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Mantle, lithospheric and crustal controls on large igneous province magmatism: petrogenesis of the Antrim Lava Group, North Atlantic Igneous Province

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Abstract

Continental large igneous province (LIP) volcanism is the result of long-lived interactions between mantle plumes, lithospheric topography, ascending melts, and crustal lithologies. Disentangling the competing effects of such factors is required to understand the petrogenesis of LIP magmas and ultimately the controls on their geochemical and isotopic diversity and on ore-forming processes. The British and Irish Paleogene Igneous Province (BIPIP), part of the North Atlantic Igneous Province, is among the best studied LIPs. Despite this, the largest onshore extrusive succession, the Antrim Lava Group (ALG), Northern Ireland, has been comparatively understudied in recent years. The ALG succession shows several notable features – including a near-hiatus in volcanism followed by coexisting eruption of depletion and enriched melts – which challenge existing models of magmatism developed in the Scottish Hebrides. New high quality major and trace element data have been collected from mafic and silicic units from across the Antrim Plateau. Combined with a large compilation of geochemical and isotopic data, these allow a self-consistent petrogenetic model for the ALG and the wider BIPIP. Geochemical indices of fractionation (MgO, CaO) correlate positively with stratigraphic height through both main lava successions suggesting two cycles of thermal maturation of the crust. In contrast La/Nd and Ba/Zr decrease with stratigraphic height indicating decreasing crustal assimilation during each maturation cycle of the system. Across the Antrim and Scottish centres, olivine-plagioclase-augite-melt (OPAM) barometry shows systematically lower storage pressures for more

tholeiitic units relative to transitional/alkali basalts, which may relate to differences in melt flux or preservation biases. There is a systematic difference in composition between the two main ALG units in the east of the Antrim Plateau, with the Lower Basalt Formation (LBF) consistently enriched in incompatible elements including Ti, Zr and V relative to the Upper Basalt Formation (UBF). Forward melting models indicate that these compositional variations cannot be reconciled by variable melt fractions of a single mantle source and instead require that the eastern UBF and Causeway Tholeiite were derived from a source which was depleted relative to that which formed the LBF. These differences do not apply in the western plateau however where UBF compositions are indistinguishable from the LBF. Simultaneous, eruption of depleted and enriched UBF in the east and west, respectively, can be reconciled by a model of localised lithospheric thinning and source depletion focused over areas of highest magmatic flux, which matches geophysical observations; this can explain similar alkali to tholeiite transitions in other LIP successions. Finally, the near-hiatus which punctuates volcanism in Antrim requires an interval of low mantle T_p and is suggested to reflect a pulsing plume and regional shutdown of most magmatism except in localised areas of thinned lithosphere.

Keywords: North Atlantic Igneous Province, LIP, plume, melt modelling, crustal assimilation

1 Introduction

Large igneous provinces (LIPs) represent records of the most voluminous magmatic events in Earth's history. Generally agreed to form during the impingement of hot mantle plumes on the base of thinned lithosphere, they are associated with sustained magmatism for several million years over a wide area (Koppers et al., 2021; White & McKenzie, 1995), and are implicated in numerous mass extinctions throughout Earth history (Ganino & Arndt, 2009; Jones et al., 2019).

Continental LIPs, wherein magmas are generated beneath thinned continental lithosphere, are ubiquitous in the geological record (Ernst et al., 2021), resulting in long-term lithospheric and crustal interactions with ascending melts. LIP and intraplate magmas commonly show temporal and spatial variation in geochemistry and isotopic composition which have been variously attributed to: lithospheric thickness variations (Kerr, 1994; White et al., 1992); variations in melting extent (Feigenson et al., 1983); chemical or lithological mantle heterogeneity (Fitton et al., 1997; Scarrow et al., 2000; Shorttle et al., 2014); or interaction with lithospheric mantle (Arndt & Christensen,

1992; Wang & Liu, 2021), or continental crust (Thompson et al., 1986; Wallace et al., 1994). Disentangling these competing influences is therefore central to understanding the petrogenesis of LIP magmas – as well as controls and triggers for mineralisation processes (e.g., Hughes et al., 2014; O'Driscoll et al., 2010) – and has thus been the topic of decades of work and debate (e.g., Baker, 2000; Hole & Natland, 2020; Kerr, 1994; Shorttle & Maclennan, 2011; Thompson et al., 1982).

The North Atlantic Igneous Province (NAIP) is among the longest- and best-studied LIPs with outcrops on both sides of the Atlantic including Northern Ireland, Scotland, Iceland, Greenland and the Faroes, with ongoing magmatism beneath present day Iceland. The Hebridean islands of Scotland in particular have represented important sites for development of early concepts in igneous petrology (e.g., Bailey et al., 1924; Harker, 1904). The NAIP was emplaced in two main phases, pre-rift (~62–56 Ma) and post-rift (from ~56 Ma) with magmatism continuing to the present day under modern Iceland (Cooper et al., 2026; Saunders et al., 1997; Wilkinson et al., 2017). Magmatism was widespread over a ~1000 km radius and its onset appears to have been near-synchronous across the provinces at ~62 Ma (Cooper et al., 2026; Millett et al., 2024; Wilkinson et al., 2017). A variety of studies applying olivine-spinel thermometry and olivine-addition methods agree that elevated mantle potential temperatures (T_p) ~1400–1500 °C characterise NAIP magmas across a wide area (Carter et al., 2024; Hole & Millett, 2016; Spice et al., 2016) and persist beneath present-day Iceland (Matthews et al., 2016), consistent with a plume model for LIP formation.

The British and Irish Paleogene Igneous Province (BIPIP), was erupted during the pre-rift phase and comprises extrusive lava fields, dyke swarms and intrusive centres in Northern Ireland, and on the Hebridean islands of Mull, Skye, Rhum, Eigg and Muck, in Scotland (Fig. 1; Saunders et al., 1997). There are three major extrusive fields presently exposed within the BIPIP, two associated with major intrusive centres on Skye and Mull and the largest by area forming the Antrim Plateau in Northern Ireland (Fig. 1; Cooper, 2004; Emeleus & Bell, 2005).

While similar in some respects to the successions on Mull and Skye, the Antrim Lava Group (ALG) shows notable differences which pose a challenge to unified models for their petrogenesis (see below; e.g., Barrat & Nesbitt, 1996; Kerr, 1994). These have led to divergent inferences regarding the controls on spatial distribution and composition of BIPIP magmatism, with suggestions of large scale magma transport (Hole et al., 2015; Kent & Fitton, 2000; White, 1992a) set against plume-driven lithospheric thinning (Bonadio et al., 2025; Kerr, 1994). Understanding the drivers of magmatic diversity

within the BIPIP therefore has broad significance in understanding the petrogenesis and evolution of volcanism at LIPs and ocean islands globally. Despite this, the ALG has been comparatively understudied, forming the focus of only a handful of petrological/geochemical investigations over the past three decades (Barrat & Nesbitt, 1996; Carter et al., 2024; Lyle, 2001; Wallace et al., 1994). This means that there have been few attempts to understand its petrogenesis through modern analytical and modelling approaches, and to place the ALG in the context of the wider NAIP.

In this study, we report new major and trace element data from a large sample set from the ALG. Combining these with previously published data from core samples (Carter et al., 2024) and compilations of major, trace and isotopic data from the BIPIP (DIGIS Team, 2023) and Iceland (Harðardóttir et al., 2022), we are able to elucidate a multi-stage petrogenetic history of the Antrim Lava Group. Importantly, we show that previous studies were biased by limited sampling. In context with the wider BIPIP, we provide a unified model for petrogenesis and demonstrate the competing mantle, crustal and lithospheric controls on magma formation and evolution, leading to highly localised volcanic systems during continental LIP emplacement. These results have important implications not only for interpreting spatial and temporal variations in magmatism but also for predicting the patterns of mineralisation in continental LIP systems.

2 Geological background

2.1 Stratigraphy of the Antrim Lava Group

Early work divided the ALG succession into three formations (Old, 1975). The Lower Basalt Formation (LBF) and the Upper Basalt Formation (UBF) constitute the main thickness of the lavas (Fig. 1d) and are separated by a period of comparative quiescence (original termed the Interbasaltic Formation; Old, 1975), during which volcanism was significantly reduced and only two restricted and relatively small volume units were erupted: the Causeway Tholeiite Formation (CTF, including the famous jointed flows of the Giant's Causeway) and the Tardree Rhyolite Complex (TRC), in the north and middle of the plateau, respectively. Aside from this activity, a significant hiatus is indicated by: the formation of thick (≤ 30 m) laterites in the uppermost flows of both the LBF and CTF (the Port na Spaniagh and Ballylagan members, respectively); formation of a regional unconformity (Western Antrim Plateau Unconformity; Cooper et al., 2026); and deposition in places of the Coagh Conglomerate Formation which bears clasts of Tardree (or similar) rhyolites (Patterson et al., 1955). (Fig. 1d). Precise geochronological constraints are limited but suggest laterite formation may have taken

~1 Myr (Cooper et al., 2026; Hill et al., 2000). This period of comparative quiescence separating LBF and UBF is referred to as the interbasaltic period hereafter. Thinner lateritic horizons are ubiquitous and, less commonly, thin sedimentary interbeds, capping individual lava flows and indicating periods of repose and weathering between eruptions (Beresford-Browne et al., 2024; Lyle, 2000).

The LBF and UBF are transitional sub-alkaline olivine basalts. They are commonly olivine phyric but only very rarely contain plagioclase phenocrysts. From petrography the crystallisation order is olivine → plagioclase → clinopyroxene, with poikilitic augite representing the latest-forming phase (Lyle, 1988) although geochemistry indicates cryptic clinopyroxene fractionation at depth (Carter et al., 2024).

In the western part of the plateau, north of the Elagh Fault, the LBF is largely absent and only the UBF is thickly exposed, directly overlying pre-Paleogene rocks (Lyle, 1985a; Patterson et al., 1955). The lavas in this area have been identified as belonging to UBF due to the presence of the rhyolite-bearing Coagh Conglomerate Formation underlying them (Cooper et al., 2026), and the lack of well-developed laterites capping the sequence. The UBF west and east of the Portrush and Bann Valley Faults are hereafter termed the W-UBF and E-UBF, respectively, except where referring to previous work which did not distinguish these or where observations apply to both E- and W-UBF successions.

2.2 Geochemistry of ALG and Hebridean lavas

Much of what is known about the ALG stems from work by Lyle and others in the 1980s (Lyle, 1980, 1985a, 1985b, 1988; Lyle & Patton, 1989; Lyle & Preston, 1993). These investigations highlighted geochemical distinctions between the two main lava sequences, with the E-UBF systematically depleted in incompatible elements relative to the LBF (Lyle, 1980, 1985b). Lyle (1985b) suggested that this reflects derivation of the E-UBF by remelting of a mantle source already depleted by extraction of the LBF but could not fully test this hypothesis with models of mantle melting. It was also noted that the W-UBF is compositionally distinct from the E-UBF which erupted in the majority of the plateau and resembles the LBF in its trace element characteristics (Lyle, 1985a, 1988).

