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An improved tectonic model for the Eocene opening of the Norwegian–Greenland Sea: Use of modern magnetic data

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Abstract

Compilation of new and vintage aeromagnetic data from the Norwegian and Greenland Seas of the NE Atlantic provides evidence for a different interpretation of several tectonic elements. The previously interpreted oceanic fracture zones (Gleipne, Surt, Bivrost, Jenegga and Vesterålen) do not exist; these were artefacts of poor navigation and wide line spacing of the vintage dataset. This reinterpretation impacts our understanding of the early spreading history of the North Atlantic, as the opening of the Norwegian–Greenland Sea between the Jan Mayen and Senja-Greenland fracture zones occurred along a stable axis without offsets of the oceanic spreading anomalies or jumps in spreading axis. These results contradict the hypothesis that a spatial relationship exists between transfer zones and fracture zones on the Lofoten margin, and on the NE Greenland margin to which they have been projected. Simplified palaeogeographic reconstruction of the aeromagnetic map to Anomaly 22 reveals that a c. 50 km wide magnetic anomaly cuts across spreading anomalies 24A, 24B and 23 from the Vøring Marginal High on the Norwegian margin to Traill Ø on the East Greenland coast. The anomaly is interpreted to represent an igneous complex referred to as the Traill-Vøring igneous complex (TVIC). The complex crosscuts anomaly 22 on the Greenland margin, suggesting that the igneous activity was active until c. 50 Ma and can be linked up with the NNE-trending initial magmatic lineament (IML) extending between Traill Ø and Kangerlussuaq. The IML has been suggested to relate to a failed attempt of direct linkage between the Reykjanes and Mohns Ridges. The magnetic response of the TVIC along the Vøring margin has previously been interpreted as representing anomaly 24A and 24B. Such an interpretation required the erroneous introduction of an abandoned spreading ridge.
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Keywords: Northeast Atlantic; Norwegian margin; Voring margin

1. Introduction

A variety of partly contradicting interpretations has been proposed for the tectono-magmatic evolution of the Vøring–Lofoten continental margin segment (Figs. 1 and 2) in recent years (Blystad et al., 1995; Brekke, 2000; Tsikalas et al., 2001, 2002, 2005; Eldholm et al., 2002; Olesen et al., 2002). The purpose of the current paper is to help resolve some of these inconsistencies using an updated magnetic database. The Geological Survey of Norway acquired a new aeromagnetic survey offshore Lofoten in 2003 and merged these data with reprocessed pre-existing aeromagnetic data from the Norwegian margin to help resolve some of these inconsistencies. Reprocessed gravity data were also used in the study. The new aeromagnetic grid and structural elements on the Greenland continental margin were restored to Europe to visualise the NE

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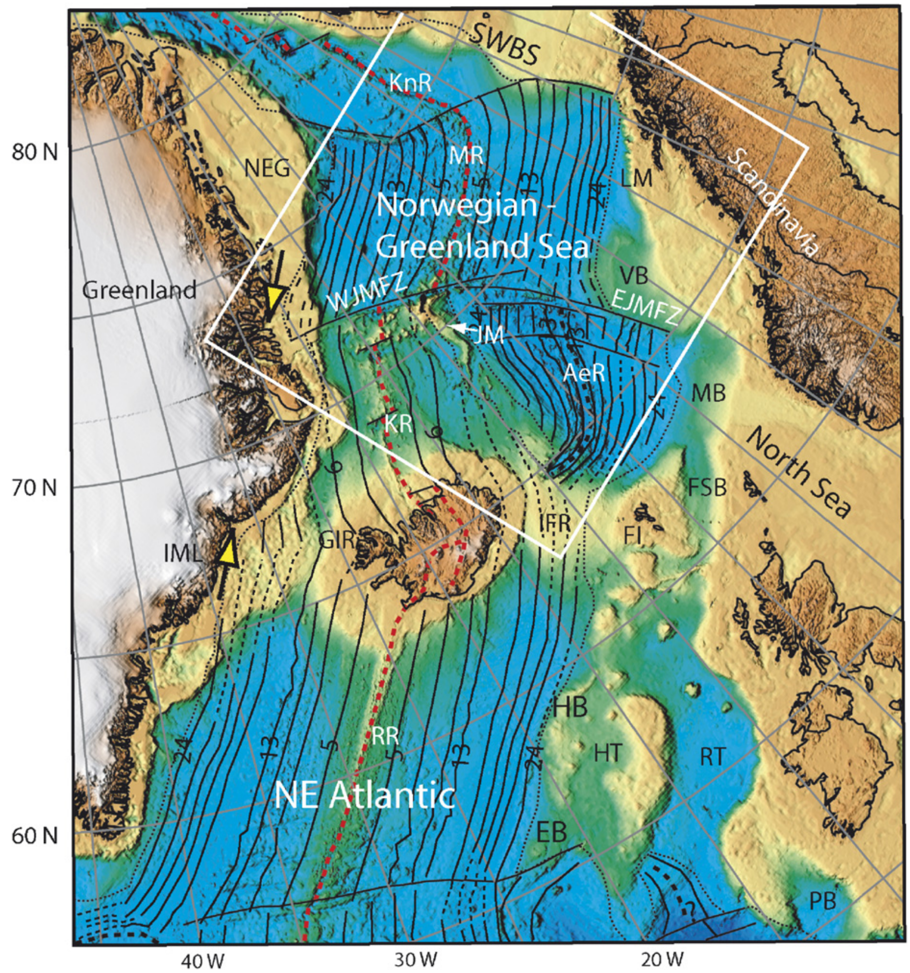

Fig. 1. Tectonic map of the NE Atlantic region (modified from Lundin, 2002). AeR = Aegir Ridge, EB = Edoras bank, EJMFZ = East Jan Mayen Fracture Zone, FI = Faroe Islands, FSB = Faroe-Shetland Basin, GIR = Greenland-Iceland Ridge, HB = Hatton Bank, HT = Hatton Trough, IML = Initial Magmatic Line, IFR = Iceland-Faroes Ridge, JM = Jan Mayen microcontinent, KnR = Knipovich Ridge, KR = Kolbeinsey Ridge, LM = Lofoten margin, MB = Møre Basin, MR = Mohns Ridge, NEG = NE Greenland, PB = Porcupine Basin, RR = Reykjanes Ridge, RT = Rockall Trough, SWBS = SW Barents Sea, VB = Vøring Basin, WJMFZ = West Jan Mayen Fracture Zone. The white frame shows the location of Figs. 2, 4 and 6.

Atlantic opening history. We also carried out an integrated interpretation of reflection seismic data and potential field data to map the igneous activity in the sedimentary basins along the Vøring–Lofoten continental margin. A possible link between the magmatic activity related to the early stages of Eocene oceanic spreading and the igneous activity within the basins received particular attention.

2. Structural framework and previous work

The general evolution of the NE Atlantic rifting and seafloor spreading history has been described by e.g. Doré et al. (1999), Roberts et al. (1999), Torsvik et al. (2001) and Lundin (2002). Fig. 3 shows the main offshore structure elements along the Vøring–Lofoten margin (Blystad et al., 1995). The Aegir and Kolbeinsey Ridge pair is commonly interpreted to represent a ridge jump from the Aegir to Kolbeinsey Ridge (Talwani and Eldholm, 1977) and the reconstruction of the NE Atlantic is therefore, somewhat complicated. The ridges have also been suggested to represent overlapping opposed spreading axes (Nunns, 1983; Larsen, 1988; Lundin and Doré, 2005; Scott et al., 2005). It is convenient to subdivide the NE Atlantic into three segments: (a) southern Reykjanes Ridge segment, (b) central Aegir and Kolbeinsey Ridge segment, and (c) northern Mohns Ridge segment. Magnetic anomalies are comparatively straightforward to interpret along the Reykjanes and Mohns Ridge segments. For the purpose of this study, we do not need to be concerned with the more complicated central segment, as long as one accepts: (1) that Greenland and Eurasia acted as rigid plates (i.e. that neither cratons was broken by major shears) and (2) that significant post-breakup deformation of the seafloor has not occurred.

Reconstructions of the oldest magnetic seafloor anomalies (Anomaly 24B to 23) along the Reykjanes and northern half of Mohns Ridges provide a good fit (Gaina et al., 2002; Mosar et al., 2002). However, the same is not true for the southern Mohns Ridge where a gap occurs, i.e. between the

