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Feeling the pulse? Paleogene chronostratigraphy of Northern Ireland and the north of Ireland temporally coupled to the North Atlantic Igneous Province

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ABSTRACT

The roles of plume and rift dynamics as drivers of the Paleogene North Atlantic Igneous Province (NAIP) continue to be contested. Despite their distal location from the proto-Icelandic plume, the Paleogene intrusive and extrusive rocks of Northern Ireland and the north of Ireland have been reported to contain some of the oldest and youngest magmatism within the NAIP. This record, seemingly decoupled from that of the broader NAIP, represents a challenge for reconstructions that rely solely on plume models. By integrating transboundary aeromagnetic surveys and targeted high-precision zircon U-Pb geochronology, we develop a revised chronostratigraphic framework for this segment of the NAIP, with activity from ca. 61.6 Ma to 55.9 Ma, and reduce its duration by up to ~8 m.y. to just ~5.5 m.y. The framework now supports a regionwide correlation for the onset of NAIP magmatism that is concurrent with established depositional events and indicates that magmatism did not extend beyond the "rift to drift" transition in the North Atlantic shortly after ca. 56 Ma. The new constraints indicate that rifting did not drive the active stress regime within ~1 m.y. of the onset of magmatism and favors a pulsing proto-Icelandic plume head impacting the distal corners of the NAIP throughout its duration.

INTRODUCTION

The North Atlantic Igneous Province (NAIP) is globally recognized as one of the most widespread and temporally protracted large igneous provinces (LIPs), with a peak in magmatic activity that coincided with the largest of the Paleocene hyperthermal events, the Paleocene–Eocene Thermal Maximum (PETM) at ca. 56.0–55.8 Ma (Jones et al., 2023). There is continued debate surrounding the end-member mechanisms that drove NAIP formation, favoring either North Atlantic lithospheric rifting or the emergence and subsequent pulsing of the proto-Icelandic plume (e.g., Nielsen et al., 2007; Hansen et al., 2009; Steinberger et al., 2019; Peace et al., 2020). Inferred episodic peaks between ca. 62 Ma and 56 Ma in magmatic productivity (Kasbohm et al., 2021; Storey et al., 2007a, 2007b; Wilkinson et al., 2017) and onshore denudation evident in sedimentary records (White and Lovell, 1997) have been used as evidence to support a pulsing plume head as the main driver for NAIP magmatism, yet they require temporal alignment of these responses across its extent.

Positioned at the NAIPs southeastern margin, the Paleogene rocks of Northern Ireland and the north of Ireland are the largest onshore area of NAIP igneous rocks belonging to the British and Irish Paleogene Igneous Province (BIPIP) (Fig. 1A) (Jones et al., 2023). They capture an important archive of the NAIP in a location distal to the projected proto-Icelandic plume (Wilkinson et al., 2017). However, their chronological record is regarded as anomalous within the context of the wider NAIP evolution. The onset of flood basalt magmatism has been indicated to be some of the earliest magmatic activity within the eastern corridor of the NAIP, potentially as early as ca. 64 Ma (^{40}Ar/^{39}Ar; Ganerød et al., 2010; Wilkinson et al., 2017), and thus precedes sedimentary proxies inferred to relate to mantle plume pulsing (White and Lovell, 1997). Radioisotopic dates also indicate that magmatism continued as late as ca. 50 Ma (Ganerød et al., 2010), long after the ca. 56 Ma "rift to drift" break-up assemblages that mark a decrease in magmatic productivity in locations proximal to the proto-Icelandic plume (Storey et al., 2007a, 2007b).

Currently, it is challenging to reconcile this fragmented and protracted chronological record of magmatism with models of sudden plume impingement east of Greenland at ca. 62 Ma. Arguably, in this distal corner of the NAIP, the previous temporal framework favors models of magmatism being caused by lithospheric thinning, as the North Atlantic opened from the southwest, and at least partial decoupling from proto-Icelandic plume activity throughout its evolution (Hansen et al., 2009; Steinberger et al., 2019). Despite the importance of accurate and precise spatio-temporal constraints for reconstructing NAIP dynamics (Kasbohm et al., 2021; Wilkinson et al., 2017), a systematic approach to the geochronology of this region has been lacking, in part due to the inherent challenges of developing chronological models within poorly exposed, predominantly mafic igneous rocks.

