

# On the Timing and Nature of Magmatism in the North Atlantic Igneous Province: New Implications from Basaltic Rocks of the Faroe Islands

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**Abstract:** In this contribution we present novel radiometric  $^{40}\text{Ar}/^{39}\text{Ar}$  ages representing a number of basaltic sills/lavas of the Faroe Islands, which themselves form part of the North Atlantic Igneous Province. Measured ages are utilised in an attempt to assess the local igneous history, where the new ages are contrasted against those of other local rocks of known ages as well as against those of comparable/neighbouring North Atlantic igneous regions. The novel ages presented in this contribution allow us to put new constraints on the timing of late stage magmatic activity and associated crustal extension of this part of the North Atlantic area. In this research we present new ages as young as ~50.5 Ma for some of the smallest Faroese sills and demonstrate that the larger and oldest local sills, grouped into the low-TiO<sub>2</sub> Streymoy/Kvívík sills and the high-TiO<sub>2</sub> Eysturoy/Sundini sills respectively (~55.5 Ma), likely formed immediately subsequent to the formation of the uppermost parts of the Enni Formation, which itself represent the latest stages of local surface magmatism at ~55.8 Ma. Gradually decreasing sill volumes coupled with successively younger ages point to systematic decrease of local igneous activity with increasing distances to active contemporaneous local rifting zones. Comparable scenarios recorded for other parts of the North Atlantic Igneous Province support our inferences regarding the nature of late-stage magmatic activity at some distances from zones of active seafloor-spreading. Comparisons between ages of Faroese igneous products versus those of e. g. central E Greenland point to a somewhat diachronous evolution pattern within this part of the North Atlantic Igneous Province subsequent to ~57.5 Ma. The lithosphere-asthenosphere boundary is commonly thought to be critical for the formation of basaltic magmas. Accordingly, the close spatial and temporal associations between many high-TiO<sub>2</sub> and low-TiO<sub>2</sub> Faroese rock suites are interpreted in the context of a regional version of this boundary.

**Keywords:** Timing Nature Magmatism, North Atlantic Igneous Province, Faroe Islands, Flood Basalts, Sill Intrusions,  $^{40}\text{Ar}/^{39}\text{Ar}$  Geochronology, Petrogenetic Interpretations

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## 1. Introduction

Basaltic rocks of the Faroe Islands Basalt Group (FIBG) form part of the North Atlantic Igneous Province (NAIP), which itself is one of the Large Igneous Provinces (LIPs) on Planet Earth [1, 2]. Combined, the igneous regions of the NAIP encompass vast areas in the North Atlantic such as in the eastern parts of the Baffin Island, in West Greenland, in East Greenland, offshore West Norway (Vøring and Møre basins), in the Faroe Islands, on the Rockall Plateau and in the NW British Isles [3] (Figure 1A). Igneous NAIP products

post-dating the main rifting event at ~55.8 Ma are to be found in Iceland and adjacent submerged Greenland-Iceland and Iceland-Faroes ridges, in Jan Mayen (smaller scale), in West and East Greenland, in submerged igneous seamounts in the Norwegian-Greenland Sea, on either side of the Reykjanes ridge, at the eastern fringes of the Rockall Plateau and in the Rockall Trough [3-6]

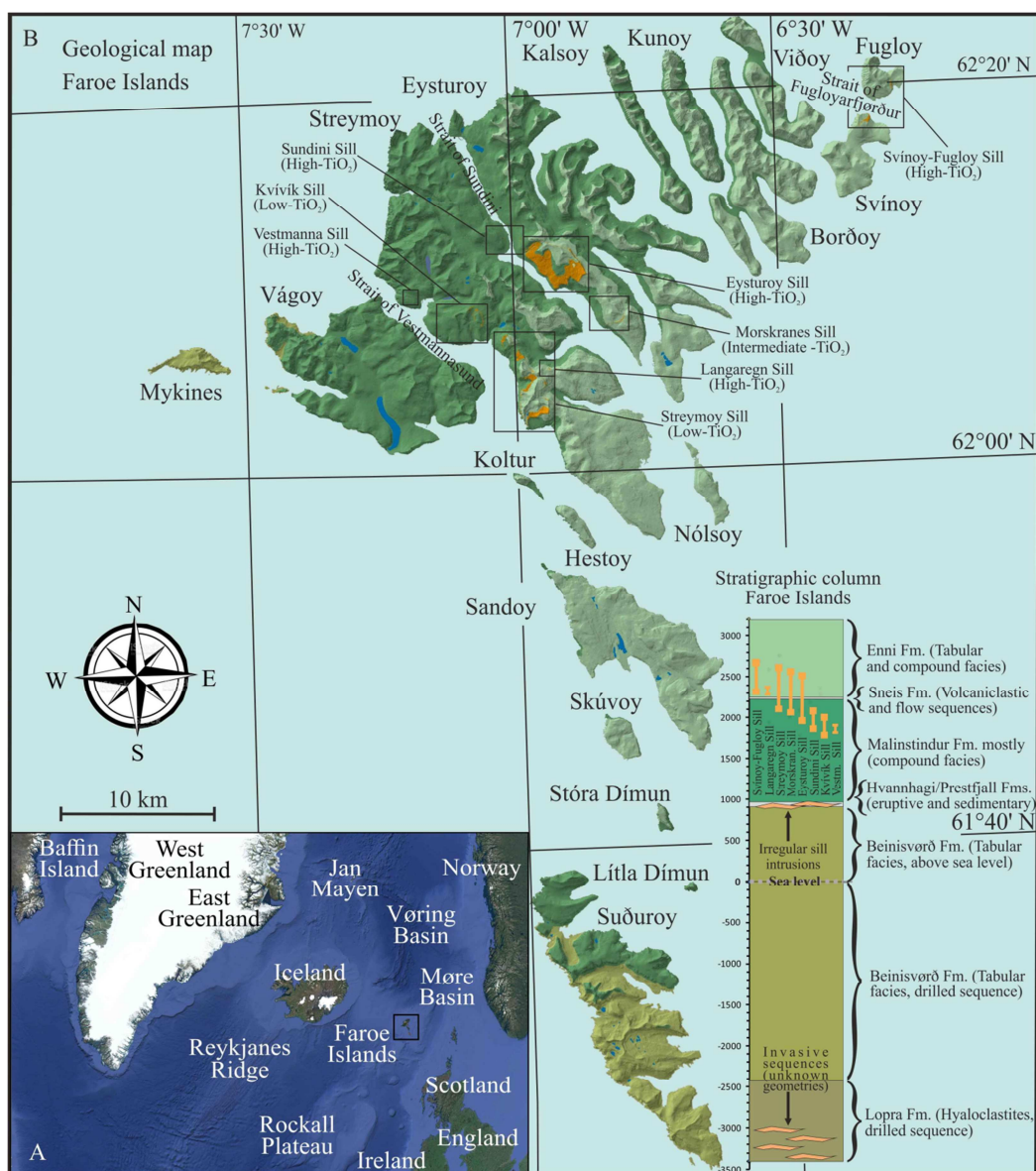
Magmatic events within the various igneous regions of the NAIP have traditionally been associated with incipient crustal extension in the Early Paleogene Period along axes in the Labrador Sea, offshore East Greenland and in the Rockall

Trough through the Shetland Basin respectively, followed by active extension-related seafloor-spreading in the NE Atlantic and in the Labrador Sea [1, 4, 7, 8]. Hence, reliable radiometric age determinations of representative igneous products within the various parts of the NAIP are essential to determine the magmatic development along the various extension/rift axes so as to evaluate the timing of lithospheric stretching that occurred in the various igneous regions prior to, contemporaneous to and subsequent to initiation of active seafloor spreading.

In this contribution we present for the first time  $^{40}\text{Ar}/^{39}\text{Ar}$  ages for a number of basaltic sills intruded into the lava succession of the Faroe Islands and for a one key local lava flow. A few  $^{40}\text{Ar}/^{39}\text{Ar}$  ages on local lava flows from previous

research [9, 3] are presented in conjunction with results of this research. Obtained new radiometric ages from the actual research are in turn utilised in order to assess/interpret the igneous evolution within the actual region in addition to being briefly contrasted against some radiometric ages of other relevant parts of the NAIP. From a more global perspective, we aim to increase the understanding of the developments of LIPs, especially during waning igneous phases within these. In this contribution we also endeavour to explain the common occurrences of close spatial and temporal co-existence of high- $\text{TiO}_2$  and low- $\text{TiO}_2$  Faroese basaltic sills and lavas in the context of mantle melting at the lithosphere-asthenosphere boundary (LAB).

## 2. Regional Geology



**Figure 1.** Maps showing the area relevant for this study. (A) The “Google Earth” based map illustrates locations of the main parts of the NAIP, including the focus of this study the Faroe Islands. (B) The map, based on topographic data from Munin Fo, Faroe Islands, shows the main basaltic formations building up the Faroe Islands: Modified from [5, 10-12]. The stratigraphic column illustrates the thicknesses of the various geological formations according to nomenclature of Passey and Jolley [13]. Orange bars indicate total vertical (stratigraphic) extent of the actual sills. Simplistic explanation on general sill trends and extents are shown on central left of (B).

Situated between East Greenland and the NW European continental margin, the FIBG makes up a relatively central part of the NAIP (Figure 1A). The exposed onshore parts of the Faroese basaltic lava pile cover around 1400 km<sup>2</sup> with a total stratigraphic extent (exposed and drilled) of around 6.6 km: [11] and refs. therein. The Faroese lava pile can be grouped into seven formations from bottom and up: the ~1075 m thick Lopra Formation; the ~3250 m thick Beinivørð Formation; the ~9 m thick Prestfjall Formation; the 40-50 m thick Hvannhagi Formation; the 1250-1350 m thick Malinstindur Formation; the up to ~30 m thick Sneis Formation and finally the ~900 m thick Enni Formation, which might have been a few hundreds of metres thicker than 900 m initially [13] (Figure 1B). The Malinstindur, Sneis and Enni formations are intruded by a few basaltic transgressive (saucer-shaped) sills of various extent and thicknesses, which likely represent the latest manifestations of igneous activity within the actual region [10, 11, 14]. Hence, the actual sills postdate all known extrusive activity in the actual area, but their absolute/radiometric ages have not been known prior to this research.

A few attempts to estimate/measure age (s) of Faroese lavas have been undertaken previously, including paleomagnetic dating [15-17] and radiometric <sup>40</sup>Ar/<sup>39</sup>Ar dating [9, 18]. Amongst these, the most recent ages by Storey *et al.* [9] appear to be most reliable and consistent with ages of comparable basaltic lavas from other parts of the NAIP. Their age determinations pointed to ages of ~60 Ma for the bottom of the Beinivørð Formation and ~57 Ma for its top sections, while they measured an age of ~55.2 Ma for upper sections of the Enni Formation.

### 3. Materials and Methods

#### 3.1. Sampling and Petrography

Initially, samples were collected from 7 Faroese sills (the Streymoy, Kvívík, Eysturoy, Morskranes, Svínøyr-Fugloy, Langaregn and Vestmanna sills) and a key Faroese lava flow, i. e. the bottom of the Malinstindur Formation, as shown in Electronic Supplement B. [19]. Noticeable proportions of the exposed parts of the Faroese sills are intensely jointed and/or have been exposed to chemical weathering. As the main bodies of individual Faroese sills display quite homogeneous petrography and geochemistry [5, 11], the foremost sampling criterion involved the acquirement of fresh specimen. Hence, great care was taken to collect representative sill and lava samples without joints or visible signs of weathering at the whole-rock scale. Due to the homogeneous nature of the actual sills, most of the sill samples represented the bulk of their main bodies displaying medium-grained texture (Streymoy, Kvívík, Eysturoy, Svínøyr-Fugloy and Morskranes sills), while samples of the much smaller Langaregn Sill in addition to the lava sample from the bottom of the Malinstindur Formation exhibited relatively fine-grained textures [19], in accordance with characteristics typical of their main/bulk bodies. The fine to medium grained

and homogeneous Vestmanna Sill [e.g. 19] probably experienced a crystallising history between these two categories. Physical dimensions, general petrography and geochemistry for the bulk of Faroese sills and lavas have also been detailed in previous studies [5, 10, 11, 20].

