Seamounts and oceanic igneous features in the NE Atlantic: a link between plate motions and mantle dynamics

CARMEN GAINA[1]*, ANETT BLISCHKE[2], WOLFRAM H. GEISSLER[3], GEOFFREY S. KIMBELL[4] & ÖGMUNDUR ERLENDSSON[5]

[1]*Centre for Earth Evolution and Dynamics (CEED), University of Oslo, Sem Sælands vei 24, PO Box 1048, Blindern, NO-0316 Oslo, Norway*

[2]*Iceland GeoSurvey, Branch at Akureyri, Rangárvöllum, 602 Akureyri, Iceland*

[3]*Alfred Wegener Institute, Helmholz Centre for Polar and Marine Research, Am Alten Hafen 26, 27568 Bremerhaven, Germany*

[4]*British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK*

[5]*Iceland GeoSurvey, Grensásvegi 9, 108 Reykjavík, Iceland*

**Correspondence: carmen.gaina@geo.uio.no*

Abstract: A new regional compilation of seamount-like oceanic igneous features (SOIFs) in the NE Atlantic points to three distinct oceanic areas of abundant seamount clusters. Seamounts on oceanic crust dated 54–50 Ma are formed on smooth oceanic basement, which resulted from high spreading rates and magmatic productivity enhanced by higher than usual mantle plume activity. Late Eocene–Early Miocene SOIF clusters are located close to newly formed tectonic features on rough oceanic crust in the Irminger, Iceland and Norway basins, reflecting an unstable tectonic regime prone to local readjustments of mid-ocean ridge and fracture zone segments accompanied by extra igneous activity. A SOIF population observed on Mid-Miocene–Present rough oceanic basement in the Greenland and Lofoten basins, and on conjugate Kolbeinsey Ridge flanks, coincides with an increase in spreading rate and magmatic productivity. We suggest that both tectonic/kinematic and magmatic triggers produced Mid-Miocene–Present SOIFs, but the Early Miocene westwards ridge relocation may have played a role in delaying SOIF formation south of the Jan Mayen Fracture Zone. We conclude that Iceland plume episodic activity combined with regional changes in relative plate motion led to local mid-ocean ridge readjustments, which enhanced the likelihood of seamount formation.

Supplementary material: Figures detailing NE Atlantic seamounts and SOIF distribution, and the location of earthquake epicentres are available at https://doi.org/10.6084/m9.figshare.c.3459729

The NE Atlantic oceanic basins have been formed since Early Eocene times following the break-up between Eurasia and Greenland. Various types of volcanic edifices (including seamounts) were emplaced on stretched continental crust before final break-up and seafloor spreading (Jones *et al.* 1994; Marty *et al.* 1998; O'Connor *et al.* 2000). The formation of oceanic crust was preceded by high magmatic activity, which resulted in additional igneous material being emplaced at the base and on top of stretched continental margins (Storey *et al.* 2007). Seamount volcanism and the emplacement of igneous centres on oceanic crust continued after seafloor spreading was established in various basins between Greenland and Eurasia. A considerable number of volcanic edifices have been identified in the NE Atlantic, mainly on remote sensing data including bathymetry and gravity data derived from satellite altimetry (e.g. Hillier & Watts 2007; Kim & Wessel 2011; Yesson *et al.* 2011) (Fig. 1).

Seamount volcanism is attributed to magmatic processes connected to the formation of new ocean floor/oceanic crust (seafloor spreading), or to the modification of this crust by subsequent intra-plate volcanism. A classic example of intra-plate volcanism is the plume-related creation of linear chains of age-progressing volcanic edifices on oceanic or continental crust (e.g. Morgan 1971). Intra-plate volcanism may also be the result of local processes such as lithosphere cracking or melt extraction from heterogeneous mantle (e.g. Forsyth *et al.* 2006), small-scale sublithospheric convection (e.g. Ballmer

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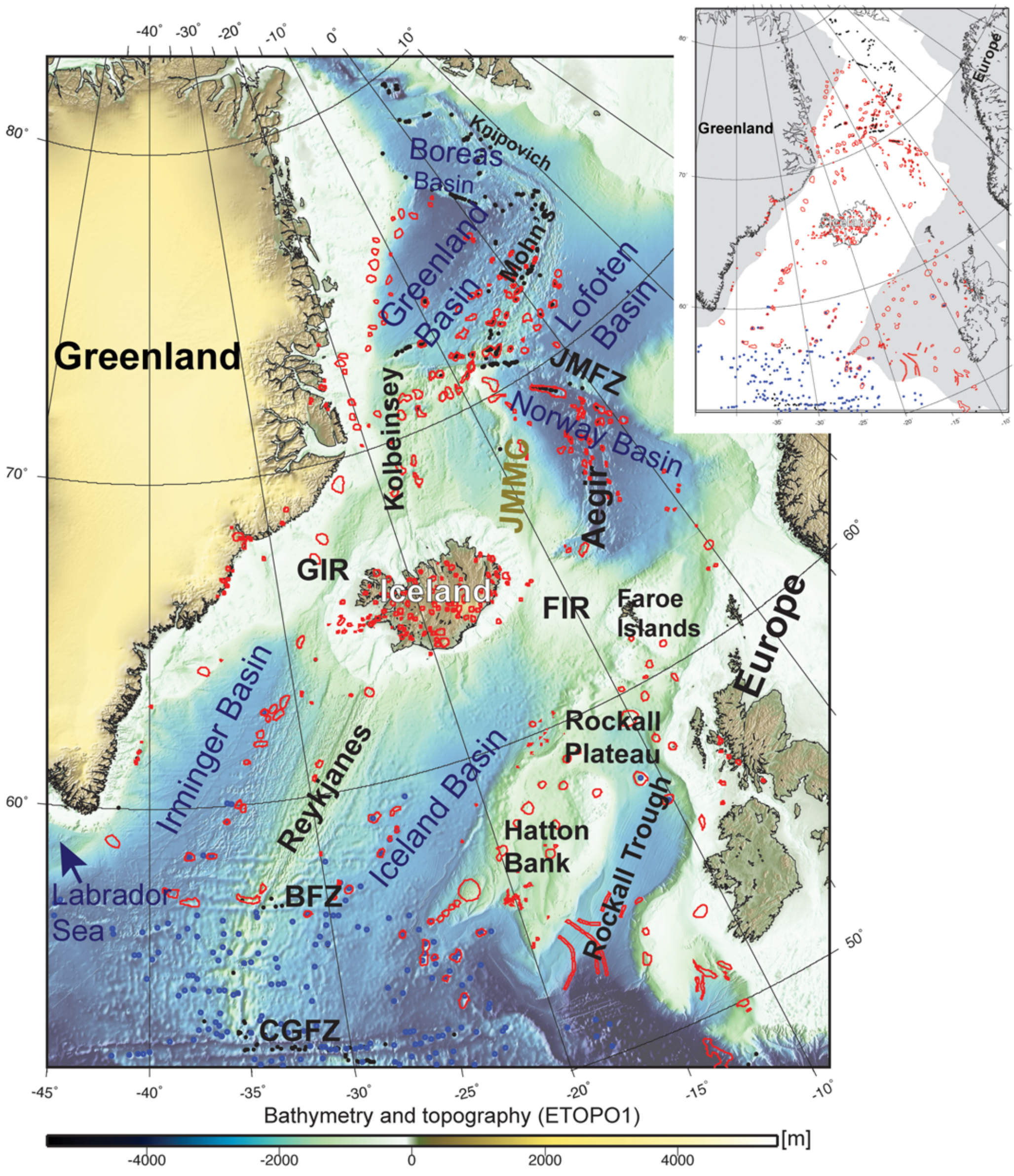


Fig. 1. Distribution of volcanic edifices (red, this study; blue, Kim & Wessel 2011; black, Yesson *et al.* 2011) in the NE Atlantic region superimposed on bathymetry (ETOPO1: Amante & Eakins 2009). Abbreviations are: BFZ, Bight Fracture Zone; CGFZ, Charlie Gibbs Fracture Zone; FIR, Faroe Iceland Ridge; GIR, Greenland Iceland Ridge; JMFZ, Jan Mayen Fracture Zone. Inset to the figure shows the distribution of seamounts on oceanic (white) and continental and extended continental crust (grey).

et al. 2009), or shear-induced melting of low-viscosity pockets of asthenospheric mantle located along the base of the lithosphere (Conrad *et al.* 2010).

This study aims to evaluate the correlations between a new database of oceanic volcanic features (seamounts and other small igneous edifices), and the oceanic crust morphology and evolution as established within the international NAG-TEC project (Hopper *et al.* 2014). We will first present the current knowledge of seamount and volcanic feature distribution in the NE Atlantic. The occurrence of these volcanic features on oceanic crust of various ages and structure is subsequently described. Possible links between NE Atlantic variations in seafloor spreading, mantle dynamics and seamount formation since the Eocene is also discussed. Our results may help in understanding the spatial and temporal interplay between volcanism and tectonics in a region that has also been heavily influenced by a pulsating mantle plume since the inception of oceanic crust formation.

Regional distribution of seamounts and volcanic edifices in NE Atlantic oceanic basins

According to the International Hydrographic Organization (IHO 1994, pages 211 and 121), a seamount is 'an isolated or comparatively isolated elevation rising 1000 m or more from the seafloor and of limited extent across the summit', whereas a knoll is 'a relatively small isolated elevation of a rounded shape rising less than 1000 m from the seafloor and of limited extent across the summit'. The first regional count of seamounts in the North Atlantic was carried out by Epp & Smoot (1989), who used multibeam data to identify approximately 800 seamounts between the equator and Iceland. More recently, seamount-like features interpreted on ship-track bathymetry data (Hillier & Watts 2007), gridded bathymetric data (Yesson *et al.* 2011), and satellite-derived gravity anomaly data and its vertical gradients (Wessel 2001; Kim & Wessel 2011) were catalogued in regional and global databases.

The igneous centres from the NE Atlantic identified in the NAG-TEC study (Hopper *et al.* 2014) is a collection of 429 features that has been divided into six subunits: offshore seamounts; igneous complexes; inactive calderas; active calderas; inactive central volcanoes; and active central volcanoes (Horni *et al.*, this volume, in review). They occur both onshore and offshore, on oceanic and on continental crust (Figs 1 & 2). An overview of the complete NE Atlantic igneous centre compilation is presented in Hopper *et al.* (2014).

In this contribution, we will focus on seamounts and igneous edifices situated on NE Atlantic oceanic crust (Fig. 1). These features were identified on published multichannel and single-channel seismic reflection profiles as mounded or bank features with dipping flanks and commonly erosional features on top (Fig. 3). In areas with no seismic control, bathymetry (SRTM30_PLUS: Becker *et al.* 2009), gravity (Andersen 2010) and magnetic gridded data (Gaina *et al.*, this volume, in review) were used for locating seamounts and other volcanic-like edifices, which are usually characterized by circular or elliptical anomalies in potential field data (Fig. 2). The seamount-like features were first manually identified on bathymetry and gravity data, and the interpretation was cross-checked with the magnetic anomaly maps. It has been assumed that a magnetic source will result in a distinct magnetic anomaly, and therefore only features with clear signatures on bathymetry, gravity and magnetic data have been considered in this database. Only features that rise more than 500 m above their surroundings and have a subcircular or well-defined base were included in the NAG-TEC database. Their structure varies and some are flat-topped, while others are more peaked. In addition, the volcanic features described in the EarthRef database (Earthref.org/SC) were also included (Fig. 3). Altogether, 175 identified features have an elevation of more than 500 m (therefore they fall into the 'knoll' category), but only 12 of them are over 1000 m in height (and can be called 'seamounts'). We suggest labelling the volcanic edifices discussed in this paper as 'seamount-like oceanic igneous features' (SOIFs), an acronym that is used in the rest of the paper.

