The Greenland–Iceland–Faroe Ridge Complex

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Abstract: The Greenland–Iceland–Faroe Ridge Complex (GIFRC) has been forming since the opening of the NE Atlantic (<55 Ma), standing out as a prominent feature on all geoscientific data-sets. Our interpretations have revealed several new potential abandoned rift centres, mapped as synclines and anticlines yielding structures. The synclines are suggested to be manifestations of former rift axes that were abandoned by rift jumps. These appear to be more common inside the GIFRC region than in the adjacent ocean basins, and can be confirmed by observations of cumulative crustal accretion data through time. A major post-40 Ma unconformity is proposed across the East Iceland Shelf, forming a distinct 16–20 myr-long hiatus that is covered by a thick, younger sedimentary section. Several seamounts were identified on multibeam datasets at around 1200 m water depth in the Vesturdjúp Basin, just south of the Greenland–Iceland Ridge. These seamounts appear to be younger in formation time than the surrounding ocean floor, possibly indicating a still active intraplate volcanic zone. Young tectonic features, such as faults, graben and transverse ridges, characterize the area and present a good example of the complexity of the GIFRC in comparison to the adjacent abyssal plain.

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The purpose of this study is to review the structural segmentation and links to chronostratigraphic processes affecting the areas of the Greenland–Iceland Ridge (GIR), the Iceland Plateau and the Iceland–Faroe Ridge (IFR) (Figs 1 & 2; Table 1). These ridges and plateau are summarized here as the Greenland–Iceland–Faroe Ridge Complex (GIFRC) and part of the North Atlantic Igneous Province (NAIP) (Fig. 1), one of the largest igneous provinces in the world (Saunders et al. 1997). This review addresses the initiation of the GIFRC, its extent, defines rift jump areas within the complex, and addresses the Iceland-type central volcanoes and seamounts in their offshore regions. In addition, crustal thickness variations are compared to structural and geochronological variations within the GIFRC based on potential field, seismic and geological sections, and surface geological field data (Table 2).

Abandoned rift systems have previously been mapped for the onshore region of Iceland for the last 16 myr (Hjartarson 2003; Jóhannesson & Sæmundsson 2009) (Table 3), and in offshore areas around Iceland by Vogt (1971), Talwani & Eldholm (1977), Hararson et al. (1997), Vogt & Jung (2009) and Erlendsson & Blischke (2013). These extinct rift systems show a distinct dip of subaerial lava-flow formation sequences from both sides towards the old rift centre (Böðvarsson & Walker 1964), which can be observed in surface geological maps (Jóhannesson & Sæmundsson 2009) (Table 4), and on seismic reflection data for offshore areas as synclines and anticlines.

Field and refraction data studies have previously defined the term Icelandic-type crust, which has been used to describe the crust beneath the Greenland–Iceland–Faroe Ridge, as it differs fundamentally from both oceanic and continental crust (Foulger et al. 2003). Oceanic crust is divided into three distinct layers: Layer 1 is referred to as sediments; Layer 2 is composed of extrusive volcanic eruptive rock, mostly pillow lava; and Layer 3 is equivalent to gabbro and cumulates ultramafic rocks. Icelandic-type crust can be divided in a similar way but pillow lavas in Layer 2 are replaced by subaerial lava flows. The seismic velocities of Icelandic-type crust are generally equivalent to those of normal oceanic crust, but have a more variable Layer 3 of overall much thicker crust (Brandsdóttir & Menke 2008). This atypical build-up of thick oceanic crust is of interest, as multichannel seismic (MCS) reflection data interpretations might shed light on the internal structures up to 15 km in depth that cannot be imaged by seismic refraction or potential field data.

The GIFRC area has long been regarded as a hotspot track, mainly formed by subaerial igneous activity (Bjarnason 2008). Its structure is, however,
poorly understood due to the lack of geological profiles, dated rock samples from the offshore areas, and difficulties in interpreting consistent magnetic chron data across the region (Gaina et al. 2017) (Fig. 3a).

It can be debated whether or not the Greenland–Iceland–Faroe Ridge and Iceland itself belong to the NAIP. The definition of a large igneous province (LIP) defines an area that has undergone extremely large accumulation of igneous rocks in a short time. In that sense, the formation of the NAIP ended by the opening of the ocean, when break-up volcanism turned into drift volcanism and concentrated around the Iceland hotspot and the Ægir, Reykjanes and Kolbeinsey mid-ocean ridges (MORs). Most published work, however, includes the GIFRC and Iceland itself in that province (e.g. Saunders et al. 1997). In that sense, the NAIP is still expanding and the duration of its formation exceeds 60 myr.

Tectonic setting

The NAIP started to form 60–63 myr ago during the pre-break-up phase of the NE Atlantic, when a deep-seated mantle plume reached the lower crust below central Greenland (Morgan 1971; Brooks 1973; White & McKenzie 1989). This caused intensive volcanism in East and West Greenland and northern Canada, as well as in the Faroe and British islands (Ganerød et al. 2010). The NE Atlantic break-up phase took place during the Late Paleocene (57–55 Ma), forming magma-rich margins across the area before the final opening of the North Atlantic rift system along structurally weak areas within the crust (Larsen & Saunders 1998; Gaina et al. 2009; Blischke et al. 2016). The central NE Atlantic was covered with extensive lava flows on adjacent elevated margins, also referred to as plateau basalts (Larsen & Watt 1985; Larsen et al. 1989; Søåger & Holm 2009). In the Early Eocene (55–54 Ma), the lithosphere finally ruptured, initiating the post-break-up phase and marking the onset of seafloor spreading in the NE Atlantic. Initially, three MOR segments formed: the Ægir, Mohn’s, and Reykjanes ridges. The initiation sequences are present in seismic reflection data as distinct seawards-dipping reflectors formations (SDR) along the break-up margins (e.g. Talwani & Eldholm 1977; Hinz 1981; Mutter et al. 1982; Larsen & Jakobsdóttir 1988; Larsen & Saunders 1998; Elliott & Parson 2008; Blischke et al. 2016; Geissler et al. 2016). The Late Paleocene and Early Eocene plateau basalts and SDR sequences that form the bulk of the NAIP were split up by the opening of the North Atlantic, and are now widely distributed and exposed along both margins of the NE Atlantic Ocean.