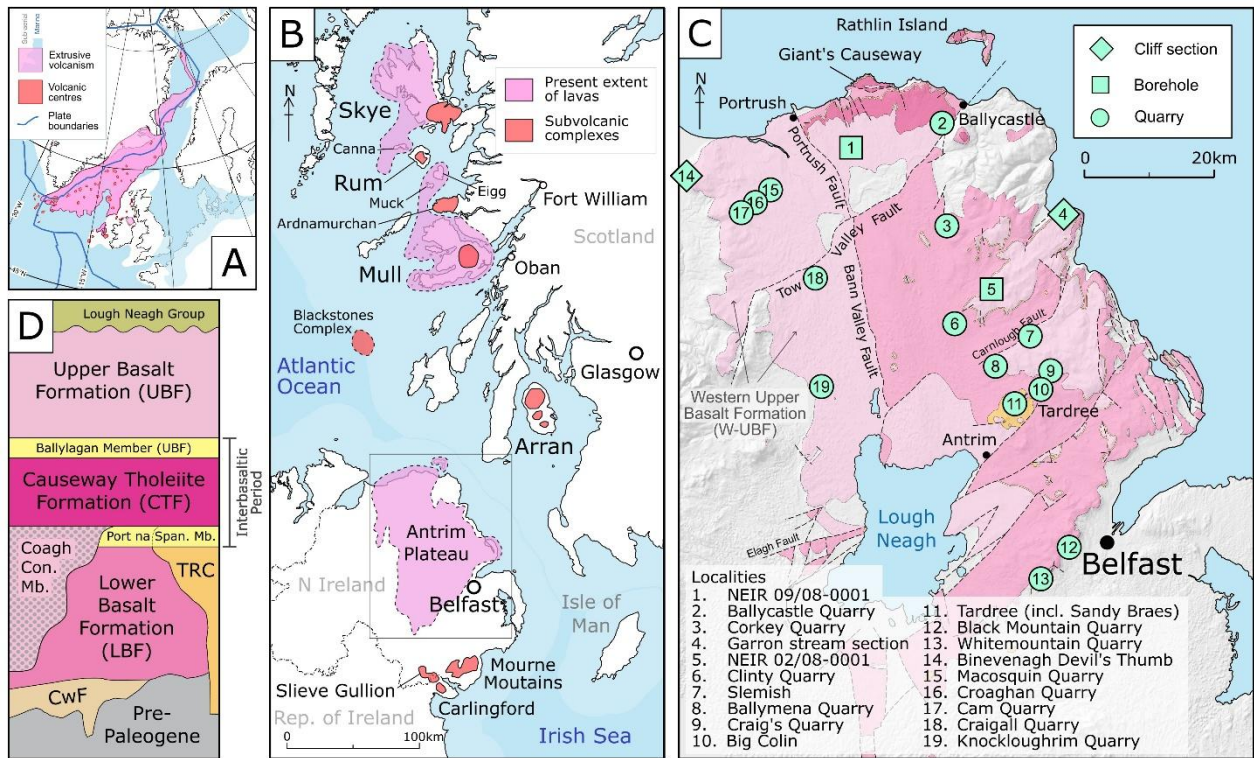


Figure 1 – Geological maps, sample locations and stratigraphy. **A:** paleogeographic reconstruction showing extent of NAIP magmatism at c. 56 Ma (adapted from Jones et al., 2023) **B:** regional map of the BIIP showing main extrusive and intrusive units (Cooper, 2004). **B:** geological map of the Antrim Lava Group, showing sample localities. **C:** stratigraphy of the Antrim Lava Group (Cooper et al., 2026). Contains data from 1:250k Geological Map of Northern Ireland, GSNI 1997. Fault locations from Anderson et al. (2016) and Cooper et al. (2026).

Barrat & Nesbitt (1996) divided the ALG lavas into three types based on chondrite normalised REE patterns: (1) convex-up, HREE-depleted patterns, reflecting deep melting in the garnet stability field; (2) LREE-enriched, flat MREE-HREE; and (3) flat LREE-depleted profiles; both (2) and (3) reflecting relatively shallower melting predominantly within the spinel field. LBF transitional/alkali basalts show deep melting signatures, while overlying CTF tholeiites show shallower type 2 and 3 profiles.

Similar shifts from alkali/transitional to more tholeiitic compositions are recognised at many BIIP centre and have been taken to represent lithospheric thinning as a key control on basalt petrogenesis (Ellam, 1992; Kerr, 1994). Several studies have drawn parallels between the UBF/LBF and the Skye Main Series Lavas and Mull Plateau Group alkali basalts based on their shared convex-up, HREE depleted signatures (Kent &

Fitton, 2000; Saunders et al., 1997). Similarly the CTF has been viewed as comparable to the more tholeiitic Skye Preshal More type dykes and Central Mull Tholeiites, both of which succeed earlier alkali basalts (Kerr, 1995; Lyle, 1985b; Saunders et al., 1997).

However, in Antrim the UBF shows both deep and shallow melting signatures (type 1 & 2; Barrat & Nesbitt, 1996). Similarly, more recent work has demonstrated deep melting signatures in late Mull dykes which complicate earlier models of simple lithospheric thinning (Kerr et al., 1999). That said, Barrat & Nesbitt (1996) studied a relatively small sample set, and did not account for the strong east-west variation in UBF compositions.

2.3 Isotopes and mantle source characteristics

The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of ALG basalts range from unradiogenic values typical of mid-ocean-ridge basalts (MORB) to much higher ratios, while $^{143}\text{Nd}/^{144}\text{Nd}$ shows a complementary trend towards unradiogenic ratios (Barrat & Nesbitt, 1996; Ellam & Stuart, 2000; Wallace et al., 1994). The radiogenic Sr endmember is unlikely to be lithospheric and is generally thought to represent one or more crustal contaminants, with Barrat & Nesbitt (1996) suggesting underlying Dalradian metasediments as the most likely assimilate. Isotopic data from samples across the NAIP, subject to contamination by a variety of crustal components, intersect at a single unradiogenic endmember suggested to represent a common asthenospheric mantle source across the North Atlantic (Ellam & Stuart, 2000). Compared to modern Iceland, where this common endmember appears to be heterogeneously mixed with a recycled pyroxenite component (Shorttle et al., 2014), there is limited evidence for lithological heterogeneity within the BIPIP (Carter et al., 2024; Hole, 2018), and a temporal progression from MORB-like to Icelandic mantle compositions has been suggested on the basis of high field strength element (HFSE) ratios (Fitton et al., 1997).

3 Sample selection and methods

3.1 Sampling strategy

A new sample set comprising 151 basalt and dolerite samples (incl. 12 subsamples/repeats) was collected from basalt flows, dykes and plugs in active quarries and cliff sections across County Antrim (Fig. 1c). In addition, a set of 17 samples was collected from the Tardree Rhyolite Complex representing a range of eruption styles including lava domes, agglomerates and tuffs (Old, 1975). These new data have been combined with 67 previously published major and trace element analyses from mineral exploration drill cores NIRE 09/08-0001 and NIRE 02/08-0001

(Carter et al., 2024), and repeat analyses of subsamples to make a total dataset of 235 analyses.

At each locality, every flow was sampled as far as practically possible and the lava sequence was logged. In addition, intrusive dykes and plugs were sampled where encountered. For each unit sampled, ~1-2 kg of the freshest accessible part was sampled, targeting non-vesiculated flow interiors, using a sledgehammer. However, in many cases individual flows were moderately weathered throughout, especially in thinner more braided flow morphologies.

For each locality the height above sea level of the base of the section/quarry was determined from a 10 m digital elevation model. The height of the base of the relevant stratigraphic unit (e.g. LBF) was then determined either from field evidence (i.e. pre-Paleogene rocks or interbasaltic period laterites outcropping within the quarry) or by interpolating from logs of nearby drilled cores or mapped contacts. To construct a composite section, the height of a sample above the base of its host unit was then calculated using its logged height in the quarry. The resulting stratigraphic height can be compared with the core samples which together form a 600 m thick composite stratigraphy spanning the full ALG sequence.

3.2 XRF

Major and trace element data were acquired by X-ray fluorescence spectroscopy (XRF) using a Panalytical Zetium wavelength dispersive XRF instrument in the Earth Surface Research Laboratory, Trinity College Dublin. All samples were sawn to remove weathered material before being ultrasonicated in deionised water followed by isopropyl alcohol. After drying they were crushed to ~2mm chips using a tungsten carbide-coated steel jaw crusher and finely powdered in an agate Tema mill. Samples were prepared for XRF analysis in two ways: for major element analysis as a fused lithium borate bead and for minor and trace element analysis as a pressed powder pellet; both according to the method of Carter et al. (2024). Secondary standards were run alongside samples and are reported by Carter et al. (2024). Loss on ignition was determined by gravimetry on approximately 2g of powder following ignition at 1000 °C for 1 hour.

3.3 Modelling fractional crystallisation

Isobaric fractional crystallisation liquid lines of descent (LLDs) were calculated for pressures of 0–2 GPa using Petrolog3 (Danyushevsky & Plechov, 2011). Fractionating phases and models used were: olivine (Herzberg & O'Hara, 2002; Toplis, 2005),

clinopyroxene and plagioclase (both Danyushevsky, 2001). A primary melt composition calculated for sample ABB032 from Carter et al. (2024) was used as the starting composition for models but similar LLDs result from a range of plausible starting compositions. The initial fO_2 was set at the quartz-fayalite-magnetite (QFM) buffer and allowed to vary freely during model runs, following the model of Kress & Carmichael (1988). Each calculation step was 0.01 % of fractionation.

To exclude the effects of magma differentiation and allow comparison between differently-fractionated samples, Na_8 and Ti_8 (i.e. Na_2O and TiO_2 corrected to $MgO = 8\%$; Klein & Langmuir, 1987) have been calculated by projecting sample compositions along a linear regression of the data to $Mg\#$ of 0.552 (equivalent to MgO of 8 wt%). Projecting against $Mg\#$ was preferred because correlations between major/trace elements and $Mg\#$ are generally stronger than with MgO . The linear regression for projection was calculated for each element from all LBF and UBF samples with $Mg\# > 40$ and $LOI < 4$ wt%.

Similarly, primary trace element concentrations have been calculated by projecting each data point to $Mg\#$ of 0.74 (the mean $Mg\#$ of calculated primary melts; Carter et al., 2024). These primary values allow comparison of sample data to results from melt modelling (see Section 3.5 below).

3.4 OPAM modelling

Olivine-plagioclase-augite-melt (OPAM) modelling to determine depths of magma storage in multiply-saturated magmas was performed using the model of Higgins and Stock (2024). This consists of a multiple-saturation prediction algorithm (yielding a probability of saturation, p_{sat}) and the calibrated OPAM barometer which provides a pressure. We used calculated pressures only where $p_{sat} > 0.5$. This was performed on all samples reported here and by Carter et al. (2024) as well as a large compilation of data from the BIIP made available via GEOROC (DIGIS Team, 2023). Plotted kernel density estimates (KDEs) were calculated using the default bandwidth algorithm (*bw.nrd0*) in the R statistical programming language, which implements Silverman's 'rule of thumb' (R Core Team, 2021; Silverman, 1986). The intrinsic model standard error on individual data points is 1.14 kbar (Higgins & Stock, 2024).

3.5 Mantle melt modelling and melt matching

To interrogate the effects of mantle potential temperature (T_p), lithospheric thickness/depth of melt segregation and mantle source composition on the chemistry of primary magmas, a large number of forward melting models were run using REEBOX

Pro (Brown & Leshner, 2016). Parameter space explored for all combinations of T_p (1400–1550°C in 25°C increments), source (primitive mantle, PM; McDonough & Sun, 1995; depleted MORB-mantle, DMM; Salters & Stracke, 2004; PM + 3% G2 pyroxenite, G2 = NMORB; Gale et al., 2013; DMM + 3% G2) and prior melt depletion (0–10% in 2% increments, see below), totalling 168 model runs and 1,629,045 individual calculated melt compositions.

The active RMC Langmuir mixing function, representing simple buoyant upwelling of a plume, was used, together with an ambient mantle T_p of 1350 °C and no plate spreading. In all following discussions it is assumed that the melting column was relatively well mixed and the pooled (rather than instantaneous) melt compositions at each decompression step are used.

To investigate the effects of remelting a source depleted by prior melt extraction, the composition of residues from different degrees of melting were calculated as:

$$X_{residue}^i = \frac{X_{source}^i - F \cdot X_{melt}^i}{(1 - F)} \quad (1)$$

Where F is the melt fraction, X is the concentration of element i , and the subscripts refer to the primary mantle source, extracted melt, and solid residue after melt extraction. Mean F was calculated by integrating F with respect to pressure over the melting region (Asimow et al., 2001):

$$F_{mean} = \frac{\int_{P_0}^{P_f} F \cdot dP}{P_f - P_0} \quad (2)$$

Residual compositions were calculated in this way for passive melting of PM and DMM sources for $F = 0$ –10%. These compositions were then input as the starting trace element compositions for further forward model runs using the same range of T_p as given above.

