Eocene to Miocene igneous activity in NE Greenland: northward younging of magmatism along the East Greenland margin

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Abstract: Radiometric dating by the 40Ar–39Ar incremental heating method was carried out on lavas, sills, dykes, and a central intrusion from NE Greenland. Eighteen samples gave acceptable crystallization ages. Lavas of both Lower and Upper Plateau Lava Series gave ages in the range 55.5–53.5 Ma and cannot be constrained to better than 56–53 Ma. Sills and dykes from Traill Ø to Shannon, with compositions fairly similar to those of the lavas, gave ages of 55.1–51.3 Ma, contemporaneous with and slightly younger than the lavas. Alkaline lavas on inland nunataks have ages of 53–50 Ma, and the Kap Broer Ruys intrusive centre has an age of 48.7 ± 0.5 Ma. An alkaline sill on Hvalrosø is much younger at 20.3 ± 0.1 Ma. There are no pre-breakup lavas onshore NE Greenland. We surmise that the hot mantle of the Iceland plume arrived and melted extensively beneath the northern basins only at the time of breakup around 55 Ma. Post-breakup intrusive events in NE Greenland coincided with plate-tectonic events such as reorganization, uplift and opening in the north. The Hvalrosø sill represents a local small melting event that may be related to coeval opening of the Lena Trough.

Supplementary materials: Details of the source data, results, and the compositions and locations of the dated samples, are available at www.geolsoc.org.uk/SUP18738.

East Greenland constitutes a volcanic rifted margin that forms part of the Tertiary North Atlantic Igneous Province (e.g. Upton 1988; Eldholm & Grue 1994; Saunders et al. 1997; Brooks 2011). The province developed before, during and after continental breakup, which took place in the earliest Eocene at around 55 Ma. The East Greenland margin extends for nearly 2000 km between 60°N and the Greenland Fracture Zone around 78°N (Fig. 1) although Tertiary igneous rocks are exposed on only c. 1000 km between 66°30’N and 75°30’N (except for one Palaeocene dyke at 63°13’N reported by Storey et al. 2007). South of 66°30’N igneous rocks are submersed on the continental shelf, where they form seaward-dipping reflector sequences that have been sampled in Ocean Drilling Program (ODP) cores, whereas north of 75°30’N igneous rocks are known only from geophysical evidence as lavas and sills intercalated in the offshore sedimentary basins (Larsen 1990; Escher & Pulvertaft 1995; Hamann et al. 2005; Tsikalas et al. 2005).

To understand the tectonomagmatic and sedimentary development of the East Greenland margin, it is important to know the ages of the constituent volcanic and intrusive parts of the margin. The present inventory of published radiometric ages of the margin comprises about 80 reliable ages of which the majority (about 60) are from the onshore area between 66°30’N (Kap Gustav Holm) and 72°N (Kong Oscar Fjord), including the Kangerlussuaq region and the Bloxseville Kyst. This is a natural consequence of the huge volume of volcanic rocks and large number of intrusions exposed in this area, and also its complicated history. By comparison, the lavas and intrusions in northern East Greenland are poorly documented. For the onshore volcanic areas north of Kong Oscar Fjord, which extend over c. 300 km from Geographical Society Ø in the south through Hold With Hope and Wollaston Forland to Shannon in the north (Fig. 2), there are, besides a K–Ar age for lavas on the inland nunataks (Rex et al. 1979), only seven published 40Ar–39Ar ages for intrusions and two for lavas (Upton et al. 1984a, 1995; Price et al. 1997). Unfortunately, most of the published 40Ar–39Ar age results do not show statistically valid age data. The lavas are notoriously difficult to date because they have very low potassium contents, and excess argon is frequently present.

At the southern and central East Greenland margin sections, the lavas were erupted in two major episodes: a Palaeocene (62–57 Ma) pre-breakup episode and an Eocene (56–55 Ma) syn-breakup episode (Saunders et al. 1997; Hansen et al. 2002; Storey et al. 2007; Brooks 2011). Minor episodes of post-breakup volcanism took place at 53–44 Ma (Tegner & Duncan 1999; Peate et al. 2003; Larsen et al. 2013) and numerous intrusions extended the activity to around 35 Ma, as reviewed by Tegner et al. (2008) and Brooks (2011). The youngest volcanic event took place in the central Blosseville region at 13–14 Ma (Storey et al. 2004).

In northern East Greenland, the published age results for the lavas and some sills and dykes fall in the broad range 59–53 Ma and thus they are usually quoted as Palaeocene–Eocene in age. This paper presents 40Ar–39Ar ages for 23 samples of lavas and intrusions from the northern East Greenland margin from Traill Ø to Shannon. The results show no Palaeocene ages, and magmatic activity on this part of the margin began and ended later than in the central and southern parts.

Geological setting and sample selection

The geology of northern East Greenland has been described in overview by Henriksen et al. (2009). Northern East Greenland (Figs 1 and 2) comprises a basement of Precambrian and early
Palaeozoic rocks variably deformed and metamorphosed during the Caledonian orogen, and a cover of late Palaeozoic, Mesozoic and Tertiary sediments and Tertiary lavas and intrusions. Large and deep, north–south- to NNE–SSW-trending faults delimit a system of Mesozoic to Tertiary sedimentary basins filled with thick deposits of Triassic to Cretaceous sediments overlain by Tertiary sediments and volcanic rocks. Faulting has taken place intermittently after the deposition of the volcanic rocks, so that the present lava areas are faulted and dissected.

The lavas and intrusions in NE Greenland were extensively mapped and described during expeditions in the 1920s, 1930s and 1950s (Backlund & Malmqvist 1932; Koch & Haller 1971). Earlier work was reviewed by Noe-Nygaard (1976) and Upton (1988). An account of the geology of the igneous rocks on Gauss Halvø and Hold With Hope was given by Upton et al. (1980).

Pre-basaltic sediments

The lavas rest on Cretaceous and older sediments and, on Wollaston Forland and Sabine Ø, also on small exposures of Tertiary sediments. Based on palynological evidence these comprise Danian and Late Thanetian to Early Ypresian strata (Jolley & Whitham 2004; Nøhr-Hansen et al. 2011).

