Compilation and appraisal of geochronological data from the North Atlantic Igneous Province (NAIP)

CAMILLA M. WILKINSON1,2*, MORGAN GANERØD1, BART W. H. HENDRIKS1,3 & ELIZABETH A. EIDE4

1Geological Survey of Norway, Post Box 6315 Sluppen, 7491 Trondheim, Norway
2Present address: Hatfield Marine Science Centre, Newport, Oregon 97365, USA
3Present address: Statoil Research Centre, Arkitekt Ebbells veg 10, 7053 Ranheim, Norway
4National Academy of Sciences, 500 Fifth Street NW, Washington, DC 20001, USA

*Correspondence: camilla.wilkinson@noaa.gov

Abstract: The North Atlantic Igneous Province (NAIP), composed of volcanic sequences and intrusive rocks, occurs onshore in Greenland, the Faeroe Islands, the UK and Ireland, and offshore surrounding these areas as well as the west coast of Norway. Geochronological data have been published for Cenozoic igneous and volcanic rocks for much of the province, and provide valuable information to analyse the evolution of the province and magmatic processes more broadly. As part of the NE Atlantic Geosciences (NAG) cooperation, we examined approximately 700 dates from over 70 published studies and created a comprehensive database to facilitate ready access to this important information. This includes U–Pb, Rb–Sr, Re–Os, 40Ar/39Ar and K–Ar ages presented relative to the Geological Time Scale 2012. 40Ar/39Ar and K–Ar ages have been recalculated to a common reference. The complete database includes data that range from approximately 177 to 0.19 Ma. Our evaluation shows that variable sample quality, ambiguous data-handling methods, inadequate data reporting and data interpretation should preclude the use of data for purposes of rigorous geochronological analysis. Through a series of filtering techniques described here, we suggest excluding > 500 dates as being of too poor a quality to use in age determinations. Our analysis highlights the need for published geochronological studies to include sufficient information to allow critical assessment of ages and interpretations. We present an ‘optimized’ dataset containing 130 ages that range from approximately 64 to 13 Ma. The filtered dataset emphasizes the need for firm chronological benchmarks and suggests that some sub-provinces in the NAIP would greatly benefit from renewed research attention.

Supplementary material: The full NAG-TEC Geochronological Database 001 and Data Evaluation 002 are available at https://doi.org/10.6084/m9.figshare.c.3554472

Gold Open Access: This article is published under the terms of the CC-BY 3.0 license.

The North Atlantic Igneous Province (NAIP), with its combined onshore and offshore volcanic sequences, is one of the most extended Large Igneous Provinces (LIPs) in the world in terms of areal extent and inferred volume (Saunders et al. 1997; Saunders 2016). It is estimated that the entire NAIP covers a total area of 1.3 × 10⁶ km². Although the related volume may be difficult to envisage, its original volume has been estimated to reach 5 × 10⁸–10 × 10⁹ km³ (e.g. Storey et al. 2007). This is comparable to some of the best recognized examples of LIPs, such as the Siberian Traps (>4 × 10⁹ km³; e.g. Ivanov 2007) and the Karoo–Ferrar Province (>2.5 × 10⁹ km³; cf. Courtillot & Renne 2003), and is larger than others, such as the Deccan Traps (c. 1.5 × 10⁹ km³; e.g. Beane et al. 1986) and the Columbia River flood basalt province (e.g. c. 2 × 10⁵ km³; cf. Reidel et al. 2013).

The classification of the NAIP as a LIP agrees with the definition of Bryan & Ernst (2008), who stated that LIPs are magmatic provinces with areal extents >1 × 10⁶ km², igneous volumes >1 × 10⁹ km³, maximum lifespans of approximately 50 myr and igneous pulse(s) of short duration (c. 1–5 myr), during which a large proportion (>75%) of the total igneous volume is emplaced. The eruption and emplacement of LIPs have been associated with processes such as crustal uplift (Saunders et al. 2007) and erosion (Campbell & Griffiths 1990; Nadin et al. 1997); continental rifting (White & Mackenzie 1989; Courtillot et al. 1999); global environmental change (Svensen et al. 2004); and mass extinction (Wignall 2001; Courtillot & Renne 2003).

From: PÉRON-PINVIDIC, G., HOPPER, J. R., STOKER, M. S., GAINA, C., DOORNENBAL, J. C., FUNK, T. & ÅRTING, U. E. (eds) 2017. The NE Atlantic Region: A reappraisal of crustal structure, tectonostratigraphy and magmatic evolution. Geological Society, London, Special Publications, 447, 69–103.
First published online November 8, 2016, https://doi.org/10.1144/SP447.10
© 2017 The Author(s). Published by The Geological Society of London.
Publishing disclaimer: www.geolsoc.org.uk/pub_ethics
One of the efforts of the NE Atlantic Geosciences (NAG) cooperation has been the assembly of the Tectonostratigraphic Atlas (TEC). This work has involved compiling published geochronological data for Cenozoic igneous rocks from the NAIP in the NAG-TEC Geochronological Database (see Fig. 1b–e). The primary aim of this paper is to examine and assess the quality and geological significance of data contained in that database. As described in the section ‘The NAG-TEC Geochronological Database’, this database brings all isotope geochronological data together relative to a common age reference system (Geological Time Scale 2012 of Gradstein et al. (2012)). This has never before been carried out on this scale for the NAIP. In some cases, insufficient reporting of the analytical protocol has prevented the recalculation of ages (Fitch et al. 1969, 1988; Mørk & Duncan 1993; Archer et al. 2005). However, full details are provided in the NAG-TEC Geochronological Database. To avoid confusion, it should be noted that other contributions in this Special Publication may refer to data taken directly from the original source without recalculation.

To demonstrate the potential applications of the database, we offer an evaluation of previously reported age data. We concentrate on K–Ar and $^{40}$Ar/$^{39}$Ar data (hereafter referred to as Ar–Ar), with the inclusion of reliable U–Pb data where available. The database offers the possibility of examining the detail of data coverage and provides a reference that can be used for testing models of LIP formation (King & Anderson 1998; Torsvik et al. 2001; Foulger 2002; Meyer et al. 2007; Ganerød et al. 2010). Finally, the database allows identification of the remaining data gaps, which will assist in focusing future research efforts in the NAIP.

The NAIP was divided in two by the opening of the North Atlantic Ocean, and its principal components are now widely distributed from Canada to the British Isles (see Fig. 1a). Although dominantly mafic in composition, the NAIP, like most other LIPs, contains a significant number of ultramafic and silicic components including: the extruded volcanic sequences of Baffin Island and West Greenland (basaltic and picritic in composition); the East Greenland continental flood basalts (basaltic in composition) and intrusions (e.g. central intrusions: sills, and dyke swarms, both mafic and felsic in composition); the seawards-dipping reflector sequences (SDRs) of the East Greenland and NW European rifted margins; the Faeroe Islands onshore and offshore volcanic sequences; and the British–Irish Palaeogene Igneous Province (BPIP), which crops out in Northern Ireland (Antrim), the Inner Hebrides of Scotland (e.g. Isles of Mull and Skye).

Fig. 1. (a) Map of the North Atlantic showing the geographical extent of the North Atlantic Igneous Province (NAIP). Filled circles indicate sampling localities related to geochronological data presented in the unfiltered NAG-TEC Database. Rectangular boxes outline areas shown in Fig. 1(b)–(e).
Obtaining precise age determinations for LIPs using various isotopic geochronological techniques is challenging for a number of reasons. In general, magmatic rocks from LIPs erupt at or near the Earth’s surface and occasionally in aqueous environments, making them susceptible to chemical alteration and weathering. The application of specific isotopic geochronological methods to these rocks also presents specific challenges. Use of the

**Fig. 1.** (b) West Greenland; (c) East Greenland; (d) the Faeroe Islands; and (e) the British–Irish Palaeogene Igneous Province (BIPIP). SDRs denote seawards-dipping reflector sequences.
U–Pb method, for example, may not be possible due to a lack of suitable minerals on which the technique can be performed (e.g. zircon), coupled with the difficulty in separating such minerals when they are present (e.g. Corfu et al. 2013). The K–Ar and Ar–Ar methods require samples that contain sufficient K, which may be problematic for the predominantly basaltic products of LIP magmatism. The Rb–Sr method uses minerals such as mica and feldspar (as does the Ar–Ar method), which are highly susceptible to alteration, resulting in ages that are relatively less precise, difficult to interpret or yield ages that may represent partial or complete overprints of processes other than crystallization (e.g. Dickin 1981).

Despite these difficulties, improvements in analytical capabilities of various isotopic systems and a better understanding of the sources of age variation have, with time, enabled more accurate data to be obtained from individual minerals in LIP rocks and have demonstrated the interpretive value of having accurate ages at the level of individual flows. For example, older geochronological datasets suggested long-lived magmatic systems, with available ages sometimes spreading over tens of millions of years, whereas more recent geochronological data demonstrate eruptions over only a few hundreds of thousands of years, or no more than 1–5 Myr (e.g. Deccan LIP: Hofmann et al. 2000). For other datasets, the opposite has proven to be the case, with new palaeomagnetic data indicating emplacement of magma over longer durations than previously thought (e.g. the Paraná–Etendeka LIP: Dodd et al. 2015).

The North Atlantic Igneous Province (NAIP)

Comprehensive descriptions of the geological setting and geochemistry of the NAIP are provided in several key publications (Upton 1988; Saunders et al. 1997; Storey et al. 1998, 2004, 2007; Meyer et al. 2007; Tegner et al. 2008; Larsen et al. 2015; Saunders 2016). The following is a summary of the main observations. The Stoker et al. (2016) contribution in this volume provides additional, detailed information. Although we exclusively focus on the Cenozoic rift-related volcanism of the NAIP, it should be appreciated that the NAIP is just a recent chapter in the story of the North Atlantic rift system, which experienced c. 400 Ma of collisional and extensional tectonics. Older structures are associated with the Caledonian and Appalachian orogenic events, which brought together the early continents of Laurentia and Avalonia as the Iapetus Ocean closed. Contractual events may have started as early as the Ordovician but culminated in Silurian to Devonian times (e.g. Cocks & Torsvik 2011). Devonian rift basins and sedimentary sequences (observed in East Greenland, Norway, Svalbard, and northernmost parts of the UK) are thought to mark the collapse of the Caledonian belts (e.g. Andersen & Jamtveit 1990; Fossen 2010). Rift basins continued to develop through non-continuous stretching of the crust into the Carboniferous, and throughout the Permian and Triassic (e.g. Suryik 1990; Stemmerik 2000; Müller et al. 2005). During the Jurassic and throughout the Cretaceous, major extension and basin formation was occurring in all parts of the proto-North Atlantic (e.g. Norwegian–Greenland Sea and North Sea; Nøttvedt et al. 2008; Osmundsen & Ebbing 2008). The separation of Greenland from the Eurasian plate took place at the Paleocene–Eocene boundary and was preceded and accompanied by one of the largest recorded volcanic events on Earth.

It is generally accepted that the formation of the NAIP was initiated during the Palaeogene, in two distinct phases that correspond to pre- and post-rift magmatic events separated by the opening (i.e. syn-rift) of the North Atlantic. Prior to c. 63 Ma, there is little evidence to suggest excessive volcanism, although ages of c. 80–64 Ma have been reported for parts of the province (e.g. East Greenland; Noble et al. 1988); offshore Shetland Isles (K–Ar study of Fitch et al. 1988); and the Rockall trough (K–Ar study of Roddick et al. 1989). However, since K–Ar studies are unable to identify excess Ar it would be necessary to independently verify an older phase by other means (i.e. Ar–Ar or U–Pb data). The products of the first phase include the emplacement of continental flood basalt sequences (e.g. West Greenland). The ages pertaining to pre-rift volcanism converge on the range 62–58 Ma (Sinton & Duncan 1998; Sinton et al. 1998; Storey et al. 1998; Hansen et al. 2002; Larsen et al. 2015), although considered by some to tend towards and beyond the upper limit in this range (e.g. >62 Ma; Ganerød et al. 2010). Following a proposed ‘gap’ or ‘hiatus’ in widespread volcanism at c. 57 Ma (e.g. Saunders et al. 1997), a second and more voluminous phase of magmatism, dated at c. 56–53 Ma coincides broadly in time with the opening of the North Atlantic (Saunders et al. 1997). Products of this second phase are exposed in SDRs in Greenland (Larsen & Saunders 1998; Tegner et al. 1998), the Faeroe Islands (e.g. Larsen et al. 1999b), and Northern Ireland (Meighan et al. 1988; Gamble et al. 1999; Ganerød et al. 2010).

Geochronological methods

The NAG-TEC Geochronological Database contains data that have been determined using a range of isotopic techniques applied to a range of
materials, such as basalt and granite (e.g. plagioclase, amphibole, biotite, whole rock and zircon), and rhyolite (e.g. sanidine, zircon, and glass). Samples identified as particularly challenging for dating studies include: dredged seafloor samples (O’Connor et al. 2000); rocks later affected by hydrothermal alteration and/or weathering (Mussett 1986; Noble et al. 1988; Lenoir et al. 2003); rocks containing no zircon (or containing zircon that is difficult to separate; e.g. Corfu et al. 2013); rocks with low K content, or very few K-bearing mineral phases (e.g. Tegner & Duncan 1999; Archer et al. 2005; Larsen et al. 2014); aphyric rocks (Sinton et al. 1998), and volcanic glass (e.g. Dickin & Jones 1983).

The majority of ages in the database have been determined by the K–Ar or Ar–Ar methods. These methods are based on the radioactive decay of naturally occurring 40K to stable 40Ar, and so in principle can be applied to any K-bearing rock or mineral. Details of the K–Ar and Ar–Ar dating methods can be found in Dalrymple & Lanphere (1969) and McDougall & Harrison (1999). Ar–Ar ages are calculated relative to a standard mineral (e.g. the Fish Canyon Tuff sanidine: Renne et al. 1998, 2010, 2011; Kuiper et al. 2008) to allow indirect determination of 40K. Ar–Ar ages may be calculated relative to a number of different standards, as well as to one of three 40K decay constants currently in use (Steiger & Jäger 1977; Min et al. 2000; Renne et al. 2010, 2011). As described below, we have recalculated the ages relative to a common reference to make age comparisons and interpretations of different datasets possible.

Inaccurate K–Ar and Ar–Ar apparent age determinations will result if data show that the rock or mineral has experienced post-crystallization disturbance, such as weathering, alteration and/or a reheating event. This kind of disturbance may result in episodic diffusive loss of radiogenic 40Ar and partial resetting of the argon clock, redistribution or loss of K, formation of altered minerals that do not retain 100% of Ar over geological time, and the incorporation of an inherited (related to a previous geological event) or ‘excess argon’ (hereafter referred to as 40ArE) component that contributes additional 40Ar, thus artificially increasing the apparent age.

A small percentage of the data featured in the NAIP database has been determined by other geochronological techniques (i.e. U–Pb and Rb–Sr). U–Pb ages (uranium series decay from 238U to 206Pb) have been considered: however, in some cases, a concordia age has been accepted. It should be noted that a concordia age is often associated with a lower uncertainty compared to the $^{206}\text{Pb}/^{238}\text{U}$ age and, therefore, it may underestimate the true uncertainty. The majority of Rb–Sr data included in the NAIP database are lower in quality compared to either U–Pb or Ar–Ar data. Rb–Sr ages in the database are often associated with high mean square weighted deviation (MSWD) values (Gibson et al. 1987; Meighan et al. 1988) or lack comprehensive data reporting (e.g. uncertainties have been changed (increased) to give a lower MSWD value: Dickin 1981).

The NAG-TEC Geochronological Database

The NAG-TEC Geochronological Database incorporates only published data related to the NAIP. It includes age data that range from 0.19 Ma (K–Ar: Jan Mayen) to 177 Ma (K–Ar: offshore UK). Every effort has been taken to make this database as complete as possible, although omissions are unavoidable. We acknowledge that a considerable amount of age data are unpublished (e.g. contained in thesis manuscripts) and these could not be included in the database. In addition, over 550 individual ages related to volcanic activity on Iceland and the present-day position of the Icelandic hotspot are in peer-reviewed literature, but not included in our database. These will form a separate contribution currently in progress.

The compilation of the NAIP database and subsequent data evaluation has relied on the information provided in the publication that originally reported the data. Inadequate data reporting is a problem and hinders thorough evaluation of the data. In some cases, studies may have failed to fully report their analytical protocol or failed to provide raw data in supplementary data tables. We note that the level of detail for analytical reporting of geochronological data 20 years ago or more was different compared to recent times for which a minimum data-reporting standard is now established (Renne et al. 2009). In other cases, studies make reference to geochronological data, but not to the original publications in which these data were first presented (e.g. Bell & Williamson 2002). The result is that much of the information on how data were acquired, and how ages were calculated, is ignored or simply lost. Therefore, it has often been impossible, or at best difficult, to verify data quality. In the current compilation only the first published occurrence of the geochronological data is used, and the information that was included there is used to rate the data quality.

Ar–Ar data are calculated relative to an assigned standard (fluence monitor) age and a $^{40}$K decay constant, which continue to be the subject of ongoing debate (Renne et al. 1998, 2010, 2011; Min et al. 2000; Kuiper et al. 2008). There are several fluence monitors currently in use by the Ar–Ar community, including sandine (e.g. Fish Canyon, Taylor Creek and Alder Creek), biotite (e.g. GA1550, Tinto
and B4) and amphibole (Hb3gr and MMHb-1), and 40K decay constants (e.g. Steiger & Jäger 1977; Min et al. 2000; Renne et al. 2010, 2011). The ages assigned to fluence monitors and the decay constant for K have changed over time. For example, ages assigned to the Taylor Creek sanidine range from 28.619 to 27.92 Ma. In addition, several 40K decay constants are currently in use, with recent redeterminations designed to reconcile U–Pb and Ar–Ar ages, and to improve precision and accuracy on existing measurements (Renne et al. 2010, 2011). This can cause confusion for non-chronologists and the misuse of Ar–Ar age data, which can lead to incorrect geological conclusions. Therefore, in keeping with the Geological Time Scale 2012 (Gradstein et al. 2012) chronostratigraphic framework, and based on the values agreed during the EARTHTIME IV Workshop (held in 2009), the entire dataset in the database has been recalculated to the reference system recommended in Kuiper et al. (2008).