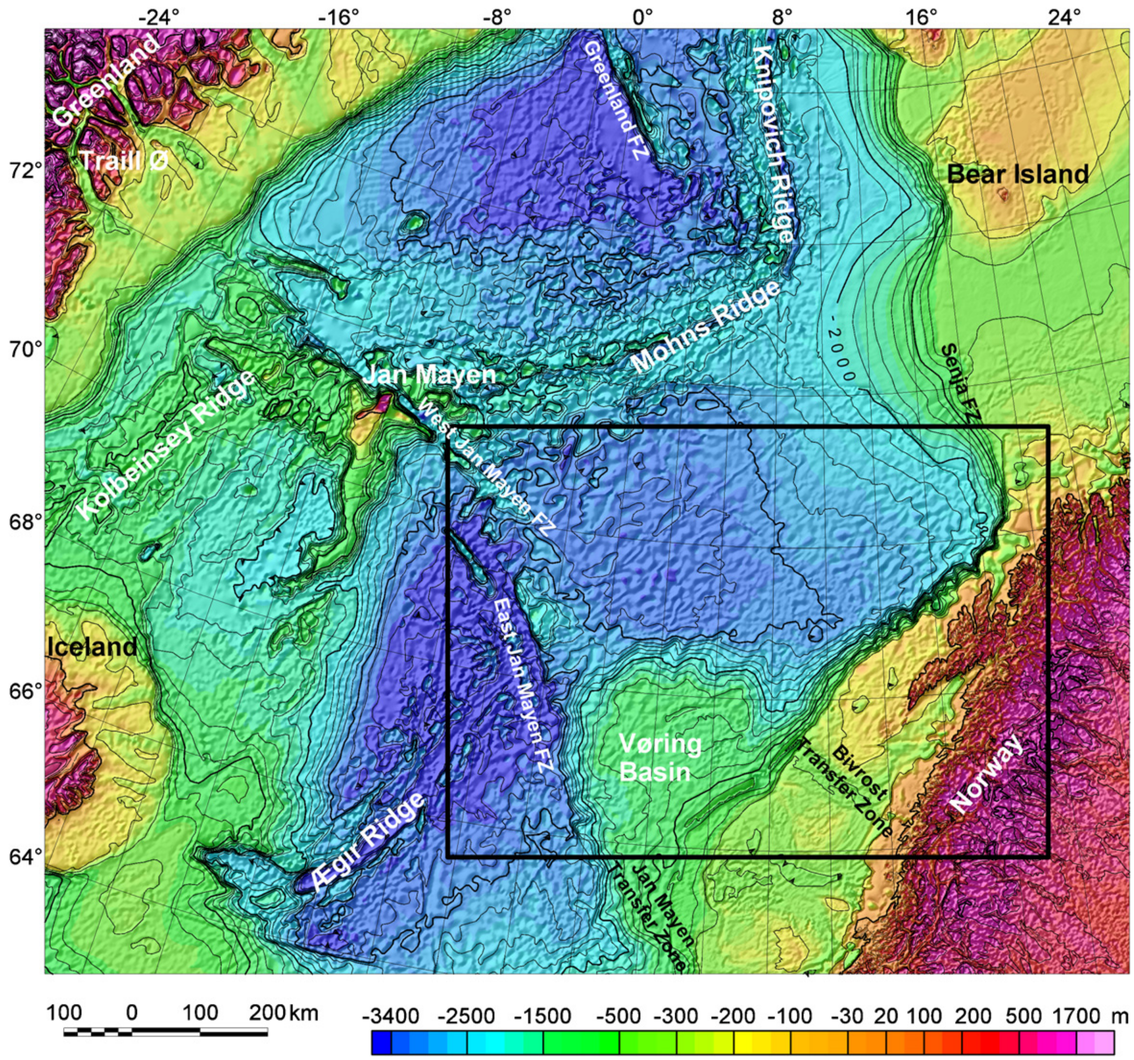

Fig. 2. Bathymetry and topography, Norwegian and Greenland Seas, 200 and 1000 m contour intervals (modified from Dehls et al., 2000). The black rectangle shows the map area of Figs. 3 and 7.

SW Vøring and conjugate NE Greenland margin. Hagevang et al. (1983) proposed an abandoned spreading ridge on the Norwegian side of the southernmost Mohns Ridge. Such a model naturally excludes the presence of equivalent age seafloor off the conjugate NE Greenland margin. Following the work by Hagevang et al. (1983) several workers (Escher and Pulvertaft, 1995; Larsen, 1990) continued to place the continent-ocean boundary (COB) of the southern NE Greenland margin along a marked free air gravity anomaly at the shelf edge. This COB interpretation results in a geometry where the oldest NE Greenland anomalies appear "truncated" southwards against the COB, i.e. they are shorter than younger anomalies. However, in more recent time it has become apparent that the oldest magnetic anomalies produced at the Mohns Ridge may continue underneath the NE Greenland shelf (Scott, 2000) (Figs. 4 and 5); the uncompensated Neogene shelf is responsible for the free air gravity anomaly previously interpreted as the COB. These southernmost magnetic anomalies are more diffuse, broader, and of higher amplitude than the narrower and more distinct linear seafloor anomalies along the northern Mohns Ridge. A similar diffuse and broad magnetic anomaly pattern also characterises the conjugate Norwegian margin (Figs. 4 and 6).

The sea-floor spreading magnetic anomalies 22–24B (Talwani and Eldholm, 1977; Eldholm et al., 1979; Hagevang et al., 1983; Vogt, 1986) are revealed in Figs. 4 and 6. Anomalies 24A and 24B refer to Chron 24n1n (52.51 Ma) and 24n3n (53.13 Ma), respectively (Cande and Kent, 1995). Several NNW-oriented oceanic fracture zones have previously been interpreted in the Vøring–Lofoten area: the Gleipne, Surt, Bivrost, Jennegga, Vesterålen and Senja fracture zones (Hagevang et al., 1983; Blystad et al., 1995; Tsikalas et al., 2001; Eldholm et al., 2002). Olesen et al. (2002) argued that the large variation in previous interpretations were partly due to the poor data coverage of the previous aeromagnetic surveys (i.e. wide line spacing). However, Tsikalas et al. (2002, 2005) applied the aeromagnetic compilation of Verhoef et al. (1996) consisting of a 5×5 km grid, and correlated the "fracture

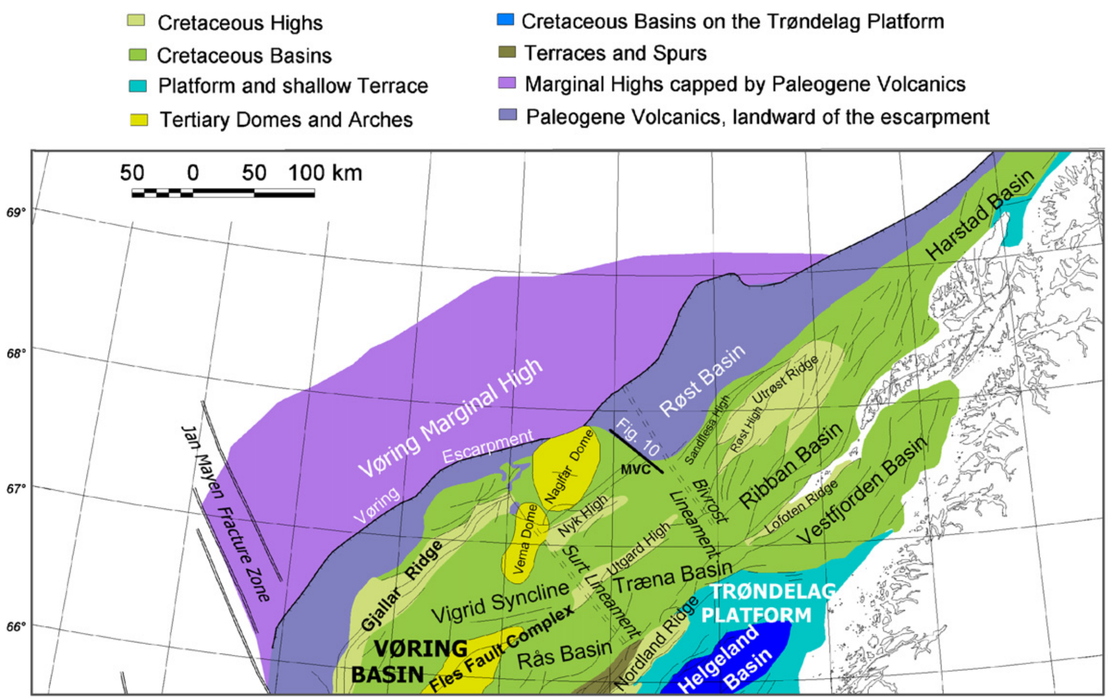

Fig. 3. Main structural elements along the Vøring–Lofoten continental margin (modified from Blystad et al., 1995). The location of the seismic profile in Fig. 10 is shown with a bold line. MVC—Myken Volcanic Complex.

zones'' on the Vøring–Lofoten margin with similar apparent breaks in the spreading anomalies 24A and 24B on the conjugate Greenland margin where the line spacing (10–20 km) is larger than for most areas along the Norwegian continental margin (4–15 km line spacing). The grid cell size is consequently of the same order as the interpreted offsets.

The interpretation of fracture zones in oceanic crust is intimately related to the proposed presence of transfer zones within the continental margin. Transfer zones (Gawthorpe and Hurst, 1993) are also known as 'accommodation zones', 'relay zones', and 'segment boundaries. They connect normal individual segments of normal faults within a sedimentary basin and are often interpreted to represent reactivation of a pre-existing grain in the underlying basement. These basement structures that often trend perpendicular to the rift trend have frequently been proposed as candidates for oceanic transform faults between spreading axis segments during the initial breakup of a continent and formation of the first oceanic crust (Colletta et al., 1988).

A COB has been interpreted along the Vøring–Lofoten continental margin (Sellevoll et al., 1988; Blystad et al., 1995). Previous interpretations of the continuation of the Vøring Escarpment into the Røst Basin vary to a large degree. The location of the Vøring Escarpment proposed by Sellevoll et al. (1988) and Mjelde et al. (1992) coincides with a sharp westward deflection in a continent-ocean transition (COT) zone. Tsikalas et al. (2001) and Berndt et al. (2001), on the other hand, have interpreted a linear COT and a gap in the Vøring Escarpment along the western margin of the Røst Basin. The Vøring escarpment corresponds to a paired negative and positive anomaly with values of −300 nT on the landward side of the escarpment and small, 0–50 nT, positive values on the seaward side. The anomaly can be modelled by the superposition of an upper series of normally magnetised flow basalts and an underlying reversely magnetised series (Roeser, 1993; Tsikalas et al., 2002). The escarpment can partly represent a coastline lava front (Brekke, 2000). The COT decreases in width from 50 km in the Røst Basin to approximately 30 km offshore Andøya (Tsikalas et al., 2002).