To address these issues, we present a revised chronostratigraphic framework for Paleogene magmatism based on: (1) the interpretation of geological relationships from national-scale, transboundary, Tellus Project airborne geophysical surveys across Northern Ireland and the north of Ireland (Hodgson and Young, 2016; Young and Donald, 2013), and (2) integration of these unprecedented insights with targeted, high-precision U-Pb zircon geochronology.

UPDATING THE PALEOGENE GEOLOGY OF NORTHERN IRELAND AND THE NORTH OF IRELAND

The Paleogene geology of the region comprises a succession of flood basalts of the Antrim Lava Group (Fig. 1B) and intrusive dike

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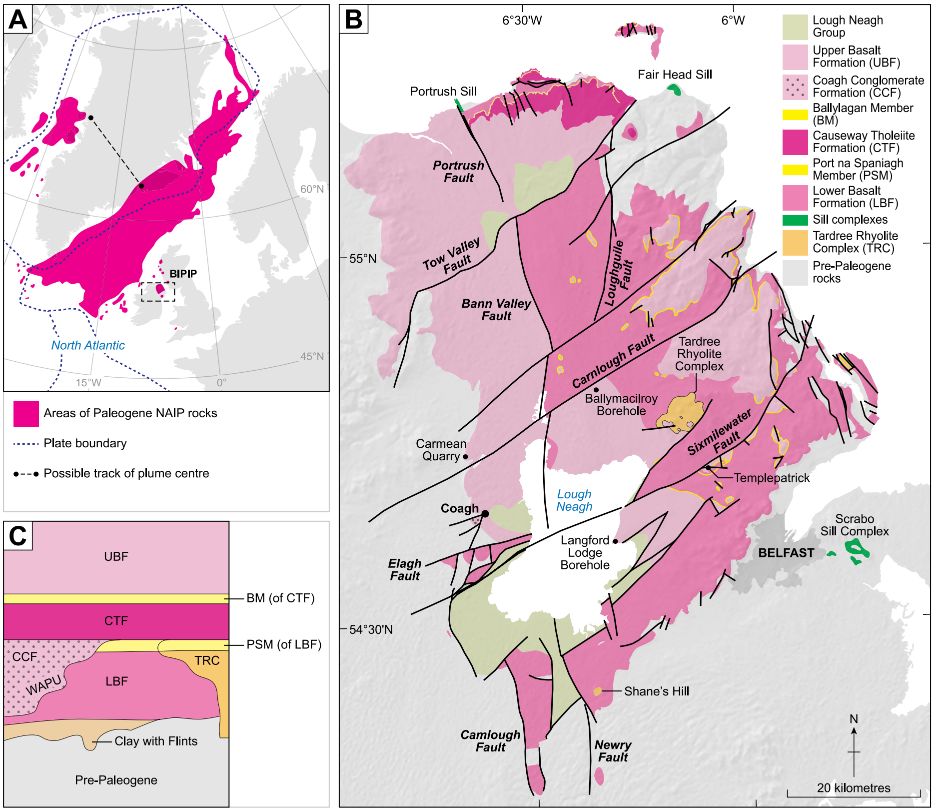

Figure 1. (A) Distribution of Paleogene rocks of the North Atlantic Igneous Province (NAIP) and British and Irish Paleogene Igneous Province (BIPIP) at ca. 56 Ma (modified from Jones et al., 2023). (B) Revised geology of Antrim Lava Group and Antrim Plateau area, Northern Ireland (modified from Cooper, 2004). (C) Revised stratigraphic scheme for Antrim Lava Group.

