-apart setting within the Vestbakken Volcanic Province reflects that the Cenozoic evolution of the NE Norwegian-Greenland Sea was complex, and as much as eight tectonic and three volcanic events have been identified (Jebesen and Faleide, 1998).

The continental margin north of Bjørnøya can be further subdivided into three segments (Figure 2): (1) a sheared margin from Bjørnøya to Sørkapp at the southern tip of Spitsbergen (74°30'–76°N), (2) an initially sheared and later rifted margin west of Svalbard between Sørkapp and Kongsfjorden (76–79°N), and (3) a complex sheared and rifted margin along NW Svalbard and SW Yermak Plateau associated with volcanism (79–81°N). The crustal thickness changes abruptly from continental crust more than 30 km thick on the Svalbard Platform, including the Svalbard archipelago, to oceanic crust 2–6 km thick in the Greenland Sea (Figure 4; profiles 9–12).

The continental margin between Bjørnøya and Sørkapp shows a narrow zone of crustal thinning dominated by two large rotated down-faulted blocks with throws of 2–3 km on each fault (Figure 4; profile 9), formed during the transform margin development (Breivik et al., 2003). The down-faulted terrace at the margin shows signs of periodic minor compression or wrench-tectonism (Grogan et al., 1999; Bergh and Grogan, 2003).

The Spitsbergen Fold-and-Thrust Belt formed between a restraining (SW of Sørkapp) and releasing (NW of Kongsfjorden) bend when Greenland slid past Svalbard during latest Paleocene and Eocene times (Figure 5) (e.g., Bergh et al., 1997; Braathen et al., 1999) (Figure 4; profile 10). West of the fold-and-thrust belt the continental crust thins rapidly across the Svalbard margin (Figures 2 and 4) (Ritzmann et al., 2002; 2004). The Hovgård Ridge probably represents a microcontinent rifted off from the Barents Sea-Svalbard margin (Figure 4; Profile 11) (Ritzmann et al., 2004). N-S trending grabens, up to 30 km wide, are present along the coast of NW Spitsbergen and SW Yermak Plateau (Figures 2 and 4). Profile 12 (Figure 4) shows a wider region of thin continental crust and a COT close to the present plate boundary at the Molloy Ridge (Ritzmann, 2003).

East Greenland margin

Opposite of the Norwegian margin, the conjugate Greenland margin has a narrow continental shelf in the south that becomes progressively wider northward (Figures 1 and 2). Integrated geophysical and geological studies have revealed pronounced differences in the crustal architecture of the East Greenland margin north and south of 72°N coinciding approximately with the landward prolongation of the West Jan Mayen Fracture Zone (WJMFZ) (e.g., Schlindwein and Jokat, 1999; Schmidt-Aursch and Jokat, 2005; Voss and Jokat, 2007). A lower crustal high-velocity body, interpreted as breakup-related magmatic underplating, is wider (190–225 km) and thicker (15–16 km) than previously thought (Voss and Jokat, 2007). Compared to the mid-Norwegian margin the dimensions of the LCB are considerably

Figure 5 Cenozoic plate tectonic evolution of the Norwegian-Greenland Sea. GR: Greenland Ridge, HR: Hovgård Ridge, VVP: Vestbakken Volcanic Basin.

larger on the Greenland side contributing to a significant asymmetry in crustal architecture between the two conjugate margins.

The fairly good definition of early seafloor spreading anomalies and the continent-ocean boundary (COB) along parts of the NE Greenland margin (Figure 2) is deteriorated in character and definition towards the south, where the seafloor spreading anomalies trend obliquely with respect to the continental slope and there are alternative views to the COB/COT location (e.g., Scott, 2000; Tsikalas et al., 2002; Voss and Jokat, 2007).

Off NE Greenland, a series of prominent, elongate N to NNE-trending highs and basins (Figure 2) are recognized on the seismic data and are outlined on the gravity and magnetic anomaly fields (Hamann et al., 2005; Tsikalas et al., 2005a). Several of the basins appear locally to be very deep although extensive sill intrusions make it difficult to image the deep basin configuration. These basins correspond to the deep Mesozoic basins on the mid-Norwegian margin and in the SW Barents Sea (Figures 2 and 5).

Margin evolution

The conjugate NW European and East Greenland margins have a prolonged history of intermittent extension and basin formation, from post-Caledonian orogenic backsliding and collapse in Devonian times, to post-Early Eocene passive margin development governed by the widening and deepening of the NE Atlantic.

