AGU PUBLICATIONS

Tectonics

RESEARCH ARTICLE
10.1002/2014TC003717

Key Points:
- 88.000 line km of new aeromagnetic data in the Norwegian-Greenland Sea
- Complete aeromagnetic coverage of the Norway Basin spreading system
- Prebreakup and postbreakup evolution of the rift/margin system/ microcontinent

Supporting Information:
- Supporting Information

Correspondence to:
L. Gernigon,
Laurent.Gernigon@NGU.NO

Citation:
Gernigon, L., A. Blischke, A. Nasuti, and M. Sand (2015), Conjugate volcanic rifted margins, seafloor spreading, and microcontinent: Insights from new high-resolution aeromagnetic surveys in the Norway Basin, *Tectonics*, *34*, doi:10.1002/2014TC003717.

Received 19 AUG 2014
Accepted 27 MAR 2015
Accepted article online 31 MAR 2015

Conjugate volcanic rifted margins, seafloor spreading, and microcontinent: Insights from new high-resolution aeromagnetic surveys in the Norway Basin

Laurent Gernigon[1], Anett Blischke[2], Aziz Nasuti[1], and Morten Sand[3]

[1]Geological Survey of Norway, Trondheim, Norway, [2]Iceland GeoSurvey, Department of Energy Technology, Akureyri, Iceland, [3]Norwegian Petroleum Directorate, Stavanger, Norway

Abstract We have acquired and processed new aeromagnetic data that cover the entire oceanic Norway Basin located between the Møre volcanic rifted margin and the Jan Mayen microcontinent (JMMC). The new compilation allows us to revisit the structure of the conjugate volcanic (rifted) margins and the spreading evolution of the Norway Basin from the Early Eocene breakup time to the Late Oligocene when the Aegir Ridge became extinct. The volcanic margins (in a strict sense) that formed before the opening of the Norway Basin have been disconnected with the previous Jurassic-Mid-Cretaceous episode of crustal thinning. We also show evidence of relationships between the margin architecture, the breakup magmatism distribution along the continent-oceanic transition, and the subsequent oceanic segmentation. The Norway Basin shows a complex system of asymmetric oceanic segments locally affected by episodic ridge jumps. The new aeromagnetic compilation also confirms that a fan-shaped spreading evolution of the Norway Basin was clearly active before the cessation of seafloor spreading and extinction of the Aegir Ridge. An important Mid-Eocene kinematic event at around magnetic chron C21r can be recognized in the Norway Basin. This event coincides with the onset of diking and increasing rifting activity (and possible oceanic accretion?) between the proto-JMMC and the East Greenland margin. It led to a second phase of breakup and microcontinent formation in the Norwegian-Greenland Sea ~26 Myrs later in the Oligocene.

1. Introduction

Since the early development of the plate-tectonic concept, the application of magnetic anomaly mapping has always been a primary source of information to understand the development of the North Atlantic Oceanic basins [*Le Pichon et al.*, 1977; *Talwani and Eldholm*, 1977; *Srivastava and Tapscott*, 1986; *Olivet*, 1996]. Recent advances in studying passive margins and their rift to drift evolution worldwide attempted to investigate better the complex relationships between rifting, breakup, and seafloor spreading segmentation [*Behn and Lin*, 2000; *Taylor et al.*, 2009; *Blaich et al.*, 2009; *Moulin et al.*, 2010; *Leroy et al.*, 2012; *Koopmann et al.*, 2014]. The singularity of volcanic segments of passive margins and the formation of isolated continental fragments (or microcontinents) also proves to be an exciting theme of research, which involves and questions inheritance, crustal structure, plate kinematics, and mantle dynamics [e.g., *Skogseid et al.*, 2000; *Müller et al.*, 2001; *Collier et al.*, 2008; *Gaina et al.*, 2009; *Yamasaki and Gernigon*, 2010; *Misra et al.*, 2015].

Our study focuses on similar thematics and is primarily based on a revised and joint interpretation of the Norway Basin flanked by the Jan Mayen microcontinent (JMMC) and the Møre volcanic rifted margin (MVRM) in the Northeast Atlantic (Figure 1). Located north of Iceland, the JMMC (Figure 1) is an isolated, continental fragment which was detached from the East Greenland margin and the MVRM during the Cenozoic [*Talwani and Eldholm*, 1977; *Auzende et al.*, 1980; *Unternehr*, 1982; *Nunns*, 1983; *Guðlaugsson et al.*, 1988; *Gunnarsson et al.*, 1989; *Kodaira et al.*, 1998; *Breivik et al.*, 2012; *Kandilarov et al.*, 2012]. Before a first breakup event in Early Eocene, the proto-JMMC was tied to the MVRM and the East Greenland margin. It was then part of a complex system of sedimentary basins and polyphase rift systems that developed in the NE Atlantic after the collapse of the Caledonides [*Doré et al.*, 1999; *Brekke*, 2000; *Tsikalas et al.*, 2012]. After significant magmatic activity along the MVRM's proto-breakup axis [*Skogseid and Eldholm*, 1987; *Planke and Alvestad*, 1999], seafloor spreading started along the nascent Aegir Ridge until it became extinct in the Early Oligocene [*Jung and Vogt*, 1997]. The geophysical investigations conducted during the 1970s and 1980s led

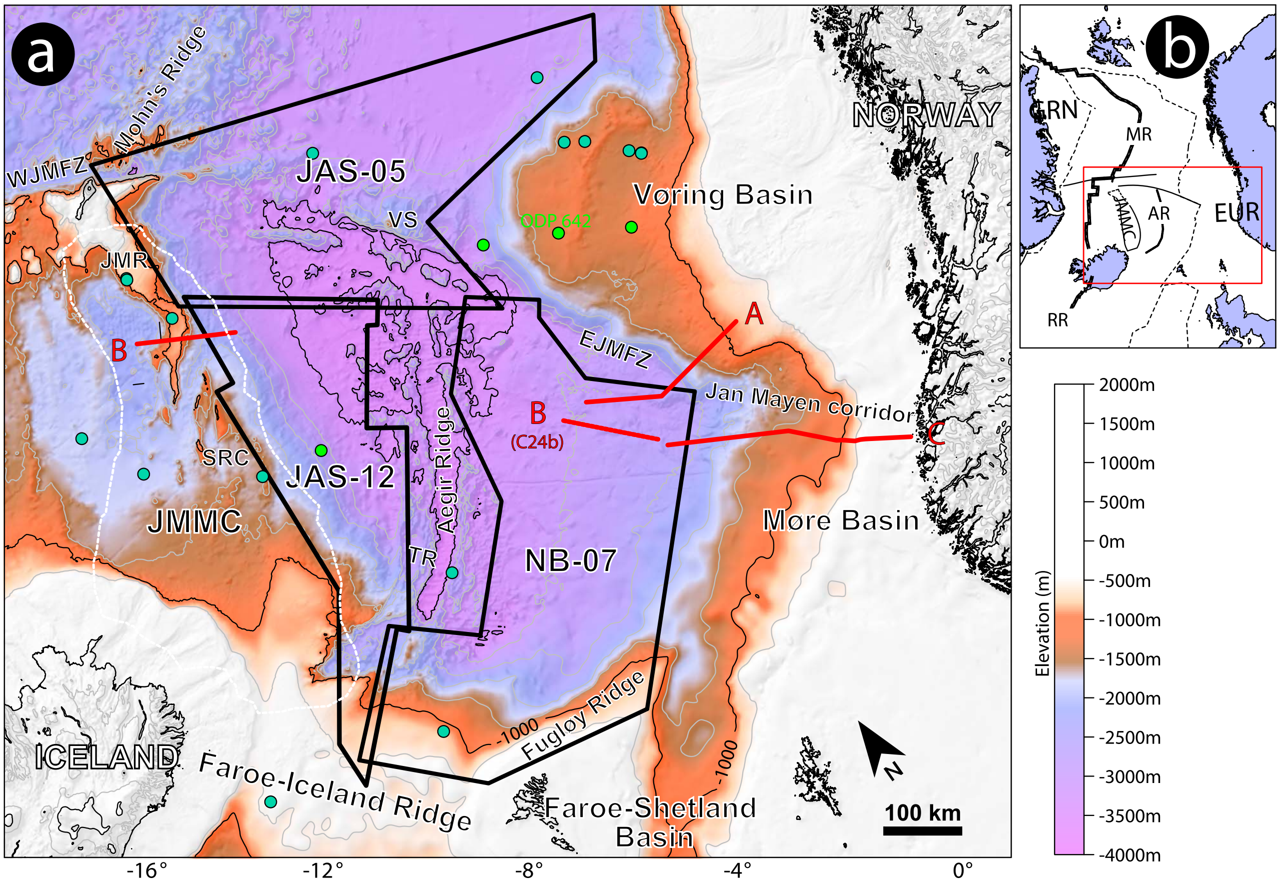

Figure 1. (a) Main physiographic features of the Norway Basin and surrounding conjugate margins. The black polygons (JAS-05, NB-07, and JAS-12) represent the outlines of the new aeromagnetic surveys, acquired between 2005 and 2012 between the Faroe-Shetland, Møre, and Vøring margin segments and the conjugate Jan Mayen "microcontinent" (JMMC). EJMFZ: East Jan Mayen Fracture Zone; JMR: Jan Mayen Ridge; SRC: (Jan Mayen) Southern Ridge Complex; TR: Treitel Ridge; VS: Vøring Spur; WJMFZ: West Jan Mayen Fracture Zone. Circles indicate the sites of Ocean Drilling Project (ODP, light green color) and Deep Sea Drilling project (DSDP, sea green color). Bathymetric data set from IBCAO vers. 3 [*Jakobsson et al.*, 2012] merged with the recent NPD/Orkustofnun multibeam data set acquired across the JMMC. A, B, and C represent the sections described in Figures 9 and 14, respectively. (b) Outline and location of the main plate boundaries in the Norwegian-Greenland Sea (modified after Bird, 2003). AR: extinct Aegir Ridge; EUR: Eurasia; GRN: Greenland; MR: Mohn's Ridge; RR: Reykjanes Ridge.

to first kinematics and tectonic models to explain the spreading evolution of the Norway Basin and the late tectonic development of the MVRM and JMMC [*Grønlie et al.*, 1979; *Unternehr*, 1982; *Nunns*, 1983] (Figure 1). However, the magnetic data coverage before 2007 was relatively poor in most of the Norway Basin [e.g., *Verhoef et al.*, 1997; *Olesen et al.*, 2010]. This led to controversial and/or poorly constrained interpretations of the oceanic basin's structure and spreading evolution [*Mosar et al.*, 2002; *Scott et al.*, 2005; *Gaina et al.*, 2009; *Le Breton et al.*, 2012; *Greiner and Neugebauer*, 2013]. Despite recent high-resolution aeromagnetic surveys that were carried out in the eastern and northern parts of the Norway Basin and along the Jan Mayen Fracture Zone [*Gernigon et al.*, 2009; *Olesen et al.*, 2010], the sparse distribution and poor quality of the existing magnetic profiles in the remaining part of the Norway Basin (line spacing >30–50 km) was still a serious and primary impediment for accurate interpretations of the (conjugate) magnetic chrons (see Figure S1 in the supporting information). Consequently, a new survey in the western and conjugate parts of the Norway Basin was needed. This triggered the acquisition of aeromagnetic survey JAS-12 that was carried out during the summers of 2011 and 2012 (Figure 1), including a compilation with all previous aeromagnetic data sets (Figure 2 and Figure S1 in the supporting information).

This new and most up-to-date aeromagnetic data compilation of the Norwegian-Greenland Sea, combined with independent gravity and seismic data, allowed us (1) to reevaluate and revise the previous magnetic chron models and spreading history interpretations; (2) to define a comprehensive tectonic model for the entire oceanic basin; (3) to better constrain and understand the prebreakup configuration of the adjacent

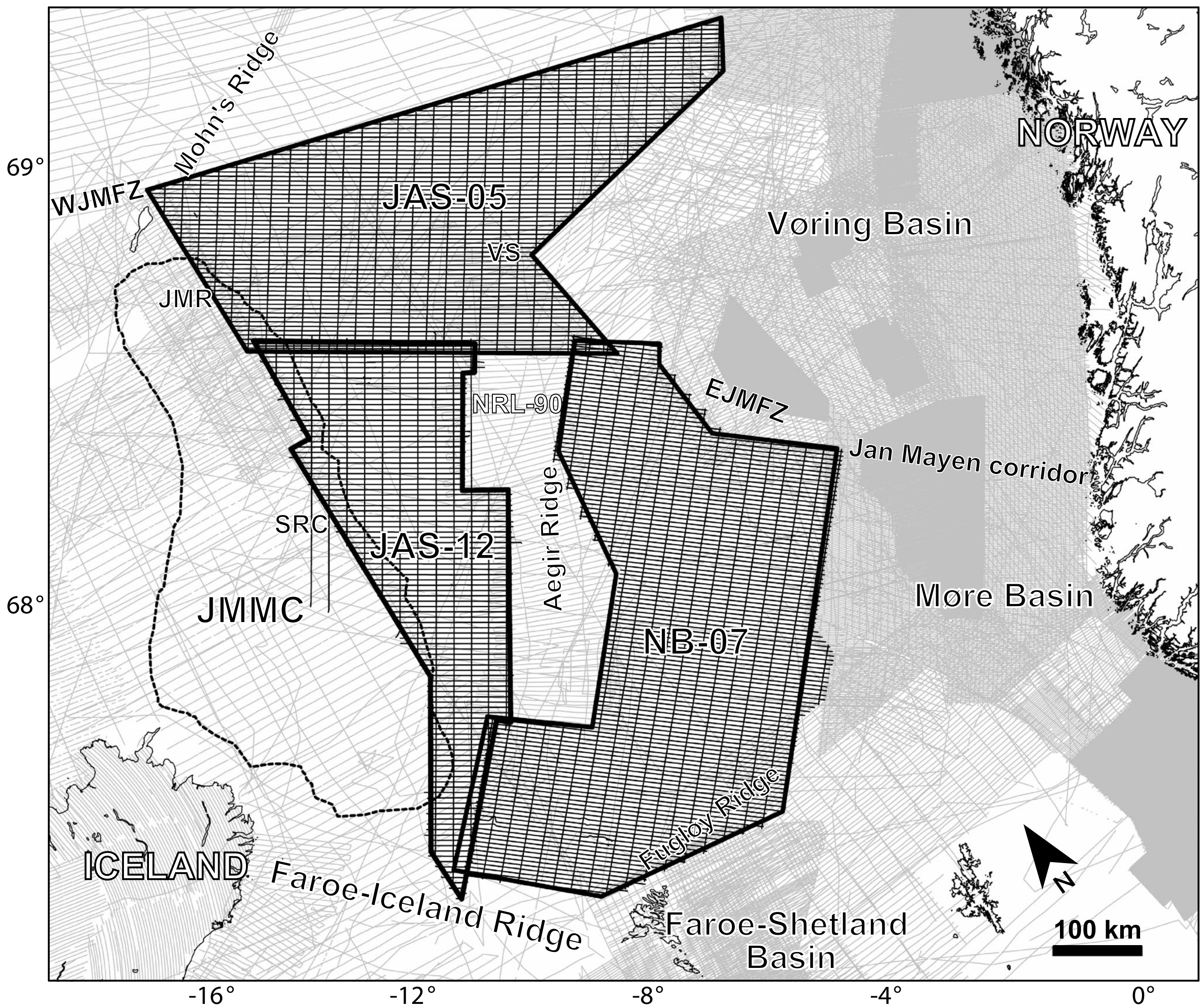

Figure 2. Distribution of magnetic data track lines: in grey—data collected before 2005 and bold lines—new aeromagnetic data discussed in this study. A total of ~88,000 km of new magnetic profiles greatly improves the magnetic coverage of the Norway Basin and surrounding volcanic rifted margins. Acquisition and details of the vintage surveys (dashed lines) are further documented in *Gernigon et al*. [2009, 2012a, 2012b] and *Olesen et al*. [2010](see also Figure S1 in the supporting information). Abbreviations same as in Figure 1.

volcanic rifted margins and its potential influence on subsequent spreading segmentation, and (4) to revise the dynamics and timing of the formation of the JMMC versus the MVRM.

2. Tectonic and Geologic Framework

The Norway Basin (Figure 1) is located between the slope of the Faroe-Iceland Ridge and the East Jan Mayen Fracture Zone [*Skogseid and Eldholm*, 1987; *Talwani and Eldholm*, 1977]. To the east it is bordered by the MVRM and to the west by the JMMC, which is situated between the extinct Aegir Ridge and the active Kolbeinsey Ridge (Figure 1). Recent seismic studies show that this inactive oceanic basin is now buried beneath a maximum of 2.5–3 km of Cenozoic sediments, particularly thick along the axis of the Aegir Ridge and in the eastern part of the spreading system [*Breivik et al*., 2006; *Gernigon et al*., 2012a; *Hjelstuen and Andreassen*, 2015]. The underlying oceanic crust varies from ~20 km near the continent-oceanic transition [*White et al*., 2008] to less than 4–5 km near the Aegir Ridge [*Breivik et al*., 2006].

Before the opening of the Norway Basin, the continental domain evolved through several rift and thermal cooling episodes that developed regionally after the extensional collapse of the Caledonides until the time of the first phase of breakup between Norway and Greenland in Early Tertiary [*Brekke*, 2000; *Skogseid et al.*, 2000; *Doré et al.*, 1999]. Significant stretching and crustal thinning particularly controlled the Mesozoic development of the MVRM, which is characterized, at present day, by a large and thick Cretaceous sedimentary basin overlying poorly constrained rift structures and older sediments [*Olafsson et al.*, 1992; *Grunnaleite and Gabrielsen*, 1995; *Brekke*, 2000; *Kvarven et al.*, 2014]. To explain the tectonic evolution of the MVRM, recent contributions [*Osmundsen and Ebbing*, 2008; *Reynisson et al.*, 2010] have suggested some similarities and analogies with magma-poor margins that are particularly well documented in the Central Atlantic [e.g., *Reston*, 2009; *Sibuet and Tucholke*, 2012; *Sutra et al.*, 2013; *Manatschal*, 2004]. Some high-velocity, lower crustal bodies with $Vp > 7.0$ km/s have been notably interpreted as (syn-rift) exhumed serpentinized mantle in the central and/or inner parts of the MVRM [*Osmundsen and Ebbing*, 2008; *Reynisson et al.*, 2010; *Lundin and Doré*, 2011; *Rüpke et al.*, 2013; *Péron-Pinvidic et al.*, 2013]. Close to the proto-breakup axis, some authors agree with the presence of thick continental blocks and consequently, a poorly thinned continental crust ($ß_{crustal}$ between 2 and 2.5) [*Reynisson et al.*, 2010]. Other studies favored, on the contrary, the presence of a thinner crust ($ß_{crustal}$ between 3 and 3.5) [*Kvarven et al.*, 2014; *Nirrengarten et al.*, 2014]. More drastic thinning ($ß_{crustal} \gg 3.5$), "Hyperextended" crust and a possible zone of exhumed serpentinized mantle have also been proposed to explain the continent-ocean transition between the MVRM and the proto-JMMC [*Péron-Pinvidic et al.*, 2013].

