

Break-up and seafloor spreading domains in the NE Atlantic

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Abstract: An updated magnetic anomaly grid of the NE Atlantic and an improved database of magnetic anomaly and fracture zone identifications allow the kinematic history of this region to be revisited. At break-up time, continental rupture occurred parallel to the Mesozoic rift axes in the south, but obliquely to the previous rifting trend in the north, probably due to the proximity of the Iceland plume at 57–54 Ma.

The new oceanic lithosphere age grid is based on 30 isochrons (C) from C24n old (53.93 Ma) to C1n old (0.78 Ma), and documents ridge reorganizations in the SE Lofoten Basin, the Jan Mayen Fracture Zone region, in Iceland and offshore Faroe Islands. Updated continent–ocean boundaries, including the Jan Mayen microcontinent, and detailed kinematics of the Eocene–Present Greenland–Eurasia relative motions are included in this model.

Variations in the subduction regime in the NE Pacific could have caused the sudden northwards motion of Greenland and subsequent Eurekan deformation. These events caused seafloor spreading changes in the neighbouring Labrador Sea and a decrease in spreading rates in the NE Atlantic. Boundaries between major oceanic crustal domains were formed when the European Plate changed its absolute motion direction, probably caused by successive adjustments along its southern boundary.

Supplementary material: Figures showing the long wavelength of the NAG-TEC magnetic anomaly grid, detailed magnetic anomalies and isochrons, and a Table documenting aeromagnetic surveys for NAG-TEC magnetic compilation are available at <https://doi.org/10.6084/m9.figshare.c.3661925>



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The North Atlantic encompasses the area between Newfoundland–Iberia and the Eurasian Basin in the Arctic Ocean (Fig. 1). It includes active and extinct spreading systems, magma-rich and magma-poor margins, and it witnessed microcontinent formation (Jan Mayen, East Greenland and Hovgaard ridges) and ridge–hotspot interactions linked to the presence of the Iceland hotspot (Fig. 1). The North Atlantic realm underwent episodic continental extension in the Permo-Triassic, Late Jurassic, and Early and mid-Cretaceous, with reactivation and basin formation influenced by pre-existing structures formed during the closure of the Iapetus Ocean (and part of the Rheic Ocean: e.g. Domeier 2015), and subsequent Baltica–Laurentia collision (e.g. Doré *et al.* 1997; Skogseid *et al.* 2000). Seafloor spreading propagated from south to north starting in Cretaceous times in distinct phases that involved the following regions: Newfoundland–Iberia, North America–Porcupine, North America–Greenland

(Labrador Sea and Baffin Bay), Greenland–Eurasia and Lomonosov Ridge–Eurasia (Eurasian Basin, Arctic Ocean) (Fig. 1) (see Seton *et al.* 2012 for a review).

The formation of oceanic crust between Greenland and Eurasia was identified and described more than four decades ago (e.g. Pitman & Talwani 1972; Vogt & Avery 1974; Srivastava & Tapscott 1986) as a late Paleocene (*c.* 55 Ma) northwards propagation of seafloor spreading. The mid-ocean ridge from the Central North Atlantic (between North America and Eurasia) was first linked with the plate boundary between the North American and Greenland plates in the Labrador Sea–Baffin Bay (Kristoffersen & Talwani 1974; Roest & Srivastava 1989; Chalmers & Laursen 1995), and later formed a triple junction SW of Greenland with the developing Reykjanes mid-ocean ridge.

In the NE Atlantic, oceanic crust was created continuously from the Early Eocene (*c.* 54–55 Ma)

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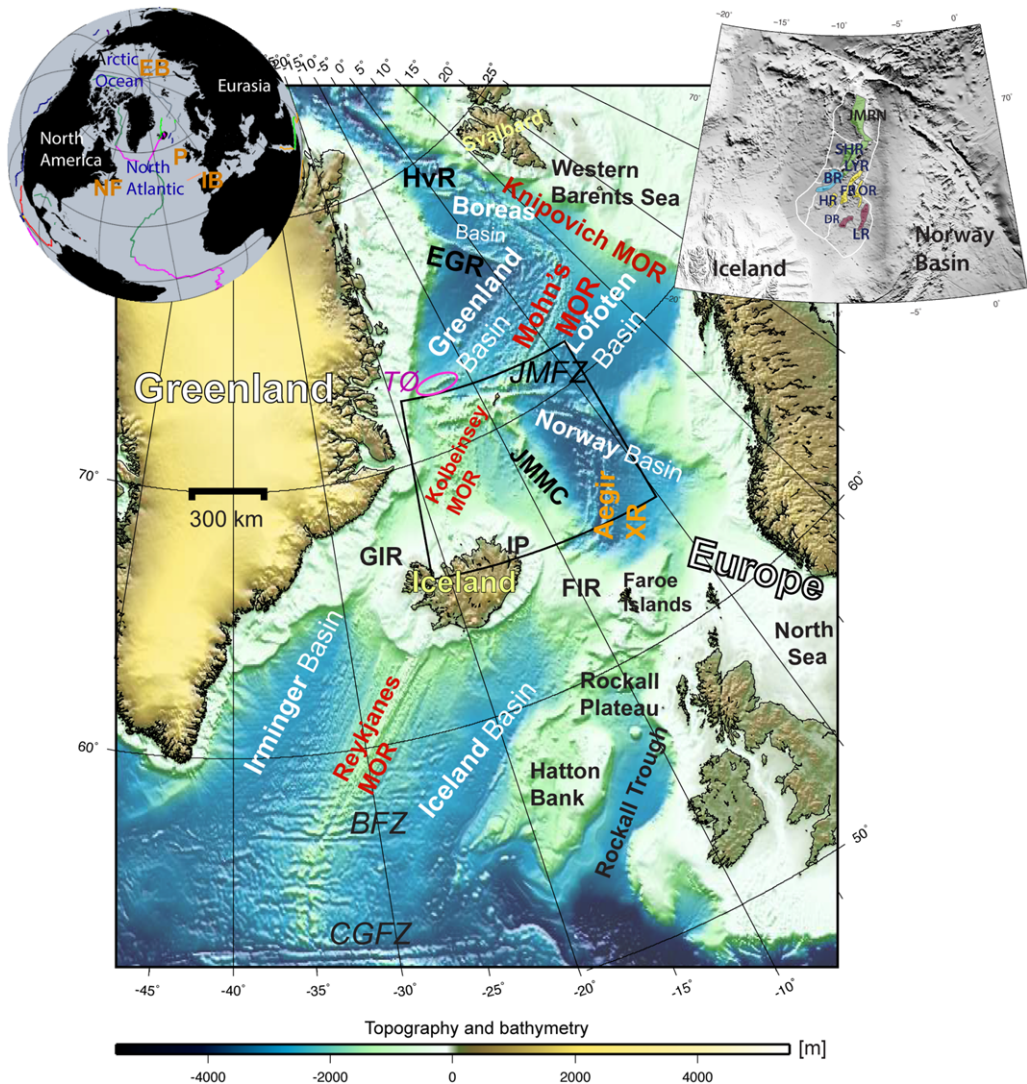


Fig. 1. NAG-TEC bathymetry built on a regional compilation that includes ETOPO1 (Amante & Eakins 2009), IBCAO3 (Jakobsson *et al.* 2012), and a number of local and regional dense bathymetric grids (Hopper & Gaina 2014). The upper-left inset figure shows the present-day plate boundaries in the North Atlantic; and the upper-right inset figure shows a close-up map of the JMMC region, indicated by the black frame on the main map. White lines indicate the tectonic domains within JMMC, with coloured polygons showing basement highs. *Abbreviations:* BFZ, Bight Fracture Zone; BR, Buðli Ridge; CGFZ, Charile Gibbs Fracture Zone; DR, Dreki Ridge; EB, Eurasia Basin; FIR, Faroe–Iceland Ridge; FR, Fálnir Ridge; GIR, Greenland–Iceland Ridge; EB, Eurasia Basin; EGR, East Greenland Ridge; HR, Högni Ridge; HvR, Hovgard Ridge; IB, Iberia; JMFC, Jan Mayen Fracture Zone; JMMC, Jan Mayen microcontinent; JMRN, Jan Mayen Ridge North; LR, Langabrun Ridge; LYR, Lyngvi Ridge; MOR, mid-ocean ridge; NF, Newfoundland; OR, Otur Ridge; P, Porcupine; SHR, Sörlahryggur Ridge; TØ, Trail Ø; XR, extinct mid-ocean ridge.

to the present, forming the Irminger and Iceland basins SW and SE of Iceland, respectively, and the Greenland and Lofoten basins NW and NE of the Jan Mayen Fracture Zone (JMFC) Complex (Fig. 1). In addition, two basins flank the submerged Jan

Mayen Microcontinent (JMMC): the eastern one, called the Norway Basin, was formed from Early Eocene to Early Miocene. The active Reykjanes mid-ocean ridge continues west of the JMMC with the Kolbeinsey Ridge, which in turn connects to

the Mohn's Ridge through an approximately 200 km-long segment of the western JMFZ (Fig. 1).

Based on a growing database of geophysical data, many authors have proposed several kinematic models explaining the formation of the NE Atlantic oceanic basins (e.g. Vogt & Avery 1974; Talwani & Eldholm 1977; Srivastava & Tapscoff 1986; Vogt 1986; Skogseid & Eldholm 1987; Gaina *et al.* 2002, 2009). The more recent models, which took advantage of new aeromagnetic data collected in the Norway Basin and neighbouring regions, show a more complex kinematic model for the evolution of the NE Atlantic (e.g. Gernigon *et al.* 2008, 2012, 2015; Gaina *et al.* 2009). Although isolated changes in the plate boundary have been previously proposed, the Gaina *et al.* (2009) model presented a comprehensive and integrated regional view of the NE Atlantic Ocean that attempted to explain and quantify the complexities in the evolution of plate boundaries in this region since the Paleocene. They proposed that a series of plate boundary readjustments were expressed by short-lived triple junctions and/or ridge propagations, particularly in the area north and south of the JMMC, and suggested that an Early Eocene tectonic event that has been observed in different regions of the NE Atlantic might be the consequence of regional changes in plate motions.

New studies have documented the detailed configuration of oceanic floor in the Norway Basin and the architecture of the JMMC (e.g. Peron-Pinvidic *et al.* 2012; Gernigon *et al.* 2015; Blichke *et al.* 2016). The seafloor spreading history for the last 20 myr has been modelled in detail by using high-resolution magnetic data along the Reykjanes, Mohn's and Kolbeinsey ridges (Ehlers & Jokat 2009; Merkur'ev *et al.* 2009; Hey *et al.* 2010; Benediktsdóttir *et al.* 2012; Merkouriev & DeMets 2014).

Our present contribution is meant to revisit the detailed evolution of oceanic basins in the NE Atlantic region by using recent magnetic and gravity anomaly maps, and a compilation of magnetic anomaly and fracture zone identifications from studies mentioned above. Based on these data and interpretations, we construct a new regional kinematic model. Finally, we discuss the distinct seafloor spreading domains identified on potential field data and described by our new kinematic model in the context of regional plate motions and associated tectonic events.

New magnetic anomaly grid of the NE Atlantic

Pioneering work that describes regional magnetic anomaly variations in the North Atlantic was made

possible by the availability of relatively dense geophysical surveys, and the thorough evaluation and processing of these data by the Geological Survey of Canada in 1995 (Verhoef *et al.* 1996). Part of this digital grid has been renewed by adding data from new aeromagnetic surveys by Olesen *et al.* (2010) and Gaina *et al.* (2011). The NAG-TEC project (Hopper *et al.* 2014) offered the opportunity to revisit the NE Atlantic magnetic anomaly data compilation, and publicly available aeromagnetic data from 1951 to 2012 have been inspected and included in a new magnetic anomaly grid of this region (see the Supplementary material) (Fig. 2).