For studying the geodynamic context of SOIF formation in various sub-basins of the NE Atlantic, we have scrutinized four main regions that display various volcanic activity patterns (Fig. 4). The structure and evolution of these sub-basins differ depending on their geographical location relative to the Iceland plume and on the proximity to additional plate boundaries – including the ones created by the formation of the Jan Mayen microcontinent (JMMC) (Fig. 1) (e.g. Gaina *et al.* 2009). In this study, we do not discuss in detail the magmatic history of Iceland or volcanism formed on extended continental crust.

Region I: south of Iceland and north of the Bight Fracture Zone

The identification of SOIFs in region I (Fig. 5a) is based on bathymetry (in most cases, satellite-derived altimetry and multibeam data for a few cases: see EarthRef.org/SC) only. The sediment thickness (Funck *et al.* 2014) in these basins is less than 2 km (Fig. 2d). The majority of SOIFs are located in three distinct areas. Few edifices (seven out of 42) are on Early Eocene crust (*c.* 52–54 Ma), close to the identified continent–ocean boundary (COB). Most of the volcanic features (28 out of 42) are located on Late Eocene–Oligocene crust (38–20 Ma), and are distributed almost symmetrically on both conjugate oceanic ridge flanks. SOIFs are not identified on the conjugate European flank in the northern Iceland Basin, at approximately 63° N, in a region with higher sediment thickness than on the Greenland flank.

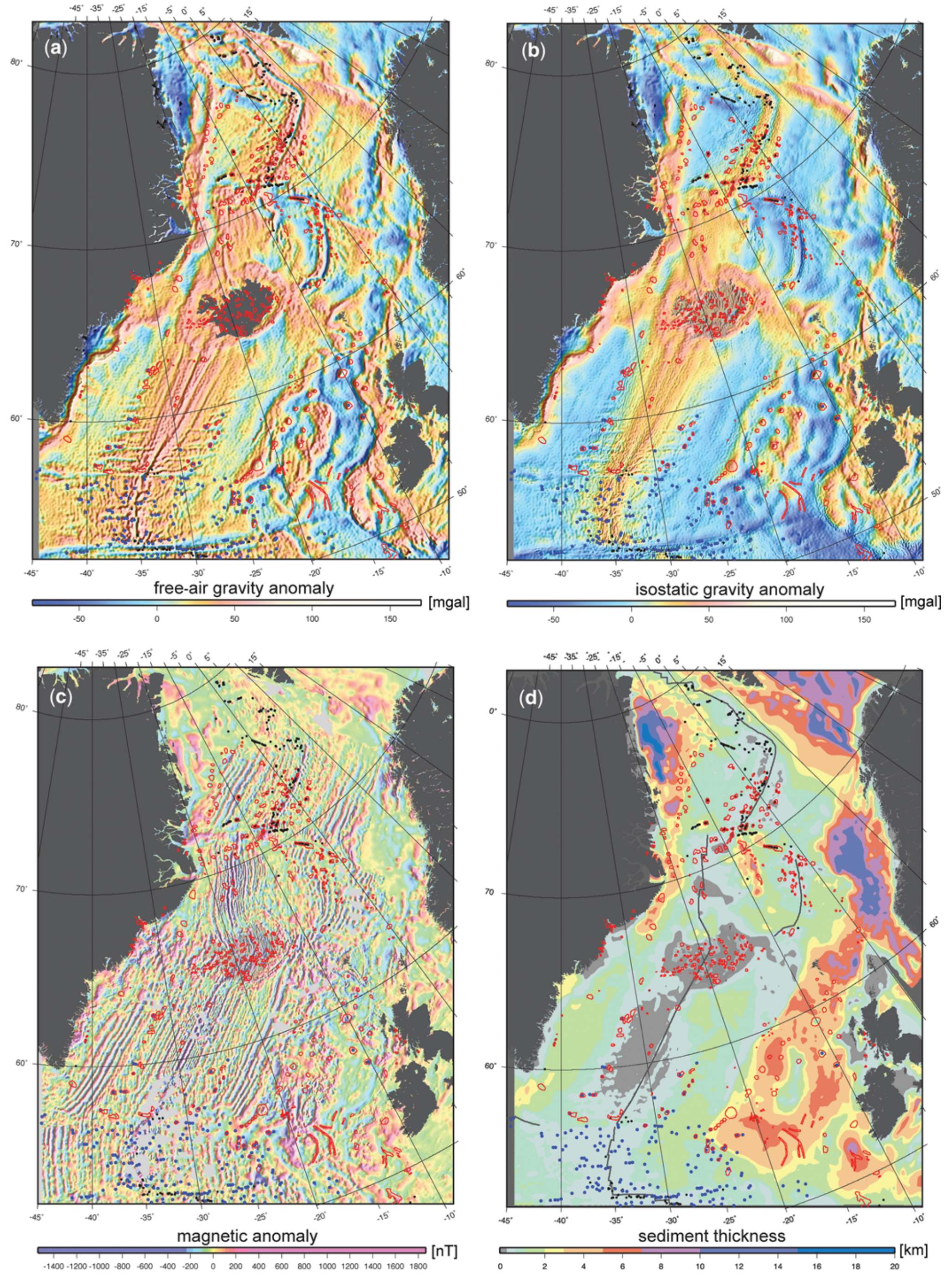


Fig. 2. (**a**) Free-air gravity (DTU10: Andersen 2010); (**b**) isostatic gravity anomaly (this was computed using the Airy–Heiskanen model, where the compensation is accomplished by variations in thickness of the constant density layers: the root is calculated using the ETOPO1 topography and bathymetry: Haase *et al.*, this volume, in press); (**c**) magnetic anomaly (Nasuti & Olesen 2014; Gaina *et al.*, this volume, in review); and (**d**) sediment thickness (Funck *et al.* 2014). Distribution of volcanic edifices as in Figure 1. Dark grey lines indicate the active and extinct plate boundaries.

Note that part of that thick sediment succession constitutes Late Miocene and younger drift deposits resulting from the onset of deep-water circulation in the NE Atlantic. Two recent seismic reflection lines crossing the northern Irminger and Iceland basins from west to east (fig. 1 in Parnell-Turner *et al.* 2015) imaged prominent high bathymetric features, including V-shaped ridges, under the sediment pile on both flanks of the Reykjavik Ridge (Parnell-Turner *et al.* 2015).

In region I, less than 20% of seamounts/volcanic edifices (seven out of 42) are on Mid-Miocene–Recent oceanic crust. Here, we do not discuss the volcanic edifices observed in the Rockall region on continental or extended continental crust: they have been described in detail in previous studies (e.g. Jones *et al.* 1994; O'Connor *et al.* 2000).

In the Irminger and Iceland basins, a clear change in the seafloor spreading regime occurred at C17 time (*c.* 38 Ma). The seafloor spreading direction changed by 20°–25° counterclockwise and the spreading rate decreased by about 30% (see Gaina *et al.*, this volume, in review). As a result, the oceanic crust was transformed from a linear, fracture-zone-free fabric to a 'stair-case'-like fabric due to the appearance of small offset fracture zones, especially in the area south of 60° N and north of the Bight Fracture Zone (Fig. 1).

A closer look at the second group of SOIFs described above reveals that the volcanic edifices are mostly elliptical in shape, and some of them coincide with the intersection between fracture zones and palaeo-mid-ocean ridges (identified as magnetic isochrons) that formed between C13 and C6. Further observations related to the oceanic crust characteristics in the regions linked to SOIF occurrences are summarized in Table 1. The crustal thickness obtained with two different methods (Fig. 5), and the seafloor spreading rates and asymmetry (Fig. 4), are described in detail in Funck *et al.* (2016) and Gaina *et al.* (this volume, in review).

Region II: the Norway Basin

The NAG-TEC SOIF database contains 34 seamounts in the Norway Basin (Fig. 5b), which were identified on the gravity, magnetics and bathymetry gridded data, with five of them cross-checked on 2D seismic reflection data. In addition, 13 SOIFs were identified as igneous centres, four of them on the eastern JMMC, in the vicinity of the COB (Peron-Pinvidic *et al.* 2012; Blischke *et al.*, this volume, in press), and therefore linked to break-up volcanism. The emplacement of these igneous centres occurred during and immediately after the initial formation of seawards-dipping reflectors (SDRs). The igneous centres cut through the SDR section and are located close to fracture/fault zones. Peron-Pinvidic *et al.* (2012) and Blischke *et al.* (this volume, in press) suggest that the igneous centres located in the vicinity of the JMMC eastern margin are related to break-up and volcanic margin formation. Six igneous centres were identified on old oceanic crust (*c.* C24) close to the JMMC and four along the Norwegian margin (Table 1).

The majority of SOIFs are on Late Eocene–Early Oligocene crust (C20–C18 to C13: i.e. 40–33 Ma), flanking the Aegir extinct spreading ridge. A small number of large, elongated seamount chains or isolated rounded seamounts are also visible along the Jan Mayen Fracture Zone (JMFZ) situated in the northern Norway Basin (Table 1). One large feature was identified at the southernmost tip of the Aegir Ridge as a possible central volcano, formed by ridge propagation just prior to its extinction (Vogt & Jung 2009).

The SOIF production in the Norway Basin may have started in post-C21 (*c.* 47 Ma) time and continued until the Early Oligocene (C13, *c.* 33 Ma). This is illustrated by the fact that only a few isolated seamounts were identified on Early Eocene crust (C24–C22). Seamounts in the Norway Basin can also be seen along the oblique SSE–NNW pseudo-faults, features visible on gravity anomaly maps (e.g. Fig. 2), and described by Breivik *et al.* (2006) and Gernigon *et al.* (2012). Note that in Region II, the appearance of SOIFs in Late Eocene time coincides with a change in the spreading regime, when a drop in the spreading rate and a change in the spreading direction resulted in a fan-shaped basin geometry.

Region III: Kolbeinsey Ridge and associated oceanic basin

A continuous mid-ocean ridge (MOR) was established west of the JMMC about 20 myr ago (Nunns 1983; Kuvaas & Kodaira 1997; Gaina *et al.*, this volume, in review), and oceanic crust continued to form until today along the Kolbeinsey Ridge (Fig. 5c). A few igneous centres (five out of 22) were identified on seismic reflection, bathymetry, gravity and magnetic anomaly gridded data along the Greenland margin (and may be linked to the Oligocene break-up processes). One of these igneous centres is located on continental crust. No igneous features are visible on the conjugate western JMMC margin.

Two prominent SOIF populations are distinguished on Late Miocene–Pliocene crust (6 Ma and younger) (Fig. 5c), both of which are located in the vicinity of fracture zones (four SOIFs near the Spar Fracture Zone) or a ridge propagator tip (four SOIFs next to the southern propagator). The third distinct population (seven out of 22) is grouped SW and west of Jan Mayen Island, and includes the Eggvin Bank – a plateau with young (<1 Ma), scattered volcanic peaks (Mertz *et al.* 2004).