To determine a best fit model for a sample, a simple least squares misfit minimisation algorithm was used. This was applied to primitive ALG data from GEOROC (MgO >8%, LOI <5%) with misfit between primitive mantle-normalised data for sample and model steps minimised for: La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Er, Tm, Yb, Lu, Zr, Hf, Ti and Y. A similar approach was taken to XRF data from this study but with a more limited set of immobile trace elements: La, Ce, Nd, Zr, Hf, Ti and Y. Samples and best fit compositions are compared in Supplementary Figs. S1-S4.

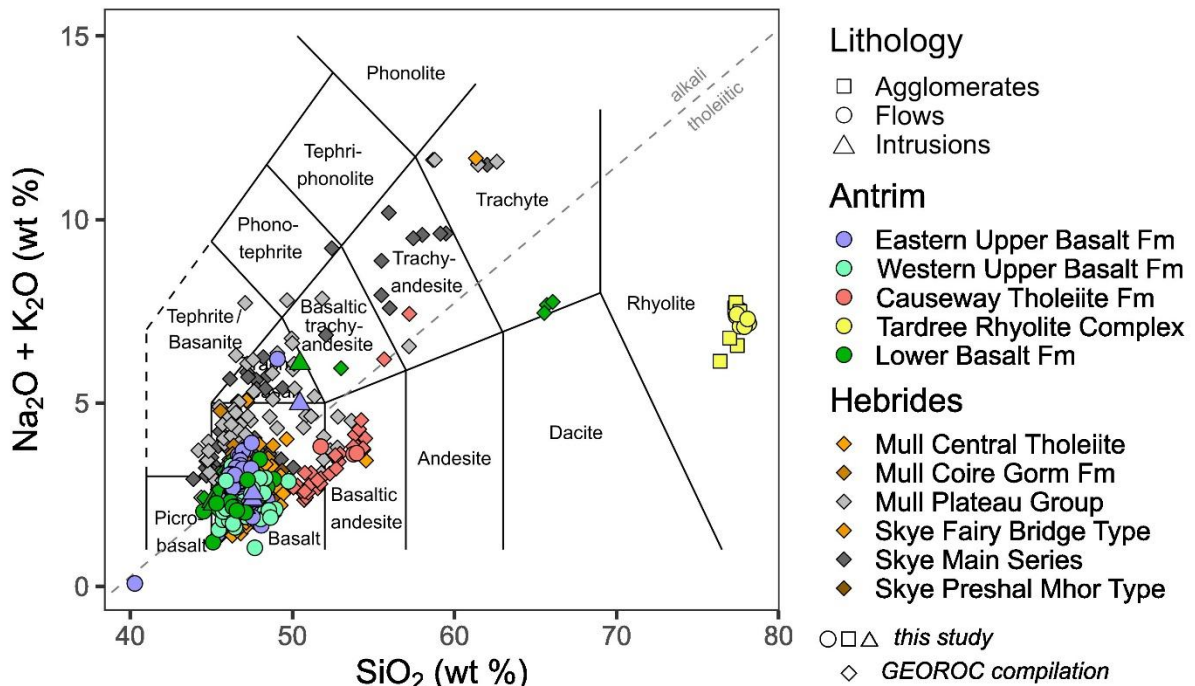


Figure 2 – Total alkali ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) versus silica plot, showing data from this study and from a compilation of ALG and Hebridean samples (DIGIS Team, 2023). The alkali-tholeiite divide is indicated by a dashed grey line.

4 Results

4.1 Major elements

The ALG samples are generally more tholeiitic than most Hebridean samples and predominantly plot within the tholeiitic basalt field with a few exceptions from dykes (Fig. 2). Basic ALG samples show a wide range of MgO (3.5–19.8 wt%) but the majority are quite primitive with 90% having MgO between 6.2 and 13.7 wt% (mean 9.9 ± 2.5 wt%) and a narrow range of SiO_2 (mean 47.1 ± 1.2 wt%). Samples from the TRC are significantly more silicic with SiO_2 ranging 73.1–78.2 wt% and $\text{MgO} < 1$ wt%.

Plotted against MgO as an index of magmatic differentiation, ALG major element abundances and Mg# (molar $\text{Mg}/[\text{Mg} + \text{Fe}]$) define liquid lines of descent (LLDs) consistent with crystallisation of olivine and clinopyroxene (Fig. 3). Samples with high MgO (> 15 wt%) do not represent plausible primary melts and reflect instead accumulation of olivine. Almost all samples plot to lower CaO at a given MgO than the line of olivine-only fractionation from a primary mantle melt attesting to clinopyroxene fractionation at some point in their crystallisation history. Most LBF and UBF samples lie

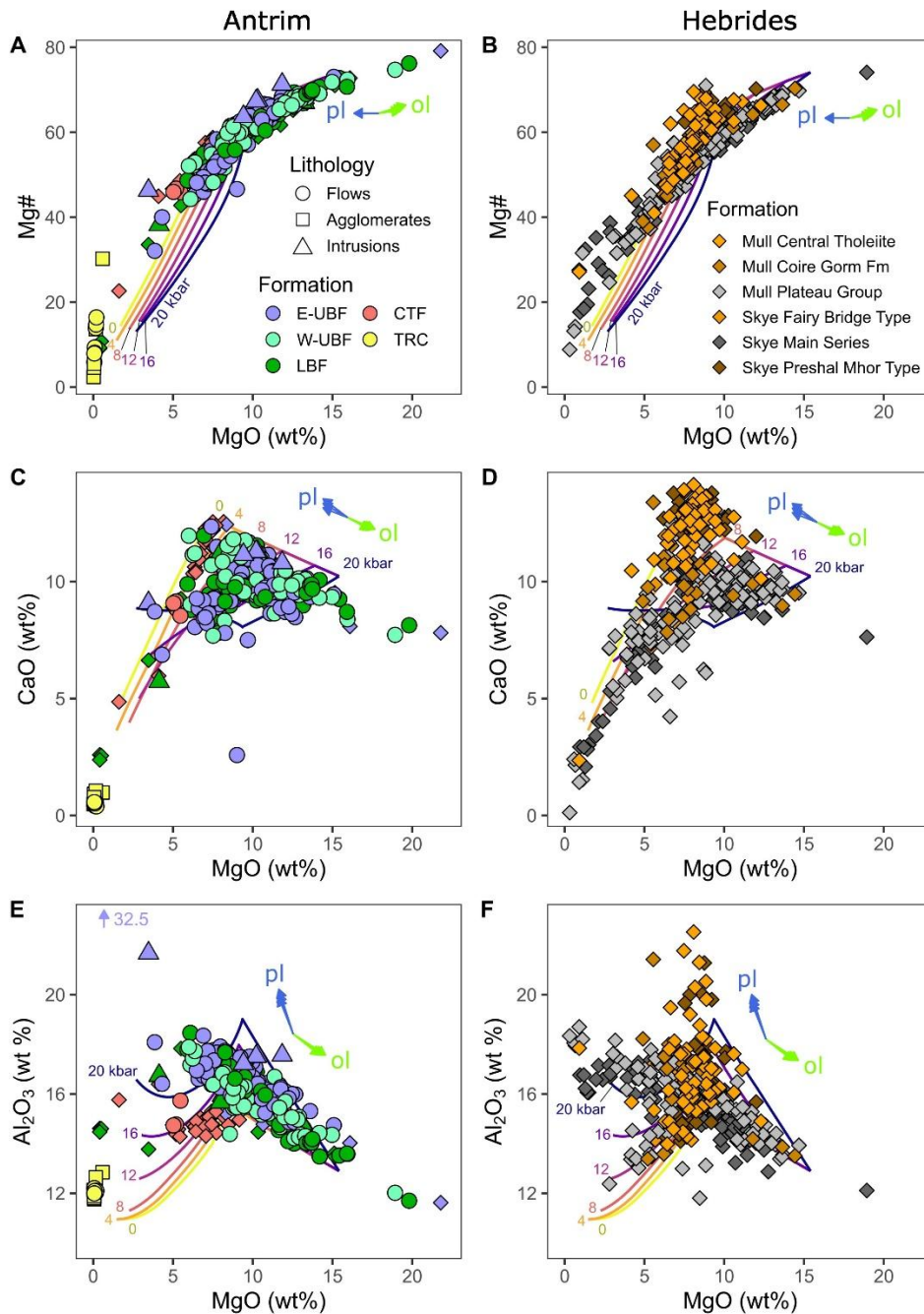


Figure 3 – Major elements differentiation trends for Antrim (left) and the Hebrides (right); literature data shown as small diamonds. **A, B:** MgO versus Mg# (molar Mg/[Mg + Fe]). **C, D:** MgO versus CaO. **E, F:** MgO versus Al₂O₃. Liquid lines of descent (LLDs) are plotted modelled from 0–20 kbar in Petrolog3 (Danyushevsky & Plechov, 2011). Vectors for addition of olivine (Fo = 80–90%) and plagioclase (An = 70–90%) are shown in green and blue, respectively.

close to modelled LLDs (Petrolog3; Danyushevsky & Plechov, 2011) for relatively high pressures (12–16 kbar). Other than the CTF samples, Al_2O_3 contents are high in most ALG samples and there is no inflection in the trend of the data, suggesting most were not saturated in plagioclase. In contrast, the CTF samples lie close to low pressure model LLDs (0–9 kbar) and have lower Al_2O_3 contents than LBF or UBF samples suggesting they have fractionated plagioclase. Hebridean samples generally show similar trends but extend to more evolved (lower MgO) compositions than ALG basalts. In addition, Preshall Mhor and Mull Central Tholeiites, show evidence for lower pressure fractionation and possibly plagioclase accumulation in some samples (Fig. 3d). Calculated LLDs for ALG basalts project towards the composition of silicic rocks from the TRC.

Within each stratigraphic unit, the lavas show broad up-section evolution towards more evolved compositions manifested by decreasing compatible elements such as MgO (and Mg#) and corresponding increases in incompatible elements such as Fe_2O_3 through both LBF and UBF (E and W) with height (Fig. 4). Across the interval between LBF and UBF this trend is broken and the lowermost UBF lavas have similar primitive compositions to the basal LBF, likewise becoming more evolved up-section.

These trends are most clearly seen in the core samples and in quarry samples from the western Antrim Plateau (W-UBF). The remaining quarry samples occupy a relatively limited stratigraphic height making it hard to discern any systematic variation. Some shorter sections from individual quarries show different trends with step changes to more primitive compositions or bimodal behaviour. In both LBF and UBF there is also a relatively wide range of compositions among the basal lava flows between different localities.

4.2 Trace elements

Rather than the repeated cycles across a similar compositional range seen in major elements (e.g. Fig. 4a), incompatible trace element abundances including Ti, Y, Zr and V show a step change across the interbasaltic period with little stratigraphic variation within each formation. The majority of E-UBF samples are significantly more depleted than the LBF (Fig. 5). This does not hold true for W-UBF samples from west of the Portrush and Bann Valley faults which are uniformly more enriched in incompatible trace elements and resemble the LBF in composition.