Lava succession in the basin

The southernmost lava exposure is a small area at Kap Mackenzie in eastern Geographical Society Ø at 72°54′N (Hald 1996). Going northward, Bontekoe Ø consists solely of volcanic rocks (Noe-Nygaard & Pedersen 1983), and major lava outcrops occur on Gauss Halvø and Hold With Hope (Hald 1978a; Upton et al. 1980). There are tiny remnants of lavas on Clavering Ø and a large lava plateau on Wollaston Forland, which extends to the islands Sabine Ø, Lille Pendulum and Kuhn Ø (Watt 1994). The northernmost lava succession occurs on eastern Shannon and extends to Kap Pansch at 75°10′N (Watt 1994). The northern lava areas thus extend for 290 km with a SW–NE-oriented trend. In an east–west direction (coast to inland) the lavas extend for up to 70 km. It is not possible to know if the more than 10 separate areas once constituted a coherent lava plateau, but we regard this as likely.

In the field, the lava succession can be divided into two series, the Lower and Upper Plateau Lava Series (LPLS and UPLS, Upton & Emeleus 1977; Upton et al. 1980).

Lower Plateau Lava Series

The LPLS is up to 450 m thick in its central area on Hold with Hope and consists of uniform, aphyric to sparsely plagioclase-phryic lava flows. The flows are all tholeiitic basalts with a fairly restricted chemical composition (5–8 wt% MgO) and a geochemically depleted character (Noe-Nygaard & Pedersen 1974, 1983; Hald 1978a, 1996; Upton et al. 1980, 1984a; Thirlwall et al. 1994; Watt 1994). The outcrops of the LPLS extend throughout the area from Geographical Society Ø in the south to Shannon in the north with much the same character.

Upton et al. (1984a) and Thirlwall et al. (1994) reported a single nephelinite in the LPLS; however, this sample is from an isolated, poor exposure in scree below the coherent LPLS succession (Upton, unpublished field notes) and has almost exactly matching compositions in the UPLS and sills in the nearby Giesecke Bjerge on Gauss Halvø (Hald 1978b); we therefore consider it to be an intrusive sheet belonging to the UPLS.

The low potassium contents of the LPLS lavas (0.1–0.5 wt%) and their generally aphyric character make samples suitable for 40Ar–39Ar dating rare. As groundmasses are never unaltered we selected mainly plagioclase-phryic lavas with as high K₂O (and
P$_2$O$_5$, which varies much less with alteration) as possible (>0.2 wt%). Lavas from Geographical Society Ø to Lille Pendulum were dated in this study. No lava samples from Shannon were suitable for dating.

**Upper Plateau Lava Series.** The UPLS is up to 350 m thick and comprises a much more varied population of rocks, from aphyric to strongly porphyritic with abundant phenocrysts of olivine and augite (Hald 1978a; Upton et al. 1980, 1984a). Plagioclase phenocrysts are infrequent. The flows also have a variable chemical composition (3–26 wt% MgO) and comprise tholeiitic basalts, alkali basalts, nephelinites, basaltic andesites, trachybasalts and picrites. Silica contents are up to 54.5 wt%, and many flows are considered to be contaminated with continental crust and lithospheric mantle material (Thirlwall et al. 1994). Trace elements suggest that the original mantle-derived melts formed at deeper levels than those of the LPLS (Thirlwall et al. 1994).

The UPLS overlies the LPLS conformably but is present only in the southern part of the lava area, on Hold With Hope and Giesecke Bjerge on Gauss Halvø (Upton et al. 1980) and on Bontekoe Ø (Nee-Nygaaed & Pedersen 1983). Measurements with compass in the field show that a change of magnetic polarity from reverse to normal coincides with the Lower to Upper Series transition in Giesecke Bjerge whereas it occurs within the Upper Series on Hold with Hope (Upton et al. 1980). This suggests that the deposition of the UPLS commenced earlier on Hold With Hope. Given the ages presented in this paper, the field observations fit with the C24r–C24n reversal. There is usually no sediment horizon between the LPLS and the UPLS, although Watt (1994) noted the presence of a 5–8 m thick conglomerate, composed entirely of basaltic pebbles, at the boundary between the two series in Tobias Dal on Hold with Hope.

Three samples from the UPLS were selected for dating; suitable samples are rare.

**Alkaline lavas of the nunatak zone**

In an area of nunataks close to the Inland Ice around 74°N, 150–200 km west of Hold With Hope (Fig. 2), scattered small remnants of strongly alkaline mafic lavas and volcanic plugs are found (Katz 1952; Brooks et al. 1979; Bernstein et al. 2000). Brooks et al. (1979) reported a K–Ar age of about 56 Ma for these rocks. Two samples were included in the present study.

**Sills and dykes**

Sills constitute a prominent part of the igneous rocks in NE Greenland. Most of them are tholeiitic and have compositions broadly corresponding to those of the LPLS lavas, but several sills on Hold With Hope and Gauss Halvø (i.e. within the bounds of the UPLS) have compositions more similar to those of the UPLS (Hald 1978a,b, 1996; Upton et al. 1984a; unpublished GEUS data). Sill intrusions are particularly thick and frequent in the Cretaceous sediments on Traill Ø and Geographical Society Ø, where several may be up to 100 m thick (Frebold & Nee-Nygaaed 1938; Koch & Haller 1971; Hald 1996; Price et al. 1997). Sills are also frequent,
though less prominent, in the sediments beneath the lava areas (Upton et al. 1980). The most extensive sill known forms the greater part of Shannon (30 km x 40 km). Samples selected for dating are mainly from coarse-grained parts of the sills interiors from which the feldspars could be separated. Sills from Traill Ø to Wollaston Forland were included in the present study.

Dykes are frequent throughout NE Greenland. On Hold With Hope there is a dense swarm of NE–SW-trending dykes that cut both LPLS and UPLS lavas and are considered to be related to the Myggbukta central complex (Upton et al. 1980, 1984b, 1995). On Wollaston Forland and Kuhn Ø a number of thick, NW–SE-trending dykes form a loose swarm (Koch & Haller 1971). Other dykes have variable directions. The dykes are theoleitic basalts, and most of them are less depleted than or similar to the LPLS lavas. For this study a NNW–SSE-trending dyke from Wollaston Forland and a NNE–SSW-trending dyke from Bontekoe Ø were selected.