Data processing

Raw aeromagnetic data (see the Supplementary material) have been processed with algorithms embedded in the commercial software Oasis montaj (<https://www.geosoft.com>). Firstly, the data for each survey have been interpolated to a regular grid with cell size equal to one-quarter of the flight line spacing. Spikes due to minor noise and artefacts were smoothed with a low-pass filter (cut-off wavelength 30–50 fiducials) in order to keep the signal intact. Outliers and spikes identified in the offshore aeromagnetic measurements were removed manually.

To compute magnetic anomalies from the raw magnetic data, field values calculated using the International Geomagnetic Reference Field (IGRF), or Definitive Geomagnetic Reference Field (DGRF) models have been subtracted from the raw measurements. Several additional corrections, including diurnal corrections, statistical corrections based on profile cross-over analysis and micro-levelling, have also been applied. Individual grids were subsequently merged into the regional magnetic anomaly grid. The long wavelength (larger than 300 km) of the resulting grid has been replaced by the CHAMP satellite magnetic anomaly model MF7 (Maus *et al.* 2009) (see the Supplementary material).

Magnetic anomaly and fracture zone identifications (picks)

For deciphering the architecture and history of oceanic crust formation in individual basins of the NE Atlantic, the two most important pieces of information are the identification of magnetic anomalies (Fig. 3) and mapping of fracture zones within the oceanic crust. Magnetic anomalies are used for dating the oceanic blocks, which are magnetized in the alternating polarities of the Earth's magnetic field as spreading occurs. A database containing a collection of magnetic anomaly picks that indicate the age

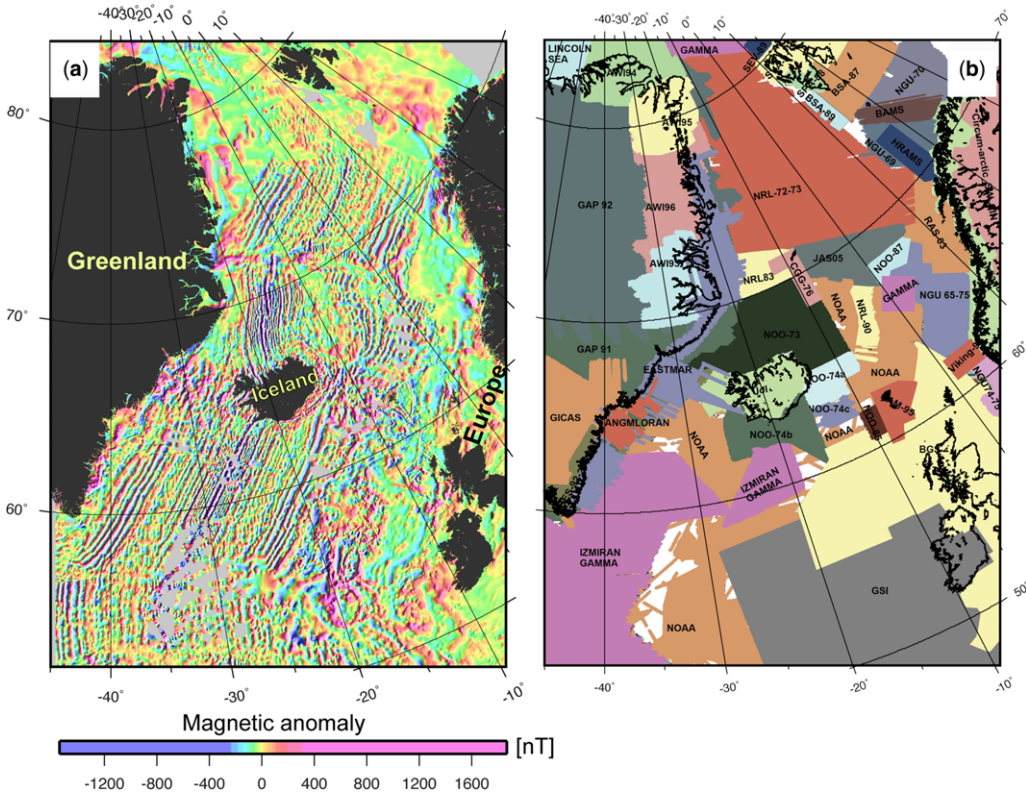


Fig. 2. NAG-TEC magnetic anomaly map (this study and Nasuti & Olesen 2014) (a) and location of various local gridded data used in this compilation (b). For a complete list of data sources see the Supplementary material.

of oceanic crust at the beginning (y) or end (o) of magnetized blocks of selected magnetic polarity reversals has been assembled and quality checked from various sources (Table 1). For dating the magnetic anomaly picks, the Ogg (2012) geomagnetic polarity scale (part of Gradstein *et al.* 2012) has been adopted.

The gravity anomaly and its derivatives (like the second vertical derivatives, vertical gravity gradient (VGG): see Sandwell & Smith 2009) are used to manually identify the central trough, or the centre of the steepest slope that define the bathymetric and gravity expression of a fracture zone. Using this approach, Matthews *et al.* (2011) interpreted fracture zones in all major oceanic basins. From that study, we have selected the fracture zone segments from the southern area of the NE Atlantic. They were supplemented with more fracture zone segments in the rest of the NE Atlantic region, including the JMFZ Complex, by using the gravity anomaly data (DTU10: Andersen 2010) and various derivatives (Haase & Ebbing 2014). The final database of magnetic anomaly and fracture zone identifications is presented in Figure 3.

A new kinematic model for the NE Atlantic Ocean

The kinematic model is built up by finding rotation parameters that bring the interpreted magnetic anomaly (and fracture zone, when possible) identifications into alignment at a particular time, which essentially defines the active oceanic spreading centre at that time. A constant motion of a crustal block or object on a sphere for a given time interval follows a great circle path and can be described through a rotation around a fixed pivot point, an Euler pole (see Cox & Hart 1986 for a basic introduction). In the case of seafloor spreading and mid-ocean ridge formation, the magnetized bodies parallel to the ridge constitute the meridians that intersect at the Euler pole, and the transform/fracture zones parallel to the direction of motion and perpendicular to the mid-ocean ridges align along small circles of the Euler pole. Rotations derived from these features should therefore bring the anomaly picks on either side of the present-day spreading axis into alignment along the palaeo-spreading centre. An isochron is built by

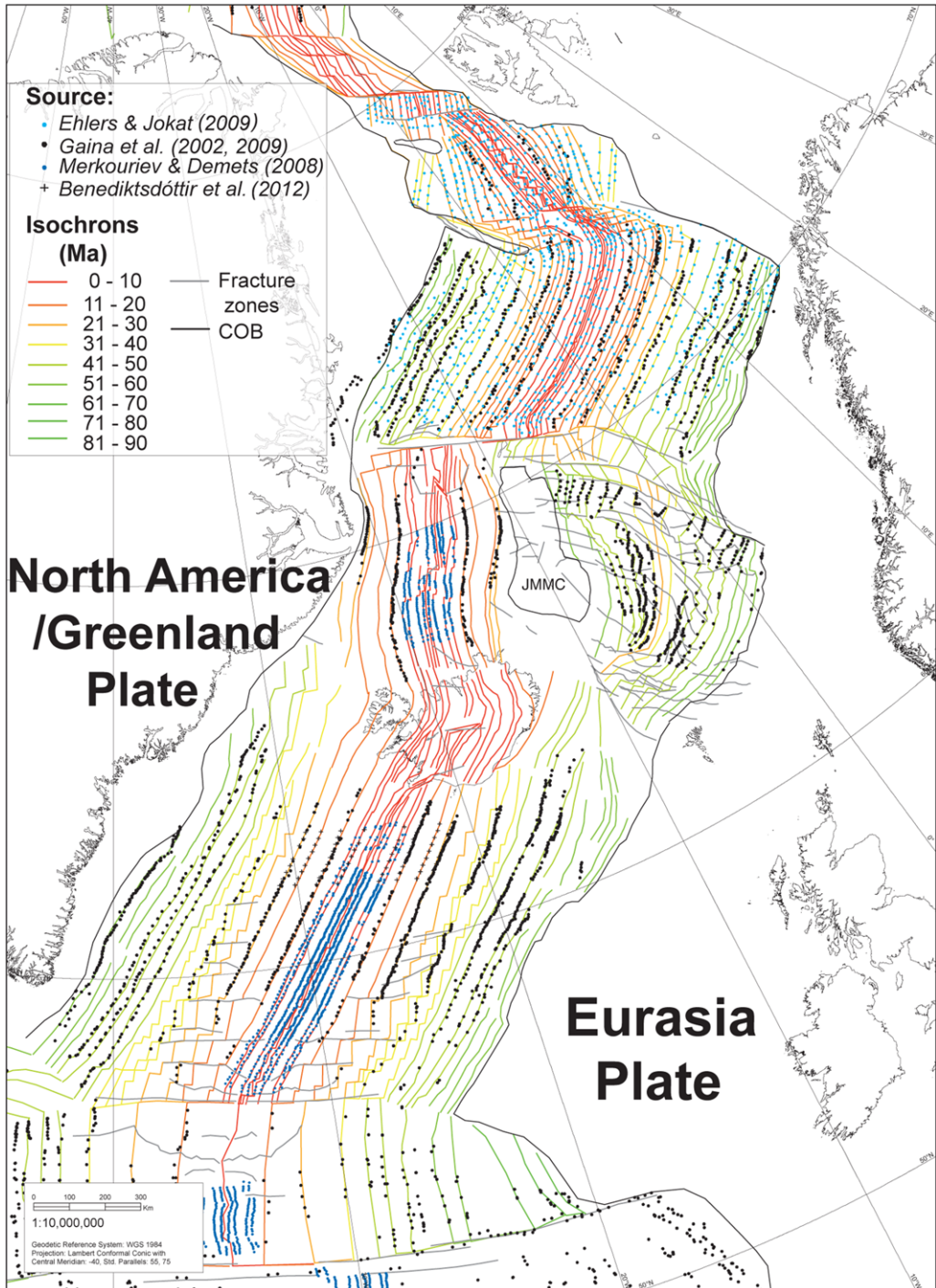


Fig. 3. Magnetic anomaly and fracture zone identifications and interpreted isochrons.

Table 1. *Magnetic anomaly identification according to various geomagnetic timescales*

Chron*	Age [Ma]				Magnetic pick identification (Reference)
	Cande & Kent 1995	Lourens <i>et al.</i> 2004	Gee & Kent 2007	Ogg 2012	
1no		0.781	0.780	0.781	Merkur'ev <i>et al.</i> (2009)
2An.1ny		2.581	2.581	2.581	Merkur'ev <i>et al.</i> (2009)
2An.3no	3.580	3.596	3.580	3.596	Ehlers & Jokat (2009)
3n.4no		5.235	5.230	5.235	Ehlers & Jokat (2009)
3An.1ny = 3ro		6.033	5.894	6.033	Benediktsdóttir <i>et al.</i> (2012); Merkur'ev <i>et al.</i> (2009)
4n.1ny		7.528	7.432	7.528	Merkur'ev <i>et al.</i> (2009)
4Any	8.699	8.769		8.771	Ehlers & Jokat (2009)
5n.2no		11.040	10.949	11.056	Benediktsdóttir <i>et al.</i> (2012); Gaina <i>et al.</i> (2009); Merkur'ev <i>et al.</i> (2009)
5r.2no	11.531			11.657	Ehlers & Jokat (2009)
5ACy		13.734	13.703	13.739	Ehlers & Jokat (2009)
5Cn.1ny = 5Bro		15.974	16.014	15.974	Benediktsdóttir <i>et al.</i> (2012); Merkur'ev <i>et al.</i> (2009)
5Cn.1no	16.293			16.268	Ehlers & Jokat (2009)
6ny		18.748	19.048	18.748	Ehlers & Jokat (2009)
6no		19.722	20.131	19.722	Gaina <i>et al.</i> (2002)
6AAno	21.859			21.159	Gaina <i>et al.</i> (2009)
7n.1no	24.730			23.962	Ehlers & Jokat (2009)
9no	27.972			27.439	Ehlers & Jokat (2009)
13ny	33.058		33.058	33.157	Gaina <i>et al.</i> (2002)
17n.1no	37.473			37.956	This study
18n.1ny	38.426			38.834	Ehlers & Jokat (2009)
18n.2no	40.130		40.130	40.321	Gaina <i>et al.</i> (2009); Gaina <i>et al.</i> (2002)
20ny	42.536		42.536	42.301	Ehlers & Jokat (2009)
20no	43.789		43.789	43.432	Gaina <i>et al.</i> (2009); Gaina <i>et al.</i> (2002)
21ny			46.264	45.683	Ehlers & Jokat (2009)
21no	47.906		47.906	47.329	Gaina <i>et al.</i> (2009); Gaina <i>et al.</i> (2002)
22no	49.714		49.714	49.335	Ehlers & Jokat (2009); Gaina <i>et al.</i> (2009); Gaina <i>et al.</i> (2002)
23n.1ny	50.778		50.778	50.613	Ehlers & Jokat (2009)
23n.2no	51.743		51.743	51.826	Ehlers & Jokat (2009)
24n.1ny	52.364		52.364	52.629	Ehlers & Jokat (2009)
24n.3no	53.347		53.347	53.933	Ehlers & Jokat (2009)
25ny	55.904		56.904	57.101	Gaina <i>et al.</i> (2002)
31no	68.737			69.269	Gaina <i>et al.</i> (2002)
33no			79.08	79.900	Gaina <i>et al.</i> (2002)
34ny			83.0		Gaina <i>et al.</i> (2002)

