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Palaeocene–Recent plate boundaries in the NE Atlantic and the formation of the Jan Mayen microcontinent

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Abstract: Breakup and sea-floor spreading between Greenland and Eurasia established a series of new plate boundaries in the North Atlantic region since the Late Palaeocene. A conventional kinematic model from pre-breakup to the present day assumes that Eurasia and Greenland moved apart as a two-plate system. However, new regional geophysical datasets and quantitative kinematic parameters indicate that this system underwent several adjustments since its inception and suggest that additional short-lived plate boundaries existed in the NE Atlantic. Among the consequences of numerous plate boundary relocations is the formation of a highly extended or even fragmented Jan Mayen microcontinent and subsequent deformation of its margins and surrounding regions. The major Oligocene plate boundary reorganization (and microcontinent formation) might have been precluded by various ridge propagations and/or short-lived triple junctions NE and possibly SW of the Jan Mayen microcontinent from the inception of sea-floor spreading (54 Ma) to C18 (40 Ma). Our model implies a series of failed ridges offshore the Faeroe Islands, a northern propagation of the Aegir Ridge NE of the Jan Mayen microcontinent, and a series of triple junctions and/or propagators in the southern Greenland Basin.

As a generally accepted model, northward propagation of sea-floor spreading from the central North Atlantic (between North America and Eurasia) rifted Greenland from Eurasia (e.g. Pitman & Talwani 1972; Srivastava & Tapscott 1986) and formed a triple junction with an existing active plate boundary between the North American plate and Greenland (Fig. 1) (Srivastava & Tapscott 1986; Roest & Srivastava 1989; Chalmers & Laursen 1995) around Late Palaeocene time (roughly before chron 24 time). This plate boundary was also active in the Arctic region, where it separated a narrow continental ridge, the Lomonosov Ridge, either as a part of the North American plate or as an independent plate, from the northeastern margin of Eurasia. On a regional scale, this plate boundary seems to be the result of a two-plate system (i.e. between Eurasia and Greenland in the NE Atlantic or between North America and Eurasia in the Arctic), but a closer inspection of geophysical data and plate geometry shows the existence of short-lived additional plate boundaries within certain domains of this system. Moreover, the formation of the Jan Mayen microcontinent and the possible influence of a mantle plume during the opening of the NE Atlantic have added more complexities to the sea-floor spreading processes.

Vogt & Avery (1974), Talwani & Eldholm (1977), Courtillot (1982), Srivastava & Tapscott (1986) and Skogseid & Eldholm (1987) pioneered geophysical data collection and kinematic modelling of the North Atlantic and Arctic oceanic domains. Talwani & Eldholm (1977) revealed some of the complexities of the opening of the NE Atlantic, including episodes of ridge relocation and changes in spreading directions in the Norway Basin as a consequence of the Labrador Sea extinction. They have also proposed an additional spreading centre SW of the Jan Mayen microcontinent to complement the fan-shaped oceanic spreading in the Norway Basin.

Nunns (1983*b*) also recognized the fan-shaped character of the spreading system and proposed that the Jan Mayen microcontinent acted as a microplate during the opening of the Norway Basin. Unternehr (1982) published detailed kinematic analyses of the opening of the Greenland, Norwegian and south of Iceland oceanic basins and recognized that the mismatch of these domains might require additional plate boundaries. The latter study suggested that the Jan Mayen microcontinent was part of Greenland during most of the Norwegian–Greenland Sea opening, but postulated a post-chron 13 (<33.5 Ma) independent movement of this block to account for unusual structures of the Jan Mayen Fracture Zone. This configuration might have required unstable triple junctions south of the Jan Mayen block until a more vigorous spreading centre (Kolbeinsey) was established between Greenland and Jan Mayen.

Major magmatic events affected the Eurasian margin, the Greenland margin, and the Jan Mayen microcontinent eastern margin before, during and after breakup (Skogseid & Eldholm 1987; Gudlaugsson *et al*. 1988; Berndt *et al*. 2001; Breivik *et al*. 2008; Tegner *et al*. 2008; Gernigon *et al*. 2009). After several decades of studies on the NE Atlantic margins, the causes of initiation of volcanism and breakup and their relationship are still debatable. Many workers postulate the influence of the Iceland plume as a major trigger for both massive and prolonged volcanism and breakup (Eldholm & Grue 1994; Skogseid *et al*. 2000; Mjelde *et al*. 2007). Because of the position of a stationary Iceland plume (Lawver & Müller 1994) closer to western Greenland than to the future location of breakup, more complex models have been proposed to explain how a mantle plume might have affected and possible triggered the breakup and early evolution of the North Atlantic. One hypothesis is that magma from the plume can be channelled at the base of the lithosphere for very long distances (Sleep 1997; Nielsen *et al*. 2002; Olesen *et al.* 2007). Models of mantle plume evolution that take into

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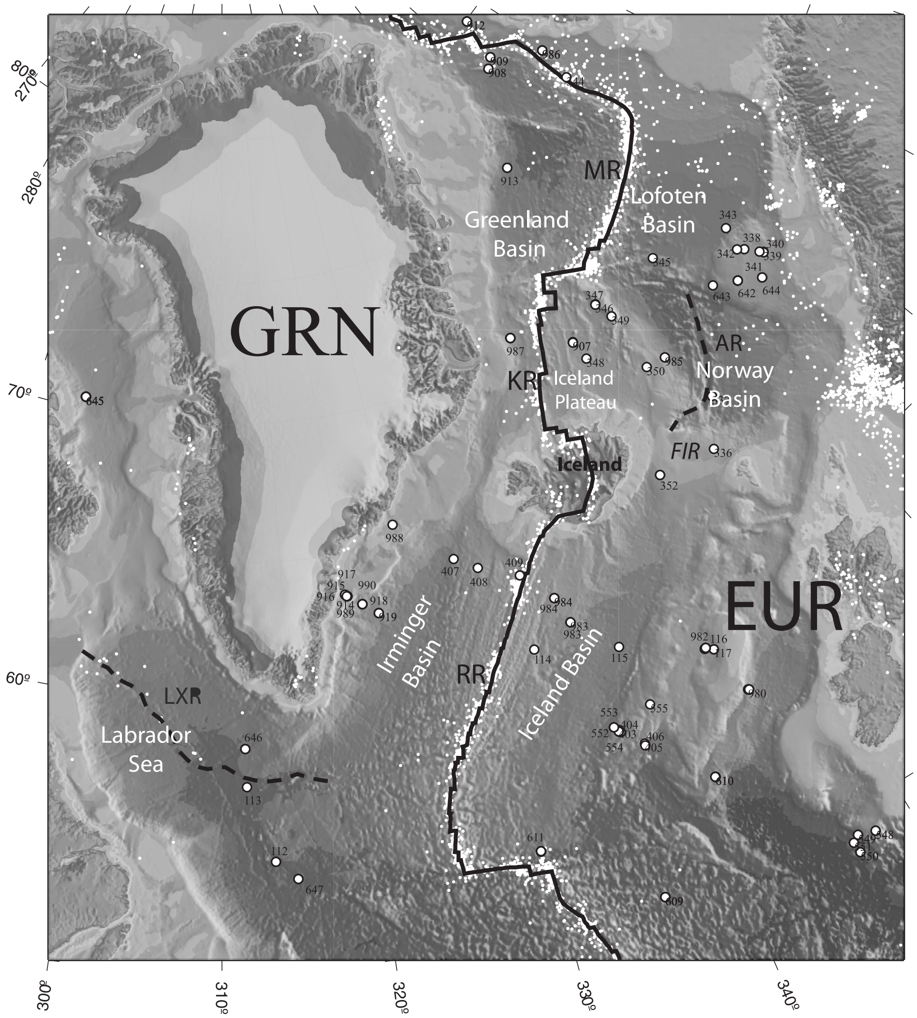

Fig. 1. Topography and bathymetry of the North Atlantic (ETOPO2) and plate boundaries. Active plate boundaries (Bird 2003) are shown by continuous black lines (from north to south): MR, Mohns Ridge; KR, Kolbeinsey Ridge; RR, Reykjanes Ridge. Main extinct ridges are represented by dashed black lines: AR, Ægir Ridge in the Norway Basin; LXR, extinct ridge in the Labrador Sea. GRN, Greenland; EUR, Eurasia; FIR, Iceland–Faeroe Ridge. Open circles indicate sites of Deep Sea Drilling Project (DSDP) or Ocean Drilling Program (ODP) drilling; small white dots indicate location of recent seismicity.

account the effect of mantle advection on plume positions postulate a closer position of the Iceland plume to the breakup position (Mihalffy *et al.* 2008). Other workers have proposed a combination of mechanisms (optionally involving mantle plumes) that acted in different stages on the margins and subsequent oceanic basins (Meyer *et al.* 2007).

In this paper, we present the results of a new study of plate boundary geometry of the NE Atlantic region since the Late Palaeocene. This refined interpretation relies on up-to-date magnetic and gravity data compilations, recent seismic data and a quantitative kinematic analysis. The proposed scenarios that result from this analysis form regional working models and hypotheses that will be tested in the light of new data and presented in future contributions.

Data and methods

Potential field data

Magnetic anomaly and fracture zone picks identified by Gaina *et al.* (2002) were used to locate the main plate boundaries during the opening of the NE Atlantic Ocean. Magnetic anomalies were inverted using the methods of Royer & Chang (1991) and Kirkwood *et al.* (1999) (further details of data uncertainties and methods have been given by Gaina *et al.* (2002)). Additional interpretation of new high-resolution magnetic data collected around the East Jan Mayen Fracture Zone (Olesen *et al.* 2007; Gernigon *et al.* 2009) was also used in the inversion to derive rotation parameters for the evolution of the northern segment of the Norway Basin (Table 1) and therefore the palaeo-positions of the northern part of the Jan Mayen microcontinent.