The GIFRC covers 480 000 km² of a thick volcanic crust that stretches 1150 km across the central NE Atlantic Ocean between the central East Greenland and the NW European margins (Fig. 1). It incorporates the Iceland Plateau, the aseismic GIR and the IFR. The GIFRC appears as a prominent phenomenon with respect to bathymetry, ocean basement morphology, gravity, palaeomagnetism, crustal thickness, geochemistry and petrology characteristics, with direct influence from the mantle plume (Figs 1–3) (e.g. Jakobsson 1972; Fitton et al. 1997; Thirlwall et al. 2004; Kokfelt et al. 2006; Thordarson & Larsen 2007; Parnell-Turner et al. 2014). Seismic refraction studies have confirmed a crustal thickness variation from 20 to 40 km within the area, accounting for at least a 3–4 times thicker crust than observed for the average oceanic crust (Funck et al. 2014) (Fig. 3c).

The western border of the GIFRC corresponds to the continent–ocean boundary (COB) of central East Greenland, and its eastern border corresponds to the continent–ocean boundary west of the Faroe Islands (Hopper et al. 2014). The GIFRC reaches up to 2100 m above sea level in SE Iceland, whereas the bathymetrically deepest points of the

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**Fig. 1.** Regional settings map showing the main volcanic facies elements (à Horni et al. 2014), major structural lineaments (Funck et al. 2014), the Iceland Plateau Rift system (Blischke et al. 2016), ocean basin morphology type map (Funck et al. 2014; Gaina et al. 2016; Geissler et al. 2016) and bathymetry data (Hopper et al. 2014) of the GIFRC, surrounding oceanic basins and continental margins. This compilation illustrates the complex segmentation of the central NE Atlantic region with its active and extinct volcanic systems (e.g. SDRs, igneous complexes and rift systems, and major boundary structural elements, such as fracture zones). *Abbreviations: CEG, central East Greenland; GIR, Greenland–Iceland Ridge; IFR, Iceland–Faroe Ridge; GIFRC, Greenland–Iceland–Faroe Ridge Complex; Fl, Faroe Islands; VB, Voring Basin; MB, Møre Basin; KR, Kolbeinsey mid-ocean ridge (MOR); ÆR, Ægir MOR; RR, Reykjanes MOR; MR, Mohn’s MOR; IMMC, Jan Mayen microcontinent; IMI, Jan Mayen Island Volcanic Complex; EJMFZ, East Jan Mayen Fracture Zone; WJMFZ, West Jan Mayen Fracture Zone; IFFZ, Iceland–Faroe Fracture Zone; TFZ, Tjörnes Fracture Zone; MB, Mid-Iceland Volcanic Belt; SISZ, South Iceland Seismic Zone; NVZ, North Iceland Volcanic Zone; EVZ, East Iceland Volcanic Zone; WVZ, West Iceland Volcanic Zone; RVB, Reykjanes Volcanic Belt; SVB, Snæfellsnes Volcanic Belt; and ÖVB, Örafajökull Volcanic Belt (Einarsson 2008; Gaina et al. 2009; Gernigon et al. 2015; Blischke et al. 2016).
complex lie at 600 m below sea level (b.s.l.) between Iceland and Greenland, within the Denmark Strait, and at approximately 500 m b.s.l. between Iceland and the Faroe Islands. The ocean basins north and south of the ridge are over 2000 m deep. The submarine areas of the GIFRC are initially believed to have formed subaerially, but have been subsiding below sea level due to erosion and cooling of the crust (Lundin & Dore´ 2004; Denk et al. 2011). The subsidence process has resulted in an approximately 1500 m difference in elevation along the GIFRC crest (Fig. 2).

Data
Primary data control is affected by potential field and section data, such as bathymetry, magnetic and gravity anomaly compilations, MCS reflection, seismic refraction, and multibeam data from the Vesturdju´p area (Funck et al. 2014; Gaina 2014; Haase & Ebbing 2014; Hopper et al. 2014; Nasuti & Olesen 2014) (Figs 3a–c & 4; Tables 1 & 2). Analogue studies and surface geology map data also proved vital for a comprehensive understanding of the area (Sæmundsson 1974, 1979; Talwani &...
Table 3. Rift zones and rift relocations

| Rift zone | Duration (Ma) | References |
|-----------|---------------|------------|
| XR52Ma (Rockall and Vøring margins) | 54–52 | Torsvik et al. (2015) |
| XR33Ma (Greenland–Iceland Ridge) | 54–33 | Torsvik et al. (2015) |
| Ægir Ridge | 52–26 | Gernigon et al. (2015) |
| XR40Ma (East Iceland insular margin) | 52–40 | Torsvik et al. (2015) |
| Iceland Plateau Rift | 49–252 | Brandsdóttir et al. (2015), Blischke et al. (2016) |
| Kolbeinsey Ridge | 25–0 | Talwani & Eldholm (1977) |
| Vesturdjúp Rift | <20 | This study |
| NW Iceland Rift Zone | 25–15 | Harðarson et al. (1997, 2008) |
| Snaefellsnes–Húnaflói Rift Zone | 15–7 | Harðarson et al. (1997, 2008) |
| Reykjanes–Langjökull–North Iceland Rift Zone | 7–0 | Sæmundsson (1979) |
| Eastern Rift Zone | 3–0 | Sæmundsson (1979) |
| Skagafjörður Rift Zone | 1.7–0.5 | Hjartarson (2003) |

Comparisons of the potential field data maps were used to define the outlines and extent of the GIFRC (Figs 2 & 3a–c). The resulting GIFRC outline is a compromise between bathymetry, gravity anomaly, magnetic anomaly and crustal thickness data, along with the geochron model, ocean-floor type map, and seismic reflection and refraction profile data across the region (Figs 1–3a–c).