A summary of the geochronological techniques applied to both onshore and offshore areas of the main geographical regions (divided into sub-provinces) of the NAIP is presented in Table 1. In total, approximately 699 ages exist for the entire NAIP (excluding Iceland). K–Ar and Ar–Ar (290 and 366 ages, respectively) are the most used analytical techniques to date products of extrusive and intrusive activity. Onshore localities, as one would expect, are associated with the greatest density of data, with a focus on Greenland, the UK and Ireland.

Data evaluation

Taking the entire province as a whole and considering all age data (+2σ uncertainty), the picture is not a simple one. The cumulative frequency diagram (Fig. 2) shows continuous NAIP volcanism spanning approximately 55 myr. There are no distinguishable pulses or across-province correlated ‘breaks or gaps’ in volcanism. It is, however, highly unlikely that all 699 dates represent emplacement ages. Therefore, it is necessary to evaluate the data in the database and produce an optimized dataset in order to better understand the time correlation across the province.

Approach to data evaluation

The filtering process comprised selection of those data that are based on tightly constrained isochrons or weighted means (e.g. 238U/206Pb ages: Ganerød et al. 2011), and ages that conform to criteria defining a statistically robust age (e.g. definition of a valid plateau/isochron for Ar–Ar step heating data: McDougall & Harrison 1999; Baksi 2005a), and have well documented analytical procedures. For data that demonstrate an elevated trapped atmospheric ratio (40Ar/36Ar atmospheric value), and where the use of the inverse isochron age is shown to be justified, the inverse isochron age has been taken as the preferred age. The reproducibility of ages (between separate samples or splits of the same sample) has also been a consideration for accepting data, and in some cases it has been possible to calculate a weighted mean age to further refine the dataset. U–Pb and Ar–Ar data that are demonstrably variable in quality and K–Ar data have been excluded from the accepted dataset but remain part of the complete NAIP Geochronological Database. Critical examination of Ar–Ar data is commonplace and has been carried out previously by Baksi (2005a, b, 2007a, b), with specific reference to Ar–Ar ages related to hotspot activity. Other examples include Jourdan et al. (2007, 2009b), who reviewed geochronological data related to terrestrial impact structures and the Karoo LIP. For the purpose of this analysis, we conducted a two-stage evaluation and filtering process. The first stage involved critical examination of published data (including a statistical assessment). A second, more rigorous filtering removed Ar–Ar whole-rock and groundmass data, because several studies have now shown that whole-rock/groundmass Ar–Ar
ages older than 20–30 myr are unreliable (e.g. Hofmann et al. 2000). A comparison between the two filtering stages is discussed later.

To allow evaluation of the data, we determined that the following information had to be accessible in the original publication:

- Sample characterization – detailed sample descriptions, including whether the samples are dredged seafloor rocks; characterization of minerals separated for dating (i.e. thin section and/or electron microprobe analysis), or X-ray fluorescence (XRF) data for whole-rock samples (i.e. K₂O content; description of any alteration (secondary minerals, zeolites) and/or inclusions that may be a source of ⁴⁰Ar⁎, and information regarding additional quantitative methods carried out to assess the alteration state, such as Alteration Index: Baksi 2007a, b). A description of alteration is critical as altered material may result in partial loss of radiogenic argon (⁴⁰Ar⁎) and lead to inaccurate estimates of K–Ar or Ar–Ar crystallization ages, and/or age estimates that are systematically too young.
- Cleaning procedures for whole rock and mineral separates – details of cleaning procedures conducted, or necessary to remove alteration. Examples may include acid leaching (i.e. nitric acid

Fig. 2. All geochronological data for the entire North Atlantic Igneous Province (NAIP) shown in terms of their cumulative distribution. Data are presented relative to the geomagnetic polarity timescale of Gradstein et al. (2012). Uncertainties are given at the 2σ level. Note: ages older than 90 Ma are not shown.
Data presentation by sub-province

As a full review of the accuracy and precision of all 699 ages available for the NAIP is outside the scope of this contribution, our evaluation has focused on onshore data. However, a summary of offshore data is provided. The evaluation of key data and subsequent filtering should be considered as a guideline concerning the current state of geochronological knowledge for the NAIP. For clarity, we present below a general geological and geochronological summary of all data included in the full NAG-TEC database (prior to filtering) with reference to key studies for each sub-province of the NAIP.

The selected dataset (following filtering) for each sub-province is presented in Tables 2–5. Data uncertainties are quoted at the 2σ confidence level. The final optimized dataset is displayed on compilation event charts (radiometric age plotted v. geographical latitude) and summary stratigraphic columns (Fig. 3).

West Greenland

General geology. The Palaeogene volcanic rocks in West Greenland (Fig. 1a) form the second largest exposed basalt succession found in the region, extending from Disko and Nuussuaq in the south, over Ubekendt Ejland, and up to Svartenhuk Halvø in the north (Saunders et al. 1997; Storey et al. 1998; Larsen & Pedersen 2009; Larsen et al. 2015). The flood basalts, which cover an area of approximately $45 \times 10^3$ km$^2$ onshore and continue further offshore ($10 \times 10^4$ km$^2$), exhibit varying stratigraphic thickness from approximately 3 km on Disko to approximately 5 km on Ubekendt Ejland and Svartenhuk Halvø. The lava succession in the Disko–Nuussuaq area has been divided into three lithostratigraphical units (Hald & Pedersen 1975), which have then been further subdivided into six formations. From old to young: (1) the Vaigat Formation (present from Disko and northwards to Svartenhuk Halvø), subdivided into three members corresponding to distinct volcanic cycles of lavas and hyaloclastites, mostly of picritic composition; (2) the Maligat Formation (present on Disko and Nuussuaq), subdivided into three major and one minor member, is dominated by feldspar-phyric tholeiitic flood basalts; (3) the Svartenhuk Formation (tholeiitic basalts, corresponding to various members including the Skalø Member); (4) the Naqerloq Formation (tholeiitic basalts corresponding to various members including the Kanisut Member); (5) the Erqua Formation (alkaline basaltic in composition); and (6) the Hare-øen Formation (olivine-phyric basaltic in composition). Lavas erupted predominantly in a subaerial environment, but the presence of hyaloclastites, breccias and marine mudstones in the Vaigat Formation and the lower part of the Maligat Formation

(HNO$_3$) for material containing ferromagnesium phases, or hydrofluoric acid (HF) for feldspars: Baksi 2007a, b).

- Criteria used to define an Ar–Ar ‘plateau age’ – for the Ar–Ar incremental heating method, it is important to know which criteria were followed to define a ‘plateau age’. For example, >50% of the cumulative $^{39}$Ar released over three or more consecutive heating steps, which overlap at the 2σ level (McDougall & Harrison 1999). However, 50–70% is considered by some to represent only a ‘mini plateau’, and a ‘plateau age’ is one defined by >70% of the cumulative $^{39}$Ar (e.g. Hofmann et al. 2000; Jourdan et al. 2007). The mean square weighted deviation (MSWD) of the plateau and/or inverse isochron age along with the probability value (P) should also be given (statistically valid if $P > 0.05$; e.g. Baksi 2003). Jourdan et al. (2009b) strongly advised that the value of $P$ is reported along with the MSWD for any given age, so that readers can estimate for themselves the statistical significance of the data.

- Presentation of full degassing information – for the Ar–Ar incremental heating method, it is important that degassing data (isotopes $^{40}$Ar, $^{39}$Ar, $^{38}$Ar, $^{37}$Ar and $^{36}$Ar; or ratios $^{40}$Ar/$^{39}$Ar; $^{40}$Ar/$^{36}$Ar; $^{37}$Ar/$^{39}$Ar and $^{38}$Ar/$^{36}$Ar) for the entire experiment, not only the steps that define the plateau or weighted mean, are included in the paper or provided in a supplementary table. This enables the atmospheric component (through the use of the inverse isochron method), Ca/K and Cl/K ratio of each degassing step to be assessed. These kinds of data can help to identify the presence of a $40$Ar$_E$ component and the mineral phase(s) being dated. For example, a lower Ca/K than expected for clean and unaltered plagioclase could imply dating of sericite (Verati & Jourdan 2013), and ages should be taken as a minimum estimate of crystallization unless episodic alteration or weathering can be shown to have occurred very soon after crystallization (e.g. Jourdan et al. 2009a; Polteau et al. 2016). The display of degassing spectrums, isochron diagrams (normal and/or inverse) and degassing data (i.e. $^{37}$Ar/$^{39}$Ar = Ca/K ratio often presented as K/Ca in publications) must be of a suitable scale so that information can be adequately checked and evaluated (Renne et al. 2009; Jourdan et al. 2009b).

- Sample irradiation information – this information should include correction factors for interfering reactions, the average J value; the monitor and monitor age; and the decay constant used for data reduction. Such information allows data from different studies to be recalculated to a common base and compared.
implies deposition in a subaqueous environment during the earliest stages of activity (Larsen & Pedersen 2009). Eocene volcanic rocks have been identified in the westernmost parts of the onshore areas, the Naqerloq Formation, the Erqua Formation and the Talerua Member of the Haresen Formation (e.g. Larsen et al. 2015). Dykes and sills occur throughout the province, and a central intrusion is situated in Ubekendt Ejland. A swarm of lamprophyre dykes cut the youngest volcanic rocks on Ubekendt Ejland (e.g. Storey et al. 1998).

**Geochronology.** All radiometric age data (Fig. 1b) that exist for West Greenland have been determined using the Ar–Ar technique (whole rock, glass, plagioclase, amphibole and K-feldspar). Ar–Ar ages for this sub-province range from 62 to 27 Ma (Storey et al. 1998; Larsen et al. 1999a, 2009, 2015), and include the Vagaat and Maligåt formations (c. 62, and c. 62–61 Ma, respectively; Storey et al. 1998), the Kanisut volcanics (c. 52 Ma: Storey et al. 1998; and c. 56–54 Ma: Larsen et al. 2015), and various dyke systems (e.g. Disko, c. 58–57 Ma (basaltic): Larsen et al. 2015; SW Greenland, c. 55–54 Ma (basaltic): Larsen et al. 1999a, b; and Ubekendt Ejland, c. 34 Ma (lamprophyre): Storey et al. 1998). Until a recent study by Larsen et al. (2015), radiometric dating concentrated almost exclusively on the southern parts of the known volcanic successions. The Ar–Ar data of Larsen et al. (2015) provide a more complete overview of the age distribution and stratigraphy, and include volcanic successions in the Ubekendt Ejland area (e.g. the Qeqertalik Member, c. 59 Ma; the Nûk takisöq Member, c. 55 Ma; and the Erqua Formation, c. 53 Ma), Hareøen, West Nuussuaq (e.g. the Ifsorisok Member, c. 58 Ma; and the Talerua Member of the Haresen Formation, c. 38 Ma) and Svartenhuk Halvø (e.g. the Tunuarsuk Member, c. 59 Ma; the Nuuit Member, c. 58 Ma; the Skaloq Member, c. 58 Ma; the Arfertuarsuk trachyte, c. 57 Ma; the Naqerloq Formation, c. 55–54 Ma; and the Sarqâta qâqâ central intrusion, c. 55–57 Ma).

**East Greenland**

**General geology.** Voluminous basaltic lavas dominate onshore East Greenland (Fig. 1a), extending from the Gap Gustav Holm region in the south to Shannon Island in the north (Saunders et al. 1997). Here we use the Greenland–Iceland Ridge to make the distinction between NE Greenland and SE Greenland. North of the Greenland–Iceland Ridge, thick successions of basalt (exceeding $160 \times 10^3 \text{ km}^3$) are preserved between Kangerlussuaq and Scoresby Sund (divided into the Lower Series Basalts and the Main (or Plateau) Series Basalts). Coastal formations of the Lower Series Basalts (between Kangerlussuaq and Nansen Fjord) include: Vandfalsdale, Mikis, Jacobsen, Hængefjeldet and the locally identified Nansen Fjord Formation (e.g. Larsen et al. 1999b; Storey et al. 2007). The Main Series Basalts are associated with two major cycles, the first represented by the Milne Land (MLF) and Geikie Plateau formations (GP), and the second by the Rømer Fjord (RF) and Skrænterne formations (SF). Sections of the NE Greenland sequence have been temporally correlated with the Middle and Upper Basalt Series of the Faeroe Islands, and the Lower Basalt Series of West Greenland (e.g. Storey et al. 2007).

The lavas of the Prinsen af Wales Formation, which overlie the Main Series Basalts (e.g. Nielsen et al. 2001), are alkaline in composition, and often strongly olivine and pyroxene-phyric. In contrast, the lavas in the northern coastal areas of Kap Dalton on Blosseville Kyst, south of Scoresby Sund (i.e. the Igtertiva Formation), are preserved in a small area, and as a result are less well studied (Larsen et al. 2013). Inland, in the Prinsen af Wales Bjerge region, the Urberget Formation is recognized. The formations notably contain pyroclastic and epiplectic material (Hansen et al. 2002; Peate et al. 2003), as well as thin picritic lava flows and hyolocastites (e.g. the Hængefjeldet Formation). The overlying Main Series Basalts (between Kangerlussuaq and Scoresby Sund) comprise approximately 300 individual flow units with a combined thickness of approximately 6 km. The eruption of lavas, predominantly tholeitic in composition, was initially rapid (i.e. < 1 Ma: Larsen & Saunders 1998; Larsen & Tegner 2006; Storey et al. 2007), then slowed and became punctuated towards the top of the sequence, as implied by intra-basaltic sedimentary rocks and preserved palaeo-soil horizons. Miocene volcanic rocks (e.g. the Vindtop Formation: Storey et al. 2004) are also found to conformably overlie the plateau basalts.