swarms, sills, and bimodal central complexes that are attributed to the NAIP. Having remained mostly unrevised since the early work of Old (1975), the Paleogene stratigraphy and igneous framework outlined here (Fig. 1C) reflects subsequent developments and advances in geological understanding of the region (see the Supplemental Material[1]). The base of the Paleogene is defined by the Clay with Flints unit, which is primarily basalt derived and sedimentary in origin (Cooper et al., 2018), overlain by the Antrim Lava Group. In ascending stratigraphic order, the Antrim Lava Group is subdivided into formations of flood basalt magmatism: (1) the Lower Basalt Formation (LBF), inclusive of its weathered top termed the Port na Spaniagh Member; (2) the Causeway Tholeiite Formation and its weathered top, the Ballylagan Member; and (3) the Upper Basalt Formation (UBF). The Tardree Rhyolite Complex is intruded through and extruded onto the LBF, defining the minimum age of the LBF. The revised stratigraphy also recognizes a regionally significant unconformity, here named the Western Antrim Plateau Unconformity, that resulted in the erosion of the LBF west of the Bann Valley Fault, with the contemporaneous deposition of the Coagh Conglomerate Formation (Fig. 1B).

The relationships of the Antrim Lava Group with respect to the intrusion of mafic dike swarms and the bimodal Slieve Gullion, Carlingford, and Mourne Mountains central complexes have long been debated (Preston, 1967; Gibson et al., 1987; Meighan et al., 1988; Gamble et al., 1999). Interpretation of total magnetic intensity images (Fig. 2A), obtained by the Northern Ireland Tellus Project (Young and Donald, 2013) and Irish Tellus Border Project (Hodgson and Young, 2016) airborne geophysical surveys, has helped established some geological relationships and relative timings, with an emphasis on the very prominent dike swarms revealed across the region (Fig. 2B). Following Cooper et al. (2012) and Anderson et al. (2016, 2018) (see the Supplemental Material), the dike swarms are defined in relative chronological order as: (1) the Erne Dike Swarm, which is offset sinistrally by ~2.5 km across the Tempo-Carnlough Fault; (2) the Killala Dike Swarm, which cuts the Killala Sill; (3) the Donegal-Kingscourt Dike Swarm, which is offset sinistrally by ~1.5 km across the Tempo-Carnlough Fault, unconformably truncated by the Western Antrim Plateau Unconformity, and overlain by the UBF on the western margin of the Antrim Plateau; (4) the Ardglass-Ballycastle Dike Swarm, which cuts the LBF; (5) the St. John's Point-Lisburn Dike Swarm, which is observed to cut through the LBF and UBF but not the Mourne Mountains Complex (Fig. 2B); and (6) the Fleetwood Dike Swarm, which cuts the early Mourne Mountains Complex intrusions (G1–G3) but not the later ones (G4–G5) (Fig. 2B). Further relationships between the Antrim Lava Group, dike swarms, sill and central complexes are observed across the region and serve to help constrain the relative timings of events (Supplemental Material).

GEOCHRONOLOGY AND REVISED TEMPORAL FRAMEWORK

Sampling made use of the relationships observed by Tellus Project surveys and targeted a range of lithologies throughout the sequence of magmatic activity including late-stage gabbroic segregates within mafic intrusions, alongside mingled mafic-felsic rocks. The locations of the samples dated by chemical abrasion–isotope dilution–thermal ionisation mass spectrometry (CA-ID-TIMS) zircon U-Pb are shown on Figure 2B (see also the Supplemental Material). Geochronology was undertaken at the British Geological Survey. Methodologies, U-Pb results, and ^{206}Pb/^{238}U (Th corrected) age interpretations are provided in the Supplemental Material, with the key findings reported here. Uncertainties are reported at the 2s level and as analytical uncertainties only; expanded uncertainties inclusive of decay constants are presented with the data in Figure 3.

The LBF is bracketed between the underlying Clay with Flints unit, with a maximum depositional age of 61.57 ± 0.040 Ma and a minimum age provided by revision of the age of the Tardree Rhyolite Complex to 61.109 ± 0.021 Ma (cf. Ganerød et al., 2011). The age of the LBF (Fig. 3) is therefore constrained to significantly later than its previous attribution based on ^{40}Ar/^{39}Ar data (Ganerød et al., 2010; Wilkinson et al., 2017).