As part of the prebreakup rifted system, the JMMC is considered as a piece of continental crust that finally separated from Greenland in the Late Oligocene [*Auzende et al.*, 1980; *Guðlaugsson et al.*, 1988; *Gunnarsson et al.*, 1989; *Gaina et al.*, 2009; *Blischke et al.*, 2011; *Gernigon et al.*, 2012a]. The nature of the subbasalt substratum and crust in most of the JMMC is uncertain and is primarily based on geophysical data interpretation [*Mjelde et al.*, 2007; *Breivik et al.*, 2012; *Kandilarov et al.*, 2012]. A seafloor gravity core and grab sampling profile interpretation at one of the JMMC ridges is suggesting the presence of both Cenozoic and Mesozoic sediments [*Polteau et al.*, 2013], but whether the Mesozoic sediments are indigenous or not is still debated [*Norwegian Petroleum Directorate*, 2013].

The onset of breakup between the MVRM and the proto-JMMC resulted in the formation of conjugate volcanic margins during Late Paleocene-Early Eocene time [*Eldholm et al.*, 1989; *Planke and Alvestad*, 1999; *Skogseid et al.*, 2000] (Figure 1). The breakup volcanism is well documented by geological outcrops and offshore geophysical data from the Vøring Marginal High up to the Faroe Platform [*Berndt et al.*, 2001a, 2001b; *Breivik et al.*, 2006; *Passey and Jolley*, 2009; *Mjelde et al.*, 2009]. Along both edges of the Norway Basin, significant magmatism is demonstrated by thick volcanic sequences (so-called Seaward Dipping Reflectors, SDRs), magmatic intrusions, and lower crustal bodies with high *Vp* wave velocities that are (partly) interpreted as magmatic underplating [*Mjelde et al.*, 2009; *White et al.*, 2008]. The SDRs, recognized on the outer parts of the MVRM and conjugate JMMC, most likely correspond to massive mid-ocean ridge basalt (MORB)-like lava flows underlying a more silicic basaltic formation sampled on the Vøring Marginal High nearby [*Meyer et al.*, 2009]. *Eldholm et al.* [1989] suggested that the pulse of breakup magmatism occurred around 56.5–55 Ma ago (equivalent to the magnetic polarity chron C24r according to the last GTS2012 polarity time scale of *Gradstein et al.* [2012]). Significant magmatic activities continued after breakup west of the Faroe Platform, where a crustal thickness of more than 30 km for the Faroe-Iceland Ridge (Figure 1) has been often interpreted to represent the track of the Iceland hot spot [*Smallwood et al.*, 1999]. The origin of significant breakup (and postbreakup) magmatism at the edge of the Norway Basin could have involved not only intrinsic (e.g., rift related) but also extrinsic geodynamic processes, including plume and/or alternative sublithospheric processes [*White*, 1992; *Meyer et al.*, 2007; *Foulger and Anderson*, 2005].

After the continental breakup in the NE Atlantic, seafloor spreading developed almost simultaneously along the Mohn's and Aegir Ridges, offset by the East Jan Mayen Fracture Zone (Figures 1 and 2) that acted as a prominent oceanic transform zone until the extinction of the Aegir Ridge [e.g., *Skogseid and Eldholm*, 1987]. The first magnetic spreading anomalies in the Norway Basin were interpreted based on vintage magnetic data acquired in the Norwegian-Greenland Sea [*Vogt et al.*, 1970]. Later, *Talwani and Eldholm* [1977] and *Nunns* [1983] identified magnetic polarity chrons C23n to possibly C7n in the Norway Basin (51.8–50.6 Ma to 24.4–23.9 Ma, according to the recent GTS2012 polarity time scale). *Vogt* [1986] later proposed a slightly different interpretation, ranging from anomaly C24n3n (53.9–53.2 Ma) (also referred to anomaly C24B in the previous literature [*Skogseid and Eldholm*, 1987; *Guðlaugsson et al*., 1988]) to anomaly C20n (43.4–42.3 Ma). Using a newer data set (NRL-90 survey), *Jung and Vogt* [1997] subsequently identified a set of magnetic chrons between C21n (47.3–45.7 Ma) and C13n (33.7–33.1 Ma). The Oligocene time interval, which corresponds to the C13n period (33.5–33.0 Ma), is often considered as a major event in the North Atlantic, when an arm of the triple junction between North America, Greenland, and Eurasia was abandoned [*Srivastava and Tapscott*, 1986; *Gaina et al*., 2002]. During this reorganization, a change in the opening direction between Eurasia and North America/Greenland from NNW-SSE to NW-SE led to the initiation of the West Jan Mayen Fracture Zone [*Talwani and Eldholm*, 1977]. Despite uncertainties regarding the extent and age of the initiation of the West Jan Mayen Fracture Zone, which could be older than C13n [see *Gernigon et al*., 2009], the post-C13 period effectively coincided with a period of westward migration of the plate boundary from the Aegir Ridge spreading center toward the proto-Kolbeinsey Ridge [*Nunns*, 1983] (Figure 1). The C13 period has generally been considered as a principal tectonic event that affected the Norway Basin and the North Atlantic, although it has been recently suggested, based on a detailed study of the Treitel Ridge (Figure 1), that C18n time (40.1–38.6 Ma) could represent a better timing for the onset of plate reorganization [*Vogt and Jung*, 2009], coinciding with a suggested seafloor spreading slowdown in the Labrador Sea [*Roest and Srivastava*, 1989]. In connection to this, a series of changes in plate directions and seafloor spreading from C20 to C18 have also been reported by *Gaina et al*. [2009], which also point out a correlation between these events and changes in spreading in the Labrador Sea.

The final evolution of the Aegir Ridge took place between magnetic chrons C12n (31–30.5 Ma) and C7 (24.4–23.9 Ma) but could not be fully understood due to an ultraslow spreading development of the Aegir Ridge before its extinction [*Jung and Vogt*, 1997; *Vogt et al*., 1970; *Breivik et al*., 2006]. Tentatively, *Talwani and Eldholm* [1977], and more recently *Vogt and Jung* [2009], placed the Aegir Ridge extinction time between chrons C8 and C7 (ca. 25–24 Ma). The complete opening of a new spreading axis along the Kolbeinsey Ridge finally resulted from the progressive dislocation of the JMMC from Greenland at around C6B (22.2–21.7 Ma ago) [e.g., *Gaina et al*., 2009; *Blischke et al*., 2011].

3. New Data Acquisition, Methods, and Modeling

3.1. New and Complete High-Resolution Aeromagnetic Mapping of the Norway Basin

The Continental Shelf Geophysics group at Geological Survey of Norway (NGU) initiated the aeromagnetic remapping project of the Norway Basin in 2005 with a survey acquired along the trend of the Jan Mayen Fracture Zone [*Gernigon et al*., 2009; *Olesen et al*., 2010] (JAS-05 in Figures 1 and 2). Furthermore, a similar high-resolution aeromagnetic regional survey was carried out in 2007 across the eastern part of the Norway Basin, showing significant improvements in quality in comparison with the previous data set [*Gernigon et al*., 2012a] (Figure S1). The full coverage of the Norway Basin was finalized during summers of 2011 and 2012, by acquiring 18,632 km of aeromagnetic profile data (JAS-12) between the eastern flank of the JMMC and the aborted Aegir Ridge. The Aegir Ridge itself was already well covered by the NRL-90 magnetic survey [*Jung and Vogt*, 1997]. The resulting aeromagnetic data compilation for the entire Norway Basin includes a total of 88,600 km of new high-resolution aeromagnetic profile data of surveys JAS-05, NB-07, and JAS-12 that were merged with the preexisting magnetic data set (Figure 2). Crossing profiles and tie profiles of the new JAS-12 survey are oriented NW-SE and NE-SW, respectively, and a line spacing of 5–6 km for the cross lines and 20 km for the tie lines (Figure 2). This final compilation provides sufficient resolution for a proper leveling and accurate qualitative and quantitative analysis of the magnetic anomalies (Figure 3). After the noise removal and head and lag corrections, the profiles have been processed using the standard International Geomagnetic Reference Field correction and standard statistical leveling methods, which involved fitting a polynomial to the intersection errors by the method of least squares [*Mauring et al*., 2002; *Gernigon et al*., 2012b]. Finally, the most recent surveys were merged with the preexisting and surrounding magnetic data of the Norwegian-Greenland Sea and MVRM [e.g., *Verhoef et al*., 1997; *Olesen et al*., 2010], in order to obtain a complete magnetic data set depicting the conjugate margins and associated oceanic domains. We then replaced the 300 km wavelength of our magnetic compilation with the one from the CHAMP (CHAllenging Minisatellite Payload) satellite magnetic model MF7 [*Maus et al*., 2008]. The MF7 model was produced using CHAMP measurements from May 2007

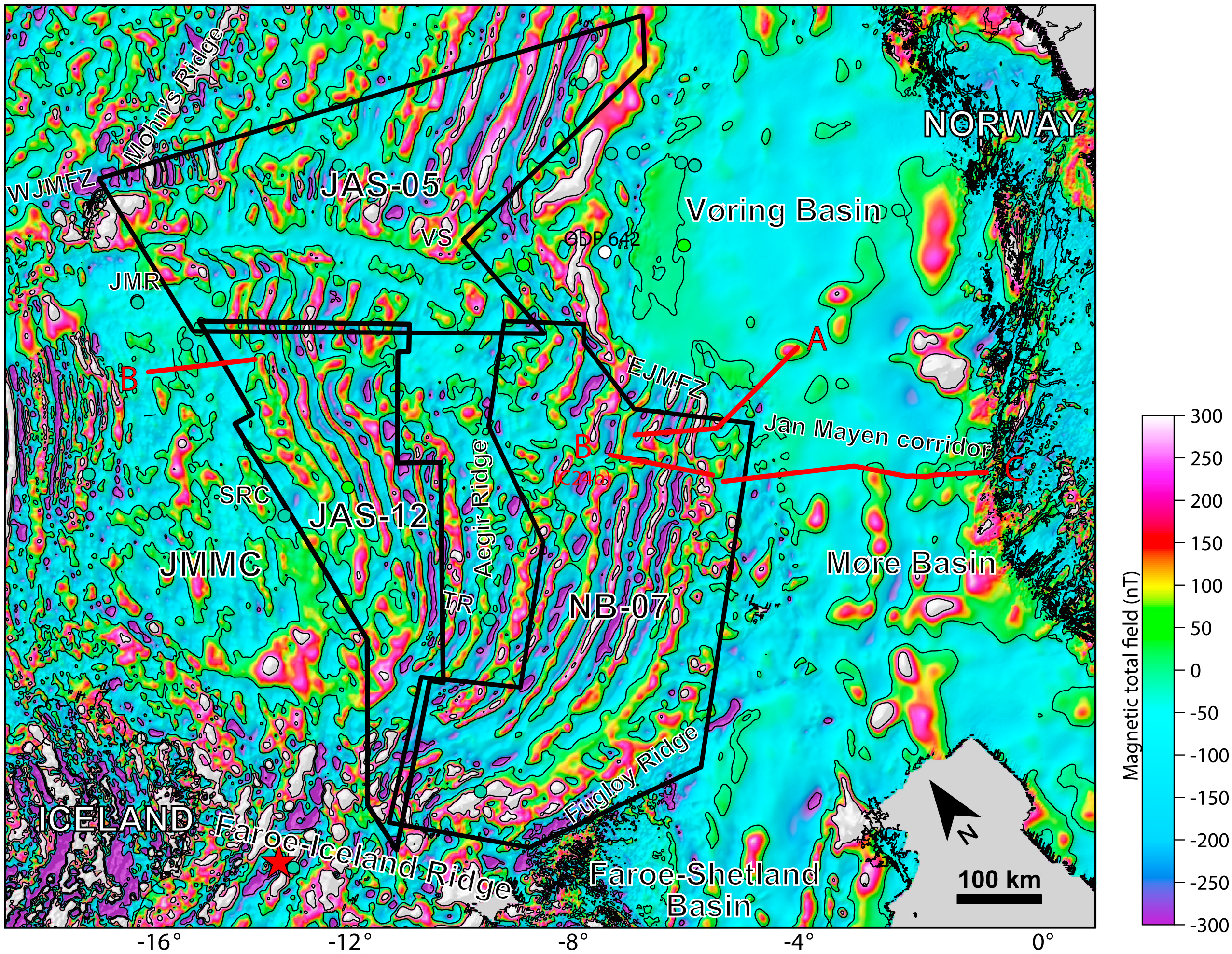

Figure 3. Magnetic total field gridded data of the Norway Basin and surrounding areas, 1 km × 1 km grid (with satellite MF7 CHAMP correction). Abbreviations same as in Figure 1.

to April 2010 and resolves the crustal magnetic field to spherical harmonic degree 133, corresponding to length scales down to 300 km (http://geomag.org/models/MF7.html). Figure 3 shows the final aeromagnetic gridded data presented and discussed in this paper. Figure 4 shows the corresponding free air gravity field [*Sandwell et al.*, 2013] that was made available for the study area.

3.2. Analysis of the New Aeromagnetic Data and New Euler Rotations

The magnetic anomalies of the ocean floor shown by the new aeromagnetic surveys (Figure 3) provide the basis for a new quantitative evaluation for the kinematic processes of the opening of the Norway Basin. The magnetic chrons have been interpreted directly on the leveled magnetic profiles. For magnetic data interpretation, both conventional and normalized derivative filters [*Miller and Singh*, 1994] were used to highlight subtle anomalies. After a comparison with vintage profiles available in the Norway Basin, we have noted some misfits and shifts of the magnetic anomalies maxima and inflection points when compared to the new data set. These shifts are easily explained by the poor navigation of the old data set, a common issue for most of the vintage magnetic profiles acquired before implementation of GPS (Global Positioning System) in the Norwegian-Greenland Sea [see *Olesen et al.*, 2007, 2010; *Gernigon et al.*, 2009, 2012a, 2012b]. The present aeromagnetic surveys were acquired using a GPS precision of ±3–5 m. The magnetic anomaly edges have been primarily picked along each (line and tie line) profile (Figure 2). More than 600 picks have been systematically identified, profile by profile, and manually defined at the inflection points of each of the magnetic chrons investigated within and around the study area. The

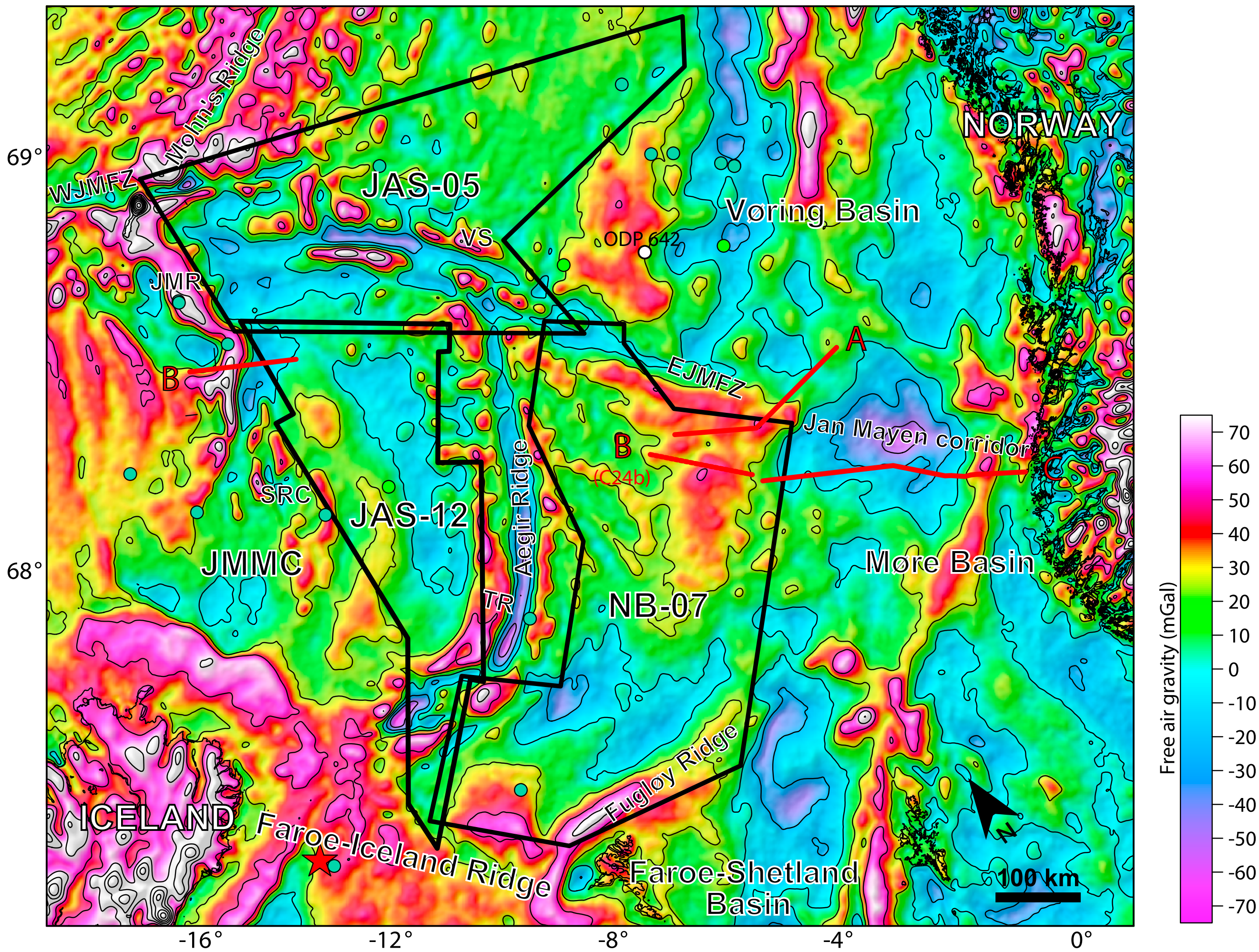

Figure 4. Gravity map of the study area. The grid represents the 1 km × 1 km grid from the Sandwell and Smith, free air gravity world compilation V20.1 [*Sandwell et al.*, 2013]. Abbreviations same as in Figure 1.

interpreted magnetic anomaly (see supporting information) was used to build a map of the magnetic isochrons (Figure 5). The chronology and ages have been interpreted using the GTS2012 polarity time scale of *Gradstein et al.* [2012].

Using the new isochrons, we have computed the Euler rotations for conjugate flanks of the Norway Basin (Table 1). The isochrons defined in this study consider the contiguous polyline, which join each identified magnetic picks. New Euler rotations were computed to best fit the conjugate isochrons identified on both sides of the extinct Aegir Ridge and to reconstruct the evolution of the JMMC in space and time (Figure 6). A cost function that measures the misfit between interpreted and rotated isochrons and the systematic exploitation of the parameter space [*Luis and Miranda*, 2008] was used to evaluate and automatically refine the best fit parameters of finite rotations. This cost function considers the minimum distances between each pick and the closest segments of the conjugate isochrons, measured in the direction perpendicular to the segments (see *Luis and Miranda* [2008] for further details).

Figure 6 illustrates the specific spreading phases of the Norway Basin in connection with the structural evolution of the JMMC and our best "approximation" of the Euler poles of rotation, also listed in Table 1. A Kernel density distribution (Gaussian function) [*Scott*, 1992] of the different Euler poles has been applied in order to highlight the main and subtle Euler poles population estimated in the study area (Figure 7).