Central intrusions

Hold With Hope contains the large central intrusions Myggbukta and Kap Broer Ruys. Upton et al. (1984b) considered these to be developed by differentiation from the UPLS magmas and thus not much younger than these. The Myggbukta complex is not well dated because it is thoroughly hydrothermally altered; we did not find any Myggbukta samples suitable for dating. The Kap Broer Ruys intrusion has been K–Ar dated to about 47 Ma (Upton et al. 1984b); we included a fresh felsite from this intrusion in the present study.

Analytical methods

Samples were dated by the 40Ar–39Ar incremental heating method in the Noble Gas Mass Spectrometry Laboratory at Oregon State University. The instrument is a MAP 215-50 gas mass spectrometer with all-metal extraction system equipped with a 10 W CO2 laser and a Heine low-blank, double-vacuum resistance furnace connected to an ultra-clean, low-volume (c. 1000 cm3) gas cleanup line. Samples were degassed in 8–17 temperature steps, from 500 °C to fusion at around 1400 °C. Zr–Al getters removed active gases. Ion beam currents were measured with the electron multiplier at m/z = 35, 36, 37, 38, 39, and 40, and intervening baselines. Measurement times, peak/baseline voltages, data acquisition and storage were computer controlled. Mass discrimination was monitored using an air pipette system. All resulting ages are calculated using the ArArCALC software package (Koppers 2002).

Unaltered phenocrysts were separated by standard mineral separation techniques. Fine-grained, unaltered whole-rocks were cored with a 5 mm diameter diamond-tipped drill bit, then sectioned into discs of 100–300 mg. Samples were irradiated at the Oregon State University TRIGA experimental reactor for 6 h at 1 MW power. The neutron flux was monitored with the FCT-3 biotite monitor. All ages are here calculated relative to an age of 28.201 Ma for the Shannon to Kap Mackenzie, but no systematic differences with location are apparent in Figure 4: the young age of the lava at Kap Mackenzie overlaps within 2σ (plateau) with the ages for lavas at Kap Stosch and Wollaston Forland. Therefore, it can only be concluded that the LPLS lavas were erupted within the 3 Ma interval of 53–56 Ma, with the arithmetic mean of 54.6 Ma for the six samples in Table 1 as the best common age estimate. In any case, the dated lavas are all earliest Eocene according to the Geological Time Scale 2012, in which the Palaeocene–Eocene boundary is placed at 56.0 Ma (Vandenbergh et al. 2012). There is no indication that undated Palaeocene lavas exist onshore; the dated lava succession in Tveêrelv on Hold With Hope is thick, well-exposed, sampled flow-by-flow, and rests on Cretaceous sediments; both field relations and chemistry indicate a single continuous succession.

Upper Plateau Lava Series (UPLS)

The Upper Plateau Lava Series encompasses lavas with much higher K2O contents than the LPLS and should therefore be easier to date. However, plagioclase phenocrysts are rare, and again, excess argon confounds the results. One sample failed to provide a reliable age because of excess argon, whereas two samples gave excellent plateaux and isochrons (Fig. 5); however, geological constraints show that the result from Tobias Dal cannot be correct. The UPLS in Tobias Dal on Hold With Hope overlies, in physical stratigraphic sequence, the dated LPLS in Tveêrelv, yet the Tobias Dal UPLS sample yielded an age of 56.5 ± 0.5 Ma, older than the range of the LPLS (Fig. 4). The only possible explanation is that the dated plagioclase contains uniformly distributed excess argon. This is a known phenomenon (Faure 1986, p. 104) and it is conceivable in the light of the conclusion of Thirlwall et al. (1994) that the UPLS is contaminated with old enriched lithospheric components. The frequent presence of excess argon in NE Greenland samples may have the same cause.

As a result of this, only one sample from the UPLS yielded an acceptable result, namely a hawaiite lava flow from the upper part of the succession on Bontekoe Ø, with an excellent plateau age of 55.17 ± 0.35 Ma. The lava succession here consists of a lower tholeiitic and an upper alkali part (Nee-Nygård & Pedersen 1983). The lower part is compositionally very similar to the LPLS in other areas (Nee-Nygård & Pedersen 1983; unpublished GEUS data), and the upper part is thought to be equivalent to the UPLS on Gauss Halvo and Hold With Hope. The obtained age is within the age range for the LPLS in Figure 4 but outside the 2σ uncertainty range for the plateau age of the nearest dated sample, 53.54 ± 0.67 Ma for the LPLS on Kap Mackenzie. It is possible that the alkaline lavas on Bontekoe Ø are older than the lavas of the UPLS elsewhere, and even older than some LPLS lavas elsewhere. Given that
Table 1. $^{40}\text{Ar}/^{39}\text{Ar}$ ages for lavas and intrusions from northern East Greenland