Most of the actual <sup>40</sup>Ar/<sup>39</sup>Ar analyses are based upon groundmass material, whilst plagioclase was used for a couple of samples (Table 1, Figure 2). Reasonable/acceptable reproducibility in repeated <sup>40</sup>Ar/<sup>39</sup>Ar analyses of groundmass and/or plagioclase crystals determined which analyses were accepted for presentation in this contribution. As it turned out, only a couple of plagioclase analyses generated results acceptable for this paper, while groundmass analyses yielded the best results for the rest of the samples. Sample qualities at the whole-rock scale were assessed on thin-sections (microscopy) and on major elements, determined by means of X-ray fluorescence (XRF) analyses, as shown in Electronic Supplement B [19].

#### 3.2. Analytical Techniques

Samples were crushed and sieved to obtain 180 – 250 µm fractions. The finer particles were decanted in tap water and the coarser residue further ultrasonically washed in acetone and de-ionized water several times. The grains deemed by optical investigations to be best suited, being void of any coatings, were handpicked under a stereomicroscope. The samples were packed in aluminium capsules together with the Taylor Creek Rhyolite (TCR) flux monitor standard along with zero age reagent grade K<sub>2</sub>SO<sub>4</sub> and optical grade CaF<sub>2</sub> salts for interference corrections. The samples were irradiated at the MTA reactor (Hungary) for c. 2 hours, with a nominal fast neutron flux density of c. 5.5×10<sup>13</sup> n\*(cm<sup>-2</sup> \*s<sup>-1</sup>). The interference correction factors for the production of isotopes from Ca and K are shown in Table 1. Groundmass and plagioclase materials were placed in a 3.5mm pit size aluminium sample disk and step heated using a defocused 3.5 mm CO<sub>2</sub> laser beam from Photon Machine Fusions 10.6 with a flat energy spectrum. The extracted gases from the sample cell were expanded into a Piston Free Stirling Cryocooler for trapping potential water vapour and further into a two-stage low volume extraction line (c. 300 cm<sup>3</sup>), both stages equipped with SAES GP-50 (st101 alloy) getters, the first running hot (c. 350°C) and the second running at room temperature. The samples were analyzed with a MAP 215–50 mass spectrometer in static mode, installed at the Geological Survey of Norway. The peaks and baseline (AMU = 36.2) were determined during peak hopping for 15 cycles (15 integrations per cycle, 30 integrations on mass <sup>36</sup>Ar) on the different masses (<sup>40–36</sup>Ar) on a MasCom electron multiplier (MC217) in analogue mode and linearly regressed back to zero inlet time. Blanks were analyzed every third measurement. After blank correction, a correction for mass fractionation, <sup>37</sup>Ar and <sup>39</sup>Ar decay and neutron-induced interference reactions produced in the reactor was undertaken using in-house software AgeMonster, written by M. Ganerød. It implements the equations from [21] and the recently proposed decay constant for <sup>40</sup>K after [22]. A <sup>40</sup>Ar/<sup>36</sup>Ar ratio of 298.56±0.31 from [23], was used for the atmospheric

argon correction and mass discrimination calculation using a power law distribution of the masses. We calculated J-values (irradiation flux parameter) relative to an age of  $28.619 \pm 0.036$  Ma for the TCR fluence monitor [22]. We used the following

criteria to determine the sample ages: at least 3 overlapping consecutive steps (95% confidence), accounting of more than 50% cumulative  $^{39}\text{Ar}$  released from the spectra analyses.

## 4. Results

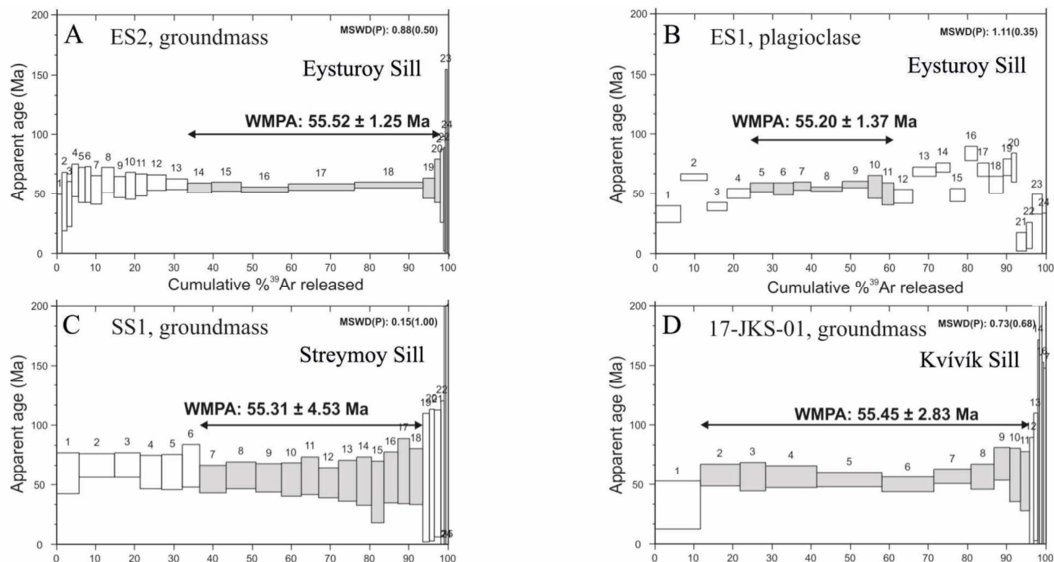
**Table 1.** Early Cenozoic  $^{40}\text{Ar}/^{39}\text{Ar}$  ages representing sills and lavas of the Faroe Islands.

| Lavass and sills   | Sample      | Material    | Steps (n) | Spectra            |                       |             | K/Ca $\pm 1.96s$      | Inverse isochron  |             |                                            |
|--------------------|-------------|-------------|-----------|--------------------|-----------------------|-------------|-----------------------|-------------------|-------------|--------------------------------------------|
|                    |             |             |           | % $^{39}\text{Ar}$ | Age $\pm 1.96s$<br>Ma | MSWD (P)    |                       | Age $\pm 1.96s$   | MSWD (P)    | Trapped<br>$^{40}\text{Ar}/^{36}\text{Ar}$ |
| Streymoy Sill      | SS1         | Groundmass  | 7-18 (12) | 57.09              | $55.31 \pm 4.53$      | 0.15 (1.00) | $0.06426 \pm 0.00179$ | $54.00 \pm 8.18$  | 0.15 (1.00) | $304.75 \pm 33.30$                         |
| Kvívík Sill        | 17-JKS-01   | Groundmass  | 2-11 (10) | 84.22              | $55.45 \pm 2.83$      | 0.73 (0.68) | $0.04452 \pm 0.00170$ | $56.27 \pm 6.29$  | 0.82 (0.59) | $297.47 \pm 7.92$                          |
| Eysturoy Sill      | ES-1        | Plagioclase | 5-11 (7)  | 36.89              | $55.20 \pm 1.37$      | 1.11 (0.35) | $0.07 \pm 0.00$       | $54.36 \pm 3.91$  | 1.29 (0.27) | $309.89 \pm 48.72$                         |
| Eysturoy Sill      | ES-2        | Groundmass  | 14-20 (7) | 64.52              | $55.52 \pm 1.25$      | 0.88 (0.50) | $0.05970 \pm 0.00241$ | $55.31 \pm 11.77$ | 1.06 (0.38) | $299.62 \pm 59.73$                         |
| Svínoy-Fugloy Sill | FS-1        | Groundmass  | 2-9 (8)   | 74.54              | $54.06 \pm 1.89$      | 1.25 (0.27) | $0.08418 \pm 0.00271$ | $59.40 \pm 6.33$  | 1.06 (0.39) | $275.21 \pm 28.32$                         |
| Svínoy-Fugloy Sill | FS-2        | Groundmass  | 4-13 (10) | 48.63              | $54.76 \pm 3.56$      | 0.27 (0.98) | $0.03 \pm 0.00$       | $52.75 \pm 14.93$ | 0.29 (0.97) | $306.51 \pm 62.50$                         |
| Morskranes Sill    | 17-JMS-01   | Groundmass  | 4-13 (10) | 70.34              | $53.16 \pm 3.90$      | 0.35 (0.96) | $0.02 \pm 0.00$       | $56.77 \pm 11.48$ | 0.35 (0.95) | $291.14 \pm 23.60$                         |
| Langaregn Sill     | 18-JLRS-01  | Groundmass  | 9-20 (12) | 63.18              | $50.72 \pm 1.25$      | 0.91 (0.53) | $0.02909 \pm 0.00096$ | $39.79 \pm 9.13$  | 0.39 (0.95) | $342.72 \pm 39.38$                         |
| Vestmanna Sill     | 16-JVEST-02 | Plagioclase | 2-9 (8)   | 56.79              | $50.31 \pm 1.59$      | 0.94 (0.47) | $0.00372 \pm 0.00003$ | $58.69 \pm 8.02$  | 0.49 (0.82) | $286.12 \pm 12.12$                         |
| Malinstindur FM    | 16-JHVAL-02 | Groundmass  | 6-18 (13) | 81.51              | $56.34 \pm 1.87$      | 1.40 (0.16) | $0.07827 \pm 0.00349$ | $50.95 \pm 3.72$  | 0.57 (0.85) | $318.20 \pm 12.47$                         |

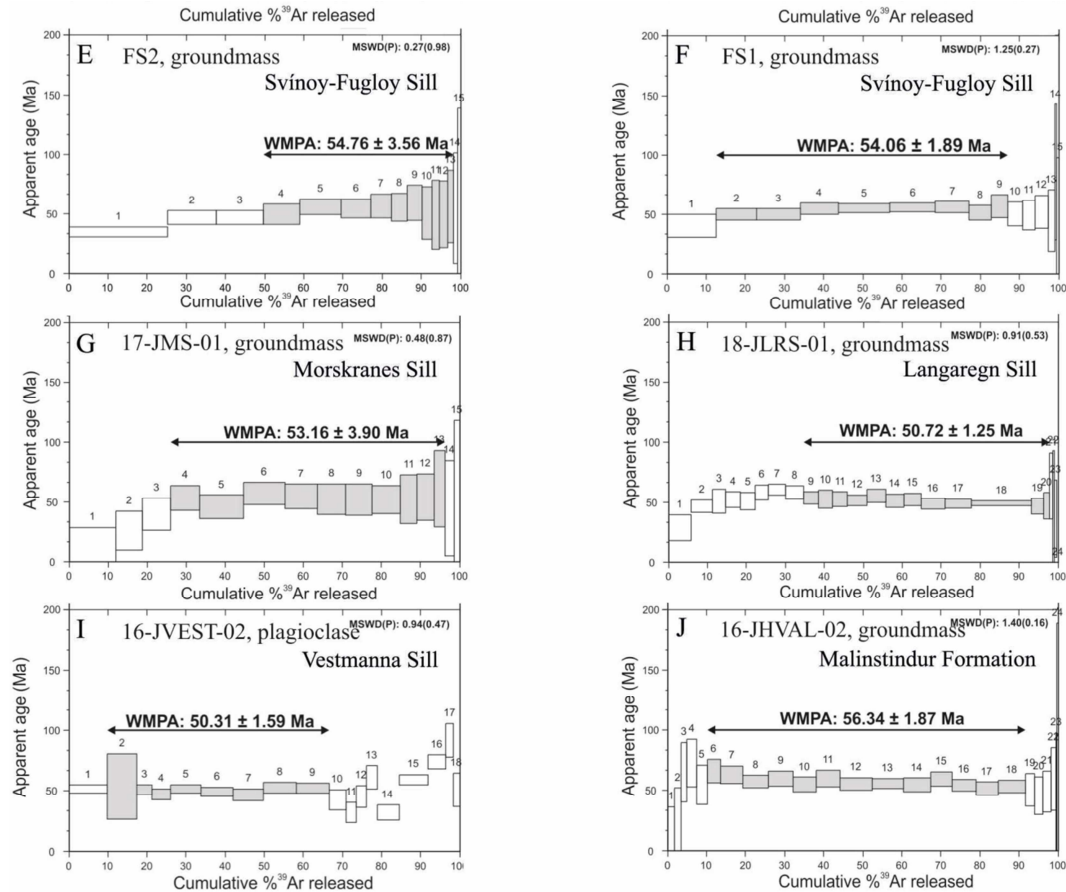
Ages are reported relative to Sanidine standard TRC ( $28.619 \pm 0.036$  Ma [22]). n = number of heating steps used/total. Age, weighted by the inverse of variance. MSWD, mean square of weighted deviations.  $\pm 1.96s$  refer to the statistical 95% confidence interval.