3. Datasets

3.1. Aeromagnetic and gravity data

A total of 10 offshore aeromagnetic surveys (Fig. 4) have been compiled for the present study. Specifications for these surveys are shown in Tables 1 and 2. The pattern of flight lines generally provides data along NW-trending profiles with a spacing of 2–5 km. The LAS-89, NAS-94, VAS-98 (Olesen et al., 2002) and RAS-03 surveys have been processed using the loop closure method (Mauring et al., 2003). The NGU-69 and NGU-73 surveys were reprocessed separately using the median levelling technique (Mauring et al., 2002) by Olesen et al. (2002). The individual grids were trimmed to c. 10 km overlap and merged using the minimum curvature algorithm (Swain, 1976; Geosoft, 2000).

In the present compilation we included the SPT-93, VGVB-94 and VBE-AM-00 surveys acquired by World

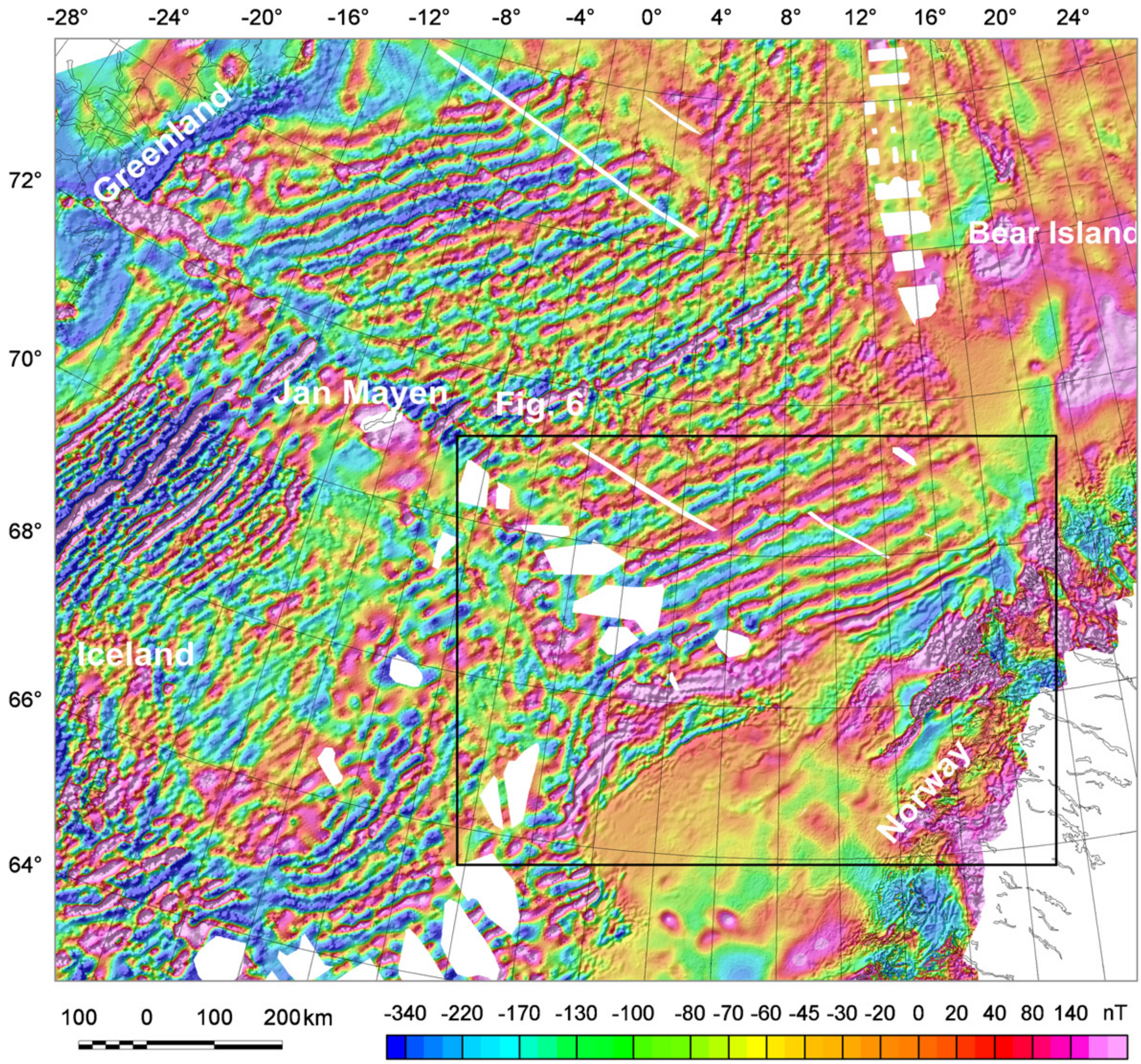

Fig. 4. Compilation of aeromagnetic surveys (Tables 1 and 2) in the Norwegian and Greenland Seas. Contour intervals: 20 and 100 nT. The black frame shows the Vøring–Lofoten continental margin area (Fig. 6).

Geoscience and TGS Nopec, respectively. We have also included the Gammaa5 grid by Verhoef et al. (1996) from the Norwegian–Greenland Seas (after a regridding of the 5×5 km grid to a grid consisting of 500×500 m cells). The Gammaa5 compilation includes the NRL-73 survey and several other aeromagnetic surveys offshore Greenland and Iceland, in addition to a large number of ship-lines in the southwestern part of our study area.

The gravity data-set is described by Skilbrei et al. (2000). An Airy-Heiskanen 'root' (Heiskanen and Moritz, 1967) has been calculated from a compiled topographic and bathymetric dataset (Fig. 2). The gravitational attraction from the 'root' was calculated using the AIRYROOT algorithm (Simpson et al., 1983). The isostatic residual (Fig. 7) was achieved by subtracting the gravity response of the Airy-Heiskanen 'root' from a Bouguer gravity grid. A 100 km Gaussian high-pass filtered map of the Bouguer grid is superimposed as a shaded relief version on the gravity residual maps in Fig. 7.

4. Interpretation methods

4.1. Data presentation and geophysical interpretation map

Histogram-equalised colour, high-frequency filtered and shaded-relief images have been produced to aid the visualisation of the regional datasets. Aeromagnetic grid and structural elements on the Greenland continental margin have been rotated back to Europe (Figs. 8 and 9) using the program system EulerR (Smethurst, 2005). We applied the rotation parameters shown in Table 3.

Fault zones within the basement, and partly within the sediments, were interpreted from the aeromagnetic map. The faults are plotted in Fig. 9. High frequency anomalies representing volcanic rocks are also included. These anomalies are often negative. The interpreted location of the easternmost boundary of the flow basalts (Blystad et al., 1995; Statoil internal data, 2003, unpublished) in the Vøring and Røst basins is added to the geophysical maps.

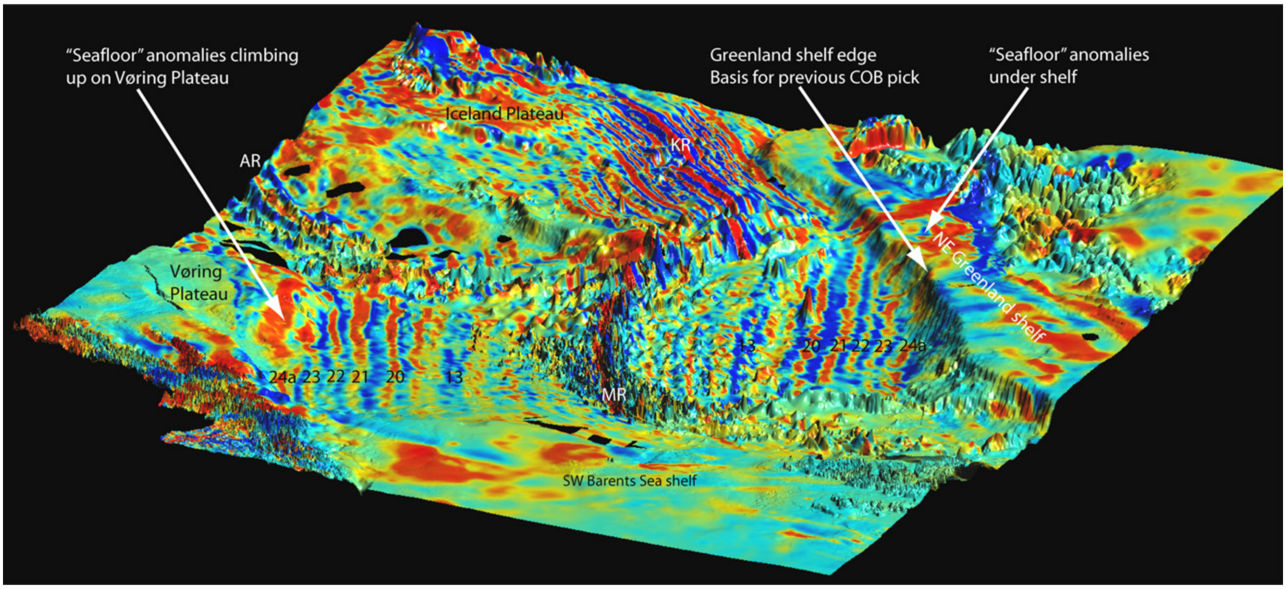

Fig. 5. Perspective view from the north of the aeromagnetic dataset (Fig. 4) draped on bathymetry/topography (Fig. 2). The E Greenland shelf edge sets up a pronounced free air gravimetric anomaly, which in the past erroneously has been interpreted as the continent-ocean boundary (COB). Note that the oldest magnetic anomalies along the Mohns Ridges on the Norwegian side climb up the slope of the Vøring Plateau. Abbreviations: AR = Aegir Ridge, MR = Mohns Ridge, KR = Kolbeisney Ridge. Numbers refer to magnetic chrons.