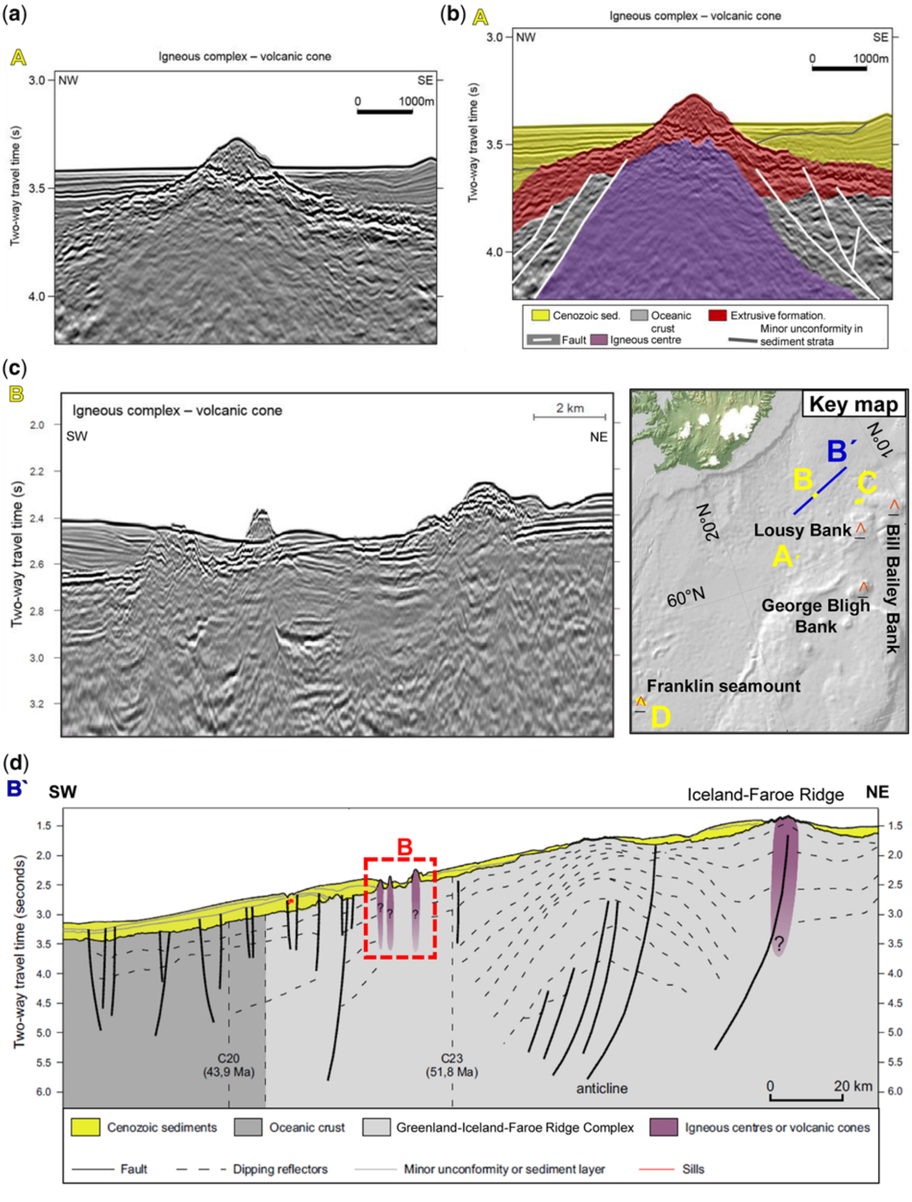
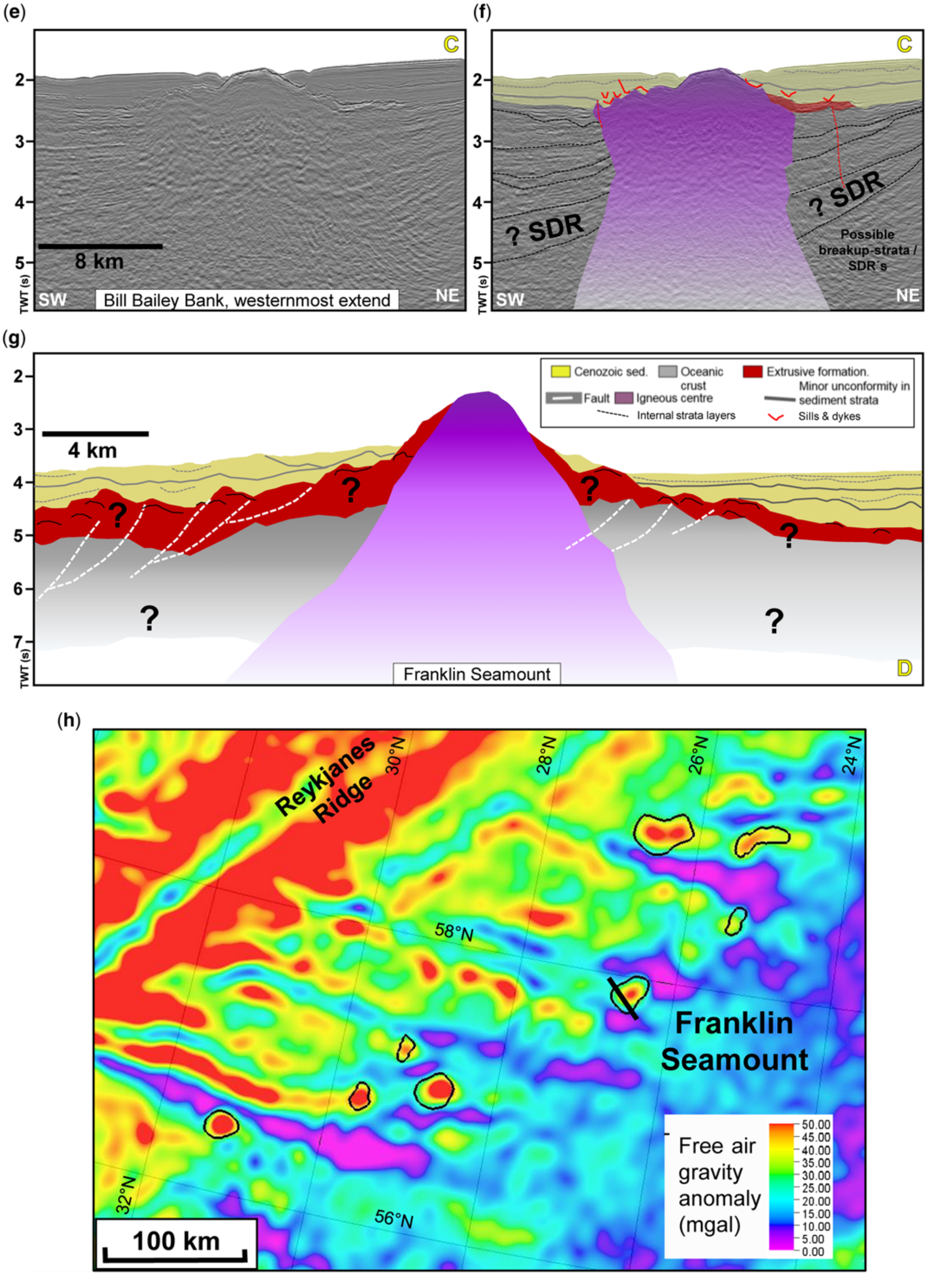


Fig. 3. Examples of seamount-like oceanic igneous features (SOIFs). These features were identified on 2D multichannel seismic reflection data (2D MCS) (National Energy Authority of Iceland; Elliott & Parson 2008) as mound or bank features with dipping flanks, sometimes with evidence of erosion at the top (**a**–**g**). SOIFs were first localized using gravity (Andersen 2010) and bathymetry data (SRTM30_PLUS: Becker *et al.* 2009). The key map shows the position of four seamounts registered in the EarthRef.org database (red open triangles), and the location of the 2D MCS profiles (A–D) as yellow and blue lines superimposed on a bathymetry map (SRTM30_PLUS: Becker *et al.* 2009). Seismic profiles A (in a & b) and C (in e & f) show examples of SOIFs situated on Early Eocene oceanic crust or very close to the COB. The Bill Bailey Bank (SMNT-606N-0103W from EarthRef.org) intrusive complex (line C in e & f) is an eroded seamount covered by Cenozoic sediments. The igneous centre imaged by profile B (in c) is also shown on a longer SW–NE-orientated profile (B’ shown in d) that is crossing the transition from normal oceanic crust in the Iceland Basin to the thicker Iceland–Faroe Ridge. Profile D (in g) shows the Franklin Seamount (SMNT-578N-0266W from EarthRef.org). (**h**) shows the free-air gravity anomaly (Andersen 2010) in the background, the location of the Franklin Seamount and other identified SOIFs (thin black contours), and the location of profile D (thick black line).



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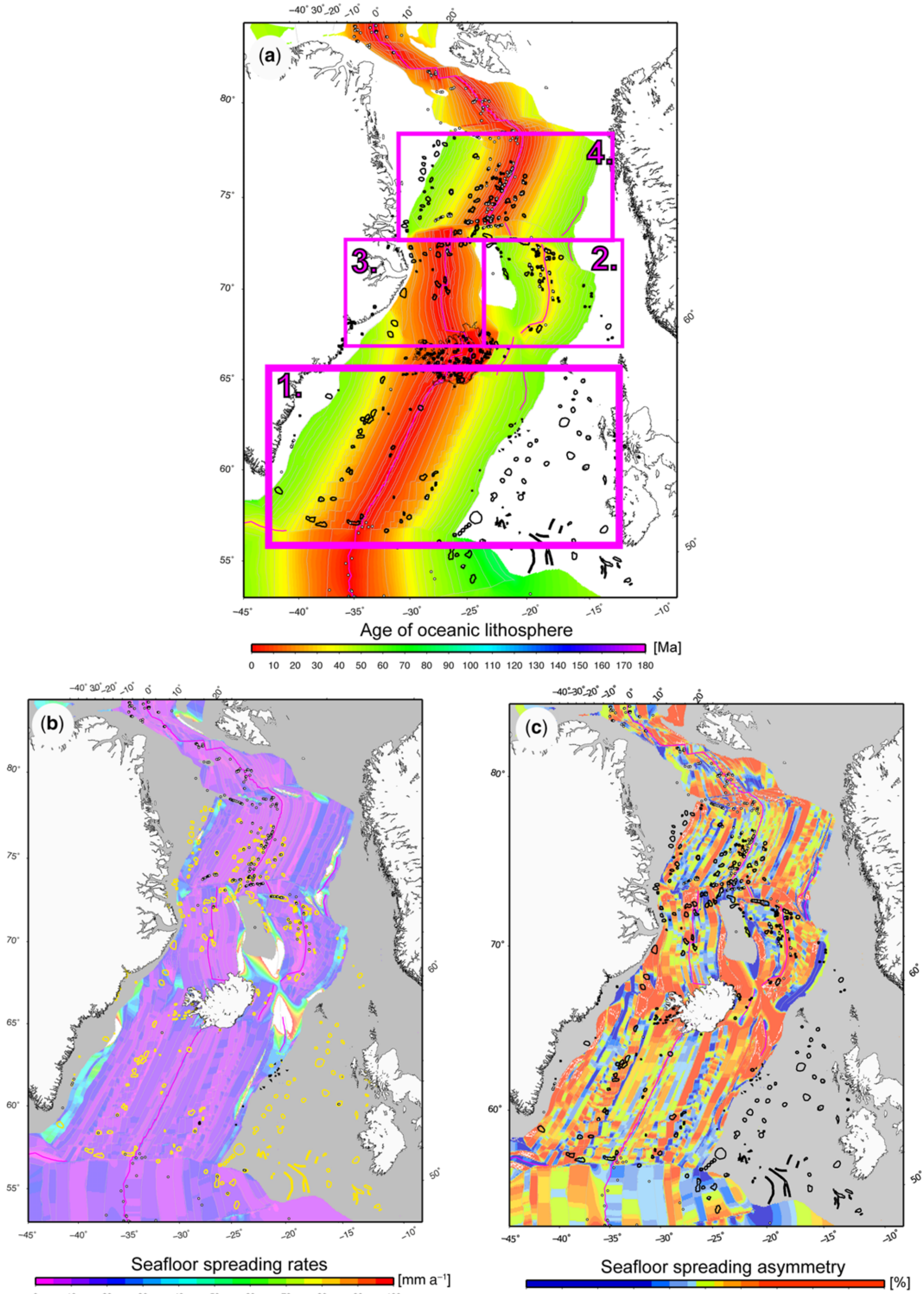


Fig. 4. Age grid (**a**), half spreading rates (**b**) and asymmetry in seafloor spreading (**c**) of the NE Atlantic oceanic crust (Gaina *et al.*, this volume. in review). The distribution of volcanic edifices is as in Figure 1. Rectangles indicate the location of the four regions discussed in the text.

