Geological Society, London, Special Publications Online First

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David Ellis and Martyn S. Stoker

Geological Society, London, Special Publications, first published February 20, 2014; doi 10.1144/SP397.1

Notes

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

DAVID ELLIS[1]* & MARTYN S. STOKER[2]

[1]*Statoil (UK) Limited, One Kingdom Street, London, W2 6BD, UK*

[2]*British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 3LA, UK*

**Corresponding author (e-mail: ddael@Statoil.com)*

Abstract: The Faroe–Shetland Basin is located offshore NW Scotland on the SE margin of the Atlantic Ocean and comprises numerous sub-basins and intra-basin highs that are host to a number of significant hydrocarbon discoveries. The principal hydrocarbon discoveries are in Paleocene–Eocene strata, although earlier strata are known, and their existence is therefore intimately linked to the opening and evolution of the North Atlantic from 54 Ma. The final rifting and separation of Greenland from Eurasia is commonly attributed to the arrival of a mantle plume which impacted beneath Greenland during early Tertiary time. Moreover, the ensuing plate separation is commonly described in terms of instantaneous unzipping of the North Atlantic, whereas in reality proto-plate boundaries were more diffuse during their inception and the linked rift system which we see today, including connections with the Arctic, was not established until Late Palaeogene–Early Neogene time. From a regional analysis of ocean basin development, including the stratigraphic record on the adjacent continental margins, the significance of the Greenland–Iceland–Faroe Ridge and the age and role of Iceland, we propose a dual rift model whereby North Atlantic break-up was only partial until the Oligo-Miocene, with true final break-up only being achieved when the Reykjanes and Kolbeinsey ridges became linked. As final break-up coincides with the appearance of Iceland, this model negates the need for a plume to develop the North Atlantic with rifting reliant on purely plate tectonic mechanisms, lithospheric thinning and variable decompressive upper mantle melt along the rifts.

It is a generally accepted model that North Atlantic seafloor spreading began at 54 Ma and rifted Greenland from Eurasia; this process continues to the present day (Pitman & Talwani 1972; Srivastava & Tapscott 1986; Fig. 1). Prior to this final rift, the North Atlantic margins had also been subjected to several earlier phases of extension between the Devonian collapse of the Caledonian Orogen and the early Tertiary break-up (Ziegler 1988; Doré *et al.* 1999; Roberts *et al.* 1999). These pre-Paleocene rifting phases exploited the collapsed Caledonian fold belt and consequently the conjugate North Atlantic margins show similar basinward stepping rift patterns (Doré *et al.* 1999). The final rifting and separation of Greenland from Eurasia at 54 Ma has also been attributed to the arrival and impact of an upwelling mantle plume which impinged on the base of the lithosphere under Greenland during early Tertiary time (e.g. White 1989; White & McKenzie 1989; Smallwood *et al.* 1999; Smallwood & White 2002). Its modern-day much-reduced expression is the Iceland plume of many authors (e.g. Courtillot *et al.* 2003). A plume here is defined as a convective upwelling of lower mantle material due to thermal instability near the core–mantle boundary (Morgan 1971).

It is interpreted that the impact of the plume head with early Tertiary rifting led to large volumes of surface and subsurface magmatic activity, including the generation of seawards-dipping reflectors and the linear and abnormally thickened (up to *c.* 30 km) Greenland–Faroes Ridge (the GFR of Holbrook *et al.* 2001; the Greenland–Iceland–Faroe Ridge or GIFR of Gaina *et al.* 2009; Fig. 1). Calculated melt volume is estimated at $5 - 10 \times 10^6$ km^3 and led to the North Atlantic being referred to as the North Atlantic Igneous Province (NAIP) (White 1988; Saunders *et al.* 1997). Production of this melt was not uniform, with initially high production and seafloor spreading at 54 Ma declining to almost zero between 35 and 25 Ma before North Atlantic plate reorganization re-established a slow but steady spreading rate up to the present day (Fig. 2).

This instantaneous unzipping model for the North Atlantic has had a major impact on regional post-Cretaceous North Atlantic plate tectonic and palaeo-geographic reconstructions, basin modelling and, consequently, hydrocarbon exploration in offshore UK, Ireland and Norway (e.g. Larsen & Watt 1985; Holmes *et al.* 1999; Knott *et al.* 1999; Roberts *et al.* 1999; Carr & Scotchman 2003). The instantaneous unzipping of the North Atlantic is

From: Cannon, S. J. C. & Ellis, D. (eds) *Hydrocarbon Exploration to Exploitation West of Shetlands*. Geological Society, London, Special Publications, **397**, http://dx.doi.org/10.1144/SP397.1

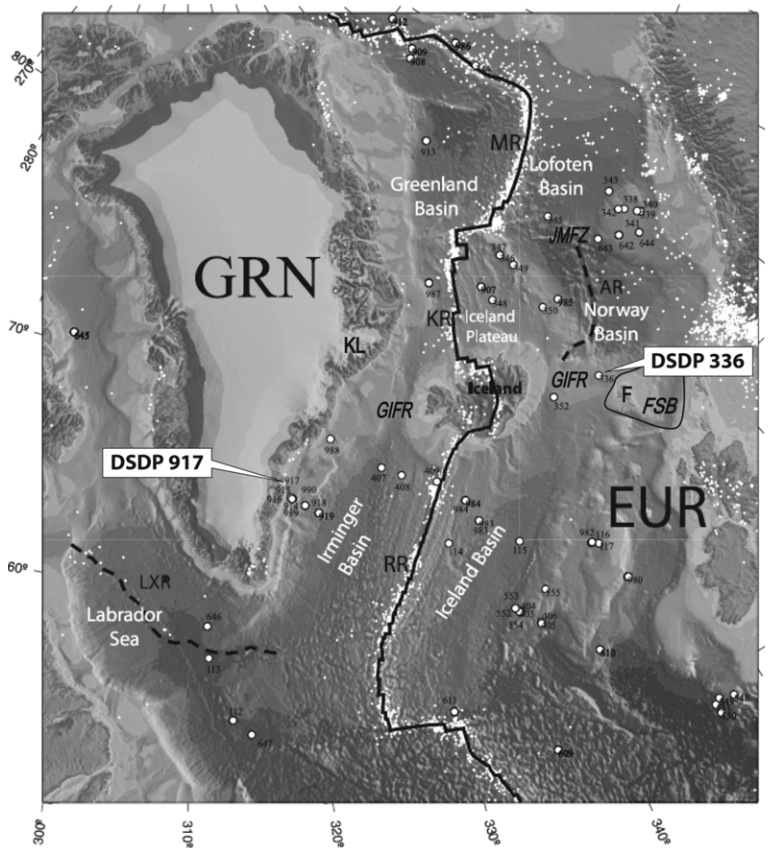

Fig. 1. Topography and bathymetry of the North Atlantic with active plate boundaries (black lines; extinct ridges are dashed black lines). From north to south: MR, Mohns Ridge; KR, Kolbeinsey Ridge; RR, Rekjanes Ridge; AR, extinct Aegir Ridge; LXR, Labrador Sea extinct ridge; GRN, Greenland; EUR, Eurasia; GIFR, Greenland–Iceland–Faroe Ridge; JMFZ, Jan Mayen Fracture Zone; F, Faroe Islands; FSB, Faroe–Shetland Basin; KL, Kangerlussuaq. Open circles indicate sites of Deep Sea Drilling Project (DSDP) or Ocean Drilling Program (ODP) drilling. Small white dots indicate location of recent seismicity (after Gaina *et al.* 2009).

also partially predicated on plate tectonic modelling packages which require 100% defined plate boundaries in order to operate (e.g. Skogseid *et al.* 2000; Gaina *et al.* 2009). In reality, the proto-plate boundaries were probably more diffuse during their inception and more analogous to the NE African Rift data coming out of Ethiopia (Beutal *et al.* 2010; Ferguson *et al.* 2010; Rychert *et al.* 2012).

As authors we use published data and interpretations to challenge the above model and suggest there is more evidence that the North Atlantic did not unzip in one event at 54 Ma or that it was driven by a plume process. The plume engine model has also recently been challenged by others (e.g. Foulger 2002; Foulger & Anderson 2005; Lundin & Doré 2005*a*, *b*; Gaina *et al.* 2009; Gernigon *et al.* 2009; Foulger 2010). On the basis of the evidence presented in this paper, we propose that the North Atlantic opening was the result of the development of opposing rifts, one developing SW from the North Atlantic (between Greenland and Norway) and the other NE from the central Atlantic (between Ireland and SE Greenland). These changed in importance and evolved through time with plate tectonic development of the North Atlantic from Paleocene time to the present.