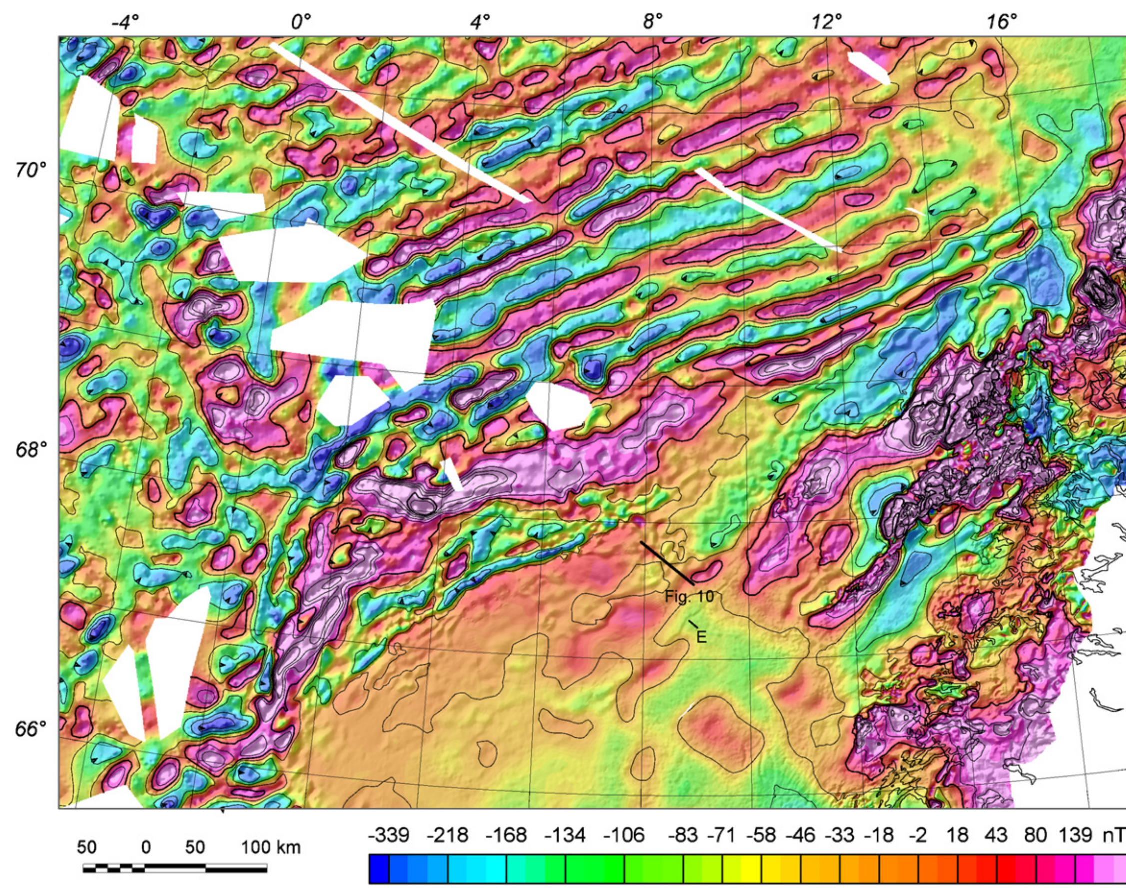

Fig. 6. Compilation of aeromagnetic surveys in the Nordland–Vøring area (enlargement of Fig. 4). The contour intervals; 20 nT (thin lines) and 100 nT (bold lines). The map includes the NRL-73 US Naval Research Laboratory 1973, VGVB-94-Vertical Gradient Vøring Basin 1994, VBEAM-00-Vøring Basin Extension Aeromagnetic Survey 2000, SPT-93-Simon Petroleum Technology 1993, RAS-03-Røst Aeromagnetic Survey 2003, LAS-89-Lofoten Aeromagnetic Survey 1989, NAS-94-Nordland Aeromagnetic Survey 1994 and VAS-1998-Vestfjorden Aeromagnetic Survey 1998 (Tables 1 and 2). The latter four surveys were acquired by the Geological Survey of Norway. The black line shows one of the interpreted seismic sections (Fig. 10). The letter 'E' denotes the magnetic anomaly produced by the continental edge.

Table 1
Offshore aeromagnetic surveys compiled for the present study (Figs. 4 and 6)

Year	Area	Operator	Survey name	Navigation	Sensor elevation (m)	Line spacing (km)	Length (km)
1969	69°–70°N	NGU	NGU-69	Decca	200	4	1
1973	Vøring Basin	NGU	NGU-73	Loran C	500	5	6
1972–1973	Norwegian-Greenland Seas	Naval Research Lab.	NRL-73		300	10–20	45
1989	Lofoten	NGU	LAS-89	GPS/LoranC/ Syledis	250	2	24
1993	Hel Graben- Nyk High	World Geoscience	SPT-93	GPS	80	0.75	19
1994	Nordland Ridge- Helgeland Basin	NGU	NAS-94	GPS	150	2	36
1994	Vøring Basin	Amarok	VGVB-94	GPS	140	1–3	32
1998	Vestfjorden	NGU	VAS-98	GPS	150	2	6
2000	Southern Gjallar Ridge	TGS-Nopec	VBEAM-00	GPS	130	1–4	17
2003	Røst Basin	NGU	RAS-03	GPS	230	2	30

The RAS-03 survey included 2.300 km reflying of the LAS-89 survey.

Table 2
Aeromagnetic grids (500 × 500 m) included in the regional compilation

Year	Area	Operator	Navigation	Sensor elevation	Line spacing (km)	Recording
1964	Andøya	NGU	Visual	150 m above ground	1	Analogue
1965	Vesterålen area	NGU	Visual	300 m above ground	2	Analogue
1971–73	Nordland-Troms	NGU	Decca	1000 m above sea level	2	Analogue

The Gammaa5 compilation (5 × 5 km grid) by Verhoef et al. (1996) from the Norwegian-Greenland Seas was regridded to a 500 × 500 m grid and included in the regional compilation (Figs. 4 and 6).

4.2. Joint interpretation of seismic and potential field data

The Geoframe Charisma Imain software at the Norwegian Petroleum Directorate (NPD) was applied for an integrated interpretation of the seismic and potential field data on a workstation. Total magnetic field data and 20 km high-pass filtered magnetic data have been superimposed on seismic sections crossing the flow basalts. Seismic lines crossing the Røst Basin and the Vøring Escarpment were analysed. One example of the selected lines is presented in Fig. 10. The objective of the study was to analyse the intrasedimentary volcanic rocks, recognized as high-amplitude seismic reflectors, and their relation to short-wavelength magnetic anomalies within the Røst Basin. In particular, we studied the anomalies to the north and west of the eastern termination of the flows basalts to see if they were due to flows or intrusions.

5. Results

5.1. Oldest (innermost) seafloor anomalies along the Vøring–Lofoten and conjugate NE Greenland margins

Oceanic spreading anomalies 24A and 24B can be traced without offsets through the survey area (Figs. 4 and 6). The eastern side of the 24B anomaly is distorted by the magnetic anomalies originating from the lava flows (seaward dipping reflectors). The western side of the 24A–B anomalies are more undisturbed and therefore, most suitable for tracing these anomalies. Line drawings of the anomalies show that they make a gentle convex, uninterrupted, bend to the west of the Røst Basin (Figs. 8 and 9). Our reinterpretation of the oceanic spreading anomalies deviates significantly from earlier interpretations with reported apparent offsets of up to 50 km (Hagevang et al., 1983; Blystad et al., 1995; Tsikalas et al., 2001, 2003, 2005; Olesen et al., 2002). The new data compilation refutes the older interpretations of significant offsets along the previously proposed zones, the apparent offsets merely being an artefact of wide profile spacing, poor navigation and poor levelling of the vintage aeromagnetic profiles. Furthermore, the gravity data (Fig. 7) do not show any linear NW-SE trending anomalies supporting the previously interpreted oceanic fracture. Brekke (2000) also questioned the large offset along the Bivrost Fracture Zone.

The difference in appearance of oldest ocean floor anomalies on the Vøring Plateau and in the Lofoten Basin probably reflects different origins. Comparison with younger seafloor anomalies (Chron 22 and younger) suggests that the older anomalies along the northern part of the Vøring and Lofoten margin mark typical seafloor, whereas the broad and diffuse anomalies along the southern Vøring margin may represent a mixture of