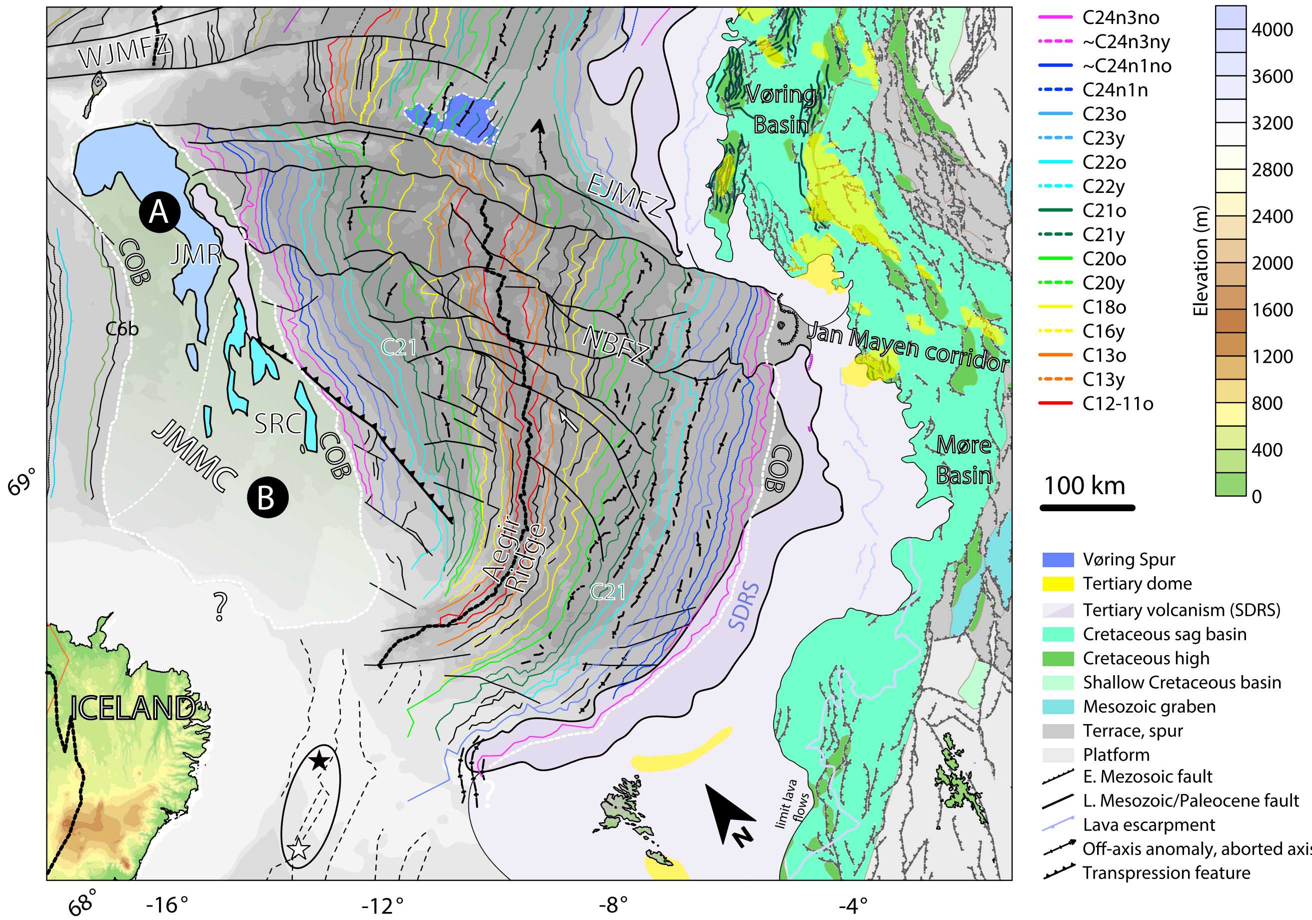

Figure 5. Magnetic and gravity data interpretation of the spreading system observed between the Møre volcanic rifted margin (MVRM) and the Jan Mayen microcontinent (JMMC). A complete conjugate set of magnetic chrons can be observed between magnetic chrons C24n3n and C12. A and B represent the location of the two continental subplate divisions proposed for the JMMC. EJMFZ: East Jan Mayen Fracture Zone; NBFZ: Norway Basin Fracture Zone; SDRs: Seaward Dipping Reflectors; WJMFZ: West Jan Mayen Fracture Zone. The grey background represents the bathymetry (see Figure 1).

3.3. Potential Field Modeling of the Oceanic and Continental Domains

Combined with the magnetic data interpretation, potential field modeling has been carried out to test the evolution of the oceanic spreading rates and estimate both basement depth and crustal thickness along selected seismic conjugate transects on the JMMC and MVRM (Figure 1).

The interpretation of the magnetic chrons in the oceanic domain has been correlated with synthetic profiles calculated using MODMAG [*Mendel et al.*, 2005] (Figure 8). The synthetic models consider different spreading rates, a constant spreading direction, and assume a 1 km thick magnetized layer with variable magnetization of 4–5 A m^{-1}. For each synthetic profile, a top oceanic basement was estimated from the sediment thickness compilation of *Laske and Masters* [1997]. Often required in a slow-spreading regime, a contamination factor of 0.85 [see *Mendel et al.*, 2005] has been considered before a forward and fictitious calculation of the spreading anomalies, until we obtained a best fit with the observed anomalies (Figure 8).

The modeling on the adjacent rifted margin and JMMC domains has been carried out on depth-converted seismic sections using the commercial software GM-SYS integrated within the GEOSOFT Oasis Montaj [*Northwest Geophysical Associates Incorporation*, 2006]. The forward modeling is based on the original approach of *Talwani* [1973]. This method computes the magnetic and gravity 2-D response of irregular polygon sets with different susceptibility, and remanence and density properties. The summation of the response from each polygon produces a signal which is compared with observed ship-track gravity and magnetic profiles. For the shallow part of the crust, the velocity model used for the depth conversion and

Table 1. Finite Rotation for the Jan Mayen Microcontinent Relative to a Fixed Eurasian Plate

Chron	Age GTS 2012 (Ma)	Longitude (λ)	Latitude (j)	Angle (Deg)	Plate
C13o north	33.705	−14.05	64.35	−8.64	A
~C16y north	35.706	−16	60.4	−6.57	A
C18o north	40.145	−13.52	63.25	−17.71	A
C20y north	42.301	−15.6	61.87	−16.7	A
C20o north	43.432	−15.6	62.23	−19	A
C21y north	45.724	−17	61.7	−20.65	A
C21o north	47.349	−18.55	60.14	−18	A
C22y north	48.566	−18.63	60.2	−21.26	A
C22o north	49.344	−18.55	60.14	−22.16	A
C23n1ny north	50.628	−19.15	59.75	−22.68	A
C23n1ny south	50.628	−13.67	62.48	−34.94	A
C23n.2no north	51.833	−18.55	60.09	−24.81	A
C24Ao north	~53.074	−20.17	58.83	−23.69	A
C24Ay north	52.62	−19.88	58.93	−23.72	A
C24By north	~53.27	−23.43	56.33	−19.67	A
C24Bo north	53.98	−23.653	55.9	−19.8	A
C12-11 undi_S	<31.034	−12.07	64.01	−3.4	B
C13o south	33.705	−13.75	64.1	−6.11	B
~C16y south	35.706	−13.57	63.43	−8.49	B
C18o south	40.145	−11.54	64.44	−22.9	B
C20y south	42.301	−11.23	64.55	−29.4	B
C20o south	43.432	−11.258	64.295	−30.9	B
C21y south	45.724	−11.35	64.265	−38.09	B
C21o south	47.349	−11.7	64.15	−41.8	B
C22y south	48.566	−11.55	63.7	−41.6	B
C22o south	49.344	−12.51	63.38	−39.74	B
C24Ao south	~53.074	−20.51	59.05	−24.3	B
C24Ay south	52.62	−19.43	59.54	−24.89	B
C24Ay south (alternative)	52.62	−12.79	62.75	−44.6	B
C24By south	~53.27	−20.22	58.76	−24.65	B
C24By south (alternative)	~53.27	−13.4	62.79	−47.99	B
C24Bo south (alternative)	53.98	−12.9	62.66	−51.7	B
C24Bo south	53.98	−19.68	58.76	−25.89	B
C13o GRN-EUR	33.705	−47.32	−62.25	−6.85	GRN-EUR
C18o GRN-EUR	40.145	−49.64	−59.58	−8.1	GRN-EUR
C20o GRN-EUR	43.432	−51.11	−56.11	−8.45	GRN-EUR
C21o GRN-EUR	47.349	−51.03	−52.9	−9.22	GRN-EUR
C22o GRN-EUR	49.344	−51.57	−47.99	−9.27	GRN-EUR
C23n.2no GRN-EUR	51.833	−58.8	−56.16	−11.37	GRN-EUR
C23n.2no south	51.833	−14.31	62	−34.75	GRN-EUR
C24Ao GRN-EUR		−57.1	−51.55	−11.02	GRN-EUR
C24Bo GRN-EUR	53.98	−57.05	−51.51	−11.4	GRN-EUR

density estimation considers a set of average regional velocity values derived from stack velocities locally and dynamically readjusted and extrapolated using check shot values derived from direct well calibration. Deeper interval velocities and density units have been constrained with average velocities derived from old refraction data and ocean-bottom seismometers (OBS) modeling available in the literature [*Vially and de Clarens*, 1986; *Planke et al.*, 1991; *Olafsson et al.*, 1992; *Mjelde et al.*, 2009; *Breivik et al.*, 2012; *Kvarven et al.*, 2014] and extrapolated onshore with other refraction experiments [*Maupin et al.*, 2013]. The OBS transects provide a first indication of the depth to basement and Moho with an accuracy usually estimated between 1 km on average and a maximum of 2 km [*Mjelde et al.*, 2009].

4. Structure of the Norway Basin and Oceanic Spreading Evolution

4.1. Continent-Ocean "Boundaries"

The new compilation documents the adjacent volcanic margin subdivisions from a transform to a rift and then to a shear margin, resulting in segmentation of the oceanic crust between the East Jan Mayen Fracture Zone and the Faroe-Iceland Ridge (Figures 1 and 5). During the breakup and early opening of the Norway Basin, a

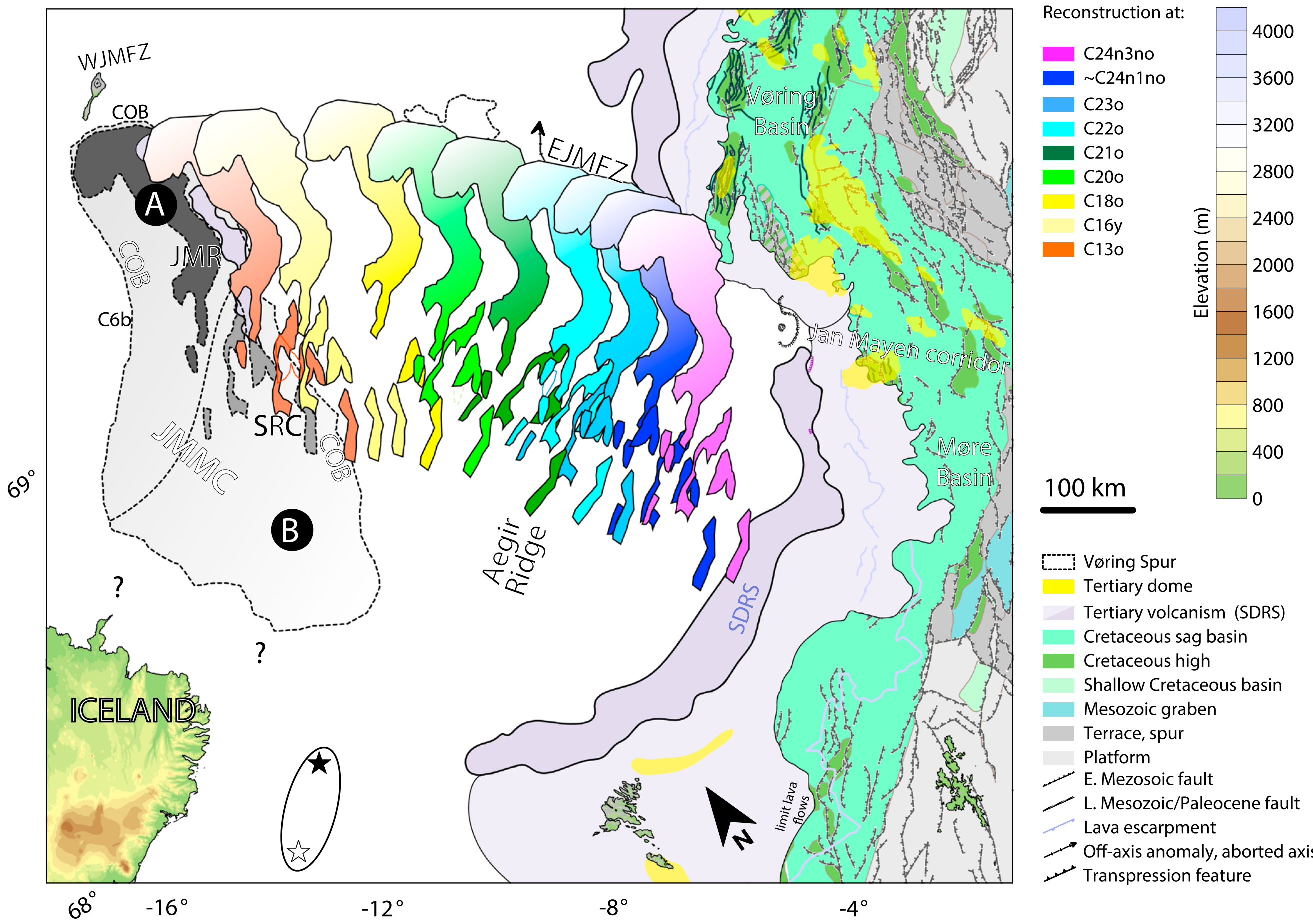

Figure 6. Time and space reconstruction of the main physiographical elements of the Jan Mayen microcontinent (e.g., the northern Jan Mayen Ridge and the Southern Ridge Complex at various times). The northern and southern parts of the JMMC (Nonrigid subplates A and B) are reconstructed with different rotations (see Table 1). The stars east of Iceland represent the average location (total mean values in white and 75% mean solution in black) of the Euler poles describing finite rotation of the JMMC relative to Eurasian plate.

large volume of volcanic rocks formed at the location of the Continent-Ocean Boundaries (COBs) usually defined as the outermost edge of unequivocal oceanic crust, where they are well defined, continuous, prominent, and coherent magnetic anomalies [e.g., *Chalmers and Laursen*, 1995; *Sibuet et al.*, 2007; *Direen et al.*, 2007; *Koopmann et al.*, 2014]. Around the Norway Basin, the COBs are difficult to map and to validate, precisely due to the presence of breakup volcanism [*Berndt et al.*, 2001a, 2001b; *Planke et al.*, 2000] (Figure 5). The surface volcanics emplaced in the outer part of the MVRM explains most of the magnetic signature (Figure 3) and "blurs" the potential magnetic sources of the underlying unconstrained substratum.

The COBs defined in this study have been mapped and interpreted slightly landward of magnetic chron C24n3n (old C24B) along the continuous and prominent magnetic lows, interpreted as stage C24r (57.1–53.9 Ma), the oldest oceanic chron edge that was earlier recognized in the Norwegian-Greenland Sea [e.g., *Skogseid and Eldholm*, 1987]. This magnetic chron stage C24r is particularly visible south of the Vøring transform margin, where the breakup-related volcanism is reduced (Figure 5). At the level of the transform margin, the COB is sharp and the Jan Mayen Fracture Zone seems to have been initiated already slightly before C24r. Landward of this limit, the nature of the crust remains open to discussion, but some embryonic oceanic segments associated with volcanic mounds (magnetic polarity chron C25?, 57.6–57.1 Ma) and preserved, extended, and intruded, continental crust may coexist (Figures 5, 8, and 9). In most of the Norway Basin, magnetic polarity chron C24n1n (also refer as C24A in the literature) and the youngest edge of magnetic chron C24n3n (old C24B) can be mapped almost continuously and with confidence on both conjugate margins until they merge together north of the Faroes platform, interpreted as a volcanic shear

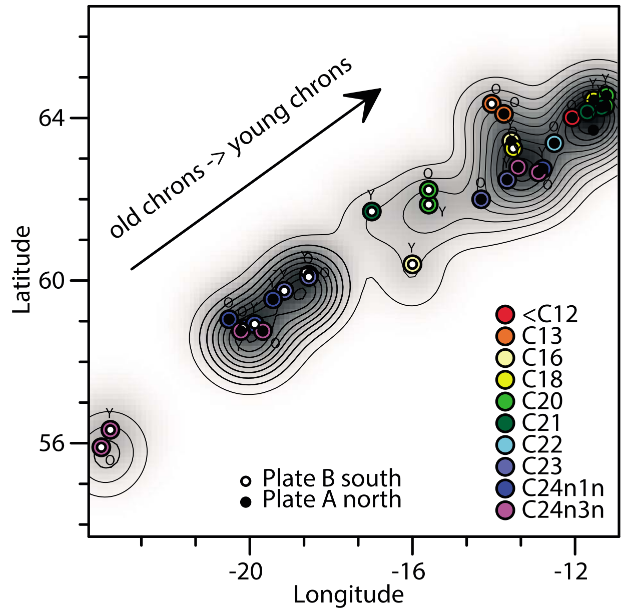

Figure 7. Classification and Kernel density distribution of the Norway Basin Euler poles of rotation deduced from the new magnetic picks. Symbol letters Y and O indicate, respectively, the young and old edges of the chrons selected to calculate the rotation poles. Also, note the broad distribution of the Euler poles showing at least two dominant groups fitting with the pre-C21 and post-C21 evolution of the spreading system between the Mid Norwegian margin and the JMMC.

margin south of the Norway Basin (Figures 5 and 8). The youngest edge of magnetic chron C24n3n is usually subparallel with the outer edge of the SDRs recognized on seismic data on both sides of the Norway Basin [e.g., *Guðlaugsson et al.*, 1988; *Gunnarsson et al.*, 1989; *Berndt et al.*, 2001a, 2001b] (see Figures 3 and 5). On the eastern side of the Norway Basin, *Mosar et al.* [2002] and *Skogseid et al.* [2000] have earlier proposed the existence of older magnetic chrons landward of the C24B and C24A in previous interpretations. In this area, the magnetic signature is mostly influenced and explained by the signature of the landward and tilted inner SDRs signature and associated sheeted dike swarm. Therefore, we cannot corroborate the existence of such older oceanic chrons or hypothetic ridge jump at that level. The new aeromagnetic compilation also does not clearly support the double C24B/C24A (e.g., C24n3n/C24n1n) anomalies and ridge jump earlier suggested by *Skogseid and Eldholm* [1987] along the northeastern flank of the JMMC (Figure 8).

The continent-ocean transition of the conjugate volcanic margins that developed on both sides of the Norway Basin may represent thinned and progressively intruded continental/transitional crust. Based on refraction data available in the MVRM, the true nature of the intervening transitional crust is still unclear and open to interpretation [e.g., *Breivik et al.*, 2012; *Mjelde et al.*, 2009; *Gernigon et al.*, 2012a]. Significant dike swarms and mafic intrusions are likely in the vicinity of the SDRs as observed onshore West and Southeast Greenland, where volcanic margins are locally exposed onshore [*Karson and Brooks*, 1999; *Geoffroy*, 2005]. The continent-ocean transition underneath the basalt could represent an alternation of microcontinental fragments interbedded with embryonic oceanic crust, overlaid by volcanic traps, as proposed, for example, in the Afar region [*Courtillot et al.*, 1980]. It could also represent intruded and flowing ductile crust as suggested in NE Greenland [*Quirk et al.*, 2014].