We have also computed sea-floor spreading parameters (finite rotations; see Table 2) for the basins north and south of the Jan Mayen microcontinent for the time interval of an active triple junction SE of Greenland (i.e. between chrons 24 and 13). This analysis was based on subsets of magnetic anomaly picks (see Figs 2 and 3) and used to test for changes in the regional kinematics and plate boundaries, as discussed below. 4

Corrected Bouguer gravity anomalies were computed using gridded free air gravity anomalies (Sandwell & Smith 1997*a*) and gridded bathymetry data (GEBCO 2003). The complete Bouguer correction was computed assuming a standard value for the difference between water and rock density of 1670 kg m^{-3}. Continent–ocean boundaries (COBs) were interpreted based on residual gravity anomalies and derivatives that were computed from the terrain-corrected Bouguer gravity anomalies (see Fig. 2 for an example of one of the gravity data derivatives used to guide the interpretation of COBs). The COB interpretations from the gravity data were calibrated and tested against the location of the oldest identifiable magnetic chrons (Figs 2 and 4), seismic

Table 1. *Finite rotations of the northern Jan Mayen microcontinent relative to a fixed Eurasia plate*

Chron	Age	Latitude	Longitude	Angle
	30.0	0.00	0.00	0.00
13y	33.1	67.11	129.15	0.62
18o	40.1	−58.90	157.90	8.52
20o	43.8	−60.03	158.66	13.22
21o	47.9	−56.49	153.68	12.89
22o	49.7	−54.60	154.09	13.57
23o	50.9	−55.44	154.43	15.99
24o	53.3	−27.28	136.06	7.11
25y (fit)	55.9	−40.00	145.00	11.40

Table 2. *Finite rotations of Greenland relative to a fixed Eurasia plate*

Chron	Age	Latitude	Longitude	Angle
Based on Gaina et al. *(2002) dataset*				
5o	10.9	66.40	133.00	2.56
6o	20.1	68.90	132.60	5.08
13y	33.1	68.32	132.60	7.68
18o	40.1	61.38	137.81	8.61
20o	43.8	57.80	135.00	8.89
21o	47.9	53.54	128.40	9.29
22o	49.7	50.66	127.80	9.56
24o	53.3	51.50	122.20	11.37
25y (fit)	55.9	52.00	122.80	12.40
Subset of magnetic data from Greenland and Lofoten basins				
5o	10.9	66.40	133.00	2.56
6o	20.1	68.90	132.60	5.08
13y	33.1	68.32	132.60	7.68
18o	40.1	58.87	133.47	7.97
20o	43.8	56.25	130.96	8.45
21o	47.9	53.56	127.71	9.24
22o	49.7	48.49	128.53	9.27
24o	53.3	51.50	122.10	11.35
Subset of magnetic data from Irminger and Iceland basins				
5o	10.9	66.40	133.00	2.56
6o	20.1	68.90	132.60	5.08
13y	33.1	68.32	132.60	7.68
18o	40.1	55.88	136.05	8.00
20o	43.8	57.80	135.35	8.15
21o	47.9	37.02	136.20	8.64
22o	49.7	42.32	136.07	9.47
24o	53.3	51.50	122.20	11.37

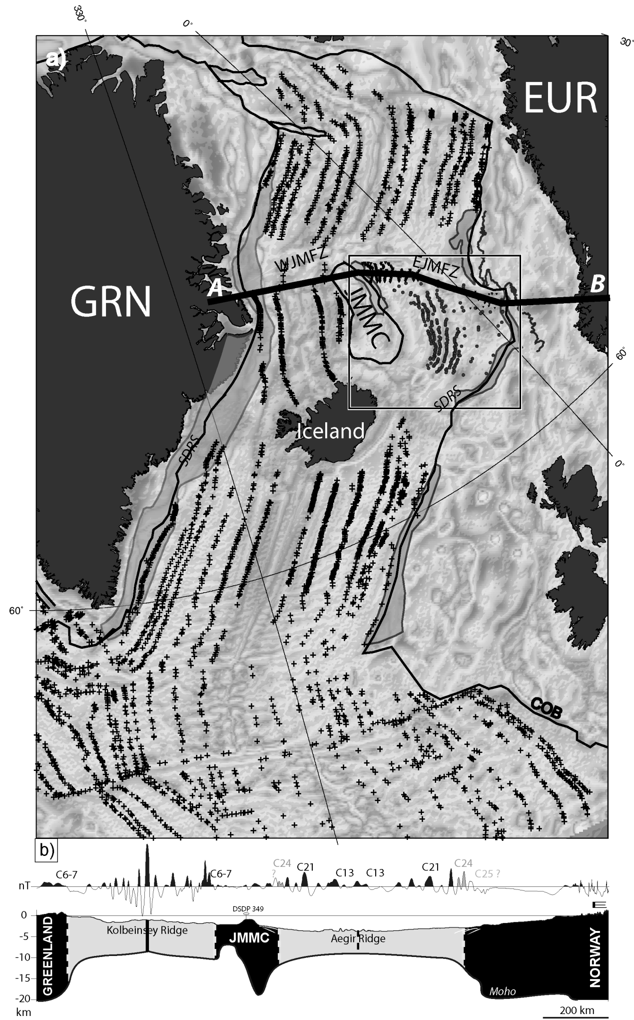

Fig. 2. (**a**) Overview of magnetic data interpretations in the NE Atlantic (+; from Gaina *et al*. 2002). The rectangle shows the location of the magnetic anomaly interpretation in the Norway Basin: ●, based on Verhoef *et al*. (1996) magnetic data compilation; ▼, based on a recent magnetic survey in the northernmost part (Olesen *et al*. 2007; Gernigon *et al*. 2009). Background image is the free air gravity anomaly (Sandwell & Smith 1997*b*; Forsberg & Kenyon 2004) highlighted by the directional derivative (120°) of the free air gravity. Seaward-dipping reflectors (SDRS) are shaded transparent light grey; black line indicates continent–ocean boundary (COB). JMMC, Jan Mayen microcontinent; EJMFZ and WJMFZ, east and west Jan Mayen Fracture Zone, respectively.
(**b**) Schematic crustal transect A–B and magnetic profile across the Norwegian–Greenland Sea. The profile shows the magnetic anomalies from C24 (and possibly C25) to the extinct Aegir Ridge in the Norway Basin, east of the Jan Mayen microcontinent, and from C6–7 to the present Kolbeinsey Ridge, west of the Jan Mayen microcontinent.

reflection lines from the Jan Mayen microcontinent (Fig. 5), and published interpretations of seismic profiles (Richardson *et al*. 1998; Korenaga *et al*. 2000; Nielsen *et al*. 2002; Hopper *et al*. 2003; Spitzer *et al*. 2005).

Seismic data

In this study we have used selected seismic lines from both the IS-JMR-01 and NPD-JM-85 seismic surveys. The IS-JMR-01 survey was collected by Wavefield Inseis ASA between 20 July and 12 August 2001, using the vessel M.V. *Polar Princess*. The survey consists of 2765 km of new filtered migrated reflection seismic recorded to a depth of 10 s and extends the earlier seismic reflection survey (NPD-JM-85) that was jointly collected by the Norwegian Petroleum Directorate (NPD) and the National Energy Authority of Iceland in 1985. This earlier survey has been described and interpreted by Skogseid & Eldholm (1987) and Gudlaugsson *et al*. (1988). The new dataset provides a better picture of the Jan Mayen structures and a better resolution of the seismic facies, which will be described in detail in a future contribution. The interpretation of the IS-JMR-01 and NPD-JM-85 seismic reflection data combined with gravity and magnetic data (Fig. 5) was integrated into our plate-tectonic context, to decipher the tectonic evolution of the Jan Mayen microcontinent and surrounding areas at a regional scale.