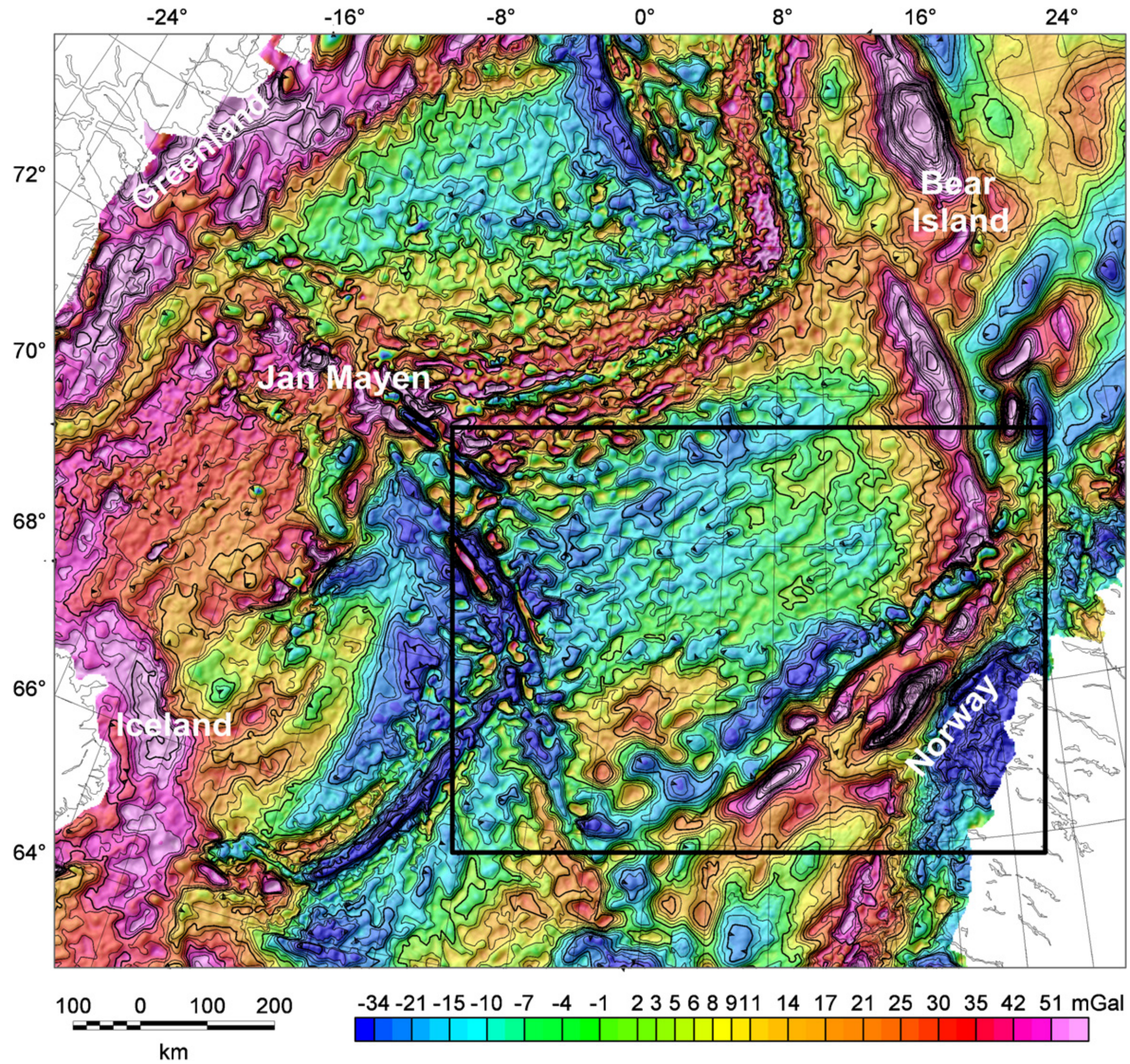

Fig. 7. Residual gravity after isostatic correction of Bouguer gravity data from the Greenland and Norwegian Seas and adjacent areas. The isostatic correction has been calculated applying the AIRYROOT algorithm (Simpson et al., 1983) to the topography/bathymetry in Fig. 2 (rock density 2670 kg/m^3 on land, 2200 kg/m^3 at sea and a crust/mantle density contrast of 300 kg/m^3). The black frame shows the map area of Figs. 3 and 6. The contour intervals are 5 mGal (thin lines) and 20 mGal (bold lines). A shaded relief version of the 100 km Gaussian high-pass filtered Bouguer gravity dataset is superimposed as on the gravity residual map in colour. The gravity data do not show any linear NW–SE trending anomalies supporting the previously interpreted oceanic fracture zones along the Vøring–Lofoten margin between the Jan Mayen and Senja fracture zones.

intruded oceanic and continental crust. The anomalies are distinctly different from the narrow and comparatively simple seafloor spreading anomalies further north. An interesting observation supporting our interpretation is that the broad and diffuse magnetic anomalies along the SE Vøring margin coincide with a significant bathymetric high, the Vøring Plateau. The Vøring Plateau has also previously been suggested to represent an area of anomalous magmatism (Vink, 1984). By accepting different origins for the anomalies in the north and south, there is no need to invoke complicated offsets or repetitions of the magnetic anomalies as previously proposed.

We also question the common interpretation of oceanic fracture zones off the Lofoten and Vøring margins (Tsikalas et al., 2002, 2005; Olesen et al., 2002; Hagevang et al., 1983; Skogseid and Eldholm, 1987; Blystad et al., 1995) as well as the interpretation of an abandoned spreading ridge off the SW Vøring margin (Hagevang et al., 1983). The interpretation of the new aeromagnetic data compilation has consequently resulted in a much simpler early seafloor spreading architecture along the Norwegian margin than has been commonly suggested in the literature. Since the fracture zones on the Norwegian margin appear to be artefacts related to data problems, it is certainly pertinent to question the existence of the correlative NE Greenland fracture zones (Tsikalas et al., 2002, 2005). Rather, there is good reason to suggest that the early opening history of the conjugate Greenland margin is equally simple as the one described for the Norwegian margin.

Development of a fracture zone during seafloor spreading does not necessarily follow the development of

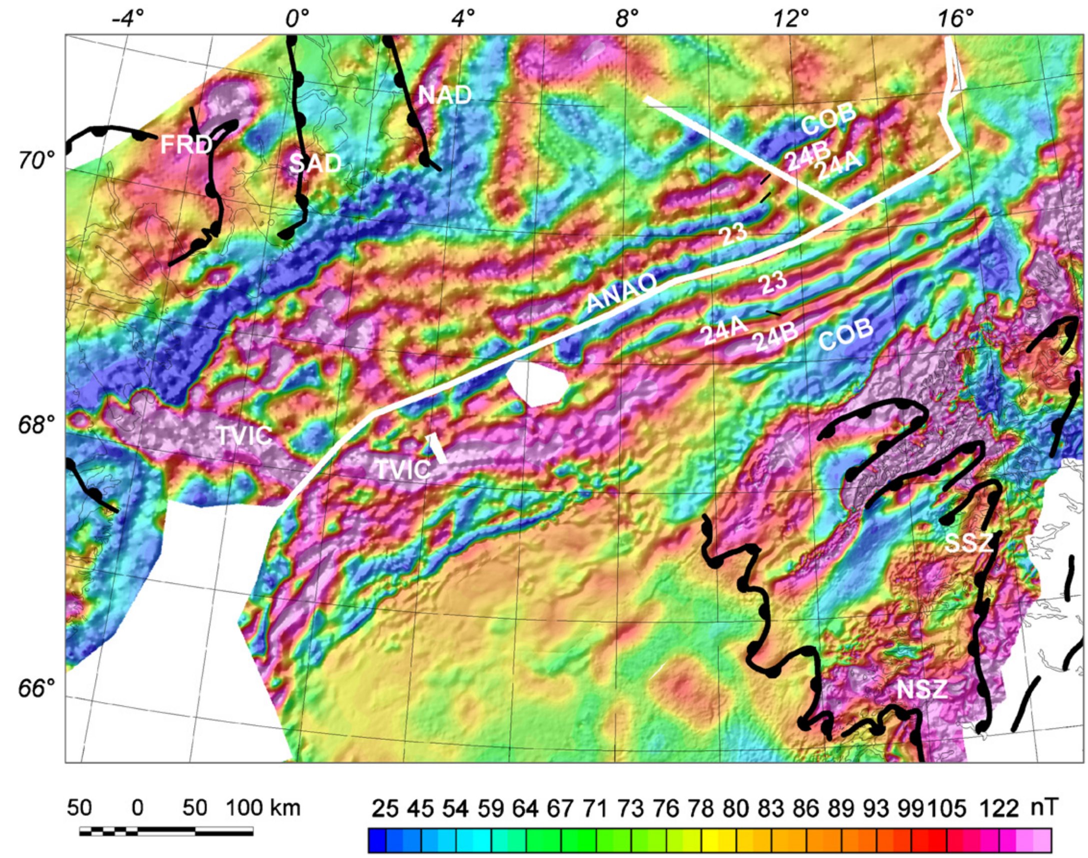

Fig. 8. Reconstruction of the Greenland margin aeromagnetic data to Chron 22 (c. 49.7 Ma). Note that the c. 50 km wide, diffuse, high amplitude aeromagnetic anomaly to the NW of the Vøring Marginal High appears to be continuous across the oceanic spreading anomalies 23, 24A and 24B as far as to Traill Ø (on the east Greenland coast) where Tertiary igneous complexes occur at the surface. This anomaly has earlier been interpreted as anomalies 24A and 24B in the Norwegian Sea. The width of the anomaly is, however, considerably wider than the corresponding anomalies offshore Lofoten further to the north. The anomaly is most likely caused by an igneous complex (refereed to as Traill–Vøring igneous complex). The introduction of this igneous complex simplifies the initial opening history and excludes the need to invoke the abandoned spreading ridge and the Gleipne Fracture Zone along the Vøring margin. The bold black lines show late Caledonian detachment zones of Hartz et al. (2002), Braathen et al. (2002) and Olesen et al. (2002). ANAO—Axis of North Atlantic opening; TVIC—Traill Ø—Vøring igneous complex; SSZ—Sagfjord Shear Zone; NSZ—Nesna Shear Zone; NAD—Northern Ardencaple Fjord Detachment; SAD—Southern Ardencaple Fjord Detachment; FRD—Fjord Region Detachment system.

a transfer zone during rifting. And vice versa, there is no reason to infer the presence of a transfer zone inboard of a fracture zone. Illustrative examples are provided by the lateral boundaries to the Vøring Basin, the Jan Mayen and Bivrost Lineaments (Figs. 2 and 3). The Jan Mayen Lineament is very faintly expressed in basement structure, if at all, and is arguably best inferred from the position of overlying en echelon compressional domes formed post-breakup (Lundin and Doré, 2002). The East Jan Mayen Fracture Zone on the other hand is a major fracture zone with a 160 km left-stepping jog in COB. In contrast, the Bivrost Lineament is well expressed in the basement structure. As argued in this paper, there is no outboard fracture zone in this position. The previously proposed Bivrost Fracture Zone was mostly an artefact of data problems.