When it comes to the basaltic sills of the Faroe Islands, it was known on beforehand that they must be younger than the local Enni Formation at  $\sim 55.8$  Ma, which most of them intrude. The  $\pm$  uncertainties in measured ages for some of the dated material (Table 1), do in a few instances result in overlapping ages for analysed samples, which in theory could

weaken some of the arguments presented below. Associated diagrams, involving Cumulative %  $^{39}\text{Ar}$  released versus K/Ca and % Radiogenic  $^{40}\text{Ar}$  ratio plots in addition to isochron ( $^{39}\text{Ar}(k)/^{40}\text{Ar}(a+r)$  versus  $^{36}\text{Ar}(a)/^{40}\text{Ar}(a+r)$  ratios) diagrams, are illustrated in Electronic Supplement A, [24], Figure A and Figure B.







**Figure 2.** Age spectra for seven basaltic sills and one selected local lava flow of the Faroe Islands from Table 1. Individual plateau ages ( $\pm 1.96\sigma$ ), presented according to interpretations of individual steps versus cumulative %  $^{39}\text{Ar}$  release, are indicated on individual part figures. Individual incremental-heating steps (boxes), used for age determinations are indicated in grey colour. Associated K/Ca and % radiogenic  $^{40}\text{Ar}$  versus cumulative %  $^{39}\text{Ar}$  release diagrams are presented in electronic Supplement A [24]. (A) and (B) represent two samples of the High- $\text{TiO}_2$  Eysturoy Sill; (C) and (D) represent two samples of the low- $\text{TiO}_2$  Streymoy and Kvívík sills respectively; (E) and (F) represent two samples from the high- $\text{TiO}_2$  Svínoy-Fugloy Sill; (G) represents the intermediate- $\text{TiO}_2$  Morskranes Sill while (H) and (I) represent the high- $\text{TiO}_2$  Langaregn and Vestmanna sills. (J) represents bottom lava flows of the Malinstindur Formation.

The range in  $^{40}\text{Ar}/^{39}\text{Ar}$  ages determined for the sills of this study span from  $\sim 50.3$  Ma to  $\sim 55.5$  Ma, i. e. a total time interval of  $\sim 5.2$  million years (myr), while the age of the single local lava flow is  $\sim 56.34$  Ma (Table 1; Figure 2).

Combined, the Faroese sills formed at relatively irregular intervals (Figure 2). The Streymoy, Kvívík and Eysturoy sills, which amongst themselves belong to two distinct geochemical groups (the low- $\text{TiO}_2$  Streymoy/Kvívík sills and the high- $\text{TiO}_2$  Eysturoy/Sundini sills respectively), formed at 55.2 to 55.5 Ma (average  $\sim 55.35$  Ma); the High- $\text{TiO}_2$  Svínoy-Fugloy Sill developed at 54.1 to 54.8 Ma; the intermediate- $\text{TiO}_2$  Morskranes sill came into being at  $\sim 53.2$  Ma while the high- $\text{TiO}_2$  Langaregn and Vestmanna sills formed at 50.3 to 50.7 Ma.

Clear and systematic variations exist between sill sizes/volumes relative to their measured ages. The oldest local sills ( $\sim 55.35$  Ma on average) display the largest volumes whereas the slightly younger Svínoy-Fugloy Sill (at  $\sim 54.45$  Ma on average) is noticeably less bulky; the Morskranes Sill (at  $\sim 53.2$  Ma) in turn is smaller than the Svínoy-Fugloy Sill, while the Langaregn and Vestmanna sills (at  $\sim 50.5$  Ma on average) are considerably less voluminous than all other local sills [5, 10].

## 5. Discussion

### 5.1. Basic Remarks

Measured and recalculated ages representing Faroese lava formations fall well within age ranges measured for similar lava successions of other igneous regions of the NAIP such as W Greenland, E Greenland NW British Isles and sills of the Vøring Basin, offshore Norway [3, 4, 25–29, 31]. Ages recorded previously for lavas of the Faroese Malinstindur and age of the Enni formation measured in this contribution (Figure 4) straddle the proposed/estimated timeline of incipient ‘main’ opening phase of the North Atlantic at  $\sim 56$  Ma to 55.6 Ma [3] and likely formed in association with this momentous event. Interestingly, a number of relatively recent research and reviews on evolutionary tendencies of continental margins of the NAIP, have indicated somewhat diachronous and complex evolution patterns prior to and subsequent to the initiation of the proposed ‘main’ rifting event at around 55.6 Ma to 56 Ma [4, 28–33].

When it comes to the driving processes necessary to initiate and maintain tectonic activity associated with

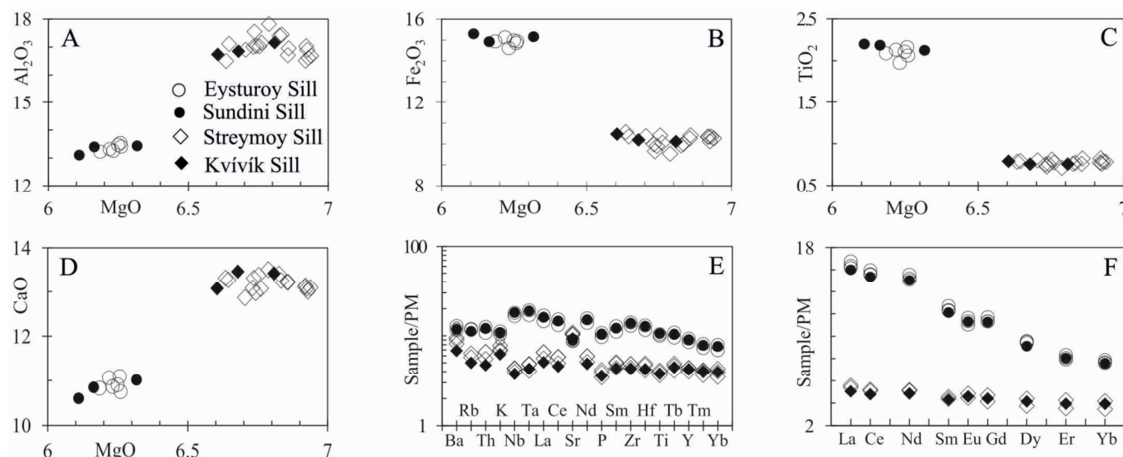
momentous events such as the opening of e. g. the N Atlantic and Labrador Sea – Baffin Bay areas during the Early Paleogene Period, some authors have invoked a “bottom-up” mechanism associated with a gigantic ascending mantle plume or perhaps a couple of plumes [26, 29, 34], while others have argued in favour of a “top-down” mechanism associated with ‘continental-drift’ and far-field extensional stresses [30, 35, 36]. In either case, extension and thinning of the crust/lithosphere must be invoked in order to explain decompression melting and magma transport in sub-vertical dyke systems in the proto Faroe Islands area and other NAIP regions prior to, simultaneously and subsequent to the main rifting event. Earlier studies on the FIBG have consistently pointed to the formation of the Malinstindur and Enni formations subsequent to a largely quiescent/hiatus period following deposition of the thick Beinissvørð Formation, during which only limited local volcanic activity took place: [13] and refs. therein).

### 5.2. Ages, Geochemistry and Spatial Distribution of Faroese Sills

The entire Faroese archipelago, currently exposed above sea level, only encompass an area of ~1400 km<sup>2</sup> out of the

supposed original ~120000 km<sup>2</sup> lava plateau [13]. Hence, tens or even hundreds of sills could in theory have been emplaced over a geographically wide area at various stages and periods of time during formation of the initial Faroese basaltic plateau, of which there exist no traces at the present time. Indeed, sill complexes have been reported for other parts of the NW European border too, including offshore Norway, the Rockall trough and Faroe-Shetland Basin. Altogether, the exposed parts of the Faroese sills extend for ~50 km in an ENE-WSW direction and ~20 km in a NNW-SSE direction. Low-TiO<sub>2</sub> and intermediate-TiO<sub>2</sub> sills extend farthest to the SSE, as compared to the bulk of the high-TiO<sub>2</sub> sills (Figure 1B). Hence, the high-TiO<sub>2</sub> varieties were probably closer to the initial axis of NE-Atlantic seafloor-spreading during their formation.

Most Faroese sills display slight mutual geochemical variations, but sill samples of the low-TiO<sub>2</sub> Streymoy-Kvívík sills and the high-TiO<sub>2</sub> Eysturoy-Sundini sills respectively, display identical mutual geochemistry/petrography and close spatial relationships [5, 11] (Figure 1B; Figure 3). The Streymoy and Eysturoy sills are by far the most voluminous of the Faroese sills and even more so, when combined with the Kvívík and Sundini sills respectively.



**Figure 3.** The diagrams (A – F) illustrate the close geochemical similarities between the Streymoy and Kvívík sills and between the Eysturoy and Sundini sills respectively (Data from: [5, 11]. Trace elements and REE are normalised to primitive mantle (PM) values of McDonough and Sun [37].

Hence, it is hardly surprising that the Streymoy and Kvívík sills display roughly similar <sup>40</sup>Ar/<sup>39</sup>Ar ages with an average of ~55.35 Ma (Table 1; Figure 2C; Figure 2D). Similarly, it is overwhelmingly likely that the high-TiO<sub>2</sub> Eysturoy Sill, which likewise display average <sup>40</sup>Ar/<sup>39</sup>Ar ages of ~55.35 Ma, formed contemporaneously to the Sundini Sill, considering their intimate geochemical and spatial relationship (Figure 3B).