| Locality                     | Sample no. | Material | Plateau age w/ 2σ (Ma) | % $^{39}\text{Ar}$ | Isochron age ± 2σ (Ma) | MSWD | $^{40}\text{Ar}/^{36}\text{Ar}$ intercept |
|------------------------------|------------|----------|------------------------|---------------------|------------------------|------|---------------------------------|
| **Lower Plateau Lava Series (north to south)** |            |          |                        |                     |                        |      |                                 |
| Lille Pendulum               | 194233     | Plagioclase | 55.42 ± 0.92           | 96.7                | 54.58 ± 5.18          | 0.07 | 317 ± 132                      |
| Blesesdal (WF)              | 194187     | Plagioclase | 53.80 ± 0.76           | 80.1                | 53.72 ± 1.92          | 0.43 | 298 ± 65                       |
| Blesesdal (WF)              | 194194     | Groundmass | 55.02 ± 0.49           | 49.9                | 55.12 ± 0.76          | 0.17 | 291 ± 26                       |
| Kap Stosch (HWH)            | 95346      | Plagioclase | 54.16 ± 0.72           | 100                 | 54.11 ± 0.84          | 0.53 | 297 ± 12                       |
| Tverrelv (HWH)              | 517303     | Groundmass | 55.52 ± 0.68           | 74.1                | 55.16 ± 2.78          | 0.12 | 297 ± 8                        |
| Kap Mackenzie (GSØ)         | 239531     | Plagioclase | 53.54 ± 0.67           | 83.6                | 53.30 ± 2.14          | 0.04 | 306 ± 82                       |
| **Upper Plateau Lava Series** |            |          |                        |                     |                        |      |                                 |
| Tobias Dal (HWH)            | 194150     | Plagioclase | 56.51 ± 0.49†           | 100                 | 56.50 ± 0.71†         | 0.39 | 296 ± 34                       |
| Bontekoe Ø                  | 1980.274   | Groundmass | 55.17 ± 0.35           | 96.1                | 55.12 ± 0.40          | 0.18 | 297 ± 5                        |
| **Inland alkaline lavas in the nunatak zone around 74°N** |            |          |                        |                     |                        |      |                                 |
| Louise Boyd Land            | 421302     | Whole-rock | 51.49 ± 0.57‡           | 77.7                | 49.80 ± 1.38‡         | 1.83 | 657 ± 302                      |
| Hobbs Land                  | 452434     | Glass     | 53.94 ± 0.64‡           | 62.3                | 53.40 ± 1.83‡         | 2.20 | 310 ± 42                       |
| **Sill intrusions (north to south)** |            |          |                        |                     |                        |      |                                 |
| Shannon                     | 194196     | Plagioclase | 51.85 ± 0.55           | 99.0                | 51.82 ± 1.12          | 0.15 | 296 ± 4                        |
| Bass Rock (LP)              | 194207     | Plagioclase | 53.71 ± 0.62           | 100                 | 53.95 ± 0.88          | 0.19 | 290 ± 15                       |
| Kefersteinsberg (SO)        | 517355     | Plagioclase | 53.98 ± 0.39           | 85.6                | 54.24 ± 0.94          | 0.10 | 276 ± 64                       |
| Hvalrosø                    | 475286     | K-feldspar | 20.31 ± 0.12           | 93.5                | 20.32 ± 0.17          | 0.27 | 295 ± 8                        |
| Freycinet Bjerg (GSØ)       | 239539     | Plagioclase | 52.58 ± 0.66           | 100                 | 52.94 ± 1.43          | 0.95 | 287 ± 31                       |
| Traill Ø south coast        | 239578     | Plagioclase | 55.14 ± 0.37           | 97.5                | 54.97 ± 0.77          | 0.80 | 299 ± 16                       |
| **Dykes**                   |            |          |                        |                     |                        |      |                                 |
| Dronning Augusta Dal (WF)   | 475289     | Plagioclase | 53.68 ± 1.59           | 78.4                | 53.67 ± 5.78          | 0.19 | 296 ± 156                      |
| Bontekoe Ø                  | 517310     | Plagioclase | 51.27 ± 1.21           | 98.4                | 51.41 ± 1.81          | 0.05 | 295 ± 6                        |
| **Central intrusion on Hold With Hope** |            |          |                        |                     |                        |      |                                 |
| Kap Broer Ruys felsite      | 228078     | K-feldspar | 48.71 ± 0.51           | 99.4                | 48.65 ± 0.52          | 0.68 | 297 ± 4                        |

Sample numbers are GGU numbers, except sample 1980.274, which is from the collections of the Natural History Museum of Denmark. Isochron ages and intercept values are from the inverse isochrons. WF, Wollaston Forland; HWH, Hold With Hope; GSØ, Geographical Society Ø; LP, Lille Pendulum; SO, Sabine Ø.

† This result is considered to be too old because of uniformly distributed excess argon in the plagioclase.
‡ The isochron result is considered to be the best, and the MSWD given is for this isochron.

The dated sill from Freycinet Bjerg in eastern Geographical Society Ø is slightly more enriched than the normal LPLS magmas. It has a plateau age of 52.58 ± 0.66 Ma, at the younger end of the LPLS range of 53–56 Ma. A sill sample from the south coast of Traill Ø is a coarse-grained central facies of a normal sill and has a good plateau age of 55.14 ± 0.37 Ma, indistinguishable from the LPLS ages. A sample of another sill from Traill Ø contains excess argon and gives only an imprecise isochron age of 56.8 ± 4.9 Ma (not shown).

Sabine Ø is crosscut by a large sill that has reacted with the surrounding sediments. The dated sample from Kefersteinsberg is from the margin of the sill and is enriched in silica and potassium; it has a very good plateau age of 53.98 ± 0.39 Ma. This is also within the age range for the LPLS.

The steep island of Bass Rock is an extension of the sill that forms the northern part of Lille Pendulum. It is compositionally similar to the LPLS on Lille Pendulum and has an excellent plateau age of 53.71 ± 0.62 Ma, which is within the 53–56 Ma age range for the LPLS. In comparison, the dated LPLS lava from Lille Pendulum gave an age of 55.42 ± 0.92 Ma (Table 1), just outside the 2σ age range for Bass Rock.

The major part of Shannon consists of one or a few very large sills. The dated sill sample comes from the east coast and is compositionally similar to the less-depleted LPLS lavas. It gave an excellent plateau age of 51.85 ± 0.55 Ma.

Hvalrosø is immediately south of Sabine Ø is 2 km × 1 km in size and consists of a single sill, which is olivine-phryic, strongly alkaline, and has a tephriphonolitic composition (after Le Maitre 2002) (Table 2). The dated material is potassic feldspar from...
pegmatitic segregation veins in the centre of the sill. The age plateau is excellent, with an age of 20.31 ± 0.12 Ma. The low 2σ is due to the high potassium content of the feldspar.

In summary, four of the dated tholeiitic sills on Traill Ø, Sabine Ø and Lille Pendulum have ages within the 53–56 Ma age range of the LPLS. Two sills on Geographical Society Ø and Shannon have slightly younger ages. The Hvalrosø Sill is unique with regard to both composition and age; at 20.31 Ma it is the youngest igneous rock yet dated in NE Greenland.

Dykes

The NNW–SSE-trending dyke from Dronning Augusta Dal in central Wollaston Forland yielded a plateau age of 53.68 ± 1.58 Ma; the large uncertainty (Fig. 8) is due to a very K-poor plagioclase (K/Ca = 0.006). Its chemistry is similar to the LPLS, and the age is within the LPLS age range. It cuts the LPLS lavas in the outcrop; however, these are only the lowest lavas above the sediments. This dyke is most probably related to the LPLS rather than to the NW–SE-trending dyke swarm in northern Wollaston Forland.
The NNE–SSW-trending dyke on Bontekoe Ø yielded a plateau age of 51.28 ± 1.20 Ma; the large uncertainty is again due to K-poor plagioclase. The dyke cuts the local UPLS and has an enriched chemistry similar to some lavas of the UPLS. The age indicates that UPSL activity may have continued beyond the 56–53 Ma interval.