* "o" and "y" stand for "old" and "young" sides of normal (n) reverse (r) magnetised oceanic crust.

calculating the best-fitting segments (that are great and small circles using the inferred Euler pole) using the reconstructed magnetic anomaly and fracture zone data, respectively. The locations and geometry of mid-ocean ridges through time are therefore represented by the seafloor isochrons (C) derived above from the magnetic anomaly and fracture zone identifications.

In this study, we have built a new set of relative plate motions between Eurasia and Greenland, and for the various blocks that make up the JMMC (Table 2). The 'relative plate motion' quantitatively describes, through Euler rotations, the position of one tectonic plate relative to another plate that is considered fixed. We use the term 'finite rotation' to quantify the motion between present day and

Table 2. Finite rotations of main tectonic blocks relative to a fixed Eurasia Plate (a positive sign indicates the northern hemisphere for latitude and eastern hemisphere for longitude)

Age (Ma)	Chron	Rotation		
		Latitude (+°N)	Longitude (+°E)	Angle (°)
Greenland–Eurasia				
11.100*	C5n.2o	67.5	133.1	2.62
19.722*	C6no	72.2	126.1	5.29
21.16 [†]	C6AAno	72.5	126.75	5.72
23.96 [‡]	C7n.1ny	72.23	127.35	6.46
27.44 [‡]	C9no	72.01	128.05	7.59
33.160	C13ny	68.3	132.3	7.66
40.320	C18n.2no	61.5	127.8	8.30
43.430	C20no	57.4	127.9	8.59
47.329	C21no	53.7	129.0	9.27
49.335	C22no	55.4	123.5	10.29
53.930	C24n.1no	50.9	123.65	11.09
57.100 (pre-break-up)	C25ny	52.5	123.8	12.32
North Jan Mayen Ridge Complex[‡]– Eurasia				
33.160	C13ny	–65.4	167.8	10.51
40.320	C18n.2no	–52.0	150.6	5.73
43.430	C20no	–40.1	143.0	4.78
47.329	C21no	–59.6	159.1	17.51
49.335	C22no	–58.6	157.8	18.02
53.930	C24n.1no	–52.2	151.1	15.32
57.100 (pre-break-up)	C25ny	–52.2	151.1	15.32
Central-west Jan Mayen Ridge Complex[§]– Eurasia				
33.160	C13ny	–64.6	167.2	10.52
40.320	C18n.2no	–50.5	150.6	5.78
43.430	C20no	–38.4	143.4	4.86
47.329	C21no	–59.1	158.9	17.53
49.335	C22no	–58.1	157.6	18.05
53.930	C24n.1no	–51.6	151.0	15.37
57.100 (pre-break-up)	C25ny	31.4	–175.8	4.65
Central-east Jan Mayen Ridge Complex– Eurasia				
33.160	C13ny	–65.4	167.8	10.51
40.320	C18n.2no	–52.0	150.6	5.73
43.430	C20no	–40.1	143.0	4.78
47.329	C21no	–59.6	159.1	17.51
49.335	C22no	–58.6	157.8	18.02
53.930	C24n.1no	–52.2	151.1	15.32
57.100 (pre-break-up)	C25ny	32.0	–172.5	4.33
South Jan Mayen Ridge Complex[¶]– Eurasia				
33.160	C13ny	–65.6	167.9	10.71
40.320	C18n.2no	–65.2	160.3	14.39
43.430	C20no	–62.3	156.0	13.11
47.329	C21no	–64.2	163.2	26.25
49.335	C22no	–63.4	162.2	26.74
53.930	C24n.1no	–59.9	157.2	23.81
57.100 (pre-break-up)	C25ny	–45.9	–176.5	8.78
33.160	C13ny	–65.6	167.9	10.71
Central-south Norway Basin – Eurasia				
33.160	C13ny	–65.4	167.8	10.51
40.320	C18n.2no	–64.5	169.0	21.16
43.430	C20no	–64.5	168.9	32.10
47.329	C21no	–64.5	168.9	46.28
49.335	C22no	–64.1	168.6	48.45
53.930	C24n.1no	–63.0	166.5	50.29
57.100 (pre-break-up)	C25ny	–63.0	166.5	50.29

*From Merkur'ev *et al.* (2009).[†]From Ehlers & Jokat (2009). For times younger than 20 Ma, we have used the North America–Eurasia rotations of Merkur'ev *et al.* (2009). For times between 20 and 33 Ma, we have used the North America–Eurasia rotations of Ehlers & Jokat (2009).[‡]The following ridges identified in the JMMC are part of this complex: the Jan Mayen Ridge North (JMRN), the SHR Sörlahryggur Ridge (SHR) and the Lyngvi Ridge (LYR) – for their present-day positions see Figure 1.[§]The following ridge identified in the JMMC is part of this complex: Buðli Ridge (BR) – for its present-day position see Figure 1.^{||}The following ridges identified in the JMMC are part of this complex: the Högni Ridge (HR), the Fáfírnir Ridge (FR) and the Otur Ridge (OR) – for their present-day positions see Figure 1.[¶]The following ridges identified in the JMMC are part of this complex: the Dreki Ridge (DR) and the Langabrunn Ridge (LR) – for their present-day positions see Figure 1.

a certain time in the geological past, and ‘stage rotation’ for the motion between two plates for a selected time interval in the geological past. For pre-break-up times, the position of the tectonic blocks is inferred from rotations based on magnetic anomaly and fracture zones for older oceanic crust in surrounding regions, in particular to the south and to the west, to constrain the motion between Greenland, North America and Eurasia from 55 and 83 Ma (Gaina *et al.* 2002).

Based on the previous interpretation (i.e. Gaina *et al.* 2009), the southern part of the JMMC was deformed as oceanic floor formed at its southern proximity, and the western relocation of the mid-ocean ridge in the Late Eocene–Oligocene gradually detached several microcontinent blocks from Greenland. The JMMC blocks’ kinematic parameters were computed by carrying out visual fits (in GPlates: <https://www.gplates.org>) for four groups of basement ridges mapped by Blischke *et al.* (2016). Note that a separate rotation set was calculated for the oceanic part of the Norway Basin based on magnetic data. Compression described in the SE part of the JMMC demonstrates that relative motion between the oceanic and stretched continental domains took place probably after the seafloor spreading reorganization in the Eocene (see Gernigon *et al.* 2012, 2015; Blischke *et al.* 2016). Although the eastern part of the Norway Basin now has complete aeromagnetic data coverage (described and analysed by Gernigon *et al.* 2015), we did not have access to the new magnetic anomaly data and our interpretation is based on the magnetic grid shown in Figure 2

The magnetic anomaly identification sets (Table 1), combined with the fracture zone segments, were used for constructing densely spaced isochrons for 30 geological times (compared to only six in previous models: e.g. Müller *et al.* 2008) which date the oceanic crust following the timescale of Ogg (2012) (Fig. 3; see also the Supplementary material). The oceanic lithospheric age grid model is constructed using the newly interpreted isochrons (Fig. 3) and the rotation parameters describing the opening of the NE Atlantic (Table 2) following the interpolation technique outlined by Müller *et al.* (2008) and employing a gridding resolution of 0.05° . The age grid has been used to compute seafloor spreading rates and directions, and deviations from symmetrical oceanic crust formation at various intervals as constrained by the kinematic model (Table 2). The asymmetry in oceanic crust accretion is expressed as percentages from 0 to 100%, where 50% indicates symmetrical seafloor spreading (Müller *et al.* 2008). Note that poor age control on various regions of the Greenland–Iceland and Faroe–Iceland ridges (Fig. 1), and between the JMMC and the Iceland Plateau, led to less reliable models of spreading rate and

asymmetry, and these areas are masked on our maps (Fig. 4).

Break-up and early seafloor spreading

Following two extensive volcanic episodes, at approximately 62 and 55 Ma, which affected the NE Atlantic margins and formed the North Atlantic Igneous Province (NAIP: e.g. Saunders *et al.* 2007), continental break-up occurred between Greenland and Eurasia before C24 time (c. 55 Ma). To show the pre-break-up configuration of the western Eurasian margin and its conjugate margin, we reconstruct the structural elements (major tectonic boundaries, faults and structural highs: Stoker *et al.* 2016) and simplified inferred sedimentary basin ages (Funck *et al.* 2014) at Paleocene–Eocene transition time (Fig. 5a).

The NE Atlantic rift spans a region of more than 3000 km in a north–south direction from the southernmost tip of Greenland to the Western Barents Sea. Devonian–Paleocene multiple rifting events led to the formation of a wide extended area of successive basins and highs confined within the Greenland and Western European Caledonian deformation zone (Fig. 5a) (see also Stoker *et al.* 2016). Four main rifting periods can be identified from sedimentary basins along the NE Atlantic margin: (1) Devonian–Carboniferous; (2) Permian–Triassic; (3) Jurassic–Early Cretaceous; and (4) Late Cretaceous–Paleocene (Fig. 5a). According to Skogseid *et al.* (2000), the Late Palaeozoic rifting is poorly constrained, but the Late Jurassic–Cretaceous rifting caused approximately 50–70 km of crustal extension and subsequent Cretaceous basin subsidence from the Rockall Trough–North Sea areas to the SW Barents Sea. A Late Cretaceous–Paleocene renewed rifting episode caused approximately 140 km of extension (Skogseid *et al.* 2000).

Plate reconstructions of gridded data (present-day magnetic anomaly, isostatic gravity and crustal thickness) at 54 Ma, the time of early seafloor spreading in the NE Atlantic, are shown in Figure 5b, c. Present-day crustal thickness estimated from gravity inversion (Haase *et al.* 2016) gives a first-order approximation of the crustal architecture and amount of margin extension due to rifting. A reconstruction at 54 Ma (the time of early seafloor spreading in the NE Atlantic) shows regions of thin and thick crust (Fig. 5c), and, most importantly, the fact that break-up did not occur where the crust was thinnest.