Table 4. Synclines and anticlines

| Label* | Syncline/anticline | Comment | References |
|--------|--------------------|---------|------------|
| a      | Strede Bank Syncline | Same as XR33Ma? | This study |
| b      | Strede Bank Anticline |       | This study |
| c      | Vesturdjúp Syncline | Connected with the VR Rift | This study |
| d      | Djúpáll Anticline | NW Iceland Rift Zone | This study |
| e      | NW Syncline | Unconformity and hiatus at the shore | Harðarson et al. (1997), Jóhannesson & Sæmundsson (2009) |
| f      | NW Iceland Anticline | Inland Iceland and off Húnaflói | Jóhannesson & Sæmundsson (2009) |
| g      | Snaefellsnes–Húnaflói Syncline | Onland Iceland | Jóhannesson & Sæmundsson (2009) |
| h      | Borgarnes Anticline | Onland Iceland | Jóhannesson & Sæmundsson (2009) |
| i      | Hreppar Anticline | Onland Iceland | Jóhannesson & Sæmundsson (2009) |
| j      | Eyvafjörður Anticline | Onland Iceland | Based on strike and dip: Jóhannesson & Sæmundsson (2009) |
| k      | Vopnafjörður Anticline | Onland Iceland | Based on strike and dip: Jóhannesson & Sæmundsson (2009) |
| l      | Heraðsfjördur Syncline | Onland Iceland | Jóhannesson & Sæmundsson (2009) |
| m      | Austurbæjarklaustur Anticline | Same as XR40Ma? | This study |
| n      | Austurbrún Syncline |       | This study |
| o      | Iceland Basin Anticline |       | Erlendsson & Blischke (2013) |
| p      | Iceland Basin Syncline | Same as XR52 Ma? | Erlendsson & Blischke (2013) |

*For the locations, see Figure 2.
Fig. 3. (a) Magnetic intensity anomaly map (Nasuti & Olesen 2014). A dotted line indicates the outline of the GIFRC and the solid thick black line indicates the continent–ocean boundary. Magnetic anomaly data appear as regular time-parallel strip patterns within the oceanic crust domain, but within the GIFRC are irregular and chaotic. This is thought to be the result of subaerial volcanism and repeatedly active areas through time in the same areas, overprinting the first-order magnetic response (Nunns et al. 1983). Synclines and anticlines are shown on the map with a name key given in Table 3. (b) Free-air gravity anomaly map (Haase & Ebbing 2014) providing an insight into the subsurface features and the main outline of the GIFRC. Gravity data are also the basis for the Moho interface and crustal thickness distribution inversions for crustal thickness estimates. Abbreviations: GIR, Greenland–Iceland Ridge; KR, Kolbeinsey MOR; JMMC, Jan Mayen microcontinent; ÆR, Ægir MOR; GG, Gridar Gorge; IFR, Iceland–Faroe Ridge; FB, Faroe Basin; LB, Lousy Bank; RR, Reykjanes MOR.
Fig. 3. (Continued) (c) Crustal thickness map based on gravity inversion of the Moho interface (Funck et al. 2014). The thin black lines show the locations of the seismically constrained Moho (SCM) points from seismic reflection data (Funck et al. 2014). The GIFRC area shows clear crustal thickness variations, and consists of a much thicker crust than the oceanic crust south and north of the ridge complex. (d) Crustal volume–GIFRC crustal thickness estimates through time, by comparing age grid data (Gaina 2014) to crustal thickness data, summarized as cumulative datasets for 1 Ma increments since break-up. This crustal accretion v. time plot is then compared with half spreading rate profiles for the NE Atlantic by Gaina et al. (2009), and for the southern part of the Norway Basin by Gernigon et al. (2015). It has been shown that the GIFRC follows the NE Atlantic opening process until the rift reorganization and transfer from the Ægir MOR across to the Iceland Plateau Rift to the Kolbeinsey MOR. After the cessation of the Ægir Ridge system, the GIFRC shows a good correlation to the idea that the mantle plume linked to the Icelandic MOR system caused the rift jumps from the Westfjord to the Snaefellsnes–Húnaflói Rift and from there to the Western Volcanic Zone. Finally, can we observe the still active rift transfer to the East Iceland Volcanic Zone (EVZ).
Submarine volcanic complexes were mapped offshore to localize rift centres mainly using high-resolution bathymetry and multibeam data, gravity-magnetic anomalies data, and seismic reflection data, where applicable.

**Mapping data compilations and methods**

The combination of various data observations was vital to validate areas of rift jumps and the formation of complex igneous structures across the GIFRC. These were obtained by accessing the palaeomagnetic arrangement, and comparing the area to the surrounding oceanic basement morphology and crustal thickness variations through time.