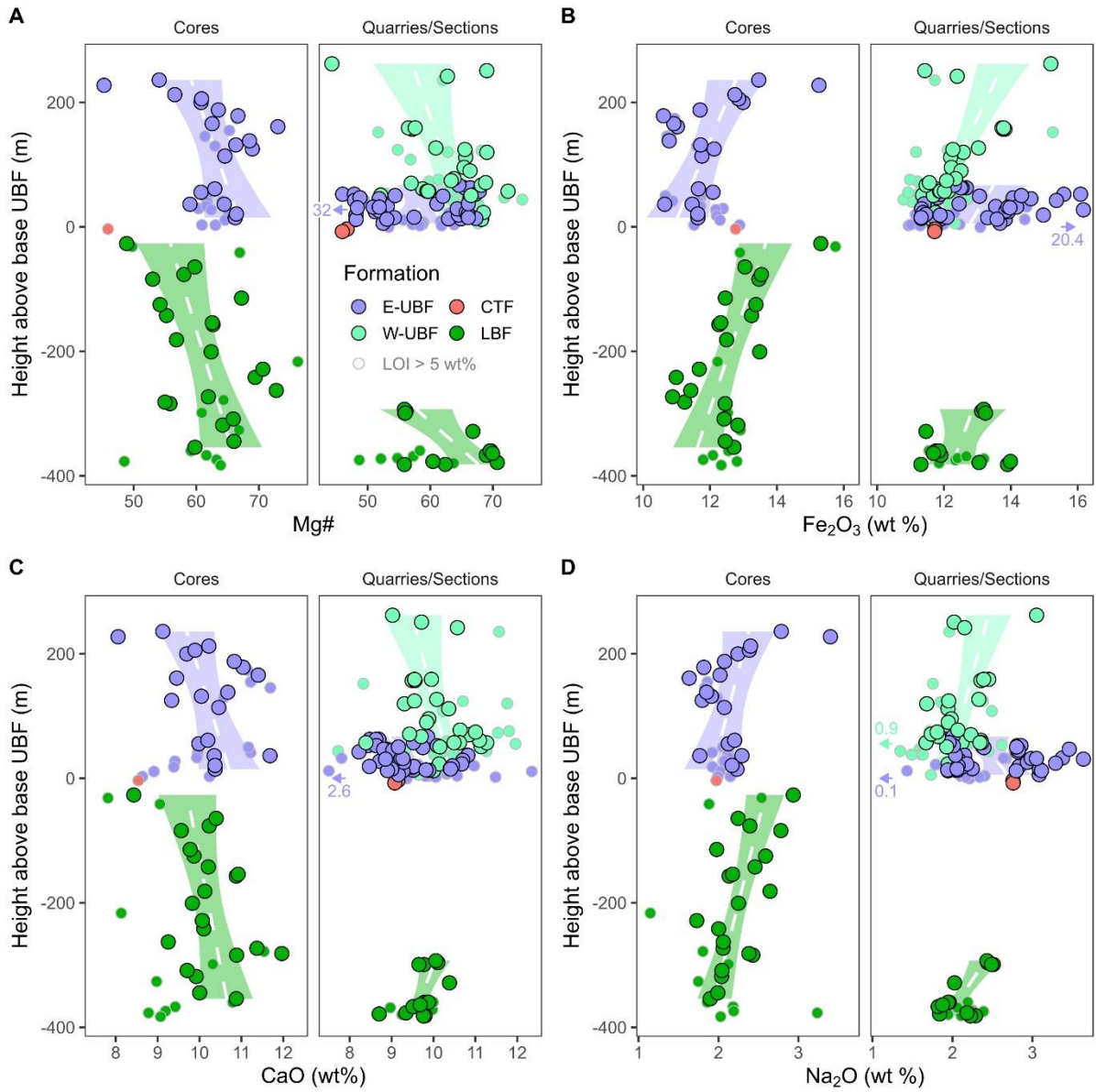


Figure 4 – Major element chemostratigraphy of the ALG, plotted relative to the base of the UBF. **A:** Mg#. **B:** Fe_2O_3 . **C:** CaO. **D:** Na_2O . Data from samples with LOI > 5% are shown as small points with a grey outline. See Section 3.1 for determination of stratigraphic height from quarry/cliff section samples. Core data are from Carter et al. (2024). Data from TRC samples are not plotted.

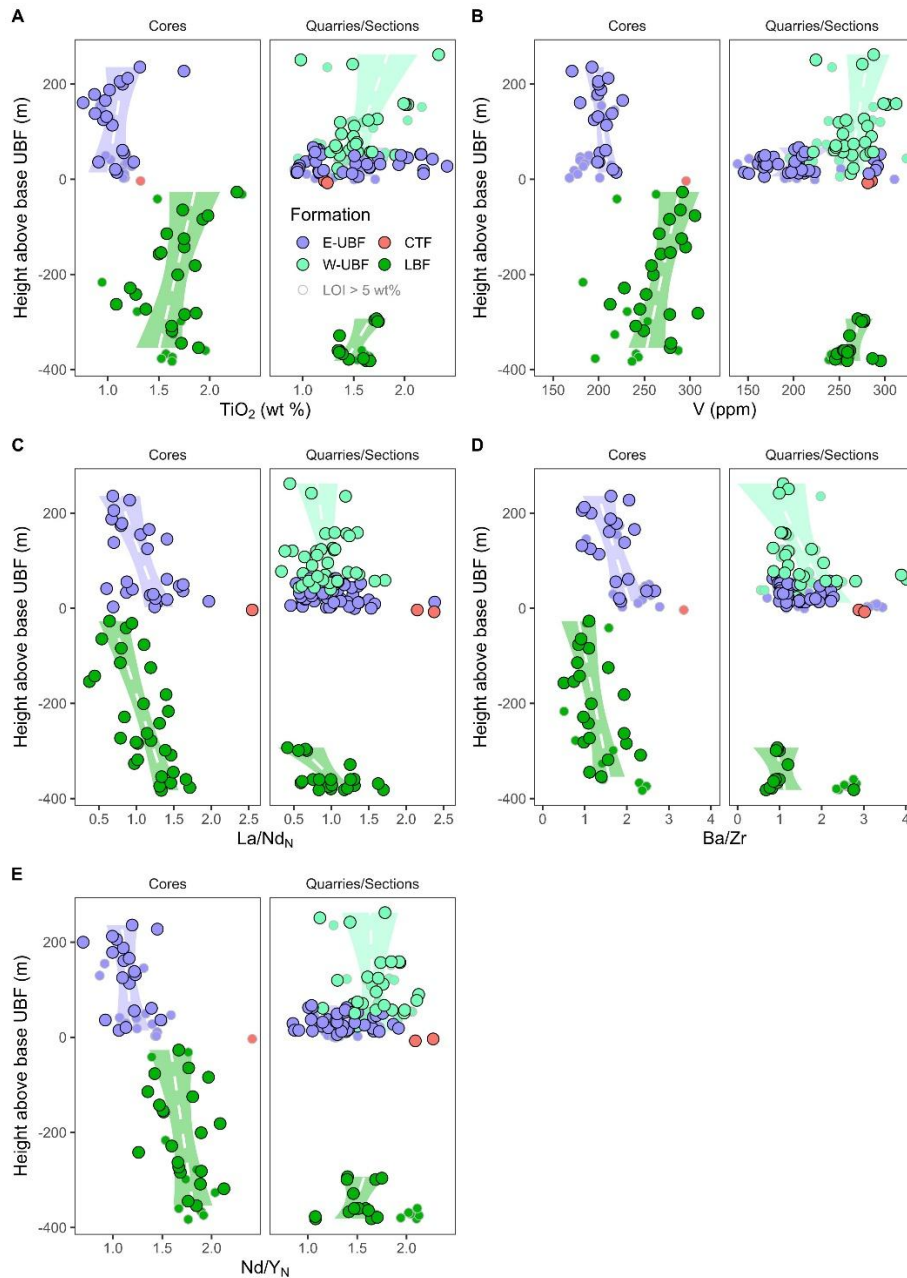


Figure 5 – Trace element chemostratigraphy of the ALG, plotted relative to the base of the UBF. **A:** TiO_2 . **B:** vanadium. **C:** chondrite normalised La/Nd (La/Nd_N). **D:** Ba/Zr . **E:** Nd/Y_N . Data from samples with LOI > 5% are shown as small points with a grey outline. See Section 3.1 for determination of stratigraphic height from quarry/cliff section samples. Core data are from Carter et al. (2024). Data from TRC samples are not plotted.

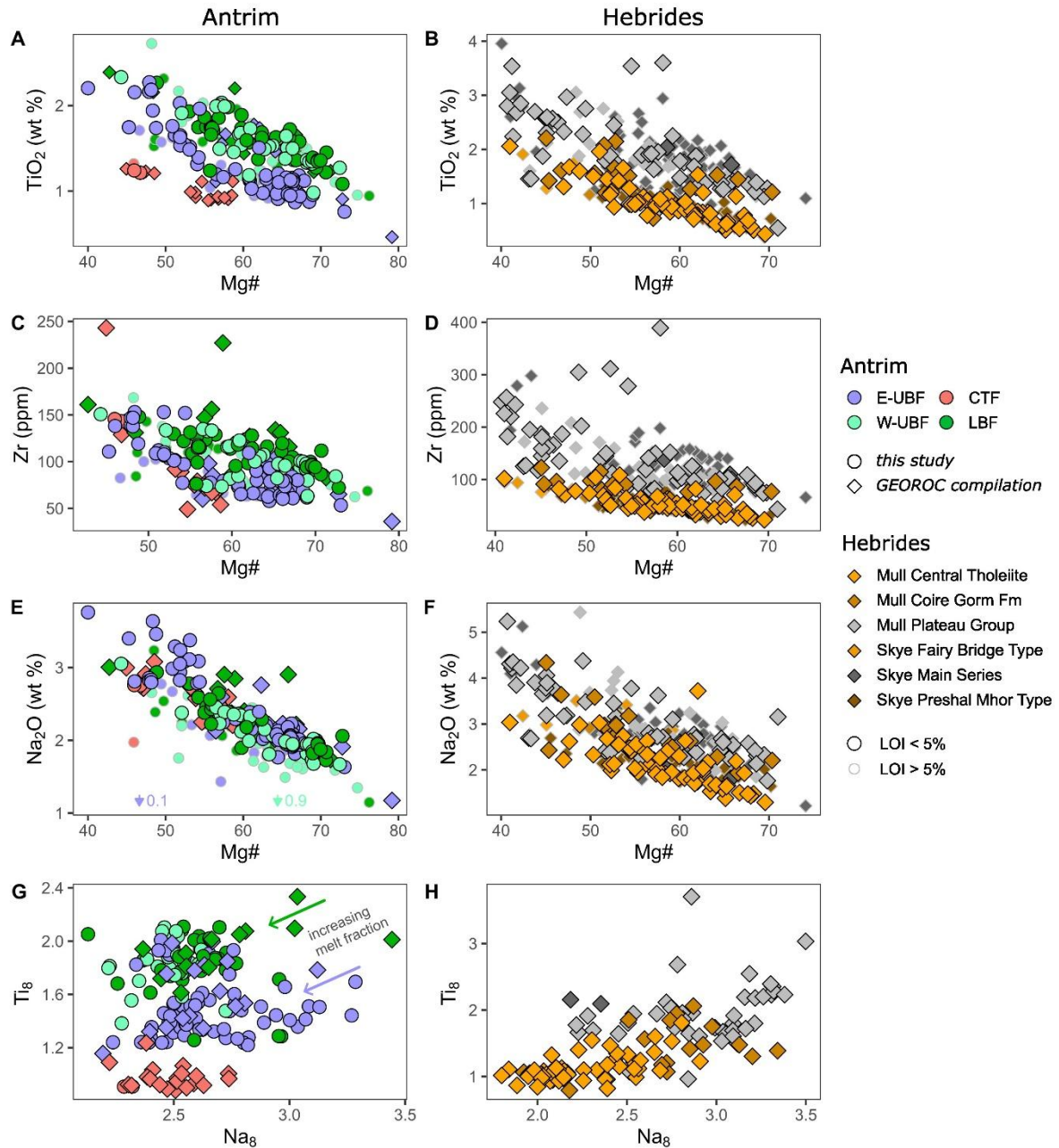


Figure 6 – Trace element liquid lines of descent for Antrim (left) and Hebrides (right). **A, B:** TiO_2 versus Mg#. **C, D:** Zr versus Mg#. **E, F:** Na_2O versus Mg#. **G, H:** Ti_8 versus Na_8 . Ti_8 and Na_8 calculated by projecting samples along a linear regression defined by the data to Mg# equivalent of 8% MgO. Only samples with Mg# > 40% plotted. Data from samples with LOI > 5% are shown as small points with a grey outline.