As it has been postulated that the impingement of the Iceland plume at the base of the lithosphere has created massive volcanism and led to continental break-up (e.g. Morgan 1972), we show the reconstructed position of the Iceland plume (Dobrovine

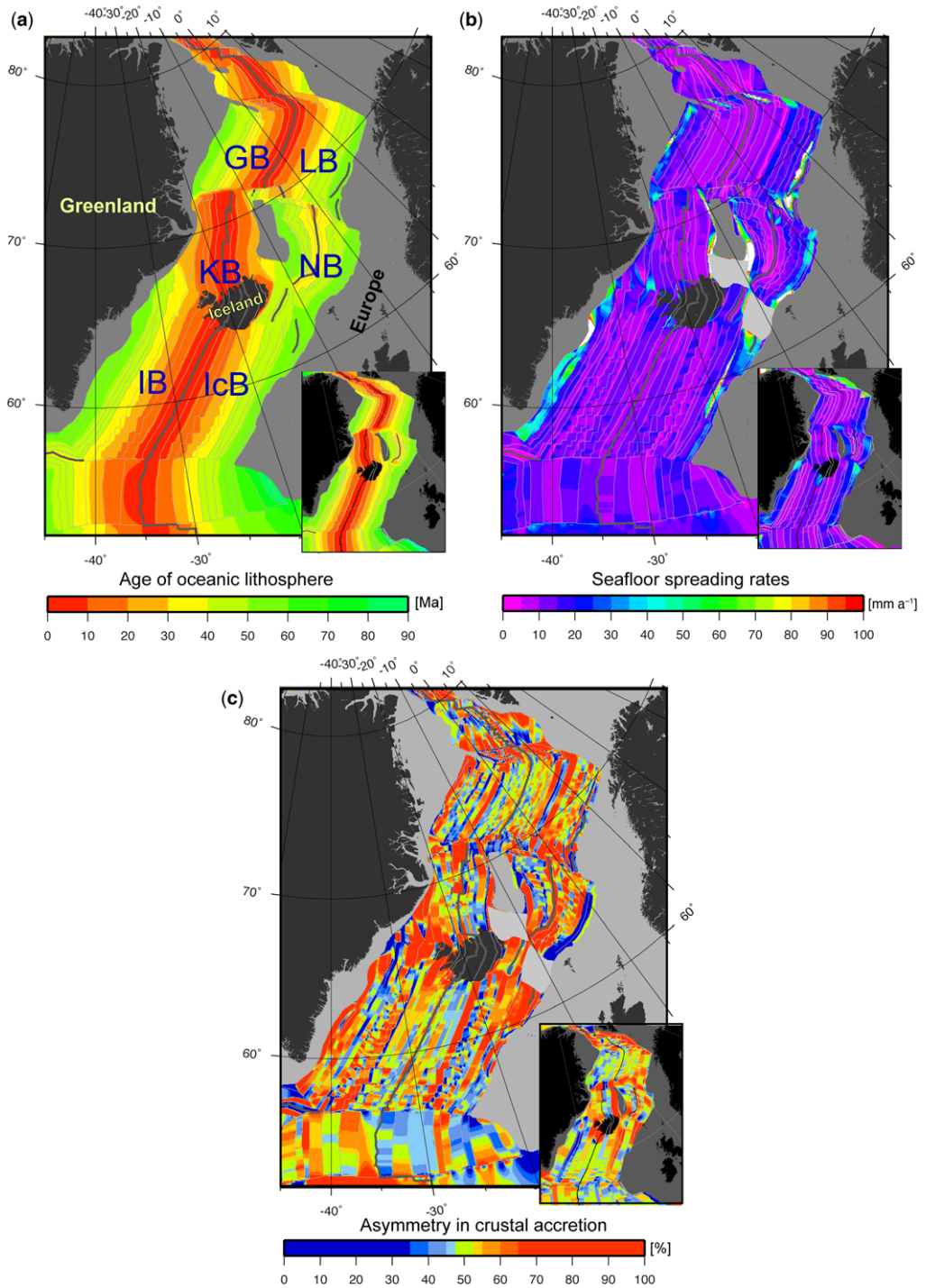


Fig. 4. Models of age of oceanic lithosphere (a), half spreading rate (b) and asymmetry in crustal accretion (c) in the NE Atlantic. Inset figures show the global grids published by Müller *et al.* (2008). Abbreviations: GB, Greenland Basin; IB, Irminger Basin; IcB, Iceland Basin; KB, Kolbeinsey Basin; LB, Lofoten Basin; NB, Norway Basin.

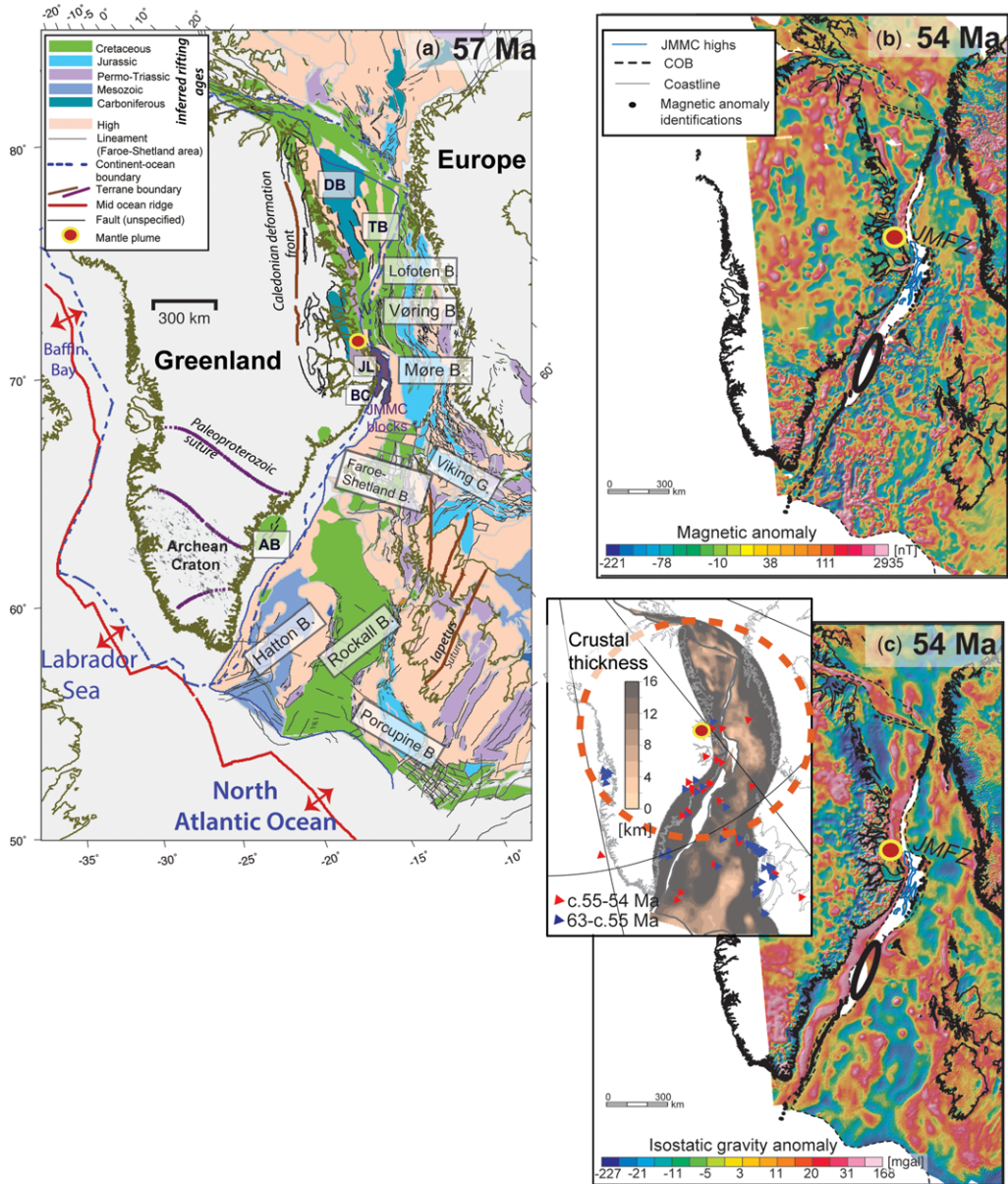


Fig. 5. (a) Pre-break-up (57 Ma) reconstruction of Greenland and Western Europe showing major sedimentary basins with inferred rifting ages and tectonic lineaments (Funck *et al.* 2014; Stoker *et al.* 2016), reconstructed plate boundaries, and modelled position of the Iceland hotspot (red and yellow circles) (Doubovine *et al.* 2012). (b) Reconstructed magnetic anomaly grid at C24 (c. 54 Ma). Black dots indicate the location of reconstructed magnetic anomaly picks. The JMMC tectonic blocks are also shown with blue outlines. The location of the postulated JMMC extension under present-day Iceland (Torsvik *et al.* 2015) is indicated by the black ellipse; (c) Reconstructed isostatic gravity anomaly grid at C24 (c. 54 Ma). Inset figure shows the reconstructed crustal thickness (based on gravity inversion: see Haase *et al.* 2016) and reconstructed locations of the dated NAIP rock samples (database of Torsvik *et al.* 2015) indicating the extent of volcanism before (between 63 and 62 Ma and c. 55 Ma), and at the break-up and incipient seafloor spreading time (c. 55–54 Ma). Orange dashed circle on the inset figure indicates a region of a mantle plume head (1000 km radius) at the base of the lithosphere (e.g. Ernst & Buchan 2002). Abbreviations: AB, Amassalik Basin; B, Basin; BC, Blossville Coast; COB, continent–ocean boundary; DB, Danmarkshavn Basin; G, Graben; JL, Jameson Land Basin; TB, Thetis Basin.

et al. 2012), which is, indeed, situated in a very close proximity to the future continent–ocean boundary COB of the Greenland Plate (Fig. 5a). Reconstructed locations of dated Paleocene–Eocene basalts (Fig. 5c) show the areal extent of the Iceland plume volcanism based on rock samples of Early–Late Paleocene (63–55 Ma, in blue) and break-up (55–54 Ma, in red) times, and as a circular area of approximately 1000 km radius as postulated by conceptual models of a mantle plume head extent (Jones *et al.* 2002).

Continental break-up and seafloor spreading occurred parallel to the Jurassic–Cretaceous sedimentary basin axes in the southern NE Atlantic and at a approximately 30° angle (clockwise) in the northern part, which was closer to the Iceland plume at that time (Fig. 5a). Oceanic crust of C24 age (oldest part at 53.93 Ma) is identified in all NE Atlantic sub-basins, but the inception of seafloor spreading may have been first registered in the NE Norway Basin, as also suggested by Gaina *et al.* (2009) and Gernigon *et al.* (2015). According to the reconstructed locations of dated Paleocene–Eocene basalts, the trend of magmatic activity closer to break-up time seems to have been more along the future margin orientation, possibly showing a change in the stress regime (Fig. 5c). The modelled Iceland plume location from 57 to 54 Ma is north of Jameson Land (Fig. 5). Very few dated NAIP samples have been described in the region north of Vøring and the conjugate NE Greenland margins (Fig. 5c), but a large volume of magmatic material has been identified along the margins in the form of seawards-dipping reflectors, inner and outer lava flows, sills intruded in the basement, and lower crustal bodies (e.g. Geissler *et al.* 2016; Horni *et al.*, this volume, in review). The presence of various NAIP volcanic structures is reflected in the high gravity and magnetic data values (Fig. 5b, c).

Gaina *et al.* (2009) suggested that break-up and seafloor spreading between Greenland and Eurasia were different in basins north and south of the Iceland. The new model presented here confirms these results. Part of the tectonic motion resulting from different opening histories of oceanic basins north and south of the Iceland region has been accommodated by extension within the JMMC, which sits at the junction between these two domains, but there are probably other, less well-documented, changes in the centre of the NE Atlantic and associated margins.

Our reconstructions (Fig. 5b, c) show that narrow oceanic basins (25–30 km) opened north of the JMMFZ. Just south of the JMMC reconstructed tectonic blocks is observed a much wider space (c. 100–130 km) between the reconstructed COBs. The position of interpreted COBs is not sufficient to infer the presence of an additional continental tectonic block, as COB interpretations could be

subjective. However, the gap in the reconstruction, plus evidence of buried continental crust under present-day SE Iceland, led Torsvik *et al.* (2015) to suggest that the JMMC is much larger and its southern fragment, which is possibly buried under present-day SE Iceland, was rifted from the Greenland continental margin situated south of the Blossville Coast (Fig. 5).