**Kap Broer Ruyas**

The felsite from the Kap Broer Ruyas central complex gave an excellent plateau age of 48.71 ± 0.51 Ma (Fig. 9), consistent with the old K–Ar age of 46–48 Ma (Upton et al. 1984b).

**Age of igneous rocks along the East Greenland margin**

Figure 10 shows a compilation of ages obtained for the Tertiary igneous rocks along the whole East Greenland margin at geographical latitudes 63–75°N; it is an extension and completion of similar compilation figures of Storey (2008). Many of the published age determinations were made using the Fish Canyon Tuff (FCT, sanidine or biotite) as flux monitor. Unfortunately, the age of the FCT has been adjusted two times, (2004) and Tegner et al. (2007). A post-breakup sill (?) in ODP Hole 918D gave an age of 53.1 Ma (Sinton & Duncan 1998; Tegner et al. 2007). The southernmost dated rock is an onshore dyke at Skjoldungen with an age of 61.8 Ma (Storey et al. 2007), suggesting widespread pre-breakup igneous activity on this segment of the margin.

The total range of ages found on this part of the margin is 63.7–50.2 Ma, which is the oldest and narrowest range on the entire East Greenland margin (Fig. 10).

**Central East Greenland margin between 66°30’N and 70°30’N**

The lava succession in this area is exposed along Blosseville Kyst and inland areas between 68°N and 70°30’N and comprises pre-, syn-, and post-breakup lavas. The pre-breakup lavas are exposed only in the Kangerlussuaq–Nansen Fjord area and in Prinsen af Wales Bjerge and are dated at 61.9–58.1 Ma (Hansen et al. 2012). The syn-breakup succession comprises the extensive and voluminous Plateau Basalts, which cover around 65000 km² (Pedersen et al. 1997) and are dated within the narrow interval 56.4–55.3 Ma (Storey et al. 2007). Post-breakup lavas occur in Prinsen af Wales Bjerge (55.2–52.8 Ma, Peate et al. 2003), offshore 68°N (48.7 Ma, Thy et al. 2007), and at Kap Dalton (49–44 Ma, Larsen et al. 2013). Furthermore, Storey et al. (2004) found an extraordinary young age of only 13.5 Ma for lavas at Vindtop in the central inland area west of Blosseville Kyst.

Central intrusions and dykes are abundant between 66°30’N and 69°N. Ages fall in a wide interval from the pre-breakup complexes Sulugssut (58.7 Ma, Storey et al. 2007) and Imilik II (56.9 Ma, Tegner et al. 1998), to the syn-breakup Skageraard intrusion (55.8 Ma, Hirschmann et al. 1997) and to a plethora of
post-breakup intrusions, mostly 50–47 Ma (Tegner et al. 2008) but with the youngest being the 35–36 Ma Bjørn and Nûk intrusions in the Kialineq area (Gleadow & Brooks 1979; Tegner et al. 2008).

Excepting the 13.5 Ma Vindtop Formation, the total range of ages along the central part of the East Greenland margin is 61.9–35 Ma. There is some indication of episodic activity in that the periods 53–51 Ma and 45–40 Ma are sparsely represented (Fig. 10).

**Northern East Greenland margin between 70°30’N and 75°N**

In Jameson Land, Traill Ø and most of Geographical Society Ø sills and dykes are abundant and there are no lavas. On Jameson Land, a sill and a dyke were dated at 52.7 ± 1.2 Ma and 53.3 ± 1.4 Ma by Hald & Tegner (2000), whereas on Traill Ø a sill was dated at c. 54 Ma and two alkali basalt dykes were dated at c. 36 Ma (Price et al. 1997). Our new results of 55.1–52.6 Ma for two sills on Traill Ø and Geographical Society Ø support the notion that most of the tholeiitic sills in this area were intruded during the same period as the lavas were extruded elsewhere. The extension to slightly younger ages may suggest that younger tholeiitic lavas have existed but have been eroded away.

This section of the margin is also the site of the large central complexes of Kap Simpson and Kap Parry, which were dated at 38–40 Ma by Rex et al. (1979). Syenites in the Werner Bjerge complex gave a Rb–Sr age of 31 ± 2 Ma (Rex et al. 1979), whereas a very precise Re–Os age of 25.8 ± 0.1 Ma was found for the molybdenum mineralization in this complex (Brooks et al. 2004).

For the lava succession on Hold With Hope, Upton et al. (1984b, 1995) published some K–Ar and 40Ar–39Ar ages. Two lava flows gave 40Ar–39Ar ages of 58.7 and 53.4 Ma, and three dykes from a regional swarm cutting the lavas gave ages between 56.7 Ma (40Ar–39Ar) and 48.3 Ma (K–Ar). The Kap Broer Ruys central complex gave an age of about 47 Ma (K–Ar), and two late intrusions cutting the Myggbukta central complex gave ages of 32.7 and 34 Ma (40Ar–39Ar and K–Ar). The uncertainties on these ages are mostly large (1–7 Ma). None of the 40Ar–39Ar step-heating experiments produced plateaux, and the ages given by Upton et al. (1995) are either total fusion ages or inferred from selected steps, where the detailed data showed a large spread of step ages and signs of both argon loss and excess argon (Upton et al. 1995, Supplementary Data). In particular, the 58.7 Ma age for an LPLS lava is a total fusion age that includes step ages of 52.4–68.5 Ma. As also noted by Upton et al. (1995), some of these ages are only tentative.
The results obtained in this study constrain the age of all the onshore tholeiitic lava successions between 73°N and 75°N to within the time interval 56–53 Ma. The uncertainties on the single ages are better than ±1.5 Ma, but because of low potassium and excess argon the age interval cannot be narrowed further. The UPLS is not significantly younger than the LPLS, consistent with the usual absence of sediments between the two series. Tholeiitic sills and dykes in the same area are in the age range 53.7–51.3 Ma, which is within to slightly younger than the age interval for the lavas, and similar to the age of the sills farther south in Jameson Land. The tholeiitic basaltic magmatism onshore apparently came to an end well before 50 Ma, after which all igneous activity in NE Greenland had either alkaline or evolved felsic character, or both (Fig. 10). However, volcanism continued in the offshore areas, where a post-early Eocene lava succession of unknown character is present (Fyhn et al. 2012).