If transfer zones on the mid-Norwegian margin and NE Greenland margin have been interpreted based on the presence of the supposed fractures mentioned in this paper, then a reevaluation is merited. Commonly, transfer zones are assumed to be important entry points for sedimentary drainage systems (Gawthorpe and Hurst, 1993), a relationship which has also been suggested for the transport of Upper Cretaceous sands from Greenland to the mid-Norwegian margin (Fjellanger et al., 2005). Our new interpretaion can consequently have indirectly implications for evaluating the petroleum potential in the Vøring and Røst Basins.

The reconstruction of the Mohns Ridge to Chron 22 (c. 49–49.7 Ma) indicates that the broad, diffuse, high amplitude magnetic anomalies on the Vøring margin may correlate with similar anomalies along the West Jan Mayen Fracture Zone (WJMFZ). Inboard of these anomalies in East Greenland lie several intrusive complexes. Dating of these dominantly alkaline intrusions span the range 47–24 Ma, but the wide age span may reflect the mixture of K/Ar, Rb/Sr, and Ar/Ar age dating methods as well as a mixture of whole rock and separate mineral analyses (summarised in Torsvik et al., 2001; Nielsen, 2002; Lundin and Doré, 2002).

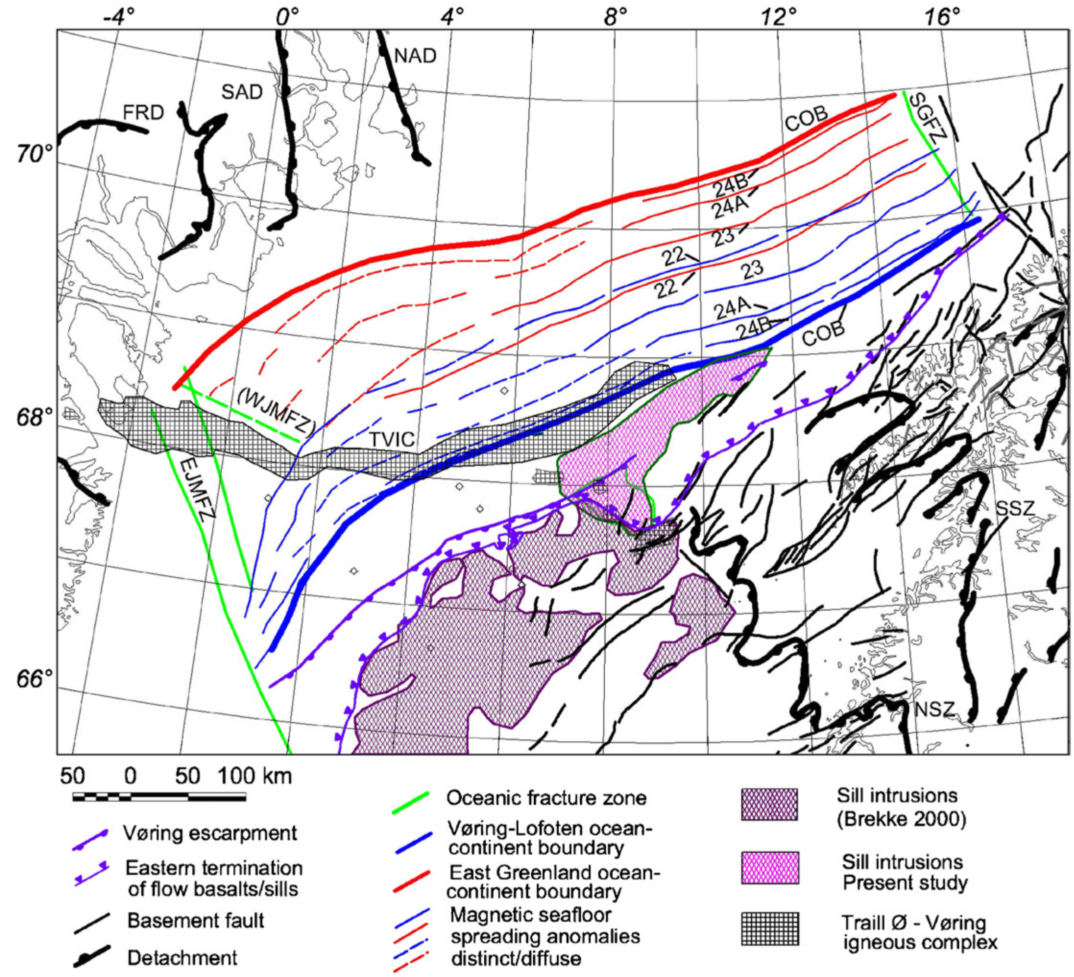

Fig. 9. Reconstruction to Chron 22 (49.7 Ma). Regional basement faults and sill intrusions on the Vøring-Lofoten continental margin. Note that the Vøring Traill igneous complex (TVIC) intrudes continental crust on either side of the early Norwegian-Greenland Sea. COB—continent-ocean boundary; EJMFZ—Eastern Jan Mayen Fracture Zone; (WJMFZ)—future location of Western Jan Mayen Fracture Zone; TVIC—Traill-Vøring igneous complex; SSZ—Sagfjord Shear Zone; NSZ—Nesna Shear Zone; NAD—Northern Ardencaple Fjord Detachment; SAD—Southern Ardencaple Fjord Detachment; FRD—Fjord Region Detachment system. Modified from Brekke (2000), Hartz et al. (2002), Braathen et al. (2002), Olesen et al. (2002) and Ebbing et al. (2006).

Table 3
Euler rotation parameters used to restore Greenland back to its 49.7 Ma position relative to Europe

Age (Ma)	Mag. Anomaly	Period	Latitude	Longitude	Angle
49.7	22	L. Ypresian	52.7	125.5	9.8

Interpolated from Gaina et al. (2002).

Nielsen (1987) and Larsen (1988) referred to an initial magmatic lineament (IML) located between the Kangerlussuaq and Traill Ø (Fig. 1). The IML may relate to a failed attempt of direct linkage between the Reykjanes and Mohns Ridges (Larsen, 1988). Here we extend this idea and speculate that the above-mentioned broad and diffuse magnetic anomalies along the Vøring margin and extending to the Traill Ø region may have developed as part of the IML (Fig. 1). While the various intrusions in East Greenland remain somewhat poorly dated, magmatic rocks in the Kangerlussuaq area are better constrained and are dominated by a c. 50 Ma event (Noble et al., 1988). This timing corresponds well with the mentioned Chron 22 event to the north. However, Price et al. (1997) used a Ar–Ar dating to demonstrate a c. 36 Ma age for syenite intrusions in the Traill Ø region. These data were used by Scott (2000) to suggest that magmatic activity along the lineament (named the Kap Syenit-Kangerlussuaq lineament) was, at least in part, related to the separation of the Jan Mayen microcontinent.

5.2. Sill intrusions and lava flows in the northern Vøring Basin

Short wavelength magnetic anomalies (Fig. 6) occur to the west of the easternmost boundary of flow basalts in the

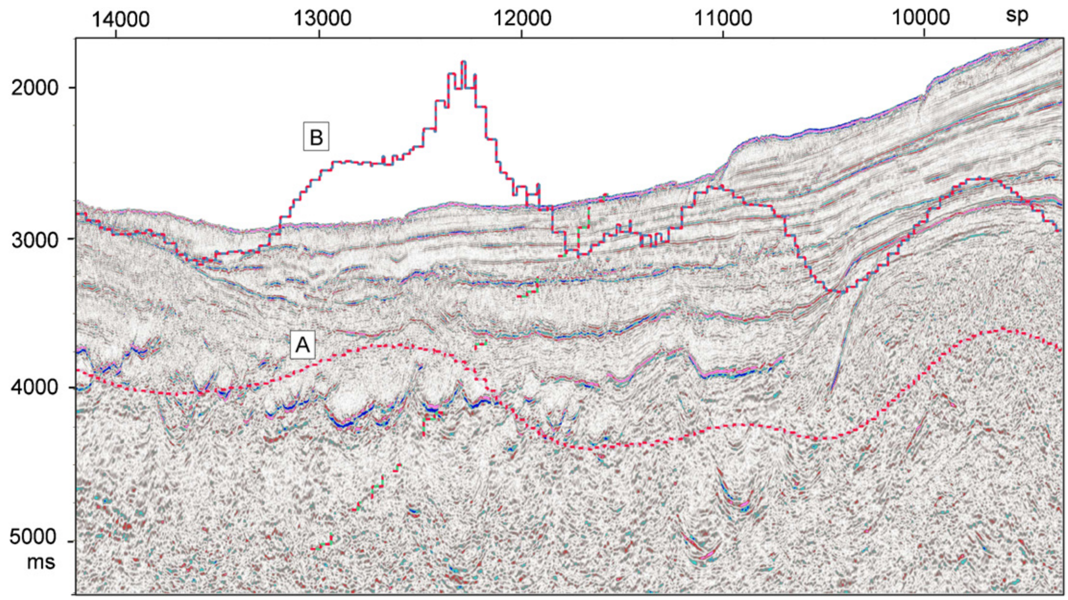

Fig. 10. Seismic line, TBN96-115A, running northwest-southeast across the Paleogene volcanics in the Røst basin. The lower curve (A, in red) represents the total magnetic field while the upper curve (B, in blue and red) shows the 20 km high-pass filtered magnetic field. Note wavy high-amplitude reflectors between 4000 ms TWT and 4500 ms TWT, which give rise to magnetic anomalies. They represent most likely sills. The magnetic anomalies show in general a rather chaotic character because of the laterally varying thickness of the volcanic rocks. The direction of the magnetisation may also vary from one flow to the other.