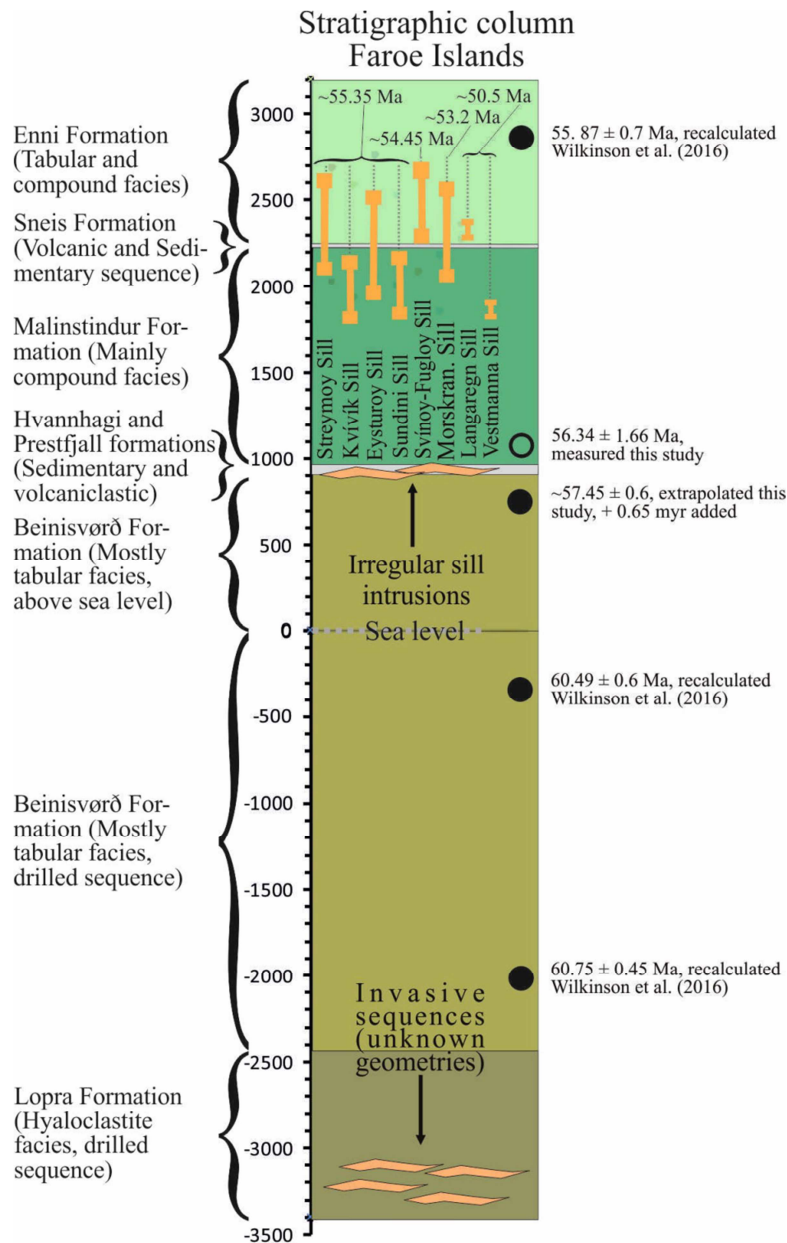
It is well established amongst petrologists that high-TiO<sub>2</sub> basaltic magmas form at relatively small-degree melting of mantle material, while their low-TiO<sub>2</sub> counterparts develop from larger degrees of mantle melting. With respect to the large contemporaneous Faroese high-TiO<sub>2</sub> Eysturoy and Sundini sills, in addition to the low-TiO<sub>2</sub> Streymoy and Kvívík sills (average age ~55.35 Ma), it is worth noting that

the average distance between these two contrasting sill groups is only ~13 km and the shortest distance a mere ~6 km (Figure 1B). Previous research have suggested that depths of the LAB define general mantle depths, at which high-TiO<sub>2</sub> melts presumably form at relatively great depths/pressures relative to those of their low-TiO<sub>2</sub> counterparts [36]. LAP depths are generally considered to increase gradually away from active rift axes. Accordingly, Faroese high-TiO<sub>2</sub> groups should be expected to have formed at somewhat greater mantle depths relative to their local low-TiO<sub>2</sub> counterparts, provided that the local LAB displayed typical seafloor-spreading architecture. If the actual low-TiO<sub>2</sub> sill group indeed formed at typical LAB configurations/depths, their magmas would have travelled for somewhat longer lateral distances compared to most of their

contemporaneous high-TiO<sub>2</sub> counterparts, which were intruded closer to the then rifting zone farther to the NW. Alternatively, melting within geographically restricted and moderately heterogeneous asthenospheric and/or lithospheric mantle sources, which were variously affected by previous metasomatic/igneous events, generated the Faroese high-

TiO<sub>2</sub> and low-TiO<sub>2</sub> sill groups [5, 11].

Sill ages versus volumes collectively point to a decrease in local melt production during formation of successively younger Faroese sill intrusions (Svínoy-Fugloy Sill at ~54.45 Ma; Morskranes Sill at ~53.2 Ma; Langaregn and Vestmanna sills at ~50.5 Ma).



**Figure 4.**  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometric ages of Faroese sills and selected lava formations/sequences are shown in relation to a stratigraphic column representing the basaltic rocks of the Faroe Islands (modified from Figure 1). Measured sill ages (average values) and age of the local Malinstindur Formation are from this study as presented in TABLE 1 and Figure 2. Original ages on Faroese lava formations from Storey et al. [9] and using  $^{40}\text{K}$  decay constant from Renne et al. [38], as shown in brackets to the right of the stratigraphic column, have been replaced by recalculated ages from the compilation of Wilkinson et al. [3] with correction according to Kuiper et al. [39] and using  $^{40}\text{K}$  decay constant of Min et al. [40]. Age for top sections of the Beinisvørð Formation is extrapolated (~0.65 myr added) based on other recalculated data for the actual region by Wilkinson et al. [3].

### 5.3. Geochronology of Faroese Sills Compared to Local Host Lavas

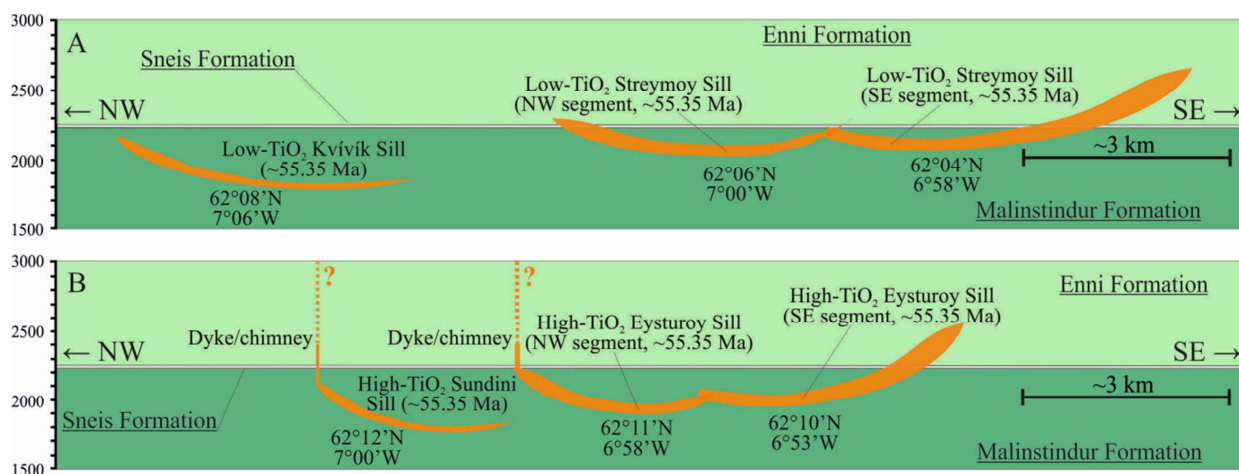
In the actual study we utilise a decay constant for  $^{40}\text{K}$  after

Renne et al. [22]. Ages obtained in this study have been contrasted with relatively recent geochronological data on other parts of the local lava pile (originally from Storey et al. [9], which employed  $^{40}\text{K}$  decay constant of Renne et al. [38],

but where we make use of recalculated ages by Wilkinson *et al.* [3] instead. Recalculated ages in the compilation of Wilkinson *et al.* [3] tend to be around 0.65 myr older than the original ones [9]. Hence, the extrapolated value shown for the top of the Beinissvørð Formation in Figure 4 result from the addition of ~0.65 myr to the original value of [9]. The radiometric  $^{40}\text{Ar}/^{39}\text{Ar}$  age of ~56.34 Ma obtained in this study for the lowermost parts of the Malinstindur Formation would appear to be a realistic one, especially when compared to the recalculated ages for the top of the Beinissvørð Formation at ~57.4 Ma and for the upper parts of the Enni Formation at ~55.8 Ma respectively (Figure 4). If these ages are indeed reliable, i. e. if their measured uncertainties of 1.66 and 0.6 myr respectively are considered to be mostly theoretical, they would indicate a hiatus period, during which the sedimentary and partly volcanoclastic Hvannhagi and Prestfjall formations were deposited, which could have lasted for up to ~1.1 myr. The entire nature of magmatism in the FIBG region appear to have changed radically from the presumed cessation of surface magmatism at ~55.8 Ma to the onset of sill emplacement at ~55.5 Ma, which could have been triggered by e. g. reorientations or changes of magnitudes of regional principal stress axes (i. e. previous sub-sections). The Faroese region could potentially have experienced another

shorter hiatus period of ~0.3 myr, lasting from cessation of local extrusive activity at ~55.8 Ma until the onset of local intrusive activity at ~55.5 Ma at the earliest. However, overlapping ages from theoretical uncertainties in measured ages renders it somewhat daring to argue in favour of a hiatus period of exactly ~0.3 myr. Also, the minimum thickness of the Enni Formation, which has commonly been estimated at >900 m (~55.8 Ma, Compilation of [3]), could in theory have been several hundred metres thicker than that initially: [13] and refs. therein.

While the current preserved rims of Faroese sills are supposed to indicate their original maximum stratigraphic heights fairly accurate (top of orange bars in Figure 4), the exposed and eroded bottom sections of some of these same sills could initially have extended to somewhat lower stratigraphic levels than is indicated with the orange bars on the same figure. It is not very likely that timing of sill emplacements did significantly govern the crustal depths where these ultimately came to rest, as there are no clear correlation between measured sill ages and their relative positions with respect to geography and stratigraphy. There exist however, noticeable degrees of overlap between some of the Faroese sills with respect to their positions/levels in the local stratigraphy (Figure 1B; Figure 4).



**Figure 5.** The basic drawings illustrate the systematic changes in intrusion depths within two Faroese sill systems (also illustrated in Figure 1 and Figure 4), where individual sills and sill segments within each group are of identical ages. Numbers on Y axes refer to the stratigraphic columns shown in Figure 1 and in Figure 4. Views are orthogonal to longest sill axes, as these typically appear as elliptical bodies in map view. Average latitudes and longitudes for central sill sections are indicated below each intrusion. (A) Longest and shortest axes of these low-TiO<sub>2</sub> elliptical sills measure: Streymoy Sill, SE segment, ~5.5 x ~3.5 km; Streymoy Sill, NW segment, ~4.5 x ~2.5 km; Kvívik Sill ~4.5 x ~2.5 km. The sill segments of the Streymoy Sill are connected/welded at their NW and SE extremes respectively, while the shortest (preserved) distance to the Kvívik Sill from the NW segment of the Streymoy Sill is around 2 km in a NW direction. (B) Longest and shortest axes of the high-TiO<sub>2</sub> elliptical sills measure: Eysturoy Sill, SE segment, ~4 x ~3 km; Eysturoy Sill, NW segment, ~3 x ~3 km; Sundini Sill ~3 x ~3 km. Segments of the Eysturoy Sill are welded at their NW and SE extremes respectively, while the SE parts of the Sundini Sill reaches the NW extreme of the Eysturoy Sill at a relatively lower altitude. Two small sub-vertical dykes/chimneys emanate from their highest N and NW points respectively.