Initial development and dating of the North Atlantic oceanic crust

Plate reconstructions and their development through time, such as those proposed for the North Atlantic, are constrained by dated sequences of magnetochrons resident in the spreading oceanic crust. It is generally accepted that North Atlantic oceanic

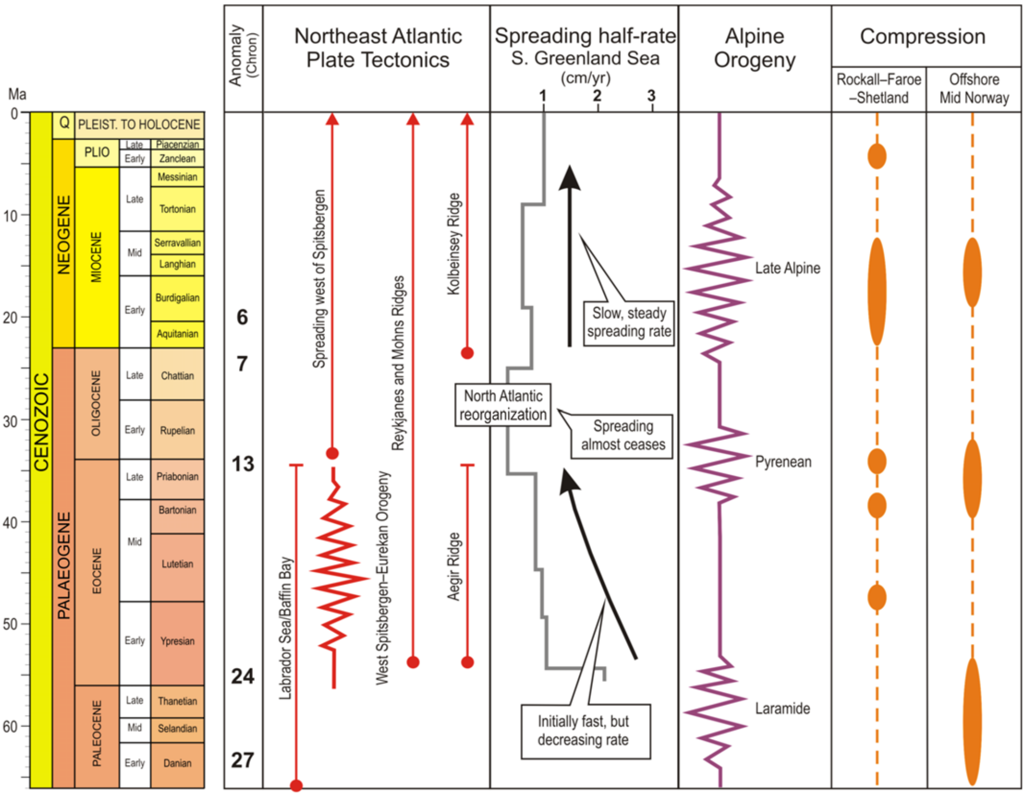

Fig. 2. Regional Palaeogene–Neogene tectonostratigraphic framework of the NW European Atlantic margin. Sources: Doré *et al.* (1999, 2008); Johnson *et al.* (2005); Ritchie *et al.* (2008); Statoil UK Ltd. Timescale from Gradstein *et al.* (2004).

crust first began forming during Chron 24 (54.5 Ma, Fig. 2). Using modern gravity and magnetic data with recent regional seismic and quantitative kinematic analysis, Gaina *et al.* (2009) published a map of North Atlantic magneto-chrons and their confidence in their location and recognition (Fig. 3). There are two key observations which can be made from this data. Firstly, the chrons defining the initial margins of the oceanic crust are not well constrained along the margins of the North Atlantic (Figs 3 & 4). For example, in some areas adjacent to the proposed continent–ocean boundary (COB) they exhibit a patchy magnetic pattern not typical of through-going magnetic seafloor striping (Figs 3 & 4). Similar anomalies have been recognized in the Labrador Sea and have been attributed to highly intruded or extended continental crust (Chalmers & Pulvertaft 2001). This implies that at break-up the crust was rifting, in a manner analogous to the separation of inter-digitating ‘fingers’, with areas of incipient oceanic crust adjacent to deforming and intruded continental crust. A uniform, instantaneous separation with general full production of oceanic crust along the entire length of the Atlantic rift therefore appears unrealistic. Similar observations have been made along the active Ethiopian and Afar rifts where magmatism is confined to elongate and independent magma chambers with associated active dyke intrusions above. These active magmatic centres are separated by laterally intervening areas of tectonic quiescence (Beutal *et al.* 2010; Pagli *et al.* 2012; Rychert *et al.* 2012).

The first definitive and continuous magneto-chron implying extensive oceanic ridge production of basalts is Chron C21 (48 Ma), which is linked to the Aegir Ridge in the Norway Basin and to the Reykjanes Ridge in the Irminger–Iceland basins SE of Greenland (Figs 1 & 3). This chron does not link across the GIFR and leads to the second major observation: the GIFR and the linear interval between the east and west Jan Mayen fracture zones (EJMFZ and WJMFZ) both exhibit patchy magnetic patterns along their entire length. Additionally, they are defined by a thickened and linear

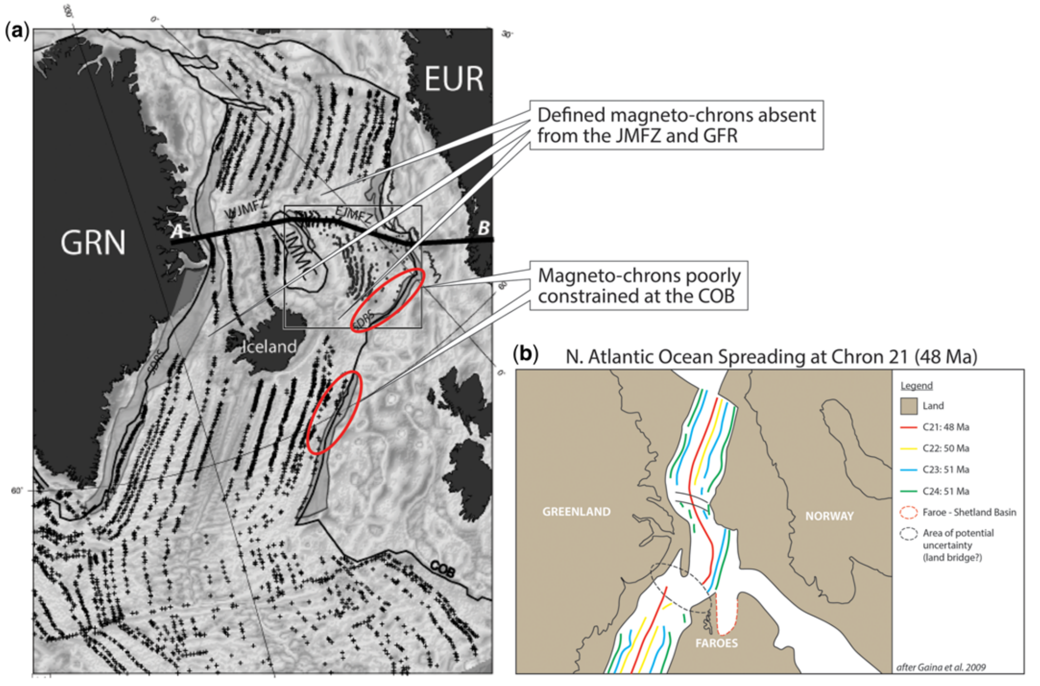

Fig. 3. (**a**) Magnetic data interpretations in the NW Atlantic. Background image is the free air gravity anomaly (Sandwell & Smith 1997; Forsberg & Kenyon 2004). Seaward-dipping reflectors (SDRS) are shaded transparent light grey. The black line indicates the continent–ocean boundary (COB). JMMC, Jan Mayen micro-continent; EJMFZ and WJMFZ, the east and west Jan Mayen fracture zones, respectively (after Gaina *et al.* 2009). (**b**) Simplified NW Atlantic magnetic interpretation (after Gaina *et al.* 2009).

crustal signature (Holbrook *et al.* 2001; Gernigon *et al.* 2009) (Fig. 3). Further interpretation of these is discussed in the following.

Evolution and dating of the oceanic ridges separating the North Atlantic province

Evolution of the North Atlantic from Late Paleocene time to the present day involved initial spreading in the Labrador Sea, along the Reykjanes Ridge, along the Aegir Ridge and then finally along the Kolbeinsey Ridge. The Oligo-Miocene linking of the Reykjanes and Kolbeinsey ridges resulted in the separation of the Jan Mayen micro-continent from east Greenland.

In conjunction with early rifting along the Reykjanes Ridge, the spreading in the Labrador Sea created a triple junction to the SE of Greenland which allowed simultaneous spreading along both rift arms (Gaina *et al.* 2002, 2009; Lundin & Doré 2005*a*) (Fig. 1). The Atlantic spreading arm utilized the collapsed Caledonian fold belt with its associated Mesozoic rift system (Lundin & Doré 2005*a*). This dual rifting involving the Labrador Sea and the Reykjanes rift continued between 54 and 33 Ma (Chron 24–Chron 13) when rifting then ceased in the Labrador Sea. Abandonment of the Labrador Sea and Baffin Bay spreading ridge resulted in a North Atlantic plate reorganization and the beginning of the next phase of North Atlantic opening (Røest & Srivastava 1989; Gaina *et al.* 2002; Lundin & Doré 2005*a*; Gaina *et al.* 2009). This coincides with Chron 13 (33 Ma) and represents a significant change in relative motion between Greenland and Eurasia from NW–SE to NE–SW (Gaina *et al.* 2009). Prior to Chron 13 (33 Ma), the NE propagation of the Reykjanes Ridge failed to penetrate any further north than the Kangerlussuaq area in east Greenland. Successive but unproductive attempts to propagate N–NE led to the gradual peeling away of the Jan Mayen micro-continent from east Greenland (Kuvaas & Kodaira 1997; Gaina *et al.* 2009; Fig. 5).