**Rift jumps, synclines and anticlines**

Relocation of the magmatic focus through rift-jumping is a prominent process in the evolution of Iceland, and appears to apply to the GIFRC in general. Rift jumps generate unconformities that have been observed across Iceland, marked as time hiatuses, often accompanied by distinct sedimentary horizons containing plant remains between lava for- mations (Denk et al. 2011). The exposed Iceland crust contains evidence of several rift jumps during the last 16 m.y. (Samundsson 1974, 1979; Jóhannesson 1980; Pálsson 1981; Hardarson et al. 1997, 2008; Hjartarson 2003). Here, the mid-Atlantic ridge axis approached the mantle plume from the SE, fully connected to it at approximately 40–35 Ma (Gaina et al. 2017) and proceeded with a WNW drift with respect to the plume at present. At the same time, the active rift axis attempted to maintain its position near the centre of the plume by repeatedly relocating its rift system, leaving behind extinct axial rift zones. Such extinct rift zones have been identified as synclinal structures within the volcanic formations across Iceland (Samundsson 1979; Jóhannesson 1980; Harðarson et al. 2008) (‘g’–‘l’ in Fig. 2 & Table 4). Our investigations and interpretation of seismic reflection data profiles across the GIFRC, specifically east and west of Iceland, have revealed several potential synclines and anticlines (‘a’–‘l’ and ‘m’–‘q’ in Figs 2, 4–6).

A seismic reflection study along the southern flank of the IFR has revealed a complex system of rifts and volcanic facies of different, but unknown, ages (Figs 5 & 6) (Erlendsson & Blischke 2013). The seismic section in Figure 6 extends along the SW slope of the IFR, with a SW–NE orientation (location given in Fig. 2). This section shows clearly the internal complex structures of two rift relocations, where syncline, anticline and SDR structures are interlayered along the IFR and Lousy Bank margins. As no core or seafloor samples are available, it is only possible to link to magnetic data interpretations to obtain an approximate time frame for these ridge jumps. The interpreted syncline may be defined as an extinct volcanic zone or rift system, possibly a remainder from first break-up events in 55–53 Ma between Europe and Greenland (Fig. 6) (Gaina et al. 2009). The syncline has clear inwards-sloping reflectors and a clearly visible anticline is observed along the western slope of that syncline. This anticline may have developed due to a westwards ridge jump, when the old volcanic zone or ridge system within the interpreted syncline became extinct. Further evolution of a new rift system can be seen as sets of SDR sequences, dipping westwards and forming the Proto-Reykjanes MOR located west of the described anticline. An extinct stratovolcano near the eastern end of the section, covering partially the previous dipping reflector, indicates a reactivation of the old rift located within the above described syncline. Remains of the youngest volcanic activity are observed within the sediments as sill intrusions, volcanic ridges and cones at the seafloor.

**Igneous complexes**

Igneous centres are subdivided into four groups in the onshore and offshore areas, such as igneous complexes, inactive and active central volcanoes, and seamounts (Fig. 1), which are described in detail by Hopper et al. (2014) and Gaina et al. (2016). These submarine complexes are compared to active igneous centres along the rift zones across Iceland, as potential present-day geological analogues (Fig. 4) that are formed due to persistent volcanic eruptive or vent systems along fault/fissure swarms (Samundsson 1979), building complex volcanic structures over time. Igneous centres can be seen on seismic reflection data as mounds with steeply dipping flanks or as flat-topped structures due to erosion.

**Palaeomagnetism arrangement, unconformities and age distribution**

Magnetic anomaly data and geochron model data (Gaina 2014; Nasuti & Olesen 2014) are key to defining the outlines of the GIFRC (Fig. 3a). The regular pattern of the magnetic anomalies on the ocean floor south and north of Iceland, that are used for age determinations, is mixed up and shows a quasi-chaotic pattern across the GIR and the IFR, making it very hard or impossible to cross-interpolate the magnetically derived age interpretations. The patchy magnetic pattern of the Greenland–Iceland–Faroe Ridge is thought to be a result of subaerial lava extrusions (Nunns et al. 1983), interacting with the topography of pre-existing flows, and
being further complicated by frequent rift jumps and erosion. Very few direct age measurements have been carried out on the offshore part of the GIFRC, and all ODP and DSDP site boreholes are outside the area. Therefore, the magnetic anomaly interpretation has been extrapolated across the ridge complex (Gaina et al. 2017).

Magnetic anomalies were compared to unconformity observations, geochron age grid interpretation (Gaina et al. 2017), localized syncline and anticline observations, and crustal thickness and ocean-floor morphology.

Unconformities are known from onshore records since 16 Ma (Denk et al. 2011; Stoker et al. 2014), but older unconformities offshore are visible on seismic reflection data as horizons, where the younger strata lie discordantly on an older erosion surface (Figs 5 & 6).

Fig. 4. Regional map showing the seismic reflection lines (see Table 2) and the geological map of Iceland (Hjartarson & Sæmundsson 2014). Black dotted lines indicate the onshore syncline and anticline from Jóhannesson & Sæmundsson 2009 (see Table 4).
Fig. 5. Geoseismic profiles from the Greenland–Iceland Ridge, North Iceland Shelf and Iceland–Faroe Ridge. Key structural features to note include: faulted and folded layering (anticlines and synclines) within the basement is observed in all sections. Profile locations are shown in Figure 2. (a) shows SDRs along the eastern Greenland margin, and synclines and anticlines in the SE part of the section (b) is the western part of the section, which is smooth and shows only indistinct sub-parallel internal layering of the crust. But further east eastwards-dipping reflectors appear; they become steeper and are clearly analogous to the SDRs found on the volcanic continental margins. This part of the profile is interpreted to be a part of thicker oceanic crust defined as the Greenland–Iceland–Faroe Ridge Complex. The structure of the basement east of the SDRs becomes rougher and more faulted, where the crust slightly changes to a typical oceanic crust. (c) shows the correlation between the infill of the Eyjafjörður Sub-basin and the outer shelf succession. A rather clear syncline and an anticline are observed in the SW part of the section. (d) is a composite section showing well-defined structures of the basaltic basement and lava sequences. Both margins appear to be affected by large normal faults, and SDR structures are observed along the Faroe Shelf, covering a nicely shaped anticline that might be interpreted as a possible crystalline basement. (Ages are based on Gaina 2014.)
Fig. 6. Geoseismic profile based on seismic reflection data, extending from the Iceland Basin along the SW slope of the Iceland–Faroe Ridge (see Fig. 2 for location and Table 4). The section shows the internal structures of the basaltic basement, where syncline, anticline and SDRs are visible, forming a complex rift propagation structure that is specific for the GIFRC. The numbers and different colours display different chronologically volcanic formations. (Ages are based on Gaina 2014.)
Oceanic basement morphology