Individual intrusions defining the two contemporaneous Faroese high-TiO<sub>2</sub> and low-TiO<sub>2</sub> sill groups, were initially emplaced at different stratigraphic levels, where intrusion depths increased towards the NW (Figure 4, Figure 5A, Figure 5B). Likewise, if the ~50.5 Ma Langaregn and the Vestmanna Sills are considered to represent a distinct magmatic event, they too display a general increase in intrusion depths towards the NW (Figure 4). It is noticeable that volumes for all these individual sills and segments

decrease systematically from the SE towards the NW. None of the sills presented in Figure 5 display any clear differences with respect to their geographical/lateral extent. The sills and segments shown in Figure 5 also become successively thinner and less developed from the SE towards the NW. For instance, the SE segment of the Streymoy Sill is 35 – 45 m thick; the NW segment of the same sill is 10 – 30 m thick with the thinnest parts occurring at its preserved basal section towards the WSW, while the Kvívik Sill thickens from 0.5 –



1 m at its basal WSW sections to 8 – 10 m at its NE rims. These trends are more or less repeated in the Eysturoy and Sundini sills where the SE segment of the former is 45 – 55 m thick, its NW segment is 10 – 20 m thick and thinning towards its basal WSW sections, while the Sundini Sill is ~0.5 – 1 m thick at its WSW basal sections and reach a maximum thickness of 6 – 8 m at its NE rims.

The observed systematic increase in intrusion/stratigraphic levels and decrease in sill sizes/volumes towards the NW for segments of the Streymoy and Eysturoy sills and the associated Kvívík and Sundini sills respectively (Figure 5), could in theory have arisen in response to one or more of the following scenarios: 1) Their overburden [s] (i. e. the Enni Formation) systematically decreased in thickness towards the NW at the time of their emplacement, thus resulting in the sills being initiated at successively greater stratigraphic depths towards the NW relative to e. g. the thin Sneis Formation; 2) Intrusion of sills at increasingly deeper crustal levels towards the NW prevented the sills from being fully developed/inflated due to impediment from an ever increasing overburden load; 3) Volumes of available magmas, which gave rise to these two sill systems, decreased noticeably from the SE towards the NW thus resulting in intrusions becoming sequentially less developed towards the NW due to magma starvation; 4) Successively decreasing sill sizes/volumes, coupled with a general decrease in their states of development towards the NW, could in theory result from their initial magmas being channelled directly through the thicker uppermost parts of these still immature intrusions, thus feeding local surface magmatism. However, the very restricted lateral extents of preserved dykes/chimneys on top of the Eysturoy and Sundini sills (for instance) do not suggest abundant magma transport via these intrusions (Fig.5B).

#### 5.4. Pre- to Syn-Rift Faroe Islands Versus Neighbouring NAIP Regions

As remarked in previous sub-sections, the bulk of the igneous products associated with the evolution of the NAIP were emplaced during the Early-Middle Paleogene Period. NAIP rocks, emplaced in W Greenland at ~64 Ma to ~28 Ma, were situated ≥1250 km from the then embryonic FIBG in the Early Paleogene Period and had a somewhat complex evolution pattern associated with local extension/rift trajectories [29], while the bulk of the British Tertiary Igneous Province (emplaced at ~64 Ma to ~42 Ma) developed along an extension/rifting trajectory situated a noticeable distance to the south and southeast of the then FIBG area: e. g. [3] and refs. therein. Hence, these two NAIP regions may not be ideally suited for direct comparison with the contemporaneous FIBG area. However, NAIP regions such as central E Greenland in particular and perhaps also to some degree the N Faroe-Shetland Basin – Møre Marginal High area, all of which occur at latitudes roughly matching those of the FIBG area, appear to be better suited for comparisons with the FIBG when it comes to tectonic and magmatic evolution shortly prior to the onset of the local hiatus period at ~57.5 Ma. Moreover, coastal areas of central

E Greenland, hosting the bulk of the NAIP products of that region, display basement thicknesses akin to those determined for the Faroe Islands previously [41, 42].

A recent study on offshore basaltic lavas of the N Faroe-Shetland Basin – Møre Marginal High area (including Lagavulin), which presumably were emplaced shortly prior to and perhaps contemporaneous to the inferred main N Atlantic rifting event, tentatively pointed to an origin from multiple local eruption sites and local sources in response to a localised rifting event [43]. These authors argued in favour of initial high-TiO<sub>2</sub> magma formation at relatively great mantle depths within the local area, as opposed to generation of their low-TiO<sub>2</sub> counterparts in response to melting at shallower mantle levels, the latter of which were presumably relatively more affected by regional extension/rifting.

It is noticeable that whilst the Faroese area apparently experienced a mostly relatively quiescent/hiatus period with only limited volcanism at ~57.45 Ma to ~56.35 Ma (Uncertainties considered to be mostly theoretical), noticeable quantities of broadly contemporaneous igneous products were deposited in the Blosseville Kyst area, central E Greenland in the same period of time. Incidentally, parts of the uppermost Faroese lava formations and parts of exposed E Greenland lavas have been correlated earlier based mainly on chemostratigraphic similarities [16, 44, 45]. In accordance with available <sup>40</sup>Ar/<sup>39</sup>Ar ages, pertinent examples include: Milne Land Fm ~56.8 Ma; Nansen Fjord Fm ~58.4 Ma to ~57.5 Ma (i. e. 58.36 Ma MSWD); Sorgenfri Gletcher diabase/sill ~57.1 Ma; Tobias Dal, Upper Plateau Lava Series ~56.5 Ma: compilation of Wilkinson *et al.* [3] and refs. therein. Consequently, if we accept that there existed a general hiatus period within the Faroese area at ~57.45 Ma to 56.35 Ma (i. e. ± uncertainties are mostly theoretical), it is possible that overall stress regimes within these two neighbouring NAIP regions were somewhat dissimilar during that period of time. Here, ‘some’ extensional activity probably prevailed in parts of the central E Greenland area as opposed to a relatively quiet period without noticeable extensional activity in the contemporaneous FIBG area. Hence, these two regions could have been decoupled from one another tectonically during this period of time, or in any case were differently affected by contemporaneous tectonic activity.

Earlier studies have pointed to a possible compositional (chemostratigraphy) association between mostly high-TiO<sub>2</sub> basaltic volcanic sequences of central E Greenland (Rømer Fjord Fm and Skrænterne Fm) and the Faroe Islands (Enni Fm), all of which were presumably emplaced shortly prior to the onset of the NE Atlantic rifting [44,45]. Relatively recent high-precision zircon U-Pb geochronological data on the Skaergaard Intrusion of central E Greenland and on the associated Basistoppen Sill point to emplacement ages from ~56 Ma to ~55.85 Ma [46], while gabbros belonging to the oldest part of the neighbouring Kærven Intrusive Complex (gabbro) have yielded <sup>40</sup>Ar/<sup>39</sup>Ar ages of around 55.8 Ma: compilation of Wilkinson *et al.* [3] and refs. therein. Hence, intrusive activity apparently took place in central E

Greenland during the same period of time in which the upper lava sections of the Faroese Enni Formation were emplaced and around 0.3-0.5 myr prior to the onset of intrusive activity in earnest within the Faroese area at ~55.5 Ma (Emplacement of the oldest sills; Figure 4).

Interestingly,  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometric ages on central E Greenland (Blosseville Kyst) lavas of the Rømer Fjord Fm and the Skrænterne Fm, which are exposed at higher stratigraphic levels relative to the Skaergaard Intrusion, have yielded ages of ~55.84 Ma (MSWD) and ~55.69 Ma (MSWD) respectively [3]. Accordingly, both surface and intrusive magmatism within some parts of central E Greenland (notably the Kangerlussuaq Fjord area) took place during the same relatively short time span, in which lavas of the relatively young Faroese Enni and Malinstindur formations were emplaced. If dykes/chimneys emanating from tops of the NW parts of the younger Eysturoy Sill and from the Sundini Sill (Figure 5B) indeed fed contemporaneous local surface magmatism, it must have been on a negligible/moderate scale, considering their restricted lateral extents.

Alternative causes for the recorded mismatch in igneous activity for central E Greenland versus the FIBG respectively at ~56 Ma to ~55.6 Ma (Merely extrusive activity in the Faroese area, as opposed to both intrusive and extrusive activity in the contemporaneous E Greenland area) could perhaps include: 1) The  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometric dating method used in the geochronological studies listed above could be less accurate than the zircon U-Pb dating system in general due to inaccurate  $^{40}\text{K}$  decay constants for instance [47]. 2) As the oldest Early Paleogene intrusions of central E Greenland were emplaced partly in top layers of the local basement and partly in the bottom layers of local lava formations, contemporaneous hitherto undetected Faroese intrusive equivalents could in theory reside in none-exposed parts of e. g. the Lopra or Beinisdvørð formations. 3) As the current extent of exposed/preserved onshore FIBG lavas represent only minor parts of the initial local lava plateau, intrusions with ages roughly similar to those of the older ones of central E Greenland could in theory have existed initially within parts of the FIBG, which were later removed by erosion (its NE fringes for instance). However, if the actual recorded/measured data and observations for these two igneous regions do indeed correctly represent igneous events in these two regions at ~56 Ma to ~55.6 Ma, it would appear that the central E Greenland area was affected by short-lived and perhaps repeated fluctuations in sizes and orientations of local principal stress axes shortly prior to the main NE Atlantic rifting event. Steady and uniform extensional forces could have prevailed within the FIBG until ~55.6 Ma, as indicated by extrusive activities. Hence, the E Greenland and Faroese regions could have been partly or wholly decoupled tectonically from one another during the time span leading up to the proposed main rifting event at ~56 Ma to ~55.6 Ma. Causative events with the potential to explain the recorded magmatic/tectonic differences between these two contemporaneous NAIP regions, could have involved the onset of northwards drifting of Greenland relative to the N

American and NW European plate margins, which occurred roughly contemporaneously [48].

### 5.5. Post-Rift Faroe Islands Versus Neighbouring Central E Greenland

It is clear from the text and data above that while presumed pre-rift to syn-rift igneous activity within the FIBG generally occurred as extrusive magmatism (~61 Ma to ~55.8 Ma), recorded local post-rift igneous activity chiefly occurred as intrusive magmatism (~55.5 Ma to ~50.5 Ma). Post-rift igneous activity in the then neighbouring central E Greenland region was of a more diverse nature, comprising both extrusive and intrusive magmatism [3]. Post-rift volcanic successions emplaced at ~49 Ma to ~44 Ma have been recorded for Kap Dalton, central E Greenland (Blosseville Kyst), along with numerous other lava successions emplaced at ~55.5 Ma to ~53.4 Ma farther to the north along the NE Greenland coast [3]. Formation of the Kap Dalton lavas was probably triggered by a regional rifting event [49]. Post-rift intrusive activity in central E Greenland include the Kærven Intrusive Complex (alkali granite) emplaced at 53.5 Ma to 53.3 Ma (U-Pb ages of other intrusions in the Kialineq District suggest emplacement at 37.9 Ma to 36.9 Ma [50]); intrusions of the Agtertia Fjord lineament and islands intruded at 50.3 Ma to 47.9 Ma; intrusions of the Kangerlussuaq Fjord lineament emplaced at 51.5 Ma to 46.3 Ma and intrusions of the Wiedeman Fjord – Kronborg Gletcher lineament intruded at 52.5 Ma to 37.3 Ma (These are  $^{40}\text{Ar}/^{39}\text{Ar}$  ages, extrapolated from Table 1 in Tegner *et al.* [25] by the addition of around 0.7 myr to their tabulated values, which would be in accordance with age recalculations in the compilation of Wilkinson *et al.* [3]). Hence, the bulk of the post-rift intrusive activity in central E Greenland took place at intervals in the period from ~53.5 Ma to ~37 Ma. Post-breakup intrusive activity in the central E Greenland area have been attributed to re-configuration of NE Atlantic spreading ridges due to failed continental rift systems in the Kangerlussuaq Fjord region [25].