Pre-breakup basin evolution

The pre-opening, structural margin framework is dominated by the NE Atlantic-Arctic Late Jurassic–Early Cretaceous rift episode responsible for the development of major Cretaceous basins such as the Møre and Vøring basins off mid-Norway, and the deep basins in the SW Barents Sea (Figures 2–4). Prior to that, Late Paleozoic rift basins formed between Norway and Greenland and in the western Barents Sea along the NE-SW Caledonian trend (Figure 2).

It has been suggested that the main Late Paleozoic–early Mesozoic rift episodes took place in mid-Carboniferous, Carboniferous–Permian and Permian–Early Triassic times (Doré, 1991). Sediment packages associated with these movements are poorly resolved, mainly because of overprint by younger tectonism and burial by thick sedimentary strata. Carboniferous rift structures are widespread in the western Barents Sea (Gudlaugsson et al., 1998) (Figure 2) below an Upper Carboniferous–Lower Permian carbonate platform, which covered large areas of the present-day Arctic continental blocks. Thick evaporites were deposited in the Late Paleozoic rift basins on the SW Barents Sea margin, and off NE Greenland.

On the mid-Norwegian margin, the Trøndelag Platform (Froan Basin) and Vestfjorden Basin (Figure 3) record significant fault activity in Permian–Early Triassic time (Brekke, 2000; Osmundsen et al., 2002). Permian–Triassic extension is generally poorly dated, but is best constrained onshore East Greenland where a major phase of normal faulting culminated in the mid-Permian and further block faulting took place in the Early Triassic (e.g., Surlyk, 1990). The later Triassic basin evolution was characterized by regional subsidence and deposition of large sediment volumes. The Lower-Middle Jurassic strata (mainly sandstones) reflect shallow marine deposition prior to the onset of the next major rift phase.

A shift in the extensional stress field vector to NW-SE is recorded by the prominent NE Atlantic-Arctic late Middle Jurassic–earliest Cretaceous rift episode, an event associated with northward propagation of Atlantic rifting (Faleide et al., 1993). Considerable crustal extension and thinning led to the development of major Cretaceous basins off mid-Norway (Møre and Vøring basins, Figures 2 and 3) and East Greenland, and in the SW Barents Sea (Harstad, Tromsø, Bjørnøya and Sørvestsnaget basins, Figures 2 and 4). These basins underwent rapid differential subsidence and segmentation into sub-basins and highs.

In the North Atlantic realm, there is evidence for modest mid-Cretaceous extension in the Vøring Basin (Doré et al., 1999), Lofoten-Vesterålen margin (Tsikalas et al., 2001), onshore East Greenland (Whitham et al., 1999), and SW Barents Sea (Faleide et al., 1993). However, Skogseid et al. (2000) and Færseth and Lien (2002) argued that no distinct structures of this age are identified within the Vøring Basin. Biostratigraphic data from the Vøring margin reveal a change from neritic to bathyal conditions and an increase in sediment accommodation space in the Aptian-Albian, attributed to eustatic sea-level rise and regional tectonism (Gradstein et al., 1999). Aptian rifting is well constrained in the SW Barents Sea (Faleide et al., 1993). Farther north, there are few signs of Cretaceous extensional deformation, but magmatism of Barremian-Aptian age is widespread within an Arctic large igneous province (LIP) (Grogan et al., 1998; Maher, 2001). Regional uplift in the north gave rise to southward sediment progradation in the Barents Sea.

By mid-Cretaceous time, most of the structural relief within the Møre and Vøring basins had been filled in and thick Upper Cretaceous strata, mainly fine-grained clastics were deposited in wide

basins. Pulses of coarse clastic input with an East Greenland provenance appeared in the Vøring Basin from Early Cenomanian to at least Early Campanian times (Færseth and Lien, 2002).

Breakup-related tectonism and magmatism

Breakup in the NE Atlantic was preceded by prominent Late Cretaceous–Paleocene rifting. At the onset of this rifting, the area between NW Europe and Greenland was an epicontinental sea covering a region in which the crust had been extensively weakened by previous rift episodes. Ren et al. (2003) suggested onset of rifting at about 81 Ma and that the main period of brittle faulting occurred in Campanian time followed by smaller-scale activity towards breakup. The Campanian rifting resulted in low-angle detachment structures that updome thick Cretaceous sequences and sole out at medium-to-deep intra-crustal levels on the Vøring and Lofoten-Vesterålen margins (Tsikalas et al., 2001; Gernigon et al., 2003; Ren et al., 2003).