Refraction profile [*White et al.*, 2008] and long offset, seismic reflection data across the northern Faroe volcanic shear margin [*Dinkelman and Keane*, 2010] show a sharp necking zone with a shallowing of the Moho depth from 30 km underneath the SDRs to 15 km west of the interpreted C24n1n magnetic chron. Ocean Bottom Seismometer modeling along the East JMMC [*Breivik et al.*, 2012] shows that the necking zone of the volcanic margin is also abrupt between the continental and the oceanic domain (<50 km width). In the distal part of the MVRM, the SDRs are underlain by what has been interpreted as thick underplating in the outer part of the Møre Marginal High [*Breivik et al.*, 2012; *Mjelde et al.*, 2009]. A high-velocity, lower crustal body layer with high *Vp* values (>7 km/s, 3–4 km thick) is also observed at the level of the first spreading magnetic anomalies C24n3n and C24n1n (C24B and C24A) constrained by the

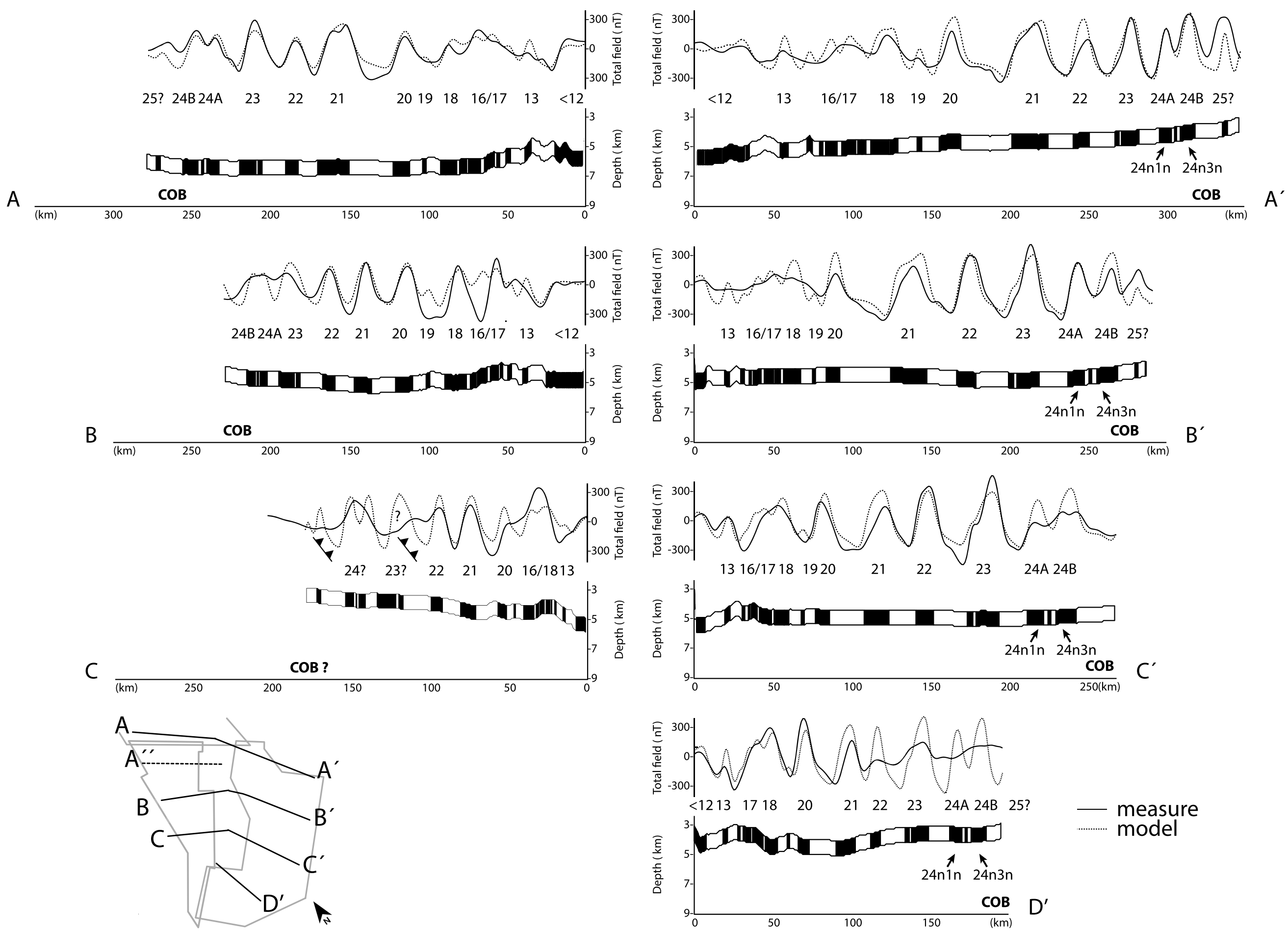

Figure 8. Selected magnetic profiles across the Norway Basin. The interpretation of the magnetic chrons has been correlated with synthetic profiles calculated using the forward modeling method of fictitious spreading rate and assuming a constant spreading direction (see text for more information).

new JAS-12 survey, east of the JMMC. This lower crustal body is compatible in size and lateral distribution with the small SDRs that have developed on the eastern flank of the ridge [*Planke and Alvestad*, 1999] and most likely represents breakup-related lower crustal intrusions similar to those interpreted and imaged along the conjugate volcanic margin segments [e.g., *Breivik et al.*, 2012; *White et al.*, 2008].

4.2. Early Seafloor Spreading of the Norway Basin (Phase 1)

Based on the NB-07 and JAS-12 surveys, the early seafloor spreading in the Norway Basin is now well defined along both sides of the Aegir Ridge and particularly between magnetic polarity chrons C24n3n and C22n (Figures 5 and 8). Even if large uncertainties remain about the pre-C24B magnetic chron picking, we have recorded locally low spreading rates during the proto-breakup stage (<5–10 mm/yr), increasing rapidly to more than 15–25 mm/yr between magnetic polarity chrons C24n3n (C24B) and C24n1n (C24A) (Figures 8 and 10). This might suggest slow spreading rates during the proto-stage of breakup (Figure 10) if we consider that the prominent but embryonic magnetic anomalies chrons locally observed landward of C24n3n are possibly C25 in age (Figure 8). After C24n1n (Phase 1), half-spreading rates of the earliest spreading are on average less than 25 ± 2 mm/yr in the eastern Norway Basin, and less than 20 ± 2 mm/yr in its western part (Figure 10). The previous NB-07 survey had already revealed the presence of off-axis features that are magnetized with reverse polarity between magnetic polarity chrons C24n3n and C22n, which were earlier interpreted as off-axis seamounts and/or some relics of aborted rift axes [see *Gernigon et al.*, 2012a]. Similar off-axis anomalies have not been recognized in the new conjugate JAS-12 survey and hence support the interpretation of local aborted and unstable rift axes that shaped the eastern side of the Norway Basin during the Early to Late Ypresian (56–47.8 Ma).

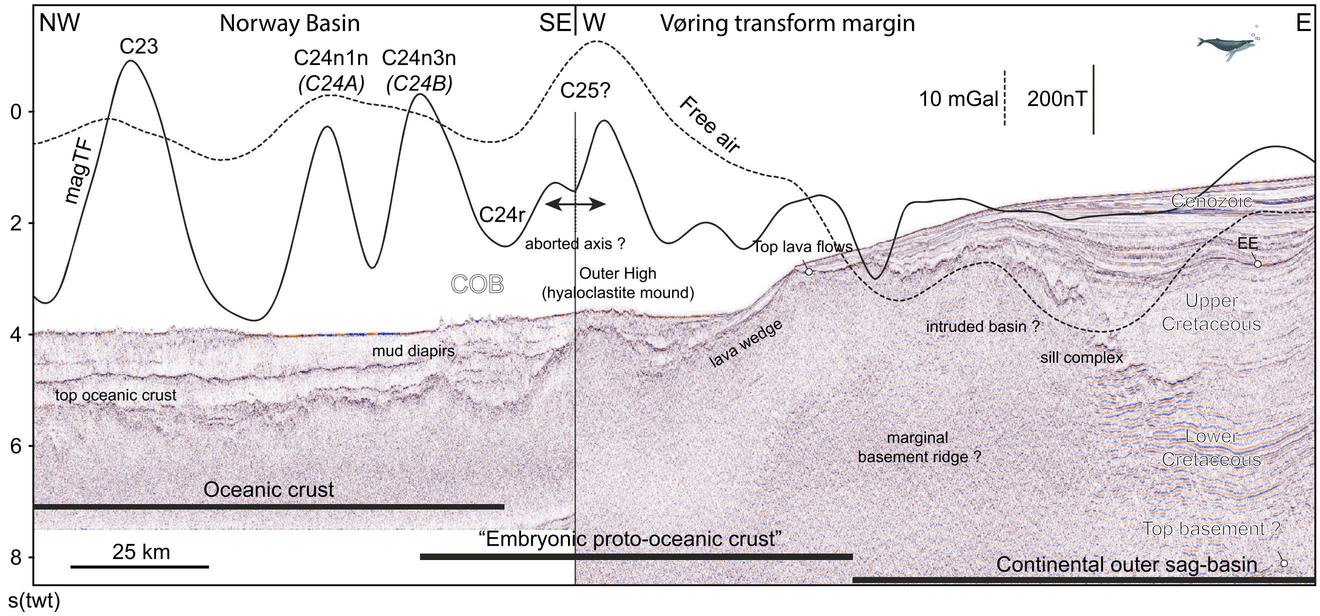

Figure 9. Seismic, gravity, and magnetic profiles across the continent-ocean transition along the Vøring transform margin, west of the Jan Mayen corridor. EE: Early Eocene horizon. Section A location is shown in Figure 1.

The new aeromagnetic data also show that the northern and central parts of the Norway Basin are divided by a small offset fracture zone (Figures 3 and 5), which appears quite different from the straight and classic signature of a "normal" fracture zone (e.g., the Jan Mayen Fracture Zone). A large band of disturbed magnetic anomalies situated west of the East Jan Mayen Fracture Zone coincides with the location of the "Norway Basin Fracture Zone" earlier introduced by *Skogseid and Eldholm* [1987] but not properly identified due to the lack of high-resolution data. Based on sparse vintage magnetic data, *Skogseid and Eldholm* [1987] interpreted the Norway Basin Fracture Zone as an ocean transform subparallel to the East Jan Mayen Fracture. The NB-07 and JAS-12 surveys prove well the presence of a major oceanic and magnetic discontinuity here but with a slightly different magnetic signature and not so linear compared to the adjacent East and West Jan Mayen Fracture Zones (Figures 3 and 5). On both sides of the Norway Basin, this discontinuity initiated around C24n3n (C24B) and shows a complex magnetic pattern characterized by discrete, noncontinuous, and oblique, magnetic lows and highs. This discontinuity defines a diffuse transition zone between two different spreading segments interpreted as distinct oceanic domains in this paper (Figure 5). The "Norway Basin Fracture Zone" is a composite feature and defines wavy to low-angle V-shaped features pointing in the direction of competing (and alternating) propagating oceanic systems interpreted in the present study (Figure 6). Similar discontinuities with low-angle V-shaped features are relatively similar to oblique structures and low-offset fracture zones also described between first-order and large-offset oceanic fractures zones in the Central Atlantic [*Muller and Roest*, 1992] and in the Gulf of Aden [*d'Acremont et al.*, 2006]. Such a pattern observed in the Norway Basin may be an indication of a relatively unstable small-offset fracture zone migrating (or oscillating) in the past along the paleo-Aegir Ridge.

4.3. Growing Fan-Shaped Structure of the Norway Basin Post Magnetic Polarity Chron C21r (Phase 2)

The new magnetic data indicate that a change in mapped fault systems occurred when spreading rates decreased after chron C21r (48.5–47.3 Ma), just before the transition from a slow to an ultraslow spreading regime (Figure 10). During this Phase 2, the spreading system started to develop obliquely (Figure 5). This coincided with the formation of nascent N-S fractures zone that accommodated a NW-SE to NNW-SSE reorientation of the spreading direction (see Figures 3 and 5). Chrons younger than C21r display larger offsets. The lateral shifts of the magnetic chrons C21n and C20n by 10 to 50 km amplify from south to north and coincide with the spreading rates development also increasing from south to north (Figure 5). In the northern part of the surveyed area, the so-called "Central Fracture Zone" [*Gernigon et al.*, 2012a] interacts with the Norway Basin Fracture Zone to produce a complex and chaotic magnetic pattern that is explained by

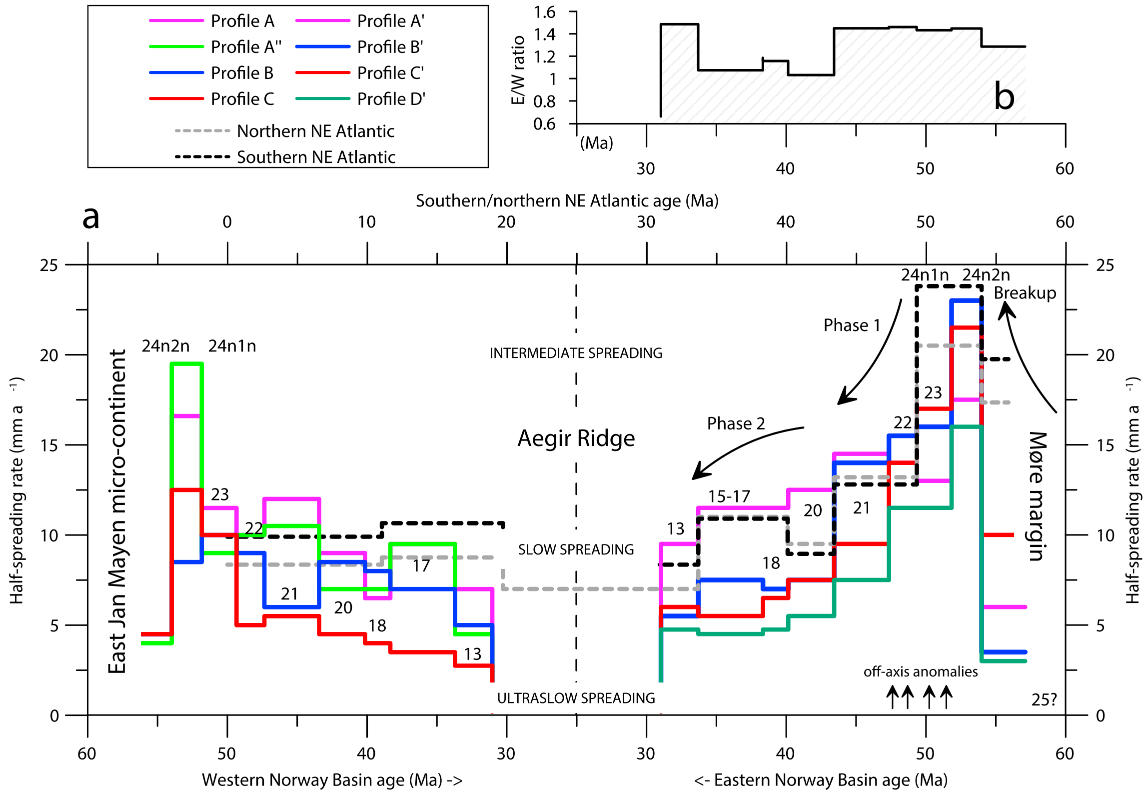

Figure 10. (a) Diagram showing the variation with time of the half-spreading rates on both sides of the Aegir Ridge (see profile location and synthetic models located in Figure 8). Boundaries between intermediate (>30 mm yr^{-1}), slow (30–10 mm yr^{-1}) and ultraslow (<10 mm yr^{-1}) half-spreading rates are indicated. Average spreading rates for the adjacent northern and southern NE Atlantic oceanic domain (grey and black dashed lines) from *Gaina et al.* [2009] have been plotted for comparison. (b) Plot of the spreading rates ratio between the eastern and western parts of the Norway Basin. The diagram illustrates the general asymmetry of the Norway Basin with faster rates observed in the eastern side of the spreading system.

significant dislocations of the oceanic basement, causing difficulties to properly identify the magnetic chrons younger than C18 (Figure 3). The Central Fracture Zone revealed by the new magnetic data set coincides with a similar trend observed in the free air gravity field (Figure 4) and interpreted as V-shaped lineations related to a deeper lateral flow of the Iceland "plume" [*Breivik et al.*, 2006]. The new aeromagnetic data simply suggest that the Central Fracture Zone is the result of a lateral offset of the spreading anomalies. Fracturing and mantle serpentinization at the level of fracture zones are common [*Cannat et al.*, 1991] and may potentially explain the density contrast highlighted by the N-S gravity trends observed along these fracture zones.

Changes in spreading direction have previously been documented [*Nunns*, 1983; *Jung and Vogt*, 1997] in the southernmost part of the Aegir Ridge that is located parallel to the hogback Treitel Ridge [*Vogt and Jung*, 2009], which is believed to have formed due to transpressional stresses across the speculative Iceland Faroes Fracture Zone (Figure 1). This change in direction also took place from a NW-SE trend to a NNW-SSE trend of relative motion between the JMMC and the Norwegian/Eurasian plate but was active after chron C18. Our results suggest that chron C21r already marked a clearer and most important plate reorganization of the Norway Basin, 7–8 My before chron C18. After chron C21r, and together with the initiation of a N-S fracture zone, we observe a fast-growing fan-shaped spreading system (Figure 5). Compared to the first phase of spreading development, a tighter clustered distribution of the finite rotation poles has also been observed for time younger than C21r (Figure 7).