Røst Basin (Fig. 9). In general there is a decrease in the amplitude of the anomalies both to the east and north-eastwards within the basin.

Typical magnetic anomalies are superimposed on seismic line TBN96-115A in Fig. 10. The location of the line is shown on Figs. 2 and 6. To the west of shotpoint 1200 (left in figure), high amplitude reflectors produce a typical 'wavy pattern' from about 4–4.4 TWT. These reflectors represent sills in the early Tertiary sediments as described previously by Brekke (2000) and Berndt et al. (2001). The magnetic total field (lower discontinuous red curve marked with 'A') and the residual field (upper curve marked with 'B', in blue and red) show anomalies that may result from these intra-sedimentary intrusive rocks. Farther to the east (right in figure), a rather smooth high-amplitude reflector from 3.75 to 3.9 TWT could represent a flow basalt. In the east, it terminates against the Sandflesa High/Myken Volcanic Complex (Fig. 3).

Low amplitudes anomalies exist towards the eastern termination of the flow basalts. The high amplitude reflectors become more abundant in the western part of the Røst Basin, giving rise to the anomalies seen on the magnetic map. As expected, the most significant anomalies occur near to the Vøring Escarpment, gradually decreasing north-eastwards. However, there is a belt of relatively strong anomalies towards the Sandflesa high/Myken volcanic complex.

From the analysis we suggest that the western half of the Røst Basin is underlain primarily by intrusions. These sills and dykes are similar in character to intrusions in the area of the Hel Graben, but represent significant lower volumes. The depths of the interpreted sills are in agreement with the calculated Euler depths (3–5 km) (Olesen et al., 2003). To the north of the Myken Volcanic Complex and the Sandflesa High, only very thin high-amplitude reflectors are seen. However, local feeder systems for these flows may be interpreted. These suggest that the intrusions represent intra-basinal sources for the basalt flows. We relate the high frequency of sills in the western Røst Basin to the adjacent c. 49–50 Ma Traill-Vøring Igneous Complex. There is no continuous magnetic anomaly coinciding with the easternmost termination of the basalt flows, indicating a rather complex package of volcanics both with regard to thickness and magnetization. Note that the continuous magnetic anomaly along the Lofoten margin is caused by the shelf edge (marked with E in Fig. 6) and not by the eastern termination of the basalts.

Berndt et al. (2001) interpreted the Lofoten lava flows to have been extruded in a submarine environment while the Vøring margin segment was flooded by subaerial lava. The Vøring Escarpment (well expressed on magnetic data, see Fig. 6) has been proposed to mark a palaeo-coastline (Planke et al., 1999), along which the scarp formed by rapid chilling of the subaerial lavas as they reached the sea. Unless the Lofoten lava flows are of a different age than the Vøring lava flows, it is difficult to understand how the palaeo coastline could have terminated at the northern tip of the Vøring Escarpment. If the Vøring Marginal High was above sea level and the Lofoten margin below sea level, the escarpment should swing to the west, marking the northern termination of a volcanic island or peninsula (the Vøring Marginal High and its E Greenland correlative).

This is not the case. Alternatively, if the Lofoten lavas were extruded subaerially instead of being submarine, the palaeo-coastline should swing northeast from the Vøring Marginal High to the landward side of the Utrøst Ridge. Such a proposition appears just as difficult to support since the escarpment ends along a linear trajectory. Conversely, the Vøring escarpment may not represent a palaeo-coastline, but marks a tectonic break that postdates the lava flows as suggested by Brekke (2000).

6. Conclusions

Opening of the Norwegian-Greenland Sea (between the Jan Mayen and Senja fracture zones) occurred along stable continental margins without offsets across minor fracture zones, or involving jumps in spreading axis. This interpretation deviates significantly from earlier interpretations with reported offsets across minor fracture zones of up to 50 km (Hagevang et al., 1983; Blystad et al., 1995; Tsikalas et al., 2001, 2002, 2005; Olesen et al., 2002). The previously proposed offset zones were merely artefacts of wide profile spacing, poor navigation and poor profile levelling of the vintage aeromagnetic profiles.

All the small fracture zones previously proposed to exist along the Norwegian margin north of the East Jan Mayen Fractue Zone are here proposed to be artefacts. Even more questionable are the correlative fracture zones off the NE Greenland margin as previously proposed by Tsikalas et al. (2002). Furthermore, the suggested presence of transfer zones in the NE Greenland margin inboard of the projected fracture zones is highly questionable. Currently the seismic database for NE Greenland is so sparse that the presence or absence of such transfer zones is difficult to validate. We consequently question the validity of the method applied by Tsikalas et al. (2002) to extrapolate the ''artificial'' fracture zones from the Norwegian margin to the conjugate NE Greenland margin.

Palaeogeographic reconstruction of the aeromagnetic map to Anomaly 22 reveals that a c. 50 km wide magnetic anomaly cutting across spreading anomalies 24A, 24B and 23 from the Vøring Marginal High on the Norwegian margin to the Traill Ø on the Greenland coast. This anomaly belt, which is proposed to reflect an igneous complex referred to as the Traill–Vøring igneous complex, cuts across anomaly 22 on the Greenland margin. Hence, if related to the mentioned igneous activity it must have lasted until c. 50 Ma. The magnetic response of this complex along the Vøring margin has earlier been interpreted to represent spreading anomalies 24A and 24B, which in turn introduced the need to invoke an abandoned spreading ridge and the Gleipne Fracture Zone in this area.

The western half of the Røst Basin is heavily intruded by mafic sills that may be related to the Traill–Vøring igneous complex. Combined interpretation of reflection seismic and potential field data reveals that the sills and dykes resemble the Hel Graben intrusions. To the north of the Myken Volcanic Complex and the Sandflesa High, only very thin high-amplitude reflectors (intrusions) are seen. However, local feeder systems for these flows may be interpreted. These suggest that the intrusions represent intrabasinal sources for the basalts.

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References

Berndt, C., Planke, S., Alvestad, E., Tsikalas, F., Rasmussen, T., 2001. Seismic volcanostratigraphy of the Norwegian Margin: constraints on tectonomagmatic brek-up processes. Journal of the Geological Society, London 158, 413–426.

Blystad, P., Brekke, H., Færseth, R.B., Larsen, B.T., Skogseid, J., Tørudbakken, B., 1995. Structural elements of the Norwegian continental shelf, Part II. The Norwegian Sea Region. Nor. Petr. Dir. Bull., vol. 8, 45pp.

Brekke, H., 2000. The tectonic evolution of the Norwegian Sea continental margin with emphasis on the Vøring and Møre basins. In: Nøttvedt, A., et al, (Eds.), Dynamics of the Norwegian Margin, vol. 167(special publication). Geological Society of London, pp. 327–378.

Braathen, A., Osmundsen, P.T., Nordgulen, Ø., Roberts, D., 2002. Orogen-parallel, extensional denudation of the Caledonides in North Norway. Norsk Geologisk Tidsskrift 82, 225–241.

Cande, S.C., Kent, D.V., 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. Journal of Geophysical Research 100, 6093–6095.

Colletta, B., Le Quellec, Letouzey, P., Moretti, I., 1988. Longitudinal evolution of the Suez rift structure (Egypt). In: Le Pichon, X., Cochran, J.R. (Eds.), The Gulf of Suez and Red Sea Rifting, vol. 153. Tectonophysics, pp. 221–233.

Dehls, J.F., Olesen, O., Bungum, H., Hicks, E., Lindholm, C.D., Riis, F., 2000. Neotectonic map, Norway and adjacent areas 1:3 mill. Nor. Geol. Unders., Trondheim, Norway.

Doré, A.G., Lundin, E.R., Jensen, L.N., Birkeland, Ø., Eliassen, P.E., Fichler, C., 1999. Principal tectonic events in the evolution of the northwest European Atlantic margin. In: Fleet, A.J., Boldy, S.A.R. (Eds.), Petroleum Geology of Northwest Europe: Proceedings of the Fifth Conference, Geological Society of London, pp. 41–61.

Ebbing, J., Lundin, E., Olesen, O., Hansen, E.K., 2006. The mid-Norwegian margin: a discussion of crustal lineaments, mafic intrusions, and remnants of the Caledonian root by 3D density modelling and structural interpretation. Journal of the Geological Society of London 163, 47–60.

Eldholm, O., Sundvor, E., Myhre, A., 1979. Continental margin off Lofoten–Vesterålen, Northern Norway. Marine Geophysical Researches 4, 3–35.

Eldholm, O., Tsikalas, F., Faleide, J.I., 2002. The continental margin off Norway 62–75°N: palaeogene tectono-magmatic segmentation and sedimentation. In: Jolley, D., Bell, B. (Eds.), The North Atlantic Igneous Province: Stratigraphy, Tectonics, Volcanic and Magmatic Processes, vol. 197(Spec. Publ.). Geological Society of London, pp. 39–68.

Escher, J.C., Pulvertaft, T.C.R., 1995. Geological map of Greenland, 1:2,500,000.Geological Survey of Greenland, Copenhagen.

Fjellanger, E., Surlyk, F., Wamsteeker, L.C., Midtun, T., 2005. Upper Cretaceous basin-floor fans in the øring Basin, Mid Norway shelf. In: Wandås, B.T.G., Eide, E.A., Gradstein, F., Nystuen, J.P. (Eds.), Onshore-offshore relationships on the North Atlantic margin. NPF (Norsk Petroleumsforening) Special Publication 12. Elsevier, Amsterdam, pp. 135–164.

Gaina, C., Roest, W.R., Muller, R.D., 2002. Late Cretaceous-Cenozoic deformation of northeast Asia. Earth Planetary Science Letters 197 (3&4), 273–286.