Seafloor spreading domains in the NE Atlantic

In this section we will discuss the relative motion between Greenland and Eurasia since the Paleocene (Fig. 6), and how inferred variations in the rate and direction of spreading between the two plates are reflected in the potential field-data pattern (Fig. 7). Based on these observations, we define several seafloor spreading domains in NE Atlantic sub-basins. A ‘seafloor spreading domain’ is defined as a region where the oceanic crust displays a certain pattern, or fabric, that can be identified as short wavelength variations mainly in the magnetic anomaly data, but also in the gravity (and sometimes bathymetric) data, and which reflects characteristics of a seafloor spreading regime. Lastly, we inspect changes in absolute plate motion of major plates in the NE Atlantic (Fig. 8), and speculate about possible connections between main kinematic adjustments in the North Atlantic and far-field stresses associated with distant tectonic events (Fig. 9).

Eurasia–Greenland stage rotations calculated from finite rotations listed in Table 2, and recalculated at equal interval of 5 myr, are shown in Fig. 6. At break-up time, the stage pole moved from a position held before 55 Ma near the equator to approximately 46° N (Fig. 6). The NE Atlantic oceanic crust was formed at a rate of 35–40 mm a⁻¹ for the first 4–5 myr in all basins, except the Norway Basin, where the spreading rate was lower (c. 25 mm a⁻¹) (Fig. 7e–g). This first stage of seafloor spreading resulted in a regular pattern of parallel-magnetized oceanic crust blocks visible on the magnetic gridded data (Fig. 7a, oceanic crust domains D1N, D1C and D1S). A sudden decrease in seafloor spreading rates occurred between 50 and 48 Ma, and coincided with a 30°–40° counter-clockwise change in spreading direction. Gaina *et al.* (2009) suggested that the southern part of the NE Atlantic was influenced more strongly by these changes as they may have been linked to a contemporaneous modification in seafloor spreading direction in the Labrador Sea. That event left its imprint on the orientation of pre- and post-C22 Bight fracture zone segments (see the red segments and arrows near the lower edge of Fig. 7a). Note that this time interval resulted in asymmetrical seafloor spreading in

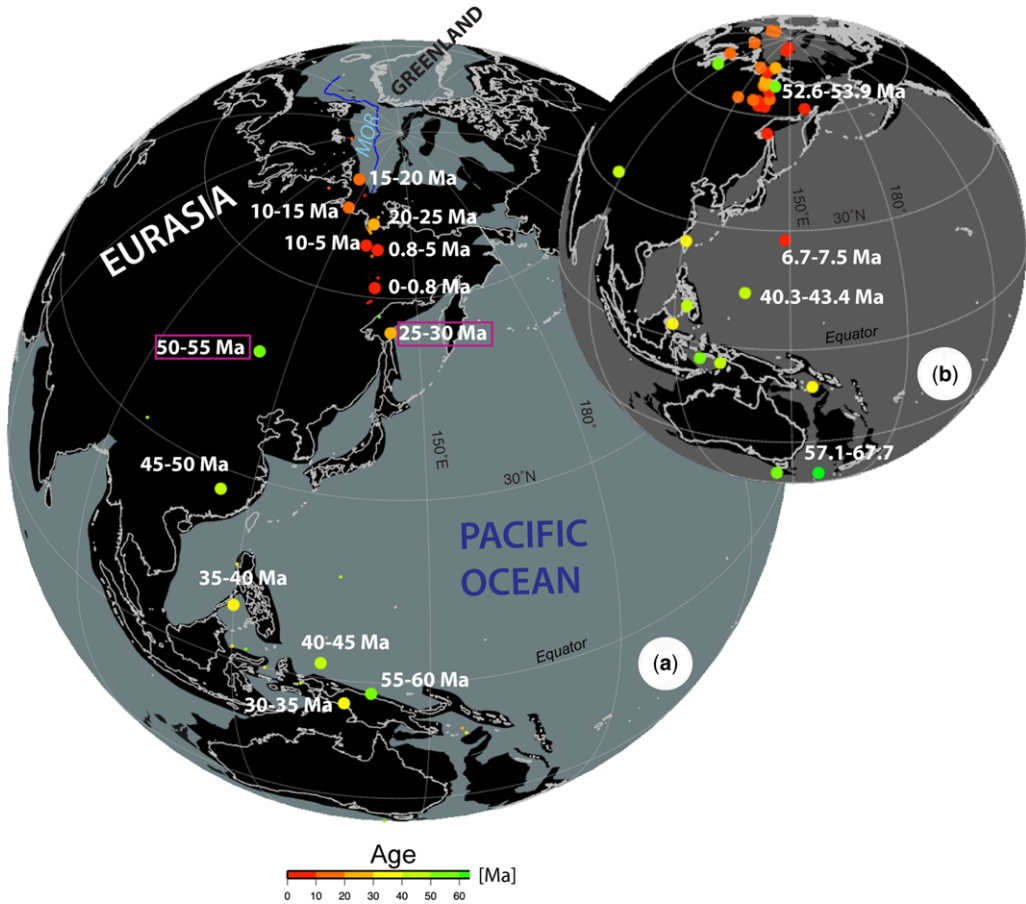


Fig. 6. Present-day location of the Greenland–Eurasia stage poles: (a) stage poles at equal interval of 5 myr; and (b) original stage poles derived from finite rotations listed in Table 2. MOR, mid-ocean ridge.

the Irminger and Iceland basins, with more crust accreted on the Greenland Plate (Fig. 4). Besides the reorientation of the Bight fracture zone and possible eastwards ridge jumps at C22 time, the seafloor fabric in the oceanic domains D1N and D1S (Fig. 7a) remained virtually the same from early seafloor spreading (*c.* 54 Ma) to C18 (*c.* 40 Ma). In the Norway Basin, the seafloor spreading pattern changed at C21 from parallel to the passive margins to fan-shaped, oblique spreading (Fig. 7a). This was likely to be the result of plate boundary re-locations north and south of the JMMC (e.g. Gaina *et al.* 2009; Gernigon *et al.* 2012, 2015; Blischke *et al.* 2016).

From approximately 50 to 30 Ma, the Greenland–Eurasia stage poles migrated southwards again, further away from the North Atlantic. The seafloor spreading rates continued to decrease in all NE Atlantic basins until approximately 35–33 Ma, when it reached rates of less than 20 mm a⁻¹, with ultra-slow spreading rates of around

10 mm a⁻¹ in the Lofoten and Greenland basins (Figs 4 & 7c). During this time interval, a clockwise rotation of the spreading direction was registered at around 45 Ma, and a counter-clockwise rotation at approximately 40 Ma (C18) (Fig. 7b–d). In the Iceland and Irminger basins, the seafloor fabric changed at C18 time from long, continuous parallel magnetic lineations, to shorter magnetic lineations offset by small fracture zone fragments ('staircase'-like domain D2S in Fig. 7a). In the Lofoten and Greenland basins, the seafloor fabric is orientated oblique to the spreading direction, as shown by the magnetic data patterns in domains D2N (Fig. 7a). The gravity data show the development of small offset fracture zones, perpendicular to the direction of spreading, in the southern part of NE Atlantic. These fracture zones are continuous from the Bight Fracture Zone to approximately 60.5° N, where they start to interfere with the V-shaped ridges, as described by numerous earlier studies (e.g. see

Vogt 1971; White *et al.* 1995) and more recently by Hey *et al.* (2010).

A global model that computed the locations of mantle plume at the surface by taking into account global plate motions for the last 130 Ma, and mantle plume conduit deviation due to advection in the mantle (Dobrovine *et al.* 2012), predicts that the Iceland mantle plume head centre crossed the Greenland COB between 40 and 35 Ma, and was located under oceanic crust for times younger than 35 Ma (Fig. 7a). The seafloor spreading domains that formed between C18 (*c.* 40 Ma) and C6 (*c.* 20 Ma) illustrate the complex geodynamics of the NE Atlantic where changes in kinematics and the influence of the Iceland plume left their imprint on the oceanic fabric. Apart from irregular oceanic crust architecture, plume–ridge interactions led to plate boundary relocations (as outlined by Gaina *et al.* 2009), the formation of the JMMC and asymmetrical seafloor spreading (Figs 4 & 7), and may explain the formation of other features observed within the oceanic domain, such as the elongated volcanic Trail Ø complex (Fig. 1) (Geissler *et al.* 2016) and seamount-like oceanic igneous features (SOIFs: see Gaina *et al.* 2016).

After the previously mentioned period of very low spreading rates (less than 20 mm a^{-1}), the JMMC formation and the westwards ridge relocation along the Kolbeinsey Ridge, the NE Atlantic oceanic crust formed again at higher rates ($20\text{--}28 \text{ mm a}^{-1}$) and, after two changes in spreading directions (at *c.* 14 and 7–8 Ma), it stabilized at approximately 20 mm a^{-1} in a NW–SE direction (Fig. 7e–g). In the Irminger and Iceland basins, oceanic spreading domain D3S gradually formed from north to south between C17 and C4 (38–7.5 Ma), showing a lateral transition from ‘staircase’ magnetic pattern to linear trends, most probably influenced by the Iceland plume flow. The youngest domain, D4S, shows a steady seafloor spreading regime achieved along the mid-ocean ridges south and north of Iceland (Fig. 7a).

Subduction in the Pacific and Mediterranean realms, and the opening of the NE Atlantic

Until the Silurian, Greenland and its Archaean and Proterozoic crust was part of Laurentia – an amalgamation of cratonic cores surrounded by terranes and deformed tectonic blocks resulting from several Precambrian orogenies (e.g. St-Onge *et al.* 2009). Following the Early Scandian (Caledonian) Orogeny in the Silurian (*c.* 425 Ma) (Torsvik *et al.* 1996), Greenland was confined between North America/Laurentia and Eurasia/Baltica. The Greenland Plate was formed in the Early Eocene, as a result of the NE Atlantic opening, but the dynamics

of this tectonic block had to accommodate tectonic changes imposed by its large neighbouring plates.

We endeavour to explore the hypothesis that some changes in the NE Atlantic evolution may have been triggered by tectonic events at the boundaries of either the Eurasia or North America plates. To place the opening of the NE Atlantic in a larger context, we combine our new kinematic model with the global model by Seton *et al.* (2012). To link the relative plate motions to a mantle reference frame, we use two alternatives: Torsvik *et al.* (2008) and Dobrovine *et al.* (2012) models (Fig. 8).

According to the two combined relative-absolute motion models (abbreviated NEATL-T2008 and NEATL-D2012), the direction of absolute motion (relative to the underlying mantle) of Eurasia and North America changed several times in the Cenozoic (Fig. 8). Although the two models differ, we note common features and trends. Both models show latitudinal motion of North America and Eurasia from 60 to 50 Ma. A major change in plate motions is shown by both models at 50 Ma, and another one at 40 Ma, most pronounced for the Eurasian Plate. A smoother change in the absolute motion of North America/Greenland is visible at 20 Ma in the NEATL-D2012 model, but also for the Eurasian Plate which started to move northwards in model NEATL-T2008 or become almost stationary in NEATL-D2012.

Major changes in tectonic plate motion could be triggered by continental collisions (e.g. Patriat & Achache 1984), changes in subduction geometry and subducted slab dynamics (e.g. Austermann *et al.* 2011), and possibly by mantle plume head impacts at the base of the lithosphere (e.g. Cande & Stegman 2011). A recent study proposes abrupt plate accelerations before continental rupture due to a rapid decrease in rift strength (Brune *et al.* 2016).

In the following, we explore whether major tectonic events at the boundaries of Eurasia, North America and Greenland, or changes in these plate motions relative to the mantle, coincide with the time of changes in seafloor spreading regimes. Variations in seafloor spreading direction and rates since the inception of the NE Atlantic are compared with the timing of major tectonic events reported in the literature (Fig. 9a). Changes in absolute plate motion at time intervals that correspond to dated boundaries between various oceanic crust fabric domains (Fig. 7a) are shown in Figure 9b.