Formations in NE Greenland are cut by multiple generations of intrusions (i.e. dykes and sills) and a large number of plutonic centres of diverse composition (e.g. Skaergaard, Kangerlussuaq, Kap Deichman, Kap Boswell, Kærmér Ø syenite intrusion, and Kærvén gabbro and granite), which have been linked to continental rifting and early seafloor spreading (e.g. Tegner et al. 1998, 2008; Lenoir et al. 2003; Larsen et al. 2014). Local-scale intrusive networks, associated with igneous centres (e.g. Kangerlussuaq Alkaline Complex), are also common. South of the Greenland–Iceland–Faeroes Ridge, offshore basalts (e.g. Roddick et al. 1989), intrusive complexes (e.g. Nualik and Kailineq regions), plutonic centres of diverse composition (e.g. Kruuse Fjord and Imilik layered gabbro intrusions: Tegner et al. 1998) and regional-scale dyke swarms, abundant along the coastal margin (Kap Gustav Holm region: Lenoir et al. 2003), have been identified.
| Locality | Unit | Lithology | Method | Mineral | Type | Age (Ma) | ± 2σ | MSWD (P) | References |
|----------|------|-----------|--------|---------|------|---------|------|----------|------------|
| Disko    | Vaigat Formation (Manitdlat Member) | Alkali picrite | Ar–Ar | Glass (264091) | Plateau | 61.86 | 1 | – | Storey et al. (1998) |
| Nuussuaq | Vaigat Formation (Naujanguit Member) | Tholeiitic basalt | Ar–Ar | Whole rock (402525) | Plateau | 61.55 | 1 | – | Storey et al. (1998) |
| Disko    | Maligât Formation (Middle Rinks Dal Member) | Tholeiitic basalt | Ar–Ar | Plagioclase (328406) | Plateau | 61.45 | 0.8 | – | Storey et al. (1998) |
| Nuussuaq | Maligât Formation (Lower Rinks Dal Member) | Tholeiitic basalt | Ar–Ar | Plagioclase (400323) | Plateau | 61.65 | 0.8 | – | Storey et al. (1998) |
| Hareøen  | Hareøen Formation (Talerua Member) | Transitionally alkaline basalt | Ar–Ar | Groundmass (113482) | Plateau | 38.9 | 0.23 | 2.23 (0.05) | Larsen et al. (2015) |
| Hareøen  | Hareøen Formation (Talerua Member) | Transitionally alkaline basalt | Ar–Ar | Groundmass (113482) | Plateau | 38.57 | 0.24 | 2.27 (0.06) | Larsen et al. (2015) |
| Hareøen  | Hareøen Formation (Talerua Member) | Transitionally alkaline basalt | Ar–Ar | Groundmass (113482) | Plateau | 38.7 | 2.10 (3.9) | | |
| Svatenhuk Halvø | Náqerloq Formation | Enriched tholeiitic basalt | Ar–Ar | Plagioclase (251372) | Plateau | 54.86 | 0.44 | 0.19 (0.99) | Larsen et al. (2015) |
| Svatenhuk Halvø | Náqerloq Formation | Enriched tholeiitic basalt | Ar–Ar | Plagioclase (278596) | Plateau | 55.91 | 0.6 | 0.06 (1.00) | Larsen et al. (2015) |
| Svatenhuk Halvø | Arfertuarsuk trachyte flow | Trachyte | Ar–Ar | Anorthoclase (1931.1) | Plateau | 57.51 | 0.24 | 4.15 (1.91) | Larsen et al. (2015) |
| Svatenhuk Halvø | Skálo Member | Tholeiitic basalt | Ar–Ar | Plagioclase (262838) | Plateau | 57.98 | 0.59 | 0.06 (1.00) | Larsen et al. (2015) |
| Svatenhuk Halvø | Nuuit Member | Tholeiitic basalt | Ar–Ar | Plagioclase (262773) | Plateau | 58.05 | 0.59 | 0.15 (0.99) | Larsen et al. (2015) |
| Svatenhuk Halvø | Tunuarsuk Member | Tholeiitic basalt | Ar–Ar | Whole rock (278566) | Plateau | 59.41 | 0.61 | 0.33 (0.90) | Larsen et al. (2015) |
| Ubekendt Eijland | Erqua Formation | Alkali basalt | Ar–Ar | Whole rock (438728) | Plateau | 53.47 | 0.52 | 0.65 (0.71) | Larsen et al. (2015) |
| Ubekendt Eijland | Nûk takisôq Member | Pitchstone | Ar–Ar | Feldspar (438740) | Plateau | 55.94 | 0.2 | 1.56 (0.18) | Larsen et al. (2015) |
| Ubekendt Eijland Western Nuussuaq and Hareøen | Qeqertalik Member | Tholeiitic basalt | Ar–Ar | Plagioclase (455809) | Plateau | 59.97 | 0.89 | 1.26 (0.26) | Larsen et al. (2015) |
| Western Nuussuaq and Hareøen | Upper Kanisut Member | Acid tuff | Ar–Ar | Alkali Feldspar (135152) | Plateau | 54.03 | 0.33 | 0.48 (0.89) | Larsen et al. (2015) |
| Western Nuussuaq and Hareøen | Middle Kanisut Member | Comendite tuff | Ar–Ar | Sanidine (410140) | Plateau | 54.86 | 0.32 | 0.91 (0.52) | Larsen et al. (2015) |
| Western Nuussuaq and Hareøen | Lower Kanisut Member | Tuff | Ar–Ar | Plagioclase (456257) | Plateau | 56.15 | 0.41 | 0.06 (1.00) | Larsen et al. (2015) |
| Western Nuussuaq and Hareøen | Upper Ifsorisok Member | Tuff | Ar–Ar | Alkali Feldspar (489172) | Plateau | 58.31 | 0.3 | 0.83 (0.58) | Larsen et al. (2015) |
| Western Nuussuaq and Hareøen | Middle Ifsorisok Member | Tuff | Ar–Ar | Alkali Feldspar (489165) | Plateau | 58.66 | 0.34 | 0.25 (0.99) | Larsen et al. (2015) |
| Hellefisk-1 well | 2889.5 m below rotary table | Tholeiitic basalt | Ar–Ar | Whole rock (02A-00-0431) | Plateau | 61.34 | 1.16 | 1.74 (0.09) | Larsen et al. (2015) |
| Hellefisk-1 well | 2938.3 m below rotary table | Tholeiitic basalt | Ar–Ar | Whole rock (02A-00-0447) | Plateau | 59.69 | 1.33 | 0.16 (0.99) | Larsen et al. (2015) |
| Disko | Dyke | Basalt | Ar–Ar | Plagioclase (176601) | Plateau | 54.62 | 0.6 | – | Storey et al. (1998) |
| Disko (northern) | Dyke | Tholeiitic basalt | Ar–Ar | Whole rock (332904) | Inverse isochron | 57.43 | 2.59 | 0.30 (0.88) | Larsen et al. (2015) |
| Disko (eastern) | Dyke | Tholeiitic basalt | Ar–Ar | Plagioclase (318800) | Plateau | 58.34 | 0.4 | 0.12 (1.00) | Larsen et al. (2015) |
| Disko Bugt (SE of Disko) | Gabbro | Tholeiitic gabbro | Ar–Ar | Plagioclase (148041) | Plateau | 58.96 | 0.51 | 1.27 (0.26) | Larsen et al. (2015) |
| Nuussuaq | Dyke | Basalt | Ar–Ar | Plagioclase (340797) | Plateau | 55.84 | 0.8 | – | Storey et al. (1998) |
| Nuussuaq (west) | Dyke | Tholeiitic basalt | Ar–Ar | Plagioclase (135129) | Plateau | 48.02 | 2.76 | 1.1 (0.36) | Larsen et al. (2015) |
| Nuussuaq (north) | Sill | Alkaline | Ar–Ar | Plagioclase (489154) | Plateau | 54.52 | 0.67 | 0.61 (0.75) | Larsen et al. (2015) |
| Nuussuaq (SE) | Tholeiitic basalt | Ar–Ar | Whole rock (318802) | Plateau | 56.42 | 1.6 | 0.66 (0.65) | Larsen et al. (2009) |
| Ubekendt Eijland | Dyke | Lamprophyre | Ar–Ar | K-Feldspar (UE500) | Plateau | 34.75 | 0.4 | – | Storey et al. (1998) |

(Continued)
Table 2. Selected data for the West Greenland sub-province (Continued)

| Locality        | Unit          | Lithology       | Method  | Mineral Type | Type  | Age (Ma) | ± 2σ | MSWD (P) | References                  |
|-----------------|---------------|-----------------|---------|--------------|-------|----------|------|----------|------------------------------|
| Ubekendt Eijland Sarqâta qâqâ | Eijland | Granophyre | Ar–Ar | Alkali Feldspar (417747) | Plateau | 55.21 | 0.3  | 2.27 (0.03) | Larsen et al. (2015) |
| Ubekendt Eijland Sarqâta qâqâ | Gabbro | Ar–Ar | Plagioclase (201449) | Plateau | 56.99 | 0.49  | 1.84 (0.09) | Larsen et al. (2015) |
| Godthåbsfjord   | Camptonite | Ar–Ar | Plagioclase (KØ17090) | Inverse Isochron | 51.46 | 1.8   | 1.38 (0.24) | Larsen et al. (2009) |}

Weighted mean age (recalculated after Larsen et al. (2015); ± 2σ) and MSWD values (in parentheses) are shown in italicized bold type. Numbers in parentheses refer to the sample numbers taken directly from the original source. Ages are corrected to Kuiper et al. (2008), and the $^{40}$K decay constant of Min et al. (2000).
Table 3. Selected data for the East Greenland sub-province

| Locality          | Unit                        | Lithology | Method   | Mineral      | Type            | Age (Ma) | ± 2σ | MSWD (P) | References                      |
|-------------------|-----------------------------|-----------|----------|--------------|-----------------|----------|------|---------|---------------------------------|
| Blosseville Kyst  | Rømer Fjord Formation       | Basalt    | Ar–Ar    | Plagioclase  | Plateau         | 55.77    | 0.5  | –        | Storey et al. (2007)             |
|                   | Rømer Fjord Formation       | Basalt    | Ar–Ar    | Plagioclase  | Plateau         | 56.08    | 0.9  | –        | Storey et al. (2007)             |
| Blosseville Kyst  | Rømer Fjord Formation       | Basalt    | Plagioclase | Weighted mean (MSWD) | 55.84 | 0.43 (0.35) | | | |
| Blosseville Kyst  | Milne Land Formation        | Basalt    | Ar–Ar    | Plagioclase  | Plateau         | 56.79    | 0.5  | –        | Storey et al. (2007)             |
| Blosseville Kyst  | Skraenerne Formation (Top)  | Basalt    | Ar–Ar    | Whole rock   | Plateau         | 55.77    | 0.5  | –        | Storey et al. (2007)             |
| Blosseville Kyst  | Skraenerne Formation        | Basalt    | Ar–Ar    | Plagioclase  | Plateau         | 55.57    | 0.9  | –        | Storey et al. (2007)             |
| Blosseville Kyst  | Skraenerne Formation        | Tephra    | Ar–Ar    | Sanidine     | Plateau         | 55.67    | 0.4  | –        | Storey et al. (2007)             |
| Blosseville Kyst  | Skraenerne Formation (Top)  | Basalt    | Ar–Ar    | Plagioclase + whole rock + Sanidine | Weighted mean (MSWD) | 55.69 | 0.30 (0.1) | | | |
| Blosseville Kyst  | Nansen Fjord Formation      | Basalt    | Ar–Ar    | Plagioclase  | Plateau         | 58.4     | 0.5  | –        | Storey et al. (2007)             |
| Blosseville Kyst  | Nansen Fjord Formation      | Basalt    | Ar–Ar    | Plagioclase  | Inverse isochron | 57.49 | 2.3  | –        | Storey et al. (2007)             |
| Blosseville Kyst  | Nansen Fjord Formation      | Basalt    | Ar–Ar    | Plagioclase  | Weighted mean (MSWD) | 58.36 | 0.48 (0.6) | | | |
| Vindtop           | Formation                  | Basalt    | Ar–Ar    | Plagioclase  | Plateau         | 13.56    | 0.4  | –        | Storey et al. (2004)             |
| Kangerdlugssuaq   | Skærgaard                  | Granophyre| Ar–Ar    | Biotite (SG-61 Biotite) | Inverse isochron | 55.74 | 1.44 | –        | Hirschmann et al. (1997)         |
| Kangerdlugssuaq   | Skærgaard                  | Granophyre| Ar–Ar    | Hornblende   | Inverse isochron | 55.82 | 1.52 | –        | Hirschmann et al. (1997)         |
| Kangerdlugssuaq   | Skærgaard                  | Ar–Ar     | Weighted mean (MSWD) | 55.8 | 1.00 (0.01) | | | | (Continued)
| Locality          | Unit                        | Lithology                  | Method   | Mineral       | Type       | Age (Ma) | ± 2σ | MSWD (P) | References          |
|-------------------|-----------------------------|----------------------------|----------|---------------|------------|----------|------|----------|---------------------|
| Igtutarajik       | Gabbroic pegmatite          | Ar–Ar                      | Biotite (1-7) | Plateau      | 47.9       | 0.4      | –    | –        | Tegner et al. (1998) |
| Sorgenfri Gletscher Skjoldungen | Diabase sill | Ar–Ar                      | Plagioclase (413907) | Plateau | 57.07 | 0.8 | – | Tegner et al. (1998) |
| Tugtilik          | Basaltic dyke               | Ar–Ar                      | Plagioclase (940211) | Plateau | 62.15 | 1 | – | Storey et al. (2007) |
| Tugtilik          | Dyke (silico-carbonatite)   | Ar–Ar                      | Biotite (417150) | Plateau | 59.01 | 0.9 | – | Storey et al. (2007) |
| Tugtilik          | Dyke (silico-carbonatite)   | Ar–Ar                      | Biotite (417151) | Inverse isochron | 58.2 | 1.2 | – | Storey et al. (2007) |
|                   |                             |                            |          | Weighted mean (MSWD) | 58.7 | 4.90 (1.17) |      |          |                     |
| Kangerlussuaq     | Biotite granite             | Ar–Ar                      | Biotite (333132) | Inverse isochron | 47.19 | 0.9 | 2.40 (0.05) | Tegner et al. (2008) |
| Kangerlussuaq     | Kangerlussuaq               | Syenite intrusion          | Ar–Ar    | Biotite (EG4583) | 51.44 | 1.1 | 0.50 (0.81) | Tegner et al. (2008) |
| Kerven            | Gabbro                      | Ar–Ar                      | Biotite (85659) | Inverse isochron | 55.79 | 1.4 | 0.80 (0.52) | Tegner et al. (2008) |
| Kerven            | Alkali granite              | Ar–Ar                      | Amphibole (40160) | Inverse isochron | 53.46 | 1.3 | 2.30 (0.08) | Tegner et al. (2008) |
| Kap Dalton        | Igtertivā Formation         | Basalt                     | Ar–Ar    | Groundmass (116344) | 49.09 | 0.48 | 0.95 (0.45) | Larsen et al. (2013) |
| Kap Dalton        | Igtertivā Formation         | Basalt                     | Ar–Ar    | Plagioclase (475269) | 43.77 | 1.08 | 0.12 (0.99) | Larsen et al. (2014) |
| Lille Pendulum    | Lower Plateau Lava Series   | Basalt                     | Ar–Ar    | Plagioclase (194233) | 55.42 | 0.92 | 0.07 (1.00) | Larsen et al. (2014) |
| Blasedal (WF)     | Lower Plateau Lava Series   | Basalt                     | Ar–Ar    | Plagioclase (194187) | 53.8 | 0.76 | 0.43 (0.86) | Larsen et al. (2014) |
| Blasedal (WF)     | Lower Plateau Lava Series   | Basalt                     | Ar–Ar    | Groundmass (194194) | 55.02 | 0.49 | 0.17 (0.98) | Larsen et al. (2014) |
| Kap Stosch (HWH)  | Lower Plateau Lava Series   | Basalt                     | Ar–Ar    | Plagioclase (95346) | 54.16 | 0.72 | 0.53 (0.83) | Larsen et al. (2014) |
| Tverrelv (HWH)    | Lower Plateau Lava Series   | Basalt                     | Ar–Ar    | Groundmass (517303) | 55.52 | 0.68 | 0.12 (1.00) | Larsen et al. (2014) |
| Kap Mackenzie (GSO) | Lower Plateau Lava Series | Basalt                     | Ar–Ar    | Plagioclase (239531) | 53.54 | 0.67 | 0.04 (1.00) | Larsen et al. (2014) |
| Tobias Dal (HWH)  | Upper Plateau Lava Series   | Basalt                     | Ar–Ar    | Plagioclase (194150) | 56.51 | 0.49 | 0.39 (0.94) | Larsen et al. (2014) |
| Location                | Type               | Technique  | Sample | Ar–Ar | Age (Ma) | Error 1σ | Error 2σ | Error 3σ | Author et al. (Year) |
|-------------------------|--------------------|------------|--------|-------|----------|----------|----------|----------|----------------------|
| Bontekoe Ø              | Upper Plateau     | Hawaiite   | Ar–Ar  | Groundmass (1980.274) | Plateau | 55.17    | 0.35     | 0.18     | 0.99 | Larsen et al. (2014) |
| Louise Boyd Land        | Inland nunatak    | Alkaline lava | Ar–Ar | Whole rock (421302) | Inverse isochron | 49.8 | 1.38     | 1.83     | 0.08  | Larsen et al. (2014) |
| Hobbs Land              | Inland nunatak    | Alkaline lava | Ar–Ar | Glass (452434) | Inverse isochron | 53.4 | 1.83     | 2.20     | 0.05  | Larsen et al. (2014) |
| Shannon                 | Inland nunatak    | Basalt sill | Ar–Ar  | Plagioclase (194196) | Plateau | 51.85    | 0.55     | 0.15     | 1.00 | Larsen et al. (2014) |
| Bass Rock (LP)          | Basalt sill       | Ar–Ar     | Plagioclase (194207) | Plateau | 53.71 | 0.62     | 0.19     | 1.00    | Larsen et al. (2014) |
| Kefersteinberg (SØ)    | Sill               | Ar–Ar     | Plagioclase (517355) | Plateau | 53.98 | 0.39     | 0.10     | 1.00    | Larsen et al. (2014) |
| Hvalrosø                | Pegmatite          | Ar–Ar     | K-Feldspar (475286) | Plateau | 20.31 | 0.12     | 0.27     | 0.99    | Larsen et al. (2014) |
| Freycinet Bjerg (GSØ)   | Basalt sill       | Ar–Ar     | Plagioclase (239539) | Plateau | 52.58 | 0.66     | 0.95     | 0.48    | Larsen et al. (2014) |
| Traill Ø south coast    | Basalt sill       | Ar–Ar     | Plagioclase (239578) | Plateau | 55.14 | 0.37     | 0.74     | 0.67    | Larsen et al. (2014) |
| Dronning Augusta Dal (WF)| Basalt dyke       | Ar–Ar     | Plagioclase (475289) | Plateau | 53.68 | 1.59     | 0.19     | 0.94    | Larsen et al. (2014) |
| Bontekoe Ø              | Basalt dyke       | Ar–Ar | Plagioclase (517310) | Plateau | 51.27 | 1.21     | 0.05     | 1.00    | Larsen et al. (2014) |
| Kap Broer Ruys felsite | Felsite            | Ar–Ar     | K-Feldspar (228078) | Plateau | 48.71 | 0.51     | 0.68     | 0.82    | Larsen et al. (2014) |

Weighted mean ages (recalculated after Hirschmann et al. (1997) and Storey et al. (2007): ± 2σ) and MSWD values (in parentheses) are shown in italics. Numbers/text in parentheses refers to sample numbers/text taken directly from the original source. Ages are corrected to Kuiper et al. (2008), and the 40K decay constant of Min et al. (2000).
| Locality                  | Unit                | Lithology | Method       | Mineral               | Type     | Age (Ma) | ± 2σ   | MSWD (P) | References              |
|--------------------------|---------------------|-----------|--------------|-----------------------|----------|----------|--------|----------|-------------------------|
| Faeroe Islands           | Upper Series        | Basalt    | Ar–Ar        | Plagioclase (32/2)    | Plateau  | 55.87    | 0.70   | –        | Storey et al. (2007)     |
| Faeroe Islands           | Middle Series       | Basalt    | Ar–Ar        | Plagioclase (X/2)     | Plateau  | 55.57    | 0.70   | –        | Storey et al. (2007)     |
| Faeroe Islands           | Lower Series        | Basalt    | Ar–Ar        | Plagioclase (89068)   | Plateau  | 57.49    | 0.60   | –        | Storey et al. (2007)     |
| Faeroe Islands           | Lower Series, Lopra | Basalt    | Ar–Ar        | Plagioclase (L1-0337.5) | Plateau  | 60.63    | 0.70   | –        | Storey et al. (2007)     |
| Faeroe Islands           | Lower Series, Lopra | Basalt    | Ar–Ar        | Plagioclase (L1-1923.1) | Plateau  | 60.83    | 0.60   | –        | Storey et al. (2007)     |
| **Faeroe Islands**       | **Lower Series, Lopra** | **Basalt** | **Weighted mean** | **(MSWD)**           | **60.75** | **0.45** | **(0.19)** |                        |