The eastern margin of the Jan Mayen micro-continent is defined by the first appearance of the oldest oceanic crust (magnetic anomaly 24b, 54 Ma) which erupted from the Aegir oceanic spreading ridge (Gaina *et al.* 2009). The western margin is similarly defined by the first appearance of true

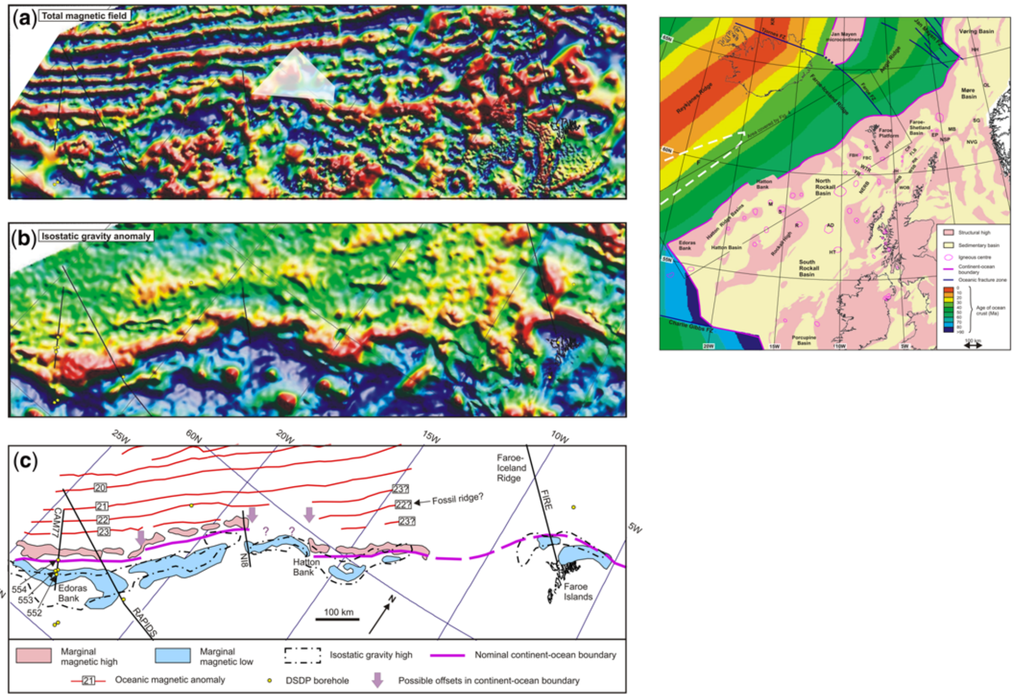

Fig. 4. Geophysical responses across the COB in the region between Edoras Bank and the Faroe–Iceland Ridge. (**a**) Total magnetic field (very poor data in the greyed area); (**b**) isostatically corrected Bouger gravity anomaly; and (**c**) selected magnetic and gravity features. Oceanic magnetic anomaly picks indicated by labels at their northeast ends. Black lines indicate the locations of the CAM77, RAPIDS, N18 and FIRE seismic profiles (Kimbell *et al.* 2005). The rectangular box on the location map locates areas a–c.

oceanic crust represented by magneto-chron 6c/7 (24 Ma) and erupted from the currently active Kolbeinsey oceanic spreading ridge. This indicates abandonment of the Aegir Ridge and the new propagating linkage of the Kolbeinsey and Reykjanes ridges in the Oligo-Miocene, the final separation of Jan Mayen from east Greenland and the destruction of any vestiges of the America–Eurasia land bridge (Gaina *et al.* 2009; Fig. 5). Onshore in east Greenland this final break-up between east Greenland and Jan Mayen is evidenced by alkaline dykes and large syenite intrusives in the Scoresby Sund-Jameson Land and Hold with Hope-Clavering Ø areas (Price *et al.* 1997). Abandonment of the Aegir Ridge in favour of the Kolbeinsey Ridge may have been via ridge 'jump' to the new ridge (Talwani & Eldholm 1977) or by via gradual abandonment of the Aegir Ridge (e.g. Nunns 1983; Muller *et al.* 2001).

The linkage between the final stages of continental rifting and oceanization is uncertain; however, the work of Van Wijk *et al.* (2001) offers a useful insight. They used a dynamic 2D finite element model for the upper and lower crust and the mantle to a depth of 120 km to study melt generation in a rifting environment. Initial unstretched thickened continental crust of 38 km was extended until lithospheric break-up resulted in a zone *c.* 150 km wide and where $\beta \geq 5$. This occurred 15 Myr after stretching was initiated. Outside of this zone transition zones up to 200 km wide (where $\beta = 1.2$–5) were developed, including an outer crustal area where thinning factors were less than 1.2 and extension had minimal effect. The stretching factors mirrored those proposed by Reemst & Cloetingh (2000) and Skogseid *et al.* (2000) for transects described along the North Atlantic volcanic margin. Results showed that decompressional partial melting took place across a 175 km wide zone and at a calculated depth of melt production between 20 and 50 km. The melt initiation began 5 Myr before break-up, with maximum melt just before break-up. Melt volumes fell in the outer edges of the transition zones where lower extension rates existed. They concluded the calculated melt volumes were in agreement with melt volumes 'per unit length of margin' observed along current-day volcanic margins. This did not require the prerequisite of a mantle plume in the North Atlantic, and lithospheric rifting alone could

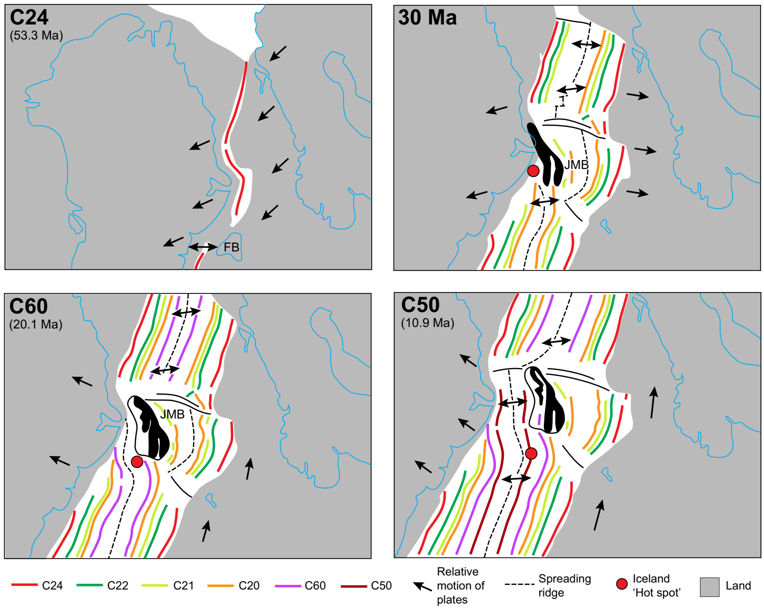

Fig. 5. Evolution of the NW Atlantic plate boundaries and kinematic evolution of the Jan Mayen micro-continent illustrated by a series of tectonic reconstructions in an absolute reference frame (after Gaina *et al.* 2009). JMB, Jan Mayen Block; FB, Faroes Block. Note Jan Mayen peels away from SE Greenland between 20 and 30 Ma, therefore allowing the potential for a long-lived land bridge between America and Eurasia via the Greenland–Faroe Ridge.

produce the enhanced melt volumes observed along the volcanic margins.

Additional evidence from the Afar proto-plate boundary also suggests it involves shallow decompressive melting of the upper mantle with vertical and lateral dyke intrusion within the rift (Ferguson *et al.* 2010; Rychert *et al.* 2012). If continental rifting involves segmented decompressive melting along the rift, the magmatic composition and volume, the eruption site timing and location and rift margin uplift will vary spatially with underlying composition of the upper mantle (see Meyer *et al*. 2007 for documentation of the geochemistry and spatial distribution of varying melts across the entire NAIP, both from enriched and depleted upper mantle sources and with or without crustal contamination).

The Greenland–Iceland–Faroe Ridge (GIFR)

The North Atlantic oceanic province has two anomalously thickened crustal elements: (1) the NW–SE Greenland–Iceland–Faroe Ridge (up to 30+ km of basaltic crust); and (2) the similarly orientated and thickened Vøring Spur located within the Jan Mayen fracture zone (thickened basaltic crust up to ≥15 km) (Fig. 1). Their linearity and non-radial orientation away from any proposed plume centre poses problems for a plume origin.

The GIFR has been drilled by DSDP site 336 which was located on its northern flank (Fig. 1). This site penetrated Middle Eocene basalts dated at 43–40 Ma (K–Ar date) at 515 m below the seabed (Talwani *et al.* 1976). The basalt grades into and is overlain by 8 m of volcanic rubble (conglomerate), which in turn is overlain by 13 m of thick red claystone. The latter is interpreted as a lateritic soil formed *in situ* by sub-aerial weathering of the basalt basement. The palaeosol is overlain by 295 m of Middle Eocene–Upper Oligocene marine mudstones, the bulk of which is probably of Middle–Late Eocene age (Stoker & Varming 2011). Micro-palaeontological evidence indicates that submergence of the GIFR at site 336 from a sub-aerial setting to a marine bathyl environment (shelf to upper slope, occurred during Late Eocene time (Talwani *et al.* 1976; Berggren & Schnitker 1983). The crest of the GIFR, sited about 400 m higher than the sea bed at site 336 (which itself is 463 m above the palaeosol), however suggests that the GIFR remained as either a continuous ridge or a string of closely spaced islands for some considerable time, possibly into Oligo-Miocene time (Talwani *et al.* 1976; Stoker & Varming 2011). Confirmation of this comes from evidence of the continued movement of flora and fauna from