The oceanic basement morphology is primarily controlled by an interplay between tectonic and magmatic processes (e.g. Carbotte & Macdonald 1994; Ito & Behn 2008), and whether an eruption takes place subaerially or subaqueously (Fig. 1). Thus, water depth has a significant influence on the morphological characteristics of lava flows. This determines the ocean-floor surface characteristics, as they are different for sheet flows, pillow basalts and hyaloclastite formations, directly linked to volcanic seismic facies occurring along rifted margins (e.g. Planke et al. 2000; Hopper et al. 2003; Elliott & Parson 2008; Gaiña et al. 2016; Geissler et al. 2016). The different morphology types (Fig. 1) are subdivided into (according to Funck et al. 2014): (1) smooth basement of strong subplanar continuous, high-amplitude, seismic reflections that are very common in the areas of SDRs; (2) transitional basement, where seismic reflections are discontinuous or absent, and the ocean floor is structurally affected and broken up by smaller-scale faults, creating a moderately irregular surface; (3) rough basement, indicating areas with significant basement relief and frequent occurrences of gravity anomalies, indicating volcanic and structural processes affecting the area, most commonly closer to the present-day MORs; (4) rubbly basement that is characterized by a seismically chaotic reflector package with limited energy penetration beneath, mostly close to the break-up margins (Elliott & Parson 2008); (5) volcanic cones and seamounts that form isolated, high-relief features of typically small peaks above the surrounding seafloor, often clustered in areas of increased magmatic activity, such as the GIFRC (Figs 6–8); and (6) the Greenland–Iceland–Faroe Ridge Complex that is a build-up of complex, overlapping rift, igneous and structural systems, thus forming an anomalously thick crust across the complex.

Crustal thickness of GIFRC

Crustal thickness derived from gravity and seismic refraction data (Haase et al. 2016) is one of the
main factors that was used to define the outline of the GIFRC. The anomalously thick crust of the GIFRC is a result of the production of the interaction between the MOR and the Iceland plume (Fig. 3c) (White & Lovell 1997; Funck et al. 2014). The thickest section of up to 40 km-thick crust of the GIFRC is located in SE central Iceland, right next to the postulated centre of the Iceland plume area, and next to the COB boundaries at its eastern and western extensions (Darbyshire et al. 2000; Allen et al. 2002; Funck et al. 2014). The average crustal thickness along the FIR and GIR is estimated to be about 30 km (Fig. 3c) (Richardson et al. 1998; Holbrook et al. 2001). As the GIFRC area is clearly a region with a thick oceanic crust (Fig. 3c), the crustal thickness grid data was compared to the age grid data presented by Gaina (2014). All crustal thickness grid points within a grid cell of 4000 × 4000 m were assigned a value of the overlapping age grid within the GIFRC area. All thickness values were summarized in 1 myr steps since break-up time. A cumulative graph was generated showing the cumulative amount of crustal thickness for each 1 myr step (Fig. 3d).

Crustal thickness variations between 15 and 40 km are observed beneath Iceland (Fig. 3c). This could be related to changes in magmatic activity of the MOR–Iceland plume system through time (Darbyshire et al. 2000) (Fig. 3d). Alternatively, these could be related to pre-existing complex structural settings within the subsurface (Fig. 6). Foulger & Anderson (2005) proposed an explanation for the increased crustal thickness in SE central Iceland, suggesting that microplates of older oceanic crust are submerged beneath that region. Recently, Torsvik et al. (2015) also proposed that geochemical data indicate that fragments of continental crust are present beneath the SE coast of Iceland, suggesting the presence of a SW extension of the Jan Mayen microcontinent, with deeply buried fragments under volcanic rocks. However, there is no evidence of a distinct lateral velocity anomaly seen in refraction data for east Iceland (Funck et al. 2014).

The review of seismic reflection profiles in Figures 5 and 6 show that the IFR is structurally complex, with multiple examples of old crustal blocks buried beneath younger subaerial volcanic sections. This vertical crustal build-up is not just due to increased magmatism from the ridge–plume system, but also due to complex structural events in that area (Blischke et al. 2016). However, changes in magmatic production and crustal

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**Fig. 8.** 3D view of the Vesturdjúp multibeam data. Cone-shaped seamounts, faults and graben structures can clearly be seen in the foreground. Part of two table mountains may be seen in the distance. The geographical location is shown in Figure 2.
accretion can be seen through time by estimating the cumulative crustal thickness for each 1 myr increment across the GIFRC (Fig. 3d). Here, it can be shown that regional events from break-up at around 55 Ma through to the present are reflected in the crustal volume inferred. These include initial break-up, regional and localized rift jumps, decreased spreading activity, and ridge cessation.