Region IV: Mohn's Ridge and associated oceanic basin

The SOIFs are divided in two distinct groups within the Greenland and Lofoten basins, which have formed along the Mohn's Ridge since C24 (*c.* 54 Ma) onwards (Fig. 5d). The first group (22 out of 70) is distributed along the Greenland margin on both extended continental crust and Early Eocene oceanic crust. The second group comprises 43 out of 70 SOIFs, and is scattered on oceanic crust younger than 28 Ma on both conjugate flanks of Mohn's Ridge. Only one large seamount is located on the present-day MOR in the southern Mohn's Ridge, referred to as the Troll Wall–Soria Moria (Pedersen *et al.* 2010), and four SOIF are located on the JMFZ.

Four seamounts are outside these two SOIF groups and are located on 44–33 Ma crust on the Greenland side. One of these seamounts is the Vesteris Seamount (Cherkis *et al.* 1994; Haase & Devey 1994), a young, large intra-plate volcano of non-plume origin.

North of Region IV, the compilation by Yesson *et al.* (2011) shows a few seamounts along the Knipovich Ridge, mostly in the Boreas Basin on the Greenland Plate. The NAG-TEC study has not included this area into its SOIF database and we will not discuss them further, as there is sparse information about volcanic centres in that region.

Discussion

SOIFs and oceanic crust formation

The distribution of SOIFs in the NE Atlantic oceanic basins, and links to the age of oceanic crust, seafloor spreading rates, asymmetry of oceanic crustal accretion and oceanic crustal thickness, are summarized in Table 1. A new grid for the oceanic lithospheric age has been constructed based on updated magnetic anomaly identification in the NE Atlantic (Gaina *et al.*, this volume, in review). The oceanic lithospheric age grid model, together with rotation parameters describing the opening of the NE Atlantic, have been used to compute seafloor spreading rates, directions and deviations from symmetrical oceanic crust formation at various intervals, as constrained by the kinematic model (see Gaina *et al.*, this volume, in review) (Fig. 4). Seafloor spreading asymmetry can be described as the percentage of crustal accretion (values from 0 to 100%) on conjugate flanks along a MOR (Müller *et al.* 2008). Symmetrical seafloor spreading is expressed as 50% asymmetry, values smaller than 50% indicate less oceanic crust on one flank, which is compensated for on the conjugate flank with a crustal accretion percentage greater than 50%. Besides the age of oceanic crust, crustal thickness and seafloor spreading parameters, we also inspected the oceanic basement seismic reflection characteristics, as described by Horni *et al.* (this volume, in review). The NE Atlantic oceanic basement has been divided into six categories: smooth, transitional, rough, very rough, rubbly and igneous provinces (Funck *et al.* 2014) (Fig. 6). We observe that most SOIFs (75%) are associated with rough basement, and only a few with smooth basement. The rough basement type, as described by Horni *et al.* (this volume, in review), is present in areas with significant basement relief of the order of 1 s two-way travel time (TWT) on seismic reflection sections. They suggest that rough basement may result from tectonic processes (e.g. faulting) and volcanic processes (e.g. intrusions, seamounts or locally robust volcanism). The smooth basement type is distinguished by long continuous, high-amplitude, seismic reflections and often appears as a single reflection, although sometimes there may be packages of strong subplanar continuous reflections. The two types of basement morphology are also reflected in bathymetry (Fig. 1) and gravity data (Fig. 2).

Note that the transition from smooth to rough oceanic crust has been mainly associated with the boundary between areas affected by higher magma supply from the Iceland plume (situated on V-shaped regions south and north of Iceland) and 'colder' areas, which were less affected, or unaffected, by the hotter mantle (e.g. Poore *et al.* 2009). Hey *et al.* (2010) postulated that a seafloor spreading asymmetry-producing mechanism is rift propagation. Rift propagation produces V-shaped ridges, a 'ridge and trough' geometry within the V-shaped elevated area, and crustal thickness variations. According to Hey *et al.* (2010), this mechanism can be triggered independently of the presence of a mantle plume, and better explains the relief of V-shaped regions in the NE Atlantic. More recently, Jones *et al.* (2014) used geophysical and geochemical data and modelling to confirm the original idea of Vogt (1971) that the V-shaped ridges are generated by the plume stem pulses that spread radially from the central plume location. The model of Jones *et al.* (2014) explains both the seafloor spreading roughness and the geochemical signatures revealed by oceanic crust samples.

SOIFs or oceanic core complexes (OCC)? We indicated that some SOIFs are located at the intersection between fracture zones and former MORs (as depicted by isochrons). The occurrence of some of these features also coincides with a decrease in spreading rate (Fig. 7a–c). These conditions would suggest that the identified bathymetric features might be oceanic core complexes (OCC). Oceanic core complexes are bathymetric features composed

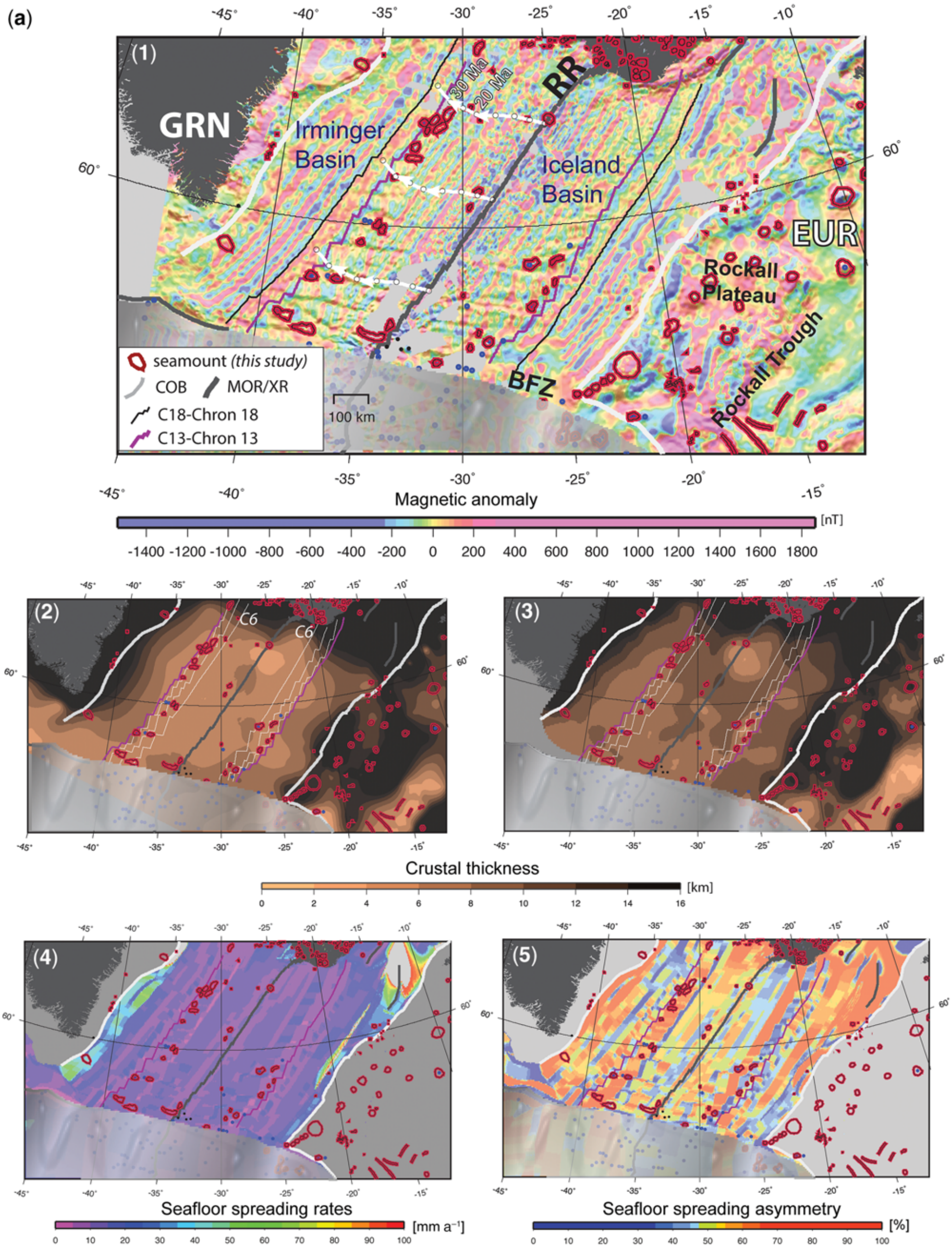
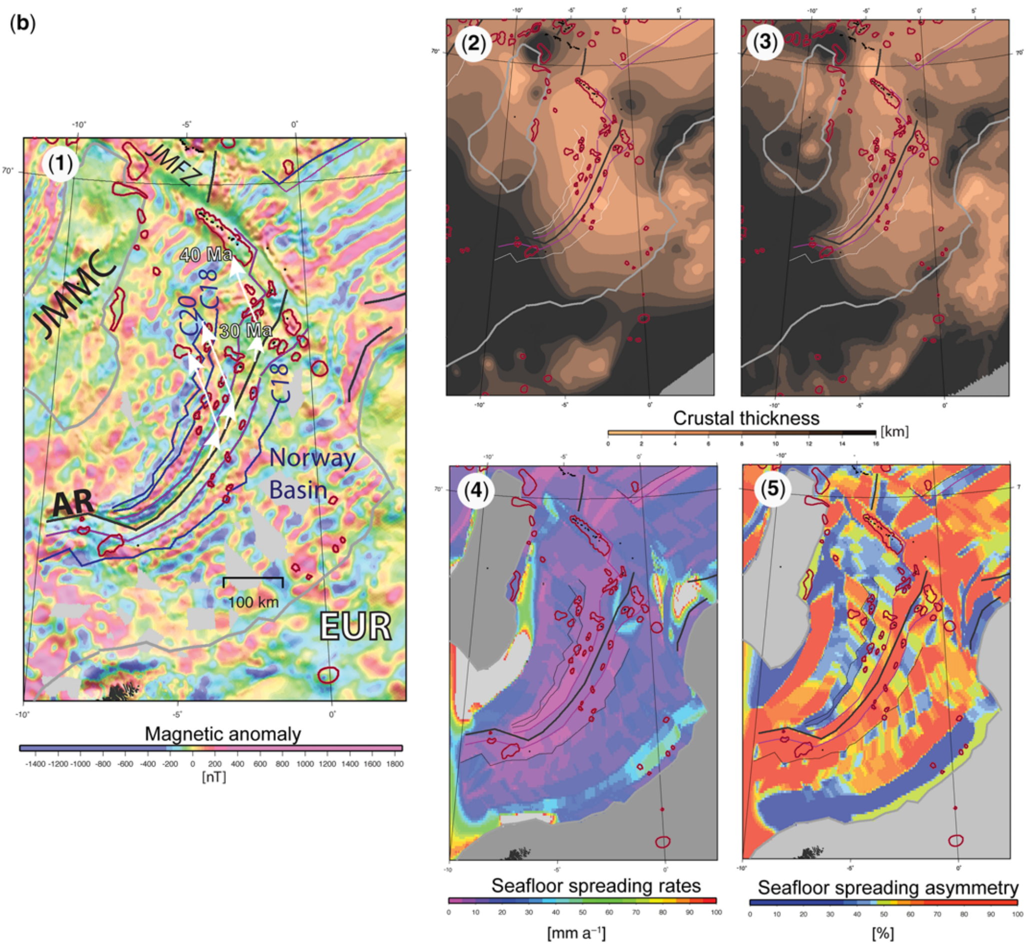