Weighted mean age (recalculated after Storey et al. (2007): ± 2σ) and MSWD value (in parentheses) are shown in *italicized bold* type. Numbers/text in parentheses refers to sample numbers/text taken directly from the original source. Ages are corrected to Kuiper et al. (2008), and the $^{40}$K decay constant of Min et al. (2000).
| Locality   | Unit               | Lithology           | Method       | Mineral                           | Type            | Age (Ma) | ± 2σ  | MSWD (P) | References* |
|------------|--------------------|---------------------|--------------|-----------------------------------|-----------------|----------|-------|----------|-------------|
| Rum        | Central Complex    | Alkaline pegmatite  | U–Pb         | Zircon (SR314)                    | Concordia age   | 60.53    | 0.08  | –        | Hamilton et al. (1998) |
| Rum        | Central Complex    | Alkaline pegmatite  | Ar–Ar        | Phlogopite (GP387)                | Inverse isochron | 61.05    | 1     | –        | Hamilton et al. (1998) |
| Rum        | Early Felsic       | Rhyodacite          | Ar–Ar        | Plagioclase (UDPNTLH and RDP)     | SGF Ideogram    | 61.08    | 0.42  | –        | Troll et al. (2008) |
| Skye       | Cuillin            | Gabbro pegmatite    | U–Pb         | Zircon (SC1/2)                    | Concordia age   | 58.91    | 0.06  | –        | Hamilton et al. (1998) |
| Skye       |                    | Trachyte dyke       | Ar–Ar        | Biotite (GP382)                   | Inverse isochron | 58.51    | 1.2   | –        | Hamilton et al. (1998) |
| Mull       | Basaltic lava      | Ar–Ar               | Whole rock (S010) | Plateau                           | 60.71           | 3.2     | –      | Mussett (1986) |
| Mull       | Basaltic lava      | Ar–Ar               | Whole rock (78/5) | Plateau                           | 61.83           | 2.8     | –      | Mussett (1986) |
| Mull       | Basaltic lava      | Ar–Ar               | Whole rock (S023) | Plateau                           | 62.13           | 2.8     | –      | Mussett (1986) |
| Mull       | Basaltic lava      | Ar–Ar               | Whole rock (S007a) | Plateau                           | 60.41           | 1.8     | –      | Mussett (1986) |
| Mull       | Basaltic lava      | Ar–Ar               | Whole rock (S043) | Plateau                           | 59.08           | 3.2     | –      | Mussett (1986) |
| Mull       | Basaltic lava      | Ar–Ar               | Whole rock (S019) | Plateau                           | 57.21           | 1.6     | –      | Mussett (1986) |
| Mull       | Basaltic lava      | Ar–Ar               | Whole rock (S020) | Plateau                           | 56.7            | 2       | –      | Mussett (1986) |
| Mull       | Basaltic lava      | Ar–Ar               | Whole rock (S100Ea) | Plateau                           | 57.71           | 2.2     | –      | Mussett (1986) |
| Mull       | Various intrusives  | Various             | Ar–Ar        | Whole rock (MD3)                  | Plateau         | 59.29    | 0.4   | 1.68 (0.09) | Chambers & Pringle (2001) |
| Mull       | Basaltic lava      | Ar–Ar               | Whole rock (SO17) | Inverse isochron                  | 62.87           | 0.48    | 2.02 (0.04) | Chambers & Pringle (2001) |
| Isle of Eigg | Eigg Lava Formation | Tephra              | Ar–Ar        | Sanidine (Eigg96-1)               | Plateau         | 62.55    | 1     | –        | Storey et al. (2007) |
| Isle of Muck | Muck Tuff         | Tuff                | Ar–Ar        | Sanidine (MT2)                    | Weighted mean   | 61.95    | 0.16  | –        | Chambers et al. (2005) |

(Continued)
Table 5. Selected data for the British–Irish Palaeogene Igneous sub-province (Continued)

| Locality          | Unit                      | Lithology | Method      | Mineral                        | Type            | Age (Ma) | ± 2σ  | MSWD (P) | References* |
|-------------------|---------------------------|-----------|-------------|--------------------------------|-----------------|----------|-------|----------|-------------|
| Isle of Muck      | Muck Tuff                 | Tuff      | Ar–Ar       | Sanidine (MT3)                 | Weighted mean   | 61.74    | 0.16  | –        | Chambers et al. (2005) |
| Isle of Muck      | Muck Tuff                 | Tuff      | U–Pb        | Zircon (Muck Tuff)             | Concordia age   | 61.15    | 0.5   | –        | Chambers et al. (2005) |
| Antrim            | Upper Basalt Formation    | Basalt lava | Ar–Ar   | Whole rock (Slimag)           | Plateau         | 59.99    | 0.64  | 1.31 (0.25) | Ganerød et al. (2010) |
| Antrim            | Lower Basalt Formation    | Basalt lava | Ar–Ar   | Whole rock (BallyMcillroy 1200) | Plateau         | 62.61    | 0.7   | 0.14 (0.94) | Ganerød et al. (2010) |
| Antrim            | Lower Basalt Formation    | Basalt lava | Ar–Ar   | Whole rock (BallyMcillroy 2320) | Plateau         | 63.71    | 0.74  | 0.16 (0.96) | Ganerød et al. (2010) |
| Antrim            | Lower Basalt Formation    | Basalt lava | Ar–Ar   | Whole rock (BallyMcillroy 2510) | Plateau         | 64.12    | 0.68  | 0.08 (1.00) | Ganerød et al. (2010) |
| Antrim            | Lower Basalt Formation    | Basalt lava | Ar–Ar   | Whole rock (Whitehead 2)       | Plateau         | 63.71    | 0.68  | 0.09 (1.00) | Ganerød et al. (2010) |
| Antrim            | Lower Basalt Formation    | Basalt lava | Ar–Ar   | Whole rock (Whitehead 3)       | Plateau         | 63.33    | 0.66  | 0.03 (1.00) | Ganerød et al. (2010) |
| Antrim            | Lower Basalt Formation    | Basalt lava | Ar–Ar   | Whole rock (Binvore)           | Plateau         | 63.01    | 0.68  | 0.04 (1.00) | Ganerød et al. (2010) |
| Antrim            | Lower Basalt Formation    | Basalt lava | Ar–Ar   | Whole rock (Keady Mt)          | Plateau         | 62.3     | 0.66  | 0.03 (1.00) | Ganerød et al. (2010) |
| Antrim            | Lower Basalt Formation    | Basalt lava | Ar–Ar   | Whole rock                      | Weighted mean (MSWD) | 63.24    | 0.61 (3.7) |           |             |
| Antrim            | Scraibo Hill Sill          | Sill      | Ar–Ar       | Plagioclase (Scrabo)           | Plateau         | 50.22    | 0.86  | 0.36 (0.78) | Ganerød et al. (2010) |
| Antrim            | Tardree rhyolite Complex   | Rhyolite  | Ar–Ar       | Sanidine (Sandy Braes)         | Plateau         | 60.9     | 0.26  | –        | Ganerød et al. (2011) |
| Antrim            | Tardree rhyolite Complex   | Rhyolite  | Ar–Ar       | Sanidine (Tardree Forest)      | Plateau         | 61.02    | 0.37  | 0.71 (0.74) | Ganerød et al. (2011) |
| Antrim            | Tardree rhyolite Complex   | Sanidine  | Ar–Ar       | Weighted mean (MSWD)           | 60.94           | 0.21 (0.28) |     |          |             |
| Antrim            | Tardree rhyolite Complex   | Rhyolite  | U–Pb        | Zircon (Tardree Forest)        | 206Pb/238U age  | 61.32    | 0.05  | –        | Ganerød et al. (2011) |
| Hebrides shelf    | Hebrides terrace           | Basalt    | Ar–Ar       | Whole rock (POS241372DS2)      | Plateau         | 62       | 0.8   | 1.80 (0.05) | O’Connor et al. (2000) |
| Location            | Type             | Rock Type      | Method         | Age (Ma) ± Error | MSWD | Notes                                                                 |
|---------------------|------------------|----------------|----------------|------------------|------|----------------------------------------------------------------------|
| Hebrides shelf      | Hebrides terrace | Basalt         | Ar–Ar Whole rock | 52.24 ± 0.8     | 1.60 (0.12) | O'Connor et al. (2000)                                                |
| Rockall Trough      | Anton Dohrn      | Basalt         | Ar–Ar Whole rock | 62.71 ± 0.6     | 2.30 (0.01) | O'Connor et al. (2000)                                                |
| Rockall Trough      | Anton Dohrn      | Basalt         | Ar–Ar Whole rock | 48.81 ± 1.7     | 0.20 (0.99) | O'Connor et al. (2000)                                                |
| Rockall Trough      | Anton Dohrn      | Basalt         | Ar–Ar Whole rock | 41.57 ± 0.6     | 1.20 (0.31) | O'Connor et al. (2000)                                                |
| Rockall Trough      | Rosemary bank    | Basalt         | Ar–Ar Whole rock | 52.64 ± 0.07    | 0.10 (0.99) | O'Connor et al. (2000)                                                |
| Rockall Trough      | Rosemary bank    | Basalt         | Ar–Ar Whole rock | 53.75 ± 0.9     | 1.90 (0.06) | O'Connor et al. (2000)                                                |
| Rockall Trough      | Rosemary bank    | Basalt         | Ar–Ar Whole rock | 53.34 ± 1.5     | 2.20 (0.02) | O'Connor et al. (2000)                                                |
| Rockall Trough      | Rosemary bank    | Basalt         | Ar–Ar Whole rock | 42.78 ± 0.4     | 1.00 (0.44) | O'Connor et al. (2000)                                                |
| Lewis               | Lewis Dyke       | Basalt         | Ar–Ar Phlogopite | 45.91 ± 0.22    | –    | Faithfull et al. (2012)                                               |
| Isle of Arran       | Drumadoon        | Dyke (quartz porphyry) | Ar–Ar Whole rock | 59.49 ± 1.6     | –    | Mussett et al. (1987)                                                 |
| Isle of Arran       | Drumadoon        | Porphyritic rhyolite sill | Ar–Ar K-Feldspar | 59.42 ± 0.18    | –    | Meade et al. (2009)                                                   |

Weighted mean ages (recalculated after Mussett (1986), Ganerød et al. (2010) and Ganerød et al. (2011): ± 2σ) and MSWD values (in parentheses) are shown in italicized bold type. Numbers/text in parentheses refers to sample numbers/text taken directly from the original source. Ages are corrected to Kuiper et al. (2008), and the 40K decay constant of Min et al. (2000). SGF, single grain fusion.
Fig. 3. Timescale (Ma) v. geographical latitude (°N) event charts showing selected age data for the North Atlantic Igneous sub-provinces (* denotes weighted mean age). Data are displayed with the geological timescale of Gradstein et al. (2012) and uncertainties are 2σ. Please note the use of a different x-axis and y-axis scale for each diagram: (a) West Greenland and (i) summary stratigraphic column displaying selected Ar–Ar data of Storey et al. (2007), for various members (Mb.) of the Vaigat and Maligáit formations; (b) East Greenland (after Larsen et al. 2014) and (ii) summary stratigraphic column with Ar–Ar data of Storey et al. (2007) for various basalt formations (Fm.), and Hirschmann et al. (1997) for the Skærgaard Intrusion (VI., Vandfaldsdalen Formation).

**Geochronology**. The chronology of East Greenland (Fig. 1c) has been established using the K–Ar, Ar–Ar and Re–Os techniques (e.g. Noble et al. 1988; Roddick et al. 1989; Neve et al. 1994; Upton et al. 1995; Price et al. 1997; Sinton & Duncan 1998; Tegner et al. 1998, 2008; Werner et al. 1998; Tegner & Duncan 1999; Hald & Tegner 2000; Heister et al. 2001; Hansen et al. 2002; Lenoir et al. 2003; Brooks et al. 2004; Storey et al. 2007; Larsen et al. 2013, 2014). Published age data show the East Greenland volcanic rifted margin is characterized by voluminous flood basalts, which coincide with the two main phases of volcanism. However, ages in excess of 100 Ma have also been
reported (e.g. K–Ar study of Noble et al. 1988). The majority of published data presented in the literature are concerned with intrusive rocks (e.g. granitic bodies, mafic sills and dykes). Their emplacement coincides in time with both major phases of volcanism, and continues into the latter part of the Cenozoic (c. 53–21 Ma).

Ar–Ar ages date the Nansen Fjord Formation at approximately 59–57 Ma (Storey et al. 2007). Older formations of the Lower Basalts have undergone considerable hydrothermal alteration (green schist grade), resulting in a variable preservation state and attempts to date them have proved unsuccessful. Lavas in the Hold with Hope region are dated at approximately 58 Ma (Upton et al. 1995), while the lowermost lavas in the Prinsen af Wales Bjerje inland region are dated at approximately 61–60 Ma (Hansen et al. 2002). The Lower Basalts

---

**Fig. 3.** (c) the Faeroe Islands and (iii) summary stratigraphic column displaying the Ar–Ar data of Storey et al. (2007) for the Upper, Middle and Lower (Enni; Malinstrindur; Beinisvøð and Lopra) formations (Fm.); and (d) the British–Irish Palaeogene Igneous Province (BIPIP) with (iv) summary stratigraphic column with Ar–Ar data of Ganerød et al. (2010) for the Antrim Upper and Lower Basalt formations (Northern Island). The age of the Intrabasaltic Formation is inferred from the age of the Tardree rhyolite (Ar–Ar and U–Pb: Ganerød et al. 2011).
preserved along the coastal margin are thought to be contemporaneous with the lowermost lavas drilled offshore SE Greenland (e.g. Tegner & Duncan 1999), the onshore dykes to the far south (e.g. Storey et al. 2007), the Lower Basalt Series of the Faeroe Islands (e.g. Larsen et al. 1999a) and the lowermost lavas in the inland Úrberg area (East Greenland). The eruption of the Lower Basalts in East Greenland was contemporaneous with the Paleocene lavas (i.e. the Maligát, Vaigat and Svarthenhuk formations) of West Greenland (e.g. Storey et al. 1998) and lavas of the small isles of the Inner Hebrides (e.g. Pearson et al. 1996). A small number of formations of the Main Basalts have been dated previously. Noble et al. (1988) suggested eruption between approximately 53 and 57 Ma, based on the K–Ar dating of basalts along the Blosseville Kyst. The basal flows of the Main Basalts (Milne Land Formation) were later dated at approximately 57 Ma (Ar–Ar; Storey et al. 2007), with a possible minimum age of approximately 54–55 Ma, based on an alkaline tephra intercalated at the top of the series (Ar–Ar: Heister et al. 2001; Storey et al. 2007). The eruption of alkaline lavas of the Prinsen af Wales Bjerge Formation, which may be intercalated with the top of the Main Basalts, are dated at approximately 56–53 Ma (Ar–Ar: Peate et al. 2003). In addition, transitional lavas of Miocene age (c. 14–13 Ma) overlying the tholeiitic lavas have also been documented (Storey et al. 2004). Intrusion emplacement has been recorded between approximately 60 and 20 Ma, with multiple units coinciding with the eruption of the Main Basalts (e.g. Sorgenfrei Gletscher Sill Complex: Tegner et al. 1998). Mafic and felsic intrusions emplaced at approximately 55–40 Ma appear to be contemporaneous with continental rifting (e.g. Noble et al. 1988; Lenoir et al. 2003; Storey et al. 2007; Tegner et al. 2008), including the well-studied Skærgaard intrusion (c. 55 Ma: Hirschmann et al. 1997) and the Kangerlussuaq intrusion (c. 47 Ma: Tegner et al. 2008).

Intrusions that were emplaced following continental rifting at approximately 50–47 Ma (e.g. tholeiitic gabbro complexes at Kap Edvard Holm, Kruuse Fjord and Imilik south of Kangerlussuaq Fjord: Neve et al. 1994; Tegner et al. 1998) have been identified; notably alkaline plutons were also emplaced prior to (e.g. the Sulugsut Complex at c. 58–59 Ma: Storey et al. 2007) and continued after the main phase of continental rifting (e.g. c. 33 Ma: Upton et al. 1995). Age data related to the East Greenland margin and the outer East Greenland shelf have also been included in the unfiltered NAG-TEC Database. Roddick et al. (1989) published whole-rock basalt K–Ar ages that ranged approximately from 71 to 34 Ma. Later studies by Tegner & Duncan (1999), Sinton & Duncan (1998) and Werner et al. (1998) applied the Ar–Ar method (whole-rock and plagioclase separates) to correlate sampled offshore units with the upper Lower Series Basalts and Main Series Basalts (e.g. c. 58–56, and c. 52–48 Ma: Tegner & Duncan 1999). The intercalated basalt and rhyolitic ash layers in the offshore units have been correlated with the base of the Lower Series Basalts (e.g. Sinton & Duncan 1998; Werner et al. 1998).

The Faeroe Islands
General geology. The Faeroe Islands are remnants of the widespread subaerial volcanic sequence that completely covered the Faeroe–Rockall Plateau to the north and west of the British Isles in the Palaeogene (Fig. 1a). The plateau was extensively covered with basalts that erupted in connection with the opening of the NE Atlantic. The majority of the basalts were erupted on dry land, but now are almost completely submerged (Waagstein 1988; Boldreel et al. 1994), except for land exposures that now exist only in the Faeroe Islands. The Faeroe Island Basalt Group (FIBG) includes: the basaltic lava sequence onshore and its offshore continuation onto the Faeroe Platform, the Faeroe–Shetland Channel, and the banks south of the Faeroe Platform. Covering an estimated area of 120 × 103 km², the FIBG has previously been correlated with basalt lava flows in East Greenland (e.g. Storey et al. 2007), and represents one of the thickest and stratigraphically most complex volcanic sections within the NAIP (Saunders et al. 1997; Waagstein et al. 2002; Storey et al. 2007; Passey & Jolley 2009).