Late Cretaceous–Paleocene rifting at the Vøring Margin covers a ~150 km wide area bounded by the Fles Fault Complex and the Utgard High on the east (Figures 2 and 3). Along the outer Møre and Lofoten-Vesterålen margins, most of the Late Cretaceous–Paleocene deformation is masked by the lavas, but the structures appear to continue seawards underneath the breakup lavas. On the Møre and Vøring margins, the Paleocene epoch was characterized by relatively deep water conditions. Depocentres in the western Møre and Vøring basins were sourced from the uplifted rift zone in the west (Hjelstuen et al., 1999). The northwestern corner of southern Norway was also uplifted and eroded, and the sediments were mainly deposited in the NE North Sea and SE Møre Basin (Martinsen et al., 1999; Faleide et al., 2002).

The Late Cretaceous–Paleocene extension between Norway and Greenland was taken up by strike-slip movements/deformation within the De Geer Zone (Figure 5). Pull-apart basins formed in the SW Barents Sea (e.g., Faleide et al., 1993; Breivik et al., 1998; Ryseth et al., 2003) and in the Wandel Sea Basin in NE Greenland (Håkansson and Pedersen, 2001). A relatively complete Paleocene succession was deposited under deep marine conditions in the Sørvestsnaget Basin and Vestbakken Volcanic Province (Ryseth et al., 2003).

Final lithospheric breakup at the Norwegian margin occurred near the Paleocene–Eocene transition at ~55–54 Ma (Chron 24r). It culminated in a 3–6 m.y. period of massive magmatic activity during breakup and onset of early sea-floor spreading. At the outer margin (e.g., Møre and Vøring margins), the lavas form characteristic SDR sequences that drilling has demonstrated to be subaerially and/or neritically erupted basalts (Eldholm et al., 1989; Planke et al., 1999). These seaward dipping reflectors have become diagnostic features of volcanic margins. During the main igneous episode at the Paleocene–Eocene transition, sills intruded into the thick Cretaceous successions throughout the NE Atlantic margin, including the Vøring and Møre basins. Magma intrusion into organic-rich sedimentary rocks led to formation of large volumes of greenhouse gases that were vented to the atmosphere in explosive gas eruptions forming several thousand hydrothermal vent complexes along the Norwegian margin (Svensen et al., 2004; Planke et al., 2005).

The evolution of the western Barents Sea-Svalbard margin was more complex due to the sheared margin setting. The SW Barents Sea margin, along the Senja Fracture Zone (Figures 2 and 5), developed during the Eocene opening of the Norwegian-Greenland Sea, first by continent-continent shear followed by continent-ocean shear, and has been passive since earliest Oligocene time. Deep marine conditions persisted in the SW Barents Sea (Sørvestsnaget Basin) throughout Eocene time, with deposition of significant sandy submarine fans during the Middle Eocene (Ryseth et al., 2003). Breakup-related magmatism in the Vestbakken Volcanic Province was followed by down-faulting and deposition of thick Eocene strata (Figures 2 and 4; profile 8).

The Bjørnøya-Spitsbergen margin segment experienced oblique continent-continent and partly continent-ocean shear with

both transtensional and transpressional components during Eocene time (Grogan et al., 1999; Bergh and Grogan, 2003). On Spitsbergen, a foreland basin was sourced from uplifted parts of the fold-and-thrust belt in the west during latest Paleocene–Eocene times (Figure 4; profile 10) (Steel et al., 1985; Mueller and Spielhagen, 1990). At the end of Eocene, sea floor spreading had reached the margin off southern Spitsbergen and a narrow oceanic basin existed between the western Barents Sea and NE Greenland continental margins (Figure 5).

After a plate tectonic reorganization in earliest Oligocene time, Greenland (and North America) moved in a more westerly direction with respect to Eurasia (Figure 5). Significant marine shallowing took place at the Eocene–Oligocene transition in the Sørvestsnaget Basin (Ryseth et al., 2003). Early Oligocene rifting, related to the change in relative plate motion, reactivated faults in the Vestbakken Volcanic Province, in particular those with a NE–SW trend. This phase was also associated with renewed volcanism partly overprinting the breakup structures (Jebsen and Faleide, 1998). Transpressional movements west of Svalbard were replaced by oblique rifting and incipient seafloor spreading when relative plate motions changed in the earliest Oligocene, and narrow grabens developed along the Svalbard margin. The formation of these grabens was probably initiated within the Eocene wrench regime as indicated by minor compression observed in the deeper parts of the grabens (Gabielsen et al., 1992; Kleinspehn and Teyssier, 1992).