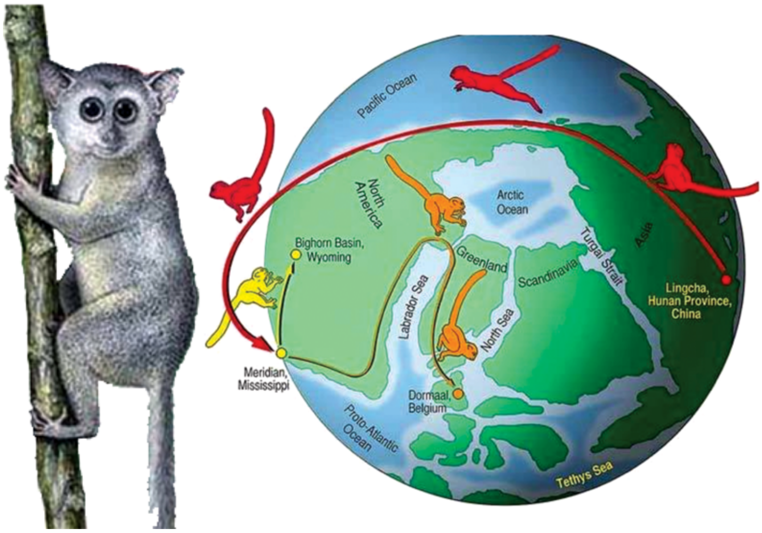

Fig. 6. The Eocene primate *Teilhardina* with fossil locations and their relative stratigraphic age superimposed on an Eocene palaeogeographic map of the globe. A North Atlantic land bridge allowed the primate to migrate from North America to Eurasia during the Eocene (Beard 2008).

America to Eurasia during the Eocene–Miocene via the 'Thulian land bridge'. Beard (2008) records that the minute monkey-like *Teilhardina magnoliana* had migrated from China via the Bering land bridge to the coastal plain of Mississippi by 55 Ma and further migrated to Europe by 47 Ma (as indicated by its discovery in Eocene deposits at Dormaal, Belgium; Fig. 6). Xiang *et al.* (2005) also noted that cornelian cherries (Cornus, cf. dogwoods) were present in North America during Paleocene time, but had later spread to Europe and Africa by Miocene time. While studying Miocene Icelandic oak pollen (Quercus), Denk *et al.* (2010) indicated linkage to the North American white and red oaks and their arrival in Iceland via a land bridge.

A model for the development of the GIFR and JMFZ

So what is the nature and derivation of the GIFR and when did it finally cease to be a land bridge between America and Eurasia? From Figure 3 it can be seen that the GIFR is linear and symmetric about Iceland, which led Morgan (1971) and others (e.g. White 1989; Smallwood *et al.* 1999; Skogseid *et al.* 2000) to suggest it represented the Paleocene–Holocene plume track of the Iceland 'hotspot'. However, Lundin & Doré (2002, 2005*b*) and Foulger (2010) both note that the GIFR is not time-transgressive in one direction as the Iceland 'hotspot' has never been positioned below the Iceland–Faroes side of the GIFR (otherwise the plume head would be located under NW Scotland today). Lundin & Doré (2005*b*) state that lithospheric drift over a fixed mantle plume for the GIFR is untenable, or would require – in the extreme – an early plume capture at the plate boundary and subsequent plume drift to have exactly matched the lithospheric drift. This would allow the 'hotspot' to remain constantly centred on the spreading ridge. Some authors (e.g. Bott 1983; White & McKenzie 1989; Smallwood *et al.* 1999) suggest that the generation of oceanic crust >7 km thick requires anomalously high asthenospheric temperatures (a mantle plume); others advocate decompressive lower-temperature melt of a fertile upper mantle (Foulger & Anderson 2005; Gernigon *et al.* 2009).

The radial plume model also fails to explain the extreme linearity of the GIFR; a clue to its formation might be explained with reference to the recent study of the Vøring Spur, within the Jan Mayen fracture zone, by Gernigon *et al.* 2009 (Fig. 7). Combining Bouguer anomaly analysis with depth to MOHO estimation, they note that the Vøring Spur between the east and west Jan Mayen fracture zones is characterized by a Bouguer 'low' in contrast to adjacent oceanic domains and coincides with thickened (>15 km) oceanic crust. Gernigon *et al.* (2009) propose that the thickened oceanic crust formed within the JMFZ during synrift extension across the NW–SE fractures, which led in turn to lithospheric thinning and subsequent decompressive melting of the mantle during the

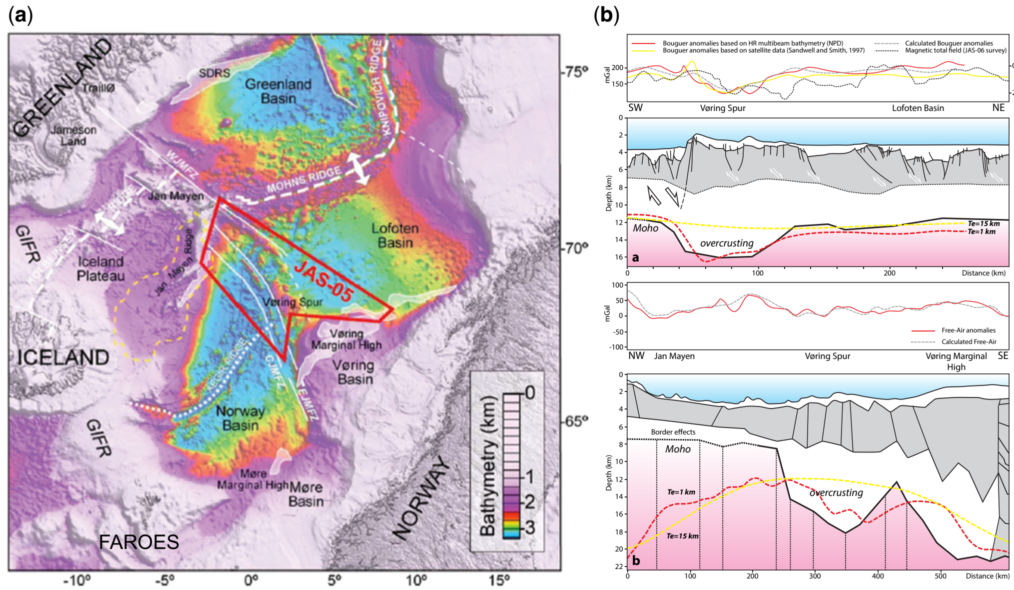

Fig. 7. (**a**) Bathymetric map and main physiographic features of the Norwegian–Greenland Sea. EJMFZ, CJMFZ and WJMFZ, the east, central and west Jan Mayen fracture zones, respectively; SDRS, seawards-dipping reflectors; GIFR, Greenland–Iceland–Faroe Ridge. JAS-05 is the gravity-magnetic survey area designation. (**b**) Gravity forward modelling and crustal model across the Vøring Spur, including gravity and density modelling. The oceanic root, observed beneath the Vøring Spur, is interpreted as a synrift oceanic and mafic feature ('overcrusting') formed during Middle–Late Eocene time (Gernigon *et al.* 2009).

Middle–Late Eocene ('overcrusting'). Similar NW–SE fracture zones have been documented along the entire North Atlantic margin (Rumph *et al.* 1993), and specifically within the Faroe Islands (Ellis *et al.* 2009) and in the Kangerlussuaq area of SE Greenland (Larsen & Whitham 2005; Guarnieri 2011). Plate reconstruction of the North Atlantic prior to 55 Ma places the Faroe Islands some 50–100 km SE of Kangerlussuaq during Late Paleocene time (Larsen *et al.* 1999; Skogseid *et al.* 2000; Larsen & Whitham 2005). This allows direct alignment of the NW–SE fracture zones described in the Faroes and Kangerlussuaq area; we therefore propose that the GIFR was formed by a similar process to that described by Gernigon *et al.* (2009) for the Vøring Spur (Fig. 8). We suggest transtensional movement across the Faroes–Kangerlussauq lineaments during Late Paleocene–Early Eocene time caused a zone of linear rifting, lithospheric thinning and decompressive melting of the upper mantle with increased magmatic activity to create the crustally thickened GIFR. Large Late Paleocene–Early Eocene intrusives have also been documented in close association with the Faroes and Kangerlussauq lineaments (Ellis *et al.* 2009; Guarnieri 2011). Walker *et al.* (2011) noted the first phase of faulting in the Faroes involved dip-slip movements along NW–SE- and North–South-orientated faults.

The orientation of these NW–SE lineaments probably represents inheritance from an earlier failed transient North Atlantic rift along a NW–SE axis from Baffin Island to the British Isles (Lundin & Doré 2005*a*). This coincided with Early Paleocene igneous activity (62–58 Ma) in the British NAIP, as represented by igneous centres such as Skye, Rhum and Mull and the NW–SE-orientated dyke swarms which extend across the UK from the Hebrides into the central North Sea and Lundy in the Bristol Channel (e.g. Brown *et al.* 2009; Hansen *et al.* 2009). However, the early Tertiary NAIP igneous activity has also been recently linked with the northern influence of the Large Low Shear Velocity Province (previously called the African Plume) at the core-mantle boundary and located beneath central Africa (Torsvik *et al.* 2006; Ganerød *et al.* 2010).