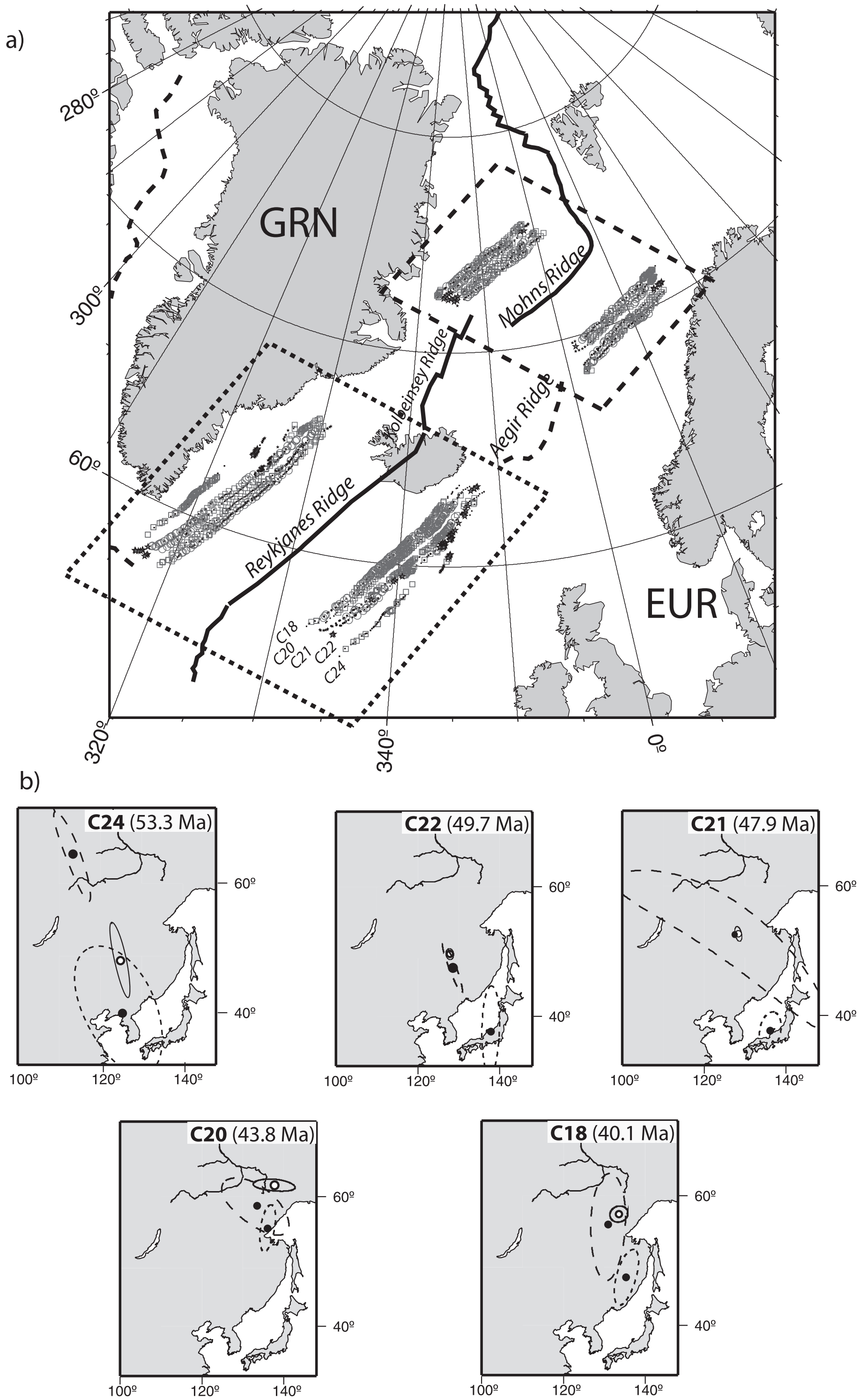

Fig. 3. (**a**) Magnetic anomaly picks (○, present-day positions; ●, reconstructed picks) in the Greenland–Lofoten oceanic basins (dashed line rectangle) and Irminger–Iceland basins (dotted line rectangle). (**b**) Locations of Euler poles and 95% confidence ellipses. For inversions of all data points (i.e. constrained by the North Atlantic triple junction geometry) the confidence ellipses are small (○), whereas for subsets of data points the uncertainty ellipses are larger (dashed line, for rotations derived from magnetic data located in basins north of Jan Mayen microcontinent; dotted line, south of Jan Mayen microcontinent). It should be noted that the 95% confidence ellipses for the northern NE Atlantic intersect most of the time with the triple junction confidence ellipses, except for chron 24. The rotations and 95% confidence ellipses for the oceanic basin south of Jan Mayen microcontinent are mostly independent, except for chrons 24 and 20, when they overlap with the triple junction ellipse and the north NE Atlantic ellipse, respectively.

Plate kinematic model

It is generally accepted that a triple junction between the Eurasia, Greenland and North American plates developed in the Late Palaeocene (*c*. 54 Ma) when spreading initiated between Greenland and Eurasia while sea-floor spreading was still active in the Labrador Sea (between Greenland and North America; e.g. Chalmers & Laursen 1995). This triple junction was active until about 33 Ma, when the sea-floor spreading in the Labrador Sea ceased completely (Roest & Srivastava 1989). This event has been considered as a main trigger of major changes in North Atlantic, and led to the establishment of a continuous plate boundary linking the NE Atlantic and the evolving Eurasian Basin. However, a detailed analysis of geophysical data (including seismic reflection data) and additional information suggests that several events affected the NE Atlantic between breakup and

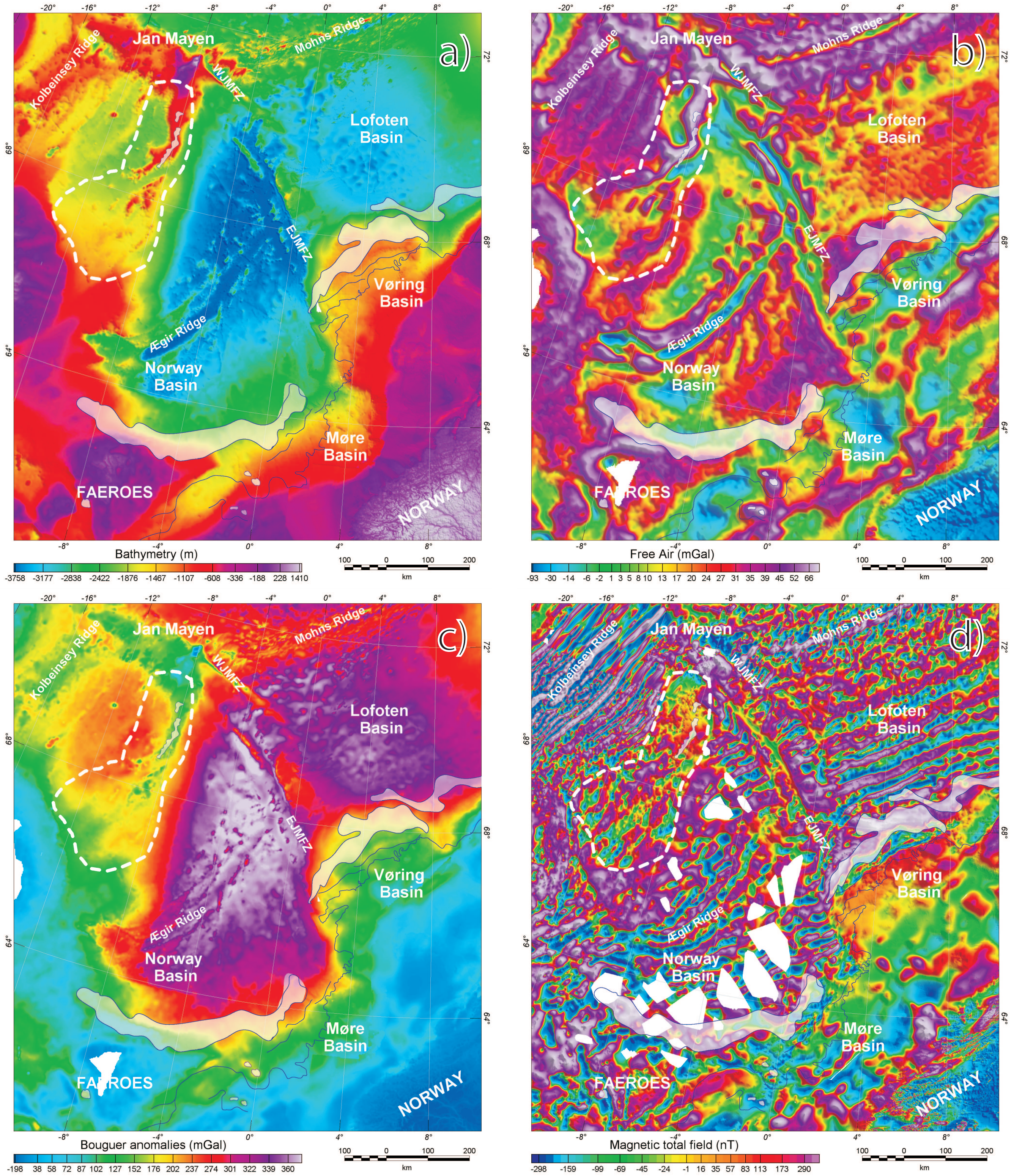

Fig. 4. (**a**) Bathymetry, (**b**, **c**) free air and Bouguer gravity anomalies and (**d**) magnetic anomaly maps of the Jan Mayen microcontinent and surrounding areas.

the final reorganization at chron 13 (33 Ma) when the triple junction became extinct and Greenland became part of North America.

Our new kinematic model relies on: (1) a refined reconstruction of the NE Atlantic based on a large regional dataset including the Labrador and Eurasian Basin magnetic anomaly interpretations (see Gaina *et al*. 2002): model 1; (2) a reconstruction of the Greenland, Lofoten and south of Iceland oceanic basins based on subset of data: model 2; (3) a reconstruction of the Jan Mayen microcontinent based on newly acquired magnetic

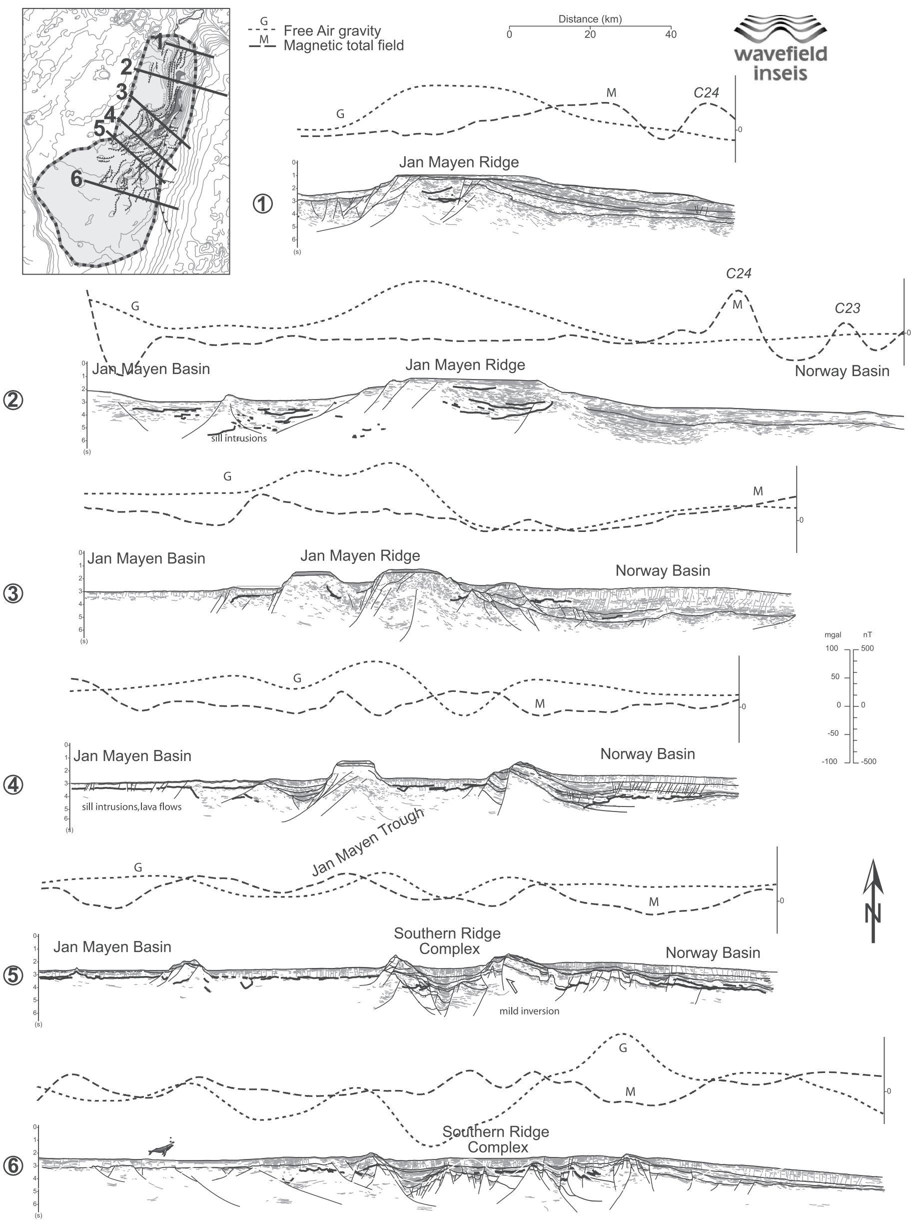

Fig. 5. Interpreted line-drawings from selected seismic lines and gravity and magnetic profiles across the Jan Mayen microcontinent.

data in the northern Norway Basin and Jan Mayen Fracture Zone region (see Gernigon *et al*. 2009, for details): model 3.