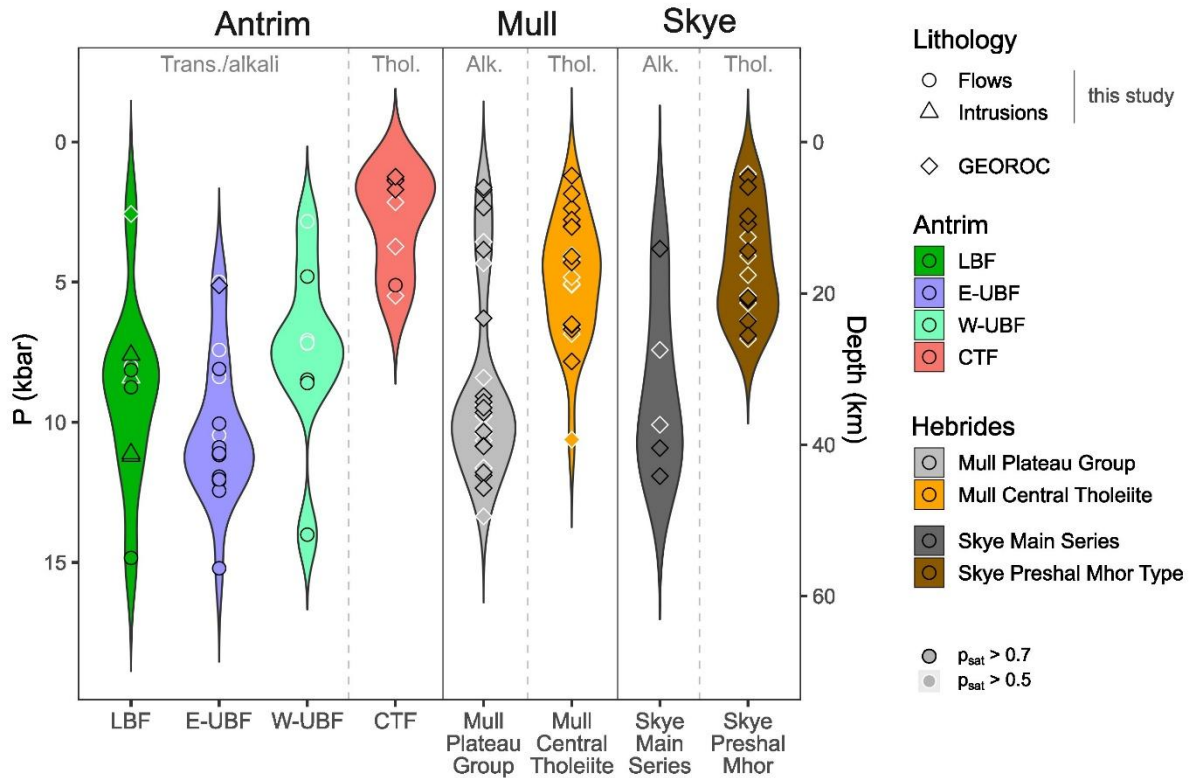


Figure 7 – pressures of melt equilibration determined by OPAM barometry (Higgins & Stock, 2024) for transitional/alkali and thoeiitic units from Antrim and the Hebrides. Distribution of pressures is indicated by a violin plot for all points with $p_{sat} > 0.5$. Points with a higher probability of saturation ($p_{sat} > 0.7$) are show with a black outline. Approximate depths have been calculated assuming a pressure gradient of 0.27 kbar/km.

What stratigraphic evolution is apparent in incompatible trace elements is generally closely correlated with samples' degree of differentiation. Plotted against Mg#, E-UBF and LBF lavas predominantly fall into two parallel but separate arrays, with LBF lavas more enriched in incompatible trace elements for a given Mg#. W-UBF samples generally fall into the same array as LBF samples. All samples from both UBF (E and W) and LBF fall into a single array when Na_2O is plotted against Mg# (Fig. 6).

Some trace element ratios correlate with stratigraphic height but do not correlate with Mg#. Lanthanum/Nd shows repeats decreasing trends from ~ 0.75 to 0.4 up section in both E-UBF and LBF, resetting across the interbasaltic period; Ba/Zr also shows very similar cyclic stratigraphic trend (Fig. 5c, d). There is no correlation between stratigraphic height and calculated primary TiO_2 or Ti_8 for either LBF or UBF. However,

Nd/Y does show a weak correlation with stratigraphic height ($R^2 = 0.2$) and an apparent continuous trend between LBF and E-UBF (Fig. 5e).

4.3 OPAM modelling

The olivine-plagioclase-augite multiple-saturation test of Higgins & Stock (2024) indicates that only a minority of samples both from this study and the GEOROC compilation of Antrim and Hebridean samples are three-phase saturated ($p_{\text{sat}} > 0.5$; this study Antrim, $n = 34/218$; GEOROC Antrim, $n = 9/75$; GEOROC Hebrides, $n = 80/332$). In each locality (Antrim, Mull, Skye) samples from tholeiitic units were more likely to be saturated than more alkalic magma series (CTF, 22% sample saturated vs UBF 16% and LBF 10%; Mull Central Tholeiite 39% vs. Mull Plateau Group 26%; Skye Preshal Mhor Type 38% vs Skye Main Lava Series 6%).

Antrim samples show a range of equilibration pressures from 1.2–15.2 kbar (mean 8.1 ± 3.8 kbar, $n = 43$; uncertainty is 1SD). Hebridean samples show a very similar range of pressures 1.1–13.4 (mean 6.7 ± 3.4 kbar, $n = 79$). Figure 7 shows a clear difference in the distribution of pressures between more transitional/alkalic (UBF/LBF, Mull Plateau Group, Skye Main Series) and more tholeiitic units (CTF, Mull Central Tholeiite, Skye Preshal Mhor Type). The former show similar distributions with predominantly deep storage (>5 kbar) with a tail of samples showing lower pressures (mean 9.0 ± 3.2 , $n = 68$). The tholeiites meanwhile show more uniform shallow depths (mean 4.4 ± 2.1 , $n = 48$) with no pressures > 10 kbar.

Pressure from OPAM modelling correlates with major element indices of differentiation including SiO_2 and Mg# with more evolved samples generally recording shallower depths of apparent melt storage (Fig. S6).

5 Discussion

5.1 Thermal maturation of the crust

The ALG succession appears to show compositional cyclicity with overall trends towards more evolved compositions in both LBF and UBF, resetting across the hiatus between the two main lava packages (the interbasaltic period; Fig. 4). Similar cycles of up-section fractionation, with sharp reversals to more primitive compositions, have been observed in the Deccan Traps LIP (Cox & Hawkesworth, 1985). Mull Plateau Group lavas show fairly constant compositions for much of their thickness but show a similar gradual decrease in MgO in the upper 300m of the succession (Kerr, 1995).

There are two possibilities for these trends: variation in the composition of parental melts, or variation in the degree of fractionation (or assimilation) from a common parental melt through each of the lava successions. The former could result from changes in mantle potential temperature or source composition, while the latter might arise due to variation in the architecture of the crustal plumbing system, variation in magma residence time in the crust, or a combination of these factors.

Variation in mantle T_p is precluded by olivine-spinel thermometry from these sample which, while indicating highly variable T_p during LBF emplacement, do not show an overall decrease in temperature through either the LBF or UBF (Carter et al., 2024). Moreover, the lack of stratigraphic variation in Ti_8 within each unit suggests each formed from a consistent parental melt composition (Fig. 6g).

A more likely origin for these trends is therefore thermal maturation of the crust and increasing complexity of magmatic plumbing during LIP emplacement. Formation of crustal sills or magma chambers is related to relaxation of viscoelastic stress through heating by prolonged magmatism (e.g., Jellinek & DePaolo, 2003). Conversely, eruption of high MgO picrites has been linked to direct tapping of near-primary mantle melt through cold impermeable cratonic lithosphere (Hole & Natland, 2020). A progression from deep ponding of dense primary melts (i.e. at the Moho) to extensive trans-crustal magmatic systems is recognised as an intrinsic aspect of LIPs, stemming from the long term thermal effects of magmatism (Black et al., 2021; Karlstrom & Richards, 2011). This suggests that the major element stratigraphy of LBF and UBF each record a cycle of increasing magma residence time in the crust, and a progression from relatively direct transport of near-primary melts to prolonged stalling of melts in crustal sills or magma chambers.

That said, various quarries expose the basal flows of the UBF and LBF across the plateau and these show significant variability in major elements and some longer sections show abrupt jumps to more mafic compositions. This is likely because individual flows are discontinuous and controlled by palaeotopography. Moreover, the magma plumbing system and degree of pre-eruptive fractionation is likely to vary between eruptive centres. The result of these factors is that flows at a given stratigraphic level (e.g. the basal flows) may well not correlate to the same eruption or even eruptive centre, and that even within a short succession, flows may have originated at different centres as the locus of activity moved spatially (e.g., rapid vent migration seen during recent eruptions on the Reyjanes Peninsula; Pedersen et al., 2022).