Eocene development of the Atlantic margin of Britain and Ireland

Recent re-evaluation of the Eocene sequences in the central North Atlantic, involving seismic, wells,

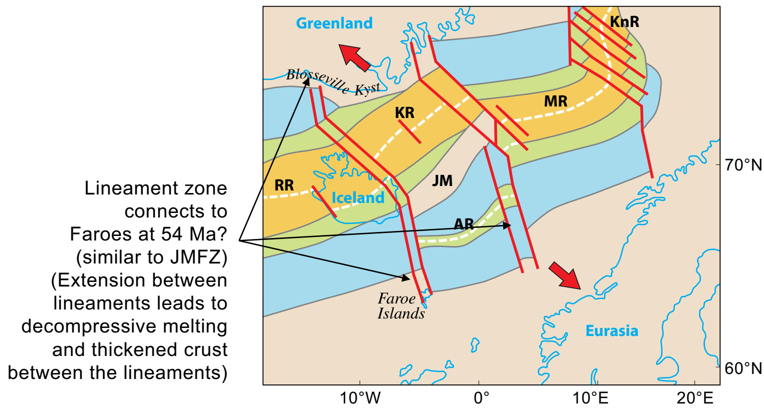

Fig. 8. Interpreted fracture lineaments connecting SE Greenland (Kangerlussuaq) and the Faroe–Shetland Basin (after Lundin & Dóre 2002; see text for additional references). The origin of the Greenland–Iceland–Faroe Ridge is interpreted to be analogous to that proposed for the thickened crust observed between the Jan Mayen Fracture zones by Gernigon *et al.* 2009 (see Fig. 7).

shallow boreholes, core data, biostratigraphy and onshore geology, has concluded that during Eocene time the northern North Atlantic rift was not connected to the SW North Atlantic rift (Stoker & Varming 2011; Stoker *et al.* 2013*a*, *b*) (Fig. 9). Eocene prograding deltaic (and fan-delta) deposits can be mapped offloading from the Munkagrunnur and Wyville Thompson ridges and the West Shetland margin into the Faroe–Shetland Basin (Robinson 2004; Ólavsdóttir *et al.* 2010, 2013; Stoker & Varming 2011; Stoker *et al.* 2013*b*) (Fig. 9). To the SW, stratigraphically equivalent rocks were deposited on the flanks of the Rockall and Hatton basins (Stoker *et al.* 2012) and Porcupine Basin (Moore & Shannon 1992; Fig. 9). These deposits are contemporary with similar deposits which accumulated in the North Sea (Jones & Milton 1994; Mudge & Bujak 1994) and onshore east Greenland (Larsen & Whitham 2005; Larsen *et al.* 2005).

On the eastern flank of the Rockall High, the inter-digitation of sub-aerial volcanic lavas and fan-delta/shallow-marine deposits in BGS borehole 94/3 can be tied to regionally synchronous unconformities across the greater Rockall–Hatton area, as well as in the Faroe–Shetland region and east Greenland (Stoker *et al.* 2012). Seismic mapping of these units in the Rockall–Hatton area indicates an archipelago of Eocene islands at or near sea level, frequently inundated but capable of supplying sediment into the local area (Stoker *et al.* 2012, fig. 10). The intra-Eocene unconformities imply a fluctuating response to relatively small sea-level rise and falls associated with the evolving North Atlantic plate tectonic regime (Shannon *et al.* 1993; Stoker & Varming 2011). This includes the post-depositional (latest Eocene/Oligocene) tilting of a number of the Eocene prograding units located on the flanks of major compressional folds, such as the Hatton High and the Wyville Thomson Ridge (Stoker *et al.* 2012).

Paleocene–Eocene sequences offshore and onshore SE and east Greenland

On the opposite side of the rift and offshore SE Greenland, DSDP borehole 917 drilled 775 m of crustally contaminated basalt with sub-aerial weathered horizons (Vallier *et al.* 1998; Fitton *et al.* 2000) (Fig. 1). In the borehole, the basalts are underlain by 10 cm of non-metamorphosed quartzitic sandstone (interpreted as being of fluvial origin) and of presumed Paleocene age, which in turn is underlain by 15.9 m of fine-grained metamorphosed sediments (Greenschist grade) including volcaniclastics. These are of presumed Late Cretaceous age and exhibit weak sedimentary structures suggestive of deposition from turbidity currents.

Onshore in SE Greenland, Upper Cretaceous and Early Paleocene shallow-marine sediments in the Kangerlussuaq area are overlain by Late Paleocene shallow-marine and fluvial deposits (Fig. 1). These in turn pass upwards and inter-digitate with, and are ultimately inundated by, Upper Paleocene–Lower Eocene flood basalts (Larsen & Whitham 2005). The depositional setting was strongly controlled by large syndepositional NW–SE oblique-slip normal faults trending along the Nansen fjord and the Christian IV glacial valley, as well as the nearby Kangerlussuaq fjord (Larsen & Whitham 2005; Guarnieri 2011). These faults also controlled the injection sites and the later deformation of

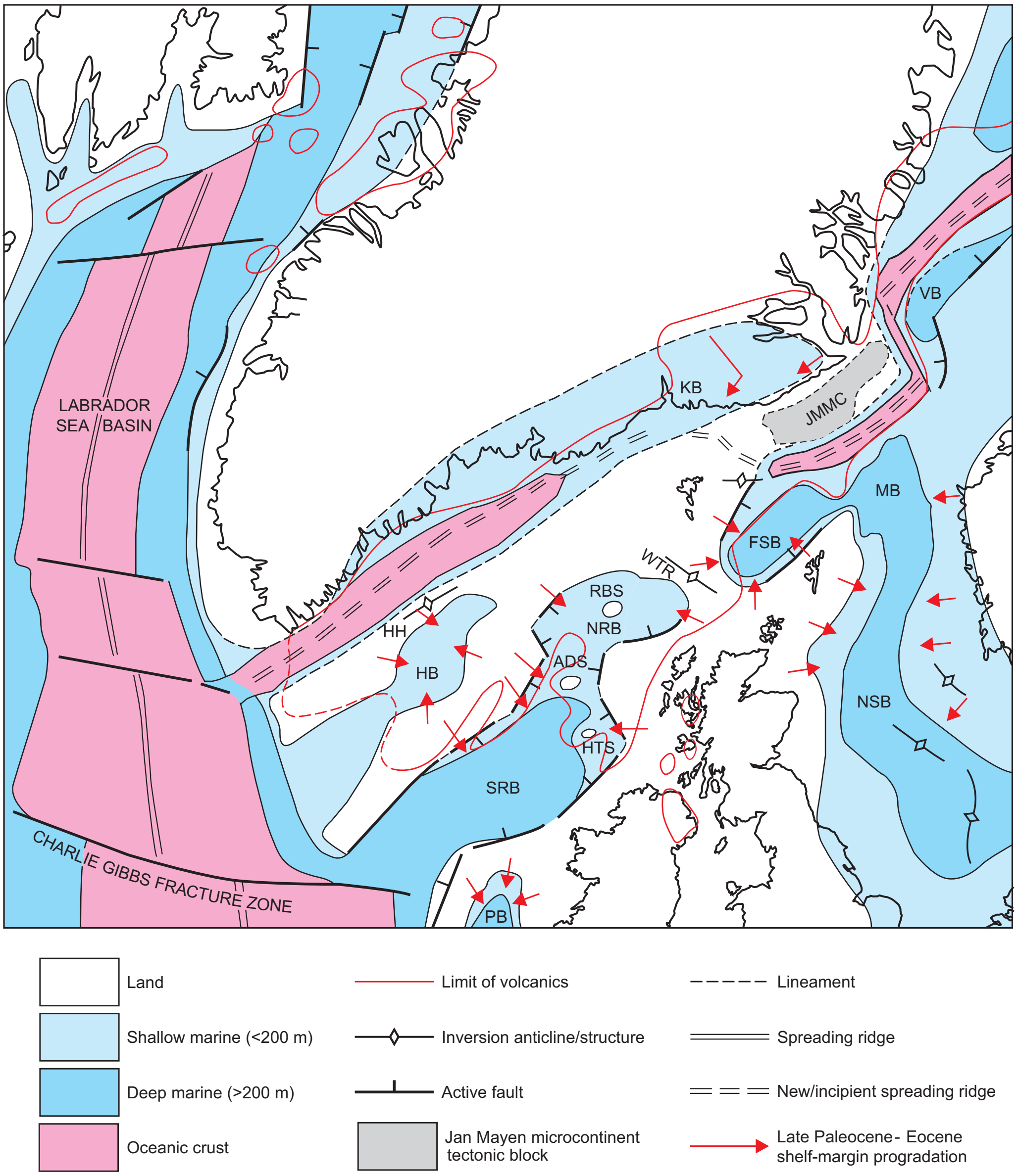

Fig. 9. Generalized palinspastic map for the Late Paleocene–Early Eocene interval (modified after Stoker & Varming 2011). ADS, Anton Dohrn Seamount; KB, Kangerlussuaq Basin; MB, Møre Basin; NRB, North Rockall Basin; NSB, North Sea Basin; PB, Porcupine Basin; RBS, Rosemary Bank Seamount; SRB, South Rockall Basin; WTR, Wyville Thompson Ridge; VB, Vøring Basin.

Early Eocene intrusives (Guarnieri 2011). The subsidiary NE–SW Sortekap fault inland from the coast further constrained the Paleocene–Early Eocene depositional system in the area (Larsen & Whitham 2005). Palaeocurrent evidence from the shallow-marine and fluvial sequences both indicate initial flow to the SE, but then critically to the SW in the centre of the basin (Larsen & Whitham 2005). The SE margin of the basin is not preserved.