Flowlines based on model 1 that show the direction of Greenland motion (with 95% confidence error ellipses attached) relative to Eurasia for nine stages from C25 (55.9 Ma) to the present day, together with the position of the reconstructed present-day outline of the Jan Mayen microcontinent (model 3), are shown on a present-day map in Figure 6. The location of a fixed Iceland hotspot (i.e. present-day position) and a moving Iceland hotspot (see Mihalffy *et al*. 2008) are also displayed to show the proximity of the thermal anomaly to past plate boundaries. A few studies have presented solutions to determine uncertainties of reconstructed hotspot locations (e.g. O'Neil & Steinberger 2005), but they require observations of age progression and hotspot track. Because such observations are not available for the Iceland plume, we do not include uncertainties of the restored Iceland plume locations. It should be noted that if we consider that the Iceland hotspot has been affected by advection in the mantle (Mihalffy *et al*. 2008) its plume head might have been much closer to the active plate boundaries during the opening of the Norway Basin. Also, according to model 1, Greenland underwent a change of direction relative to Eurasia at C21 (47.9–49 Ma) and C18 (39.5–41.2 Ma) (Figs 6 and 7). The change in direction at C21 was preceded by a faster spreading episode (Fig. 7) followed by a reversal in spreading direction rates (i.e. oceanic crust north of the Jan Mayen microcontinent spread faster than that south of the microcontinent) that lasted until C13. To better distinguish between local and regional kinematics, we computed flowlines based on the magnetic data in the northern and southern part of NE Atlantic (model 2, Fig. 8). These models suggest that a change in spreading direction in the Labrador Sea mostly affected the oceanic basins located south of Iceland, but not the Norwegian–Greenland Sea (note the difference in the sea-floor fabric direction illustrated by Fig. 8). In addition, components of the Jan Mayen microcontinent (the northern part of the Jan Mayen

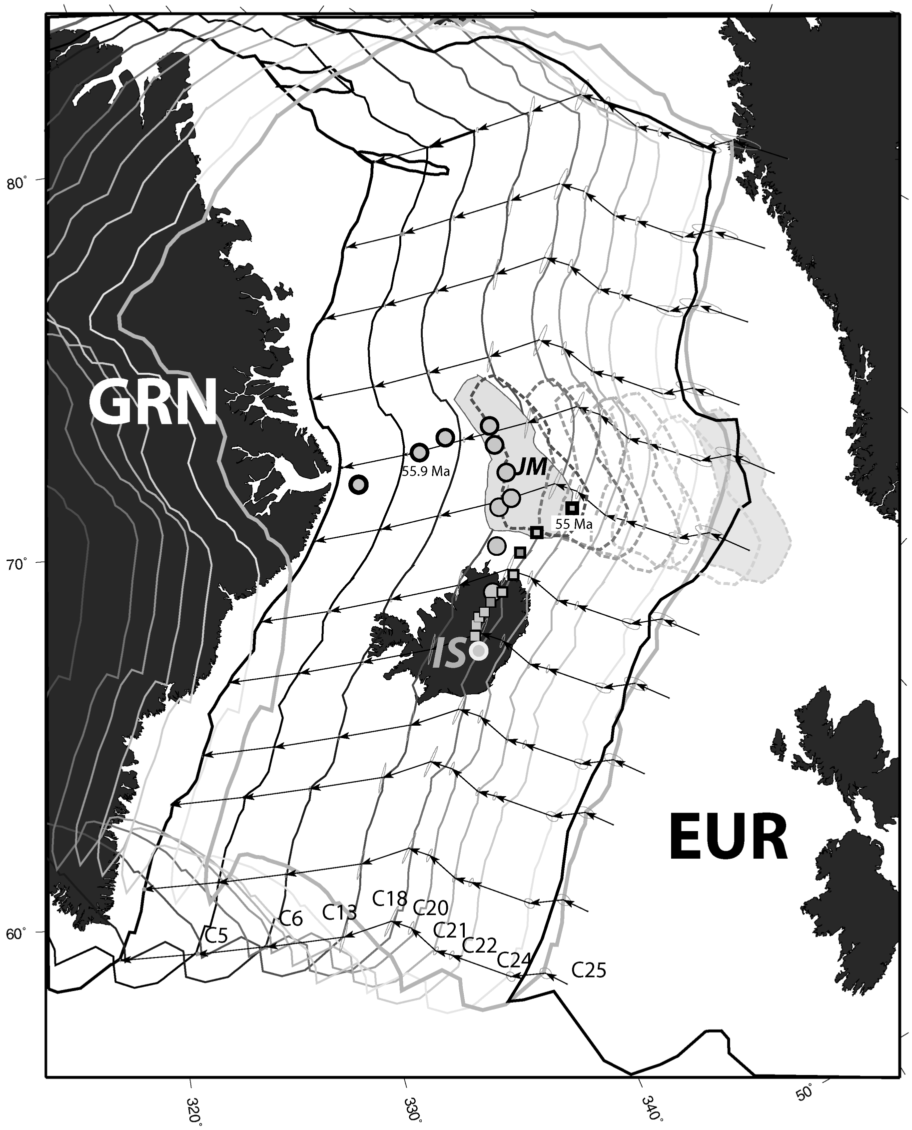

Fig. 6. Reconstructed positions of Greenland (grey contours), present-day outline of Jan Mayen microcontinent (grey, dashed lines), and Iceland hotspot (circles and squares) relative to a fixed Eurasian plate (note that the Jan Mayen microcontinent is rotated according to magnetic chrons interpreted in the northern part of the Norway Basin). Flowlines, motion vectors and 95% confidence ellipses that describe the trajectory of Greenland for a series of stage poles are also shown. The position of the Iceland hotspot is computed according to a stationary hotspot model (Müller *et al*. 1993), here shown as circles for the same time intervals as the reconstructed Greenland and Jan Mayen microcontinent. Open squares show position of the Iceland hotspot based on a moving hotspot model related to advection in the mantle (from Mihalffy *et al*. 2008), here shown for every 5 Ma from the present to 55 Ma. (Note the position closer to Eurasia and the Jan Mayen microcontinent at the time of breakup–sea-floor spreading nucleation (around 55 Ma).)

Ridge) appear to have moved independently (i.e. not as a part of Greenland) during the opening of the Norway Basin, as the flowline computed for a Jan Mayen microcontinent block as part of Greenland (green line and circles plotted immediately north of the Norway Basin) does not coincide with the synthetic flowline computed for an independent northern segment of the Jan Mayen microcontinent (magenta line and circles in Fig. 8).

As an additional test, we have examined the spatial distribution of the two sets of motion vectors describing sea-floor spreading north and south of the Jan Mayen microcontinent. We have plotted these vectors north of the Norway Basin to determine the possibility of an extra plate boundary (i.e. a triple junction) that might have existed because of the differences in sea-floor spreading in the Greenland–Lofoten basins compared with that south of the Jan Mayen microcontinent (e.g. Gernigon *et al*. 2009). The vector triangles (Fig. 9) suggest that an extensional or transtensional extra boundary could have fitted our modelled geometry from C24 to C18. After this, the motion between the two systems started to be accommodated by a transform fault.

To assess the tectonic forces that were active shortly before breakup and during sea-floor spreading in the NE Atlantic, we have computed absolute and relative plate motion vectors for selected locations on the Greenland and Eurasian plates based on a global plate pattern that includes rotations for the North Atlantic according to Gaina *et al*. (2002) and a hybrid absolute framework by Torsvik *et al*. (2009) (Fig. 10). These vectors illustrate the direction of movement based on main stage poles (for each reconstruction the stage rotation is computed between the previous chron and current chron (i.e. in the C25 reconstruction, the arrows show the motion between C31 and C25).

Based on our kinematic model and geological observations, we have constructed an updated evolution model of the NE Atlantic at key intervals defined by magnetic isochrons, kinematic parameters, and rules of plate tectonics. We also include the position of a stationary hotspot (i.e. in present-day position) and a moving hotspot (Mihalffy *et al*. 2008) to allow any straightforward relationship between the hotspot position and plate boundary evolution to be inferred. Below we present the major stages of this model and then describe in detail the implications for the formation of the Jan Mayen microcontinent.