Significant changes in seafloor spreading direction in the NE Atlantic were at approximately 50–49, 40, 33–29 and 15 Ma (Fig. 9a). The boundaries between different seafloor spreading fabrics in the NE Atlantic are dated at C21 (*c.* 47 Ma), C17–C18 (*c.* 40 Ma), C6 (*c.* 20 Ma) and C4 (*c.* 8–7 Ma) (Fig. 7a). Greenland’s large neighbouring

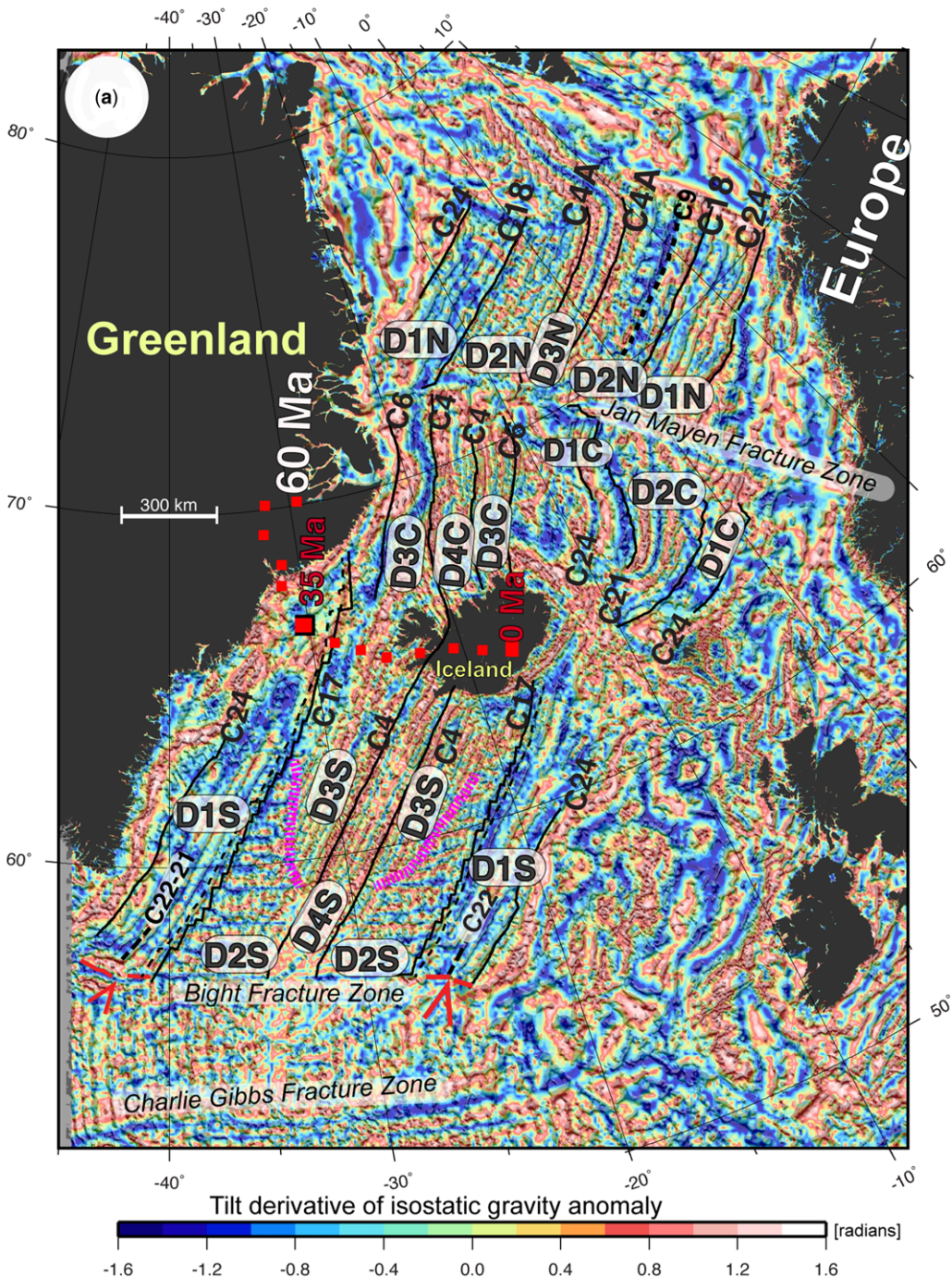


Fig. 7. Identification of seafloor spreading domains in the NE Atlantic Ocean. (a) Tilt derivative of isostatic gravity anomaly shaded by the tilt derivative of magnetic anomaly (illuminated from 120° N), which highlights the direction of magnetized bodies. Distinctive domains of oceanic crust (D1–D4, N – north, C – central and S – south) morphology are delineated by selected isochrons (age shown by chron (C) number). Red squares show the modelled position of the Iceland plume at 5 myr intervals (Dubrovine *et al.* 2012). The red segments and arrow show a change in spreading direction at C22 visible in the seafloor fabric. Greenland–Eurasia seafloor spreading directions (b)–(d).

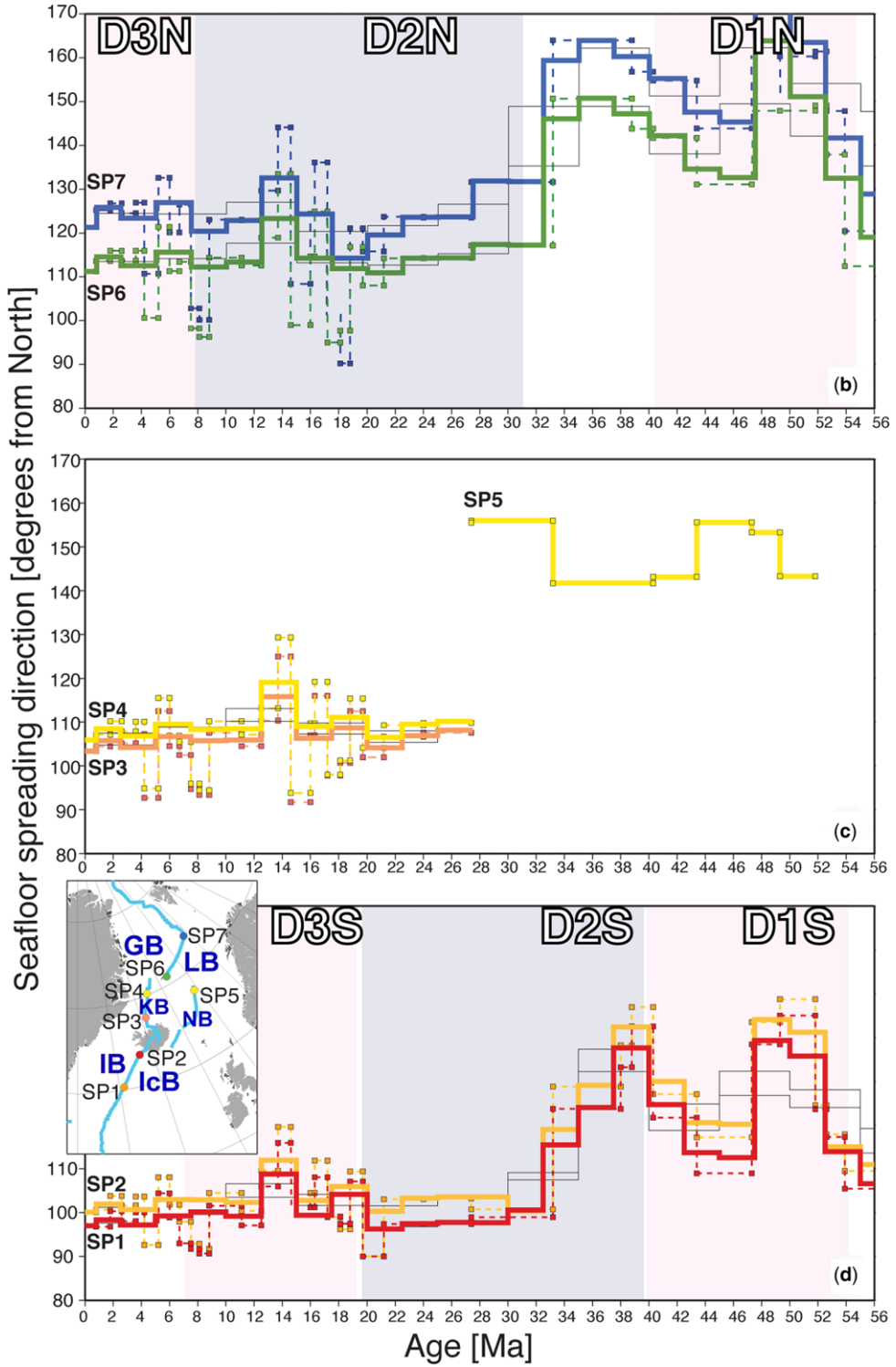
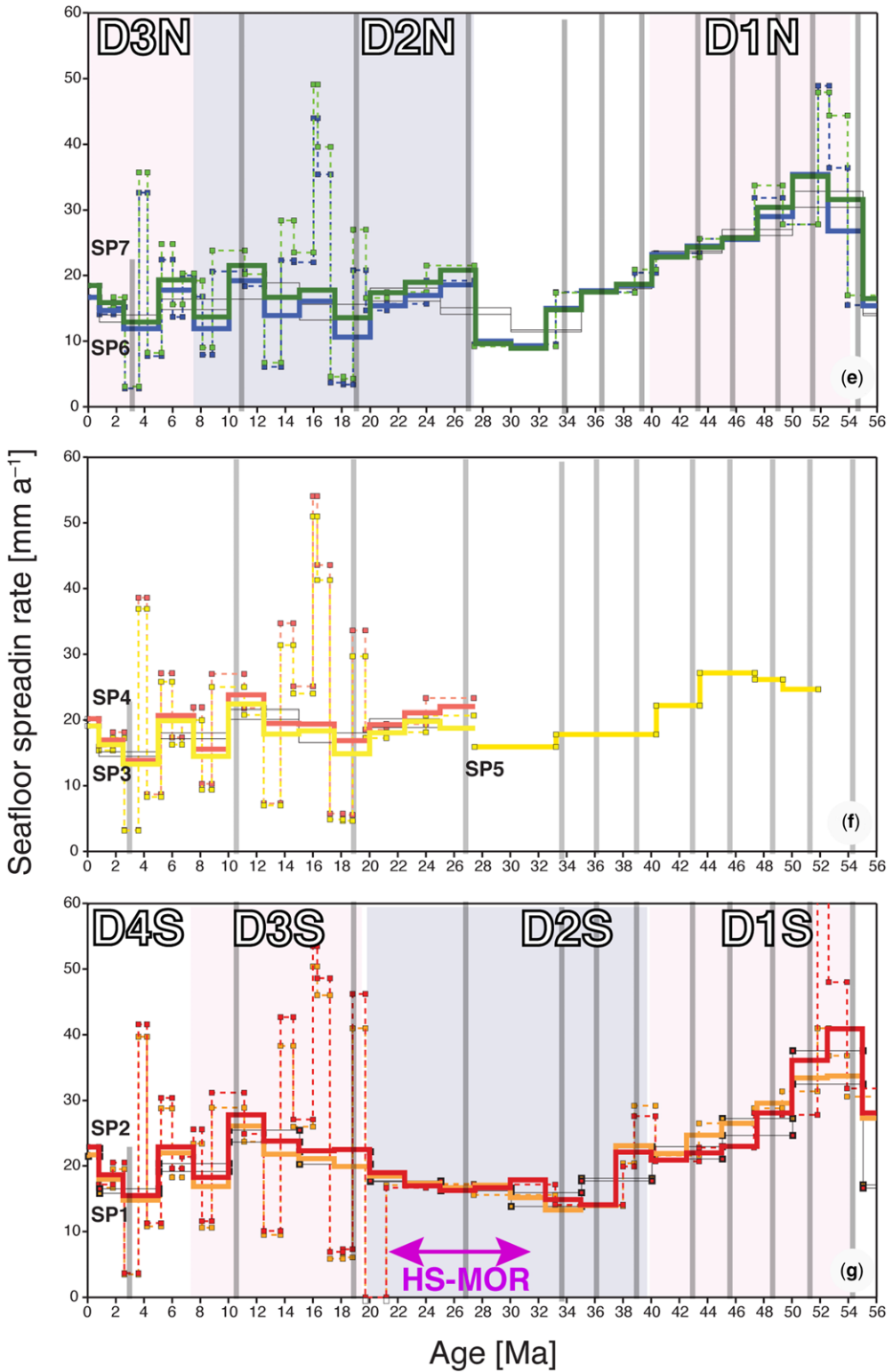