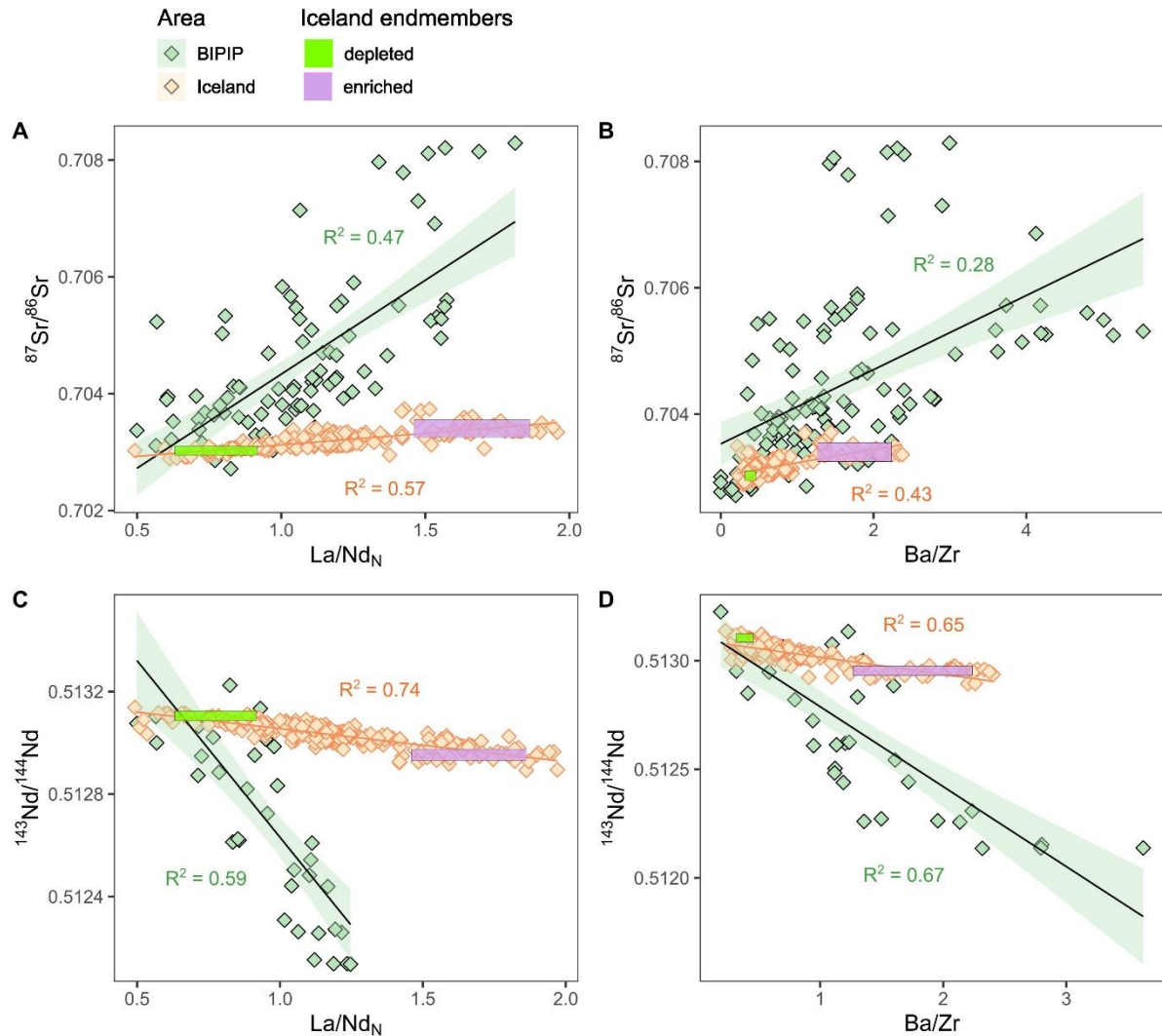


Figure 8 – contrasting trace element and isotopic signatures of BIPIP and Icelandic basalts. **A:** $\text{La}/\text{Nd}_\text{N}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$. **B:** Ba/Zr versus $^{87}\text{Sr}/^{86}\text{Sr}$. **C:** $\text{La}/\text{Nd}_\text{N}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$. **D:** Ba/Zr versus $^{143}\text{Nd}/^{144}\text{Nd}$. BIPIP data ($45\% < \text{SiO}_2 < 52\%$) from GEOROC (DIGIS Team, 2023). Iceland data ($6\% < \text{MgO} < 14\%$) from compilation of (Harðardóttir et al., 2022). Endmember compositions calculated as the mean ($\pm 2\sigma$) of Icelandic samples in the 0-10th percentile and 90-100th percentile of $^{143}\text{Nd}/^{144}\text{Nd}$ following the approach of (Shorttle & MacLennan, 2011).

5.1.1 Crustal assimilation

A notable feature of the ALG chemostratigraphy is a broad decrease in La/Nd and Ba/Zr with stratigraphic height (Fig. 5c, d). Variations in La/Nd can reflect changes in source or melting characteristics; equally, LREE enrichment can result from assimilation of similarly enriched crustal materials (e.g. Moine metasediments [$\text{La}/\text{Nd}_\text{N} \geq 2.5$;

Thompson et al., 1986). Isotopic ratios of Sr and Nd are ubiquitously modified from primary mantle values across the BIIP and have been widely attributed to crustal anatexis (Ellam & Stuart, 2000; Peate et al., 2012; Wallace et al., 1994). Lanthanum/Nd and Ba/Zr of BIIP basalts ($45 < \text{SiO}_2 < 52\%$; DIGIS Team, 2023) strongly correlate, positively and negatively respectively, with $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ (Fig. 8). Similar correlations are apparent in data from modern Icelandic basalts and are widely attributed to variable contributions from a lithologically heterogeneous mantle source (e.g., Shorttle et al., 2014). Plotting BIIP and Icelandic data together, the two datasets appear to share a common depleted endmember characterised by low La/Nd, unradiogenic Sr isotopes and radiogenic Nd (Fig. 8). However, the trend of BIIP data is clearly distinct and does not intersect the enriched Icelandic endmember. If high La/Nd or Ba/Zr in BIIP samples were to represent an enriched mantle component, its Sr and Nd isotopic composition would be unrealistically extreme, nearing or surpassing the most enriched endmembers observed globally in ocean island basalts ($^{87}\text{Sr}/^{86}\text{Sr} > 0.708$, $^{143}\text{Nd}/^{144}\text{Nd} < 0.5124$; cf. Stracke et al., 2005). Rather, many previous studies have concluded that crustal assimilation exerts a primary control on radiogenic isotopes in continental basalts (e.g., Ellam & Stuart, 2000; Thompson et al., 1982; Wallace et al., 1994). The strong correlations seen between trace element and isotopic ratios is therefore notable and suggest that La/Nd and Ba/Zr primarily reflect crustal contamination in BIIP basalts and can be an effective proxy in the absence of radiogenic isotopic data. That is not to say that the data can conclusively exclude the presence of enriched components in the source of BIIP basalts – such variation could contribute to some of the scatter in the trends – but these are not the primary control on isotopic and LREE compositions.

Applied to our data this suggests that LBF and UBF show two successive cycles of decreasing crustal assimilation with the earliest magmas the most contaminated, inconsistent with a straightforward model of assimilation fractional crystallisation. This could be viewed as counter to the evidence from major elements; development of a more extensive crustal plumbing system would also facilitate prolonged heating and contact with crustal country rock. However, melt inclusions from Mull basalt-hosted olivines show much of the crustal contamination occurs very early in the crystallisation sequence, in many cases prior to or synchronous with earliest olivine crystallisation (Peate et al., 2012).

Positive correlations between Mg# and isotopic indices of contamination have long been recognised in continental flood basalts (Cox & Hawkesworth, 1985; Thompson et al., 1982; Wallace et al., 1994). In part these may relate to the heat of magmas with the

most primitive having the greatest thermal potential to assimilate wall-rocks. Heat transfer may be further facilitated by turbulent ascent, and thermal modelling also predicts higher assimilation by more primitive magmas and high ascent rates (Reynolds number ~ 2000 ; Huppert et al., 1985). Alongside this, repeated heating and anatexis may reduce the productivity of crustal lithologies such that fusible components of the country rock are depleted and high flux melt pathways become armoured over time (e.g., Amstutz et al., 2025). This effect has been suggested to explain the progression from granitic to gabbroic compositions seen in the Paleogene Carlingford Igneous Centre (Meade et al., 2014). In this framework, the cyclic decrease in crustal contamination through LBF and UBF sequences is consistent with two cycles of maturing long-lived magmatic systems punctuated by a near-hiatus, cooling and resetting.

Altogether, then the trend of the ALG in the thickest and most complete sections appears to define a clear example of thermal maturation of the crust with two main phases. As with major element cyclicity, the apparent resetting of the sequence at the base of the UBF suggests that the hiatus between their eruption was long enough that the crust largely cooled, and that later UBF (W and E) lavas were erupted through a crustal plumbing system unrelated to the earlier phase of volcanism.

5.2 Depths of melt equilibration

The architecture of crustal magma storage is intimately linked to melt flux and thermal maturation of the crust (e.g., Baxter et al., 2023; Black et al., 2021; Gleeson et al., 2020). It is therefore instructive to consider the equilibration pressures recorded by the OPAM geothermobarometer (Higgins & Stock, 2024).

The saturation test of Higgins & Stock (2024) predicts that the majority of ALG samples are not three phase saturated. This is consistent with forward crystallisation models which suggest that most samples equilibrated at depths >10 km and are too primitive to have saturated plagioclase; all samples indicated as three-phase saturated have $\text{MgO} \leq 9$ whereas the majority (61%) of ALG basalts have $\text{MgO} > 9\%$. The primitive compositions abundant during earliest LBF and UBF magmatism are very unlikely to have developed three phase saturation. Thus, there is an inherent bias in the OPAM barometer towards more evolved samples which may mask aspects of the petrogenesis of the broader sample set. As a result, it is not possible to directly resolve stratigraphic variation in the pressure of melt storage through the LBF and UBF, largely due to the

small proportion of samples for which a pressure can be calculated. However, all successions (LBF, E-UBF and W-UBF) record a general trend of increasing p_{sat} with stratigraphic height and a higher proportion of three-phase-saturated melts later in the eruptive sequence of each unit (Fig. S5). Although not directly indicative of the pressures of melt storage this is consistent with limited upper crustal melt storage during the early emplacement of each succession followed by thermal maturation and development of transcrustal melt systems.

The pressures recorded by OPAM-saturated ALG basalts are also positively correlated with MgO and negatively with SiO_2 , suggesting that degree of evolution might correlate with increasing availability of shallow melt storage regions. However, since Si and Mg are used in barometer parameterisation these observations are not strictly independent.

For LBF and UBF, calculated pressures of melt storage (mean 9.3 ± 3.1 kbar, $n = 35$) agree reasonably well with inferences from petrological modelling which suggest differentiation at pressures of $\sim 12\text{--}16$ kbar best fit both major elements (Fig. 3) and olivine Ni contents (Carter et al., 2024). Slightly lower pressures from OPAM could relate to the biases discussed above, with more primitive basalts predominantly fractionating at pressures >10 kbar resulting in suppression of plagioclase saturation.

As the OPAM parameterisation was calibrated on experiments ≤ 10 kbar; higher pressures involve extrapolation beyond the calibration range. Since pressure is calculated via a regression-based model, as long as three-phase saturation has been achieved, and pressures are within a few kbar of the calibration range these are likely to robustly represent pressures >10 kbar but may be less accurate than pressures <10 kbar. The combined evidence indicates deep melt storage characterised the majority of LBF and UBF magmas although a handful of samples recording low pressures (<5 kbar) suggest some limited melt re-equilibration in the upper crust.

5.2.1 Shallower melt storage for tholeiitic units?

Compared to UBF and LBF, the CTF records much shallower average pressures (Fig. 7), consistent with previous suggestions of eruption from a shallow magma chamber (Simms, 2021). Very similar trends are recorded on both Mull and Skye with transitional/alkali basalts from the main phase of magmatism (Mull Plateau Group, Skye Main Lava Series) recording generally deeper pressures than succeeding tholeiitic units (Mull Central Tholeiite, Skye Preshal Mhor Type; Fig. 7). These differences both in Antrim and the Hebrides suggest a common process throughout the BIPIIP.

One possible explanation is the potential for false positives during algorithmic determination of three-phase saturation, with a 20% false positive rate for the algorithm of (Higgins & Stock, 2024) at $p_{\text{sat}} > 0.5$. Since there are major element differences in the respective compositions of transitional and tholeiitic units, these could impart a bias in the event of false positives, although Higgins & Stock (2024) did test for compositional bias. Nonetheless, to assess this we can apply a more stringent filter requiring the calculated probability of saturation is > 0.7 necessitating a greater degree of compositional similarity to three-phase saturated magmas for a sample to be considered. With such a filter applied the distinction in equilibration pressure between transitional/alkali and tholeiitic units is still apparent in Antrim, Mull and Skye samples (Fig. 7). Moreover, there is no systematic correlation between p_{sat} and pressure of equilibration for any of the formations studied (Fig. S7).

Tholeiitic magmas are likely to have formed by higher degree melting (e.g., Kerr, 1994). It is possible therefore that their volume or volume flux into the crust was higher relative to smaller fraction transitional/alkali melts facilitating the generation and/or maintenance of eruptible upper crustal magma bodies. This could impart a preservation bias with smaller melt bodies more likely to freeze and remain unerupted. The large thickness of CTF lava flows (< 30 m) has been noted in comparison to typical thicknesses of ~ 10 m for LBF and UBF flows (Lyle & Preston, 1993) and suggests the former were fed by relatively larger bodies of eruptible magma, though filling of paleotopography may also play a role (Simms, 2021). However, this fails to explain why deeper pressures are not also recorded by tholeiite eruptions which tapped deeper melt storage regions. Previous work on Iceland and Galapagos has suggested that higher melt fluxes drive “shoaling” of melt storage regions to shallower crustal depths (Baxter et al., 2023; Gleeson et al., 2020) and could help to explain the link between tholeiitic magmas and low equilibration pressures.