The earliest, ~E-W–trending Erne Dike Swarm yields a date of 61.346 ± 0.085 Ma and therefore occurred within the constrained window of the LBF (Fig. 3). Meanwhile, the Killala Sill is dated at 60.957 ± 0.041 Ma and is cut by the Killala Dike Swarm, which shows the latter to be marginally younger than the LBF.

[1]Supplemental Material. The supplemental materials include an account of the Paleogene regional geology of Northern Ireland and north of Ireland region, providing background information on the associations and timings of the component parts, including the Antrim Lava Group, central complexes, sill complexes and dike swarms, and revision to the stratigraphy. Previous geochronological and paleomagnetism constraints are presented. Methods used for acquisition of Tellus airborne geophysics, sampling, and CA-ID-TIMS zircon U-Pb dating are provided. Discussion of the U-Pb age constraints is made with the addition of images of the zircons analyzed. A data table is provided for the CA-ID-TIMS work completed during this study. Please visit https://doi.org/10.1130/GEOL.S.31400634 to access the supplemental material; contact editing@geosociety.org with any questions.

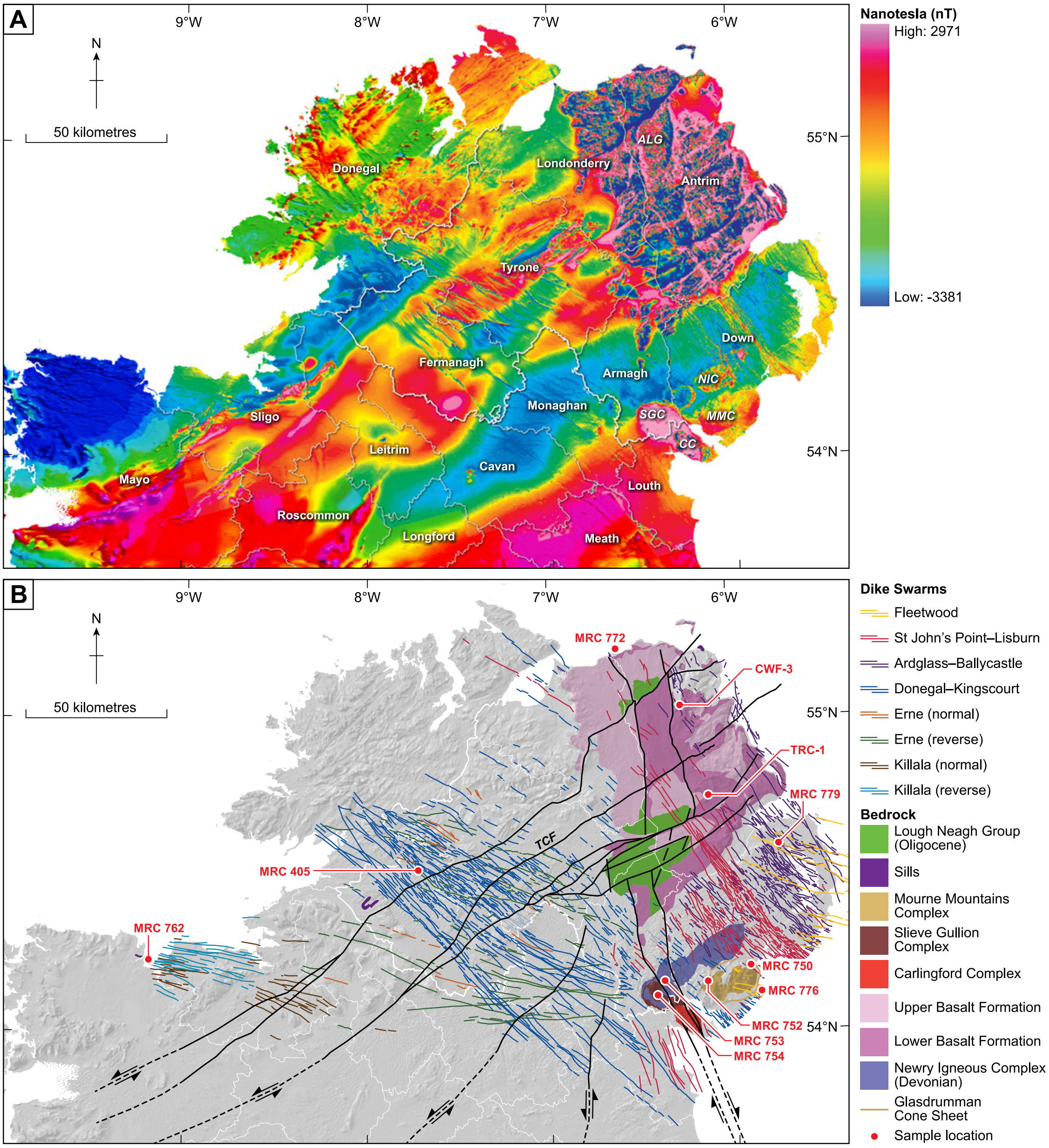

Figure 2. (A) Tellus Project total magnetic intensity image of Northern Ireland and north of Ireland (nT—nanotesla). (B) Interpreted dikes swarms and regionally significant faults with locations of U-Pb sample sites (modified from Anderson et al., 2016, 2018). ALG—Antrim Lava Group; NIC—Newry Igneous Complex; SGC—Slieve Gullion Complex; MMC—Mourne Mountains Complex; CC—Carlingford Complex; TCF—Tempo-Carnlough Fault.