5. Conjugate Volcanic Rifted Margins: Prebreakup Crustal Configuration and Kinematic Considerations

5.1. Crustal Structure of the Møre Volcanic Rifted Margin

Based on the new rotations presented in previous chapters, the MVRM and the JMMC can be reconstructed to their positions at breakup and early seafloor spreading stages (Figures 11 and 12). Figure 13 illustrates the

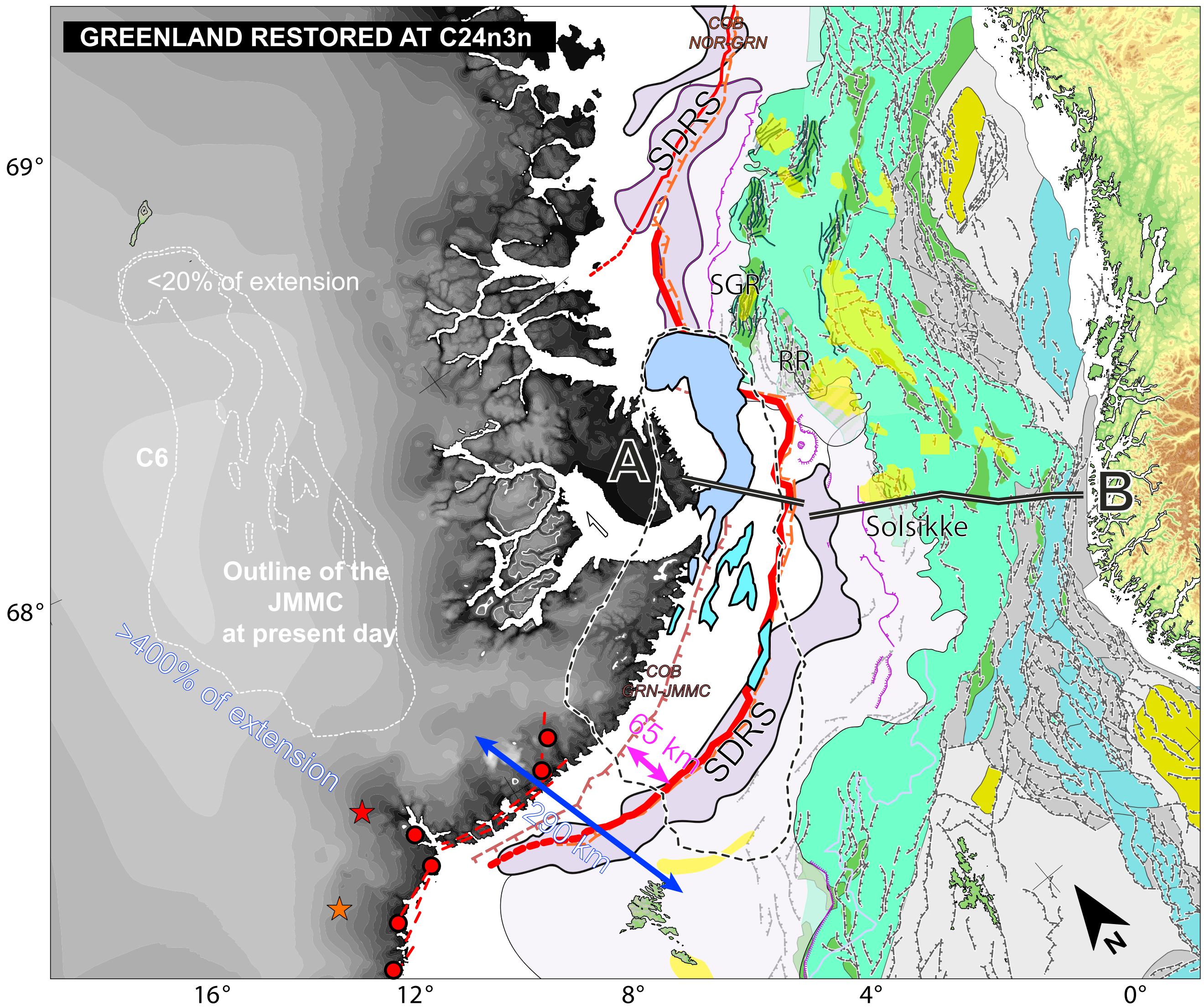

Figure 11. Reconstruction for magnetic chron C24n3n time showing tectonic features discussed in this study. The main physiographic elements (undeformed) and the outline of the Jan Mayen microcontinent, as defined by the oldest magnetic anomalies recognized at present day, were restored slightly after the first phase of breakup between the Norwegian and Greenland plates. A significant overlap exists between the present-day outline of the JMMC and the original space allocated and available between Greenland and the Møre volcanic rifted margin at magnetic chron C24n3n (~54 Ma). This overlap is mainly explained by the Cenozoic and significant postbreakup (continental and oceanic) extension expected south of the JMMC before chron C6b. Location of the coast-parallel dike complexes (61–47 Ma, red dashed lines) and main intrusions onshore Greenland (red circles) from *Klausen and Larsen* [2002], *Tegner et al.* [2008], and *Larsen et al.* [2013].

present-day crustal configuration of MVRM and JMMC with oceanic crust removed at magnetic chron C24n3n. The thin crust of the MVRM shows a substantial crustal thinning ($\beta_{crustal} > 2.5$) under the large regional sag Cretaceous basin defined west of the crustal necking zone (Figures 13b and 14). The presence of deep lower crustal bodies with *Vp* values of 7.2–7.3 km/s observed in the outer part of the MVRM [e.g., *Kvarven et al.*, 2014] could have been compatible with layers of heavily serpentinized mantle as observed at continental-ocean transitions of several magma-poor margins (see velocity review by *Minshull* [2009]). However, seismic data interpretation and potential field modeling suggest that the size of the blocks and the thickness of the continental blocks/raft expected and preserved beneath the Cretaceous Basin (Figure 13a) are larger and thicker compared to the allochthonous blocks often described in hyperextended domains where underlying exhumed and denuded mantle are shown to exist (see Iberian margin at similar scale after *Sutra et al.* [2013] (Figure 13b). The continental crust preserved on top of the outer lower crustal bodies in the outer part of the MVRM remains relatively thick (>5–8 km) to favor a broad zone of exhumed and denudated serpentinized mantle adjacent to the oceanic domain. *Vp*

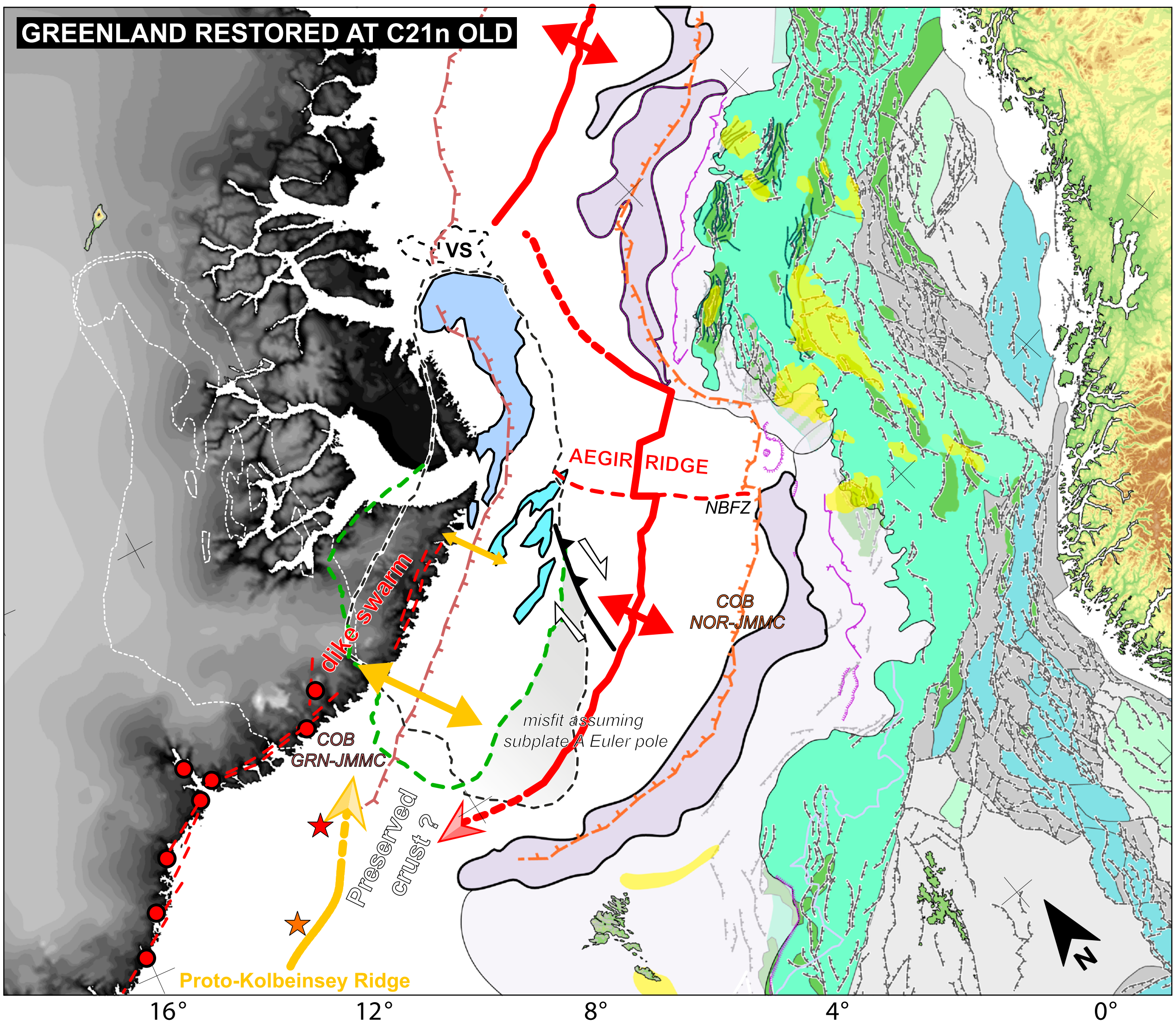

Figure 12. Reconstruction at C21n time (old edge ~47.9 Ma) showing tectonic features and continental fragments involved in this study. This Mid-Late Eocene event coincides with an important phase of reorganization in the Norway Basin. Chron C21n marks the onset of serious extension into the southern JMMC in order to counterbalance the subsequent growth and fan-shaped development of the Norway Basin spreading system. This period should coincide with the onset of extension between East Greenland and the proto-JMMC in front of the propagating Reykjanes Ridge located to the south. The main physiographic elements of the JMMC (undeformed) have been restored at that stage based on the two sets of rotation poles defined between the JMMC and the Norwegian plate (fix).

velocities of 7.2–7.3 km/s, as modeled by *Kvarven et al*. [2014] for the underlying lower crustal bodies, would require an increased process of serpentinization that usually is symptomatic of more drastic crustal thinning ($ß_{crustal} \gg 4$) and/or complete mantle denudation [e.g., *Hopper et al*., 2007; *Sutra et al*., 2013; *Nirrengarten et al*., 2014]. Such a crustal configuration is not so obvious in the outer part of the MVRM (Figure 13). To explain the magnetic anomalies observed in the central part of the MVRM (Figures 3 and 13), our potential field modeling also suggests the preservation of a middle level of continental crust, with high magnetic susceptibilities (0.06 SI), associated with the continental crustal rafts observed on seismic data (Figure 13a). We favor a tectonic scenario, increased where a large part of the crust observed underneath the Cretaceous sedimentary basin could represent both preserved upper continental basement and middle to lower crustal lenses of inherited and intruded, high-grade metamorphic rocks. We rather interpret the nature of the crust closer to the SDRs as a similar mixture of residual continental crust later affected by breakup-related intrusions. No zone of exhumed and serpentinized continental mantle has been clearly identified continentward of magnetic chron C24n3n.

10.1002/2014TC003717

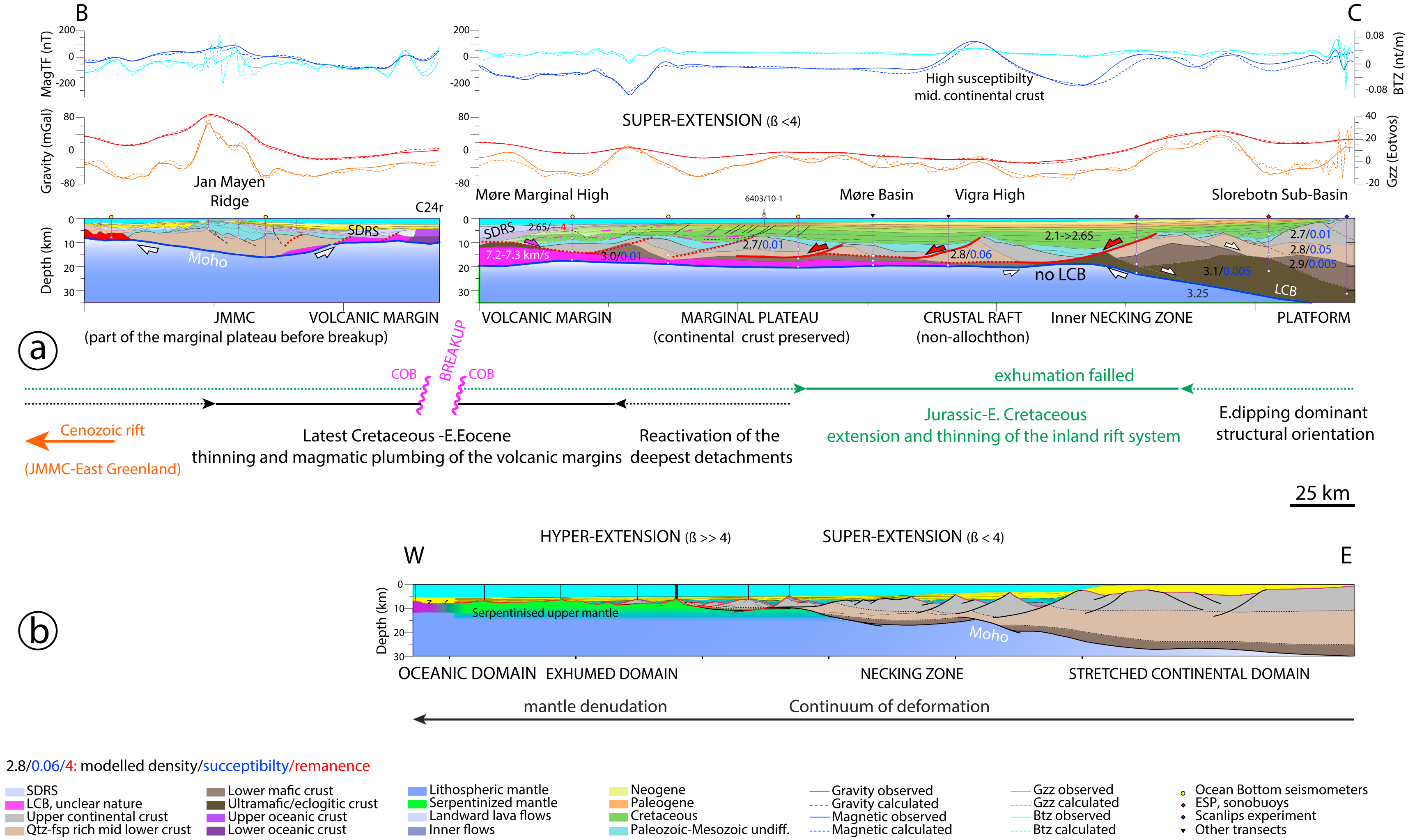

Figure 13. (a) Conjugate volcanic rifted sections between the MVRM and the JMMC (sections B and C located in Figure 1). (b) Comparison (same 1 × 1 scale) with the Iberian archetype proposed for hyperextended and magma-poor margins (section after *Sutra et al.* [2013]). Seismic refraction/reflection observations and potential field modeling have been used to constrain the main crustal geometries and tectonomagmatic domains, offshore Norway. Refraction studies refer to *Vially and de Clarens* [1986], *Planke et al.* [1991], *Olafsson et al.* [1992], *Mjelde et al.* [2009], and *Breivik et al.* [2012].

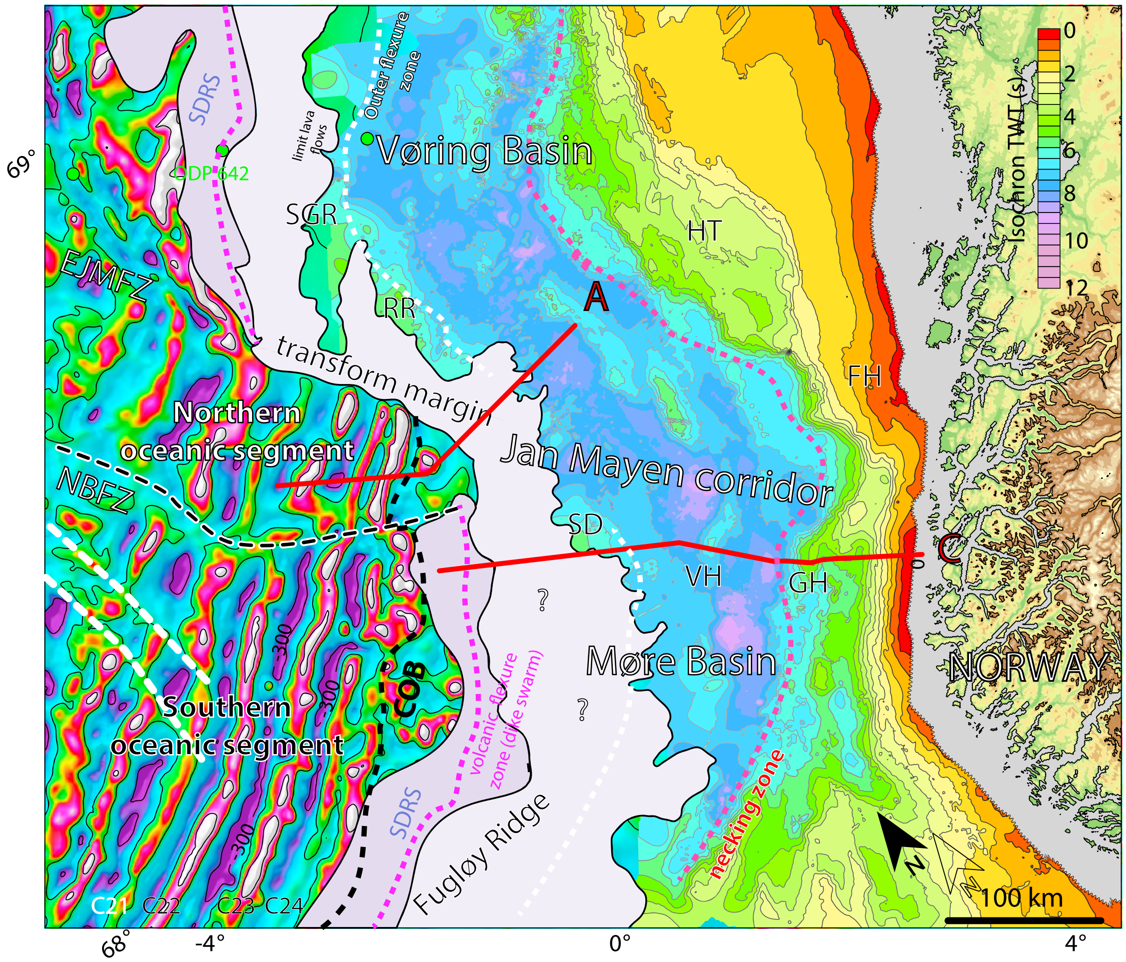

Figure 14. Structural configuration of the pre-Cretaceous sag (base Cretaceous unconformity complex in two-way time) around the Jan Mayen corridor and relationships with the distribution of volcanism and the subsequent oceanic segmentation (see main text for details and discussion). FH: Frøya High; GH: Gossa High; HT: Halten Terrace; RR: Rån Ridge; SGR: South Gjallar Ridge; SD: Solsikke Dome; VH: Vigra High. A and C represent the sections described in Figures 8 and 13, respectively. Outline of the SDRs after *Berndt et al*. [2001b].

5.2. Space Problem, Overlaps, and Jan Mayen "Microcontinent" Deformation

The plate reconstruction at chron C24n3n time (Figure 11) shows the location of the proto-JMMC near breakup time and suggests that the proto-JMMC could have represented the missing part(s) of a continental marginal plateau (as defined by *Lister et al*. [1986]) inferred to have existed between Greenland and the MVRM (Figure 13a). The northern part of the JMMC was originally located west of the MVRM in the southern prolongation of the South Gjallar-Rån ridges (pre-Cenozoic and pre-Cretaceous highs) located in the vicinity of the Vøring transform margin (Figure 14). In the outer Vøring Basin, this ridge system has been earlier interpreted as crustal mullions [*Gernigon et al*., 2003]. Assuming the predrift configuration, continental crust including Paleozoic? to Mesozoic sediments could be preserved underneath the lava flows in the northern JMMC and outer MVRM. The southernmost segments of the JMMC's Southern Ridge Complex (Figure 1) were also located closer to the Møre Marginal High (Figure 10) and may possibly include parts of the proto-oceanic crust and volcanic traps emplaced during the Early Eocene epoch.