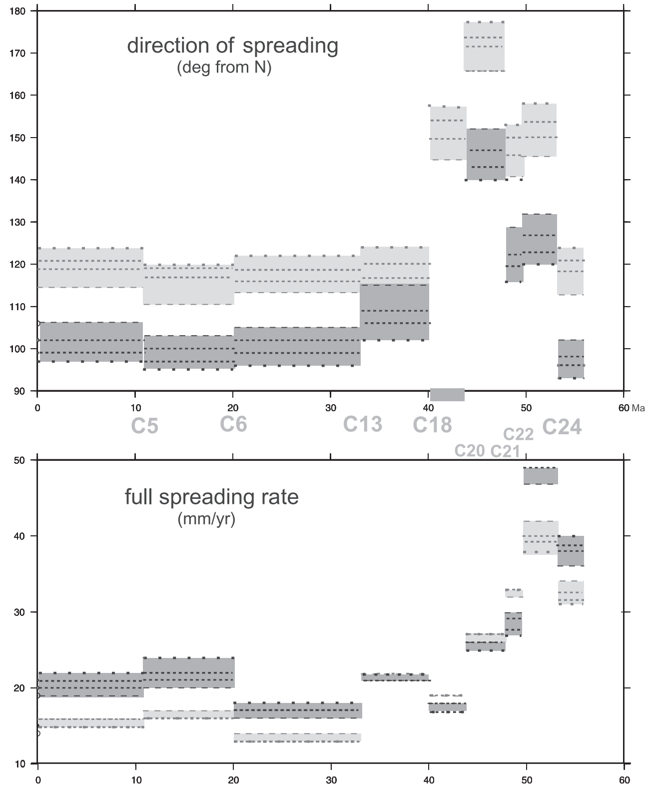

Fig. 7. Spreading rates and directions for NE Atlantic opening computed for a range of locations on active spreading ridges (see Fig. 8). Light grey, northern NE Atlantic; dark grey, southern NE Atlantic; spacing of dotted lines decreases for locations closer to Iceland. This analysis is based on rotations listed in Table 2.

55.9 Ma (chron 25); breakup stage (Fig. 10a)

Extension and finally continental breakup along the NE Atlantic margin occurred after several rift episodes over a period of *c.* 350 Ma (e.g. Ziegler 1988; Skogseid 1994; Glennie 1995). Sea-floor spreading seems to have become established at around 55 Ma (Eldholm & Talwani 1982; Srivastava & Tapscott 1986; Vogt 1986; Ziegler 1988; Skogseid *et al*. 2000). The oldest magnetic anomaly consistently interpreted along the margins of Eurasia and Greenland within the NE Atlantic is C24 (around 53.3 Ma according to the time scale of Cande & Kent (1995)), although older linear magnetic anomalies can be observed locally in the NE Norway Basin (Fig. 2b).

It has been observed that the eastern part of the Norway Basin (offshore NW Møre Basin) displays an excess of oceanic crust (Fig. 4). Skogseid *et al*. (2000) interpreted an oceanic extinct ridge just south of this area (i.e. double chron 24A–C24B), but our preferred interpretation is that sea-floor spreading had an early start in the northern part of the Norway Basin. Based on modern aeromagnetic data, Gernigon (2002) interpreted pre-C24 spreading anomalies south of the Jan Mayen transform margin and postulated that this could represent early embryonic spreading cells older than C24 (possibly formed at C25).

Prior to breakup, at C25, the Eurasian plate had a NE–SW absolute plate motion, whereas Greenland moved faster in an almost east–west direction (Fig. 10a). This difference in the absolute plate motion might have played an important role in the breakup process, as the hotspot location was considerably further from the subsequent Eurasia–Greenland plate boundary. However, within this regional plate setting, and in the absence of the Iceland plume, it remains enigmatic exactly how the North Atlantic rifting processes evolved during the latest stages of rifting and how the sea-floor spreading centres became established.

Many studies have focused on the observation that the margins are often characterized by narrow continent–ocean transitions (COTs) of <100 km width, and that lateral crustal extension factors preceding breakup are anomalously low; these observations have led to discussions about possible depth-dependent stretching mechanisms at the lithospheric scale (e.g. Roberts & Kusznir 1997; Davis & Kuznir 2004; Gernigon *et al*. 2006). There has been much discussion surrounding the spatial and temporal significance of the observed outer margin lava flows, seaward-dipping reflectors (SDRs), and associated intrusions that occur dominantly across the outer margin regions. One shortcoming of all these studies is that uncertainties remain about how the spreading centre first ruptures the surface and how this location is related to the late-stage continental faulting.

The final stages of rifting and the initiation of oceanization processes could be characterized by a lithospheric rupture creating, in the upper crust, a narrow rift, with expansion being mainly caused by intrusion of mantle wedges at depth with lateral extension accommodated by the intrusion of basalt dykes above. Field observations from East Greenland where such a system is exposed onshore confirm that the continental crust located beneath the inner SDRs is considerably dilated and intruded by gabbroic to alkali plutons and margin-parallel dykes that feed overlying traps and SDRs (Karson & Brooks 1999; Geoffroy 2005; Klausen 2006). Recent modelling also shows that the initial distribution of mafic intrusions at depth could significantly contribute to the localization of the deformation and subsequent punctiform initiation of the spreading cells developed along volcanic margins (Callot 2002; Callot & Geoffroy 2004; Geoffroy *et al*. 2007; Gac & Geoffroy 2009; Yamasaki & Gernigon 2009).

The localization of early igneous activity may not only be related to the distribution of late-phase extensional faults and lithospheric thinning, but could also be associated with old crustal zones of weakness. This observation is consistent with a conclusion of Geoffroy *et al*. (1998) that even during the extrusive phase of large igneous province (LIP) evolution magma is channelled through pinpoint crustal pathways that extend downwards to the mantle and may be associated with reactivated suture zones. It is considered probable that within the North Atlantic early magmatic activity also affected more outboard zones of weakness, and it is possible that these were sufficiently damaged that they became the focus of subsequent igneous activity and finally became the sites of crustal rupture after localization of the deformation and rapid thinning of the lithosphere.

53.3 Ma (chron 24); early spreading history (Fig. 10b)

Between the breakup and the formation of the first oceanic crust with normal magnetic polarity (C24), the absolute plate motions of both Eurasia and Greenland changed counter-clockwise to an ENE–WSW direction, with a more pronounced counter-clockwise change in the relative motion from ESE–WNW to east–west. Sea-floor spreading was not continuous between the Greenland (and associated proto-Jan Mayen microcontinent) and the Eurasian margins. Plate margin geometries, motion vectors and magnetic lineations suggest the existence of ‘buffer’ and

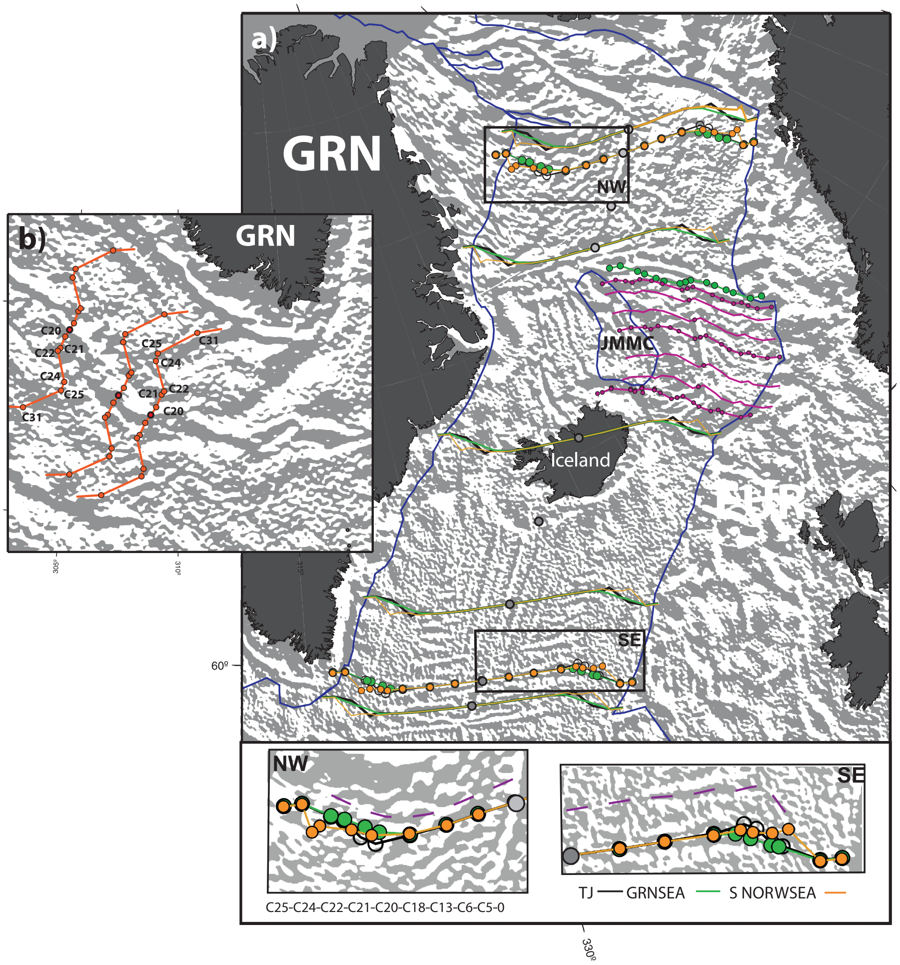

Fig. 8. (**a**) Flowlines between Eurasia and Greenland using the rotation parameters constrained by the triple junction data (black line), magnetic data in the northern NE Atlantic (green lines) or southern NE Atlantic (orange lines) (see Table 2). Background is the directional derivative (70°) of free air gravity anomaly. It should be noted that the flowlines based on data in the southern part of the region show a kink at chron 22 (49.7 Ma) that corresponds to a change in plate motion observed in the Labrador Sea (i.e. between Greenland and North American plates; see (**b**)). This change in plate motions is observed on fracture zones in the Irminger and Iceland basins (see inset SE; dashed red line indicates the general trend of oceanic crust fabric), but not in the Greenland Sea (see inset NW). (**b**) Flowlines showing the direction of extension and sea-floor spreading in the Labrador Sea (orange lines) from chron 31 (68.7 Ma) to chron 20 (43.8 Ma). (Note the change in the sea-floor spreading direction at chron 22 (C22).)

adjacent 'weakened' regions offshore the Faeroe Islands block and SE Lofoten Basin, where plate boundaries attempted to propagate within the Greenland continental domain, or form short-lived triple junctions north and south of the Jan Mayen continental blocks (e.g. Brooks 1973). The existence of a triple junction NE of the Jan Mayen microcontinent (SE Lofoten Basin) is predicted by the kinematic model and has also been suggested by Gernigon *et al*. (2009). The intersections of mid-ocean ridges with the margin of Greenland north and south of the reconstructed Jan Mayen tectonic blocks coincide with major tectonic lineaments and volcanic episodes described by Hald & Tegner (2000) and Tegner *et al*. (2008), and are in agreement with the suggestion by Tegner *et al*. (2008) that post-breakup magmatism along these lineaments is due to evolving plate boundaries and that some of them could represent failed continental rifts.