Extrusive activity along the E Greenland margin in a time span from ~55.2 to ~55.5 Ma, i. e. broadly contemporaneous to intrusions of the five oldest and largest Faroese basaltic sills, has only been recorded for lavas of NE Greenland [3]. With respect to the contemporaneous central E Greenland region, the lack of any igneous products displaying radiometric ages of ~55.6 Ma to ~53.5 Ma seem to suggest that this particular area could have experienced a relatively quiescent period during this period of time, i. e. prior to the formation of the oldest parts of Kærven Intrusive Complex [50]. Accordingly, renewed intrusive activity in central E Greenland, which lasted for more than 16 myr altogether, began in earnest broadly contemporaneous to the final stages of intrusive activity in the then neighbouring Faroe Islands. Thus, it appears reasonable to assume that the Faroese and central E Greenland regions were somewhat decoupled from one another tectonically and magmatically during the period of time that followed the onset of the main rifting event in the NE Atlantic. While regional rifting events probably governed the subsequent igneous

activity in central E Greenland [25, 49], the FIBG area most likely gradually drifted away towards the ESE from axes/zones of active rifting and magmatism in the time span from ~55.5 Ma to ~50.5 Ma and later on as well, as suggested by the diminishing local igneous activity.

### ***5.6. Faroe Islands and Seafloor-Spreading in the Early Paleogene Period***

The arguments from previous sub-sections seem to suggest that the evolution of the FIBG area during relatively late stages of local Early Paleogene magmatism (i. e. from ~56.4 Ma to ~50.5 Ma), probably occurred in response to regional tectonic events related to the ultimate rifting of the NE Atlantic, which could have been somewhat different when compared to those affecting the then neighbouring regions of the north Faroe-Shetland Basin and the central E Greenland area. With respect to earlier igneous activity in these parts of the then embryonic N Atlantic (according to previous sub-sections), it appears that central E Greenland experienced extrusive and major intrusive activity, while the Faroe Islands experienced a more quiet/hiatu period at ~57.4 Ma - ~56.3 Ma (If  $\pm$  uncertainties are considered mostly theoretical.). Merely extrusive activity took place in the Faroe Islands at ~56 Ma - ~55.6 Ma ( $\pm$  uncertainties, Table 1.), while contemporaneous central E Greenland potentially experienced a brief hiatus period. While noticeable intrusive activity took place in the Faroe Islands at a relatively restricted period of time from ~55.5 Ma to ~50.5 Ma, intrusive activity commenced and went on for some considerable time (~53.5 Ma - ~37 Ma) in central E Greenland. These apparent differences in igneous activities seem to point to two somewhat tectonically decoupled regions, which perhaps experienced some kind of alternating magmatism during the time period from ~57.4 Ma to ~50.5 Ma? The occurrences of a number of Early/Mid Paleogene regional rifting centres, as suggested for central E Greenland earlier [25, 49] and the northern Faroe-Shetland Basin [43], would be in accordance with recent research on the NE Greenland region, where several isolated seafloor spreading events presumably triggered local magmatism and the subsequent main NE Atlantic rifting event at these latitudes [31]. Hence, if one accepts that significant proportions of neighbouring NAIP regions formed in response to regional rifting events and that the central E Greenland and Faroese regions could have been tectonically decoupled subsequent to ~57.5 Ma, it does not appear unrealistic to ascribe the bulk of the magmatic pulses, which built up the Faroe Islands in the Early Paleogene Period (From ~57.5 Ma to ~50.5 Ma  $\pm$  uncertainties), to regional extension and local rifting events. In turn, these regional/local events probably developed/coalesced into a common main seafloor-spreading axis/zone themselves in the then embryonic N Atlantic.

General principles on melt production and effusion rates of e. g. basaltic lavas suggest that relatively slow effusion/intrusion rates (compound lava flows and/or smaller sills) may be associated with decompression melting at relatively slow extension/spreading rates whilst high (er)

effusion/intrusion rates (laterally extensive simple/tabular lava flows and/or voluminous sills) are indicative of fast (er) extension/spreading rates [51, 52]. Accordingly, the mostly compound-type lavas of the Malinstindur Formation [13] probably point to relatively sluggish extension/spreading rates during its formation (< ~56.35 Ma). In addition to compound flows, the common occurrences of thick simple/tabular lavas in the Enni Formation (+ Sneis Fm.), indicate alternating periods with moderate versus greater rates of melting and extension/spreading towards the end of local surface magmatism in the Faroese area at around ~55.8 Ma (Table 1, Figure 4). Geochemical similarities between lavas of the Skräenterne and Rømer Fjord formations of central E Greenland with those of e. g. the contemporaneous Faroese Enni Formation [16, 44, 45] could in theory well reflect similarities in extension rates within their respective mantle sources during melting, thus resulting in broadly similar igneous products.

Recent research on the north Faroe-Shetland Basin region identified an initial line of continental-breakup located ~50 km to the NNW off the Faroe Islands in the Early Paleogene Period [43]. Accordingly, the oldest Faroese sills (The low-TiO<sub>2</sub> Streymoy and Kvívík sills; the high-TiO<sub>2</sub> Eysturoy and Sundini sills) were emplaced on average ~75 km from the incipient seafloor spreading axis. If an average spreading rate of ~0.013 m per year for the last ~56 myr is accepted for the eastern fringes of the evolving N Atlantic rift system, the distances to the active rift system of the younger Faroese sills during their emplacement were: For the Svinoy-Fugloy Sill (average age ~54.4 Ma) the distance was around 89.3 km; for the Morskranes Sill (age ~53.2 Ma) the distance was approximately 104.9 km and the Vestmanna and Langaregn sills (average age ~50.5 Ma) were on average emplaced 140 km from the then active rifting axis. Consequently, the observed decrease in sill sizes/volumes with decreasing ages seem to reflect a decrease in local igneous activity with increasing distances to the active N Atlantic rift system, i. e. crustal extension rates within the actual region apparently abated gradually and finally came to a more or less standstill in the matter of ~5 to 5.3 myr following the initial breakup. In this context it is worth noticing, that an absence of mutual alignments between dykes that initially fed the Faroese sills and between dykes/chimneys emanating from a few of these seemingly point to a near-absence of extension-related stress fields in the uppermost crust during their intrusive phases. The sills themselves however, did generate compression-related stresses in their host basalts upon their vigorous intrusions and subsequent inflations/evolvments.

### ***5.7. Potential Depths of Origin for Early Paleogene Faroese Mafic Melts***

When it comes to basaltic lavas and intrusive rocks of various ages building up the various regions of the NAIP, these are customarily grouped into high-TiO<sub>2</sub> versus low-TiO<sub>2</sub> basaltic compositions. The former are commonly interpreted to have formed by low-degree melting of suitable mantle materials at noticeable depths (I. e. at relatively high pressure), while the

latter are often interpreted to have formed by larger degrees of mantle melting at relatively shallower mantle depths (i. e. at relatively low pressure). Recent studies on petrogenetic evolutions of Faroese basaltic rock suites and of similar rock types the NW European margin, employed  $\text{TiO}_2$  compositions in order to distinguish between formation of basaltic magmas at deep versus shallower mantle levels [8, 43, 45]. These authors infer a lithosphere base that was more or less smooth with relatively continuous and gradual transitions between thick and thinner lithosphere, following its extension and stretching. In reality however, the LAB, the depth of which may be important for the extent of mantle melting to produce basaltic magmas [36], could in reality vary noticeably over relatively short geographical distances in some igneous regions, depending on their previous tectonic histories [30, 42, 53]. In the context of high- $\text{TiO}_2$  versus low- $\text{TiO}_2$  compositions in basaltic magmas, it

is pertinent to note that  $\text{TiO}_2$  contents in such magmas are not particularly sensitive to pressure during melting, but rely chiefly on the degrees of melting of suitable sources, where  $\text{TiO}_2$  contents decrease with increasing degrees of melting irrespective of ambient pressure conditions [54, 55]. Also,  $\text{TiO}_2$  contents in basaltic magmas remain relatively stable during moderate percentages of fractional crystallisation of e.g. plagioclase and pyroxenes from these [11]. Source fertility and content of fluids in actual mantle sources, in addition to a ready supply of heat so as to increase local temperatures govern overall melting percentages (Table 2). In turn, temperatures required to reach some local solidus (TS) or temperatures in excess of the local solidus (TE) can be gained by either heat supply from lower local stratigraphic levels at fixed pressures or by local adiabatic upwelling so as to initiate and/or maintain local decompression melting [36].

**Table 2.** Changes in solidus temperatures, melt percentages and major element compositions as functions of changes in physical conditions during formation of basaltic magmas by mantle melting.

|                           | <sup>a, b</sup> Increasing fertility<br>(basaltic material<br>added?) | <sup>c; d; e; f</sup> Increasing<br>temperature (fixed<br>pressure) | <sup>a; e; f; g</sup> Increasing<br>pressure (fixed<br>temperature) | <sup>b; f; g; h</sup> Increasing % melting<br>(fixed temp. and press.) | <sup>h; i</sup> Increasing fluid/ $\text{H}_2\text{O}$<br>content<br>(Metasomatism?) |
|---------------------------|-----------------------------------------------------------------------|---------------------------------------------------------------------|---------------------------------------------------------------------|------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| Solidus                   | Decreasing $P_0$                                                      |                                                                     | Increasing $P_0$                                                    |                                                                        | Decreasing $P_0$                                                                     |
| Melt %                    | Increasing                                                            | Increasing                                                          | Decreasing                                                          |                                                                        | Increasing                                                                           |
| $\text{SiO}_2$            |                                                                       | <sup>j</sup> Decreasing -<br><sup>k</sup> Increasing                | Decreasing                                                          | <sup>l</sup> Decreasing -<br><sup>m</sup> Increasing                   |                                                                                      |
| $\text{Al}_2\text{O}_3$   |                                                                       | decreasing                                                          |                                                                     | Decreasing                                                             | decreasing                                                                           |
| $\text{FeO}_{\text{tot}}$ | Increasing                                                            | Increasing                                                          | Increasing                                                          | Increasing                                                             | Increasing                                                                           |
| $\text{MgO}$              |                                                                       | Increasing                                                          |                                                                     | Increasing                                                             | Increasing                                                                           |
| $\text{CaO}$              |                                                                       | <sup>j</sup> Increasing -<br><sup>k</sup> Decreasing                |                                                                     | <sup>l</sup> Increasing -<br><sup>m</sup> Decreasing                   |                                                                                      |
| $\text{Na}_2\text{O}$     |                                                                       | Decreasing                                                          |                                                                     | Decreasing                                                             |                                                                                      |
| $\text{TiO}_2$            |                                                                       | Decreasing                                                          | Slight increase                                                     | Decreasing                                                             |                                                                                      |

Superscript letters from a to i point to studies of: a[56]; b[57]; c[58]; d[59]; e[60]; f[54, 55]; g[61]; h[62]; i[63]. jValid at temperatures below  $\sim 1350^\circ\text{C}$ ; kValid at temperatures above  $\sim 1350^\circ\text{C}$ ; lValid at melting percentages lower than  $\sim 15\%$ ; mValid at melting percentages larger than  $\sim 15\%$ .  $P_0$  refer to pressure (GPa) at solidus.