**GIFRC rift centres and rift relocations**

The complexity of the GIFRC appears to be closely connected to frequent rift jumps. Several rift jumps are known and documented (Table 3). One specific example is the Ægir Ridge system that formed during the initial opening of the NE Atlantic, with an initial break-up phase between 55 and 53 Ma, and was fully established around 50 Ma (Gaina et al. 2009; Gernigon et al. 2015). It propagated from north to south, spanning the distance between the IFR and the Jan Mayen Transform Zone (Blischke et al. 2016). Spreading on the Iceland Plateau rift took place simultaneously with that on the Ægir Ridge from 49 to 25 Ma along the Iceland–Faroe Fracture Zone, before the complete rift transfer to the Kolbeinsey Ridge system, connecting the Reykjanes Ridge directly and separating the Jan Mayen microcontinent from the central East Greenland coast (Brandsdóttir et al. 2015; Blischke et al. 2016).

Cessation of seafloor spreading and extinction of the Ægir MOR system occurred in the Early Oligocene, around 24–21 Ma, coinciding with the activation of the Kolbeinsey Ridge around anomaly C6b, or 22–21 Ma (Gernigon et al. 2015), and Iceland becoming an insular shelf probably due to the plume–ridge activity (Fig. 3d). Intensive volcanism and a high lava production rate accompanying the initiation of the Kolbeinsey MOR led to the formation of the Iceland Shelf as a volcanic region within the GIFRC.

The NW Rift Zone is thought to have formed some 24 myr ago west of the NW peninsula of Iceland (Harðarson et al. 1997) (Table 4). It was most likely to have been a direct continuation of the Kolbeinsey Ridge, forming its oldest and southernmost part. It was active for 8–10 myr until approximately 15 Ma. Its exact location has always been speculative, as its manifestations have never been clear in geophysical potential field data. However, in seismic reflection data profiles, syncline structures can be seen (syncline ‘e’ in Figs 2 & 5c). The site is just north of the GIR and is approximately parallel to the 15 Ma time line according to the geochron model of Gaina (2014). We suggest that this hypothetical NW Rift Zone, thought to be found somewhere on the insular shelf off the NW peninsula of Iceland (Harðarson et al. 1997), correlates with syncline ‘e’, thus confirming this ancient spreading axis by geophysical data. The seawards-dipping formations of the NW Rift Zone are nearly totally submerged below the seafloor, except for their easternmost extensions, exposed along the outermost coast of the Icelandic Westfjords, where they form the anticline structure ‘f’ shown in Figures 2, 5c and 9b. A lignite horizon overlies these formations, representing a 1–1.5 myr hiatus before the next rift jump and before the onset of the Snæfellsnes–Húnaflói Zone took place (Riishuus et al. 2013) (Figs 2 & 3d).

The Snæfellsnes–Húnaflói Rift Zone formed approximately 14–15 myr ago by an eastwards spreading centre relocation from the NW Rift Zone, and was active for about 8–10 myr (Harðarson et al. 2008). This rift zone is present onshore west Iceland as regional dipping formations that form a distinct syncline centre line of that rift zone (Fig. 2). There are two segments of the rift zone located in Snæfellsnes and Húnaflói, respectively, which may have been connected by a transform fault system. The majority of the Icelandic subaerial Miocene volcanic strata was formed in this rift zone.

The present-day rift zones formed approximately 6 myr ago by relocating active spreading from the Snæfellsnes–Húnaflói Rift Zone to its present location, forming the Western Volcanic Zone (WVZ) and the Northern Volcanic Zone (NVZ) (Sæmundsson 1974, 1979; Jóhannesson 1980) (Figs 2 & 4). However, the rift zone remained active until about 5 myr ago (Pringle et al. 1997). Separately, the most recent rift relocation to the Skagafjörður Rift Zone took place in north Iceland, becoming activated at 1.7 Ma and forming a temporary rift axis for about 1 myr (Hjartarson 2003). The East Iceland Volcanic Zone (EVZ) in south Iceland appears to be an evolving spreading system (Sæmundsson 1979) (Figs 1 & 3d). This zone was initiated 2–3 myr ago, and is slowly propagating to the SE from the WVZ towards the EVZ, forming a dual-zone rift system (Einarsson 2008).

**Central volcanoes and seamounts on the GIFRC**

Central volcanoes play an important role in the build-up and structure of the Icelandic volcanic strata and have been studied intensively (e.g. Sæmundsson 1979; Harðarson et al. 2008). Very little is known about their existence and role within the submarine areas of the GIFRC. The central volcanoes of Iceland can be divided into rift zone and off-rift central volcanoes. The off-rift central volcanoes often form high and prominent stratovolcanoes (e.g. Snæfellsjökull and Eyjafjallajökull) (Fig. 2),
Fig. 9. Schematic cross-section based on an interpreted seismic section and the geological map of Iceland. This section extends from the East Greenland margin, across the Greenland–Iceland Ridge, Iceland and Iceland–Faroe Ridge and towards the Faroe Shelf. The main purpose of this section is to illustrate in a schematic way the development, basement dip, and synclines and anticlines across GIFRC based on seismic reflection data (for Section (a) and Section (b) see Fig. 5), surface geology mapping and data observations (for Section (b) see Fig. 4 and Hjartarson & Sæmundsson 2014), and data modelling (Böðvarsson & Walker 1964).
in contrast to rift zone central volcanoes that are lower and more irregular in shape, and many of them have formed calderas. The lifespan of an individual central volcano, until it cools down, has been found to vary from 300 kyr to over 1 myr (Sæmundsson 1979; Harðarson et al. 2008). The only known example of an active submarine central volcano today is the Njörður volcano situated on the Reykjanes Ridge close to the Icelandic shelf (Höskulðsson et al. 2013).

More than 40 inactive former rift zone central volcanoes are known in the Neogene formations of Iceland. They are often deeply eroded, and represented by acid and intermediate rocks, local cone sheets swarms, and swarms of regional dykes and faults (Sæmundsson 1979).