49.7 Ma (chron 22o) (Fig. 10c)

It has been suggested that a sharp change in the direction of spreading occurred between Greenland and North America around C25 (Roest & Srivastava 1989). This change is recorded by both magnetic data distribution and fracture zone orientation in the Labrador Sea. Detailed interpretation of the magnetic anomalies in the Labrador Sea reveals that additional kinematic changes might have occurred in the time interval between C25 and C20 (Fig. 8b). Flowlines based on the kinematic model of Gaina *et al*. (2002) indicate that Greenland changed its direction of motion relative to North America from SW–NE to SSW–NNE at C24 and then again to SW–NE at C22 (Fig. 8). These changes are also reflected in the oceanic area between Greenland and Eurasia, south of Iceland. Flowlines based on rotations inferred from magnetic data observed in the Irminger and Iceland basins also show a sharp kink at C22, but this change is not observed for the model constrained by the magnetic data from the Greenland and Lofoten basins, and is smoother for the model constrained by all data (Fig. 8). This might indicate internal deformation of the Greenland plate that affected only the oceanic crust SE and SW of Greenland, or a complex NE Atlantic plate boundary that reflects or adjusts a sum of local events as it propagates northward.

Our model suggests an almost continuous sea-floor spreading in the NE Atlantic, interrupted by ocean-ridge propagators localized on the NE and SW sides of the Jan Mayen microcontinent. A renewed episode of volcanism from 50 to 47 Ma has been reported by Tegner *et al*. (2008) in the area south of Kangerlussuaq Fjord. This location was very close to the evolving Reykjanes Ridge at chron 22, and suggests a causal relationship between the onset of this volcanism and the nearby location of the propagating ridge.

The propagator NE of the Jan Mayen microcontinent changed its previous direction and possibly joined the mid-ocean ridge in the Greenland Sea to form a triple junction that included a third ridge or a leaky transform SW of the Greenland Sea along the

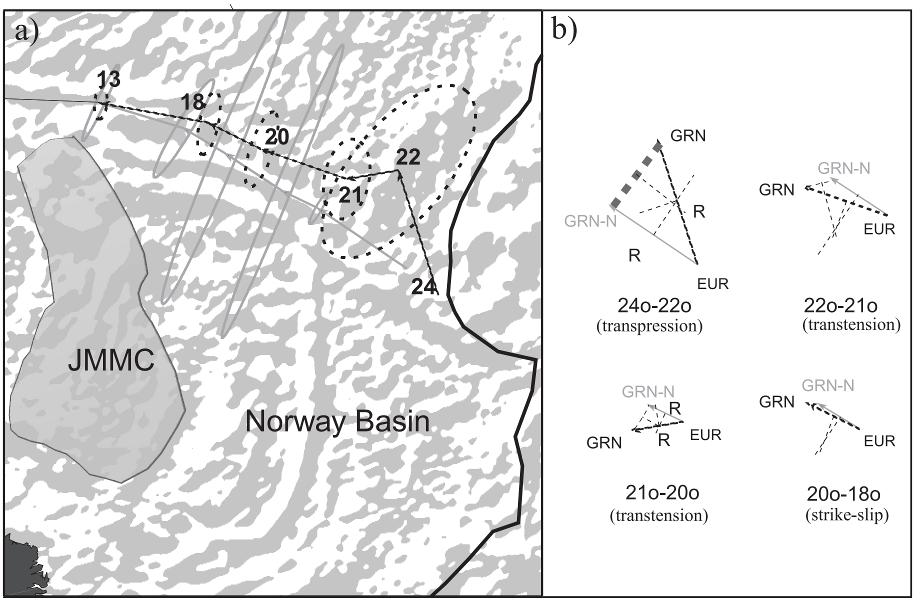

Fig. 9. (**a**) Vectors of motion and their 95% confidence ellipses for Greenland–Eurasia motion as registered in the Lofoten Basin (GRN-N–EUR, grey line) and Iceland Basin (GRN–EUR, dotted black line) calculated for a point situated in the SE Lofoten Basin. (**b**) Triangles formed by closing the motion vectors indicate that an extra plate boundary was required in this region to accommodate transpression and transtension generated by different kinematics of the oceanic areas north and south of the Norway Basin.

trend of the Jan Mayen Fracture Zone. A rapid, almost east–west Greenland absolute motion (compared with a very slow Eurasian plate motion) may have contributed to the vigorous sea-floor spreading between the two plates that lasted from C24 to C22 (see also Fig. 7).

47.9 Ma (chron 21o) (Fig. 10d)

In the middle Eocene, a major change in the absolute and relative plate motions (see also Figs 6 and 7) placed the southern Jan Mayen microcontinent blocks at the intersection with the Reykjanes mid-ocean ridge at C21. This situation might have led to rift propagation into the southern Jan Mayen microcontinent and possible intrusions in the highly extended crust. This period also coincides with the onset of atypical melt production along the trend of the Jan Mayen Fracture Zone as proposed by Gernigon *et al*. (2009). North of the Jan Mayen microcontinent, the NE propagator and a SW propagator or a connection with the Jan Mayen triple junction continued to coexist because extra space was created by the extension between the Jan Mayen microcontinent area and Greenland Sea.

43.8 Ma (chron 20o) (Fig. 10e)

The sea-floor spreading rates show a continuous decrease after C22, a trend also observed in the Labrador Sea. Together with a slowing in the absolute plate motion of Greenland, these events could be explained by one of the phases of the Eurekan orogeny caused by the collision of Greenland and Ellesmere Island (Oakey 2005). This might be also reflected by the major discrepancies between spreading directions in the northern and southern NE Atlantic (Fig. 7). Prior to and during this period, plate boundary readjustments have been recorded along the East Jan Mayen Fracture Zone, where north–south strike-slip displacement and dislocation of the oceanic crust have been described for Early Eocene time (Gernigon *et al*. 2009).

In our model, the continuation of mid-ocean ridge propagation south and SW of the Jan Mayen microcontinent tectonic blocks led to their faster counter-clockwise rotation. As a result, compression could be expected and required in the western part of the Norway Basin to accommodate the deformation. Although the magnetic data coverage east and SE of the Jan Mayen microcontinent is sparse, we observe that the magnetic stripes of ages older than 44 Ma seems to have lost their linear signature, reflecting fractured oceanic crust possibly caused by local compression. Mild compression features have also been observed in seismic data for the eastern part of the Jan Mayen microcontinent (Fig. 5) and confirm the interpretation of Gunnarsson *et al*. (1991) based on earlier seismic data. The ridge continues to propagate more or less continuously within the Jan Mayen microcontinent, leading to higher stretching and/or magmatic dilatation of the continental crust. Simultaneously, the mid-ocean ridge from the Norwegian Sea seems to propagate southwestward. Although the magnetic anomalies offshore Faeroes indicate a series of traces of propagators and V-shaped fracture zones, it is still difficult to know whether a triple junction developed in that region as previously suggested by Smallwood & White (2002), or whether competing propagators may have isolated an oceanic microplate south or SE of the Jan Mayen microcontinent.

40.1 Ma (chron 18o) (Fig. 10f)

In Late Mid-Eocene, the direction of Greenland plate movement relative to Eurasia changed from SSE–NNW to NW–SE and rates of sea-floor spreading in the NE Atlantic decreased below 20 mm a^{-1}, the lowest rate since breakup inception (Fig. 7). At C18, a small increase in the spreading rate accompanied a change in the spreading direction. Our model shows three separate active mid-ocean ridges in the NE Atlantic: (1) the southern branch, which slowly propagated SW of the Jan Mayen microcontinent; (2) the central branch (in the Norway Basin), which was completely disconnected from the northern and southern plate boundaries propagating in the SW Lofoten Basin; (3) the northern segment, which probably continued onshore Greenland within the Kong Oscar Fjord area. Regional dykes and sills in Jameson Land and on Traill Ø are dated at 55–52 Ma and *c*. 35 Ma (Price *et al*. 1997; Hald & Tegner 2000). Our plate-tectonic model suggests that the Greenland Sea plate boundary continued in a direction parallel to or coincident with the trend