A relatively wide span of melting percentages of slightly heterogeneous mantle sources have the potential to produce basaltic magmas of variable  $\text{TiO}_2$  compositions, where  $\sim 4.5\%$  to  $\sim 7.5\%$  and  $\sim 16\%$  to  $\sim 21\%$  mantle melting of variously metasomatised or enriched lherzolitic sources would result in high- $\text{TiO}_2$  and low- $\text{TiO}_2$  basaltic magmas respectively [11]. If high- $\text{TiO}_2$  basaltic magmas in general are derived from melting at relatively fixed high pressures and  $< \sim 5\%$  mantle melting: [11, 20] and refs. therein, a slowly ascending vertical column of mantle sources of around 50 kilometres and covering a considerable geographical extent would be required in order to produce the  $\sim 2.5$  km high- $\text{TiO}_2$  main/middle section of the Beinivörð Formation, as reported previously [13]. Obviously, substantial additional mantle melting would be required in order to produce the remaining high- $\text{TiO}_2$  (and low- $\text{TiO}_2$ ) basaltic rocks of the FIBG.

With respect to geochemical ‘evidences’ on formation of basaltic melts that display ‘garnet signature’, most often interpreted to have formed at deep mantle levels by melting within the garnet-lherzolite stability field, recent research suggests that pooled and near-fractionated melts of compositionally and thermally variable peridotites in the

spinel-lherzolite and plagioclase-lherzolite stability fields commonly display similar highly variable trace element and isotope garnet signatures [64]. Mantle sources from a number of central European localities, which underwent previous rifting/extension events, commonly contain compositionally variable sub-continental lithospheric mantle (SCLM) xenoliths that in turn are intensely metasomatised by alkali or silica-saturated/oversaturated basaltic melts, which formed by low-percentage melting within the underlying asthenospheric mantle [65, 66].

Therefore, upper parts of the asthenosphere and lower parts of the SCLM in any areas, previously exposed to extension/rifting and/or subduction-related processes, could have been pervasively laced with comparable metasomatic agents. Hence, it may be envisaged that intensely metasomatised mantle zones/regions could possess generally increased fertility, in addition to noticeable lower average/overall solidus temperatures, when compared to those of other more or less pristine mantle zones/regions. Extension across ancient suture zones, which are linked to previous constructive and/or destructive plate margins, was commonplace during formation of the NAIP and is thought to

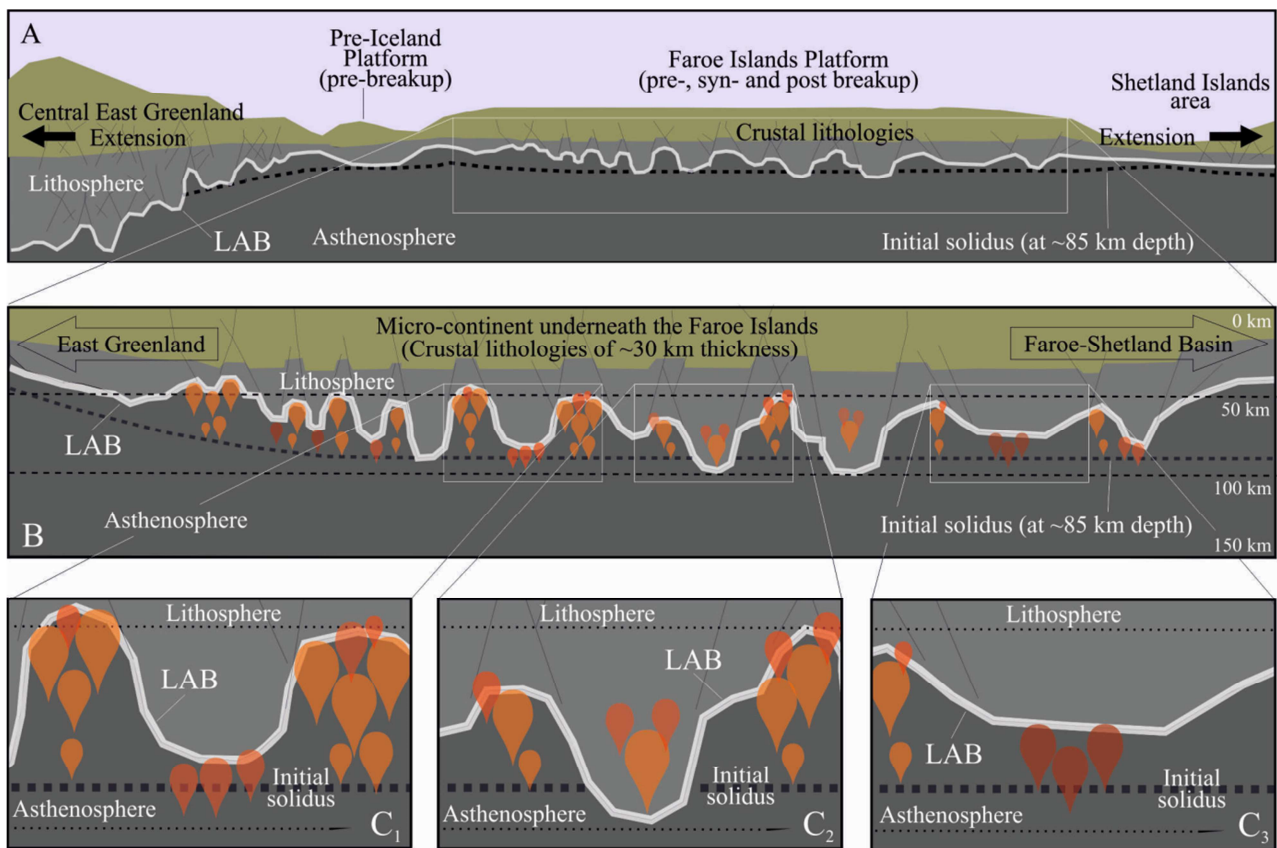


have had the potential of eroding lithospheric material from lower SCLM levels before ultimately redistributing it to the underlying asthenosphere [67]. Hence, when reflecting on the text discussed in this sub-section, it seems reasonable to expect that compositionally heterogeneous and fertile mantle zones within the NAIP existed adjacent to older suture zones, which previously experienced relatively pervasive igneous-related metasomatism and repositioning of SCLM materials. In turn, such enriched zones could have served as nucleus/seeds that triggered and generously maintained rifting and mantle melting within parts of the NAIP in the past, in preference to rifting/magmatism at/in neighbouring less affected mantle regions. Regarding the production of high-TiO<sub>2</sub> basaltic magmas derived from relatively deep-seated NAIP mantle sources, a scenario also involving melting at shallower mantle levels of sources comprising metasomatised SCLM and/or asthenospheric materials, which in turn exhibit noticeably decreased solidus temperatures and markedly increased fertility, offers an

appealing alternative explanation on formation of such magmas. In addition, the potential issue with garnet signatures may require more than a single explanation [64].

### 5.8. Early Paleogene Faroese Magmas and Lithosphere Configuration

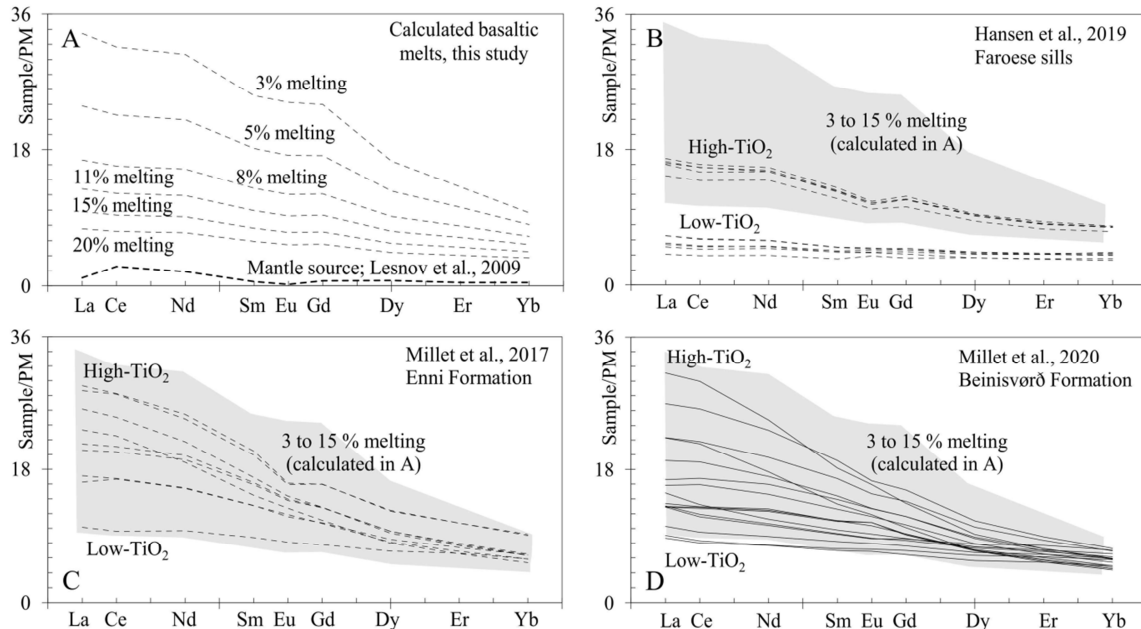
With respect to basaltic rocks of the Faroe Islands, high-TiO<sub>2</sub> and low-TiO<sub>2</sub> lavas occur as intimately associated and alternating layers in numerous localities [8, 13, 45, 68], thus indicating a direct spatial and temporal relationship, i. e. in broad concurrence with the characteristics displayed by the four oldest Faroese sills [5, 11]. In order to properly constrain the general petrogenetic history of basaltic rocks like those of the Faroe Islands by means of their TiO<sub>2</sub> contents for instance, it would be advantageous to address mantle architectures as related to geography, which have the potential to noticeably influence geochemical compositions of basaltic magmas in general.



**Figure 6.** Profiles indicating idealised lithosphere-asthenosphere boundaries (LAB) in the E. Greenland, Iceland, Faroe Islands and Shetland Islands regions in the Early Paleogene Period (modified general LAB geometries from an earlier study [53]). Inverted reddish droplets indicate low-percentage high-TiO<sub>2</sub> melts, vine-red droplets indicate moderate-percentage intermediate-TiO<sub>2</sub> melts, while inverted orange droplets point to relatively large-percentage low-TiO<sub>2</sub> melts. (A) The entire proto Faroe Islands area was affected by the extension between E Greenland and the NW European margin in the Early Paleogene Period. (B) Extension/stretching across the Faroe Islands Platform in the Early Paleogene Period triggered widespread decompression melting at mantle levels between solidus and the LAB, thus leading to the formation of high-TiO<sub>2</sub> and low-TiO<sub>2</sub> magmas. (C<sub>1</sub>) The lid effect could have resulted in the formation of low-percentage high-TiO<sub>2</sub> melts at relatively deep mantle levels and higher-percentage low-TiO<sub>2</sub> melts at shallower mantle levels. Adiabatic ascent of noticeable quantities of low-TiO<sub>2</sub> magmas could have triggered low-percentage melting of particularly fertile surrounding mantle materials to produce additional low-percentage high-TiO<sub>2</sub> melts at relatively shallow levels. In addition, one would expect a noticeable spread in TiO<sub>2</sub> compositions within large individual batches of magmas. Production of some high-TiO<sub>2</sub> melt batches from low-percentage melting of ordinary mantle lherzolites at relative shallow levels may be envisaged too, where these melts segregated from their sources prior to any low-TiO<sub>2</sub> melt production from larger-percentage melting. (C<sub>2</sub>) Partly as in C., but with additional inferred melting in the sub-continental lithospheric mantle. (C<sub>3</sub>) Partly as in C., but also with the production of intermediate-TiO<sub>2</sub> melts from moderate-percentage melting at moderately deep mantle levels.