Fig. 7. \(^{40}\text{Ar}–^{39}\text{Ar}\) age spectra and plateau ages for six sill intrusions in NE Greenland.
Table 2. Chemical composition of the Hvalrosø sill and potassic rocks dredged from the central Lena Trough

| GGU-no.:   | 475286  | 262-35  | 262-83  |
|------------|---------|---------|---------|
| Locality:  | Hvalros | PS 66   | PS 66   |
| Area:      | NE Greenland | C. Lena Trough | C. Lena Trough |
| Rock type: | Tephrophonolite | Trachyandesite | Trachyandesite |

| Major elements (wt%) | 49.51 | 51.3 | 51.1 |
|----------------------|-------|------|------|
| SiO₂                 | 13.90 | 2.21 | 1.68 |
| Al₂O₃                | 17.72 | 18.16| 18.33|
| Fe₂O₃                | 7.21  | 7.43 | 7.25 |
| MnO                  | 0.13  | 0.15 | 0.15 |
| MgO                  | 5.40  | 5.22 | 6.10 |
| CaO                  | 6.87  | 8.63 | 9.52 |
| Na₂O                 | 4.71  | 4.00 | 4.04 |
| K₂O                  | 3.34  | 1.94 | 1.26 |
| P₂O₅                 | 0.71  | 0.28 | 0.20 |
| Volatiles            | 1.46  | 1.74 | 1.74 |
| Sum                  | 98.96 | 98.69| 98.94|

| Trace elements (ppm) | Sc  | 18.1 | 27.1 | 29.2 |
|----------------------|-----|------|------|------|
| Ni                   | 64.0| 58.8 | 80.8 |      |
| Rb                   | 85.0| 53.1 | 33.2 |      |
| Sr                   | 794 | 444  | 354  |      |
| Y                    | 23.3| 22.1 | 21.5 |      |
| Zr                   | 234 | 176  | 137  |      |
| Nb                   | 92.6| 28.5 | 17.7 |      |
| Cs                   | 1.8 | 0.76 | 0.45 |      |
| Ba                   | 1453| 488  | 300  |      |
| La                   | 52.5| 13.3 | 9.2  |      |
| Ce                   | 96.4| 32.3 | 23.1 |      |
| Pr                   | 10.5| 4.60 | 3.34 |      |
| Nd                   | 38.5| 20.4 | 15.3 |      |
| Sm                   | 6.49| 4.71 | 3.75 |      |
| Eu                   | 1.99| 1.68 | 1.37 |      |
| Gd                   | 5.76| 4.79 | 4.09 |      |
| Tb                   | 0.85| 0.71 | 0.64 |      |
| Dy                   | 4.31| 4.15 | 3.84 |      |
| Ho                   | 0.83| 0.79 | 0.76 |      |
| Er                   | 2.27| 2.23 | 2.20 |      |
| Tm                   | 0.33| 0.30 | 0.30 |      |
| Yb                   | 2.08| 2.05 | 2.00 |      |
| Lu                   | 0.32| 0.30 | 0.29 |      |
| Hf                   | 5.29| 4.03 | 3.21 |      |
| Ta                   | 7.38| 1.92 | 1.22 |      |
| Pb                   | 6.00| 1.39 | 1.09 |      |
| Th                   | 8.33| 1.27 | 0.78 |      |
| U                    | 1.86| 0.40 | 0.25 |      |

Fe₂O₃ is total iron as Fe₂O₃. Data for the Lena Trough are from Nauret et al. (2011).

The alkaline activity in NE Greenland was, on the other hand, protracted from the nunatak lavas at 53–50 Ma, to central com-
plexes at c. 49 Ma (Kap Broer Ruys and, by inference, Myggbukta), 40–38 Ma (Kap Parry and Kap Simpson) and 31–26 Ma (Werner Bjerge), and to 20.3 Ma for the Hvalrosø sill.

In summary, the igneous activity in NE Greenland started later than at the more southerly parts of the margin. The tholeiitic interval lasted less than 5 Ma so that this part of the activity came to an end earlier than farther south (Fig. 10). In contrast, the alkaline activity in NE Greenland was protracted over 30 Ma (50–20 Ma) compared with 20 Ma (55–35 Ma) in central East Greenland.

Magmatism related to the tectonic development of the North Atlantic

The alkaline activity in NE Greenland was protracted from the nunatak lavas at 53–50 Ma, to central complexes at c. 49 Ma (Kap Broer Ruys and, by inference, Myggbukta), 40–38 Ma (Kap Parry and Kap Simpson) and 31–26 Ma (Werner Bjerge), and to 20.3 Ma for the Hvalrosø sill.

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The conjugate NE Greenland and Voring margins

This part of the North Atlantic is situated north of the Jan Mayen Fracture Zone (Fig. 1). Around the time of breakup at 56–55 Ma, the NE Greenland margin was located immediately west of the Voring Marginal High (Hinz et al. 1987).

The volcanic rocks on the Voring margin are known from numerous seismic surveys and were sampled by drilling at ODP Site 642 on the Voring Marginal High. The 914 m thick volcanic succession consists of a lower series of basaltic andesites, andesites, dacites and rhyolite with a large proportion of crustal melts, and an upper series of tholeiitic basalts (Viereck et al. 1988, 1989; Parson et al. 1989; Meyer et al. 2009). The acid lavas of the lower series would have been highly viscous and were most probably erupted from a local central volcano such as occur scattered on the NW European shelf (Ritchie et al. 1999). They have no known counterpart in NE Greenland although similar volcanoes could be concealed beneath the volcanic areas on the shelf. The upper series basalts are geochemically depleted like the LPLS basalts in NE Greenland, and their inferred mantle sources and melting conditions appear to have been similar (Neumann et al. 2013). The lower series has been dated to 56.9–55.0 Ma by the 40Ar–39Ar incremental heating method (Sinton et al. 1998); however, it is reversely magnetized and referred to magnetochron C24r (Hinz et al. 1987; Schönharting & Abrahamsen 1989) so that the age must lie in the 57–54 Ma interval (Vandenberge et al. 2012). The Voring basalts are thus contemporaneous with the NE Greenland basalts.