Fig. 5. Distribution of volcanic edifices (see Fig. 1) in the four NE Atlantic main regions superimposed on various geophysical data and models. (**a**) Iceland and Irminger basins (region I), (**b**) Norway Basin (region II), (**c**) east of Jan Mayen microcontinent (region III); (**d**) Lofoten and Greenland basins (region IV). Background images are: (**1**) the magnetic anomaly grid (Gaina *et al.*, this volume, in review); (**2**) the crustal thickness derived from seismic refraction data (Funck *et al.* 2016); (**3**) the crustal thickness from gravity inversion (Haase *et al.*, this volume, in press); (**4**) half seafloor spreading rates; and (**5**) seafloor spreading asymmetry (Gaina *et al.*, this volume, in review). Dark grey lines show the location of active and extinct plate boundaries; light grey is the interpreted COB. Isochron C13young (33.2 Ma) is shown in magenta, and other selected isochrons are shown as thin blue (or white) lines. White thick arrows indicate the motion of Greenland relative to the underlying mantle for the last 40 myr. Abbreviations: AR, Aegir Ridge; EUR, Europe; GRN, Greenland; JMFZ, Jan Mayen Fracture Zone; JMMC, Jan Mayen microcontinent; KnR, Knipovich Ridge; KR, Kolbeinsey Ridge; MR, Mohn’s Ridge; RR, Reykjanes Ridge.



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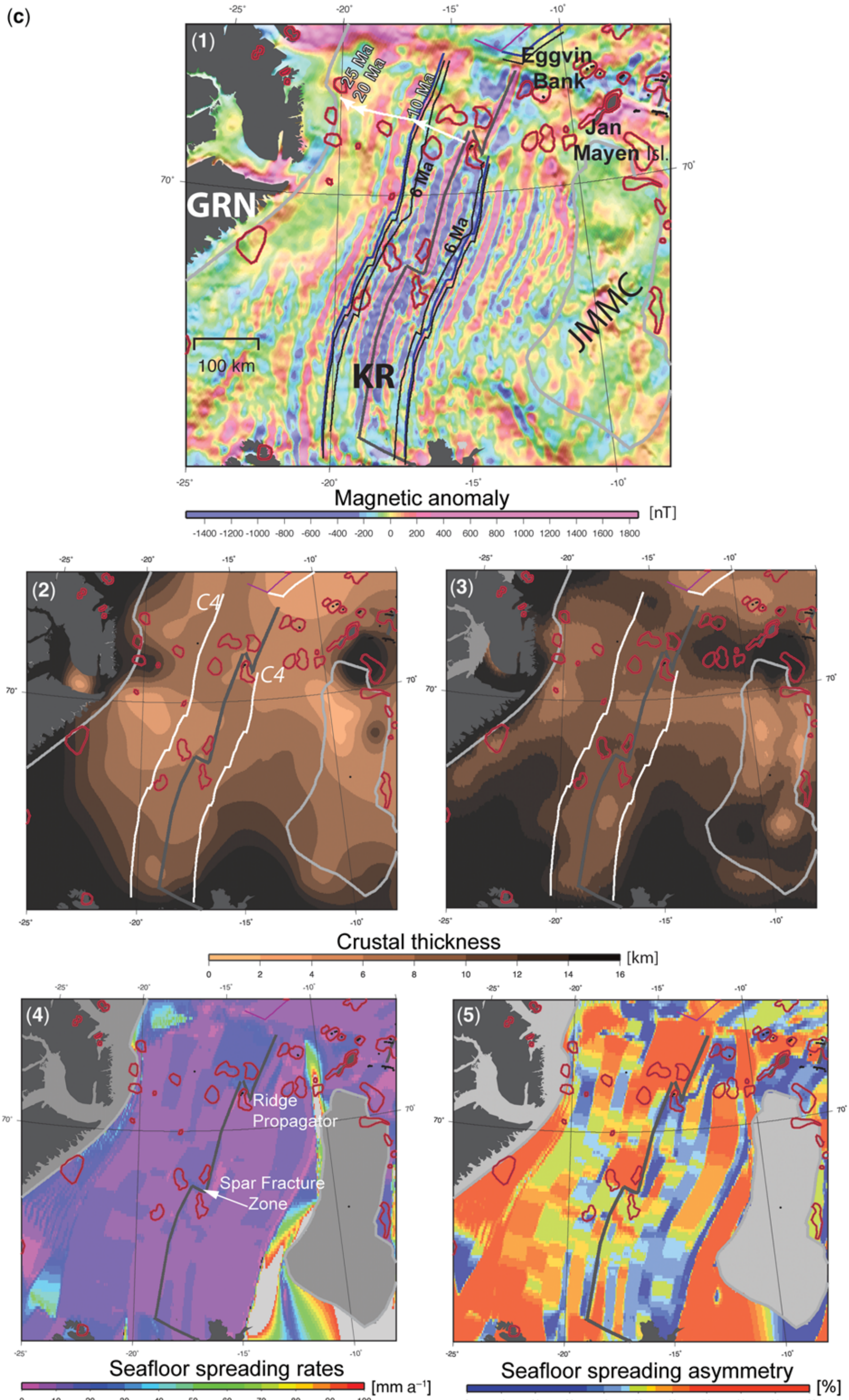
of mantle rocks exposed on the seafloor by large detachment faulting. These tectonic features can have lengths up to 150 km and widths up to 15 km, with a height of between 500 and 1500 km (MacLeod *et al.* 2009). It has been postulated that OCCs can be associated with serpentinized peridotites and, therefore, have very weak magnetization (e.g. Sato *et al.* 2009). The general view about OCC suggests that they form in a tectonic regime with very low magma supply (e.g. MacLeod *et al.* 2009). Detailed studies of OCCs at the Mid-Atlantic Ridge (e.g. Ildefonse *et al.* 2007; Mallows & Searle 2012) show that OCC formation is discontinued when the magma supply increases, although models (e.g. Olive *et al.* 2010) and observations (e.g. in Cayman Trough: Hayman *et al.* 2011) postulate that they can form under a spectrum of magma injection rates.

Our criteria to identify SOIFs included height above 500 m and relatively high total magnetic field values (>100 nT on the NAG-TEC magnetic map, which shows the total magnetic field 2 km upwards continued from the original measurement position). Therefore, if any of the identified SOIFs in this study happen to be an OCC, then that feature was formed in a tectonic regime able to generate rounded to elliptical bathymetric structures that are surrounded, covered or intruded by basaltic rocks that have remanent magnetization.

Previous detailed studies on seamount volcanism in the NE Atlantic focused on the enigmatic Vesteris Seamount (Mertz & Renne 1995) located in the Greenland Basin (Fig. 5d), and the igneous centres situated in the Rockall region (Fig. 5a). These seamounts have been dredged and a few petrological studies have been published (e.g. Cherkis *et al.* 1994; Haase & Devey 1994; O'Connor *et al.* 2000). The young episodic alkaline volcanism of the Vesteris Seamount has been attributed to intra-plate



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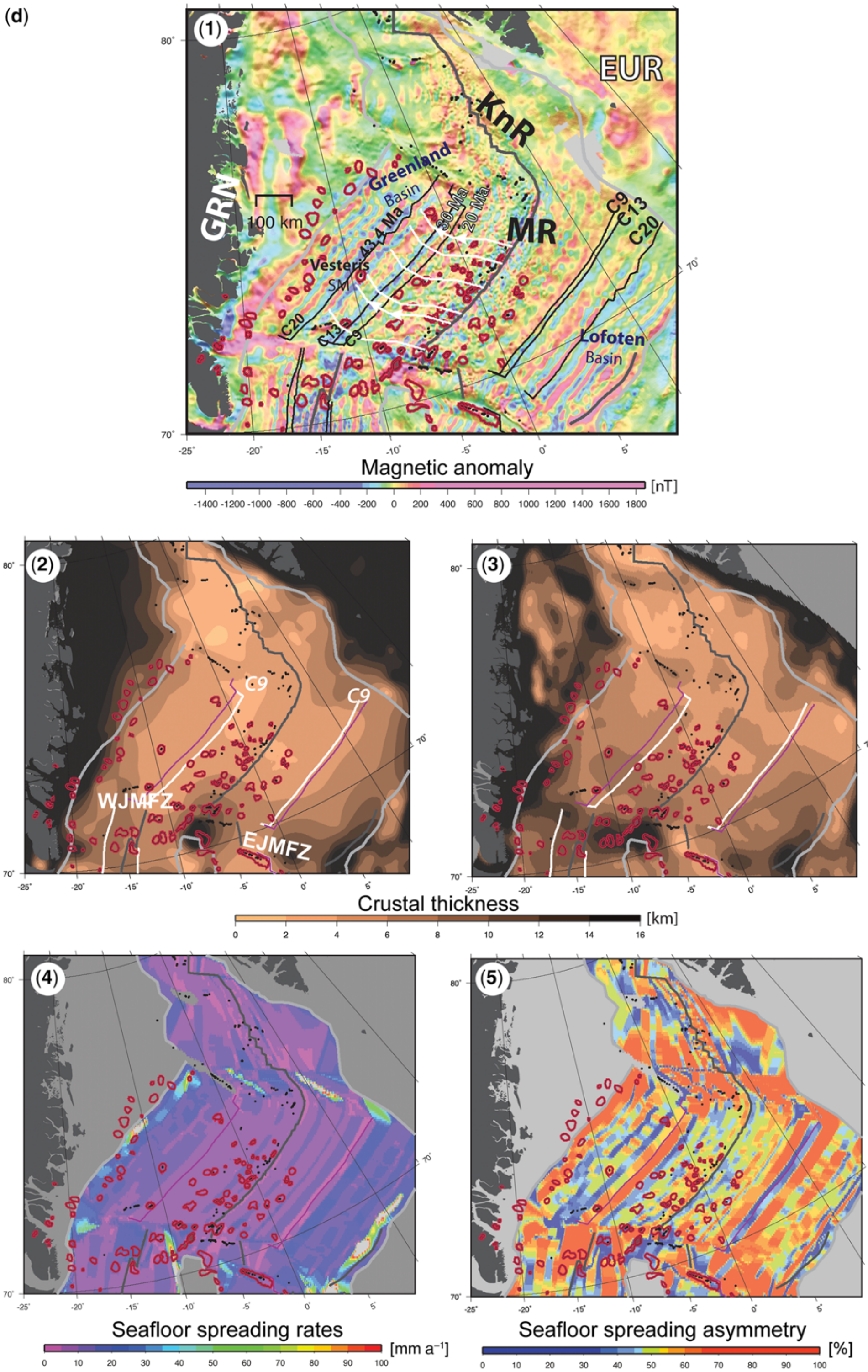