Fig. 7. (Continued)



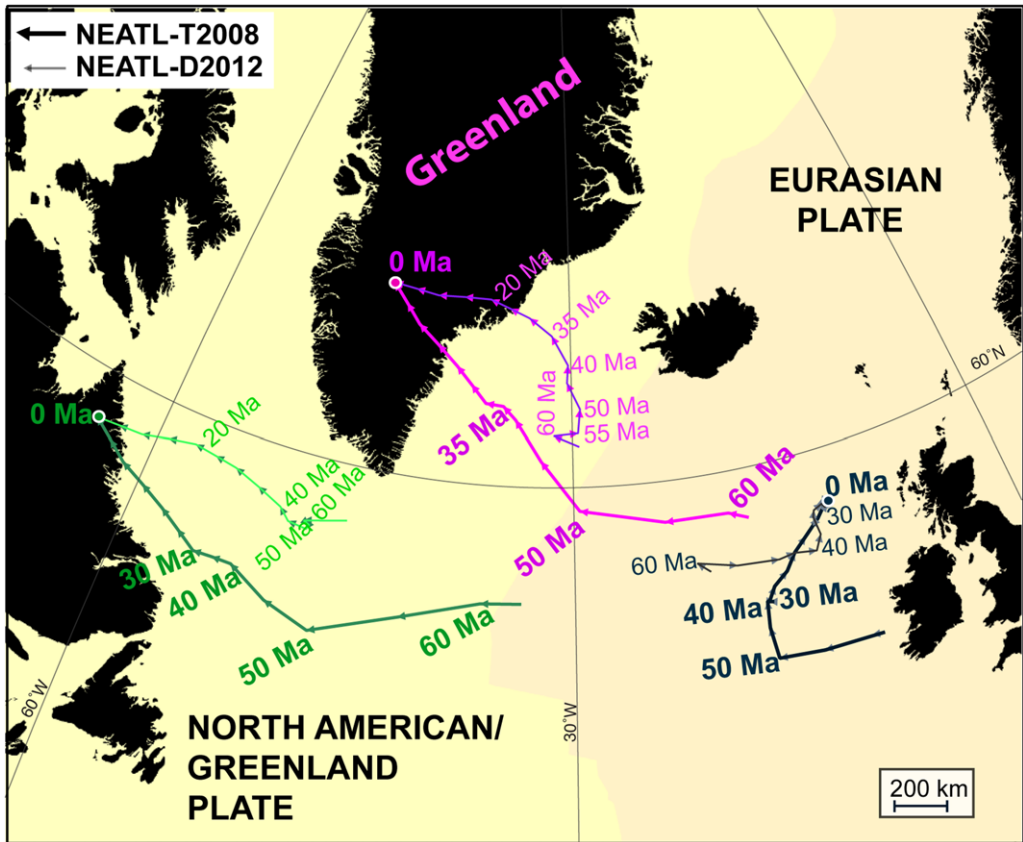


Fig. 8. Motion paths showing the direction of absolute motion (relative to the mantle) for North America (in green), Greenland (in magenta) and Eurasia (in black and grey) calculated at 5 myr intervals from 65 Ma to the present for two global models (thick lines – Torsvik *et al.* 2008; thin lines – Doubrovine *et al.* 2012) where relative plate motions between Eurasia, Greenland and North America have been replaced with the rotations presented in this study.

plates, Eurasia and North America, were bordered throughout the Cenozoic by active plate boundaries where the Pacific and smaller oceanic plates were continuously subducted. For example, the Farallon Plate had a long history of subduction under the western North America. We compare the vectors of absolute plate motion of this plate at 56, 55 and 52 Ma (Fig. 9b), and observe a considerable increase in its absolute plate velocity post-56 Ma. A detailed scrutiny of the slab graveyard under North

America revealed a gap in the subducted material identified in tomographical models. This gap, named ‘the Big Break’, was dated as Paleocene–Eocene (60–40 Ma) (Sigloch 2011). Large oceanic plateau subduction or obduction, slab break-off and the Laramide Orogeny in the western North America were also linked by several authors (e.g. Livaccari *et al.* 1981; Sigloch *et al.* 2008; Liu *et al.* 2010). Although the causal relationship between changes in the subduction regime at the western

Fig. 7. (Continued) Greenland-Eurasia full spreading rates (e)–(g). Seafloor spreading rates and directions are calculated for eight seed points along the active and extinct mid-ocean ridges in NE Atlantic oceanic sub-basins (locations and corresponding seed-point with matching colours are in the (d) inset map). The values are calculated based on stage poles at the exact age of identified isochrons (dashed thin lines), averaged at 2.5 myr intervals (thick lines), and at 5 myr intervals (thin horizontal grey lines). Pink and light blue boxes indicate the oceanic domain limits, as in Figure 7a. Grey thick vertical lines show postulated pulses of Iceland plume activity (Parnell-Turner *et al.* 2014). HS-MOR indicates hotspot-ridge interaction interval.

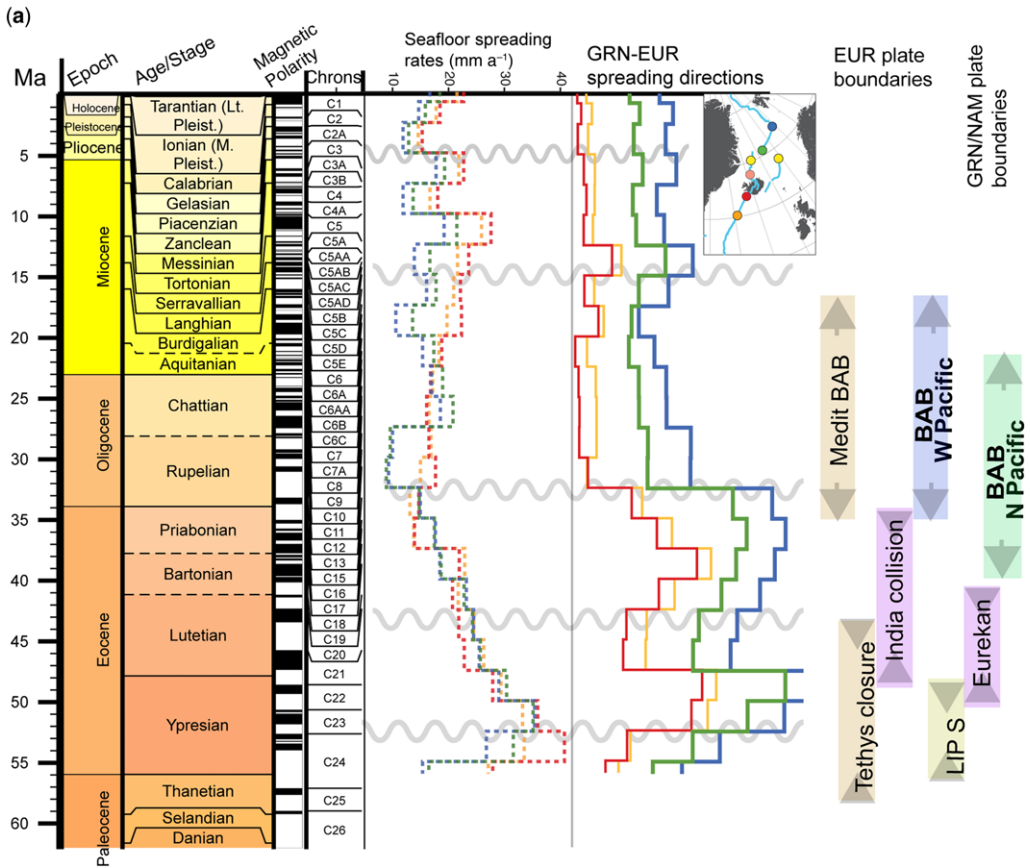


Fig. 9. Chart showing possible correlations between plate motion changes in the NE Atlantic and Cenozoic regional tectonic events. Abbreviations: AFR, Africa Plate; BAB, back-arc basins; EUR, Eurasia Plate; FAR, Farallon Plate; GRN, Greenland Plate; IND, India Plate; KUL, Kula Plate; LIP S, large igneous province subduction; Medit, Mediterranean region; NAM, North America Plate; PAC, Pacific Plate; Sboff, slab break-off; VAN, Vancouver Plate. Seafloor spreading rates and directions (a) are calculated for seven locations (seed points) on present-day and extinct mid-ocean ridges in the NE Atlantic (see inset map for seed point locations and Figure 7b–d for more details). Grey undulating lines indicate changes in spreading rates and/or directions that coincide with postulated compressional dome formation along the NE Atlantic continental margins.

North American plate boundary and its subsequent dynamics is not clear, we flag this connection as a future topic to be explored.

The Eurasian Plate, the third largest tectonic plate on Earth, is bordered on the west side by the Atlantic mid-ocean ridge, and to the south and east by a composite plate boundary formed by transform faults, subduction trenches and collisional segments, which in turn continue within NE Asia into an extensional intra-continental boundary that links with the Gakkel Ridge in the Arctic Ocean. In the geological past, the southern part of Eurasia was the locus of several trenches where the Neo-Tethys Ocean was consumed (for a review see Dilek 2006), and where massive continental collisions

formed the largest Cenozoic mountain belt: the Alpine-Himalaya (e.g. Suess 1893). The collision of various microblocks in the Mediterranean realm, the India–Asia collision and the Arabia–Asia collision occurred in mid-late Cenozoic, and dramatically affected the southern boundary of the Eurasian Plate (e.g. Yin 2010). In the western and northern Pacific, NE and SW of the junction with the Eurasia and North America plate boundary, the continental margins of North America and Eurasia underwent massive changes in the late Eocene–Oligocene. Numerous marginal back-arc basins were formed during that time period and this was linked to changes in subducted slab dynamics (e.g. Yin 2010).