Gawthorpe, R.L., Hurst, J.M., 1993. Transfer zones in extensional basins: their structural style and influence on drainage development and stratigraphy. Journal of the Geological Society of London 150, 1137–1152.

Geosoft, 2000. Geosoft GridKnit, Grid stitching tool for OASIS Montaj, Tutorial and user guide, Geosoft Incorporated, 28pp.

Hagevang, T., Eldholm, O., Aalstad, I., 1983. Pre-23 magnetic anomalies between Jan Mayen and Greenland-Senja Fracture Zones in the Norwegian Sea. Marine Geophysical Researches 5, 345–363.

Hartz, E.H., Eide, E.A., Andresen, A., Midbøe, P., Hodges, K.V., Kristiansen, S.N., 2002. $^{40}Ar/^{39}Ar$ geochronology and structural analysis: Basin evolution and detrital feedback mechanisms, Hold With Hope region, East Greenland. Norsk Geologisk Tidsskrift 82, 341–358.

Heiskanen, W.A., Moritz, H., 1967. Physical Geodesy. W.H. Freeman, San Fransisco, 364pp.

Larsen, H.C., 1988. A multiple and propagating rift model for the NE Atlantic. In: Morton, A.C., Parson, L.M. (Eds.), Early Tertiary Volcanism and the Opening of the NE Atlantic, vol. 39(Spec. Publ.). Geological Society of London, pp. 157–158.

Larsen, H.C., 1990. The East Greenland Shelf. The Geology of North America, The Arctic Ocean region, vol. L. Geological Society of America, pp. 185–209.

Lundin, E.R., 2002. Atlantic—Arctic seafloor spreading history. In: Eide, E.A. (coord.), BATLAS—mid Norway plate reconstructions atlas with global and Atlantic perspectives. Nor. Geol. Unders., pp. 40–47.

Lundin, E.R., Doré, A.G., 2002. Mid-Cenozoic post-breakup deformation in the 'passive' margins bordering the Norwegian-Greenland Sea. Marine and Petroleum Geology 19, 79–93.

Lundin, E.R., Doré, A.G., 2005. NE Atlantic break-up: a re-examination of the Iceland mantle plume model and the Atlantic-Arctic linkage. In: Doré, A.G., Vining, B.A. (Eds.), Petroleum Geology: North–West Europe and Global Perspectives—Proceedings of the Sixth Petroleum Conference, Geological Society of London, pp. 739–754.

Mauring, E., Beard, L.P., Kihle, O., Smethurst, M.A., 2002. A comparison of aeromagnetic levelling techniques with an introduction to median levelling. Geophysical Prospecting 50, 43–54.

Mauring, E., Mogaard, J.O., Olesen, O., 2003. Røst Basin Aeromagnetic Survey 2003 (RAS-03). Ra 3 aeromagnetic compilation. Data acquisition and processing report. NGU Report 2003.070, 20pp.

Mjelde, R., Sellevoll, M.A., Shimamura, H., Iwasaki, T., Kanazawa, T., 1992. A crustal study off Lofoten, N. Norway, by use of 3-component ocean bottom seismographs. Tectonophysics 212, 269–288.

Mosar, J. Torsvik, T.H., the BAT team, 2002. Opening of the Norwegian and Greenland Seas: plate tectonics in mid Norway since the Late Permian. In: Eide, E.A. (coord.), BATLAS—Mid Norway Plate Reconstruction Atlas With Global and Atlantic Perspectives. Nor. Geol. Unders., pp. 48–59.

Nielsen, T.F.D., 1987. Tertiary alkaline magmatism in East Greenland: a review. In: Fitton, J.G., Upton, B.G.J. (Eds.), Alkaline Igneous Rocks, vol. 30 (special publications). Geological Society of London, pp. 489–515.

Nielsen, T.F.D., 2002. Palaeogene intrusions and magmatic complexes in East Greenland, 66–75°N. Geological Survey of Denmark and Greenland Report 2002/113, 249pp.

Noble, R.H., Macintyre, R.M., Brown, P.E., 1988. Age constraints on Atlantic evolution: timing of magmatic activity along the E Greenland continental margin. In: Morton, A.C., Parson, L.M., (Eds.), Early Tertiary Volcanism and the Opening of the NE Atlantic, vol. 39(Spec. Publ.). Geological Society of London, pp. 201–214.

Nunns, A.G., 1983. Plate tectonic evolution of the Greenland-Scotland Ridge and surrounding regions. In: Bott, M.H.P., Saxov, S., Talwani, M., Thiede, J. (Eds.), Structure and Development of the Greenland-Scotland Ridge: New Methods and Concepts. Plenum Press, New York, pp. 11–30.

Olesen, O., Lundin, E., Nordgulen, Ø., Osmundsen, P.T., Skilbrei, J.R., Smethurst, M.A., Solli, A., Bugge, T., Fichler, C., 2002. Bridging the gap between the onshore and offshore geology in Nordland, northern Norway. Norwegian Journal of Geology 82, 243–262.

Olesen, O., Ebbing, J., Skilbrei, J.R., Lundin, E., 2003. Interpretation of potential field data along the Lofoten continental margin, Part I. NGU Report 2003.070, 68pp.

Planke, S., Alvestad, E., Eldholm, O., 1999. Seismic characteristics of basaltic extrusive rocks. Leading Edge 18, 342–348.

Price, S., Brodie, J., Whitham, A., Kent, R., 1997. Mid-Tertiary rifting and magmatism in the Traill Ø region, East Greenland. Journal of the Geological Society of London 154, 419–434.

Roberts, D.G., Thompson, M., Mitchener, B., Hossack, J., Carmichael, S., Bjørnseth, H.-M., 1999. Palaeozoic to Tertiary rift and basin dynamics: mid-Norway to the Bay of Bicsay—a new context for hydrocarbon prospectivity in the deep water frontier. In: Fleet, A.J., Boldy, S.A.R. (Eds.), Petroleum Geology of Northwest Europe: Proceedings of the Fifth Conference, Geological Society of London, pp. 7–40.

Roeser, H.A., 1993. Magnetische Messungen auf See. Mitteilungen der Deutschen Geophysikalischen Gesellschaft 2, 11–24.

Scott, R.A., 2000. Mesozoic-Cenozoic evolution of East Greenland: Implications of a reinterpreted continent-ocean boundary location. Polarforschung 68, 83–91.

Scott, R.A, Ramsey, L.A., Jones, S.M., Sinclair, S., Pickles, C.S., 2005. Development of the Jan Mayen microcontinent by linked propagation and retreat of spreading ridges. In: Wandås, B.T.G., Eide, E.A., Gradstein, F., Nystuen, J.P. (Eds.), Onshore-offshore relationships on the North Atlantic margin. NPF (Norsk Petroleumsforening) Special Publication 12. Elsevier, Amsterdam, pp. 69–82.

Sellevoll, M.A., Olafsson, I., Mokhtari, M., Gidskehaug, A., 1988. Lofoten margin, North Norway: crustal structure adjacent to the ocean-continent transition. Norges Geologiske Undersøkelse 3 (Special Publ.), 39–48.

Simpson, R.W., Jachens, R.C., Blakely, R.J., 1983. AIRYROOT: a Fortran program for calculating the gravitational attraction of an Airy isostatic root out to 166.7 km. United States Department of the Interior, Geological Survey, Open-File Report 83–883, 24pp.

Skilbrei, J.R., Kihle, O., Olesen, O., Gellein, J., Sindre, A., Solheim, D., Nyland, B., 2000. Gravity anomaly map, Norway and adjacent ocean areas. Scale 1:3 million. Nor. Geol. Unders. Trondheim.

Skogseid, J., Eldholm, O., 1987. Early Cenozoic crust at the Norwegian continental margin and the conjugate Jan Mayen Ridge. Journal of Geophysical Research 92, 11471–11491.

Smethurst, M., 2005. A software tool to rotate spatial data on the surface of the sphere (Earth) for Geosoft's Oasis Montaj. NGU Report 2005.057, 18pp.

Swain, C.J., 1976. A Fortran IV program for interpolating irregularly spaced data using the difference equations for minimum curvature. Computers & Geosciences 1, 231–240.

Talwani, M., Eldholm, O., 1977. Evolution of the Norwegian-Greenland Sea. Geological Society of America Bulletin 88, 969–999.

Torsvik, T.H., Mosar, J., Eide, E.A., 2001. Cretaceous-Tertiary geodynamics: a North Atlantic exercise. Geophysical Journal International 146, 850–866.

Tsikalas, F., Faleide, J.I., Eldholm, O., 2001. Lateral variations in tectono-magmatic style along the Lofoten-Vesterålen volcanic margin off Norway. Marine and Petroleum Geology 18, 807–832.

Tsikalas, F., Eldholm, O., Faleide, J.I., 2002. Early Eocene sea floor spreading and continent-ocean boundary between Gleipne and Senja fracture zones in Norwegian-Greenland Sea. Marine Geophysical Researches 23, 247–270.

Tsikalas, F., Eldholm, O., Faleide, J.I., 2005. Crustal structure of the Lofoten–Vesterålen continental margin, off Norway. Tectonophysics 404, 151–174.

Verhoef, J., Roest, W.R., Macnab, R., Arkani-Hamed, J., Members of the Project Team, 1996. Magnetic anomalies of the Arctic and North Atlantic Oceans and adjacent land areas. GSC Open File 3125, Parts a and b (CD-ROM and project report), Geological Survey of Canada.

Vink, G.E., 1984. A hotspot model for Iceland and the Vøring Plateau. Journal of Geophysical Research 89 (B12), 9949–9959.

Vogt, P.R., 1986. Geophysical and geochemical signatures and plate tectonics. In: Hurdle, B.G. (Ed.), The Nordic Seas. Springer, New York, pp. 413–664.