Our potential field modeling (Figure 13a) supports the presence of a relatively thick continental fragment (15 km) in the central JMMC, in agreement with previous interpretations and seismic refraction results [*Guðlaugsson et al*., 1988; *Gunnarsson et al*., 1989; *Mjelde et al*., 2007; *Breivik et al*., 2012]. Our refined prebreakup plate reconstruction suggests that the central and northern parts of the proto-JMMC could have been accommodated in the remaining space available between the Norwegian and Greenland continental plates (Figure 11). However, the southern part of the JMMC, as observed at the present day, could not fit in the space available between Norway/Eurasia and Greenland already at the time of chron C24n3n (Figure 11). Whatever the nature of the crust in the southern JMMC is? (continental, oceanic?), the plate overlapping suggests that younger and significant deformation and/or igneous overprinting most likely affected the JMMC during the Cenozoic and after the first phase of breakup in the Norwegian-Greenland Sea [e.g., *Gaina et al*., 2009; *Gernigon et al*., 2012a]. Such a deformation could have begun at any time between chron C24n3n time and the second breakup phase between East Greenland and the JMMC at around chron C6b time [*Vogt*, 1986]. If we compare the present-day outline and size of the JMMC with the space between East Greenland and the MVRM when restored at chron C24n3n (~54–53 Ma) (Figure 11), we infer that more than 400% of postbreakup extension must have occurred in the southernmost part of the JMMC. On the other hand, only 20–30% of extension is proposed for the northern parts of the JMMC. This also means that the subplates defined at the locations of the north JMMC (A) and South Jan Mayen Ridge Complex (B) (Figure 6) were not entirely rigid during the spreading of the Norway Basin but also experienced an internal deformation that increased from north to south during the spreading of the Norway Basin.

Cenozoic volcanic flows and sills affect a large part of the JMMC [*Guðlaugsson et al*., 1988; *Gunnarsson et al*., 1989; *Blischke et al*., 2011] and have contributed to the complex magnetic signal as observed at the present day. Combined with the poor magnetic coverage of the JMMC, it remains difficult to clearly identify the nature of the crust between the Aegir and Kolbeinsey Ridges. The existence of an intermediate and extinct oceanic ridge has earlier been proposed for the western part of the Jan Mayen Basin [*Talwani and Eldholm*, 1977; *Grønlie et al*., 1978; *Unternehr*, 1982], but its suggested presence was later dismissed by *Vogt et al*. [1980] who favored a continuous spreading evolution after (and mostly east of) chron C6b. Taking into consideration the proto-JMMC space issue (Figure 11), we, however, consider that a complex microplate system involving both continental and isolated oceanic fragments could have likely developed in the southern part of the JMMC before its ultimate breakup with the East Greenland margin at magnetic chron C6b [e.g., *Gaina et al*., 2009; *Blischke et al*., 2011]. Even though direct dating in the southern part of the JMMC is required to validate the proper timing issue, the spreading scenario suggests that the period of growing fan-shaped development of the Norway Basin post chron C21r (Phase 2) should have been accommodated with a counterbalanced extension in the southern part of the proto-JMMC (and reciprocally) before the second breakup stage. This phase 2 (Figure 12) may also coincide with a coeval onset of compression/transpression observed along the eastern flank of the JMMC [*Gunnarsson et al*., 1989; *Gaina et al*., 2009; *Blischke et al*., 2011] and possibly extending into the oceanic domain (Figures 5 and 12). Local transpression on the eastern flank of the Southern Ridge Complex may be required to accommodate the nonuniform deformation of the contemporaneous and counterbalanced extensive system expected in the Norway Basin and in the southern part of the proto-JMMC. This could explain the complexity and unclear nature of magnetic patterns observed at that location (Figures 3 and 8).

6. Discussion and Tectonic Implications

6.1. Prebreakup Setting: Aborted SuperExtension Phase and Formation of Volcanic Margins

The nature of the crust and the nature of deformation involved before the breakup and during spreading in the Norway Basin are still debatable. Large uncertainties remain about the thickness and nature of the crust beneath the Møre sedimentary basin and the mode of deformation involved in the outer parts of the MVRM before the opening of the Norway Basin. Based on ambiguous analogies with the continent-ocean transition zone recognized on magma-poor systems [e.g., *Boillot et al*., 1989; *Reston*, 2009; *Sibuet and Tucholke*, 2012], recent scenarios have suggested that the breakup of the MVRM and subsequent opening of the Norway Basin may have been preceded by a phase of mantle exhumation and denudation in the outer part of the MVRM [*Péron-Pinvidic et al*., 2013] thus fitting the stretching/thinning/exhumation/breakup evolutionary sequence proposed for magma-poor margins [*Sutra et al*., 2013; *Mohn et al*., 2012; *Tugend et al*., 2014; *Lavier and Manatschal*, 2006]. The validity of a zone of exhumed continental mantle, east of the Norway Basin, could not be confirmed in our study. Even if more investigation is required to solve this issue, our potential field model and recent OBS modeling [*Kvarven et al*., 2014] suggest that a reasonable amount of continental crust is preserved in the outer part of the MVRM (Figure 13). In terms of timing, the breakup is Early Tertiary in age and does not necessarily represent the ultimate stage of a continuous and severe crustal and lithospheric deformation (thinning phase) that initiated more than 90 Myr ago in Late Jurassic time in the MVRM. We consider that it is difficult to explain a continuous thinning phase for more than 30–50 Myr without any strain hardening and/or breakup in between [e.g., *Yamasaki and Stephenson*, 2009]. Even if a thin crust does exist in the inner part of the Møre Basin (Figure 14a), a large part of the outer Møre Basin shows moderate to "super" crustal extension ($ß_{crustal} < 3.5$). A large part of the Møre Basin also represents an "aborted" rifted system which is dominantly the consequence of an independent and early thinning lithospheric event [e.g., *Olafsson et al.*, 1992]. This severe thinning episode (including a tectonic sagging phase) grew in Late Jurassic and probably slowed down around Mid Cretaceous time (Albo-Aptian?), even if no consensus on how far into Cretaceous time the extension continued [e.g., *Lundin and Doré*, 1997; *Brekke*, 2000; *Faerseth and Lien*, 2002; *Gernigon et al.*, 2003; *Tsikalas et al.*, 2012].

We interpret the outer part of the MVRM as the remnant of a continental marginal plateau (as defined by *Lister et al.* [1986]) and preserved terraces lying in the northern prolongation of the Fugløy Ridge, which even show thicker continental crust preserved [*White et al.*, 2008] (Figures 1 and 14). Massive volcanism and typical SDRs [*Planke et al.*, 2000] recorded along the proto-breakup axis are also a major difference compared to the "Iberian-type" magma-poor system, where such significant volcanic wedges are not observed [*Brönner et al.*, 2011; *Sibuet and Tucholke*, 2012]. Although we have evidence for a renewed phase of extension and normal faulting during the latest Cretaceous and Paleocene, the main magmatotectonic event (climax) leading to the formation of the distal volcanic margin and subsequent spreading of the Norway Basin occurred during the Paleocene-Early Eocene period (Figure 13a). This late episode may have involved independent and decoupled magmatotectonic processes including rift localization and massive crustal dilatation by diking and lithospheric plumbing [e.g., *Nicolas et al.*, 1994; *Callot et al.*, 2001; *Ebinger and Casey*, 2001; *Geoffroy*, 2005; *Buck*, 2006].

6.2. Spreading Segmentation and Inheritance

It has been suggested that oceanic transform faults and oceanic segmentation are inherited from the continental plate breakup [*Lister et al.*, 1986; *Behn and Lin*, 2000]. Even if there is a general agreement that inheritance has an important control on the evolution of rift systems in continental domains, a direct implication of the inheritance within contiguous oceanic domains is not clear [*Taylor et al.*, 2009; *Bellahsen et al.*, 2013]. Some authors point out that oceanic transform faults develop in newly formed lithosphere and cannot extend into the continents [e.g., *Taylor et al.*, 2009; *Gerya*, 2012]. Our observations confirm that some oceanic transforms in the Norway Basin simply and clearly developed after breakup, especially after C21r, when the spreading direction locally changed from NW-SE to NNW-SSE (Phase 2). However, the regional-scale Jan Mayen Fracture Zone and low-offset fracture zones, such as the Norway Basin Fracture Zone (or pseudo fault), can be traced up to C24r and seem to have initiated with the onset of breakup at C24 time (Figure 5). Even if we cannot see direct evidence of a contiguous and orthogonal set of normal and transfer faults, the main segmentation of the Norway Basin suggests that the breakup volcanism and the subsequent spreading of the Norway Basin, between the Jan Mayen Fracture Zone and the Norway Basin Fracture Zone, reflect the earlier continental rift geometry of the MVRM (Figure 14). The oceanic segment defined between the Jan Mayen Fracture Zone and the Norway Basin Fracture Zone formed in the prolongation of the Jan Mayen corridor lying in the prolongation of the Vøring transform margin (Figures 5 and 14). The Jan Mayen corridor is thought to represent a large crustal and basin-scale accommodation and transfer zone between the Møre and Vøring margins already reflected by the structural style of the pre-Cretaceous and Early Cretaceous rift system (Figure 14). On the continental domain, the Jan Mayen corridor is defined from the C24r magnetic anomaly up to the Gossa and Frøya highs eastward (Figure 14) and coincides with distinct magnetic (Figure 3) and low-gravity signatures (Figure 4). *Torske and Prestvik* [1991] had earlier mentioned the atypical character of this corridor, which may indicate a deeper subcrustal weak zone that could have provided easy pathways in the lithosphere for melts or volatiles. *Maystrenko and Scheck-Wenderoth* [2009] also pointed out distinctive crustal and upper mantle features at the level of the Jan Mayen corridor.

During the late rifting stage and the onset of breakup, the location of the Jan Mayen corridor seems to coincide with the location of the paleo-Vøring transform margin, clearly linked with the prominent and very large offset Jan Mayen Fracture Zone (Figure 3). One of the popular conceptual models of ridge-transform pattern formation suggests that passive margins are characterized by a contiguous orthogonal set of normal and transfer faults [*Lister et al.*, 1986]. Only a few NW-SE faults have been observed in the prolongation of the Jan

Mayen and Norway Basin fractures zones to support an idea of contiguous and orthogonal transfer faults at the origin of the oceanic fracture zone. However, recent studies in different settings show that even oblique transfer systems can reactivate during the onset of breakup and favor the nucleation of the fracture zones as direct transform [*Bellahsen et al.*, 2013] or nontransform offsets leading subsequently to real transform fault [*Taylor et al.*, 2009; *Gerya*, 2012].

The peculiar character of the Jan Mayen corridor (strictly defined in the continental domain) is also reflected in the magmatic nature of the continent-ocean transition that developed in the outer part of this peculiar and oblique continental domain. Prebreakup and synbreakup magmatism and volcanism are limited in this zone, interpreted as a distinct volcanic segment, where SDRs and the thick volcanic lava plateaus are either lacking or limited [*Berndt et al.*, 2001a, 2001b] (Figures 9 and 14). Later development of the fracture zones in the Norway Basin have been controlled by far-field forces, magmatic processes, spreading rates, and oceanic crust rheology that maintain a decoupled “inprint”, inherited from the breakup stage.

6.3. Early Spreading Asymmetry of the Norway Basin

An interesting observation is the complete asymmetry of the Norway Basin spreading system that is highlighted by the new aeromagnetic coverage (Figure 10). Spreading asymmetries observed in the Norway Basin are not restricted to this oceanic domain but are pervasive northward even into the Eurasian Basin [*Vogt et al.*, 1982; *Muller et al.*, 2008] Independent spreading investigations of the North Atlantic previously showed that ~65% of the initial lateral accretion locally developed closer to the Greenland plate and could have been the result of a ridge/plume interaction [*Müller et al.*, 1998] or the consequence of inherited colder lithosphere [*Hopper et al.*, 2003]. Our new aeromagnetic compilation shows that the Norway Basin rather developed faster spreading rates toward the Norwegian/Eurasian plate (Figure 10b). The eastern part of the Norway Basin shows spreading rates higher than 10–50% compared to its western conjugate (Figure 10). The asymmetry is particularly important from C24 to C20 time (Figure 10b). Repeated ridge jumps proposed in this study could explain the oceanic crust asymmetry observed along the eastern side of the Aegir Ridge (Figure 10). Similar Eocene ridge jumps have been proposed farther south along the Greenland-Iceland Ridge [*Larsen and Jakobsdóttir*, 1988; *Smallwood and White*, 2002] and may also have occurred south of the Iceland-Faroe Ridge [*Erlendsson and Blischke*, 2013]. Such instabilities could explain some of the off-axis magnetic anomalies observed along the eastern and faster side of the Norway Basin spreading system [*Gernigon et al.*, 2012a]. Even if more refraction data should be acquired, this asymmetry of the Norway Basin also appears to fit the asymmetric thickness of the early oceanic crust. The distribution of the high-velocity gabbroic oceanic crust [*Breivik et al.*, 2006, 2012] looks thicker along the eastern side of the Norway Basin, which was characterized by higher spreading rates.

Few models of ridge jumps controlled by hot spot activity have been suggested earlier [*Müller et al.*, 2001; *Mittelstaedt et al.*, 2011]. *Mittelstaedt et al.* [2011] showed that larger plume excess temperatures could inhibit ridge jumps by weakening the ridge axis. In Mittelstaedt et al.’s model, ridge jumps are rather promoted by an increasing melt supply off axis. Due to the proximity of the Icelandic “hot spot”, a similar ridge jump scenario is favored for the Norway Basin preferentially, and would occur in response to magma migration along the base of an evolving lithosphere. Alternatively, other models could explain the asymmetric accretion of the Norway Basin. It could have involved a progressive migration of the ridge axis over the asthenosphere, leading to the skewing of the thermal field and shear traction at the base of the conjugate plates [*Barker and Hill*, 1980; *Stein et al.*, 1977; *Hayes*, 1976]. Assuming such a thermal model, faster accretion is predicted on the cooler plate [*Hayes*, 1976; *Barker and Hill*, 1980]. *Hopper et al.* [2003] suggested, for example, that inherited cold lithosphere may explain the asymmetry of the early spreading activity between the Greenland margin and the Hatton margin, farther south. In this model, the Greenland plate, being bounded by thick Archaean lithosphere would have developed faster spreading rates compared to the rifted Eurasian plate, which was plate bounded by younger and presumably warmer lithosphere. The new magnetic data presented here suggest an opposite situation in the Norway Basin. The Norway Basin rather developed clearly with more accretion toward the Norwegian/Eurasian plate, where the lithosphere was affected by important prebreakup thinning as previously discussed. This means that the model proposed by *Hopper et al.* [2003] for Southeast Greenland cannot necessarily be applied to the Norway Basin configuration.

6.4. Jan Mayen "Microcontinent" Formation: Nature, Timing, and Cenozoic Rift Development

When dealing with the opening of the Norway Basin, there are few published studies [e.g., *Talwani and Eldholm*, 1977; *Nunns*, 1983; *Unternehr*, 1982; *Jung and Vogt*, 1997; *Skogseid et al*., 2000; *Gaina et al*., 2009; *Greiner and Neugebauer*, 2013] that clearly document the required magnetic anomaly identification. These previous contributions have all suggested a compensating rifting and/or spreading episode(s) between East Greenland and the south Aegir Ridge. However, a closer look at these early publications shows that there was no general consensus about the timing of the fan-shaped development of the spreading. *Talwani and Eldholm* [1977] inferred that the fan-shaped development of the Norway Basin could have initiated between C20 and C7 while *Unternehr* [1982] proposed that it rather formed between anomalies C13n and C5D (17.5–17.2 Ma) during the rotation of the JMMC. *Vogt* [1986] argued that an additional oceanic spreading system was required to compensate for the fan-shaped spreading. He proposed that it could have been initiated by the northward propagating spreading along the growing Kolbeinsey Ridge between C18 (40.1–38.6 Ma) and C6b (22.2–21.7 Ma) time. *Nunns* [1983] suggested that C20 could have marked the onset of the JMMC dislocation to the west, but *Müller et al*. [2001] concluded that chron C13n was a better candidate [e.g., *Lundin and Doré*, 2002]. Our new and complete mapping of the Norway Basin confirms and validates the existence of a fan-shaped geometry for the Norway Basin. The new data do not support the orthogonal or en echelon offset spreading ridge scenario alternatively proposed by *Scott et al*. [2005]. In the model of *Scott et al*. [2005], the structure of the Norway Basin was interpreted to be the result of a competition between the propagating tip of the Kolbeinsey Ridge and the retreating tip of the Aegir Ridge, associated with orthogonal spreading corridors displaced by several post-C18 oceanic transforms and shear zones, none of which are observed on the new compilation.

In the present study, the new data also show that an important spreading reorganization affected the Norway Basin during the transition from Early to Mid Eocene [e.g., *Olesen et al*., 2007; *Gernigon et al*., 2012a]. The chron C21n marks the onset of a significant tectonic change in the Norway Basin at around 48.5–47.3 Myr ago (Figure 12). Phase 2 marks a change in spreading rates after chron C21r (48.5–47.3 Ma) (Figure 10), concomitant with a fan-shaped development which became more pronounced at that stage.

There is a time gap of almost 25 Myr from the beginning of Phase 2 at ~ C21r to the establishment of a complete breakup between the proto-JMMC and East Greenland at around chron C6b. As suggested by the predrift reconstruction and the strong overlaps of the JMMC outline displayed in Figure 12, the southern half of the JMMC must have been severely extended after the first phase of breakup. The fan-shaped oceanic development of the Norway Basin was particularly active after chron C21r. Taking into account the plate kinematics and expected counterbalanced geometries, the growing fan-shaped development of the Norway Basin should have therefore coincided with a phase of increasing rifting in the southern part of the JMMC that has been confirmed by seismic interpretations [*Guðlaugsson et al*., 1988; *Gaina et al*., 2009; *Blischke et al*., 2011]. The C21 event corresponds well with recent ^{40}Ar-^{39}Ar age reevaluations of the regional, coast-parallel, Igtertiva dike swarm along the Bosseville Kyst at around 49–44 Ma [*Larsen et al*., 2013]. The growing phase of extension south of the proto-JMMC, required to accommodate the fan-shaped development of the adjacent Norway Basin, would correlate more precisely with this diking event before a northward propagation of the proto-Kolbeinsey Ridge and subsequent related magmatic events [e.g., *Tegner et al*., 2008; *Gaina et al*., 2009] (Figure 12).

We have also noted that the Mid Eocene reorganization around anomaly C21r coincides as well with localized magmatic pulses in and around the Norway Basin [*Parkin et al*., 2007; *Gernigon et al*., 2009]. Sudden sediment influxes have also been recorded at that stage into the Faroe-Shetland Basin, the Greenland coastal areas, and also into the Rockall Plateau [*Sørensen*, 2003; *Larsen et al*., 2005; *Stoker et al*., 2012]. The Mid-Eocene reorganization also matches the onset of compression and dome formation in the MVRM (see review and updated timing by *Doré et al*. [2008]) (Figure 12). This series of concomitant magmatotectonic and stratigraphic events recorded in the Early to Mid-Lutetian also supports the importance of this Mid-Eocene magmatotectonic event in the Norwegian-Greenland Sea and surrounding "passive" rifted margins.

Finally, the origin and location of this rift leading to the second phase of breakup and final isolation of the JMMC are still questionable [*Müller et al*., 2001; *Gaina et al*., 2009; *Yamasaki and Gernigon*, 2010]. This rift was probably influenced by magmatism, but it should primarily have involved a rift/ridge overlap and a dual rift system geometry between the dying Aegir Ridge and nascent Kolbeinsey Ridge [*Auzende et al*., 1980; *Unternehr*, 1982; *Gernigon et al.*, 2012a; *Ellis and Stoker*, 2014]. Nonetheless, it was most likely preceded by a propagating magmatic and diking event that initiated (at least) 7–8 Myr before the establishment of a stable oceanic accretion system between the JMMC and East Greenland.