Overlying the Lower Paleocene sediments in Kangerlussuaq are a thick succession of Upper Paleocene–Lower Eocene sub-aerial basalts. These were emplaced from east to west and buried a significant Late Paleocene landscape, including deeply incised palaeo-valleys (Larsen *et al.* 1989; Pedersen *et al.* 1997). The basalts range up to 6 km thick on the coast, and thin to 2–3 km inland and regionally northwards to *c.* 1 km in the Trail Ø area (Price *et al.* 1997). The east Greenland sequence contains age-equivalent basalts of the Beinisfjord, Malinstindur and Enni formations which have been described from the Faroe Islands, and which are now located between Iceland and NW Scotland (Passey & Jolley 2009) (Fig. 1). Additionally, the Kangerlussuaq area has younger Eocene lava formations – the Upper Geikie, Rømer, Skrænterne and Igtertiva formations – which are not present in the Faroe Islands (Pedersen *et al.* 1997; Larsen *et al.* 1989, 1999) (Fig. 10). Recent dating of the youngest Kangerlussuaq volcanic sequence, the Igtertiva Formation in the Kap Dalton area, suggests eruption into the late Early Eocene between 49 and 47.9 Ma (Larsen *et al.* 2005). The significance of this is that offshore of the Faroe Islands the equivalent rocks are represented by NE-seawards-dipping reflectors and oceanic crust, whereas in SE Greenland they comprise east–west prograding sub-aerial basalts. This apparent contradiction is addressed in the following.

In SE Greenland, Middle Eocene fluvial and shallow-marine sediments overlie the Igtertiva basalts in the Kap Dalton area and demonstrate a NE–SW progradational sequence, as identified by palaeocurrent data (Larsen *et al.* 2005). This is the opposite direction to the Early Eocene landscape developed in the Faroe–Shetland Basin, which was from south to north (Larsen *et al.* 2005; Stoker & Varming 2011).

The dual rift model

On the basis of the above data, we propose that during Late Paleocene–Early Eocene time two active rift systems were trying to split America and Greenland from Eurasia until 33 Ma (Chron 13) (Fig. 11). The first was developing SW–NE along the SE margin of Greenland and along the

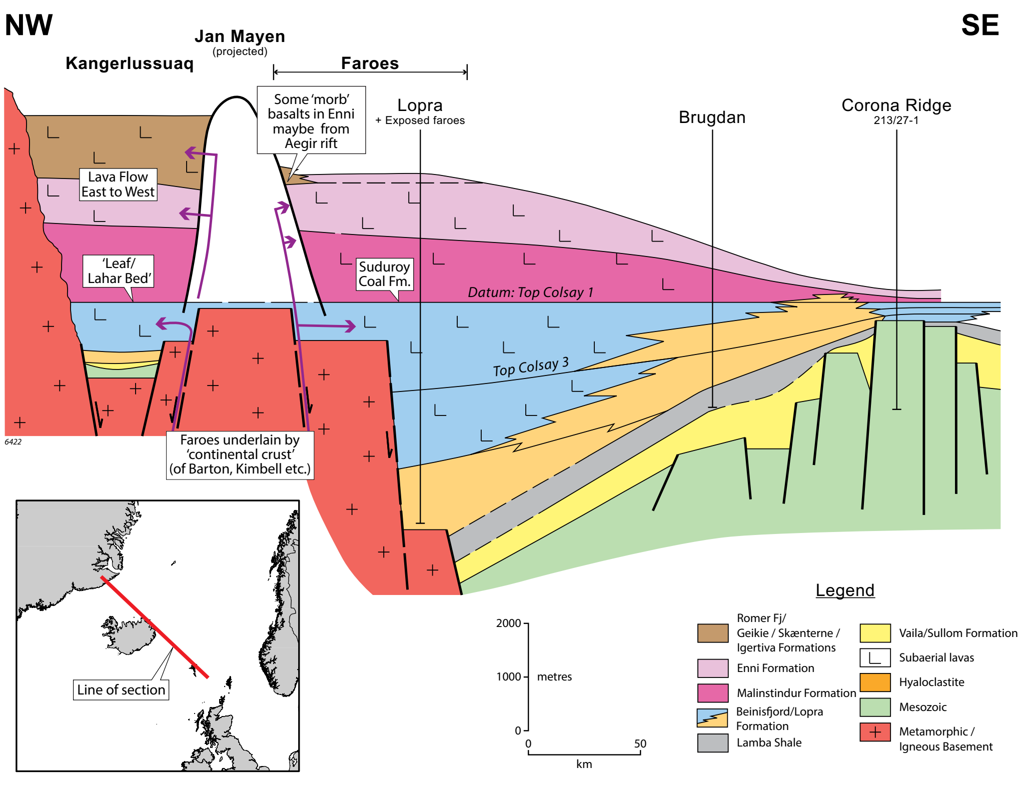

Fig. 10. Early Eocene (54 Ma) schematic geological cross-section from SE Greenland (Kangerlussuaq) and across to the Faroe Islands and the Faroe–Shetland Basin (FSB). Section is balanced on the regionally correlated Colsay 1 Sandstone Formation, based on FSB well penetrations and outcrop studies in the Faroes and SE Greenland (see text for references).

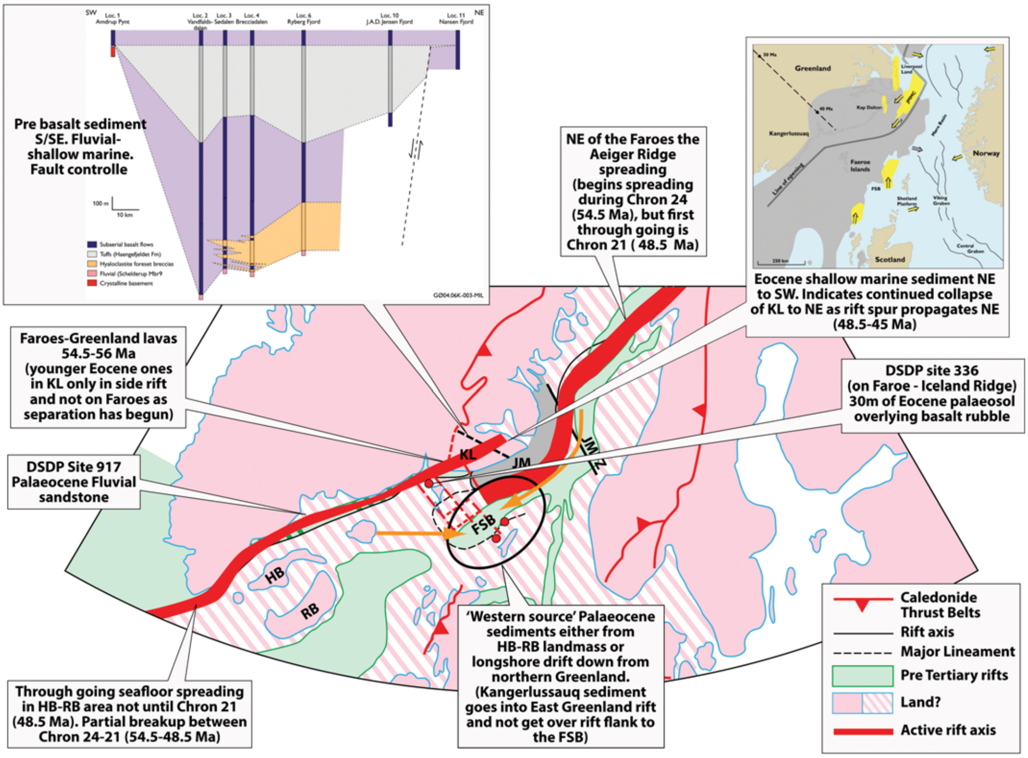

Fig. 11. Summary diagram citing evidence for two NW Atlantic active rift systems attempting to split America and Greenland from Eurasia until 33 Ma (Chron 13). One developed SW–NE along the SE margin of Greenland and formed the line of the proto-Reykjanes Ridge. It penetrated into the Kangerlussauq area where it was unable to penetrate further. A second NE–SW-propagating rift, represented by the Aegir spreading ridge, developed from the Norwegian–Greenland Sea and extended into the area north of the Faroe Islands. The two rifts were independent of each other and did not conjoin, leaving Jan Mayen firmly attached to east Greenland and the Faroes as the centre of a land bridge between east Greenland and Eurasia. The land bridge lasted until at least 33 Ma (and possibly until 25 Ma). KL, Kangerlussuaq; JM, Jan Mayen; JMFZ, Jan Mayen fracture zone; FSB, Faroe–Shetland Basin; HB, Hatton Bank; RB, Rockall Bank.

line of the proto-Reykjanes Ridge. It penetrated into the area of Kangerlussauq and possibly into the Trail Ø area where it was unable to penetrate further northwards (Figs 9 & 11). A second NE–SW propagating rift, represented by the Aegir spreading ridge, developed from the Norwegian–Greenland Sea and extended into the area north of the Faroe Islands. The two rifts were independent of each other and did not conjoin, leaving Jan Mayen firmly attached to east Greenland in the Kangerlussuaq and Hold-with-Hope area, with the Faroe region as the centre of a land bridge between East Greenland and Europe. The land bridge lasted until at least 33 Ma (and possibly until 25 Ma). The opposed ridge system has been previously cited by others, although the timing and the ridges involved has varied (see Dewey & Windley 1988; Lundin *et al.* 2002; Lundin & Doré 2005*a*; Gaina *et al.* 2009). The dual ridge system can explain the difference in timing and nature of the flood basalt sequences in the Kangerlussuaq rift, which were dominantly sub-aerial and emplaced east–west, against the synchronous development of seawards-dipping reflectors and early oceanic crust from the propagating Aegir rift north of the Faroe Islands (and east of Jan Mayen). The lateral by-passing of the two rift tips would induce severe fracturing in the area of the palaeo-Faroe Island location and anticlockwise rotation of the regional stress field, allowing igneous material to erupt from local volcanic centres (particularly along NW–SE- and NE–SW-orientated fractures). The anticlockwise rotation of the regional stress field has been observed from Paleocene–Early Eocene onshore fault analysis in the Faroe Islands (Walker *et al.* 2011) and later during the Oligo-Miocene separation of Jan Mayen from Greenland (Gaina *et al.* 2009) (Fig. 5).