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Table 1. *Summary of SOIF distribution in regions I–IV and underlying oceanic crust characteristics*

Region/ subregion	Oceanic crust age (Ma)	Number of SOIFs	Seafloor spreading rate (mm a^{-1})	Seafloor spreading asymmetry (%)	Oceanic basement type (Funck *et al.* 2014)	Oceanic crustal thickness (Funck *et al.* 2016) (km)	Oceanic crustal thickness (Haase *et al.*, this volume, in press) (km)	Tectonic features
I-1	54–52	7	45–40	Eastern flank <50%	Smooth	>10 km	>10 km	
I-2	34–20	28	15–20	Eastern flank <50%	Rough	8–10	8–11	Intersection with fracture zones (FZ)
I-3	8–0	7	15–23	Eastern flank >50% (SOIFs associated with boundaries between excess/deficit)	Rough	6–9	8–11	
Region I total		42						
II-1	COB-54	5						
II-2	54–52	6	50–40	Eastern flank <50%	Rough Norwegian margin; smooth JMMC	8–10	10–12	Some associated with oblique FZ
II-3	47–30	33	28–18	Eastern flank >50% (SOIFs associated with excess crustal production or boundaries between excess/deficit)	rough	4–6 (seems to be confined to thinner crust)	6–8	Some associated with oblique FZ
Region II total		44						
III-1	COB-25	5	22–20	Eastern flank <50%	Smooth	10–14	10–12	
III-2	19–14	7	15–20		Rough	6–8	8–12	
III-3	6–2.6	10	21–15	Eastern flank <50% (SOIFs associated with excess crustal production or boundaries between excess/deficit)	Rough	8–10	12–14	Fracture zones, rift propagator
Region III total		22						
IV-1	COB-49	22	15–33	Eastern flank <50% (SOIF associated with excess crustal production or boundaries between excess/deficit)	Smooth	6	8–10	
IV-2	27.4–0	43	22–10	27–21 Ma eastern flank <50%; 21–0 Ma eastern flank >50% or symmetrical spreading (SOIFs associated with excess crustal production or boundaries between excess/deficit)	Rough	2–6	6–10	
Region IV total		65						

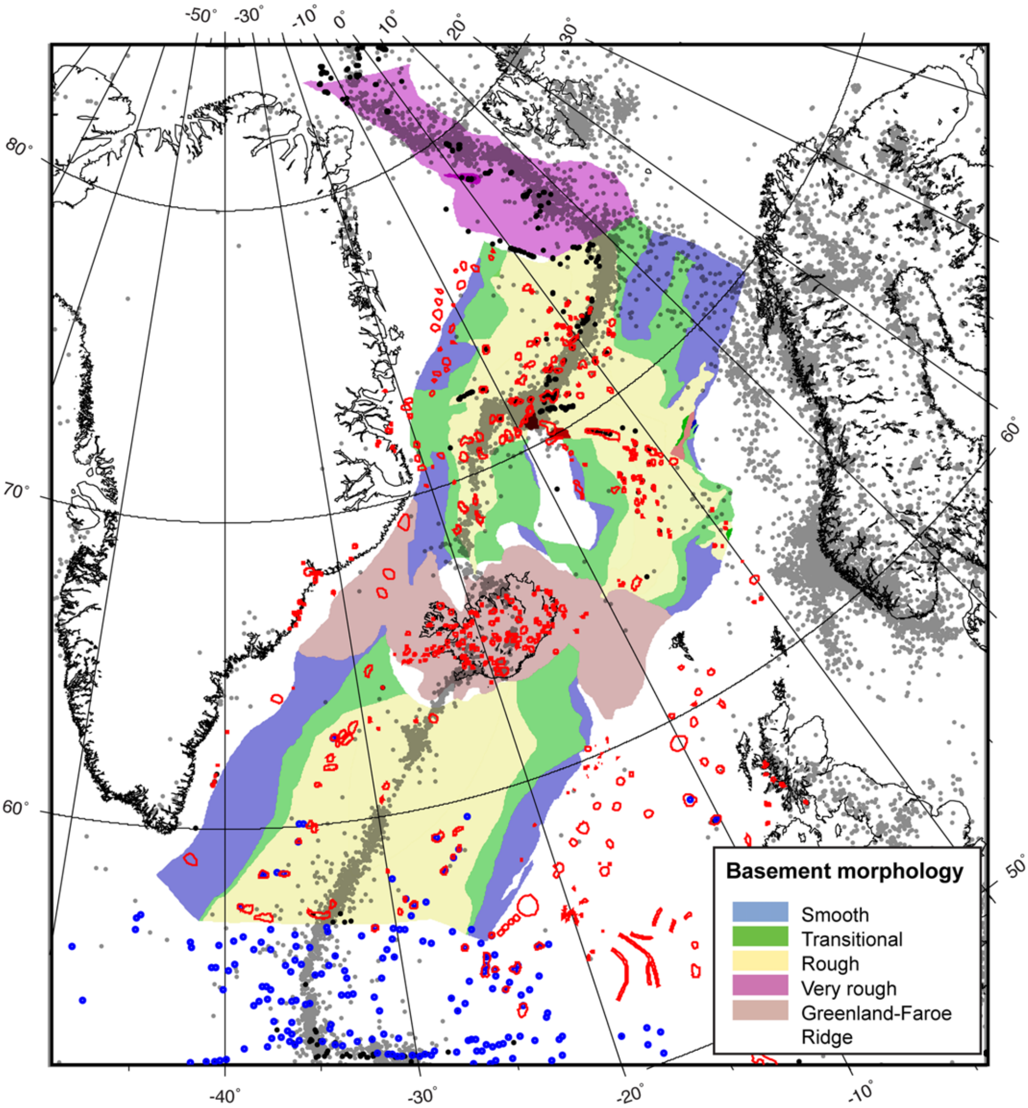

Fig. 6. Oceanic basement morphology based on seismic characteristics (Funck *et al.* 2014). The distribution of volcanic edifices is as in Figure 1. Grey dots indicate the location of earthquake epicentres (0.1–6.5 magnitude) from January 1978 to October 2012 according to the International Seismological Centre database (http://www.isc.ac.uk/).

stresses, as the volcanic edifice is situated on older oceanic crust, at the intersection of major structural features (Haase & Devey 1994). In contrast, the episodic volcanism (from the Late Cretaceous to the Mid-Eocene) that formed the igneous edifices situated on extended continental crust in the Rockall region was linked to the Iceland plume pulsations which may have occurred at 5–10 myr intervals (O'Connor *et al.* 2000). The third group of NE Atlantic seamounts/submarine volcanic edifices documented by petrological studies is located in the Eggvin Bank region, situated between Jan Mayen Island and the Kolbeinsey Ridge (Fig. 5c). The off-axis, transitional to alkaline lavas are similar to the Jan Mayen Island basalts, but the near-axis tholeiites resemble the SE Iceland lavas, indicating a change in the mantle composition (Trønnes *et al.* 1999; Mertz *et al.* 2004), or different magma sources along the Kolbeinsey Ridge.

Most of the NE Atlantic SOIFs located on oceanic crust lack absolute ages, as only few seamounts or volcanic edifices have been dredged and dated.

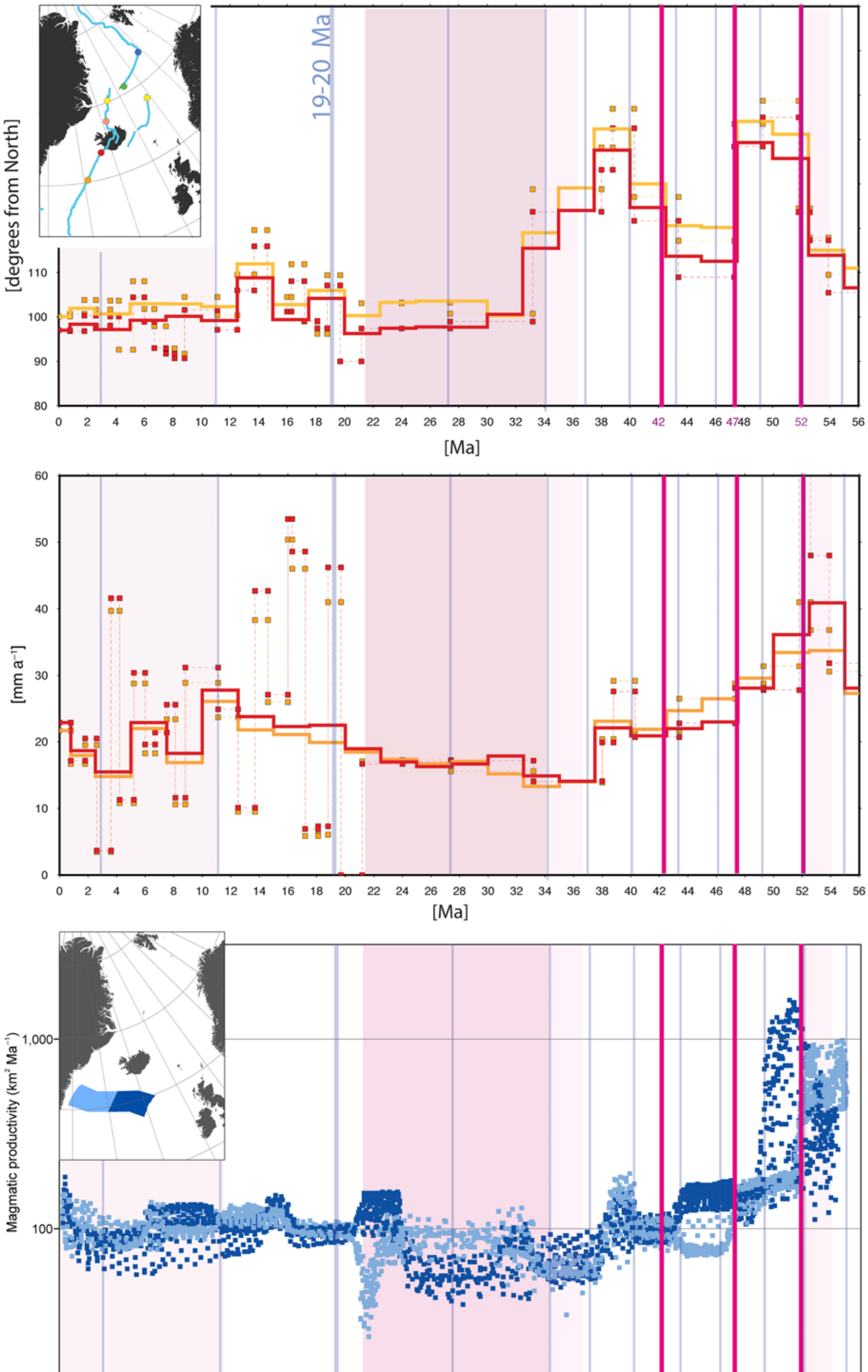

Fig. 7. Spreading direction (upper panel), spreading rates (middle panel, modified from Gaina *et al.*, this volume, in review) and magmatic crustal production (lower panel) calculated values in (**a**). The Iceland and Irminger basins.