An alternative explanation is that differences in pressure of melt storage might relate to differences in rheology between more alkali-rich and -poor basalts, since alkali basalts have lower viscosities for a given temperature and water content (e.g. Kushiro et al., 1976). Added to that, more alkali-rich melts have been shown to crystallise over a wider temperature range than depleted melts, resulting in preservation biases in eruptive sequences due to the latter preferentially freezing in the crust (Neave et al., 2019). The combination of these factors may explain the OPAM barometry, with only alkali melts able to erupt directly from lower crustal reservoirs to the surface along narrow dykes. In contrast, more viscous tholeiitic magmas may be prone to stalling due to their inherently higher viscosity and smaller temperature interval of crystallisation. Assembly

of a relatively large shallow crustal body of tholeiitic melt necessitates prolonged storage, fractionation and assimilation, and is consistent with the large eruptive volumes observed for the CTF, their more evolved character and their distinctive trace element and isotopic composition (see also Section 5.4.2 below).

Although it seems unlikely that the differences in melt storage depths are solely a result of biases in the barometer, it is difficult to unambiguously distinguish between the remaining possibilities. Given re-equilibration at shallow depths will overprint deeper storage for a given magma, the high pressures recorded by most transitional/alkali basalts suggests that shallow melt storage regions were absent or bypassed by most erupted magmas. The uniformly shallower storage characterising tholeiitic units therefore suggests either preferential development/utilisation of upper crustal storage, possibly due to elevated and localised melt flux; preservation biases inherent to erupting depleted magma compositions; or a combination of these factors.

5.3 Competing controls from lithospheric thickness and source depletion on trace element compositions

By comparing with compiled isotopic data from ALG and Hebrides we are able to show that while, as discussed above, LREE are largely overprinted by crustal assimilation, the middle-to-heavy REE and HFSE (incl. Ti and Zr) appear to primarily reflect mantle source and melting processes and are minimally affected by such processes.

The parallel and distinct arrays defined by Ti, Y, Zr and V abundances against Mg# indicate independent liquid lines of descent for E-UBF and LBF which cannot be reconciled by fractional crystallisation (Fig. 6).

When corrected for fractional crystallisation to primary magma compositions (see Section 3.3 above), the data fall into two clear groups with the majority of primitive (MgO >8 wt%) LBF and W-UBF having $\text{TiO}_2^{\text{primary}} > 1$ wt% and almost all E-UBF having $\text{TiO}_2^{\text{primary}} < 1$ wt% (Fig. 9c). These differences can be mapped to magma types defined on the basis on different REE profiles, allowing comparison with results of Barrat & Nesbitt (1996) and broader data across the BIPIP. Convex up HREE-depleted REE profiles, indicative of deep garnet-present melting, are associated with high $\text{TiO}_2^{\text{primary}}$; flatter profiles are associated with low $\text{TiO}_2^{\text{primary}}$. The degree of HREE depletion can be parameterised by the chondrite-normalised ratio $(\text{Sm}/\text{Yb})_{\text{N}}$ or equivalently $(\text{Nd}/\text{Y})_{\text{N}}$ which strongly correlates with the former and has the advantage of both elements being readily measurable by XRF, allowing comparison with a wider range of data.

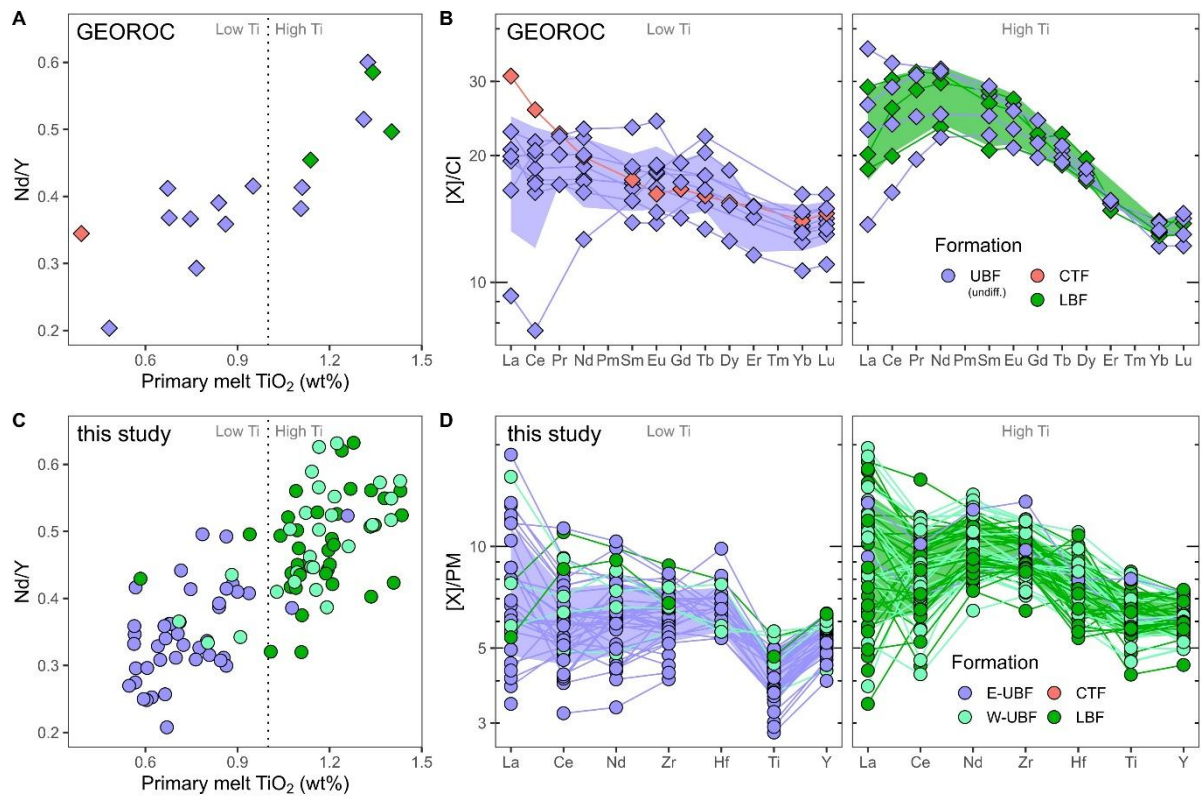


Figure 9 – comparison of TiO_2 contents and REE patterns of ALG samples from GEOROC (top) and this study (bottom). A, C: primary melt TiO_2 versus Nd/Y_N for GEOROC samples (A) and this study (C). B: chondrite-normalised rare-earth element diagram for low and high TiO_2 samples (left and right, respectively). D: primitive mantle normalised spider diagram for low and high TiO_2 samples from this study.

The ratio $(\text{Nd}/Y)_N$ shows a positive correlation with $\text{TiO}_2^{\text{primary}}$ ($R^2 = 0.70$) for all primitive ALG samples (Fig. 9). This suggests that TiO_2 enrichment is controlled by depth of melting via concomitant variation in the degree of melting. We test this by comparing the compositions of primitive ALG basalts from this study and GEOROC with the results of forward melting models from primitive and depleted MORB mantle sources (PM, DMM; see Section 3.5).

The high Ti convex-up REE characteristics of LBF and W-UBF magmas can be reproduced by decompression melting of either primitive mantle or depleted MORB mantle predominantly in the presence of garnet (Fig. 10). Best fit models are consistent in suggesting final depths of melting of 2.5-2.75 GPa for most LBF magmas in the GEOROC database. In contrast, low Ti E-UBF are uniformly depleted in incompatible

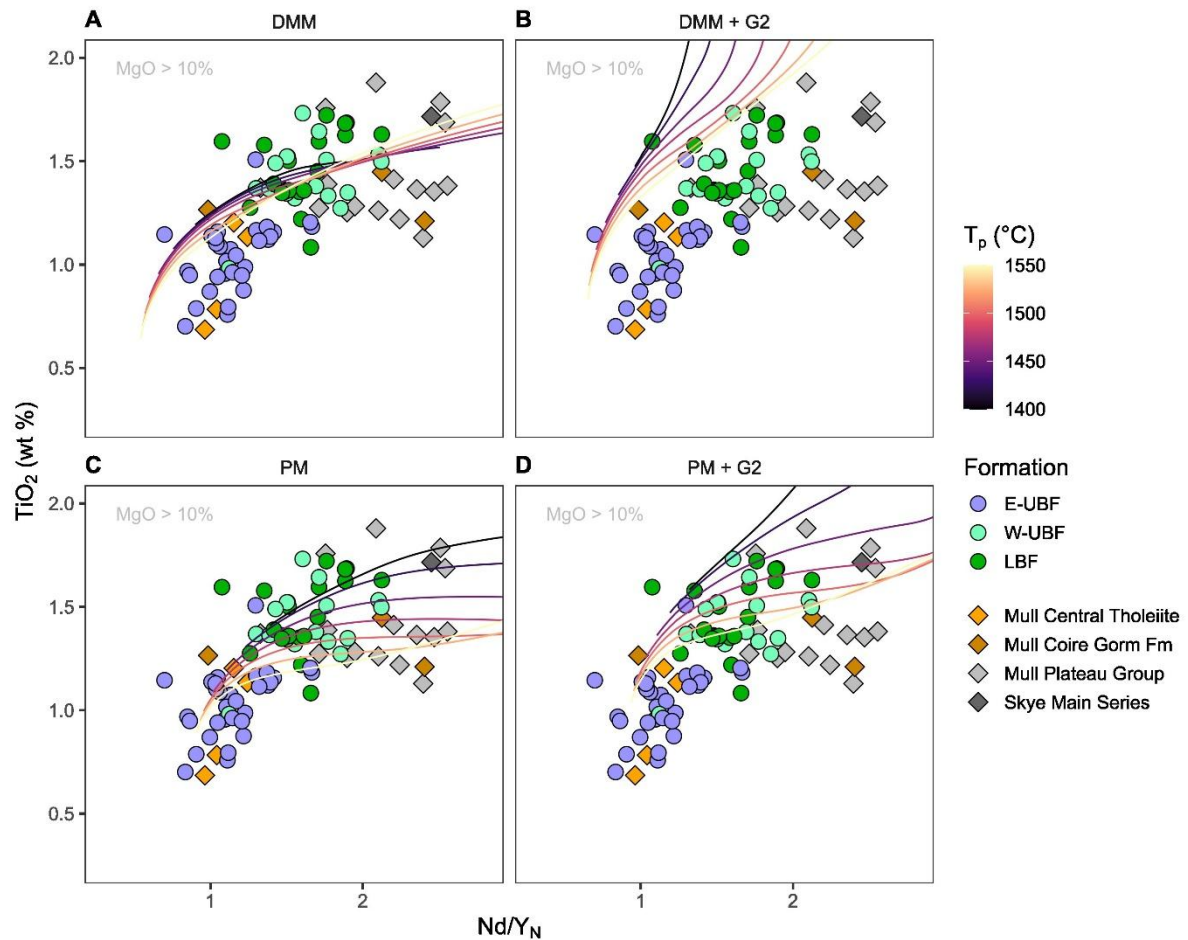


Figure 10 – comparison of trace elements from primitive Antrim and Hebrides basalt with polybaric melting models. TiO_2 versus Nd/Y_N is plotted samples with $MgO > 10$ wt% and $LOI < 5$ wt% and compared with forward melting models from **A:** depleted MORB mantle (DMM). **B:** DMM + 3% G2 pyroxenite. **C:** primitive mantle (PM). **D:** PM + 3% G2 pyroxenite. Models are shown for mantle T_p of 1400-1550 °C. Model compositions plotted are for pooled melts calculated using REEBOX Pro (Brown & Lesher, 2016). See Section 3.4 for details and model parameters.

high field strength elements including Ti, Zr and Y relative to LBF. Simple polybaric melting models cannot match the HFSE composition of either LBF or E-UBF for any of the sources modelled, with E-UBF samples having systematically lower Ti than predicted by models (Fig. 10). Polybaric melting of a single source is further precluded by a lack of correlation between Na_8 and Ti_8 across the different units. Instead, for a given Na_8 (i.e. degree of melting), LBF, CTF and E-UBF are all offset from one another with CTF having the lowest Ti_8 and LBF the highest (Fig. 6g). In comparison transitional/alkali and tholeiitic units in Mull and Skye form a more coherent trend (Fig.