Central volcanoes also exist on the shelf area all around Iceland (Figs 1, 7 & 8). Several central volcanoes have been inferred from potential field data east and west of Iceland, and in some cases confirmed by dredging (Kristjánsson 1976; Jónsson et al. 1997). They are thought to have formed subaerially, but have been submerged as their emplacement area cooled down, while drifting away from the spreading axis.

Seamounts are defined as isolated topographical features of volcanic origin, rising from the ocean floor that did not rise high enough to break through the sea level and turn into islands. Their height differs from some hundred metres up to 4000 m. They follow a distinctive pattern of growth, activity and cessation, and are generally formed near mid-ocean spreading ridges, over upwelling mantle plumes (hotspots) and in island-arc convergent settings (Staudigel & Clague 2010). Thus, they can give important clues as to where old rift systems might have been located in magmatically inactive areas.

Seamount features have been mapped across the GIFRC area, and north and south of Iceland (Funck et al. 2014; Gaima et al. 2016). They are mostly situated on the deep ocean floor on both sides of the Reykjanes and Kolbeinsey ridges (Fig. 1). Some are near to the GIFRC but very few on the ridge complex itself. Possibly the igneous complexes on the GIFRC were formed subaerially, partially eroded after cessation and submerged due to thermal cooling. However, shapely seamounts have been found close to the ridge complex, specifically on the flanks of east and west Iceland’s offshore areas (Figs 1, 7 & 8). In the Vesturdjúp Basin, west of Iceland and just south of the GIR at around 1200 m depth, a group of small seamounts has been identified (Figs 7 & 8). Helgadóttir (2012) has described and discussed these as volcanoes or mud volcanoes. Most of them are cone-shaped ridges, but eroded table-like mountains are also found. Because of these various types of igneous-complex-like structures, conventional volcanism appears to be the most likely cause for these features. The largest cone rises to around 500 m above the surroundings, with a diameter of 5000 m. These seamounts appear to be much less eroded and younger than the neighbouring ocean floor, and possibly indicate a flank igneous system or intraplate volcanism, accompanied by young tectonism with faults, graben and transverse ridges characterizing this area (Fig. 8).

Discussion

In order to assess the development of the GIFRC as an igneous complex within the NAIP, this section addresses individual key stages that affected the GIFRC since the break-up of the North Atlantic (Fig. 3d).

Initial break-up

The GIFRC started to form along with the continental break-up between Greenland and Eurasia, and the initiation of the seafloor spreading, 55–53 and 36 Ma, north and south of the GIFRC (Gaina et al. 2009; Gernigon et al. 2015), but not affecting the GIFRC to a great extent (Fig. 3d). During the Eocene, the Eurasian and North American continental margins were located very close to each other and the plume situated below Greenland, sustaining a subaerial connection between the two continents, and forming a land bridge between Greenland and the Faroes and onwards to the European continent. This is supported by geoseismic investigations (Parnell-Turner et al. 2014), as well as palaeobotanical evidence (Denk et al. 2011).

Active rifting north and south of the GIFRC

The first rifting phase (53.36–49 Ma) of the NE Atlantic after break-up affected the GIFRC area heavily, with the emplacement of large volumes of extrusive and intrusive magmatic material building up the oldest part of the complex (Fig. 3d). During this phase, overlapping rift systems were active (Figs 5, 6 & 9) that overlaid older crustal segments and led to very thick crustal formation from east Iceland to the IFR region (Fig. 3c).

Rift orientation and Ægir Ridge transition

Continuous spreading was active in the Reykjanes MOR system to the south, but rift transfer started to form from the Ægir Ridge system along the Iceland Plateau Rift (IPR) corridor south of the JMMC between approximately 49 and 40 Ma. This is reflected in crustal accretion of the GIFRC, with increased magmatic activity between the IPR.
system and the Iceland–Faroe Fracture Zone (IFFZ) (Blischke et al. 2016) (Figs 1 & 3d). Recent reconstruction work of the region indicates that the East Iceland Shelf edge is parallel to the proto-Reykjanes Ridge location at anomaly C19n (40.32 Ma) (Gaina et al. 2014; Blischke et al. 2016), cutting into the older crust of the IFR area (Fig. 3c, d).

Decrease in spreading rate along the Ægir MOR system

The Greenland–Eurasian plate system moved NW relative to the mantle plume, which was situated at 35–30 Ma below the Greenland margin (Fig. 1) (Torsvik et al. 2015). Oceanic spreading was active along the Reykjanes and the Ægir MORs, but was gradually slowing down to ultra-slow-spreading past 30 Ma within the Ægir MOR system (Gernigon et al. 2015). This also directly affects the GIFRC, where much lower crustal accretion volume through time can be observed (Fig. 3d) in connection with the slowing down of the rift systems. Rift jumps possibly took place in a westwards direction that can be seen in the seismic reflection record in the form of synclines and anticlines along the Greenland–Iceland and Iceland–Faroe ridges (Figs 2, 6 & 9).

Ægir Ridge cessation: Kolbeinsey Ridge insular shelf

Spreading activity along the Ægir Ridge ceased around 22 Ma (Gernigon et al. 2015) (Fig. 3d) and seafloor spreading concentrated only along the Kolbeinsey Ridge from 24 Ma onwards. The process of establishing a new plate boundary and ultimately the Kolbeinsey Ridge resulted in the extension of the Greenland margin situated immediately north of the Reykjanes Ridge, which led to the final detachment of the Jan Mayen microcontinent (JMMC) from the central East Greenland margin (Blischke et al. 2016). The initiation of the Kolbeinsey Ridge, and the interaction between the Iceland plume and the newly formed MOR system, led to an increase in magmatic and volcanic activity along the GIFRC area, as well as further north along the western to SW margin of the JMMC.