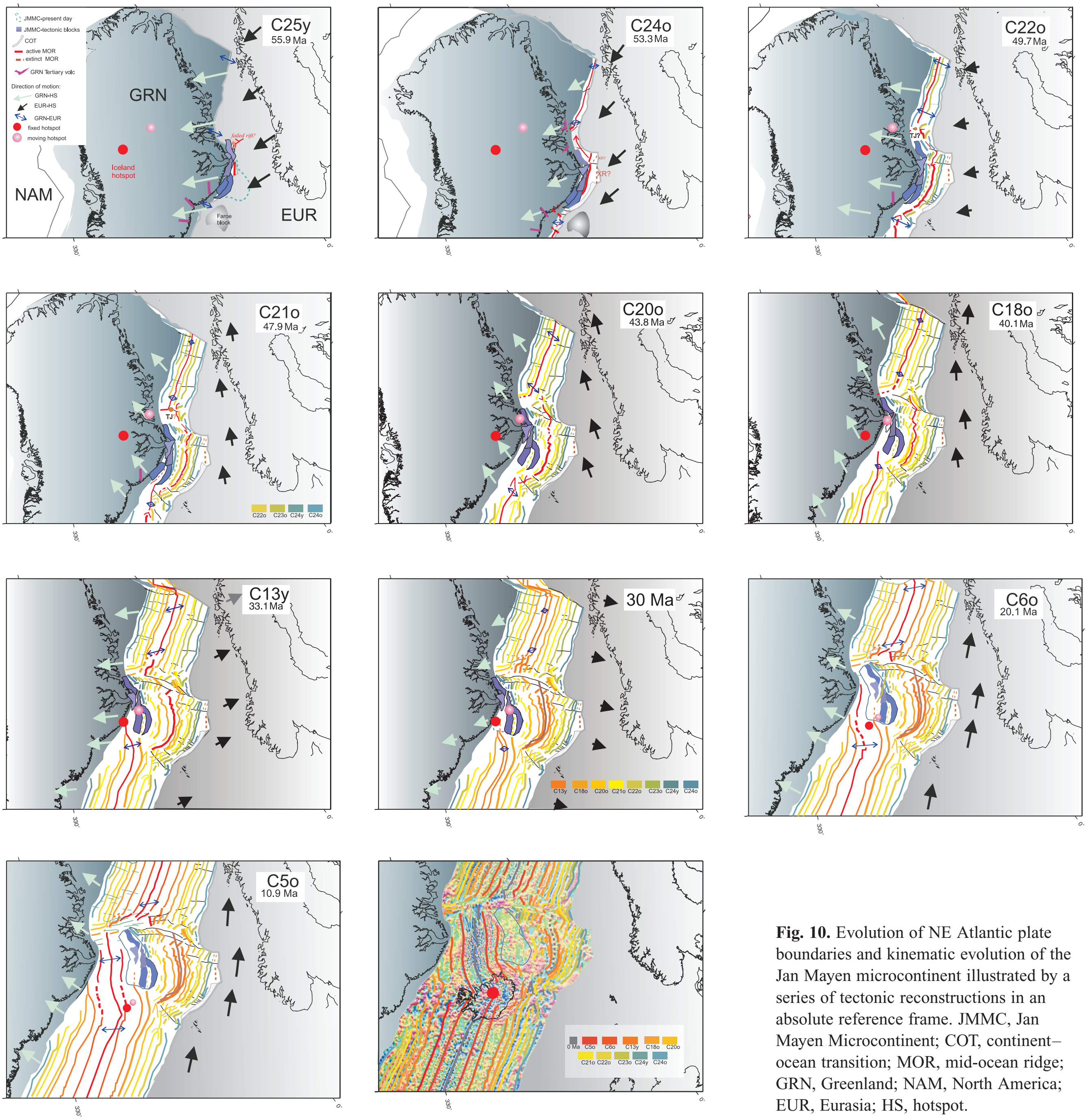

Fig. 10. Evolution of NE Atlantic plate boundaries and kinematic evolution of the Jan Mayen microcontinent illustrated by a series of tectonic reconstructions in an absolute reference frame. JMMC, Jan Mayen Microcontinent; COT, continent–ocean transition; MOR, mid-ocean ridge; GRN, Greenland; NAM, North America; EUR, Eurasia; HS, hotspot.

of Kong Oskar Fjord from breakup until approximately C13. This model might explain the continuation of an episodic magmatic pulse off Jameson Land and Traill Ø.

33.1 Ma (chron 13y)–30 Ma (Fig. 10g and h)

A remarkable change in spreading direction and major plate boundary reorganization took place around C13 time, as for the first time Eurasia and Greenland had opposite absolute plate motion directions. Relative motion between Greenland and Eurasia changed from NW–SE to NE–SW. In addition, the eastern margin of Greenland crossed the Iceland plume central location (in the case of a stationary plume). The proximity of the magma supply from the Iceland plume might have fed the NE Atlantic spreading system more vigorously (Nielsen *et al.* 2002), leading to a starvation of sea-floor spreading in the Labrador Sea and a final relocation of the mid-ocean ridge from the Norway Basin to the Iceland Plateau. We note that the final northward propagation was preceded by almost a standstill of the spreading system with a drop in spreading rates (Fig. 7) and almost stationary Eurasian and Greenland plates (Fig. 10g).

North of the Jan Mayen microcontinent, the Mohns and Aegir ridges were linked by the Jan Mayen Fault Zone until 30 Ma when the Aegir Ridge became extinct. Magnetic anomaly patterns in the South Greenland Basin suggest that the Mohns Ridge was linked with a short-lived ridge that jumped westward from the Norway Basin when the Aegir Ridge became extinct (as suggested by Grønlie *et al*. 1978).

20.1–10.9 Ma (C6o–C5o) (Fig. 10i and j)

The Jan Mayen microcontinent became completely detached from the Greenland margin, and by the time of C5 a continuous spreading ridge has been established through the NE Atlantic linking the Reykjanes Ridge with the Kolbeinsey Ridge, and through a new West Jan Mayen Fracture Zone system, the Mohns Ridge. It should be noted that the ridge also crossed the Iceland hotspot location, along the trend of the Greenland–Iceland–Faeroes Ridge, and this interaction could have triggered mechanical instabilities and eastward ridge jumps within the Iceland region (Smallwood & White 2002).

The Jan Mayen microcontinent formation in the context of the new NE Atlantic model for plate boundary evolution

The plate-tectonic model that we have constructed and the changes in plate boundaries inferred from this model had implications for the Jan Mayen microcontinent formation. In the following we assess these implications using information from the regional potential field data and interpretation of seismic data from the Jan Mayen microcontinent.

The Jan Mayen microcontinent

Previous models. It is now accepted that a large part of the Jan Mayen microcontinent consists of continental crust (e.g. Grønlie *et al*. 1978; Talwani *et al*. 1978; Myhre 1984; Skogseid & Eldholm 1987; Gudlaugsson *et al*. 1988; Gunnarsson *et al*. 1991; Kuvaas & Kodaira 1997). However, its internal structure and the series of events that led to its formation are not yet fully understood. The relationship between Jan Mayen microcontinent formation, regional plate tectonics and volcanism is of particular importance.

K–Ar ages of rocks from Jan Mayen Island confirm that the emergent part of the Jan Mayen Ridge is very young, mostly post-Pleistocene in age (Fitch *et al*. 1965). Nd–Sr–Pb isotope analysis also indicates that rocks from the Jan Mayen Island have an enriched mantle source (Svellingen & Pedersen 2003). The interpretation of the geochemical analysis casts doubt on the plume hypothesis, but confirms that there is no evidence for continental contamination. Consequently, Jan Mayen Island itself should not be considered as part of the Jan Mayen microcontinent.

The continental nature of the Jan Mayen microcontinent defined south of the East Jan Mayen Fault has been mostly confirmed by seismic reflection and refraction surveys across the northern and central block (Myhre 1984; Gudlaugsson *et al*. 1988; Johansen *et al*. 1988; Kuvaas & Kodaira 1997) and from gravity studies (Grønlie & Talwani 1982).

Previous kinematic models suggest that the microcontinent formed once the Aegir Ridge became extinct and the spreading axis 'jumped' westwards to form the Kolbeinsey Ridge approximately between isochron C13 (32 Ma) and C7 (25 Ma) (Vogt & Avery 1974; Talwani & Eldholm 1977; Nunns 1983*a*). Müller *et al*. (2001) proposed a sequence of six events that may lead to the formation of a plume-related microcontinent. They recognized that volcanism can accompany the formation of a microcontinent, but the observed associated magmatic provinces differ as a result of episodic hotspot activity, the shape of the plume or the ridge jump distance. Although the Müller *et al*. (2001) mechanism for the ridge jump–propagation works fairly well in NE Atlantic (explaining post 10 Ma ridge jumps towards the Iceland hotspot), the amount and timing of magmatism related to the Jan Mayen microcontinent formation is less constrained. Repeated ridge jumps and possible ridge propagation, as reported by Talwani & Eldholm (1977), Unternehr (1982), Lundin & Doré (2002) and, more recently, Brandsdottir *et al*. (2006), may cast doubt on the idea of a sudden jump of the ridge system. These findings could suggest instead a gradual and progressive dislocation of tectonic blocks that later formed the present-day microcontinent, or, more likely, a combination of both processes. In this case, the nature of the southernmost part of the Jan Mayen microcontinent could be considered as partly oceanic or may reflect a complex system of highly attenuated and intruded crust.

Jan Mayen microcontinent structure based on earlier and new geophysical data. Examination of the gravity (Sandwell & Smith 1997*b*) and magnetic (Verhoef *et al*. 1996; Olesen *et al*. 2007; Gernigon *et al*. 2009) data reveals a highly variable character of the Jan Mayen region. The magnetic signature of the northern part reveals broad and subdued anomalies, whereas the central and southern part is dominated by higher and linear magnetic anomalies (Fig. 4d). The gravity anomaly shows a relatively broad high-amplitude area (which corresponds to the Jan Mayen ridge), and a gravity low that flanks the Jan Mayen ridge in the eastern part. To the south the gravity character changes and a mixture of (almost parallel) highs and lows can be observed, which suggest a different and more complex tectonic setting (Fig. 4c).

A broad, sinuous gravity high also occurs bordering the block toward the Norway Basin. Based on the gravity signature and the few reliable magnetic profiles available east of the Jan Mayen microcontinent, we have drawn a tentative interpretation of the COB. A precise boundary is currently difficult to establish, especially for the southern part, not only because of the complicated sea-floor spreading pattern, but mostly because of poor data coverage in this part of the Norwegian–Greenland Sea. In the southernmost part of the Jan Mayen microcontinent, younger volcanic activity might have also overprinted both the magnetic and gravity signatures (Fig. 4), and a detailed interpretation of the southern Jan Mayen microcontinent structure requires additional data. However, in the northern and central part of the microcontinent, both potential field data and recent seismic lines clearly illustrate a progressive and dramatic change in structure from a relatively uniform continental block in the north (e.g. the Jan Mayen Ridge) to a dislocated continental or transitional domain where several horsts and grabens can be observed. This structural architecture explains the potential field signature and indicates that the Jan Mayen microcontinent experienced severe extensional regimes increasing from north to south (Fig. 4).