The Slieve Gullion Layered Complex and Ring Dike yield ages of 60.701 ± 0.020 Ma and 60.826 ± 0.029 Ma, respectively, some ~4 m.y. earlier than their previous attribution of ca. 56.5 Ma (Gamble et al., 1999). However, because dikes of the Erne Dike Swarm are observed to curve into this complex, it is clear that its activity extended back into LBF times.

Indirect minimum age constraints on the Causeway Tholeiite Formation and UBF are provided by phreatic vents (Supplemental Material) related to the Portrush Sill Complex dated at 58.453 ± 0.029 Ma and thus do not conflict with the ca. 59 Ma $^{40}Ar/^{39}Ar$ date for the UBF (Ganerød et al., 2010; Wilkinson et al., 2017). The youngest previously documented age, yielded by the Scrabo Sill Complex (ca. 50 Ma, $^{40}Ar/^{39}Ar$; Ganerød et al., 2010), is not supported by U-Pb dates and is revised to 61.318 ± 0.041 Ma (Fig. 3). The latest magmatic events are captured by the Glasdrumman Cone Sheet at 56.594 ± 0.039 Ma and the Mourne Mountains Complex oldest (G1) 56.465 ± 0.025 Ma and youngest (G5) 55.918 ± 0.036 Ma granites, the ages of which are revised from the previous less precise U-Pb dates (56.4 ± 1.4 Ma, 55.3 ± 0.8 Ma; Gamble et al., 1999). Crosscutting relationships with the Mourne Mountains Complex indicates intrusion of the Fleetwood Dike Swarm occurred within the ~500-k.y. interval between G1 and G5.

IMPLICATIONS FOR NAIP EVOLUTION

The spatio-temporal distribution of BIPIP and NAIP magmatism is critical for discriminating between postulated models of a pulsing plume head that would lead to strongly correlated events versus the progression of the Atlantic rift system to the northeast over time causing localized extension and temporally disparate magmatic events. Any unifying model, therefore, needs to accommodate our revised chronostratigraphic record within the broader context of NAIP evolution (Fig. 4).