When it comes to lithosphere thicknesses and general LAB geometries in the North Atlantic area during the Early Paleogene Period, previous studies have pointed to the probable existence of ancient suture zones from previous tectonic events in literally all of the igneous regions of the NAIP, including the FIBG area [4, 5, 30, 32, 33, 67]. Consequently, it doesn't appear unreasonable to infer irregular LAB geometries, comparable to those presented by [53] for instance, for some of the igneous regions building up this LIP (Figure 6A and Figure 6B). Scenarios like those displayed in Figure 6 illustrate that mantle environments with uneven LAB geometries could have the potential to generate melts of various geochemical compositions, during periods with crustal extension/thinning and associated adiabatic mantle upwelling. In the tentative model (s) presented in Figure 6B and Figure 6C, high-TiO<sub>2</sub> basaltic melts are ideally formed by low-percentage melting at relatively great mantle depths within relatively restricted vertical melting intervals, whilst their low-TiO<sub>2</sub> counterparts ideally formed by relatively high-percentage melting at relatively shallow mantle depths within a relatively wide vertical melting interval. We further envisage (tentatively) that high-TiO<sub>2</sub> basaltic magmas originating from low-percentage melting of metasomatised and/or underplated basaltic materials, occasionally formed at the peripheries of (and in response to) large volumes of hot low-TiO<sub>2</sub> basaltic magmas at shallow to moderate mantle depths, which pooled in the neighbourhood

of the local LAB beneath the Faroese area in the Early Paleogene Period (Figure 6B and Figure 6C). In point of fact, one suitable analogue here would be the incompatible element-enriched basaltic rocks recorded for parts of the Skaergaard Intrusion, E Greenland. It formed by re-melting of some of its older parts, in the presence of trace amounts of fluids, in response to intrusive activity associated with emplacement of the adjacent basaltic Basistoppen Sill [46]. Formation of basaltic magmas from melting of fertile mantle sources and/or mantle sources variously affected by previous melting and/or metasomatising events in e. g. deep keels of the SCLM beneath the Faroese area in the Early Paleogene Period, as visualised in Figure 6B and Figure 6C<sub>2</sub>, remain potential options when it comes to production of both high-TiO<sub>2</sub> and low-TiO<sub>2</sub> melts at mantle depths, which did not necessarily differ noticeably from one another: previous discussion and suggestions [5, 11]. In this context it is perhaps worthwhile to reflect on the fact that all developing basaltic melts, including low-TiO<sub>2</sub> melts that ultimately formed by comparatively high-percentage mantle melting, went through low-percentage melting phases too during their earlier stages of formation, no matter the compositions of their mantle sources. Shouldn't it be expected that at least some of these melts ultimately segregated from their mantle sources at relatively shallow mantle levels too, when melting percentages reached 4 to 6 for instance, much as they do at deeper mantle levels?



**Figure 7.** REE in basaltic melts normalised to primitive mantle values (PM from McDonough and Sun [37]). (A) Batch melting calculations on REE compositions representing average values of metasomatised spinel lherzolites from Lesnov et al. [69] in the presence of residual olivine (84 %), orthopyroxene (15.5 %) and spinel (0.5 %). Mineral/melt partition coefficients and batch melting equation are from Rollinson [70] and refs. therein). The LREE tend to become relatively much more enriched than do their MREE and HREE in particular with decreasing percentages of calculated melting. (B) Calculated melts (3 – 15 %) are contrasted against Faroese sills from Hansen et al. [11]. (C) Calculated melts (3 – 15 %) are contrasted against lavas of the Enni Formation from [45]. (D) Calculated melts (3 – 15 %) are contrasted against lavas of the Beinissvørð Formation from [8].

When it comes to the oldest contemporaneous high-TiO<sub>2</sub> and low-TiO<sub>2</sub> Faroese sill groups, their close spatial

relationships and differences in geochemical compositions have previously been attributed to melting of neighbouring

mantle sources variously affected by metasomatism at mantle depths that did not necessarily differ much (Figure 6C<sub>2</sub>)[11]. These authors effectively demonstrated that various percentages of melting of fertile metasomatised mantle materials (spinel lherzolites) may adequately explain the entire range in geochemistry displayed by the Faroese basaltic sills irrespective of their TiO<sub>2</sub> makeup. A few additional batch melting calculations carried out in this contribution (Figure 7A) strongly suggest that an array of melting percentages of a compositionally relatively wide variety of fertile metasomatised spinel lherzolites can reproduce the REE compositions of not only the Faroese sills (Figure 7B), but also of local high-TiO<sub>2</sub> and low-TiO<sub>2</sub> lavas such as those representing the Beinísvørð and Enni formations (Figure 7C; Figure 7D).

The tentative hypotheses put forward here regarding the bulk of Faroese igneous products initially developed from local magma sources rather than from more distant ones, suggest that chemostratigraphically similar basaltic sequences of the FIBG and East Greenland do not necessarily originate from common mantle sources situated in between these two igneous regions, as has been tentatively suggested earlier [44, 45] and refs, therein). Indeed, the age comparisons between these two igneous regions (Previous sub-sections.) suggest some degrees of contemporary differences with respect to their regional stress regimes (Principal stress axes.) and magmatic activity. An alternative mechanism, with a potential to explain chemostratigraphical similarities between e.g. the Faroese Enni formation and the Skránterne and Rømer Fjord formations of central E Greenland, would be similar lithospheric extension rates that resulted in near-identical melting percentages within broadly similar mantle sources.

As such, the potential existence of a contemporary Iceland microcontinent between central E Greenland and the developing FIBG, as suggested previously [67], would not be at odds with measurements, observations and interpretations presented in this contribution.

## 6. Summary and Concluding Remarks

In this contribution we present new <sup>40</sup>Ar/<sup>39</sup>Ar ages for most of the sills exposed on the Faroe Islands, in addition to new and recalculated <sup>40</sup>Ar/<sup>39</sup>Ar ages for some of the Faroese basaltic lava formations. Altogether, the new radiometric ages and compiled recalculated radiometric ages presented in this study point to the formation of the entire basaltic lava successions and sills of the Faroe Islands during a time interval from ~61 Ma to ~50.5 Ma, i. e. it took at least ~10.5 myr for the initial Faroese basaltic plateau and its intrusive systems to develop. As no reliable radiometric ages are available for the Faroese Lopra Formation yet, the Faroe Islands could in theory be a few hundred thousand years older than the currently recorded maximum ages. Also, volcanism to build up the Enni Formation could be slightly younger than is presented in this paper, as we do not know its initial thickness with absolute certainty. moreover, we have

generally considered ± uncertainties of calculated ages to be mostly theoretical, while in reality the ages of some of these rock suites may overlap somewhat. Based on the geochronological results obtained in this study, in addition to associated tectonic and geochemical interpretations, a few inferences regarding timing and sequences of events within the FIBG during the Early Paleogene Period are presented below:

1. Subsequent to the formation of the lowermost Lopra Formation, in response to outpourings of basaltic hyaloclastic material in a shallow-marine or in a marshy sub-aerial environment at ≥ ~61 Ma, the overlying Beinísvørð Formation developed between ~61 Ma and ~57.45 Ma (~3.55 myr in total) in response to significant outpourings of magmas hosted mostly in tabular lava flows, suggestive of noticeable rates of extension/effusion.
2. The mostly sedimentary and pyroclastic Presthagi and Hvannhagi formations, residing on top of the Beinísvørð Formation, were deposited during a largely hiatus/quiescent period with reduced volcanic activity, which lasted from ~57.5 to ~56.3 Ma (~1.2 myr combined, if ± uncertainties are considered to be mostly theoretical.).
3. The Malinstindur Formation, resting atop Presthagi and Hvannhagi formations, and the overlying Sneis and Enni formations formed in the time span from ~56.35 Ma to ~55.85 Ma, i. e. within a relatively narrow time interval of ~0.5 myr (If ± uncertainties are considered to be mostly theoretical.). Increased occurrences of thick tabular/simple lava flows in the uppermost Enni Formation relative to the underlying Malinstindur Formation could point to increased local extension/effusion rates in the latest stages of local surface magmatism.
4. Subsequent to the deposition of the (presumed) top layers of the Enni Formation at ~55.85 Ma, changes in the regional stress fields triggered the formation of relatively voluminous basaltic sill intrusions in the form of the Streymoy, Kvívík, Eysturoy and Sundini sills at ~55.5 Ma to ~55.2 Ma (average ~55.35 Ma). Successively less voluminous saucer-shaped basaltic sills were intruded into the Faroese lava pile at ~54.75 Ma to ~54.05 Ma (Svínoy-Fugloy Sill, average ~54.4 Ma); at ~53.15 Ma (Morskranes Sill) and at ~50.7 Ma to ~50.3 Ma (Langaregn and Vestmanna sills, average ~50.5 Ma). The ± age uncertainties for these are considered to be mostly theoretical too.
5. Comparison between radiometric ages measured for rock suites of the Faroe Islands and central E Greenland seem to suggest that igneous activity in (parts of) these two neighbouring NAIP regions were partly or wholly decoupled from time to time subsequent to around 57.5 Ma.

With respect to suitable mantle sources, the melting of which gave rise to the igneous products that built up the

initial Faroese lava plateau in the Early Paleogene Period, a few petrogenetic models have been presented in earlier studies, most of which have the potential to explain much of measured and observed characteristics typical for the FIBG. In this contribution we point to an alternative approach regarding basaltic melt formation in a mantle environment with an irregular LAB configuration. We speculate that some of the precursor magmas building up the Faroese archipelago may have formed initially at various mantle depths by various percentages of melting of suitable mantle sources adjacent to an irregular LAB, thus providing high-TiO<sub>2</sub> and low-TiO<sub>2</sub> basaltic magmas. Other local magmas, giving rise to some of the Faroes sills for instance, may have formed at roughly equal mantle depths by varying percentages of melting of metasomatised/fertile spinel lherzolite sources. We envisage general sub-vertical transport of the molten rocks, which initially built up Faroese lavas and sills, via multiple feeder systems, which themselves in turn were supplied from multiple magma sources generated over relatively wide geographic areas within the FIBG region.

## Future Works

It would be desirable to acquire some additional <sup>40</sup>Ar/<sup>39</sup>Ar radiometric ages representing a number of Faroese lava horizons, notably from the Beinissvørð, Malinstindur, Sneis and Enni formations within the foreseeable future, in addition to a few supplementary radiometric ages representing selected local sills (Research is in progress).

## Data Availability

Diagrams depicting cumulative % <sup>39</sup>Ar released versus K/Ca ratios as well as isochron plots for relevant sill and lava samples, from Table 1 and Figure 2, are shown in electronic Supplement A, published in Mendeley Data, Hansen and Ganerød, March 2023a:

<https://doi.org/10.17632/87gtjjh5gb.5>

Detailed geological maps of the Faroe Islands, showing geographical sample localities, photomicrographs illustrating the petrography of relevant basaltic rock samples and, plots illustrating MgO compositions versus other major element oxides are depicted in Figure A, Figure B, Figure C and Table A in electronic supplement B, which was published in Mendeley Data, Hansen and Ganerød, March 2023b:

<https://doi.org/10.17632/2y29tsw7nh.1>

## Author Contributions

JH was responsible for sample collection and sample preparation for quality check. JH also produced the bulk of the actual paper. MG was responsible for everything related to acquirement of radiometric data, which are shown in Table 1, Figure 2 and in diagrams displayed in electronic Supplement A, in addition to providing description of analytical techniques.

## Disclaimer

The authors declare that they have no conflict of interest and nothing to disclaim.

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