The Jan Mayen Trough and the Jan Mayen Basin have been tentatively interpreted as highly attenuated continental crust. Previous interpretations suggested that these anomalous 'basin' lows were continental and that the 'oceanic' character of the seismic reflection data was caused by (1) a high-impedance sedimentary layer, (2) a volcanic ash layer, (3) intra-sedimentary sills, or (4) lava flows (Gudlaugsson *et al*. 1988). Regardless of the exact nature of the crust within these grabens, they are often interpreted to reflect post-breakup (Early Tertiary) extension, which could have already been active in Eocene–Oligocene time, long before the final split between the Jan Mayen microcontinent and Greenland.

A new kinematic model for the formation of the Jan Mayen microcontinent. Magnetic anomaly data (Figs 2 and 4d) and kinematic parameters indicate that breakup and sea-floor spreading started to detach parts of the Jan Mayen microcontinent as early as C25 (around 56 Ma). Before breakup, the Jan Mayen microcontinent was probably composed of a few continental blocks (including the Jan Mayen Ridge) located in the southern prolongation of the outer Vøring Basin, probably as a direct continuation of the South Gjallar–Rån ridges, a Mesozoic ridge complex defined both at the base Tertiary and base Cretaceous levels (Gernigon *et al*. 2003). Therefore, the Jan Mayen microcontinent probably also experienced deformation related to the late Cretaceous–Late Palaeocene rifting and thinning phases recorded in the outer Møre and Vøring basins (Gernigon *et al*. 2003, 2006). We also note that most of the tilted features observed at present on the Jan Mayen microcontinent have been influenced by post-breakup uplift and tilting of the microplate. It is also possible that some of the dipping wedge interpreted as volcanic SDRs could partly represent older synrift sedimentary features. In the light of this working hypothesis, we could also question the origin of the Jan Mayen Basin, located west of the Jan Mayen Ridge. It is possible that this basin could have initiated earlier in Cretaceous time and reactivated later during the final rifting leading to the second and ultimate phase of breakup between the proto-Jan Mayen microcontinent and Greenland.

During the first breakup stage, our kinematic model suggests that a system of propagating ridges formed north and NE of the Jan Mayen Ridge leading to a counter-clockwise rotation of this block between C25 and C24 (Fig. 10a). The ridge propagating from the southern NE Atlantic seems to have failed to join the active ridge in the Norway Basin, resulting in the formation of a wide zone of extension and/or transtension south and SE of the Jan Mayen microcontinent. The presence of inherited features on the Eurasian margin and the existence old Archaean crust on the Faeroes block (Bott *et al*. 1974) and East Greenland margin probably hindered breakup initiation and the establishment of a continuous sea-floor spreading system in this region. In addition, the presence of weak heterogeneities in the lithosphere as described by Callot (2002) could also have influenced the rift and proto-ocean ridge distribution in that area. Last, but not least, melting heterogeneities in the sub-lithospheric mantle may have triggered the breakup and early sea-floor spreading in regions situated far from mantle plumes, as suggested and modelled in various studies (Thompson & Gibson 1991; Callot & Geoffroy 2004; Geoffroy *et al*. 2007; Yamasaki & Gernigon 2009).

Kinematic reconstructions (Fig. 10b) suggest that extension occurred in the SE part of the Jan Mayen microcontinent at about C21 (48 Ma). We suggest that at this time the southernmost tip of the Aegir Ridge was still active, competing with the northernmost part of the ridge axis from the southern NE Atlantic. However, because of the intricate pattern of magnetic anomalies on the Icelandic plateau, this interpretation does not exclude other scenarios. Irrespective of the exact configuration of the oceanic crust off the Faeroes and on the Icelandic Plateau, the southern part of the Jan Mayen microcontinent was definitely exposed to extensional forces and we postulate a rift propagation that extended and dislocated the southernmost blocks of the microcontinent.

We interpret a series of competing ridges (and V-shaped pseudo-fault patterns) south and SE of the Norway Basin at C20 (44 Ma) time, and a final westward ridge jump of the southern ridge at C18 (40 Ma). This jump propagated again into the southern part of the Jan Mayen microcontinent and led to extension of its southwestern margin. The two episodes of extension in the southern part of the Jan Mayen microcontinent resulted in a certain amount of counter-clockwise rotation of its southwestern part. This led to the fan-shaped spreading development of the Norway Basin in its later stage and to local compression on the east or SE margin of the Jan Mayen microcontinent (and possibly the NW margin) as observed in seismic data (Fig. 5b, line 6). A gravity high along the SE margin and the highly disrupted magnetic anomaly pattern in the SW Norway Basin may represent the loci of compressive stress (Fig. 5a). All these observations support and agree with our kinematic model and demonstrate the importance of such integrated studies from large-scale geodynamic to basin-scale investigations.

Around 30 Ma, the Aegir Ridge became extinct and the ridge propagating from the southern NE Atlantic managed to completely detach the southern part of the Jan Mayen microcontinent by C6 (20 Ma). It should be noted that the modelled readjustment of plate boundaries north of the Jan Mayen microcontinent implies short periods of compression or transpression between the Jan Mayen Ridge and Greenland (Fig. 10g and h).

The Jan Mayen microcontinent complex tectonic history is also reflected by the presence of major unconformities, which are identified within the seismic reflection data. Dating of these reflectors could be relatively simple if the observations of the plate model are used. Tentatively we suggest that the deepest observed unconformity could represent the first breakup unconformity between the Jan Mayen microcontinent and the Norwegian margin, and subsequent unconformities could represent the various ridge jumps before the final ridge jump, which led ultimately to the microcontinent rifting from East Greenland at some time after 30 Ma.

Mechanisms of microcontinent formation

Our understanding of microplate formation has advanced in recent decades as a result of studies revealing detailed structure (mainly with a wealth of high-resolution onshore or offshore data) and attempting complex modelling (e.g. Hey *et al*. 1985; Sempere & MacDonald 1986; Lonsdale 1988; Bird & Naar 1994; Wilson & Hey 1995; Katz *et al*. 2005; Koehn *et al*. 2007). However, most of these studies focused on homogeneous microplates whose composition is either purely oceanic or continental. It should be noted that the overall extension at a mid-ocean ridge is orders of magnitude larger than at an extensional continental rift; and continental and oceanic microplates behave differently while they are forming (e.g. oceanic microplates can grow while they rotate). Models on rift or ridge propagation show that inherited structures (Van Wijk & Blackman 2005; Koehn *et al*. 2007), stress-dependent damage around the microplate corners (Hieronymus 2004), hotspot magmatic heating rate, spreading rate, sea-floor ages and the location of a hotspot (Mittelstaedt *et al*. 2008) are important parameters that determine the formation and evolution of a microplate.

There have been few attempts to explain the causes and detailed evolution of a stranded continental block within an oceanic basin. For example, the models of Müller *et al*. (2001) and Gaina *et al*. (2003) postulate that a strong thermal anomaly (possible a mantle plume) is responsible for repeated ridge jumps that lead to the formation of continental slices and isolate them within oceanic crust. Although they did not analyse the processes of microcontinent formation in detail, Eagles *et al*. (2002) described a kinematic model for the Danakil microplate and rift propagations that resulted in oceanization around a continental block. Recently, Collier *et al*. (2008) presented a study on the Seychelles microcontinent in the Indian Ocean and concluded that external plate boundary forces, rather than the impact of a mantle plume, were largely responsible for the rifting of this continental block from India. It should be noted that all these examples of microcontinents were associated with episodic magmatic events and were situated at a certain stage of their evolution in proximity to a thermal anomaly.

Our study of the evolving plate boundaries in the NE Atlantic and the separation of the Jan Mayen microcontinent suggests that the inherited structure (rigid continental blocks separated by older Mesozoic rifts), horizontal forces as a result of the separation of major tectonic plates, the proximity of the Iceland hotspot and the distribution of magma within the lithosphere are all important ingredients for the formation of the microcontinent. However, the exact succession of events, the causes and consequences remain to be established by more detailed data and modelling.

Conclusions

A new kinematic model has been constructed for the evolution of the NE Atlantic. This model is based on magnetic and gravity data interpretation, and seismic and geological observations, and has been constructed using quantitative reconstruction tools.

We have identified a series of plate boundary readjustments expressed by short-lived triple junctions and/or ridge propagations particularly in the area north and south of the Jan Mayen microcontinent. Although isolated changes in the plate boundary in the NE Atlantic have been previously suggested in the literature, this is the first time that a comprehensive and integrated regional model has presented the complexities in the evolution of plate boundaries along the entire NE Atlantic.

In particular, we have analysed the implication of these tectonic events for the formation of the Jan Mayen microcontinent. The new plate kinematic model and preliminary interpretations of potential field and seismic data indicate that the Jan Mayen microcontinent experienced a significantly longer and more complex tectonic evolution than has previously been considered. Several tectonic blocks within the Jan Mayen microcontinent have been interpreted, and we suggest that the southernmost extended, fragmented character of the Jan Mayen microcontinent is a product of several failed ridge propagation attempts of the Kolbeinsey Ridge. This interpretation agrees with a preliminary result of Brandsdottir *et al*. (2006), which suggests a series of failed rifts on the Icelandic Plateau and contradicts models that postulate sudden relocation of the plate boundary from the Norway Basin to the west of the Jan Mayen microcontinent. In addition, we have identified several compressional events SE and NW of the Jan Mayen microcontinent that are partially confirmed by geophysical evidence.

Our model implies a series of failed ridges offshore the Faeroe Islands, a northern propagation of the Aegir Ridge NE of the Jan Mayen microcontinent, and a series of short-lived triple junctions and/or propagators in the southern Greenland Basin. The propagation of plate boundaries within the Greenland plate led to episodic magmatic events, as suggested by Tegner *et al*. (2008).

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