The term "microcontinent" was initially defined morphologically rather than genetically to describe both aseismic oceanic and/or continental upstanding bathymetric features [*Heezen and Tharp*, 1965]. *Scruton* [1976] refined and clarified the concept of "microcontinent." One of the main criteria of *Scruton* [1976] to define a "microcontinent" is the preservation of prerift continental basement, whereas the crust around should be oceanic. In this context, this traditional term of "microcontinent" [*Scruton*, 1976] might be partly inappropriate for a large part of the Jan Mayen "microplate system" where the integrity and preservation of massive continental units might have been seriously affected by isolated oceanic accretion even before the formation of the Kolbeinsey Ridge. Due to the large amount of extension proposed for the southern part of the JMMC, we suggest that some intermediate microoceanic fragments (Cenozoic) might be present in the southern/southernmost parts of the JMMC. This could be supported by refraction data interpretations across the Iceland Plateau and the southernmost extent of the JMMC [*Brandsdóttir et al.*, 2013]. However, the complex area across the south JMMC would need additional geophysical data and rock samples to fully understand the nature of the extensive system and type of crust really involved between the well-mapped western extent of the Aegir Ridge system and the eastern extent of the Kolbeinsey Ridge system.

7. Conclusions

1. The volcanic margins (in a strict sense) that formed before the opening of the Norway Basin seem to be disconnected with the previous thinning system that led to the Cretaceous sag development of the MVRM. The significant amount of breakup magmatism (SDRs), the huge amount of prebreakup sag sedimentation, and the presence of thin but preserved continental crust without the systematic occurrence of underlying and/or exhumed serpentinized terranes make the MVRM appear to be quite different from (Iberian type) magma-poor margins, even if the processes leading to the early thinning events seem to be similar to some extent.
2. The amount of breakup volcanism and subsequent oceanic crust segmentation, highlighted by the new aeromagnetic compilation, show good relationships with some of the structures of the prebreakup rift system and, in particular, the Jan Mayen corridor which is interpreted as a large transfer system at the scale of the rifted margin. We propose that there is correlation between the continental margin segmentation and subsequent oceanic accretion.
3. The oceanic crust and adjacent COBs of the Norway Basin are now better mapped by a number of aeromagnetic surveys and a new magnetic grid of the area. The opening of the Norway Basin may have been controlled by potential ridge jumps leading to local complexities. The new compilation confirms that accretion developed faster on the eastern side of the Norway Basin. Both differential spreading rate and episodic ridge jumps may explain the spreading asymmetry.
4. We observe a significant change in the Norway Basin's oceanic spreading system around magnetic chron C21r (49–47.9 Ma), and we suggest that this is related to a major tectonic event in the Norwegian-Greenland Sea. This Mid-Eocene event initiated a faster rate of extension of the southern JMMC area and acted as a counterpart to the fan-shaped development of the Aegir Ridge system. The amount of extension required in the southern and southernmost parts of the JMMC suggests that oceanic accretion was possibly involved in the southern part of the JMMC, even before the second phase of breakup, leading to the complete separation of this microplate complex.

Acknowledgments
The JAS-05, NB-07, and JAS-12 data acquisition has been financed and carried out by the Continental Shelf Geophysics team at NGU in collaboration with ConocoPhillips, the Faroes Earth and Energy Directorate, Jardfeingi, the Norwegian Petroleum Directorate, Norske Shell, Statoil, Total Norge (JAS-09 to NB-07), and ISOR/Orkustofnun (JAS-12). R. Lynum, E. Dalsegg, and J. Gellein participated in the fieldwork. J. Luis (University of Algarve) is acknowledged for providing the Matlab code used to calculate the Euler poles of rotation. Schlumberger is acknowledged for providing Petrel academic licenses. Seismic data have been provided by ISOR, NPD, and the Diskos consortium. The authors are grateful to C. DeMets, P. Vogt, and C. Gaina for relevant comments and suggestions, and we thank D.G. Roberts for the linguistic remarks.

References

Auzende, J. M., P. Beuzart, J. Bonnin, J. L. Olivet, B. Sichler, and P. Unternehr (1980), Mode de dislocation des continents lors des stades initiaux d'ouverture, paper presented at 8éme Réunion des Sciences de la Terre de la Société Géologique de France.

Barker, P. F., and I. A. Hill (1980), Asymmetric spreading in back-arc basins, *Nature*, *285*, 652–654.

Behn, M. D., and J. Lin (2000), Segmentation in gravity and magnetic anomalies along the U.S. East Coast passive margin: Implications for incipient structure of the oceanic lithosphere, *J. Geophys. Res.*, *105*(B11), 25,769–25,790, doi:10.1029/2000JB900292.

Bellahsen, N., S. Leroy, J. Autin, P. Razin, E. d'Acremont, H. Sloan, R. Pik, A. Ahmed, and K. Khanbari (2013), Pre-existing oblique transfer zones and transfer/transform relationships in continental margins: New insights from the southeastern Gulf of Aden, Socotra Island, Yemen, *Tectonophysics*, *607*, 32–50.

Berndt, C., R. Mjelde, S. Planke, H. Shimamura, and J. I. Faleide (2001a), Controls on the tectono-magmatic evolution of a volcanic transform margin: The Vøring Transform Margin, NE Atlantic, *Mar. Geophys. Res.*, *22*(3), 133–152.

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

Blaich, O. A., J. I. Faleide, F. Tsikalas, D. Franke, and E. Leon (2009), Crustal-scale architecture and segmentation of the Argentine margin and its conjugate off South Africa, *Geophys. J. Int.*, *178*(1), 85–105.

Blischke, A., T. S. Arnarson, and K. Gunnarsson (2011), The structural history of the Jan Mayen Microcontinent (JMMC) and its role during the rift "jump" between the Aegir to the Kolbeinsey Ridge, paper presented at AAPG, 3P Arctic - The Polar Petroleum Potential Conference &Exhibition, AAPG, Halifax, Nova Scotia, Canada.

Boillot, G., G. Féraud, M. Recq, and J. Girardeau (1989), "Undercrusting" by serpentinite beneath rifted margins: The example of the west Galicia margin (Spain), *Nature*, *341*, 523–525.

Brandsdóttir, B., E. E. Hooft, R. Mjelde, Y. Murai, and H. Shimamura (2013), Origin and evolution of the Iceland Plateau and Kolbeinsey Ridge, N-Atlantic, paper presented at IASPEI, Gothenburg, Sweden.

Breivik, A. J., R. Mjelde, J. I. Faleide, and Y. Murai (2006), Rates of continental breakup magmatism and seafloor spreading in the Norway Basin-Iceland plume interaction, *J. Geophys. Res.*, *111*, B07102, doi:10.1029/2005JB004004.

Breivik, A. J., R. Mjelde, J. I. Faleide, and Y. Murai (2012), The eastern Jan Mayen microcontinent volcanic margin, *Geophys. J. Int.*, *188*(3), 798–818.

Brekke, H. (2000), The tectonic evolution of the Norwegian Sea continental margin with emphasis on the Vøring and Møre basins, in *Dynamics of the Norwegian Margin*, edited by A. Nøttvedt et al., *Geol. Soc. London Spec. Publ.*, *136*, 327–378.

Brönner, A., D. Sauter, G. Manatschal, G. Peron-Pinvidic, and M. Munschy (2011), Magmatic breakup as an explanation for magnetic anomalies at magma-poor rifted margins, *Nat. Geosci.*, *4*(8), 549–553.

Buck, W. R. (2006), The role of magma in the development of the Afro-Arabian Rift System, in *The Afar Volcanic Province Within the East African Rift System*, edited by G. Yirgu, C. Ebinger, and P. K. H. Maguire, *Geol. Soc. London Spec. Publ.*, *259*, 43–54.

Callot, J. P., C. Grigné, L. Geoffroy, and J. P. Brun (2001), Development of volcanic passive margins: Two-dimensional laboratory models, *Tectonics*, *20*(1), 148–159, doi:10.1029/2000TC900030.

Cannat, M., V. Mamaloukasfrangoulis, J. M. Auzende, D. Bideau, E. Bonatti, J. Honnorez, Y. Lagabrielle, J. Malavieille, and C. Mevel (1991), A geological cross-section of the Vema Fracture-Zone Transverse Ridge, Atlantic-Ocean, *J. Geodyn.*, *13*(2–4), 97–117.

Chalmers, J. A., and K. H. Laursen (1995), Labrador Sea—The extent of continental and oceanic-crust and the timing of the onset of sea-floor spreading, *Mar. Petrol. Geol.*, *12*(2), 205–217.

Collier, J. S., V. Sansom, O. Ishizuka, R. N. Taylor, T. A. Minshull, and R. B. Whitmarsh (2008), Age of Seychelles-India break-up, *Earth Planet. Sci. Lett.*, *272*(1–2), 264–277.

Courtillot, V., A. Galdeano, and J. L. Le Mouel (1980), Propagation of an accreting plate boundary: A discussion of new aeromagnetic data in the Gulf of Tadjurah and southern Afar, *Earth Planet. Sci. Lett.*, *48*, 144–160.

d'Acremont, E., S. Leroy, M. Maia, P. Patriat, M. O. Beslier, N. Bellahsen, M. Fournier, and P. Gente (2006), Structure and evolution of the eastern Gulf of Aden: Insights from magnetic and gravity data (Encens-Sheba MD117 cruise), *Geophys. J. Int.*, *165*(3), 786–803.

Dinkelman, N. G., and P. Keane (2010), Northeast Atlantic continental margin: Improved sub-basalt imaging, *GeoExpro*, *7*(3), 54–56.

Direen, N. G., I. Borissova, H. M. J. Stagg, B. Colwell, and P. A. Symonds (2007), Nature of the continent ocean transition zone along the southern Australian continental margin: A comparison of the Naturaliste Plateau, SW Australia, and the central Great Australian Bight sectors, in *Geological Society, London, Special Publications*, edited by G. D. Karner, G. Manatschal, and L. M. Pinheiro, pp. 239–263, Geol. Soc. London.

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

Doré, A. G., E. R. Lundin, N. J. Kusznir, and C. Pascal (2008), Potential mechanisms for the genesis of Cenozoic domal structures on the NE Atlantic margin: Pros, cons and some new ideas, in *Compressional Deformation Within Passive Margins: Nature, Causes and Effects*, edited by H. Jonhson et al., *Geol. Soc. London Spec. Publ.*, *306*, 1–26.

Ebinger, C. J., and M. Casey (2001), Continental breakup in magmatic provinces: An Ethiopian example, *Geology*, *29*(6), 527–530.

Eldholm, O., J. Thiede, and B. Taylor (1989), Evolution of the Vøring volcanic margin, in *Proceedings of the Ocean Drilling Program, Scientific Results*, vol. 104, edited by O. Eldholm, J. Thiede, and E. Taylor, pp. 1033–1065, Ocean Drilling Program, College Station, Tex.

Ellis, D., and M. S. Stoker (2014), The Faroe–Shetland Basin: A regional perspective from the Paleocene to the present day and its relationship to the opening of the North Atlantic Ocean, in *Hydrocarbon Exploration to Exploitation West of Shetlands*, edited by S. J. C. Cannon and D. Ellis, Geol. Soc. London, London.

Erlendsson, Ö. & Blischke, A. (2013), The Law of the Sea project: 2D Seismic reflection and seismic refraction data, and their interpretations in Icelandic waters. Iceland Geosurvey, ISOR 2013/067. Published for the Icelandic national energy authority. 60 pages. + 2 maps.

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

Foulger, G. R., and D. L. Anderson (2005), A cool model for the Iceland hotspot, *J. Volcanol. Geoth. Res.*, *141*(1-2), 1–22.

Gaina, C., W. R. Roest, and R. D. Müller (2002), Late Cretaceous-Cenozoic deformation of northeast Asia, *Earth Planet. Sci. Lett.*, *197*, 273–286.

Gaina, C., L. Gernigon, and P. J. Ball (2009), Palaeocene-Recent plate boundaries in the NE Atlantic and the formation of the Jan Mayen microcontinent, *J. Geol. Soc. London*, *166*, 601–616.

Geoffroy, L. (2005), Volcanic passive margins, *Compt. Rendus Geosci.*, *337*(16), 1395–1408.

Gernigon, L., J. C. Ringenbach, S. Planke, B. Le Gall, and H. Jonquet-Kolsto (2003), Extension, crustal structure and magmatism at the outer Voring Basin, Norwegian margin, *J. Geol. Soc. London*, *160*, 197–208.

Gernigon, L., O. Olesen, J. Ebbing, S. Wienecke, C. Gaina, J. O. Mogaard, M. Sand, and R. Myklebust (2009), Geophysical insights and early spreading history in the vicinity of the Jan Mayen Fracture Zone, Norwegian-Greenland Sea, *Tectonophysics*, *468*(1–4), 185–205.

Gernigon, L., C. Gaina, O. Olesen, P. J. Ball, G. Peron-Pinvidic, and T. Yamasaki (2012a), The Norway Basin revisited: From continental breakup to spreading ridge extinction, *Mar. Petrol. Geol.*, *35*(1), 1–19.

Gernigon, L., J. Koziel, and A. Nasuti (2012b), Jan Mayen Aeromagnetic Survey JAS-12—Part A: Acquisition, processing, Rep. 2012.069, 116 pp., Geological Survey of Norway, Trondheim.

Gerya, T. (2012), Origin and models of oceanic transform faults, *Tectonophysics*, *522*, 34–54.

Gradstein, F. M., J. C. Ogg, M. Smith, and G. Ogg (2012), *The Geologic Time Scale 2012*, Elsevier Science Ltd, Oxford, U. K.

Greiner, B., and J. Neugebauer (2013), The rotations opening the Central and Northern Atlantic Ocean: Compilation, drift lines, and flow lines, *Int. J. Earth Sci.*, *102*(5), 1357–1376.

Grønlie, G., M. Chapman, and M. Talwani (1978), Jan Mayen ridge and iceland plateau, *Norsk Polarinstitut skrifter*, *170*, 25–48.
Grønlie, G., M. Chapman, and M. Talwani (1979), Jan Mayen Ridge and Iceland Plateau: Origin and evolution, *Norsk Polarinst Skrifter*, *170*, 25–47.
Grunnaleite, I., and R. H. Gabrielsen (1995), Structure of the more basin, mid-Norway continental margin, *Tectonophysics*, *252*(1–4), 221–251.
Guðlaugsson, S. T., K. Gunnarsson, M. Sand, and J. Skogseid (1988), Tectonic and volcanic events at the Jan Mayen Ridge microcontinent, in *Early Tertiary Volcanism and the Opening of the NE Atlantic*, edited by A. C. Morton and L. M. Parson, *Geol. Soc. London Spec. Publ.*, *39*, 85–93.
Gunnarsson, K., M. Sand, and S. T. Guðlaugsson (1989), Geology and hydrocarbon potential of the Jan Mayen Ridge Rep. OS-89036/JHD-07, 156 pp., Oljedirektoret (Norwegian Petroleum Directorate)/Orkustofnun (Icelandic National Energy Authority).
Hayes, D. E. (1976), Nature and implications of asymmetric sea-floor spreading "Different rates for different plates", *Geol. Soc. Am. Bull.*, *87*, 994–1002.
Heezen, B. V., and M. Tharp (1965), Tectonic fabric of the Indian Ocean, *Phil. Trans. Roy. Soc. Lond. Ser. A*, *258*, 90–106.
Hjelstuen, B. O., and E. V. Andreassen (2015), North Atlantic Ocean deep-water processes and depositional environments: A study of the Cenozoic Norway Basin, *Mar. Petrol. Geol.*, *59*, 429–441.
Hopper, J. R., T. Dahl-Jensen, W. S. Holbrook, H. C. Larsen, D. Lizarralde, J. Korenaga, G. M. Kent, and P. B. Kelemen (2003), Structure of the SE Greenland margin from seismic reflection and refraction data: Implications for nascent spreading center subsidence and asymmetric crustal accretion during North Atlantic opening, *J. Geophys. Res.*, *108*(B5), doi:10.1029/2002JB001996.
Hopper, J. R., T. Funck, and B. E. Tucholke (2007), *Structure of the Flemish Cap Margin, Newfoundland: Insights Into Mantle and Crustal Processes During Continental Breakup*, *Geol. Soc. London Spec. Publ.*, 282(1), 47–61.
Jakobsson, M., et al. (2012), The International Bathymetric Chart of the Arctic Ocean (IBCAO) version 3.0, *Geophys. Res. Lett.*, *39*, doi:10.1029/2012GL052219.
Jung, W. Y., and P. R. Vogt (1997), A gravity and magnetic anomaly study of the extinct Aegir Ridge, Norwegian Sea, *J. Geophys. Res.*, *12*(B3), 5065–5089, doi:10.1029/96JB03915.
Kandilarov, A., R. Mjelde, R. B. Pedersen, B. Hellevang, C. Papenberg, C. J. Petersen, L. Planert, and E. Flueh (2012), The northern boundary of the Jan Mayen microcontinent, North Atlantic determined from ocean bottom seismic, multichannel seismic, and gravity data, *Mar. Geophys. Res.*, *33*(1), 55–76.
Karson, J. A., and C. K. Brooks (1999), Structural and magmatic segmentation of the Tertiary East Greenland Volcanic Rifted Margin, in *Continental Tectonics*, edited by C. Mac Niocaill and P. D. Ryan, pp. 313–338, Geol. Soc. London, London.
Klausen, M. B., and H. C. Larsen (2002), East Greenland coast-parallel dike swarm and its role in continental breakup, in *Volcanic Rifted Margins*, edited by M. A. Menzies et al., *Geol. Soc. Am. Spec. Pap.*, *362*, 133–158.
Kodaira, S., R. Mjelde, K. Gunnarsson, H. Shiobara, and H. Shimamura (1998), Structure of the Jan Mayen microcontinent and implications for its evolution, *Geophys. J. Int.*, *132*(2), 383–400.
Koopmann, H., B. Schreckenberger, D. Franke, K. Becker, and M. Schnabel (2014), The late rifting phase and continental break-up of the southern South Atlantic: The mode and timing of volcanic rifting and formation of earliest oceanic crust, in *Magmatic Rifting and Active Volcanism*, edited by T. J. Wright et al., *Geol. Soc. London Spec. Publ.,* in press.
Kvarven, T., J. Ebbing, R. Mjelde, J. I. Faleide, A. Libak, H. Thybo, E. Flueh, and Y. Murai (2014), Crustal structure across the Møre margin, mid-Norway, from wide-angle seismic and gravity data, *Tectonophysics*, *626*, 21–40.
Laske, G., and G. Masters (1997), A global digital map of sediment thickness, *Eos Trans. AGU*, *78*(F483). [Available at http://mahi.ucsd.edu/Gabi/sediment.html.]
Larsen, H. C., and S. Jakobsdóttir (1988), Distribution, crustal properties and significance of seaward-dipping sub-basement reflectors off East Greenland, in *Early Tertiary Volcanism and the Opening of the Northeast Atlantic*, edited by A. C. Morton and L. M. Parson, *Geol. Soc. London Spec. Publ.*, *39*, 95–114.
Larsen, L. M., A. K. Pedersen, E. V. Søorensen, W. S. Watt, and R. A. Duncan (2013), Stratigraphy and age of the Eocene Igtertiva Formation basalts, alkaline pebbles and sediments of the Kap Dalton Group in the graben at Kap Dalton, East Greenland, *Bull. Geol. Soc. Den.*, *61*, 1–18.
Larsen, M., C. Heilmann-Clausen, S. Piasecki, and L. Stemmerik (2005), At the edge of a new ocean: Post-volcanic evolution of the Paleogene Kap Dalton Group, East Greenland, paper presented at Petroleum Geology: North-West Europe and Global Perspectives-Proceedings of the 6th Petroleum geology Conference, Geol. Soc. London.
Lavier, L. L., and G. Manatschal (2006), A mechanism to thin the continental lithosphere at magma-poor margins, *Nature*, *440*(7082), 324–328.
Le Breton, E., P. R. Cobbold, O. Dauteuil, and G. Lewis (2012), Variations in amount and direction of seafloor spreading along the northeast Atlantic Ocean and resulting deformation of the continental margin of northwest Europe, *Tectonics*, *31*, TC5006, doi:10.1029/2011TC003087.
Le Pichon, X., J. C. Sibuet, and J. Francheteau (1977), The fit of the continents around the North Atlantic Ocean, *Tectonophysics*, *38*, 169–209.
Leroy, S., et al. (2012), From rifting to oceanic spreading in the Gulf of Aden: A synthesis, *Arab. J. Geosci.*, *5*(5), 859–901.
Lister, G. S., M. A. Etheridge, and P. A. Symonds (1986), Detachment faulting and the evolution of passive continental margins, *Geology*, *14*, 246–250.
Luis, J. F., and J. M. Miranda (2008), Reevaluation of magnetic chrons in the North Atlantic between 35°N and 47°N: Implications for the formation of the Azores Triple Junction and associated plateau, *J. Geophys. Res.*, *113*, B10105, doi:10.1029/2007JB005573.
Lundin, E., and A. G. Doré (2002), Mid-Cenozoic post-breakup deformation in the "passive" margins bordering the Norwegian-Greenland Sea, *Mar. Petrol. Geol.*, *19*(1), 79–93.
Lundin, E. R., and A. G. Doré (1997), A tectonic model for the Norwegian passive margin with implications for the NE Atlantic: Early Cretaceous to break-up, *J. Geol. Soc. London*, *154*, 545–550.
Lundin, E. R., and A. G. Doré (2011), Hyperextension, serpentinization, and weakening: A new paradigm for rifted margin compressional deformation, *Geology*, *39*(4), 347–350.
Manatschal, G. (2004), New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps, *Int. J. Earth Sci.*, *93*(3), 432–466.
Maupin, V., et al. (2013), The deep structure of the Scandes and its relation to tectonic history and present-day topography, *Tectonophysics*, *602*, 15–37.
Mauring, E., L. P. Beard, O. Kihle, and M. A. Smethurst (2002), A comparison of aeromagnetic levelling techniques with an introduction to median levelling, *Geophys. Prospect.*, *50*(1), 43–54.
Maus, S., F. Yin, H. Lühr, C. Manoj, M. Rother, J. Rauberg, I. Michaelis, C. Stolle, and R. D. Müller (2008), Resolution of direction of oceanic magnetic lineations by the sixth-generation lithospheric magnetic field model from CHAMP satellite magnetic measurements, *Geochem. Geophys. Geosyst.*, *9*, Q07021, doi:10.1029/2008GC001949.
Maystrenko, Y., and M. Scheck-Wenderoth (2009), Density contrasts in the upper mantle and lower crust across the continent-ocean transition: Constraints from 3-D gravity modelling at the Norwegian margin, *Geophys. J. Int.*, *179*(1), 536–548.