Post-Paleocene to Oligo-Miocene inversion events in the North Atlantic province

The anticlockwise rotation of the regional stress field from 54 to 25 Ma could also partially explain the episodic and gradual inversion of anticlinal and domal structures in the North Atlantic throughout Eocene time, and particularly during the Oligo-Miocene (Johnson *et al.* 2005; Doré *et al.* 2008; Ritchie *et al.* 2008). In the Faroe–Shetland region, the disposition of the Eocene succession is folded about the axes of uplift which form the bathymetric highs of the Fugloy, Munkagrunnur and Wyville Thomson ridges. This implies that a major phase of ocean margin structuring took place during Late Palaeogene–Early Neogene time (Johnson *et al.* 2005; Stoker *et al.* 2005*b*; Ritchie *et al.* 2008; Ólavsdóttir *et al.* 2010). The Hatton High (of the Rockall Plateau) was also folded in this interval, as witnessed by the tilting of the Eocene deltaic wedges on this feature (Stoker *et al.* 2012).

A major consequence of Oligo–Miocene compressional deformation in the Faroe–Rockall region was the formation of the Faroe Conduit (combining the present-day Faroe–Shetland and Faroe Bank channels), which today forms the main passageway for deepwater exchange across the Greenland–Scotland Ridge (Stoker *et al.* 2005*a*, *b*). This Early Neogene instigation of the gateway is consistent with ^{13}C, ^{18}O, taxonomic and sedimentological data from DSDP and ODP sites in the North Atlantic region, which reveal a Miocene instigation for the overflow of North Atlantic deep water into the previously isolated Tethyan (warm water) Reykjanes rift basins to the south (cf. Stoker *et al.* 2005*a*, *b*).

Hot fluid flow evidence coincident with the two major tectonic phases of evolution of the North Atlantic (Eocene and Oligo-Miocene plate rifting and reorganization)

Microthermometry and apatite fission track analysis (AFTA) from the Faroe–Shetland Basin and East Greenland indicates two periods of hot fluid flow through post-Paleocene units until the present: a Late Paleocene–Early Eocene event and another around 20–25 Ma (Parnell *et al.* 1999; Scotchman *et al.* 2006; Parnell & Middleton 2009). The first is coincident with the early North Atlantic rifting phase and the second with the major Oligo-Miocene plate reorganization of the North Atlantic, which led to the separation of Jan Mayen from Greenland and North Atlantic regional uplift. Both phases are associated with the highest ocean spreading rates and therefore elevated heat flows (Fig. 2). An omni-present plume from the Paleocene to the present cannot rationally explain these two pulsed hot fluid flows in itself, or the fact that despite these fluid flushes the regional vitrinite reflectance and AFTA data suggest low thermal maturity for most of the Mesozoic–Cenozoic sequences in the Faroe–Shetland Basin and onshore east Greenland (except when in close proximity to intrusive bodies) (Surlyk *et al.* 1986; Stemmerik *et al.* 1992; Carr 1999; Scotchman *et al.* 2006). The AFTA and vitrinite reflectance data could therefore suggest a lower regional thermal gradient more indicative of shallow melts restricted to plate boundaries and not the higher gradient expected from a large-radius mantle-derived plume impacting across the base of the lithosphere.

The dual rift model and Paleocene–Early Eocene sediment provenance studies

The dual rift model may also explain the dichotomy expressed in published North Atlantic Paleocene reservoir provenance studies (e.g. Jolley & Morton 2007; Morton *et al.* 2012*a*, *b*). These studies involved heavy mineral and palynological analysis to identify several Scottish source areas for Paleocene sandstones in the Faroe–Shetland Basin; they also identified a 'westerly' sourced sandstone component (the FSP3 zircon signatures of Jolley & Morton 2007 and Morton *et al.* 2012*a*, *b*).

The palynological data suggest a Greenland affinity but the heavy mineral rutile/zircon data, though distinguishing a non-Scottish source, cannot distinctly type the 'western' source area. In the single rift model the zircons and other heavy minerals from SE Greenland should be observed in the Faroe–Shetland Basin (which was directly SE of Kangerlussuaq) in palaeo-reconstructions (e.g. Larsen *et al.* 1999; Skogseid *et al.* 2000; Larsen & Whitham 2005). In particular, the zircon age data profile of westerly FSP3 sandstones does not match surface sampling of Kangerlussuaq basement terrains (Morton *et al.* 2012*b*). The Kangerlussuaq low-RuZi sandstones have two main age groups at *c.* 2700–2750 Ma and *c.* 2950–3100 Ma, with a subsidiary peak at *c.* 3200 Ma. Over 50% of the Archaean grains are older than 2950 Ma (Whitham *et al.* 2004). The *c.* 2950–3100 Ma and *c.* 3200 Ma age peaks are either absent or very poorly developed in the FSP3 sandstones, and zircons older than 2950 Ma form only 5–11% of the Archaean population. Derivation of the FSP3 sandstones from the Kangerlussuaq area of east Greenland is therefore dismissed (Morton *et al.* 2012*a*, *b*).

With the currently proposed synchronous dual rift model, any westerly sourced sediments from Kangerlussauq would have entered the northerly progressing rift off SE Greenland and been unavailable to the Faroe–Shetland Basin (Figs 9 & 11). The alternative locations for westerly derived FSP3 sandstones may have been derived from the now-rifted Jan Mayen micro-continent or other areas in NE–central Greenland (which are presently below the icecap). Westerly derived America–Greenland pollen spores can, in contrast, be common to both rifts due to their less-dense silt size and their potential for greater aqueous and regional wind-blown distribution.

The age and role of Iceland

With the progressive dual rift model we now consider the age and role of Iceland. Plume protagonists propose that Iceland is the present signature of a Northern Hemisphere deep mantle plume which impacted the area of NW Greenland during Late Cretaceous–Early Paleocene time, and then migrated via Kangerlussuaq with time and Greenland plate movement to its current Iceland position (e.g. White 1989; White & McKenzie 1989; Smallwood *et al.* 1999; Smallwood & White 2002). Other authors disagree and propose non-plume origins for Iceland (e.g. Foulger 2002; Foulger & Anderson 2005; Lundin & Doré 2005*a*, *b*; Gaina *et al.* 2009; Gernigon *et al.* 2009; Foulger 2010).

In the context of the dual propagating rift model and the potential final separation of America–Greenland from Eurasia during Oligo-Miocene time, we note the following pertinent facts regarding Iceland.

- The oldest dated outcrops are 17 Ma (Miocene) in NW Iceland and 13 Ma in east Iceland (Moorbath *et al.* 1968; Ross & Mussett 1976; Hardarson *et al.* 1997).
- The time-transgressive V-shaped ridges, extending up to 1000 km along the Reykjanes and Kolbeinsey ridges, are limited to Oligocene–Holocene oceanic crust (Jones *et al.* 2002). Hey *et al.* (2010) and Benediktsdóttir *et al.* (2012) indicate that the V-shaped ridges are not symmetrical about the Reykjanes Ridge axis and this implies formation from either a 'pulsating plume' (the conventional view), or – in their preferred view – the requirement of a simple rift propagation away from central Iceland. They also note the V-shaped ridges have different geographic extent and patterns north and south of Iceland and that this asymmetry is best explained by rift propagation, and not by pulses in a symmetrically radial plume.
- Iceland is dominated by tholeiite basalts (typical Mid-Ocean Ridge Basalts) and not picrites or komatiites which are more distinctive of hotter core–mantle origins (Foulger *et al.* 2003; Presnall 2003; Søager & Holm 2011). Lower mantle picrites are predicted to have higher MgO concentrations of *c.* 15–30% (Gill *et al.* 1992; Lundin & Doré 2005*a*). Iceland basalts have ±10.5% Mg and are highly depleted with respect to major and trace element composition; they could therefore originate from lower temperatures.
- A larger-than-expected proportion (*c.* 10%) of compositionally acidic (rhyolite) and intermediate (andesitic) rocks occur in Iceland (Foulger & Anderson 2005; Foulger 2010).
- Mesozoic-age zircons (representing continental crust derivation) have been described from Mount Hvitserker in NE Iceland (Paquette *et al.* 2006, 2007) and from more widespread Icelandic locations (Bindeman *et al.* 2012).
- Records of elevated $^{87}Sr/^{86}Sr$ and Pb ratios in rhyolites and basalts in SE Iceland are indicative of an enriched upper mantle source (Prestvik *et al.* 2001; Søager & Holm 2011). Storey *et al.* (2004) also describe similar enriched Middle Miocene lavas in east Greenland.
- Tomographic studies show that the low-velocity anomaly below Iceland extends only into the upper mantle (at ±400 km depth) and not to the core–mantle boundary. It is a vertical and cylindrical anomaly of 200–250 km diameter at depths down to 200 km, but an elongate dyke-like form at greater depths and parallel to the mid-Atlantic Ridge trend (Ritsema *et al.* 1999; Foulger *et al.* 2001; Montelli *et al.* 2003; Hung *et al.* 2004). The latter suggests a closer relationship to the greater regional morphology, shallow melts and tectonics of the mid-Atlantic rift system rather than a deep mantle plume.