Sills are frequent on both conjugate margins. There are extensive sills in the Voring Basin inboard of the lava areas (Skogseid et al. 1992; Planke et al. 2005; Neumann et al. 2013); two such sills have been dated by the U–Pb (zircon) method to 56.3 ± 0.4 Ma and 55.6 ± 0.3 Ma (Svensen et al. 2010). On the East Greenland margin, sills occur both onshore and in the offshore sedimentary basins, mainly inboard of the offshore lava areas (Hamann et al. 2005; Tsikalas et al. 2005). The age interval of 55–52 Ma obtained in this study for five basaltic sills onshore overlaps with the age of the Voring sills and the conjugate basalt lava plateaux, but also extends to slightly younger ages.

Pre-breakup volcanism and sedimentation

Pre-breakup magmatism took place along the southern part of the East Greenland margin from South Greenland to the southern Blosseville Kyst around 68°30’N (Fig. 1). As we see it, the Iceland plume beneath Greenland here delivered hot mantle material to melt beneath the thinning lithosphere over a distance of about 1000 km. There are no pre-breakup extrusive or intrusive rocks in the onshore areas in NE Greenland; however, pre-breakup volcanism may have been located closer to the proto-breakup line where the lithosphere was thinner, and it is thus possible that pre-breakup volcanic rocks are present in the offshore areas. Seismic sections are inconclusive (Tsikalas et al. 2005). If a pre-breakup volcanic succession is confined to the vicinity of the proto-breakup line, the trend of the breakup line north of the Jan Mayen Fracture Zone,
cutting across the basin and away from the present NE Greenland coast (e.g. Gaina et al. 2009), can explain the absence of such rocks onshore NE Greenland. However, it is likely that the magma production varied along the rift zone as it did during breakup, with magma production decreasing northwards (Voss et al. 2009). Voss et al. suggested the existence of a lithospheric-scale barrier, and we speculate that such a barrier may have blocked northwards flow of hot plume mantle before breakup, resulting in little or no melting prior to breakup within the rift system north of the barrier.

A large-scale feature that could have acted as a barrier is the Caledonian fold belt. This huge belt runs approximately north–south east of the Caledonian Front (Fig. 1) and is interpreted to continue south beneath the Blosseville Kyst basalts and run into the Atlantic Ocean in the southern part of the Blosseville Kyst (Pedersen et al. 1997). The strength of the Caledonian lithosphere could have caused the strong eastward deflection of the early line of breakup in the southern part of the Blosseville kyst seen in all reconstructions (e.g. Gaina et al. 2009). If the Caledonian lithosphere was also significantly thicker than the unmodified Precambrian lithosphere, it could have acted as an efficient barrier for northwards mantle flow at the base of the lithosphere. As the Caledonian mountain-building event was a continent–continent collision, it is conceivable that the resulting lithosphere would have been thickened, but its thickness at the time of breakup cannot be established.

In the onshore part of NE Greenland during the Palaeocene, there was no volcanic succession to disturb or block the drainage channels, and the occurrence of Palaeocene marine sandstones in Wollaston Forland shows that sand was being actively transported towards the basins in the east (Nøhr-Hansen et al. 2011). It is thus likely that the offshore basins contain a well-developed Palaeocene sandstone succession.

**Syn-breakup volcanism**

The oldest linear magnetic anomalies recorded along the NE Atlantic margins are anomalies 24A and 24B (e.g. Hinz et al. 1987; Larsen 1990; Eldholm & Grue 1994; Skogseid et al. 2000; Gaina et al. 2009; Gernigon et al. 2012). Continental breakup thus took place almost simultaneously along the whole margin south of the Greenland–Senja Fracture Zone within the time interval represented by magnetochron 24r (57–54 Ma). Volcanism was copious along all parts of the margin, but there was a production gradient north of the Greenland–Iceland–Faroes ridge where the magma production decreased northwards, both along the eastern Jan Mayen margin (Breivik et al. 2012) and along the NE Greenland margin (Voss et al. 2009; Tsikalas et al. 2012), based on the northward decreasing amount of magmatic underplating. This led Voss et al. (2009) to suggest the existence of the lithospheric-scale barrier discussed above.

Petrological analysis of the lavas on Hold with Hope led Thirlwall et al. (1994) to conclude that the Lower Series basalts were produced by melting of mantle typical of the Iceland plume and not the ambient asthenospheric mantle. The reason for the geochemically depleted character of the lavas was argued to be a high degree of melting (around 20%) beneath a thin lithosphere. We speculate that the degree of melting was particularly high because the stretching and thinning during the Palaeocene in the northern areas took place with little or no accompanying volcanism, creating a lithospheric thinspot.

**Alkaline volcanism away from the margin**

The 53–50 Ma strongly alkaline mafic volcanic rocks in the nunatak zone, situated c. 200 km inland from the continental margin, can be explained as products of local small-scale melting (Bernstein et al. 2000) and are not easily interpreted within the large tectonic framework of the North Atlantic. They are in a similar geological setting, away from the margin and immediately following the flood basalts, to the alkaline rocks in the Prinsen of Wales Bjerge Formation at 69°N (Fig. 10; Peate et al. 2003). Somewhat similar alkaline mafic volcanic rocks are also found off mid-Norway, likewise situated c. 200 km landwards of the continental margin, and K–Ar dated at 55.7 ± 0.9 Ma (Bugge et al. 1980). Prestvik et al. (1999) noted that the occurrences in Norway and NE Greenland may be associated with zones of lithospheric weakness at the continental ends of the Jan Mayen Fracture Zone. As the events are local they need not be contemporaneous.

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Fig. 8. $^{40}$Ar/$^{39}$Ar age spectra and plateau ages for two dyke intrusions in NE Greenland. Uncertainties are ±2σ.

Fig. 9. $^{40}$Ar/$^{39}$Ar age spectrum and plateau age for a felsite from the Kap Broer Ruys alkaline intrusion.
Fig. 10. Radiometric ages of Tertiary igneous rocks along the East Greenland margin, plotted versus geographical latitude. Uncertainties are omitted for clarity. The compilation of data used is given in the supplementary material, with references.