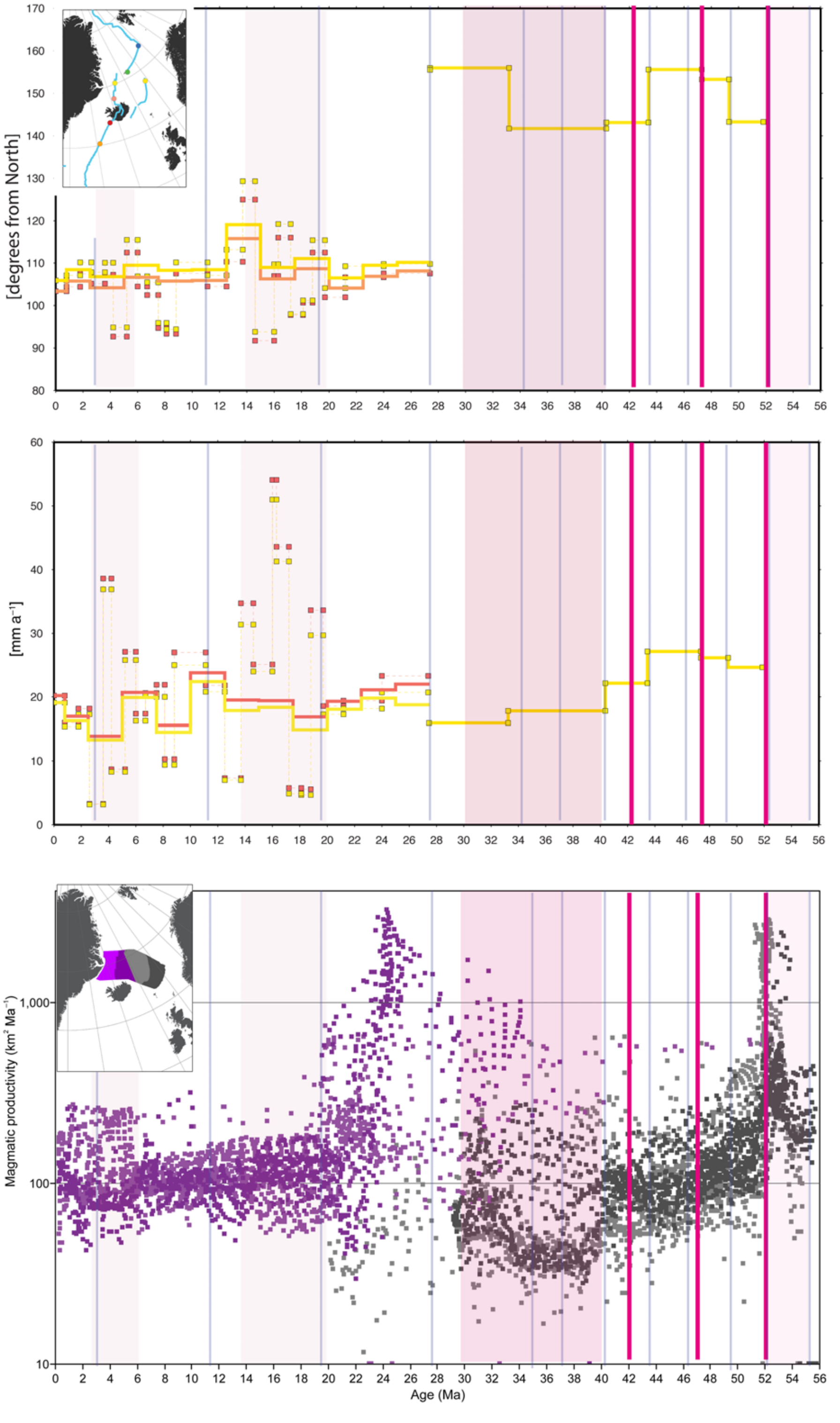

Fig. 7. (**b**) the Norway Basin and Kolbeinsey region.

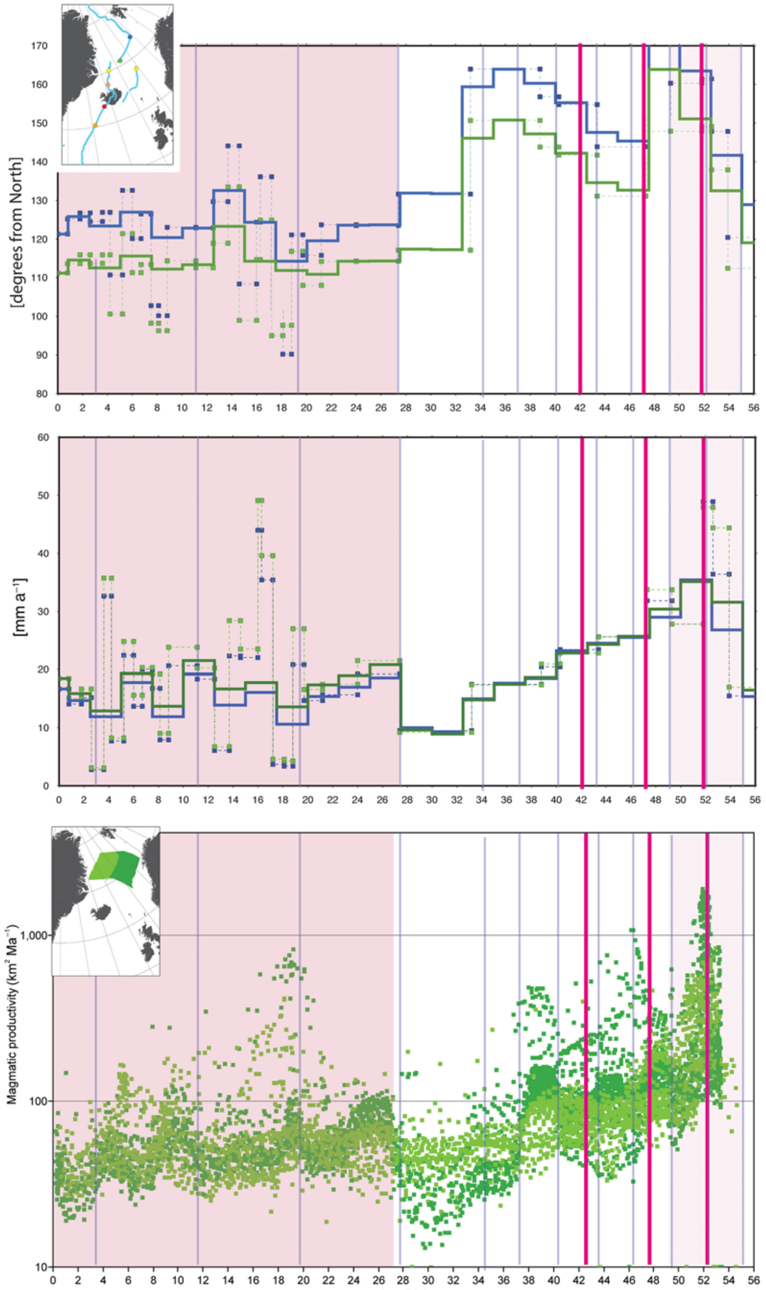

Fig. 7. (**c**) the Greenland and Lofoten basins. Inset map in the upper panels show the location of 'seed points' along the plate boundaries used as starting points to compute seafloor spreading rates and directions (look for matching colours). The magmatic crustal production is calculated by multiplying gridded data of oceanic spreading rates (Gaina *et al.*, this volume, in review) and crustal thickness (Haase *et al.*, this volume, in press). Inset maps on the lower panels show the selected corridors selected for this calculation. The results from different corridors illustrate similarities and contrasts in the crustal productivity variations. Different colours are used for conjugate sides in each corridor to illustrate asymmetries. Time intervals of SOIF formation are marked in various shades of pink (darker for higher SOIF production). Seamount ages from the Rockall region (O'Connor *et al.* 2000) are shown by magenta vertical lines. Times of Iceland plume magmatic pulses (Parnell-Turner *et al.* 2014) are indicated by thin light blue lines.

The amount of lithospheric flexure due to the formation of a volcanic edifice can reveal the age of loading and, indirectly, the approximate age of the volcanic feature built on oceanic crust. We have not attempted to establish accurate ages for the oceanic volcanic edifices in the oceanic basins of the NE Atlantic, but consider that they were formed not long after the underlying oceanic crust. This hypothesis is probably more accurate in the case of SOIFs developed as a result of tectonic changes accommodated at ridge–fracture zone junctions or as ridge propagation.

Based on our data compilations (Table 1) and SOIF description (Figs 5 & 6), we infer that: (1) 75% of SOIFs are associated with rough basement formed at low spreading rates, and with seafloor spreading asymmetries; (2) 35% of NE Atlantic SOIFs cluster on Late Eocene–Early Oligocene crust and 38% on Miocene–Present oceanic crust; and (3) SOIFs are associated with tectonic changes accommodated at ridge–fracture zone junctions or at ridge propagators. These observations lead to the conclusion that the SOIF magmatic activity is mostly linked to the normal oceanic crust production at times of spreading direction readjustments. We note that SOIFs occur on crust produced at intermediate spreading rates and on smooth to transitional basement, but most of them are associated with low spreading rates, asymmetry in crustal accretion and rough basement (Figs 5 & 6; Table 1). Batiza (2001) postulated that off-ridge volcanism is mainly encountered in regions with intermediate to high spreading rates and abundant melt supply. However, Standish & Sims (2010) described young off-axis volcanism along the ultraslow spreading SW Indian Ridge and suggest that this volcanism is the result of magma rising along faults, which contributes to off-axis accretion of oceanic crust. Some SOIFs can be OCCs formed in a slow seafloor spreading regime that was affected by episodes of higher than normal magma injection supply.

SOIFs and the Iceland plume. The NE Atlantic region has been strongly influenced by the Iceland mantle plume before, during and after continental break-up and subsequent seafloor spreading. Massive volcanism that predated and assisted the continental break-up formed the North Atlantic Igneous province (NAIP) in two pulses, at approximately 62 and 55 Ma, and was spread along the Greenland and NW European margin (e.g. Storey *et al.* 2007). Subsequently, the Iceland plume-related magmatic activity formed the Greenland–Faroe province (GIR and FIR in Fig. 1) from the Eocene onwards (Soager & Holm 2009). However, age-progressing seamount chains are absent from the NE Atlantic region.