The first phase of flood basalt magmatism (LBF) aligns with other robust constraints for the onset of magmatism reported across the BIPIP in Scotland at ca. 61.7 Ma (CA-ID-TIMS U-Pb zircon, $^{40}Ar/^{39}Ar$ sanidine; Árting et al., 2018; Fig. 4). This well-defined timing for the onset magmatism across the BIPIP aligns with the estimates for the paleoenvironmental changes at the ca. 61.6 Ma Danian–Selandian boundary (Clemmensen and Thomsen 2005), which saw, following 40 m.y. of carbonate deposition, the first siliciclastic sediment influx to

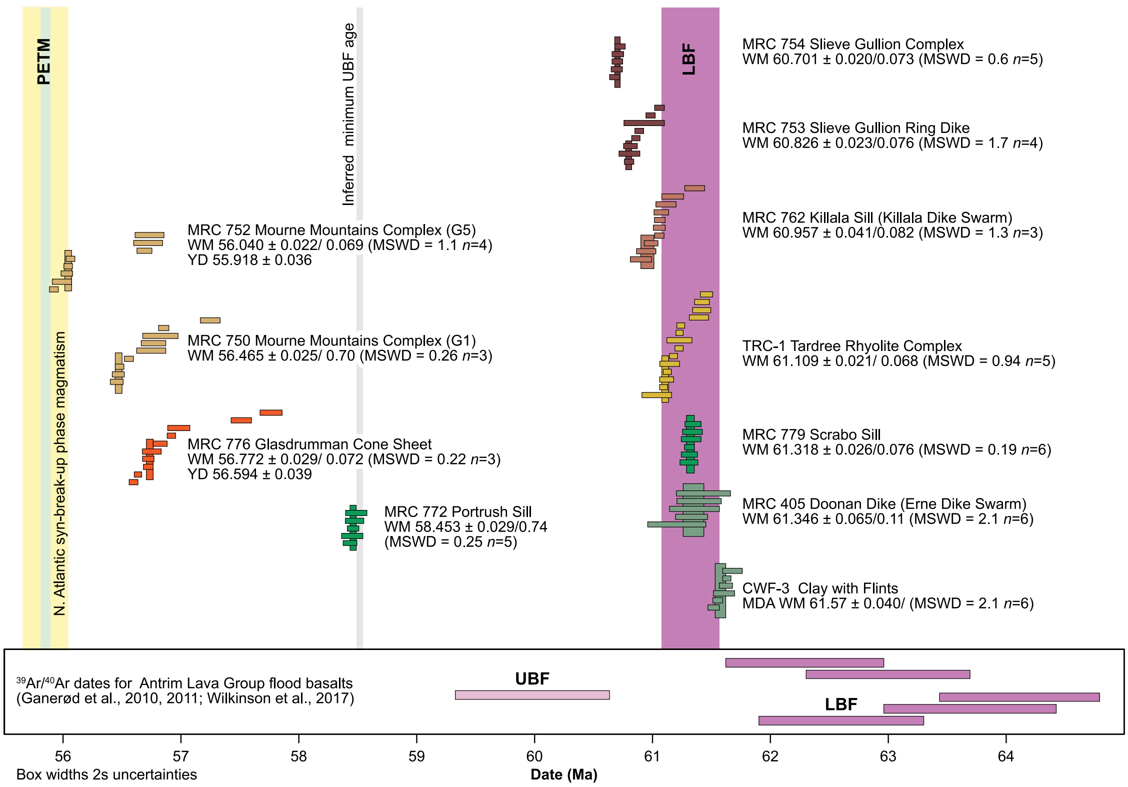

Figure 3. Radioisotopic geochronology results of igneous events within the study area (sample locations are in Fig. 2B). Dark shaded bars represent 2s uncertainties for $^{206}Pb/^{238}U$ (Th corrected) dates of individual zircon chemical abrasion–isotope dilution–thermal ionisation mass spectrometry (CA-ID-TIMS) U-Pb analyses, and overlapping boxes indicate weighted mean (WM) and mean square of weighted deviates (MSWD) of the selected number (*n*) of dates contributing to the age interpretation; the youngest date (YD) is also presented where a statistically acceptable MSWD is not formed from *n* ≥3 analyses. Age uncertainty is presented in the form: ± analytical only uncertainty/total uncertainty including tracer calibration and U decay constants. PETM—Paleocene–Eocene Thermal Maximum; UBF—Upper Basalt Formation; LBF—Lower Basalt Formation.