The formations of the FIBG have an approximate stratigraphic thickness of 6.5 km (Passey & Jolley 2009), and include the Lopra Formation, the Beinisvörð Formation (also referred to as the Lower Basalt Series), the Malinstindur Formation (also referred to as the Middle Basalt Series) and the Enni Formation (also referred to as the Upper Basalt Series). The Lopra Formation, encountered only in the Lopra Drill Hole (Lopra-1A with a depth of 3565 m), consists of volcaniclastic sequences and hyaloclastite later intruded by sills (e.g. Ritchie et al. 2011). A shift from the evolved hyaloclastites in the Lopra Formation to a geochemically more primitive sequence marks the horizon between the Lopra and the base of the Beinisvörð Formation, of which approximately 900 m is exposed on the islands of Suðuroy and Mykines (e.g. Ellis et al. 2002; Passey 2004). The Prestfjall Formation, a 10 m-thick coal- and clay-bearing sequence is identified between the Beinisvörð and Malinstindur formations, and marks a hiatus between the pre-rift phase of volcanism and the main rifting phase of volcanism in the NAIP. The Prestfjall Formation is followed by the Hvannhagi
Formation (Tuff–agglomerate zone) cut by various and irregular intrusions, which has been interpreted as a second start-up phase of volcanic activity and, more precisely, as the onshore onset of the synrift volcanic phase. The Malinstindur Formation consists of compound flow units, with an upwards evolution from olivine-phryic and aphyric basalts to plagioclase-phryic basalts (e.g. Waagstein 1988). Passey & Jolley (2009) introduced the Sneis Formation, defined by basal reddened volcaniclastic sandstone containing woody material, overlain by beds of volcaniclastic conglomerate. The Enni Formation marks the top of the FIBG and is approximately 900 m thick, although it has been suggested that at least 1 km of the sequence has been removed by erosion (e.g. Waagstein et al. 2002). Intrusions (i.e. sills and dykes) are numerous, and include two major sill complexes (Streymoy Sill and Eysturoy Sill), as well as several other minor sill complexes (e.g. described by Hald & Waagstein 1991; Hansen et al. 2011).

Geochronology. The Faeroe Island Basalt Group (FIBG) has been the focus of several dating efforts and relative dating studies including palynological and biostratigraphical studies (Lund 1983, 1988; Ellis et al. 2002; Jolley & Bell 2002; Passey & Jolley 2009), palaeomagnetic studies (Tarling & Gale 1968; Riisager et al. 2002), and K–Ar and Ar–Ar studies (Fig. 1d), which have been applied to basalts of the three main formations, including those sourced from the Lopra Drill Hole (e.g. Noe-Nygaard 1966; Tarling & Gale 1968; Waagstein et al. 2002; Storey et al. 2007). K–Ar studies, in particular, have highlighted the difficulty in dating the basalts owing to pervasive low-temperature alteration (which often includes low-grade metamorphism, as indicated by the presence of a number of zeolite zones: Waagstein et al. 2002; Jørgensen 2006), and resulting in significant 40Ar loss (e.g. Noe-Nygaard 1966; Tarling & Gale 1968; Fitch et al. 1978, which re-examined the work of Tarling & Gale 1968). Waagstein et al. (2002) published whole-rock mean K–Ar ages (based on multiple samples), yielding an age range of approximately 60–56 Ma. This study also included several whole-rock Ar–Ar plateau ages, which produced a larger age range of approximately 64–55 Ma, with individual ages slightly older, but significantly more precise, than their K–Ar equivalents. A later study conducted by Storey et al. (2007) produced Ar–Ar plateau ages for basalts samples of the Lopra Formation, and Lower, Middle and Upper Basalts. To avoid the problems experienced by others, pure mineral separates (plagioclase) were targeted, yielding an age range of approximately 60–55 Ma. Storey et al. (2007) reported simple age spectra (clear middle- to high-temperature plateaus), commonly exhibiting Ar-loss from low-temperature heating steps.

The British–Irish Palaeogene Igneous Province (BIPIP)

General geology. The British–Irish sub-province of the NAIP is located on the SE margin of the assumed proto-Icelandic plume head (Fig. 1a, e), which is proposed as being responsible for creating the NAIP (Campbell & Griffiths 1990; Lawver & Müller 1994; Torsvik et al. 2001; Ganerød et al. 2010). This sub-province has been referred to by several different names in the literature (e.g. the British Tertiary Igneous Province (BTIP) and The Hebridean Province). For this review we have adopted the term the ‘British–Irish Palaeogene Igneous Province’ (BIPIP; e.g. Meade et al. 2009). Main extrusive and intrusive activity is confined to a time window from the Danian to the Ypresian in the Palaeogene period leading up to continental rifting at approximately 56 Ma (Chambers et al. 2005; Storey et al. 2007). The BIPIP was a site of intense trap-forming volcanic activity of predominantly basaltic composition that covered an estimated area of ca. 10 788 km²; this estimate includes landwards flows documented from present-day remnants.

The main units of the BIPIP now comprise the major lava fields of Skye and Mull in Scotland, and the Antrim plateau in Northern Ireland (Cooper 2004; Emeleus & Bell 2005). Later, significant volumes of silica-rich magmas formed isolated central complexes and granite intrusions at Skye, Rum, Mull, Ardnamurchan, Arran, Mourne, Slieve Gulion, Carlingford and Lundy (Emeleus & Bell 2005). NW–SE- to N–S-trending dyke swarms and arrays of volcanic plugs are characteristic of the BIPIP (Speight et al. 1982; Cooper et al. 2012), and have been interpreted as feeders for the lava fields (Kerr 1997). The majority of the dykes post-date the lavas, and are in greatest abundance close to the central complexes. The dykes are thought to be contemporaneous with the emplacement of the complexes (Jolly & Sanderson 1995): however, pre-lava dykes have been documented in Northern Ireland (Cooper et al. 2012).

Two major lava sequences are preserved and located in the Inner Hebrides: the Skye Lava Group and the Mull Lava Group. The lavas on Canna and NW Rum are considered to belong to the Skye Lava Group (Emeleus 1997), whereas the Eigg Lava Formation (which outcrops at Eigg, Muck and SE Rum) and the lavas of Morvern and Ardnamurchan are interpreted to be part of the Mull Lava Group (Emeleus 1997; Emeleus & Bell 2005). The Skye Lava Group (SLG) as a whole is the most complex sequence in the BIPIP, and includes a variety of formations and members.
based on distinct lithological lava associations intercalated with sedimentary sequences and red beds. However, the units are not easily correlated across the island as the lava flows are not laterally persistent due to several sets of dissecting faults. Based on the complex nature of the SLG, we direct the reader to the overview presented in Emelus & Bell (2005). The SLG is intruded by several igneous complexes, collectively termed The Skye Central Complex, including (from oldest to youngest) Cuillin, Srath na Creitheach, and the Western and Eastern Red Hills (Bell & Harris 1986).

The Mull Lava Group (MLG) overlies the Gribun Mudstone Member (e.g. Emelus & Bell 2005), and includes the tholeiitic basalts of the Staffa Lava Formation, and the predominately olivine-basalts of the Mull Plateau Lava Formation (MPLF: Emelus & Bell 2005). The entire MLG is cut by three major intrusive centres (which offset each other) comprising gabbros, granophyres and granites, and later ring dykes that cut through centres (Emelus & Bell 2005). This was followed by extrusion of the olivine-poor pillowed tholeiitic lavas, known as the Mull Central Lavas (MCL) into water-filled calderas (Bailey et al. 1924).

Northern Ireland hosts the massive Antrim Lava Group. Volcanism initiated with sporadic explosive eruptions in the north, followed by covering of the karstified early Upper Maastrichtian limestones (Simms 2000; Mitchell 2004) by the Lower Basalt Formation (LBF: Old 1975; Cooper 2004). A time of volcanic dormancy in a wet and humid climate caused a thick weathering profile (>30 m) of latereite to form on the top of the LBF (Hill et al. 2000). This period is referred to as the Interbasaltic Formation (IBF) and is laterally extensive across the plateau. The volcanic dormancy was interrupted by the Tardree rhyolite (central Antrim) and the impressive columnar-jointed quartz-tholeiitic Causeway Member in the north. Both the Tardree rhyolite and the Causeway Member are enclosed within the IBF. The subsequent second cycle of voluminous basaltic volcanism is represented by the olivine tholeiite lavas of the Upper Basalt Formation (UBF: Lyle 1979). Boreholes from the Langford Lodge and BallyMcIlroy No. 1 projects have documented thicknesses of 531 and 346 m for the LBF and UBF, respectively (Manning et al. 1970; Thompson 1979). Dolerite plugs and several dyke sets cut the ALG and are thought to have functioned as feeders for higher level flows, now removed by erosion (Walker 1959; Cooper et al. 2012). The central complexes of the Irish and Northern Ireland section of the BPIP represent the eroded roots of volcanic systems similar to those seen in Scotland. At each centre, erosion and faulting have exposed different levels of the sub-volcanic system from upper-crustal magma chambers (e.g. Mourne), to high-level dyke and sheet intrusions (e.g. Carlingford), and shallow ring-fault systems (e.g. Slieve Gullion) (Cooper & Johnston 2004; Preston 2009).

**Geochronology.** To date, geochronological studies concerned with the Skye Lava Group (SLG) have been scarce. Hamilton et al. (1998) used the Ar–Ar and U–Pb methods to constrain the timing of eruption for the Skye Main Lava succession (SMLS: NW Rum and Canna) at approximately 61 Ma. The study suggests the presence of eroded clasts for all members of the Rum Central Complex within intra-lava sediments of the SMLS; the age of the Rum Central Complex could thus provide a maximum age for the SMLS. Chambers et al. (2005) dated the Canna Lava Field, which yielded an Ar–Ar weighted mean age of 60.89 ± 0.23 Ma. A number of dyke swarms and intrusive centres that dissect the lavas have also been dated. Dickin (1981) dated units from the Cuillin (inferred to mark the end of main basaltic activity in the area) and the Western and Eastern Red Hills centres with the Rb–Sr method and obtained ages of 59.3 ± 0.7, 58.7 ± 0.9 and 53.5 ± 0.4 Ma, respectively. Hamilton et al. (1998) dated pegmatitic intrusions on Cuillin and Rum using U–Pb zircon geochronology and reported ages of 58.9 ± 0.1 and 60.5 ± 0.1 Ma, respectively. The same study also reported an Ar–Ar age of 60.7 ± 0.5 Ma for a second Rum pegmatite (phlogopite: inverse isochron age). This Ar–Ar age is identical to the U–Pb age for related pegmatites. Hamilton et al. (1998) also obtained an age of 58.1 ± 0.6 Ma for a trachyte dyke intruding the upper part of the Skye Lavas (biotite: inverse isochron age).

Basalt lavas of the MLG have previously been dated by the Ar–Ar step heating method. Mussett (1986) presented ages that ranged from approximately 58 to 61 Ma, suggesting that basaltic magmatism lasted for approximately 3 Ma. Gabbros, granophyres and granites that intrude the MLG were dated to approximately 57–56 Ma (Ar–Ar plateau ages: whole rock). A later study carried out by Chambers & Pringle (2001) also dated flows of the MLG using the Ar–Ar method (including the lower lavas), and reported a similar age range (c. 62–58 Ma: whole rock) to that of the study by Mussett (1986). The felsic intrusions are themselves cut by various dyke structures (e.g. the Loch Ba ring dyke on Mull), which are themselves cut by the NW–SE-trending regional dyke swarm. This demonstrates the complex nature of volcanism in the BPIP. The Small Isles of the Inner Hebrides preserve basalt lava flows and intercalated tuffs (e.g. Eigg Lava Formation on the Isle of Muck), and are dated to approximately 63 Ma (e.g. Dagley & Mussett 1986; Pearson et al. 1996). A relatively
recent study by Chambers et al. (2005) dated two exposures of the Muck Tuff, yielding slightly younger Ar–Ar sanidine and U–Pb zircon ages of approximately 61 Ma.

The Lower and Upper Basalt formations (LBF and UBF) of the Antrim Lava Group (ALG) yield an age range of approximately 62–63 and 59 Ma (whole rock: Ar–Ar plateau age), respectively (Ganerød et al. 2010). Numerous ages have been reported for the Tardree rhyolite (e.g. Meighan et al. 1988; Gamble et al. 1999; Ganerød et al. 2011), the Mourne granite intrusions at approximately 51–56 Ma (e.g. Gibson et al. 1987; Thompson et al. 1987; Gamble et al. 1999) and Slieve Gullion at approximately 56–57 Ma (e.g. Meighan et al. 1988; Gamble et al. 1999). Lundy Island is recognized as the most southerly known remnant of the NAIP. It is predominantly granitic in composition (Fitch et al. 1969; Thorpe et al. 1990) and forms part of a small plutonic complex. Mussett et al. (1976, 1988) reported K–Ar ages for dolerite dykes ranging from approximately 54 to 44 Ma.

Offshore studies: a summary. The complete NAG-TEC database contains 116 age dates taken from a range of offshore studies. The majority of published geochronology data relate to basalt, 40 of which have been determined using the K–Ar technique. For example, Roddick et al. (1989) presented basalt K–Ar ages from ODP samples (offshore East Greenland); however, the data are described by the author as too variable and imprecise to provide useful age information. K–Ar basalt data also exists for a number of other offshore localities including: the Iceland–Faeroe ridge and outer Voring plateau (Talwani & Eldholm 1977); mid-Norwegian margin (Bugge et al. 1980), and offshore Shetlands and the Hebrides shelf ( Hitchen & Ritchie 1993). In addition Fitch et al. (1988) presented K–Ar dates based on drill-cored tuff samples. The ages range from approximately 177 Ma to approximately 14 Ma and encompass the full range of ages in the complete database, with the exception of offshore Svalbard and the western Barents Sea margin for which previous studies have offered Pliocene ages (e.g. Talwani & Eldholm 1977; Mørk & Duncan 1993).

The remaining data, obtained using the Ar–Ar technique, cover localities including offshore East Greenland (plagioclase and whole-rock basalt: Sinton & Duncan 1998; Tegner & Duncan 1999), the Voring margin (glass and plagioclase: Sinton et al. 1998), offshore west Greenland (whole-rock basalt: Nelson et al. 2015), the Hebrides Shelf (plagioclase and whole-rock basalt: Sinton et al. 1998; O’Connor et al. 2000) and the Rockall Trough (whole-rock basalt, biotite and plagioclase: O’Connor et al. 2000; Archer et al. 2005). Svensen et al. (2010) provided statistically valid U–Pb zircon concordia ages of 55.6 ± 0.15 and 56.3 ± 0.2 Ma for the Utgaard Upper and Lower Sill (Mid-Norwegian margin).

Discussion

An optimized age model for the NAIP

Filtering of geochronological data can be conducted at different levels. For example, filtering criteria could be based on the ability to carry out additional quality control checks (e.g. Baksi 2007a, b; Verati & Jourdan 2013) or by only accepting data determined on pure mineral separates or determined by the Ar–Ar and U–Pb methods. We have established filtering criteria that attempt to take into account the fact that magmatic rocks of the NAIP are notoriously difficult to date due to very few suitable phases for the U–Pb technique, low potassium contents of the whole rocks (which impacts the usefulness of the Ar–Ar and K–Ar methods), whole rock or groundmass as the only viable materials for dating, and partial to complete alteration of samples during or after crystallization.

In order to systematically check all 699 dates, access to complete datasets, including details of the experimental protocol, is required. For many of the published results, this level of detail is not available. Thus, to avoid automatic exclusion of a large number of data from the database, we have adopted a set of filtering criteria for quality control, which has led to the identification of a set of statistically significant age data. We apply different levels of rigour and share the results with these different filtering approaches.

The final optimized age model for the NAIP (following the first-level filtering) contains 130 ages related to extrusive and intrusive activity covering West Greenland, East Greenland, the Faeroe Islands and the BIPIP. The optimized dataset contains 124 ages determined by the Ar–Ar method and six by the U–Pb (isotope dilution thermal ionization mass spectrometry (ID-TIMS)) method. Figure 3 displays selected radiometric data for each sub-province, and shows a general younging of activity with increasing geographical latitude (in particular for East Greenland, West Greenland and the BIPIP). The precision and accuracy of some selected ages could be challenged further, and would be improved with more thorough statistical analysis. Following a second, more aggressive level of filtering, whereby all whole-rock and groundmass data were also removed because of well-documented problems concerning partial or complete alteration, the age model for the NAIP contains 86 ages, 80 of which are determined by the Ar–Ar method and six by U–Pb.

A review of the two final selected datasets suggests that 86 ages can be considered accurate, 38
are uncertain owing to a lower precision compared to other data (e.g. Meighan et al. 1988; Waagstein et al. 2002) and six are not well characterized (i.e. poor data reporting: Hirschmann et al. 1997; Chambers et al. 2005). Where insufficient data reporting has not permitted evaluation of the data at a comparable level to other published results, the data have been acknowledged but are not part of the selected datasets (e.g. Noble et al. 1988; Tegner & Duncan 1999).

The current state of geochronological knowledge

The smaller age dataset for the NAIP produced through our filtering process yields a more tightly constrained picture of the current state of geochronological data for the NAIP. The dataset obtained for each sub-province through the data analysis and filtering process described above provides experimentally consistent age estimates for the start and end of magmatic activity. In West Greenland, the Vaigat Formation represents the earliest magmatic event with an age of 61.9 ± 1.0 Ma (Storey et al. 1998). Activity continued until 34.8 ± 0.4 Ma (dyke, Ubekendt Ejland: Storey et al. 1998). For East Greenland, age information relating to the Tugtilik and Skjoldungen dykes, which yield ages of 62.2 ± 1.0 and 59.0 ± 0.9 Ma, respectively (Storey et al. 2007), allows an inferred age of >61 Ma for the start of the magmatic activity in East Greenland. The Vindtop Formation is dated at 13.6 ± 0.4 Ma (Storey et al. 2004) and marks the youngest basalt formation in East Greenland. For the Faeroe Islands, the Lower Series Basalts (Lopra Formation) is dated at 60.8 ± 0.5 Ma (weighted mean, recalculated after Storey et al. 2007) and represents the start of activity for this sub-province, which continued until 55.9 ± 0.7 Ma (Upper Series Basalts: Storey et al. 2007). The Antrim Lower Basalt Formation yields the oldest age determined for volcanism of the BIPIP, suggesting activity started at approximately 63.2 ± 0.6 Ma (weighted mean, recalculated after Ganerød et al. 2011). Onshore dyke systems (Outer Hebrides, Scotland) extend activity to 45.9 ± 0.2 Ma (Faithfull et al. 2012).