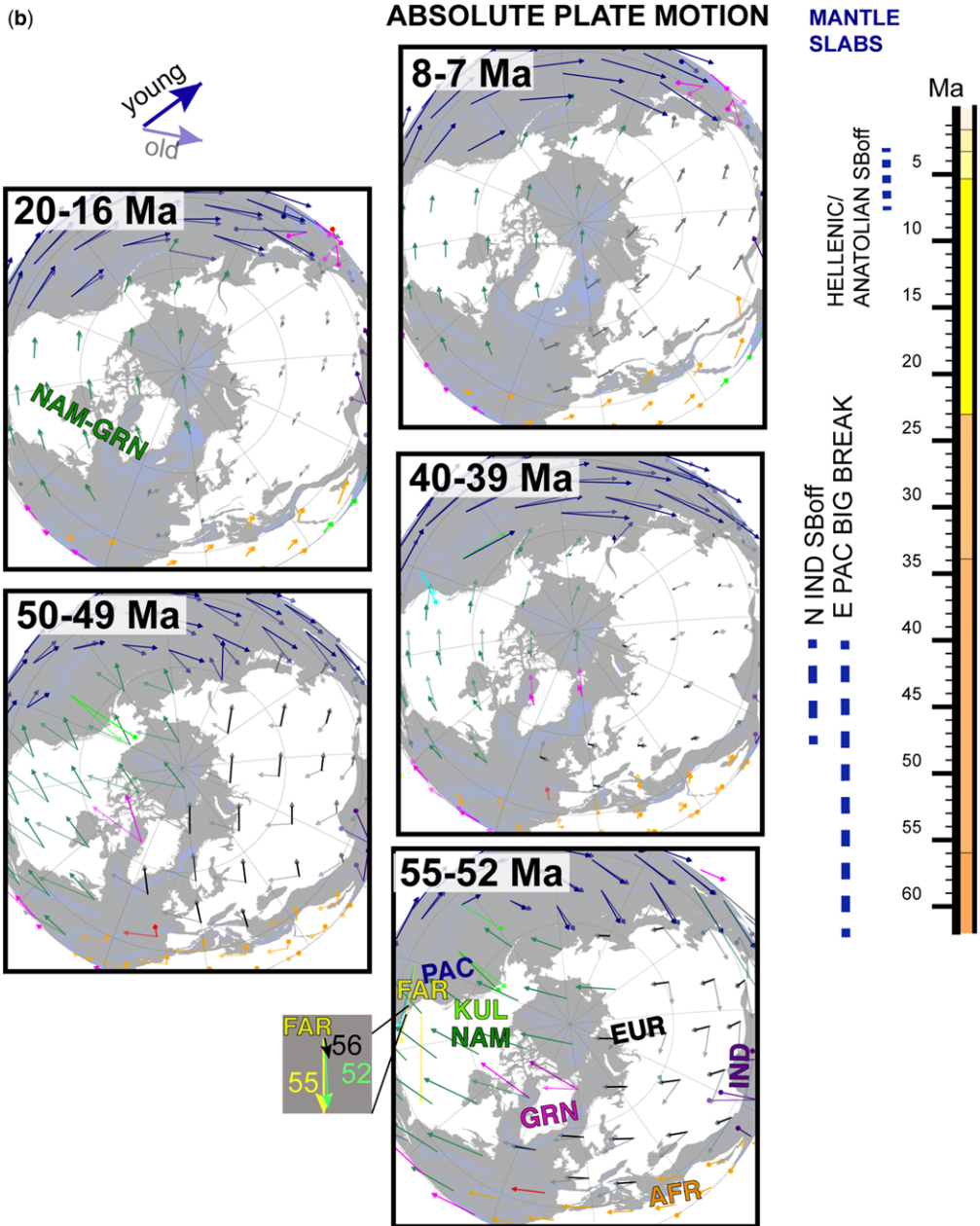


Fig. 9. (Continued) (b) shows a series of Cenozoic reconstructions with absolute velocity vectors for major tectonic plates in the northern hemisphere. The absolute plate motion is calculated using the Seton *et al.* (2012) global model, where relative plate motions between Eurasia, Greenland and North America have been replaced with the rotations presented in this study.

Around 50 Ma, North America, Greenland and Eurasia changed their absolute motion in a clockwise direction towards north. This may have been triggered by the soft India collision at the southern

Eurasian margin and possible readjustment of the North American Plate after oceanic plateau subduction and/or slab break-off. The northwards motion of Greenland due to seafloor spreading in both

the Labrador Sea/Baffin Bay and the NE Atlantic led to the Eureka deformation between northern Greenland and the High Arctic domain (e.g. Piepjohn *et al.* 2013). A change in spreading direction and a decrease in seafloor spreading rate in the NE Atlantic are contemporaneous with compression and deformation on Ellesmere Island (Fig. 9).

The absolute motion vectors of all three main plates in the North Atlantic decreased at approximately 40 Ma (Fig. 9b). The timing coincides with subduction reinitiation along the western margin of North America (Sigloch *et al.* 2008) and initiation of subduction along the Aleutian Trench (Jicha *et al.* 2006), approximately 1000 km south of the previous plate boundary. A change in spreading directions at this time is observed more clearly in the southern part of the NE Atlantic, but the oceanic crust fabric changed along the entire ocean (see the boundaries between oceanic domains 1 and 2 in the northern and southern part of the NE Atlantic – D1N, D1S and D2N and D2S in Fig. 7a).

The first massive volcanism in the NE Atlantic region was recorded around 62 Ma (e.g. Storey *et al.* 2007), and continued intermittently until 55 Ma, when the second large-scale magmatic output led to continental break-up. During the opening of the NE Atlantic Ocean, pulses of magmatic activity affected the NE Atlantic at regular intervals, in the first 20 myr after break-up at every 3 myr and after that only every 8 myr (shown as grey vertical lines in Fig. 7e–g) (Parnell-Turner *et al.* 2014). One of these pulses of magmatic activity occurred at around 40 Ma, and a slight increase in spreading rate can be observed before a relatively sharp reduction in magmatic productivity at 39–37 Ma in the south NE Atlantic (Fig. 7e–g).

For the following 20 myr (from 40 to 20 Ma), oceanic crust in the NE Atlantic seems to go through a series of continuous readjustments of plate boundary directions in an ultra-slow spreading regime. During this time a 'staircase'-like plate boundary developed in the Iceland and Irminger basins (Fig. 7a), and multiple ridge relocations and intra-continental rifts occurred south of and within the JMMC (see Blischke *et al.* 2016). By 22–20 Ma, the Aegir Ridge was extinct and a fully developed Kolbeinsey mid-ocean ridge was building a new oceanic basin west of the JMMC. Interestingly, at around 35–32 Ma, the Euler stage pole describing the opening of NE Atlantic moved northwards by approximately 4500 km (from SE Asia to Japan Sea) (Fig. 6). This is the time when marginal back-arc basins formed in the Japan, Okhotsk and South China seas, apparently as a result of India–Eurasia collision and subsequent lateral extrusion of SE Asia (Yin 2010). Changes at the distal Eurasian plate boundaries may have affected the reorganization of the North Atlantic, as in Early Oligocene

(c. 35–30 Ma) seafloor spreading in the North Atlantic was gradually focusing on its NE branch (in the NE Atlantic), and eventually the Labrador Sea/Baffin Bay Basin was abandoned.

From 30 Ma to present day, the Eurasia–Greenland/North America stage poles were clustered in NE Asia, along the boundary between the two major plates (Fig. 6). A change in relative plate motions around 7 Ma has been reported by Merkuriev & DeMets (2008) and was accompanied by a sudden decrease in seafloor spreading rate (Fig. 7e–g). The Eurasian absolute plate motion shows a change in a clockwise direction around that time (Fig. 9b), with larger angles in its SW part. The third largest orogenic plateau in the world, the Anatolian Plateau, was also formed in latest Miocene times. Recently, Schildgen *et al.* (2014) proposed a model where the inception of this plateau was directly linked with oceanic slab break-off and tearing, and rapid Hellenic Trench retreat. These circumstantial overlaps in time between various tectonic events that occur at boundaries of a large tectonic plate, such as collision, large topographical feature formation, slab break-off and subsequent change in plate motions, are noted here and may be used as hypotheses that can be tested by future studies and geodynamic modelling.

The opening of the NE Atlantic and Cenozoic compressional events on NE Atlantic passive margins

For the last two decades an on-going discussion has attempted to elucidate the nature and processes involved in the Early Paleocene–Present reactivation of NE Atlantic passive margins (e.g. Doré & Lundin 1996; Japsen & Chalmers 2000; Lundin & Doré 2002; Ritchie *et al.* 2003; Gomez & Verges 2005; Doré *et al.* 2008; Stoker *et al.* 2010; Tuitt *et al.* 2010; Japsen *et al.* 2012; Yamato *et al.* 2013; Døssing *et al.* 2016). Cenozoic compressional domes have been described on the Vøring, Faroe–Shetland and Hatton margins, in the Rockall Basin (for a short summary see Kimbell *et al.* 2016), and in the NE Greenland margin (Price & Whitham 1997; Hamann *et al.* 2005). Few distinct phases of compressional dome formation along the west European margin are identified for post-break-up times in the NE Atlantic: Early and Mid-Eocene, Mid-Eocene–Oligocene and Mid-Miocene (e.g. Doré *et al.* 2008; and see the summary in Kimbell *et al.* 2016). Previous studies have postulated a range of possible causes for post-break-up compression along the NE Atlantic margins, and they range from, for example, ridge-push and gravity potential forces, mantle convection (including small-scale convection along passive margins), far-field stresses, and

differential compaction (for a comprehensive review see Doré *et al.* 2008).

The time intervals with relatively sharp changes in seafloor spreading rates and/or directions are highlighted in Figure 9. Notable variation in spreading rates and spreading directions between Eurasia and Greenland derived from our study are observed for the Early Eocene (*c.* 52 Ma), Mid-Eocene (ca 42 Ma), Early Oligocene (*c.* 33 Ma), Mid-Miocene (*c.* 15 Ma) and Late Miocene–Pliocene (*c.* 7–5 Ma). We observe that they coincide with postulated formation of compressional domes along the NE Atlantic continental margins. Other studies have pointed to this correlation, emphasizing the role of different spreading rates along the NE Atlantic spreading axes: for example, on the formation of Miocene domes in the Vøring and Faroe–Shetland basins (e.g. Mosar *et al.* 2002).

We do not attempt to discuss in detail the correlation between the occurrences of compressional domes along the NE Atlantic margins and the timing of regional tectonic events, but we would like to point out that changes at the distant plate boundaries of the Eurasian and North American plates discussed in the previous section, and schematically shown in Figure 9, have a temporal connection with NE Atlantic continental margin reactivation. In particular, periods of slab break-off described along the southern European plate margin and western Pacific plate shortly predate changes in plate motion that may result in seafloor spreading rate readjustments and therefore a reorientation in intra-plate stresses.

Conclusions

An updated magnetic anomaly grid of the NE Atlantic, together with a new interpretation of the oceanic crust age in the Irminger, Iceland, Lofoten, Greenland and Norway basins, and west of the Jan Mayen microcontinent (JMMC), have prompted us to revisit the kinematic history of this region. Continental break-up occurred parallel to the Mesozoic rift axes in the southern NE Atlantic, but obliquely to the previous rifting trend in the northern NE Atlantic. The modelled location of the Iceland plume at 57–54 Ma is below the East Greenland continental margin, just north of the Jameson Land Basin, and very close to the break-up line, which can probably explain the rupture of continental lithosphere at an angle with previous rifted basin axes. Oceanic lithospheric ages, spreading rates and asymmetries in crustal accretion were calculated based on a dense set of isochrons. The new model includes a detailed kinematic history, including ridge jumps which led to the asymmetrical crustal accretion in the following areas: SE Lofoten

Basin, the Jan Mayen Fracture Zone (JMFZ) region, Iceland and offshore Faroe Islands.

We describe various spreading regimes and associated oceanic crust fabrics, and we attempt to link changes in spreading directions and rates with large-scale tectonic events. Boundaries between major oceanic crust domains were mainly formed at the time of changes in the European absolute plate motion, which, in turn, may have been caused by successive changes in the subduction or collisional regime along its eastern and southern boundaries. Variations in the subduction regime in the NE Pacific, followed by a change in the absolute motion of the North American Plate could have caused the Eureka deformation between NW Greenland and Ellesmere Island. These events caused seafloor spreading changes in the neighbouring Labrador Sea/Baffin Bay and a decrease in spreading rates in the NE Atlantic. The collision between India and Eurasia, crustal extrusion, and the formation of marginal back-arc basins along the eastern boundary of Eurasia coincide with a northwards jump of the rotation pole between Eurasia and Greenland, and the gradual demise of the triple junction between North America, Greenland and Eurasia.

Distal changes in plate motions triggered by collision and changes in subduction dynamics may have determined the rates and spreading directions in the NE Atlantic, but magmatic productivity reflected in oceanic crust fabric was also influenced by the local mantle dynamics. The new kinematic model, as well as geophysical data, confirm that several oceanic crust domains in the NE Atlantic bear the imprint of the Iceland hotspot pulsations, as shown by other previous studies.

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