Post-breakup margin evolution

The mid-Norwegian margin experienced regional subsidence and modest sedimentation since Middle Eocene time and developed into a passive rifted margin bordering the oceanic Norwegian–Greenland Sea. The mainly sheared western Barents Sea–Svalbard margin had a more complex development and the different segments reached the passive margin stage at different times (see previous section).

Mid-Cenozoic compressional deformation (including domes/anticlines, reverse faults, and broad-scale inversion) is well documented on the Vøring margin, but its timing and significance are highly debated (Doré and Lundin, 1996; Vågnes et al., 1998; Lundin and Doré, 2002; Løseth and Henriksen, 2005; Stoker et al., 2005a). The main phase of deformation is clearly Miocene in age but some of the structures were probably initiated earlier in Late Eocene–Oligocene times.

The Miocene succession preserves a record of deep-water sedimentation that indicates an expansion of contourite sediment drifts (Eiken and Hinz, 1993; Laberg et al., 2005; Stoker et al., 2005b). Plate tectonic reconstructions indicate that the Fram Strait finally opened as a North Atlantic–Arctic Gateway in the Miocene (between 20 and 10 Ma; Engen et al., 2008) having major impact on ocean circulation. Deep water exchange was also enhanced through a southern gateway (the Faroe Conduit) and the general subsidence of the Greenland–Scotland Ridge (Stoker et al., 2005b).

There is increasing evidence on the Norwegian margin for Late Miocene outbuilding on the inner shelf (Molo Formation; Eidvin et al., 2007) indicating a regional, moderate uplift of Fennoscandia. At the western Barents Sea margin, a Late Miocene uplift event increases in amplitude eastwards within the Vestbakken Volcanic Province and may be related to pre-glacial tectonic uplift of the Barents Shelf (Jebsen and Faleide, 1998).

Over the entire shelf there is a distinct unconformity, which changes on the slope to a downlap surface for huge prograding wedges of sandy/silty muds sourced on the mainland areas around the NE Atlantic and the shelf (e.g., Barents Sea). This horizon marks the transition to glacial sediment deposition during the Northern Hemisphere Glaciation since about 2.6 Ma. Pliocene sedimentation is interspersed with ice-rafted debris signifying regional cooling and formation of glaciers. Large Plio–Pleistocene depocenters formed fans in front of bathymetric troughs scoured by ice streams eroding the shelf (Faleide et al., 1996; Laberg and Vorren, 1996; Dahlgren et

al., 2005; Nygård et al., 2005; Rise et al., 2005). Plio–Pleistocene uplift and glacial erosion of the Barents Shelf and deposition of large volumes of glacial deposits in submarine fans along the margin resulted in a regional tilt of the margin (Dimakis et al., 1998). In terms of post-opening sediments, the glacial component constitutes more than half of the total volume deposited on the mid-Norwegian and western Barents Sea margins. The greatly enhanced Plio–Pleistocene deposition rates within the fans induced excess pore pressure and sediment instability resulting in a series of submarine slides of various sizes and timing (Bryn et al., 2005; Evans et al., 2005; Solheim et al., 2005; Hjelstuen et al., 2007).

Concluding remarks

The continental margin off mainland Norway and western Barents Sea–Svalbard, 62–82°N, evolved in response to the Cenozoic opening of the Norwegian–Greenland Sea as a mainly rifted and sheared margin, respectively. The margins exhibit a distinct along-margin segmentation reflecting structural inheritance extending back to a complex pre-breakup geological history. The lithospheric breakup was accompanied by massive, regional magmatism within the North Atlantic Volcanic Province. The breakup was preceded by a rift episode, clearly recognized by low-angle normal faulting on the outer margin during the Campanian. The fault activity continued toward breakup but appears to have been less frequent during the Paleocene. This is ascribed to focussing toward the incipient plate boundary, an area now covered by lavas, as well as to a more ductile lithospheric response when the thermal regime changed. After breakup, the passive margin evolved in response to subsidence and sediment loading during the widening and deepening of the Norwegian–Greenland Sea. Sedimentation was modest until the Late Pliocene when the Northern Hemisphere Glaciation led to rapid progradation and greatly increased sedimentation rates forming huge, regional depocenters near the shelf edge offshore Mid-Norway and in front of bathymetric troughs in the northern North Sea and western Barents Sea.

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