Mendel, V., M. Munschy, and D. Sauter (2005), MODMAG, a MATLAB program to model marine magnetic anomalies, *Comput. Geosci.*, *31*(5), 589–597.
Meyer, R., J. van Wijk, and L. Gernigon (2007), The north Atlantic igneous province: A review of models for its formation, in *Plates, Plumes and Planetary Processes*, edited by G. R. Foulger and D. M. Jurdy, *Geol. Soc. Am. Spec. Pap.*, *430*, 525–552.
Meyer, R., J. Hertogen, R. B. Pedersen, L. Viereck-Gotte, and M. Abratis (2009), Interaction of mantle derived melts with crust during the emplacement of the Voring Plateau, NE Atlantic, *Mar. Geol.*, *261*(1–4), 3–16.
Miller, H. G., and V. Singh (1994), Potential-field tilt—A new concept for location of potential-field sources, *J. Appl. Geophys.*, *32*(2–3), 213–217.
Minshull, T. A. (2009), Geophysical characterisation of the ocean-continent transition at magma-poor rifted margins, *Compt. Rendus Geosci.*, *341*(5), 382–393.
Misra, A. A., N. Sinha, and S. Mukherjee (2015), Repeat ridge jumps and microcontinent separation: Insights from NE Arabian Sea, *Mar. Petrol. Geol.*, *59*, 406–428.
Mittelstaedt, E., G. Ito, and J. van Hunen (2011), Repeat ridge jumps associated with plume-ridge interaction, melt transport, and ridge migration, *J. Geophys. Res.*, *116*, B01102, doi:10.1029/2010JB007504.
Mjelde, R., I. Eckhoff, S. Solbakken, S. Kodaira, H. Shimamura, K. Gunnarsson, A. Nakanishi, and H. Shiobara (2007), Gravity and S-wave modelling across the Jan Mayen Ridge, North Atlantic: Implications for crustal lithology, *Mar. Geophys. Res.*, *28*(1), 27–41.
Mjelde, R., T. Raum, A. Kandilarov, Y. Murai, and T. Takanami (2009), Crustal structure and evolution of the outer Møre Margin, NE Atlantic, *Tectonophysics*, *468*(1–4), 224–243.
Mohn, G., G. Manatschal, M. Beltrando, E. Masini, and N. Kusznir (2012), Necking of continental crust in magma-poor rifted margins: Evidence from the fossil Alpine Tethys margins, *Tectonics*, *31*, TC1012, doi:10.1029/2011TC002961.
Mosar, J., E. A. Eide, P. T. Osmundsen, A. Sommaruga, and T. H. Torsvik (2002), Greenland - Norway separation: A geodynamic model for the North Atlantic, *Norw. J. Geol.*, *82*(4), 281–298.
Moulin, M., D. Aslanian, and P. Unternehr (2010), A new starting point for the South and Equatorial Atlantic Ocean, *Earth Sci. Rev.*, *98*(1–2), 1–37.
Muller, R. D., and W. R. Roest (1992), Fracture-zones in the North-Atlantic from combined Geosat and Seasat data, *J. Geophys. Res.*, *97*(B3), 3337–3350, doi:10.1029/91JB02605.
Müller, R. D., W. R. Roest, and J. Y. Royer (1998), Asymmetric sea-floor spreading caused by ridge-plume interactions, *Nature*, *396*(6710), 455–459.
Müller, R. D., C. Gaina, W. R. Roest, and D. L. Hansen (2001), A recipe for microcontinent formation, *Geology*, *29*(3), 203–206.
Muller, R. D., M. Sdrolias, C. Gaina, and W. R. Roest (2008), Age, spreading rates, and spreading asymmetry of the world's ocean crust, *Geochem. Geophys. Geosyst.*, *9*, Q04006, doi:10.1029/2007GC001743.
Nicolas, A., U. Achauer, and M. Daignieres (1994), Rift initiation by lithospheric rupture, *Earth Planet. Sci. Lett.*, *123*, 281–298.
Nirrengarten, M., L. Gernigon, and G. Manatschal (2014), On the nature, structure and age of lower crustal bodies in the Møre volcanic rifted margin, *Tectonophysics*, *636*, 143–157.
Northwest Geophysical Associates Incorporation (2006), GM-SYS gravity and magnetic modeling software, Users Guide v 4.10, 110 p.
Norwegian Petroleum Directorate (2013), Petroleum resources on the Norwegian continental shelf 2013 exploration Rep., 63 pp., Norwegian Petroleum Directorate, Stavanger.
Nunns, A. G. (1983), Plate tectonic evolution of the Greenland-Scotland Ridge and surrounding regions, in *Structure and Development of the Greenland-Scotland Ridge*, edited by M. H. P. Bott et al., pp. 1–30, Plenum Press, New York.
Olafsson, I., E. Sundvor, O. Eldholm, and G. Kjersti (1992), Møre Margin: Crustal structure and analysis of expanded spread profiles, *Mar. Geophys. Res.*, *14*, 137–163.
Olesen, O., J. Ebbing, E. Lundin, E. Mauring, J. R. Skilbrei, T. H. Torsvik, E. K. Hansen, T. Henningsen, P. Midboe, and M. Sand (2007), An improved tectonic model for the Eocene opening of the Norwegian-Greenland Sea: Use of modern magnetic data, *Mar. Petrol. Geol.*, *24*(1), 53–66.
Olesen, O., et al. (2010), New aeromagnetic and gravity compilations from Norway and adjacent areas—Methods and applications, in *Petroleum Geology: From Mature Basins to New Frontiers. Proceedings of the 7th Petroleum Geology Conference*, edited by B. A. Vining and S. C. Pickering, pp. 559–586, Geol. Soc. London.
Olivet, J. L. (1996), Kinematics of the Iberian plate, *Bull. Cent. Rech. Explor. Prod. Elf Aquitaine*, *20*, 131–195.
Osmundsen, P. T., and J. Ebbing (2008), Styles of extension offshore mid-Norway and implications for mechanisms of crustal thinning at passive margins, *Tectonics*, *27*, TC6016, doi:10.1029/2007TC002242.
Parkin, C. J., Z. C. Lunnon, R. S. White, and P. A. F. Christie (2007), Imaging the pulsing Iceland mantle plume through the Eocene, *Geology*, *35*(1), 93–96.
Passey, S. R., and D. W. Jolley (2009), A revised lithostratigraphic nomenclature for the Palaeogene Faroe Islands Basalt Group, NE Atlantic Ocean, *Earth Environ. Sci. Trans. Roy. Soc. Edinburgh*, *99*, 127–158.
Péron-Pinvidic, G., G. Manatschal, and P. T. Osmundsen (2013), Structural comparison of archetypal Atlantic rifted margins: A review of observations and concepts, *Mar. Petrol. Geol.*, *43*, 21–47.
Planke, S., and E. Alvestad (1999), Seismic volcanostratigraphy of the extrusive breakup complexes in the northeast Atlantic: Implications from ODP-DSDP drilling, paper presented at Proceedings of the Ocean Drilling Program, Scientific Results, College Station, Tex (Ocean Drilling Program).
Planke, S., J. Skogseid, and O. Eldholm (1991), Crustal structure off Norway, 62° to 70° North, *Tectonophysics*, *189*(1–4), 91–107.
Planke, S., P. A. Symonds, E. Alvestad, and J. Skogseid (2000), Seismic volcanostratigraphy of large-volume basaltic extrusive complexes on rifted margins, *J. Geophys. Res.*, *105*(B8), 19,335–19,351, doi:10.1029/1999JB900005.
Polteau, S., S. Planke, R. Myklebust, and G. Hickman (2013), Seabed sampling for stratigraphy and seep studies offshore Greenland and Norway, paper presented at 75th EAGE Conference & Exhibition incorporating SPE EUROPEC 2013, EAGE, London, U. K.
Quirk, D. G., A. Shakerley, and M. J. Howe (2014), A mechanism for construction of volcanic rifted margins during continental breakup, *Geology*, *42*(12), 1079–1082.
Reston, T. J. (2009), The extension discrepancy and syn-rift subsidence deficit at rifted margins, *Petrol. Geosci.*, *15*(3), 217–237.
Reynisson, F., J. Ebbing, E. R. Lundin, and P. T. Osmundsen (2010), Properties and distribution of lower crustal bodies on the mid-Norwegian margin, in *Petroleum Geology: From Mature Basins to New Frontiers-Proceedings of the 7th Petroleum Geology Conference*, edited by B. A. Vinning and S. C. Pickering, pp. 843–854, Geol. Soc. of London, London, U. K.
Roest, W. R., and S. P. Srivastava (1989), Seafloor spreading in the Labrador Sea: A new reconstruction, *Geology*, *17*, 1000–1004.
Rüpke, L. H., D. W. Schmid, M. Perez-Gussinye, and E. Hartz (2013), Interrelation between rifting, faulting, sedimentation, and mantle serpentinization during continental margin formation-including examples from the Norwegian Sea, *Geochem. Geophys. Geosyst.*, *14*, 4351–4369, doi:10.1002/ggge.20268.

Sandwell, D., E. Garcia, K. Soofi, P. Wessel, M. Chandler, and W. H. Smith (2013), Toward 1-mGal accuracy in global marine gravity from CryoSat-2, Envisat, and Jason-1, *Leading Edge*, *32*(8), 892–899.

Scott, D. W. (1992), *Multivariate Density Estimation: Theory, Practice, and Visualization*, John Wiley, New York.

Scott, R. A., L. A. Ramsey, S. M. Jones, S. Sinclair, and C. S. Pickles (2005), Development of the Jan Mayen microcontinent by linked propagation and retreat of spreading ridges, in *Onshore-Offshore Relationships on the North Atlantic Margin*, edited by B. T. G. Wandås et al., pp. 69–82, *Norwegian Petroleum Society (NPF) Spec. Publ.*, *12*, 69–82.

Scruton, R. A. (1976), Microcontinents and their significance, in *Geodynamics Progress and Prospects*, edited by C. L. Drake, pp. 177–189, AGU, Washinghton, D. C.

Sibuet, J. C., and B. E. Tucholke (2012), The geodynamic province of transitional lithosphere adjacent to magma-poor continental margins, in *Conjugate Divergent Margins*, edited by W. U. Mohriak et al., Geol. Soc. London, doi:10.1144/SP1369.1115.

Sibuet, J. C., S. Srivastava, and G. Manatschal (2007), Exhumed mantle-forming transitional crust in the Newfoundland-Iberia rift and associated magnetic anomalies, *J. Geophys. Res.*, *112*, B06105, doi:10.1029/2005JB003856.

Skogseid, J., and O. Eldholm (1987), Early Cenozoic crust at the Norwegian continental margin and the conjugate Jan Mayen Ridge, *J. Geophys. Res.*, *92*, 11,471–11,491, doi:10.1029/JB092iB11p11471.

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

Smallwood, J. R., and R. S. White (2002), Ridge-plume interaction in the North Atlantic and its influence on continental breakup and seafloor spreading, in *The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes*, edited by D. W. Jolley and B. R. Bell, *Geol. Soc. London Spec. Publ.*, *197*, 15–37.

Smallwood, J. R., R. K. Staples, K. R. Richardson, R. S. White, and I. R. E. W. Group (1999), Crust generated above the Iceland mantle plume: From continental to oceanic spreading centre, *J. Geophys. Res.*, *104*, 22,885–22,902.

Sørensen, A. B. (2003), Cenozoic basin development and stratigraphy of the Faroes area, *Petrol. Geosci.*, *9*, 189–207.

Srivastava, S., and C. R. Tapscott (1986), Plate kinematics of the North Atlantic, in *The Geology of North America, Volume M, The Western North Atlantic Region*, edited by P. R. Vogt and B. E. Tucholke, pp. 379–404, Geol. Soc. Am.

Stein, S., H. J. Melosh, and J. B. Minster (1977), Ridge migration and asymmetric sea-floor spreading, *Earth Planet. Sci. Lett.*, *36*, 51–62.

Stoker, M. S., G. S. Kimbell, D. B. McInroy, and A. C. Morton (2012), Eocene post-rift tectonostratigraphy of the Rockall Plateau, Atlantic margin of NW Britain: Linking early spreading tectonics and passive margin response, *Mar. Petrol. Geol.*, *30*, 98–125.

Sutra, E., G. Manatschal, G. Mohn, and P. Unternehr (2013), Quantification and restoration of extensional deformation along the Western Iberia and Newfoundland rifted margins, *Geochem. Geophys. Geosyst.*, *14*, 2575–2597, doi:10.1002/ggge.20135.

Talwani, M. (1973), Computer usage in the computation of gravity anomalies, *Methods Comput. Phys.*, *13*, 343–389.

Talwani, M., and O. Eldholm (1977), Evolution of the Norwegian-Greenland Sea, *Geol. Soc. Am. Bull.*, *88*, 969–999.

Taylor, B., A. Goodliffe, and F. Martinez (2009), Initiation of transform faults at rifted continental margins, *Compt. Rendus Geosci.*, *341*, 428–438.

Tegner, C., C. K. Brooks, R. A. Duncan, L. E. Heister, and S. Bernstein (2008), Ar-40-Ar-39 ages of intrusions in East Greenland: Rift-to-drift transition over the Iceland hotspot, *Lithos*, *101*(3–4), 480–500.

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

Tsikalas, F., J. I. Faleide, O. Eldholm, and O. A. Blaich (2012), The NE Atlantic conjugate margins, in *Phanerozoic Passive Margins, Cratonic Basins and Global Tectonic Maps*, edited by D. G. Roberts and A. W. Bally, pp. 141–201.

Tugend, J., G. Manatschal, N. J. Kusznir, E. Masini, G. Mohn, and I. Thinon (2014), Formation and deformation of hyperextended rift systems: Insights from rift domain mapping in the Bay of Biscay-Pyrenees, *Tectonics*, *33*, 1239–1276, doi:10.1002/2014TC003529.

Unternehr, P. (1982), Etude structurale et cinématique de la mer de Norvège et du Groenland - Evolution du microcontinent de Jan Mayen, PhD thesis, 228 pp., Université de Bretagne Occidentale (UBO), Brest.

Verhoef, J., W. R. Roest, R. Macnab, J. Arkani-Hamed, and Members of the Project Team (1997), Magnetic anomalies of the Arctic and North Atlantic Oceans and adjacent land areas., Geol. Soc. Canada, Open File 3125.

Vially, R., and P. de Clarens (1986), Rapport d'interprétation de la campagne Refranorge 2. Premiére partie: Mer de Norvége, *Institut Français du Pétrole*, *34*, –136.

Vogt, P. R. (1986), Geophysical and geochemical signatures and plate tectonics, in *The Nordic Seas*, edited by B. Hurdle, pp. 411–662, Springer, New York.

Vogt, P. R., and W. Y. Jung (2009), Treitel Ridge: A unique inside corner hogback on the west flank of extinct Aegir spreading ridge, Norway basin, *Mar. Geol.*, *267*(1–2), 86–100.

Vogt, P. R., N. A. Ostenso, and G. L. Johnson (1970), Magnetic and bathymetric data bearing on sea-floor spreading north of Iceland, *J. Geophys. Res.*, *75*, 903–920.

Vogt, P. R., G. L. Johnson, and L. Kristjansson (1980), Morphology and magnetic anomalies north of Iceland, *J. Geophys.*, *47*, 67–80.

Vogt, P. R., L. C. Bernero, and S. P. Srivastava (1982), Asymmetric geophysical signatures in the Greenland-Norwegian and Southern Labrador Seas and the Eurasia Basin, *Tectonophysics*, *89*, 95–160.

White, R. S. (1992), Crustal structure and magmatism of North Atlantic continental margins, *J. Geol. Soc. London*, *149*, 841–854.

White, R. S., L. K. Smith, A. W. Roberts, P. A. F. Christie, N. J. Kuznir, and iSIMM_team (2008), Lower-crustal intrusion on the North Atlantic continental margin, *Nature*, *452*(27), 460–464.

Yamasaki, T., and L. Gernigon (2010), Redistribution of the lithosphere deformation by the emplacement of underplated mafic bodies: Implications for microcontinent formation, *J. Geol. Soc. London*, *167*(5), 961–971.

Yamasaki, T., and R. Stephenson (2009), Potential role of strain hardening in the cessation of rifting at constant tectonic force, *J. Geodyn.*, *47*, 47–62.