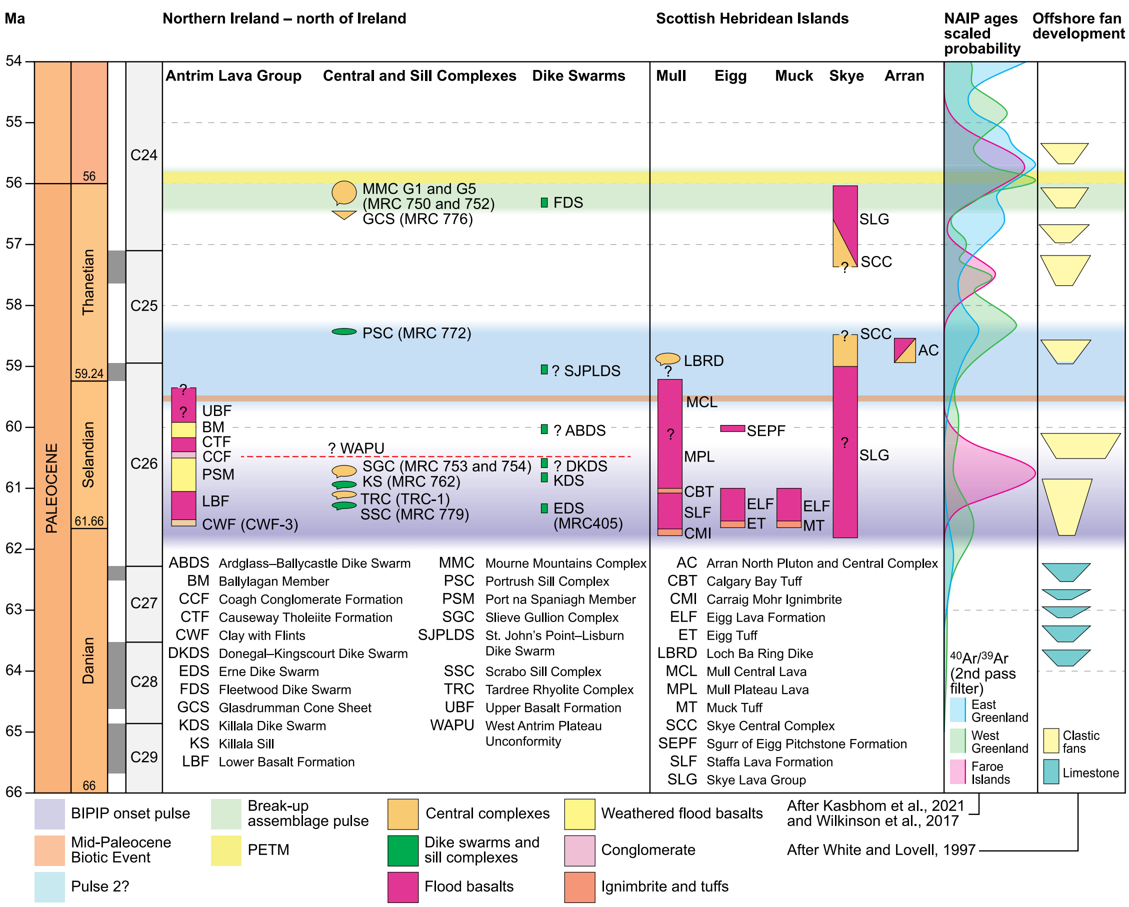

Figure 4. Chronostratigraphy of Antrim Lava Group, sill and central complexes, and dike swarms based on new U-Pb ages constraints (time scale from Speijer et al., 2020). Comparison of Northern Ireland and north of Ireland with British and Irish Paleogene Igneous Province (BIPIP) of Scotland (Árting et al., 2018; Gooday et al., 2024), offshore basin development adjusted to stratigraphic boundaries, and magmatic date distributions for regions of NAIP magmatism closer to the projected Icelandic plume is shown. NAIP—North Atlantic Igneous Province; PETM—Paleocene–Eocene Thermal Maximum.

offshore basins around the United Kingdom and are argued to be a proxy for plume pulse impacts (Fig. 4) (White and Lovell., 1997). Across the entirety of the NAIP, an abrupt onset of magmatism is defined by the close temporal alignment between the onset of magmatism across the BIPIP and that of the broader eastern NAIP, proximal to the proto-Icelandic plume, albeit defined by lower-resolution geochronology (Fig. 4; Wilkinson et al., 2017).