**Eocene to Oligocene post-breakup intrusive activity**

Post-breakup intrusions on the NE Greenland margin are all alkaline and are far less numerous than farther south; none the less, they span a wider time interval than farther south (Fig. 10). They come in age groups of c. 49 Ma, 40–36 Ma and 30–25 Ma.

The 49 Ma Kap Broer Ruys and (inferred coeval) Myggbukta complexes on Hold With Hope are similar in age to both lavas (Larsen et al. 2013) and several intrusions on the East Greenland margin between 65°N and 70°N (Fig. 10). Bernstein et al. (1998) and Tegner et al. (1998, 2008) suggested that the 50–47 Ma group of intrusions on the central East Greenland margin reflect melting owing to the proximity of the centre of the Iceland plume to the continental margin at that time, but this explanation cannot apply also for the intrusions on Hold With Hope more than 500 km farther north. Gernigon et al. (2012) outlined an important mid-Eocene plate reorganization in the Norwegian Basin at 49–48 Ma, including changes in both spreading rate and direction. There may be a connection between this and the many intrusions emplaced on the East Greenland margin at the same time, but the specific cause remains speculative.

The 40–36 Ma age group comprises the Kap Simpson and Kap Parry intrusive complexes and some alkali basaltic dykes, all on Traill Ø. Traill Ø lies on the landward extension of the Jan Mayen Fracture Zone and also landward of a large elongate magnetic high offshelf that has been interpreted as igneous and termed the Traill–Voring igneous complex. The age of the Voring end of this (the Voring Spur) is around 50–49 Ma according to Olesen et al. (2007) and extended to mid- to late Eocene (i.e. c. 48–34 Ma) by Gernigon et al. (2009). Only the late Eocene part fits with the ages of the intrusions on Traill Ø, but Gernigon et al. (2009) proposed that the Jan Mayen Fracture Zone has acted as a leaky transform along which magmas have been produced intermittently since breakup and until now. Similar-aged intrusions in SE Greenland around 67°N have been connected to a pronounced regional uplift at that time (Tegner et al. 2008). More than one mechanism may thus have been involved in the magma production.

The Werner Bjerge complex in northern Jameson Land apparently spans a range of ages between 30 and 25 Ma (Rex et al. 1979; Brooks et al. 2004). During this time, the Ægir Ridge was becoming extinct and the Kolbeinsey Ridge was propagating northwards past the Blosseville Kyst and Jameson Land. Thus, rifting and spreading had moved much closer to the NE Greenland margin, but a direct causal connection is difficult to make.

**Miocene magmatism**

In the early Miocene, at 22 Ma, the Kolbeinsey Ridge had propagated north to connect to the Mohn Ridge via the western Jan Mayen Fracture Zone, and thereby the modern spreading system had been established (e.g. Gaina et al. 2009). Magmatism on the conjugate margins had presumably stopped. Magmatism possibly continued at local seamounts away from the spreading ridge, as is seen in recent time on Jan Mayen (Trønnes et al. 1999), Vestersibanken (Haase & Devey 1994) and the Eggvin Bank (Mertz et al. 2004). There are remnants of Miocene volcanic rocks on Svalbard, but these seem to be younger (7–2 Ma, Skjelkvåle et al. 1989) and have different compositions (Sushchevskaya et al. 2009). The 20 Ma age for the alkaline Hvalrosø sill in NE Greenland is difficult to relate to a specific tectonic event. The most significant event around 20 Ma is the opening of the Lena Trough and the gateway between the Atlantic and the Arctic oceans. This began much earlier but, because of the highly oblique spreading, only around 20 Ma were the continental crusts of Greenland and Svalbard no longer in contact (Jakobsson et al. 2007; Engen et al. 2008). The distance to Hvalrosø is 800 km; however, the unusual chemical composition of the Hvalrosø sill also points towards the Lena Trough, where similarly unusual, potassic high-alumina alkali basalts have been dredged (Nauret et al. 2011) (Table 2). These are presumably of recent age. They were interpreted as originating in subcontinental lithospheric mantle, and the Hvalrosø sill probably originated in very similar mantle bearing plagiogopite, which provided the high K and Al in the melts.

**Conclusions**

The 18 new reliable radiometric ages of igneous rocks from NE Greenland constitute the largest available age dataset from the NE Greenland continental margin. The rocks are difficult to date because of the very low K contents of the tholeiitic basalts and frequent presence of excess argon, also encountered in this study. Despite precise ages for single samples, the range of ages for the Lower Plateau Lava Series is large and its age can be constrained only within the interval 56–53 Ma. One result from the UPLS lies within the age interval for the LPLS. Tholeiitic sills and dykes throughout the region from Traill Ø to Shannon, with compositions fairly similar to the lavas, range in age from 55.14 ± 0.37 Ma to 51.27 ± 1.21 Ma; that is, many were emplaced at the same time as the lavas and some are slightly younger.

There are no pre-breakup volcanic rocks in NE Greenland. Such rocks may exist in the offshore basins near the proto-breakup line, but it is also possible that they were never formed. This could happen if a lithosphere-scale barrier, such as the Caledonian lithosphere, curtailed or stopped the northward flow of hot Iceland plume mantle. The barrier became less effective at breakup and allowed the hot mantle to travel north beneath the thinning lithosphere, where it underwent high degrees of melting and thereby produced the geochemically depleted basalts.

The presence of Palaeocene sandstones onshore NE Greenland and the lack of concomitant volcanic rocks that could block the drainage systems indicate good transport conditions and suggest that the offshore basins may contain a well-developed Palaeocene sandstone succession.

At the post-breakup stage, alkaline magmas were produced intermittently over a long time span, mainly at 53–49 Ma (inland lavas, Kap Broer Ruys, Myggbugta?), 40–36 Ma (Kap Parry, Kap Simpson), 30–25 Ma (Werner Bjerge) and 20 Ma (Hvalrosø). Each of these periods coincides with plate-tectonic events such as reorganization (50–49 Ma, around 30 Ma), uplift (40–36 Ma) and opening in the north (20 Ma). The 20 Ma sill has an unusual composition that points distinctly to the north. In all cases, direct causal connections are difficult to prove.

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