We note the coincidence that the oldest rocks in Iceland post-date the break-away of Jan Mayen in the Oligo-Miocene (33–24 Ma) (Fig. 5) and the dating of the V-shaped ridges beginning in the Oligocene. Similarly, at the point of final break-up, Iceland would have been positioned where the new rift intersected the zone of the Caledonian suture between Scotland and east Greenland, a point noted by Foulger & Anderson (2005). The link to the underlying Caledonian orogen is further strengthened by the fact that the volcanism in Iceland is apparently from a shallow (decompressive) melt and an enriched (eclogitic) upper mantle, and not a deep-rooted plume. We therefore propose that Iceland was initiated during Oligo-Miocene time at the point where the juncture of the Reykjanes and Kolbeinsey ridges crossed the Scotland–Greenland Caledonian orogenic trend. This implies that an earlier proto-Iceland hotspot is not required to explain earlier Paleocene–Eocene rifting and volcanism, and regional plate tectonics can provide a simpler explanation (e.g. van Wijk *et al.* 2001; Foulger & Anderson 2005; Lundin & Doré 2005*a*; Gaina *et al.* 2009). The evidence for an enriched upper mantle source for some Iceland basalts and rhyolites and the Middle Miocene basalts of east Greenland (Storey *et al.* 2004) can also be attributed to melting in the upper mantle of buoyant subducted Iapetus oceanic crust (Foulger & Anderson 2005; Bindeman *et al.* 2012), from a residual Caledonian orogenic root (Bott *et al.* 1974; Ryan & Dewey 1997) or from a metasomatized upper mantle (Storey *et al.* 2004).

The North Atlantic geoid

Evidence for the plume is often invoked from the observation of the positive geoid (*c.* 60 m) covering a large sector of the North Atlantic and NW Europe and the resultant low mean Atlantic water depths (Marquart 1991; Köhler 2004; Lundin & Doré 2005*b*) (Fig. 12). It is interesting to note that the maximum geoid anomaly is non-radial but quasi-linear at its maximum between Iceland and the central Atlantic between Iberia and Newfoundland. This encompasses the modern central Atlantic spreading ridges and the area of the defunct Early Paleocene triple junction SE of Greenland, the time when both the Labrador Sea and proto-Reykjanes spreading ridges were active.

Lundin & Doré (2005*a*, *b*) noted that the geoid anomaly has a 3000–4000 km diameter while mantle tele-seismic investigations around Iceland suggest an upper mantle thermal anomaly of only 1000 km radius. Further, this is not centred above the 200–250 km wide low-velocity zone underneath Iceland. If the geoid does represent the thermal effect of a plume from Middle Paleocene time to the present day, then it is also significantly larger than the extent of the North Atlantic igneous province and cannot rationally explain the non-radial and highly disparate distribution of Paleocene–Early Eocene magmatism in space and time (e.g. the west Greenland and Baffin Bay picrites v. the BTIP more normal basalts erupted around 58–62 Ma).

Lundin & Doré (2005*a*, *b*) have demonstrated that there is no direct association between geoids and hotspots around the Earth, and suggested that an alternative explanation should be investigated. We speculate that the relevant timings and distribution of the rifting zones in the North Atlantic with their associated melts could have formed the large area of thickened North Atlantic basaltic crust. In particular, the greatest elevation of the geoid coincides with the area of the palaeo-triple junction and the spreading of the central Atlantic ridges into the Labrador Sea and the proto-Reykjanes Ridge (Figs 1 & 12). Synchronous lateral heat flow from both the Labrador Sea and the proto-Reykjanes Ridge would have lifted Greenland at the expense of other areas and generated the 'fossil' centre of the of the geoid (Fig. 12). Transient and synchronous uplift followed by subsidence in west and east Greenland has been

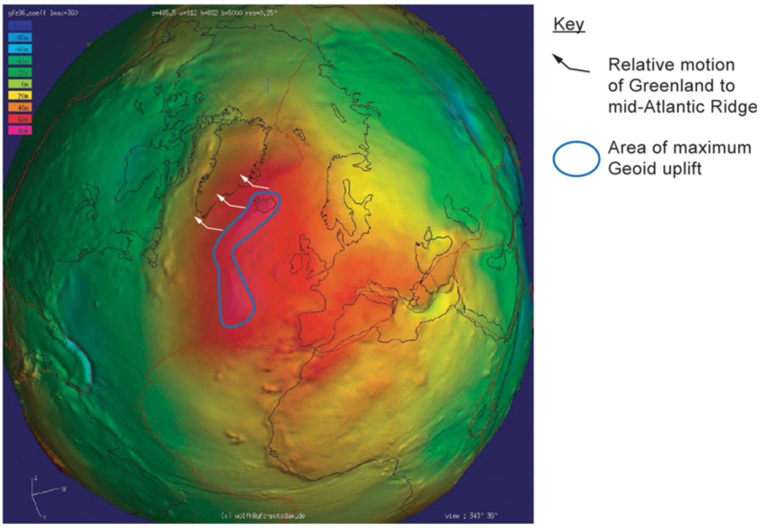

Fig. 12. The North Atlantic geoid anomaly (from Köhler 2004). The geoid anomaly coincides approximately with the extent of the North Atlantic topographic-bathymetric anomaly (Sandwell & Smith 1997); it is not centred on Iceland and is more widespread than the upper mantle low-velocity anomaly (e.g. Ritsema *et al.* 1999; Foulger *et al.* 2001).

documented by Dam *et al.* 1998, who ascribed it to the impact and then the lateral spreading of a plume head; however, it could equally be ascribed to synchronous rift flank uplift in the Labrador Sea and along the Reykjanes Ridge, followed by subsidence as full rifting occurred and magma was depleted from the upper mantle and erupted onto the rift margins. The location of Greenland away from the centre of the plate-tectonic-induced geoid has since been changed by plate migration of Greenland from 62 Ma to the present day. Additionally, the geoid has probably been reinforced by crustal thickening under Europe and north Africa by the Pyrenean and Alpine orogenies between 62 and 14 Ma (Figs 2 & 12).

In our opinion, it was not until the Reykjanes and Kolbeinsey ridges crossed the Scotland–Greenland Caledonian orogenic track that Iceland and its associated smaller upper mantle anomaly came into being, thereby creating the more local geoid around it. The timing and the different interactions of the varying rift zones could also explain the disparate timing of post-Paleocene–Holocene uplift and subsidence of basins and continental margins around the North Atlantic, something not possible with an omni-present and radial plume (Lundin & Doré 2005*b*).

Conclusions

- On the basis of regional geological and other data, we suggest that the opening of the North Atlantic between Eurasia and North America–Greenland was only partial until the Oligo-Miocene (33–25 Ma). The true final break-up occurred when the Reykjanes and Kolbeinsey ridges conjoined in the area of SE Greenland and offshore Kangerlussauq.
- Initial attempts at North Atlantic rifting involved two opposing and almost by-passing rifts. These were the proto-Reykjanes Ridge (rift) system propagating NE along the SE Greenland margin and the SW-propagating Aegir Ridge between Norway and offshore east Greenland. Although rifting along the Atlantic margin of Ireland, Britain and the Faroe Islands may have been initiated at 54 Ma, true development of continuous oceanic crust in both rifts did not develop until Chron 21 (48 Ma).
- The two initial propagating rifts failed to join during Paleocene–Early Eocene time in the palaeo-location of Kangerlussuaq and the Faroes Islands. The Jan Mayen micro-continent was still firmly attached to Greenland and continued to form a section of a land bridge between America–Greenland and Eurasia via the volcanic Faroe Islands and into NW Britain. The attempt of the two rifts to by-pass each other in this area caused anticlockwise rotation of the regional stress field.
- Oligo-Miocene North Atlantic plate reorganization, including the separation of Jan Mayen from SE Greenland, destroyed any relict Thulian land bridge and initiated the mixing of cold northern Atlantic waters with warmer southern Tethyan waters.
- Oligo-Miocene plate reorganization in the North Atlantic created the final break between Greenland and Europe and coincided with the appearance of Iceland and the production of the V-shaped seabed ridges to the north and south of the island.
- The dual rift model negates the need for a plume to develop the North Atlantic; the rifting can be wholly explained by plate tectonic mechanisms, lithospheric thinning and variable decompressive upper mantle melting along the rifts. Recent studies from the Afar rift in Ethiopia have shown that decompressive melt generation and dyke swarm propagation are more important than plume influence in the evolution of the proto-plate boundary (Ferguson *et al.* 2010; Rychert *et al.* 2012).
- The dual rift model with de-compressive upper mantle melts more closely confined to the plate tectonically induced rifts would imply a lower and more segmented regional heat-flow from 54 Ma to the present. This is in contrast to a higher regional heat-flow evoked by a large radius mantle plume. The implied lower heat-flow with its variable timing and geographical distribution will significantly change results from regional basin modeling studies and the type and timing of hydrocarbon generation around the North Atlantic, in contrast to results from a regional plume model with elevated heat-flow.

We would like to thank Michael Larsen and Gillian Foulger for their thorough reviews and very helpful suggestions for improving the paper, and colleagues in industry, the BGS and academia for stimulating discussions. We would also like to thank drafting staff in both Statoil (UK) Limited and the BGS for help in preparation of the figures. The contribution of MSS is with the permission of the Executive Director, BGS (NERC). This paper reflects the research and views of the authors and not necessarily those of Statoil or the British Geological Survey.

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