Recent age models based on palaeomagnetic chron interpretations of the ocean floor around Iceland indicate a major hiatus crossing the insular shelf near the eastern to SE coast (Gaina et al. 2017) that may possibly be identified on seismic reflection data interpretations (Fig. 5). We suggest that this hiatus is related to increased magmatic accretion (Fig. 3d) of the central Iceland region, with extrusive rock discordantly overlying older igneous formation and crust, forming a much thicker crust in that area. The subcrop of this unconformity boundary is buried beneath thick layers of sediments, 8–10 km inside the bathymetric shelf break, according to Jónsson & Kristjánsson (1997), but can be seen near the anticline ‘m’ in Figures 2 and 5d. The age of the volcanic rocks at the edge of the East Iceland Shelf might be 20–24 Ma, which would correlate to the original opening time of the Kolbeinsey Ridge system during its initiation. The age of the underlying volcanic basement for that section might be around 40 Ma according to the age model by Gaina et al. (2017) (Fig. 3a), corresponding to a hiatus time span of approximately 16–20 myr.

This increase in magmatic activity, and most probably thermal uplift of the GIFRC area, created the insular shelf of proto-Iceland; thus creating a major hiatus and related unconformity between the young formations of the Kolbeinsey Ridge and the older volcanic basement of the IFR and GIR (Figs 5d & 9c). This early stage of the subaerial insular shelf region is today mostly submerged, but forms large areas of the insular shelf in the east, west and north of Iceland.

Miocene: Pliocene rift jumps on Iceland

In the Early Miocene, the mid-Atlantic ridge axis approached and crossed the location of the Iceland plume (Harðarson et al. 2008). Since then, the spreading ridge systems in Iceland have remained linked to the plume. As the spreading axis moves away from the central plume location, the rift centres are periodically recaptured by the plume through rift-jumping. It has been proposed that a complete rift cycle for Iceland lasts for at least 12 myr, from initial propagation to extinction (Harðarson et al. 1997, 2008). The control on rift-jumping is clearly related to the interaction of the static mantle plume with the overlying NW-migrating plate of Eurasia (Gaina et al. 2017). Relocation of active magmatism towards the plume may simply be a response to this migration.

As the North Atlantic Ocean widened, the marginal eastern and western parts of the land bridge cooled, partially eroded and gradually submerged (Denk et al. 2011), as can be seen as a base Cenozoic sediment horizon in Figures 5d and 9. This first took place along the eastern area of the IFR, followed by the western area due to its proximity to the mantle plume. Palaeobotanical observations indicate that the latest evidence for plant migration on land between Europe and Iceland is dated at around 9 myr ago, and between Greenland and Iceland around 6 myr ago (Denk et al. 2011). The age of the GIR and the IFR as submarine areas is therefore less than 10 myr, and the age of Iceland as an isolated island is approximately 6 myr.
Conclusions

The Greenland–Iceland–Faroe Ridge Complex (GIFRC) has been in development since the opening of the NE Atlantic at around 55 Ma. It appears as a prominent feature in all geological and geophysical datasets. Its shape and size can be drawn in slightly different ways according to the various data sources available. Despite a small area outline compromise between the different datasets, comprising bathymetry, gravity, magnetic and crustal thickness maps along with seismic profiles over the region, all show the area as an anomalous feature within the oceanic crustal fabric of the NE Atlantic.

Published synclines and anticlines have been summarized (Table 3), and several new synclines and anticlines that were revealed in seismic reflection data across the GIFRC east, west and north of Iceland (Figs 2, 5, 6 & 9). Specifically, the offshore anticlines and synclines may be related to old rift systems prior the forming of Iceland as an insular shelf region (>24 Ma). Synclines are suggested to be manifestations of former rift axes that have been abandoned by rift jumps. These rift jumps appear to be more common inside the GIFRC region than in the ocean basins south and north of the area, and can also be confirmed by the observation of cumulative crustal accretion through time (Fig. 3d).

Thus, the GIFRC represents a complex region of crustal accretion in three dimensions due to overlapping rift systems, complex interlinked rift and transform zones, and several unconformities that suggest a variable uplift and subsidence history for the ridge complex. An excellent example to visualize such processes of vertical crustal accretion and rift jumps is seen in seismic reflection data that extends along the SW slope of the Iceland–Faroe Ridge (IFR). They clearly display the internal structures of basement blocks, separated by a syncline and younger rift system, and the formation of an anticline across the deeply buried basement blocks that are overlain by SDR structures (Fig. 6).

We suggest a major hiatus (from 40 to 24–20 Ma) and a related unconformity at the boundary of the volcanic insular shelf edge of east Iceland and the Faroe Ridge, buried beneath thick layers of sediments, 8–10 km inside the bathymetric shelf break (Fig. 5d).

We suggest that the hypothetical NW Rift Zone, thought to be somewhere on the insular shelf off the NW peninsula of Iceland (Harðarson et al. 1997), correlates with syncline ‘e’ just north of the Greenland–Iceland Ridge (GIR) (Figs 2 & 5), parallel to age line 15 Ma of the geochron model by Gaina et al. (2017), and thus confirms this ancient spreading axis by geophysical data.

Several seamounts were observed on multibeam datasets from the Vesturdjúp Basin west of Iceland, just south of the GIR at around 1200 m depth (Figs 2, 7 & 8). Most of them are cone shaped, but ridges and table mountains are also found. These seamounts appear to be much less eroded and younger than the neighbouring ocean floor, and might indicate a still active flank or intraplate volcanic zone. Young tectonism with faults, graben and transverse ridges also characterize the area, and most of the volcanic cones are located along fault plans or/and within the graben of the Vesturdjúp (Fig. 8), giving a good example of the complexity of the GIFRC in comparison to simple ocean-floor areas.

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