About 100 igneous centres have been identified in Iceland and the surrounding regions (Fig. 1), and most of them show the evolution of volcanism connected to mid-ocean ridge–plume interactions. All other seamount and igneous feature clusters described in this study do not show distinct linear trends, and we infer that they cannot fall into the hotspot seamount chain category. Some of the NW–SE-trending seamounts in the Greenland Basin may resemble linear seamounts formed in the direction of plate motion relative to the mantle (so-called 'hot lines' or melting anomalies elongated in the direction of plate motion). The motion of Greenland relative to the mantle for the last 40 myr (shown by the white arrow in Fig. 5d) appears to have been sub-parallel to these seamount trends in the Greenland Basin.

Plume-related volcanism has been invoked to explain the formation of seamounts in the Rockall region (O'Connor *et al.* 2000), and the elevated bathymetry and V-shaped ridges south of Iceland in the Iceland and Irminger basins (White *et al.* 1995; Jones *et al.* 2002). In order to study any possible correlations between episodic pulsations of the Iceland plume (Jones *et al.* 2002; Parkin *et al.* 2007; Parnell-Turner *et al.* 2014) and the formation of seamounts in the basins situated south and north of Iceland, we examined the evolution of oceanic crust production. We computed the amount of oceanic crustal accretion in our selected regions (Figs 4 & 5) by taking into account the crustal thickness derived from gravity anomaly inversion (Haase *et al.*, this volume, in press) and the spreading rates (Gaina *et al.*, this volume, in review), and compared the magmatic production and spreading rates fluctuations with suggested episodes of high plume activity (Fig. 7). According to recent studies based on high-quality seismic reflection data, the Iceland plume activity had peaks every 3 myr from 55 to 35 Ma, and every 8 myr from 35 Ma to the present day (Parnell-Turner *et al.* 2014). We observed that the identified periods of SOIF production south and north of Iceland and the Greenland–Faroe Ridge (GIR and FIR in Fig. 1) fall within pulses of higher activity of the Iceland plume, but not every pulse resulted in SOIF cluster production. The three periods of seamount formation in the Rockall region, dated at 52, 47 and 42 Ma by O'Connor *et al.* (2000), coincide with pulses in the magmatic crustal production in all oceanic basins (mostly asymmetrical on conjugate flanks), decreases in spreading rates and changes in spreading directions, but have no obvious connection with SOIF production (Fig. 7).

We notice that SOIF formation in the basins north of the JMFZ coincides with an increase in spreading rates and magmatic production, reflected in higher crustal thickness. South of the JMFZ, Late Eocene–Early Miocene SOIF formation occurred when the spreading rates and magmatic crustal production first decreased and became highly asymmetrical (Fig. 7). Parnell-Turner *et al.* (2014) observed that the Iceland plume fluctuations are superimposed on a rapidly cooling temperature structure manifested by a northwards shift from smooth to rough crust in the Iceland and Irminger basins. The NE Atlantic oceanic basement morphology model (Funck *et al.* 2014) and kinematic history (Gaina *et al.*, this volume, in review) also show changes at the times of Iceland plume pulsations, as postulated by Parnell-Turner *et al.* (2014). We infer that SOIF formation south of Iceland occurred as plume activity decreased, but coincided with a considerable change in plate motion, which resulted in transtensional motion that allowed localized additional melting along the newly formed fracture zones and ridge propagators. Interestingly, recent seismic activity (from ISC catalogue: http://www.isc.ac.uk); appears to cluster in some of the SOIF locations (Fig. 6). Apart from the seismicity associated with active mid-ocean ridges, we observed seismic activity in Region I in the proximity of the SOIF cluster located on Oligocene oceanic crust, in Region II in the Norway Basin and in Region IV close to SOIFs situated on Oligocene–Miocene oceanic crust. A more conservative seismic event catalogue, the EHB Bulletin (http://www.isc.ac.uk/ehbbulletin), shows much less intraplate seismic activity in the southern part of the NE Atlantic Ocean. Note that the seismic events extracted from the EHB Bulletin indicate only earthquakes with magnitude greater than 3, which occurred before 2008. We suggest that a link may exist between seismic events and SOIF distribution, and indicates that lithosphere weakening due to tectonic activity combined with subsequent volcanic loading may leave a long-lasting imprint and facilitate subsequent crustal deformation.

'Paired' SOIFs

Although SOIF formation in all NE Atlantic sub-basins occurs on conjugate flanks of the same age,

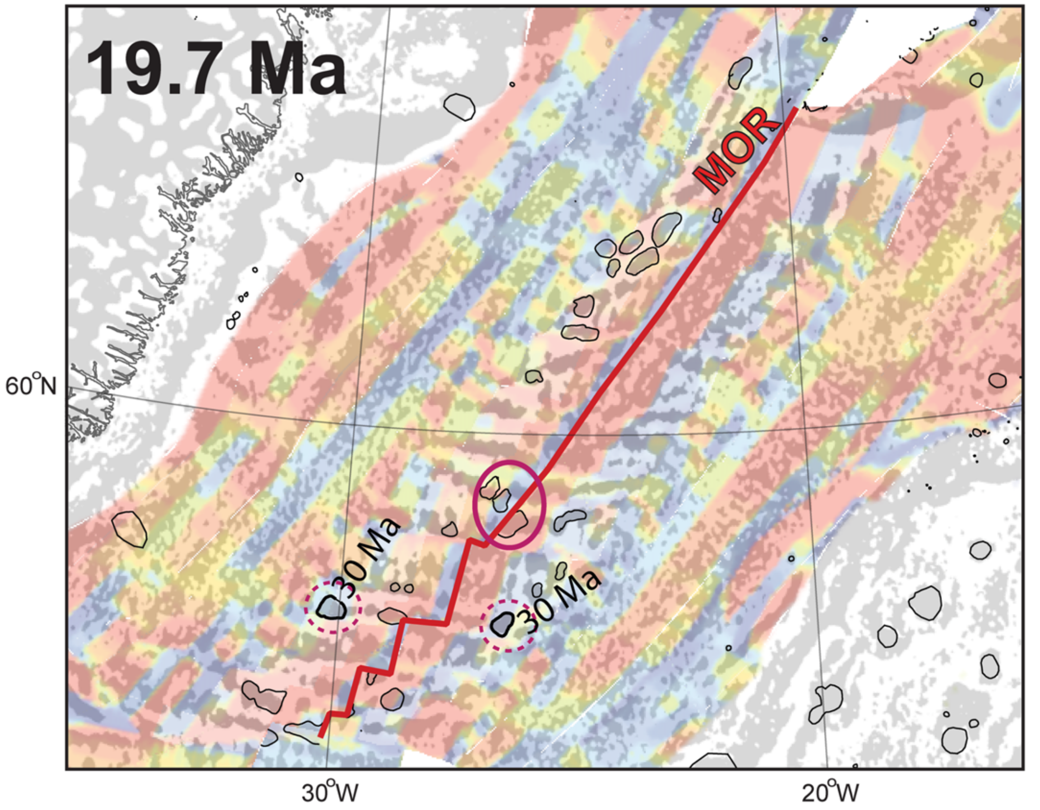

Fig. 8. Plate reconstruction at C6 (19.7 Ma). Background gridded data are the free-air gravity curvature (Sandwell & Smith 2009) in the grey palette and the spreading asymmetry (colour palette as in Fig. 4). SOIF outlines are in black; the pink ellipse shows the position of possible paired SOIFs along Reykjanes Ridge at C6 time.

there are very few 'paired basement ridges', which are volcanic edifices built at mid-ocean ridges (MORs) and equally split on both flanks by subsequent MOR evolution. Vogt & Jung (2005) described a series of paired basement ridges in the North Atlantic realm, including V-shaped ridges of Reykjanes Ridge, and suggested that small-scale conjugate ridge pairs are generated by axial magmatic centres that are not fixed to a mantle frame. They also postulate that the magma centres pulsate at 0.2–1.0 myr intervals and may be active for at least 1 myr, creating several off-axis ridge pairs. Among our identified SOIF, we observed two cases of small-scale conjugate volcanic pairs. Figure 8 shows the reconstructed locations of one pair of such conjugate volcanic features at the intersection between the Reykjanes MOR and a non-offset fracture zone at approximately 20 Ma. The underlying oceanic crust shows asymmetry on conjugate flanks (Fig. 8), and was formed at the time when the seafloor spreading direction changed to clockwise and the spreading rate increased (Fig. 7a). According to the Parnell-Turner *et al.* (2014), the model of the Iceland plume pulsation episodes, the 19–20 Ma formation of the paired SOIF along the Reykjanes axis, coincides with the increase in mantle plume activity. However, this may only be a coincidence, as the size and number of paired SOIF cannot justify a clear link between the two processes. Changes in plate motion and transtension at the MOR–fracture zone intersection seem to be a more realistic explanation for the formation of these small-scale paired SOIFs along the Reykjanes Ridge.

Conclusions

We have inspected the new NE Atlantic database of oceanic volcanic edifices including seamounts and igneous centres (abbreviated as SOIFs in this study) in four different regions situated south and north of the Greenland–Faroe Ridge. SOIF occurrences are distributed differently in the four regions, but we have identified three distinct 'pulses' of abundant seamount cluster formation. SOIFs on older oceanic crust (54–50 Ma) are situated on smooth oceanic basement. If the seamounts were formed at the time of, or shortly after, seafloor spreading, then their emplacement coincides with an increase in spreading rates and higher magmatic productivity. Large seamounts were formed on the Rockall plateau and in the Rockall Trough around 52 Ma, and the Iceland plume activity increased at 55 and 52 Ma, which could indicate that the Early Eocene SOIF formation in the NE Atlantic may have resulted from higher than usual mantle plume activity.

The second SOIF group is located on Late Eocene–Early Miocene oceanic crust of the Irminger, Iceland and Norway basins. This group is located on rough oceanic basement, in the proximity of newly formed tectonic features, such as fracture zones, ridge propagators and V-shaped ridges. In the Late Eocene, seafloor spreading rates dropped and the crustal production became highly asymmetrical. We suggest that the formation of these volcanic edifices is mostly related to kinematic changes, which led to local readjustments of MOR segments and fracture zones. The third SOIF population is observed on Mid-Miocene–Present oceanic crust, mostly located in the Greenland and Lofoten basins, but also on conjugate flanks of the Kolbeinsey Ridge. In addition, these SOIF clusters are associated with rough oceanic basement and fracture zones, V-shaped ridges, and ridge propagators. Early–Mid-Miocene (*c.* 27 Ma) oceanic crust registered an increase in spreading rate and magmatic productivity, which appears to coincide with a burst of seamount formation north of the JMFZ. South of the JMFZ, this activity was delayed until about 11 Ma, as shown by the higher number of seamounts emplaced on crust of this age and younger. It is not clear which processes initiated and dominated this third period of SOIF formation, as it seems that both tectonic/kinematic and magmatic triggers were present. However, the Early Miocene relocation of the mid-ocean ridge from the Ægir Ridge to the Kolbeinsey Ridge, west of the Jan Mayen microcontinent, may have played a role in delaying SOIF formation south of the JMFZ.

We note that the identified periods of seamount production south and north of Iceland and the Greenland–Faroe Ridge fall within Iceland plume pulses of higher activity, but not every pulse resulted in SOIF cluster production. We conclude that the episodic activity of the Iceland plume, combined with regional changes in relative plate motion, led to local MOR readjustments that enhanced the likelihood of seamount and other igneous feature formation. Further studies aimed at dating the identified SOIFs will help in understanding the connection between tectonic and magmatic activity in the NE Atlantic.

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