The cumulative frequency of selected data for the NAIP and per sub-province (Fig. 4) is shown to provide a general overview. East Greenland and the BIPIP appear to show activity occurring over a similar duration: however, it could be inferred that magmatic activity in the BIPIP commenced 5 Ma prior to East Greenland (Fig. 4a). Both West Greenland and the BIPIP show high levels of magmatism prior to the break-up of the North Atlantic, whereas the opposite can be seen for East Greenland. There appears to be a shift onshore from predominantly extrusive to intrusive behaviour at approximately 60 Ma for the BIPIP and minor offshore extrusive volcanism recorded after approximately 55 Ma. This type of shift is less obvious for the other sub-provinces: however, it is possible to identify punctuated, younger (<50 Ma) activity across the sub-provinces. Although the Faeroe Islands appear to be the exception, this could simply be a consequence of a small sample dataset bias. The removal of Ar–Ar ages based on whole rock and groundmass has had a significant impact on the distribution of geochronological data for the BIPIP (Fig. 4b). Following the second level of filtering, magmatic activity is primarily focused prior to break-up of the North Atlantic.

Geochronological data have contributed significantly to the discussion about the duration of flood basalt volcanism (Baksi 2005a, b, 2012; Storey et al. 2007; Barry et al. 2010, 2012). LIP events with lifespans of more than 15 myr are generally considered to have been multiple-pulsed events (Bryan & Ernst 2008). In the NAIP, a ‘gap’ or ‘hiatus’ in widespread volcanism has previously been suggested (e.g. Saunders et al. 1997); however, despite carrying out the evaluation and filtering process, we have not been able to recognize a gap or identify multiple ‘pulses’ in activity. Storey et al. (2007) previously suggested the possibility of a short regional hiatus (c. 6 Ma) in volcanic activity in East Greenland between a ‘first phase’ of activity identified at approximately 61–59 Ma, and correlated with palaeomagnetic studies (e.g. Riisager et al. 2002), and a ‘second phase’ of early–middle Eocene age (c. 54–34 Ma), correlated with apparent gaps ages of magmatic activity in East Greenland and the Faeroe Islands (Storey et al. 1998, 2007). With the recent data presented by Larsen et al. (2014, 2015) and the analysis of the suite of published geochronological data from this study, significant pauses in regional volcanism do not seem to have taken place, although breaks in volcanism may have occurred on a local scale. Despite the combination of increased data coverage in some areas and the information revealed by this analysis, gaps in data in other areas, erosion (complete or partial removal of volcanic units) and challenges in correlating stratigraphy across large geographical regions all affect the ability to recognize a cross-province correlated gap.

Recommendations for future work

Earlier studies that contributed new age data and analysed existing age data from the NAIP made significant contributions to understanding the evolution of the province. The current study couples newer,
published results and a more refined, filtered dataset, and emphasizes the need for firm chronological benchmarks and consistent data reporting in order to continue to increase our understanding of the magmatic evolution of the region. For example, it may be worthwhile to consider geochronometers such as the U–Pb method, which has been used with success on mafic rocks from other LIPs.
(e.g. Svensen et al. 2012; Corfu et al. 2013), for broader applications in the NAIP, although Ar–Ar data will remain the mainstay for the province because of their broad applicability to the full suite of rocks in the region. The exclusion of over 500 dates in this analysis indicates that many historical NAIP geochronological data do not have high enough precision (due to sample quality and/or analytical and instrumental factors) or lack enough documentation to allow rigorous assessment. The dataset also highlights that the current state of geochronological knowledge for some sub-provinces would greatly benefit from renewed interest and resampling. Nonetheless, data coverage will always be an issue in this enormous region. The following are recommendation for future work.

**Faeroe Islands.** New data could target the Lower, Middle and Upper Series Basalts of the Faeroe Islands, as the selected dataset shows insufficient geochronological data for this sub-province. The lack of suitable or accessible samples may make this effort challenging. However, sill intrusions (cf. Hansen et al. 2011) could be targeted as their ages are currently unconstrained.

**British–Irish Palaeogene Igneous Province (BIPIP).** A systematic sampling strategy of the BIPIP dyke swarms is highly recommended. The curvilinear dyke swarms of the BIPIP (Speight et al. 1982; Cooper et al. 2012) have received little geochronological attention. Dating the different dyke sets could provide temporal constraints regarding pulses of extension and rifting, magma initiation, and the end of magmatism for higher-level lava flows now removed by erosion. Sampling has been undertaken as part of the Tellus project (lead by the Geological Survey of Northern Ireland) for the Irish–Northern Irish dyke swarms and, if dated, will provide crucial data for geodynamic models of the NAIP.

A recent re-evaluation of the emplacement dynamics of the Ardmurachan cone sheets indicates that all centres are closely linked in time (Burchardt et al. 2013). It may be useful to re-analyse and provide new age determinations for the Ardmurachan Complex, which would update the low precision K–Ar ages reported by Mitchell & Reen (1973) and further test the model of Burchardt et al. (2013). Areas that would benefit from geochronological revision include the lava sequences in Antrim. The whole-rock dates derived by Ganerød et al. (2010) should be followed up by mineral separate analysis. The Mull Lava Group (MLG) is not well represented (we excluded most of the data in the study of Chambers & Pringle 2001), and no direct age determinations exist for the Skye Lava Group (SLG) in our selected dataset. New geochronological constraints derived from mineral separates for the MLG and a renewed interest in the units of SLG is strongly encouraged.

**Data reporting.** Adequate data reporting in future work would greatly ease any further evaluation of data that may be conducted. Critical examination of a number of studies has been hindered by the lack of access to detailed datasets. To that end, it is essential that the publication of data follows the minimum suggested by Renne et al. (2009) and Jourdan et al. (2009b), and the full analytical protocol is described including pre-treatment methods. It is difficult to objectively evaluate age data based only on the information in summary data tables or age plots (i.e. $^{40}$Ar/$^{39}$Ar age spectrum and inverse isochron). In addition, all results should be published and not only selected ages (i.e. as supplementary information), including data that are more complex and difficult to interpret. This would benefit geochronologists, as well as non-geochronologists, who are interested in the relevance of a given age and associated geological interpretation.

We recommended that interpretations based on the comparison of Ar–Ar data are carried out once a common reference point has been established and all data have been recalculated. For example, Meade et al. (2009) dated K-feldspar from the Drumloonsill on the Isle of Arran (BIPIP) and obtained an age of $59.04 \pm 0.13$ Ma, calculated relative to the Fish Canyon sanidine (FCs) age of $28.02 \pm 0.16$ Ma. They directly compared their age to Chambers (2000), who obtained a biotite age of $57.85 \pm 0.15$ Ma for the northern granite body using the Taylor Creek sanidine age of $27.92$ Ma (Renne et al. 1998). Meade et al. (2009) interpreted protracted felsic magmatism based on these two ages being distinguishable at the 95% confidence level. However, if the age of Chambers (2000) is recalculated relative to the FCs age used by Meade et al. (2009), the ages are indistinguishable at the 95% confidence level (new biotite age of $58.71 \pm 0.15$ Ma). It is possible to conduct a quick recalibration of an Ar–Ar age using a tool such as ArArReCalc (i.e. equation (7) in http://www.earth-time.org/ArArReCalc_Explanation.pdf). For a more rigorous recalulation, it is necessary to correctly propagate all uncertainties (see http://earth ref.org/ERDA/139/ or Cameron & Hodges 2016).

**Summary and conclusions**

The North Atlantic Igneous Province (NAIP) is one of the most extensive Large Igneous Provinces (LIPs) in the world, with an original volume estimated to be in the range $5 \times 10^6$–$10 \times 10^6$ km$^3$. The age and duration of magmatism in the NAIP has been the focus of research for over 50 years.
We have compiled published geochronological data into a single comprehensive database. The unfiltered NAG-TEC Geochronological Database contains 699 dates ranging from 0.19 to 177 Ma from over 60 publications. Over half the ages in the database (366) have been obtained using the Ar–Ar method. We have therefore recalculated all Ar–Ar (and K–Ar) data to a common age reference system following the calibrations in Kuiper et al. (2008), in line with the Geological Time Scale 2012 of Gradstein et al. (2012).

We have used the NAG-TEC Database to assess the quality and geological significance of published age data. Based on this assessment and following a first round of filtering, a selected dataset is provided containing 130 ages. Removal of Ar–Ar whole-rock and groundmass dates during a second round of filtering has produced a selected dataset containing 86 ages.

The datasets suggest that identified and recorded magmatism associated with the NAIP pre-rift phase started in the early Paleocene (c. 64–63 Ma) and continued into the Eocene (c. 56 Ma: synrift phase). Episodes of post-rift volcanism took place between approximately 56 and 50 Ma and numerous intrusions extended the activity from around 50 to 35 Ma, with the youngest recorded at approximately 20 Ma. We can use the selected datasets to show the approximate start, periodicity and end of volcanism for the sub-provinces of the NAIP, but the data do not confirm the existence of a province-wide ‘gap’ in or multiple pulses of volcanic activity.

The construction of the NAG-TEC Geochronological Database and subsequent re-examination of published data suggest targets for future work that might include areas that currently lack reliable, well-constrained ages (e.g. Faeroe Islands). Similarly, targeting some areas for combined U–Pb and Ar–Ar analysis may be warranted both to calibrate the ages across different areas and to help reconcile gaps in data due to lack of exposure, erosion or alteration. Particular attention should be paid to providing geochronological information for complex dyke systems (e.g. BIPIP), and data relating to the Antrim, Mull and Skye Lava groups must be updated.

We advise caution in accepting reported ages without a standard set of accompanying documentation. Studies using the Ar–Ar method should recalculate ages to a common reference to avoid confusion and over-interpretation of data. Although the expectations for data reporting have improved over the past number of years, our examination found that the level of data documentation has not been consistent, making critical evaluation of the results challenging. Publication of future data should be accompanied by full experimental details and should follow recommended data-reporting protocols (e.g. Renne et al. 2009).

We would like to thank the following industry partners: Bayerngas Norge AS; BP Exploration Operating Company Ltd; Bundesanstalt für Geowissenschaften und Rohstoffe (BGR); Chevron East Greenland Exploration A/S; ConocoPhillips Skandinavia AS; DEA Norge AS; Det norske oljeselskap ASA; DONG E&P A/S; E.ON Norge AS; ExxonMobil Exploration and Production Norway AS; Japan Oil, Gas and Metals National Corporation (JOGMEC); Maersk Oil; Nalcor Energy – Oil and Gas Inc.; Nexen Energy ULC; Norwegian Energy Company ASA (Noreco); Repsol Exploration Norge AS; Statoil (UK) Ltd; and Wintershall Holding GmbH. CMW would like to thank Susanne Butter and Per-Terje Osmundsen for thoughtful and constructive comments on earlier versions of this manuscript, and Fred Jourdan and Lotte M. Larsen for thorough, detailed and thought-provoking reviews that have greatly improved this contribution.

References

ANDERSEN, T.B. & IAMTVEIT, B. 1990. Uplift of deep crust during orogenic extensional collapse – a model based on field studies in the Sogn–Sunnfjord region of western Norway. Tectonics, 9, 1097–1111, https://doi.org/10.1029/Tc009i005p01097

ARCHER, S.G., BERGMAN, S.C., LIFFE, J., MURPHY, C.M. & THORNTON, M. 2005. Palaeogene igneous rocks reveal new insights into the geodynamic evolution and petroleum potential of the Rockall Trough, NE Atlantic Margin. Basin Research, 17, 171–201, https://doi.org/10.1111/j.1365-2117.2005.00260.x

BAILEY, E.B., CLOUGH, C.T., WRIGHT, W.B., RICHEY, J.E. & WILSON, G.V. 1924. Tertiary and Post-Tertiary Geology of Mull, Loch Aline, and Oban. Memoirs of the Geological Survey, Scotland.

BAKSI, A.K. 2003. Critical evaluation of 40Ar/39Ar age for the Central Atlantic Magmatic Province; timing, duration and possible migration of magmatic centers. In: HAMES, W.E., MCHONE, J.G., RENNE, P.R. & RUPPEL, C. (eds) The Central Atlantic Magmatic Province: Insights from Fragments of Pangea. American Geophysical Union, Geophysical Monographs, 136, 77–90.

BAKSI, A.K. 2005a. Evaluation of radiometric ages. In: FOULGER, G.R., NATLAND, J.H., PRESNALL, D.C. & ANDERSON, D.L. (eds) Plates, Plumes and Paradigms. Geological Society of America, Special Papers, 388, 55–70.

BAKSI, A.K. 2005b. Evaluation of radiometric ages pertaining to rocks hypothesized to have been derived by hotspot activity, in and around the Atlantic, Indian, and Pacific Oceans. In: FOULGER, G.R., NATLAND, J.H., PRESNALL, D.C. & ANDERSON, D.L. (eds) Plates, Plumes and Paradigms. Geological Society of America, Special Papers, 388, 55–70.

BAKSI, A.K. 2007a. A quantitative tool for detecting alteration in undisturbed rocks and minerals – I: water, chemical weathering, and atmospheric argon. In: FOULGER, G.R. & JURDY, D.M. (eds) Plates, Plumes and Planetary Processes. Geological Society of America, Special Papers, 388, 285–303.

BAKSI, A.K. 2007b. A quantitative tool for detecting alteration in undisturbed rocks and minerals – II: application to argon ages related to hotspots.
Baksi, A.K. 2012. ‘Data reporting norms for $^{40}$Ar/$^{39}$Ar geochronology’ – comment. *Quaternary Geochronology*, 12, 50–52, https://doi.org/10.1016/j.quasci.2012.07.004

Barr, T.L., Self, S., Kelley, S.P., Reidel, S., Hooper, P. & Widdowson, M. 2010. New $^{40}$Ar/$^{39}$Ar dating of the Grande Ronde lavas, Columbia River Basalts, USA: implications for duration of flood basalt eruption episodes. *Lithos*, 118, 213–222, https://doi.org/10.1016/j.lithos.2010.03.014

Barr, T.L., Self, S., Kelley, S.P., Reidel, S., Hooper, P. & Widdowson, M. 2012. Response to Baksi, A., ‘New $^{40}$Ar/$^{39}$Ar dating of the Grande Ronde lavas, Columbia River Basalts, USA: implications for duration of flood basalt eruption episodes’ by Barry et al. 2010 – Discussion’. *Lithos*, 146, 300–303, https://doi.org/10.1016/j.lithos.2012.04.011

Bean, J.E., Turner, C.A., Hooper, P.R., Subbarao, K.V. & Walsh, J.N. 1986. Stratigraphy, composition and form of the Deccan Basalts, Western Ghats, India. *Bulletin of Volcanology*, 48, 61–83, https://doi.org/10.1007/BF01073513

Bell, B.R. & Harris, J.W. 1986. *An Excursion Guide to the Geology of the Isle of Skye*. Geological Society of Glasgow, Glasgow.

Bell, B.R. & Williamson, I.T. 2002. Tertiary igneous activity. In: Trewin, N.H. (ed.) *The Geology of Scotland*. Geological Society, London, 371–407.

Boldreel, L.O., Graversen, O. & Andersen, M.S. 1994. Tertiary development of the Faeroe–Rockall Plateau based on reflection seismic data. *Bulletin of the Geological Society of Denmark*, 41, 162–180.

Brooks, C.K., Tegner, C., Stein, H. & Thomassen, B. 2004. Re–Os and $^{40}$Ar/$^{39}$Ar ages of porphyry molybdenum deposits in the East Greenland volcanic-rifted margin. *Economic Geology*, 99, 1215–1222.

Bryan, S.E. & Ernst, R.E. 2008. Revised definition of large igneous provinces (LIPs). *Earth-Science Reviews*, 86, 175–202, https://doi.org/10.1016/j.earscirev.2007.08.008

Bugge, T., Prestvik, T. & Rokoengen, K. 1980. Lower tertiary volcanic rocks off Kristiansund – mid Norway. *Marine Geology*, 35, 277–286, https://doi.org/10.1016/0025-3227(80)90121-8

Burchardt, S., Troll, V.R., Mathieu, L., Emeleus, H.C. & Donaldson, C.H. 2013. Ardnamurchan 3D cone-sheet architecture explained by a single elongate magma chamber. *Scientific Reports*, 3, 2891, https://doi.org/10.1038/srep02891

Campbell, I.H. & Griffiths, R.W. 1990. Implications of mantle plume structure for the evolution of flood basalts. *Earth and Planetary Scientific Letters*, 99, 79–93.

Cameron, M.M. & Hodges, K.V. 2016. ArAr – a software tool to promote the robust comparison of K–Ar and $^{40}$Ar/$^{39}$Ar dates published using different decay, isotopic, and monitor-age parameters. *Chemical Geology*, 440, 148–163.

Chambers, L.M. 2000. Age and duration of the British Tertiary Igneous Province: implications for the development of the ancestral Iceland plume. PhD thesis, University of Edinburgh.