The timing of intrusion of the Erne Dike Swarm, during the constrained window for LBF extrusion, supports the notion that this swarm may have been part of the subvolcanic feeder systems for this part of the Antrim Lava Group (Preston, 1967). Importantly for early NAIP reconstructions, the active stress regime constrained within the temporal interval between this and the other dike swarms is documented as being one of far-field alpine compression (Cooper et al., 2012; Anderson et al., 2016, 2018) rather than one dominated by Atlantic rifting.

The resurgence of flood basalt magmatism (UBF), after periods of quiescence, remains broadly constrained ca. 59 Ma. However, there are features across the NAIP that indicate this resurgence was not an isolated event. Within the BIPIP, significant central complexes and granitic plutons were emplaced between ca. 59 Ma and 58.5 Ma (Skye and Arran; Fig. 4). The mid-Selandian (ca. 59 Ma) also saw renewed development of offshore clastic fan systems, indicative of crustal uplift and onshore denudation, argued to be in response to plume activity (White and Lovell, 1997). An increase is also observed in dated magmatism from Greenland (ca. 58.5 Ma; Fig. 4). These indicators of a pulse of activity follow the loosely constrained mid-Paleocene Biotic Event at ca. 59.5 Ma (Bernaola et al., 2007), requiring further investigation to understand its relationship to the NAIP.

Whereas east Greenland saw increased magma productivity toward continental break-up and seafloor spreading in the North Atlantic ca. 56 Ma, which was argued to be a plume pulse response (Storey et al., 2007a, 2007b), the magmatism in the study area was volumetrically subordinate to that of earlier pulses and spatially confined to the onshore eastern margin and Fleetwood Dike Swarm within the Irish Sea (Supplemental Material), reaching the NAIP's most southerly extent along this corridor within its very latest expression (ca. 55.96 Ma; Lundy igneous complex; Lisica et al., 2025). The restricted Irish Sea focus of the last pulse of magmatism within the BIPIP follows the zone of lithospheric erosion attributed to plume activity during the NAIP and mirrors the location of a present-day hot asthenosphere finger emanating from the Icelandic plume (Schoonman et al., 2017; Bonadio et al., 2025). Contrary to previous geochronology (Ganerød et al., 2010), our results indicate that melt-generating thermal anomalies in this area were shut down as seafloor spreading commenced in the North Atlantic (ca. 56–55 Ma). Reported thermal interactions between the Fleetwood Dike Swarm and Morcombe gas field and other Clyde Belt basins in the Irish Sea (Liingaard et al., 2012) suggest that these distal interactions of the NAIP should also be considered when assessing the build-up to the PETM at ca. 55.8 Ma, in addition to the more extensive interaction of magmatism with organic-rich basin sequences closer to the proto-Icelandic plume (Storey et al., 2007a).

SUMMARY

The revised chronostratigraphic model presented constrains NAIP magmatism across Northern Ireland and the north of Ireland to 5.5 m.y. between ca. 61.6 Ma and ca. 55.9 Ma. These new constraints indicate a close temporal coupling with magmatism proximal to, and commonly attributed to, the pulsing proto-Icelandic plume until continental break-up. Considering this temporal alignment, in tandem with the time-constrained evidence for far-field alpine compression across the BIPIP (Cooper et al., 2012; Anderson et al., 2016, 2018), the evidence presented argues against an independent evolution of NAIP magmatism in this region due to a northeastward progression of Atlantic rifting.

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