Chambers, L.M. & Pringle, M.S. 2001. Age and duration of activity at the Isle of Mull Tertiary igneous centre, Scotland, and confirmation of the existence of subchrons during Anomaly 26r. *Earth and Planetary Science Letters*, 193, 333–345.

Chambers, L.M., Pringle, M.S. & Parrish, R.R. 2005. Rapid formation of the Small Isles Tertiary centre constrained by precise $^{40}$Ar/$^{39}$Ar and U–Pb ages. *Lithos*, 79, 367–384.

Cocks, I.R.M. & Torsvik, T.H. 2011. The Palaeozoic geography of Laurentia and western Laurussia: a stable craton with mobile margins. *Earth-Science Reviews*, 106, 1–51, https://doi.org/10.1016/j.earscirev.2011.01.007

Cooper, M.R. 2004. Palaeogene Extrusive Igneous Rocks. In: Mitchell, W.I. (ed.) *The Geology of Northern Ireland*, Our National Foundation. Geological Survey of Northern Ireland, Belfast, 167–178.

Cooper, M.R. & Johnston, T.P. 2004. Palaeogene intrusive igneous rocks. In: Mitchell, W.I. (ed.) *The Geology of Northern Ireland – Our Natural Foundation*. Geological Survey of Northern Ireland, Belfast, 179–198.

Cooper, M.R., Anderson, H., Walsh, J.J., Van Dam, C.L., Young, M.E., Earls, G. & Walker, A. 2012. Palaeogene Alpine tectonics and Icelandic plume-related magmatism and deformation in Northern Ireland. *Journal of the Geological Society, London*, 169, 29–36, https://doi.org/10.1144/0016-76492010-182

Corfu, F., Polteau, S., Planke, S., Faleide, J.I., Svensen, H., Zayoncheck, A. & Stolbov, N. 2013. U–Pb geochronology of Cretaceous magmatism on Svalbard and Franz Josef Land, Barents Sea Large Igneous Province. *Geological Magazine*, 150, 1127–1135, https://doi.org/10.1017/S0016756813000162

Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P. & Besse, J. 1999. On causal links between flood basalts and continental breakup. *Earth and Planetary Science Letters*, 166, 177–195.

Courtillot, V.E. & Renne, P.R. 2003. On the ages of flood basalt events. *Comptes Rendus Geoscience*, 335, 113–140.

Dagley, P. & Mussett, A.E. 1986. Palaeomagnetism and radiometric dating of the British Tertiary igneous province: Muck and Eigg. *Geophysical Journal of the Royal Astronomical Society*, 85, 221–242.

Dalrymple, G.B. & Lanphere, M.A. 1969. *Potassium–Argon Dating: Principles, Techniques and Applications to Geochronology*. Freeman, San Francisco, CA, USA.

Dickin, A.P. 1981. Isotope geochemistry of Tertiary igneous rocks from the Isle of Skye, N.W. Scotland. *Journal of Petrology*, 22, 155–189.

Dickin, A.P. & Jones, N.W. 1983. Isotopic evidence for the age and origin of pitchstones and felsites, Isle of Eigg, NW Scotland. *Journal of the Geological Society, London*, 140, 691–700, https://doi.org/10.1144/jgs140.4.0691

Dodd, S.C., Mac Niocaill, C. & Muxworthy, A.R. 2015. Long duration (>4 Ma) and steady-state volcanic activity in the early Cretaceous Parana–Etendeka large igneous province; new palaeomagnetic data.
from Namibia. *Earth and Planetary Science Letters*, **414**, 16–29, https://doi.org/10.1016/j.epsl.2015.01.009

ELLIS, D., JOLLEY, D.W., BELL, B.R. & O’CALLAGHAN, M. 2002. The stratigraphy, environment of eruption and age of the Faroes Lava Group, NE Atlantic Ocean. In: JOLLEY, D.W. & BELL, B.R. (eds) The North Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes. Geological Society, London, Special Publications, **197**, 253–269, https://doi.org/10.1144/GSL.SP.2002.197.01.10

EMELEUS, C.H. 1997. *Geology of Rum and the Adjacent Islands: Memoir for the 1:50000 Geological Sheet 60 (Scotland)*. British Geological Survey, Keyworth, Nottingham.

EMELEUS, C.H. & BELL, B.R. 2005. British Regional Geology: The Palaeogene Volcanic Districts of Scotland. British Geological Survey, Keyworth, Nottingham.

FAITHFULL, J.W., TIMMERMAN, M.J., UPTON, B.G.J. & RUMEY, M.S. 2012. Mid-Eocene renewal of magmatism in NW Scotland: the Loch Roag Dyke, Outer Hebrides (vol 169, pg 115, 2012). *Journal of the Geological Society, London*, **169**, 363–364, https://doi.org/10.1144/0167-66492011-117Err

FITCH, F.J., MILLER, J.A. & MITCHELL, J.G. 1969. A new approach to radio-isotopic dating in orogenic belts. In: KENT, P.E., SATTERTHWAIT, E. & SPENCER, A.M. (eds) *Time and Place in Orogeny*. Geological Society, London, Special Publications, **3**, 157–195, https://doi.org/10.1144/gsl.sp.1969.003.01.09

FITCH, F.J., HOOKER, P.J., MILLER, J.A. & BRETERON, N.R. 1978. Glauconite dating of Palaeocene–Eocene rocks from East Kent and the time-scale of Palaeogene volcanism in the North Atlantic region. *Journal of the Geological Society, London*, **135**, 499–512, https://doi.org/10.1144/gsjgs.135.5.0499

FITCH, F.J., HEARD, G.L. & MILLER, J.A. 1988. Basaltic magmatism of Late Cretaceous and Palaeogene age recorded in wells NNE of the Shetlands. In: MORTON, A.C. & PARSON, L.M. (eds) *Early Tertiary Volcanism and the Opening of the NE Atlantic*. Geological Society, London, Special Publications, **39**, 253–262, https://doi.org/10.1144/gsl.sp.1988.039.01.23

FOSSEN, H. 2010. Extensive tectonics in the North Atlantic Caledonides; a regional view. In: LAW, R.D., BUTLER, R.W.H., HOLDSWORTH, R.E., KRABBENDAM, M. & STRACHAN, R.A. (eds) *Continental Tectonics and Mountain Building: The Legacy of Peach and Horne*. Geological Society, London, Special Publications, **335**, 767–793, https://doi.org/10.1144/SP.335.31

FOULGER, G.R. 2002. Plumes, or plate tectonics processes? *Astronomy & Geophysics*, **43**, 6.19–6.23.

GAMBLE, J.A., WYSOCZANSKI, R.J. & MEIGHAN, I.G. 1999. Constraints on the age of the British Tertiary Volcanic Province from ion microprobe U–Pb (SHRIMP) ages for acid igneous rocks from NE Ireland. *Journal of the Geological Society, London*, **156**, 291–299, https://doi.org/10.1144/jgs.156.2.0291

GANERØD, M., SMETHURST, M.A. ET AL. 2010. The North Atlantic Igneous Province reconstructed and its relation to the Plume Generation Zone: the Antrim Lava Group revisited. *Geophysical Journal International*, **182**, 183–202, https://doi.org/10.1111/j.1365-246X.2010.04620.x

GANERØD, M., CHEW, D.M., SMETHURST, M.A., TROLL, V.R., CORFU, F., MEADE, F. & PRESTVIK, T. 2011. Geochronology of the Tardree rhyolite complex, Northern Ireland; implications for zircon fission-track studies, the North Atlantic igneous province and the age of the Fish Canyon sanidine standard. *Chemical Geology*, **286**, 222–228, https://doi.org/10.1016/j.chemgeo.2011.05.007

GIBSON, D., MCCORMICK, A.G., MEIGHAN, I.G. & HALLIDAY, A.N. 1987. The British Tertiary igneous province – young Rb–Sr ages for the Mourne Mountains Granites. *Scottish Journal of Geology*, **23**, 221–225, https://doi.org/10.1144/sjg23020221

GRADSTEIN, F.M., OGG, J.G., SCHMITZ, M.D. & OGG, G.M. 2012. *The Geologic Time Scale 2012*. Elsevier, Amsterdam.

HALD, N. & PEDERSEN, A.K. 1975. Lithostratigraphy of the early Tertiary volcanic rocks of central West Greenland. *Rapport – Gronlands Geologiske Undersøgelse [1964]*, **69**, 17–24.

HALD, N. & TEGNER, C. 2000. Composition and age of tertiary sills and dykes, Jameson Land Basin, East Greenland; relation to regional flood volcanism. *Lithos*, **54**, 207–233.

HALD, N. & WAAGSTEIN, R. 1991. The dykes and sills of the Early Tertiary Faeroe Island basalt plateau. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **82**, 373–388.

HAMILTON, M.A., PEARSON, D.G., THOMPSON, R.N., KELLY, S.P. & EMELEUS, C.H. 1998. Rapid eruption of Skye lavas inferred from precise U–Pb and Ar–Ar dating of the Rum and Cuillin plutonic complexes. *Nature*, **394**, 260–263.

HANSEN, J., JERRAM, D.A., MCCAFFREY, K. & PASSEY, S.R. 2011. Early Cenozoic saucer-shaped sills of the Faroe Islands: an example of intrusive styles in basaltic lava piles. *Journal of the Geological Society, London*, **168**, 159–178, https://doi.org/10.1144/0167-66492010-012

HANSEN, H., PEDERSEN, A.K. ET AL. 2002. Volcanic stratigraphy of the southern Prinzen of Wales Bjerge region, East Greenland. In: JOLLEY, D.W. & BELL, B.R. (eds) *The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes*. Geological Society, London, Special Publications, **197**, 183–218, https://doi.org/10.1144/gsl.sp.2002.197.01.08

HEISTER, L.E., O’DAY, P.A., BROOKS, C.K., NEUHOFF, P.S. & BIRD, D.K. 2001. Pyroclastic deposits within the East Greenland Tertiary flood basalts. *Journal of the Geological Society, London*, **158**, 269–284, https://doi.org/10.1144/0012-821X(96)00250-6

HELL, I.G., WORDEN, R.H. & MEIGHAN, I.G. 2000. Geochemical evolution of a palaeolerite: the Interbasaltic Formation, Northern Ireland. *Chemical Geology*, **166**, 65–84.

HIRSCHMANN, M.M., RENNE, P.R. & McBRINNEY, A.R. 1997. 40Ar/39Ar dating of the Skaergaard intrusion. *Earth and Planetary Science Letters*, **146**, 645–658, https://doi.org/10.1016/S0012-821X(96)00250-6

HITCHEN, K. & RITCHIE, J.D. 1993. New K–Ar ages, and a provisional chronology, for the offshore part of the British Tertiary Igneous Province. *Scottish Journal of Geology*, **29**, 73–85, https://doi.org/10.1144/sjg29010073
Hofmann, C., Féraud, G. & Courtillot, V. 2000. 40Ar/39Ar dating of mineral separates and whole rocks from the Western Ghats lava pile: further constraints on duration and age of the Deccan traps. Earth and Planetary Science Letters, 180, 13–27, https://doi.org/10.1016/S0012-821X(00)00159-X

Ivanov, A.V. 2007. Evaluation of different models for the origin of the Siberian traps. In: Foulger, G.R. & Jurdy, D.M. (eds) Plates, Plumes, and Planetary Processes: Geological Society of America, Special Paper, 388, 669–691.

Jolley, D.W. & Bell, B.R. 2002. The evolution of the North Atlantic Igneous Province and the opening of the NE Atlantic. In: Jolley, D.W. & Bell, B.R. (eds) The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes. Geological Society, London, Special Publications, 197, 1–13, https://doi.org/10.1144/GSL.SP.2002.197.01.01

Jolly, R.J.H. & Sanderson, D.J. 1995. Variation in the form and distribution of dykes in the Mull swarm, Scotland. Journal of Structural Geology, 17, 1543–1557.

Jourdan, F., Feraud, G., Bertrand, H. & Watkeys, M.K. 2007. From flood basalts to the inception of oceanic crust: example from the 40Ar/39Ar high-resolution picture of the Karoo large igneous province. Geochemistry, Geophysics, Geosystems, 8, Q02002, https://doi.org/10.1029/2006gc001392

Jourdan, F., Marzoli, A. et al. 2009a. 40Ar/39Ar ages of CAMP in North America: implications for the Triassic–Jurassic boundary and the 40K decay constant bias. Lithos, 110, 167–180, https://doi.org/10.1016/j.lithos.2008.12.011

Jourdan, F., Renne, P.R. & Reimold, W.U. 2009b. An appraisal of the ages of terrestrial impact structures. Earth and Planetary Science Letters, 286, 1–13, https://doi.org/10.1016/j.epsl.2009.07.009

Jørgensen, O.F. 2006. The regional distribution of zeolites in the basaltic lavas of the Faroe Islands and the significance of zeolites as palaeo-temperature indicators. Geological Survey of Denmark and Greenland Bulletin of the Geological Society of Denmark, 51, 123–156, http://www.geus.dk/publications/bull

Kerr, A.C. 1997. The geochemistry and significance of plugs intruding the Tertiary Mull–Mowrav lava succession, western Scotland. Scottish Journal of Geology, 33, 157–167, https://doi.org/10.1144/sig330.2015

King, S.D. & Anderson, D.L. 1998. Edge-driven convection. Earth and Planetary Science Letters, 160, 289–296.

Kuiper, K.F., Deino, A., Hilgen, F.J., Krijgsman, W., Renne, P.R. & Wijbrans, J.R. 2008. Synchronizing rock clocks of Earth history. Science, 320, 500–504, https://doi.org/10.1126/science.1154339

Larsen, L.M. & Pedersen, A.K. 1999. Tectonism and volcanism at the southeast Greenland rifted margin: a record of plume impact and later continental rupture. In: Wise, S.W., Jr (ed.) Proceedings of the Ocean Drilling Program, Scientific Results, Volume 152. Ocean Drilling Program, College Station, TX, 503–533.

Larsen, L., Pedersen, A.K. & Storey, M. 1999b. Trans-Atlantic correlation of the Palaeogene volcanic successions in the Faeroe Islands and East Greenland. Journal of the Geological Society, London, 156, 1081–1095, https://doi.org/10.1144/jgs048

Larsen, L.M., Rex, D.C., Watt, W.S. & Guise, P.G. 1999a. 40Ar/39Ar dating of alkali basaltic dykes along the southeast coast of Greenland: Cretaceous and Tertiary igneous activity along the eastern margin of the Labrador Sea. Geology of Greenland Survey Bulletin, 184, 19–29.

Larsen, L.M., Waagstein, R., Pedersen, A.K. & Storey, M. 1999b. Trans-Atlantic correlation of the Palaeogene volcanic successions in the Faeroe Islands and East Greenland. Journal of the Geological Society, London, 156, 1081–1095, https://doi.org/10.1144/jgs048
Geological Sheet 36). 2nd edn. Memoirs of the Geological Society, Northern Ireland.

MCDougall, I. & Harrison, T.M. 1999. Geochronology and Thermochronology by the 40Ar/39Ar Method. 2nd edn. Oxford University Press, New York.

Mead, F.C., Chew, D.M., Trolli, V.R., Ellam, R.M. & Page, L.M. 2009. Magma Ascent along a Major Terrane Boundary: crustal contamination and Magma Mixing at the Drumadoon Intrusive Complex, Isle of Arran, Scotland. Journal of Petrology, 50, 2345–2374.

Meighan, I.G., McCorkmick, A.O., Gisbon, D., Gamble, J.A. & Graham, I.J. 1988. Rb–Sr isotopic determinations and the timing of the Tertiary volcanic rock formations in NE Ireland. In: Morton, A.C. & Parson, L.M. (eds) Early Tertiary Volcanism and the Opening of the North-East Atlantic. Geological Society, London, Special Publications, 39, 349–360, doi: 10.1144/GSL.SP.1988.039.01.03

Meyer, R., Van Wijk, J. & Gernigon, L. 2007. The North Atlantic Igneous Province: a review of models for its formation. In: Foulier, G.R. & Jurdy, D.M. (eds) Plate, Plumes, and Planetary Processes. Geological Society of America, Special Papers, 430, 525–552.

Min, K.W., Mundil, R., Renne, P.R. & Ludvig, K.R. 2000. A test for systematic errors in 40Ar/39Ar geochronology through comparison with U/Pb analysis of a 1.1-Ga rhyolite. Geochimica et Cosmochimica Acta, 64, 73–98. https://doi.org/10.1016/S0016-7037(99)00204-5

Mitchell, J.G. & Reen, K.P. 1973. Potassium–argon ages from the Tertiary Ring Complexes of the Ardmurcan Peninsula, Western Scotland. Geological Magazine, 110, 331–340.

Mitchell, W.I. 2004. Cretaceous. In: Mitchell, W.I. (ed.) The Geology of Northern Ireland, Our Natural Foundation. Geological Survey of Northern Ireland, Belfast, 149–160.

Mussett, A.E. 1986. 40Ar–39Ar step heating ages of the Tertiary igneous rocks of Mull, Scotland. Journal of the Geological Society, London, 143, 887–896, https://doi.org/10.1144/gsjgs.143.6.0887

Mussett, A.E., Dagley, P. & Eckford, M. 1976. The British Tertiary igneous province; palaeomagnetism and ages of dykes, Lundy Island, Bristol Channel. Geophysical Journal of the Royal Astronomical Society, 46, 595–603.

Mussett, A.E., Dagley, P., Hodgson, B. & Skelhorn, R.R. 1987. Palaeomagnetism and age of the quartz-porphyry intrusions, Isle of Arran. Scottish Journal of Geology, 23, 9–22, https://doi.org/10.1144/sjg230.10009

Mussett, A.E., Dagley, P. & Skelhorn, R.R. 1988. Time and duration of the British Tertiary Igneous Province. In: Morton, A.C. & Parson, L.M. (eds) Early Tertiary Volcanism and the Opening of the North-East Atlantic. Geological Society, London, Special Publications, 39, 337–348, doi: 10.1144/GSL.SP.1988.039.01.29

Müller, R., Nystuen, J.P., Eide, F. & Lie, H. 2005. Late Permian to Triassic basin infill history and palaeogeography of the Mid-Norwegian shelf–East Greenland region. In: Wandel, B.T.G., Nystuen, J.P., Eide, E. & Gradstein, F.M. (eds) Onshore–Offshore Relationships on the North Atlantic Margin, Norwegian Petroleum Society, Special Publications, 12, 155–189.

Mork, M.B.E. & Duncan, R.A. 1993. Late Pliocene basaltic volcanism on the western Barents Shelf margin; implications from petrology and 40Ar/39Ar dating of volcaniclastic debris from a shallow drill core. Norsk Geologisk Tidsskrift, 73, 209–225.

Nadin, P.A., Kuszniir, N.J. & Cheadle, M.J. 1997. Early Tertiary plume uplift of the North Sea and Faeroe–Shetland basins. Earth and Planetary Science Letters, 148, 109–127.

Neve, R.J., Brandriss, M.E., Bird, D.K., McWilliams, M.O. & O’Neill, J.R. 1994. Tertiary Plutons Monitor Climate-Change in East Greenland. Geology, 22, 775–778, https://doi.org/10.1130/019-7613(1994)022<0775:Tpmcc>2.3.co;2

Nelson, C.E., Jerrom, D.A., Clayburn, J.A.P., Halton, A.M. & Roberge, J. 2015. Eocene volcanism in offshore southern Baffin Bay. Marine and Petroleum Geology, 67, 678–691, https://doi.org/10.1016/j.marpetgeo.2015.06.002

Nielson, T.F.D., Hansen, H., Brooks, C.K., Lesher, C.E. & Parties, A.F. 2001. The East Greenland continental margin, the Prinsen at Wales Bjerge and new Skagaard intrusion initiatives. Geology of Greenland Survey Bulletin, 189, 83–98.

Noble, R.H., MacIntyre, R.M. & Brown, P.E. 1988. Age constraints on Atlantic evolution: timing of magmatic activity along the E Greenland continental margin. In: Morton, A.C. & Parson, L.M. (eds) Early Tertiary Volcanism and the Opening of the NE Atlantic. Geological Society, London, Special Publications, 39, 201–214, https://doi.org/10.1144/GSL.SP.1988.039.01.19

Noe-Nygard, A. 1966. The invisible part of the Faroes. Meddelelser fra Dansk Geologisk Forening, 16, 191–195.

Ojd, R.A. 1975. The age and field relationships of the Tardree Tertiary rhyolite complex, County Antrim, N. Ireland. Bulletin of the Geological Survey of Great Britain, 51, 21–40.

Osmundsen, P.T. & Ebbing, J. 2008. Styles of extension offshore mid-Norway and implications for mechanisms of crustal thinning at passive margins. Tectonics, 27, https://doi.org/10.1029/2007tc002242

Pasey, S.R. 2004. The Volcanic and Sedimentary Evolution of the Faeroe Plateau Lava Group, Faeroe Islands and the Faeroe–Shetland Basin, NE Atlantic. PhD, University of Glasgow.

Pasey, S.R. & Jolley, D.W. 2009. A revised lithostratigraphic nomenclature for the Palaeogene Faroe Island Basalt Group, NE Atlantic Ocean. Earth and Environmental Science Transactions of the Royal Society of Edinburgh, 99, 127–158.

Pearson, D.G., Emeleus, C.H. & Kelley, S.P. 1996. Precise 40Ar/39Ar age for the initiation of Palaeogene
volcanism in the Inner Hebrides and its regional significance. *Journal of the Geological Society, London*, **153**, 815–818, https://doi.org/10.1144/gsjgs.153.6.0815

Peate, D.W., Baker, J.A. *et al.* 2003. The Prinsef of Wales Bjerje formation lavas, East Greenland: the transition from tholeiitic to alkalic magmatism during Palaeogene continental break-up. *Journal of Petrology*, **44**, 279–304, https://doi.org/10.1093/petrology/44.2.279

Polteau, S., Hendriks, B.W.H. *et al.* 2016. The Early Cretaceous Barents Sea Still Complex: distribution, $^{40}Ar/^{39}Ar$ geochronology, and implications for carbon gas formation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **441**, 83–95, https://doi.org/10.1016/j.palaeo.2015.07.007

Preston, J. 2009. Tertiary igneous activity. In: Holland, C.H. & Saunders, I.S. (eds) *The Geology of Ireland*. Dunedin Academic Press, Edinburgh, 353–373.

Price, S., Brodie, J., Whitham, A. & Kent, R. 1997. Mid-Tertiary rifting and magmatism in the Traill Ø region, East Greenland. *Journal of the Geological Society, London*, **154**, 419–434, https://doi.org/10.1144/gsjgs.154.3.0419

Reidel, S.P., Camp, V.E., Tolan, T.L., Martin, B.S., Ross, M.E., Wolff, J.A. & Wells, R.E. 2013. The Columbia River flood basalt province; stratigraphy, areal extent, volume, and physical volcanology. In: Reidel, S.P., Camp, V.E., Ross, M.E., Wolff, J.A., Martin, B.S., Tolan, T.L. & Wells, R.E. (eds) *The Columbia River Flood Basalt Province*. Geological Society of America, Special Papers, **497**, 1–43, https://doi.org/10.1130/2013.2497(01)

Renne, P.R., Swisher, C.C., Deino, A.L., Karner, D.B., Owens, T.L. & DePaolo, D.J. 1998. Intercalibration of standards, absolute ages and uncertainties in $^{40}Ar/^{39}Ar$ dating. *Chemical Geology*, **145**, 117–152, https://doi.org/10.1016/S0009-2541(97)00159-9

Renne, P.R., Deino, A.L. *et al.* 2009. Data reporting norms for $^{40}Ar/^{39}Ar$ geochronology. *Quaternary Geochronology*, **4**, 346–352, https://doi.org/10.1016/j.quageo.2009.06.005

Renne, P.R., Mundil, R., Balco, G., Min, K.W. & Ludvig, K.R. 2010. Joint determination of $^{40}K$ decay constants and $^{40}Ar/^{36}K$ for the Fish Canyon sanidine standard, and improved accuracy for $^{40}Ar/^{39}Ar$ geochronology. *Geochimica et Cosmochimica Acta*, **74**, 5349–5367, https://doi.org/10.1016/j.gca.2010.06.017

Renne, P.R., Balco, G., Ludvig, K.R., Mundil, R. & Min, K. 2011. Response to the comment by W.H. Schwarz *et al.* on ‘Joint determination of $^{40}K$ decay constants and $^{40}Ar/^{36}K$ for the Fish Canyon sanidine standard, and improved accuracy for $^{40}Ar/^{39}Ar$ geochronology’ by PR Renne *et al.* (2010). *Geochimica et Cosmochimica Acta*, **75**, 5097–5100, https://doi.org/10.1016/j.gca.2011.06.021

Rissager, P., Rissager, J., Abrahamsen, N. & Wagstein, R. 2002. New paleomagnetic pole and magnetostratigraphy of Faroe Islands flood volcanics, North Atlantic igneous province. *Earth and Planetary Science Letters*, **201**, 261–276.

Ritchie, D.K., Ziska, H., Johnson, H. & Evans, D. (eds) 2011. *Geology of the Faroe–Shetland Basin and Adjacent Areas*. BGS Research Report RR/11/01. British Geological Survey, Keyworth, Nottingham.

Rodnick, J.C., Srivastava, S.P. *et al.* 1989. K–Ar dating of basalts from Site 647, ODP Leg 105. In: *Proceedings of the Ocean Drilling Program, Scientific Results, Volume 105*. Ocean Drilling Program, College Station, TX, 885–887.

Saunders, A.D. 2016. Two LIPs and two Earth-system crises: the impact of the North Atlantic Igneous Province and the Siberian Traps on the Earth-surface carbon cycle. *Geological Magazine*, **153**, 201–222, https://doi.org/10.1017/S0016756815000175

Saunders, A.D., Fitton, J.G., Kerr, A.C., Norris, M.J. & Kent, R.W. 1997. The North Atlantic Igneous Province. In: Mahoney, J.J. & Coffin, M.F. (eds) *Large Igneous Provinces*. American Geophysical Union, Geophysical Monograph, **100**, 45–93.

Saunders, A.D., Jones, S.M., Morgan, L.A., Pierce, K.L., Widowsom, M. & Xu, Y.G. 2007. Regional uplift associated with continental large igneous provinces: the roles of mantle plumes and the lithosphere. *Chemical Geology*, **241**, 282–318, https://doi.org/10.1016/j.chemgeo.2007.01.017

Simms, M.J. 2000. The sub-basaltic surface in northeast Ireland and its significance for interpreting the Tertiary history of the region. *Proceedings of the Geologists’ Association*, **111**, 321–336.

Sinton, C.W. & Duncan, R.A. 1998. $^{40}Ar/^{39}Ar$ ages of lavas from the Southeast Greenland margin, ODP Leg 152 and the Rockall Plateau, DSDP Leg 81. In: Saunders, A.D., Larsen, H.C. & Wise, W. (eds) *Proceedings of the Ocean Drilling Program, Scientific Results, Volume 152*. Ocean Drilling Program, College Station, TX, 387–402.

Sinton, C.W., Kitchen, K. & Duncan, R.A. 1998. $^{40}Ar/^{39}Ar$ geochronology of silicic and basic volcanic rocks on the margins of the North Atlantic. *Geological Magazine*, **135**, 161–170.

Speight, J.M., Skelhorn, R.R., Sloan, T. & Knapp, R.J. 1982. The dyke swarms of Scotland. In: Sutherland, D.S. (ed.) *Igneous Rocks of the British Isles*. John Wiley & Son, Chichester, 449–459.

Steiger, R.H. & Jäger, E. 1977. Subcommission on geochronology: convention on the use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters*, **36**, 359–362.

Stemberik, L. 2000. Late Palaeozoic evolution of the North Atlantic margin of Pangea. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **161**, 95–126.

Stoker, M.S., Stewart, M.A. *et al.* 2016. An overview of the Upper Palaeozoic–Mesozoic stratigraphy of the NE Atlantic region. In: Peron-Pinvidic, G., Hopper, J.R., Stoker, M.S., Gains, C., Doornenbal, J.C., Funck, T. & Arteng, U.E. (eds) *The NE Atlantic Region: A reappraisal of Crustal Structure, Tectonostatigraphy and Magmatic Evolution*. Geological Society, London, Special Publications, **447**. First published online August 11, 2016, https://doi.org/10.1144/SP447.2

Storey, M., Duncan, R.A., Pedersen, A.K., Larsen, L.M. & Larsen, H.C. 1998. $^{40}Ar/^{39}Ar$ geochronology of the West Greenland Tertiary volcanic province. *Earth and Planetary Science Letters*, **160**, 569–586.
STOREY, M., PEDERSEN, A.K. ET AL. 2004. Long-lived postbreakup magmatism along the East Greenland margin: evidence for shallow-mantle metasomatism by the Iceland plume. Geology, 32, 173–176, https://doi.org/10.1130/G19889.1

STOREY, M., DUNCAN, R.A. & TEGNER, C. 2007. Timing and duration of volcanism in the North Atlantic Igneous Province: implications for geodynamics and links to the Iceland Hotspot. Chemical Geology, 241, 264–281.

SURLYK, F. 1990. Timing, style and sedimentary evolution of late Palaeozoic–Mesozoic extensional basins of East Greenland. In: HARDMAN, R.F.P. & BROOKS, J. (eds) Tectonic Events Responsible for Britain's Oil and Gas Reserves. Geological Society, London, Special Publications, 55, 107–125, https://doi.org/10.1144/GSL.SP.1990.055.01.05

SVENSEN, H., PLANE, S., MALTHE-SØRENSEN, A., JAMTVET, B., MYKLEBUST, R. & RASMUSSEN EIDEM, T. 2004. Release of methane from a volcanic basin as a mechanism for initial Eocene global warming. Nature, 429, 542–545.

SVENSEN, H., PLANE, S. & CORFU, F. 2010. Zircon dating ties NE Atlantic sill emplacement to initial Eocene global warming. Journal of the Geological Society, London, 167, 433–436, https://doi.org/10.1144/0016-76492009-125

SVENSEN, H., CORFU, F., POLETAU, S., HAMMER, O. & PLANE, S. 2012. Rapid magma emplacement in the Karoo Large Igneous Province. Earth and Planetary Science Letters, 325, 1–9, https://doi.org/10.1016/j.epsl.2012.01.015

TALWANI, M. & ELDHOLM, O. 1977. Evolution of the Norwegian-Greenland sea. Geological Society of America Bulletin, 88, 969–999, https://doi.org/10.1130/0016-7606(1977)88<969:EOTNS>2.0.CO;2

TARLING, D.H. & GALE, N.H. 1968. Isotopic dating and palaeomagnetic polarity in the Faeroe islands. Nature [London], 218, 1043–1044.

TEGNER, C. & DUNCAN, R.A. 1999. A 40Ar/39Ar chronology for the Volcanic history of the southeast Greenland rifted margin, Leg 163. In: LARSEN, H.C., DUNCAN, R.A., ALLAN, J.F. & BROOKS, K. (eds) Proceedings of the Ocean Drilling Program, Scientific Results, Volume 163. Ocean Drilling Program, College Station, TX, 53–62.

TEGNER, C., DUNCAN, R.A., BERNSTEIN, S., BROOKS, C.K., BIRD, D.K. & STOREY, M. 1998. 40Ar/39Ar geo-chronology of Tertiary mafic intrusions along the East Greenland rifted margin: relation to flood basalts and the Iceland hotspot track. Earth and Planetary Science Letters, 156, 75–88.

TEGNER, C., BROOKS, C.K., DUNCAN, R.A., HEISTER, L.E. & BERNSTEIN, S. 2008. Ar:40 Ar-39 Ar ages of intrusions in East Greenland: rift-to-drift transition over the Iceland hotspot. Lithos, 101, 480–500, https://doi.org/10.1016/j.lithos.2007.09.001

THOMPSON, P., MUSSETT, A.E. & DAGLEY, P. 1987. Revised 40Ar/39 Ar age for Granites of the Mourne Mountains, Ireland. Scottish Journal of Geology, 23, 215–220, https://doi.org/10.1144/sjg23020215

THOMPSON, S.J. 1979. Preliminary Report on the Ballymacilroy No. 1 Borehole, Co. Antrim, Ahoghill. Geological Survey of Northern Ireland, Open-file Report, 63.

THORPE, R.S., TINDELE, A.G. & GLEDHILL, A. 1990. The petrology and origin of the Tertiary Lundy Granite (Bristol Channel, UK). Journal of Petrology, 31, 1379–1406, https://doi.org/10.1016/petrology/31.6.1379

TORSVIK, T.H., MOSAR, J. & EIDE, E.A. 2001. Cretaceous–Tertiary geodynamics: a North Atlantic exercise. Geophysical Journal International, 146, 850–866.

TROLL, V.R., NICOLL, G.R., DONALDSON, C.H. & EMELEUS, H.C. 2008. Dating the onset of volcanism at the Rum Igneous Centre, NW Scotland. Journal of the Geological Society, London, 165, 651–659, https://doi.org/10.1144/0016-76492006-190

UPTON, B.G.J. 1988. History of Tertiary igneous activity in the N Atlantic borderlands. In: MORTON, A.C. & PARSON, L.M. (eds) Early Tertiary Volcanism and the Opening of the NE Atlantic. Geological Society, London, Special Publications, 39, 429–453, https://doi.org/10.1144/GSL.SP.1988.039.01.38

UPTON, B.G.J., EMELEUS, C.H., REX, D.C. & THIRLWALL, M.F. 1995. Early Tertiary magmatism in NE Greenland. Journal of the Geological Society, London, 152, 959–964, https://doi.org/10.1144/GSL.JGS.1995.152.01.13

VERATI, C. & JOURDAN, F. 2013. Modelling effect of sericitization of plagioclase on the 40K/40 Ar and 40Ar/39Ar chronometers; implication for dating basaltic rocks and mineral deposits. Geological Society, London, Special Publications, 378, https://doi.org/10.1144/sp378.14

WAAGSTEIN, R. 1988. Structure, composition and age of the Faeroe basalt plateau. In: MORTON, A.C. & PARSON, L.M. (eds) Early Tertiary Volcanism and the Opening of the North-East Atlantic. Geological Society, London, Special Publications, 39, 225–238, https://doi.org/10.1144/GSL.SP.1988.039.01.21

WAAGSTEIN, R., GUISE, P. & REX, D. 2002. K/Ar and 40Ar/39Ar whole-rock dating of zeolite facies metabreached flood basalts: the Upper Paleocene basalts of the Faeroe Islands, NE Atlantic. In: JOLLEY, D.W. & BELL, B.R. (eds) The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes. Geological Society, London, Special Publications, 197, 219–252, https://doi.org/10.1144/GSL.SP.2002.197.01.09

WALKER, G.P.L. 1959. Some observationa on the Antrim basalts and associated dolerite intrusions. Proceedings of the Geologists' Association, 70, 179–205.

WERNER, R., BOGAARD, P.V.D., LACASSE, C. & SCHMINCKE, H.U. 1998. Chemical composition, age, and sources of volcaniclastic sediments from Sites 917 and 918. In: SAUNDERS, A.D., LARSEN, H.C. & WISE, S.W., Jr (eds) Proceedings of the Ocean Drilling Program, Scientific Results, Volume 152. Ocean Drilling Program, College Station, TX.

WHITE, R. & MACKENZIE, D. 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. Journal of Geophysical Research, 94, 7685–7729.

WIGNALL, P.B. 2001. Large igneous provinces and mass extinctions. Earth-Science Reviews, 53, 1–33.