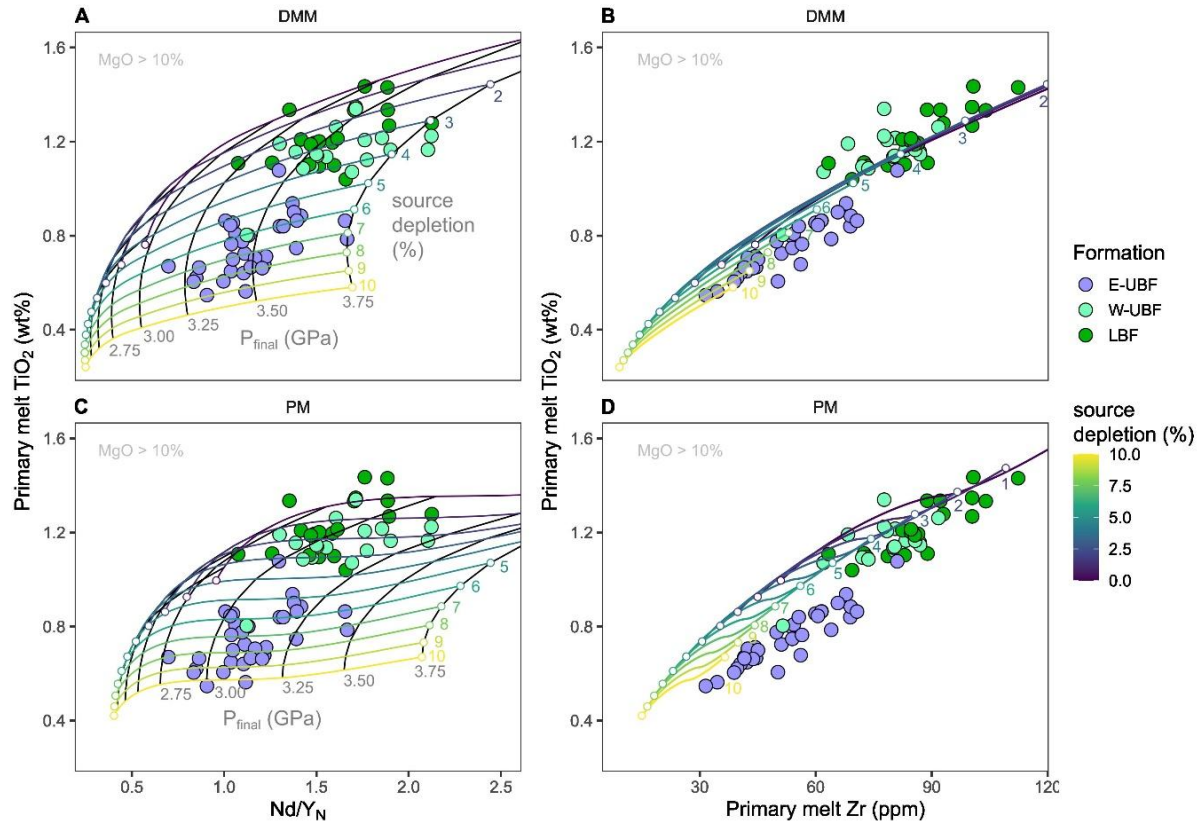


Figure 11 – comparison of trace elements from primitive Antrim basalts with polybaric melting models incorporating variable depletion of starting source composition ($T_p = 1500^\circ\text{C}$ plotted). **A:** Primary melt TiO_2 versus Nd/Y_N compared with DMM melting model. **B:** Primary TiO_2 versus primary Zr (DMM melting model). **C:** Primary TiO_2 versus Nd/Y_N (PM melting model). **D:** Primary TiO_2 versus primary Zr (PMM melting model). Primary TiO_2 and Zr was calculated for primitive samples ($\text{MgO} > 10\%$) by projecting along a linear regression defined by the data to $\text{Mg\#}$ of 74% corresponding to primary mantle melts (Carter et al., 2024). Model compositions plotted are for pooled melts calculated using REEBOX Pro (Brown & Leshner, 2016) with depleted starting compositions calculated manually. See Section 3.5 for details and model parameters.

6h), suggesting that their differing compositions largely reflect differences in the degree of melting (albeit Kerr, 1995, has suggested some differences in the mantle source for Mull Plateau Group and Coire Gorm Type lavas based on trace element systematics).

Despite some textural differences (Lyle, 1985a) the W-UBF are compositionally indistinguishable from the LBF, strongly suggesting their mantle sources and petrogenesis were similar. Altogether the data indicate that E-UBF and LBF/W-UBF cannot have formed from differential melting of the same mantle source and that the E-

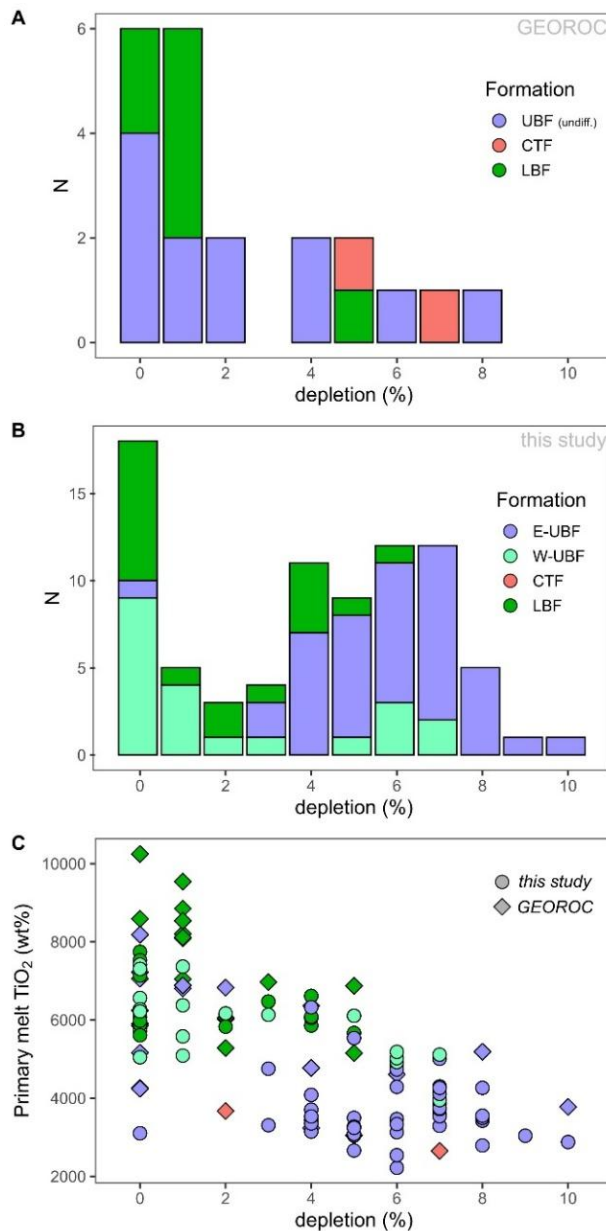


Figure 12 – best fit model source compositions. **A:** histogram of source depletion for best fit model melt compositions for ALG samples from GEOROC (DIGIS Team, 2023). **B:** histogram of source depletion for best fit model melt compositions for ALG samples from this study. **C:** primary melt TiO_2 versus best fit model source depletion for all samples.

UBF source was depleted in incompatible trace element relative to that which produced the LBF. This distinction in trace element abundances was noted by Lyle (1985b, 1988) who suggested that the E-UBF might be derived from a source which had already been depleted by melt extraction to form the LBF.

To test this, we ran forward melting models of progressively melt depleted mantle sources (see Section 3.5). These models are much more successful in explaining the composition of the low Ti E-UBF magmas than models of polybaric melting alone and suggest that the E-UBF can be explained by remelting of DMM which has been further depleted by ~5–9% melt extraction to form the LBF (Fig. 11). The somewhat flatter REE profiles and lower Nd/Y suggest that the E-UBF also formed by slightly shallower melting than the LBF. Best fit melt compositions for E-UBF samples are systematically derived from more depleted source compositions and generally slightly lower pressure melting (Fig. 12).

As discussed above (Section 5.1.1), literature data indicates that LREE enrichment correlates markedly with isotopic indicators of crustal assimilation across the BIPIIP (Fig. 8), and this holds true for the E-UBF. Of the published low TiO₂ samples with Sr isotope data available, all those showing LREE enrichment have elevated ⁸⁷Sr/⁸⁶Sr (Fig. 13). The only low-Ti UBF sample with near-primary Sr isotopes shows marked LREE depletion, consistent with shallow melting of a depleted source, as suggested by melt modelling. Conversely, high-Ti samples with convex REE profiles are generally the least isotopically contaminated, while those with elevated ⁸⁷Sr/⁸⁶Sr ratios show a flatter but LREE enriched pattern which may reflect that of the crustal contaminants, likely underlying Dalradian metasediments (Barrat & Nesbitt, 1996). Contamination appears to affect the MREE and HREE far less; there is no correlation between radiogenic isotope ratio and Nd/Y for BIPIIP basalts (Fig. S9). This suggests that while LREE characteristics have been variably overprinted by crustal assimilation, the depth of melting indicated by MREE/HREE ratios are minimally affected and faithfully record the petrogenesis of the primary magma.

Overall, the trace element abundances of E-UBF lavas are best reproduced in our models by remelting of source depleted by extraction of ~5–9% melt relative to that which formed the LBF and W-UBF, which require <4% melt depletion (Figs. 10, 11). The E-UBF also appears to have formed via somewhat higher degrees of melting and mostly within spinel stability field as indicated by lower Nd/Y ratios, relative to the LBF. The steady trend of decreasing Nd/Y through both LBF and E-UBF meanwhile suggests a gradual decrease in the average pressure of melting throughout emplacement of the ALG (Fig. 5).

These results are somewhat contrary to those of Barrat & Nesbitt (1996) who suggested that much of the UBF showed convex up signatures of deep melting. However, the two datasets are easily reconciled since that of Barrat & Nesbitt (1996) is on a small number

of samples and appears to be biased towards high Ti convex up UBF samples which are in fact rare in the succession (Fig. 9a cf. 9c). They also neglect the east-west distinction in UBF lava stratigraphy and composition.

Our larger dataset from across the Antrim plateau suggests that, in fact, high Ti magmas are rare in the main UBF sequence east of the Portrush Fault (Fig. 9c). It is possible that sampling quarries might impart some bias since these tend to preferentially exploit larger sheet flows. However, there is no correlation between flow thickness and key geochemical parameters such as Ti_8 , Zr or Nd/Y (Fig. S8). Furthermore, the distinctions between LBF and E-UBF hold true for the data from drill cores which presents as far as possible an unbiased dataset for the full given that almost every flow was sampled (Carter et al., 2024). Moreover, earlier studies are clear in recognising the depleted character of the E-UBF relative to the LBF (Lyle, 1980, 1985b; Lyle & Patton, 1989).

The combined trace element characteristics LBF and W-UBF indicate they both formed as deep melts of a slightly LREE-depleted mantle source under similar conditions (T_p , lithospheric thickness). Most E-UBF samples, however, require a source that was depleted relative to that which produced the LBF and melted to a somewhat shallower depth, resulting a flatter MREE to HREE pattern and lower HFSE abundances. Although a lack of primitive samples precludes direct comparison with melting models, the CTF shows the same characteristics of source depletion (low Ti_8) and shallow melting (flat REE, sometimes LREE depleted) as E-UBF but to a greater extent, suggesting it derives from a more depleted source which melted almost entirely within the spinel field (Figs. 10–12). LREE enrichment in many CTF and UBF samples reflects crustal contamination, while MREE and HREE are less or little affected.

5.3.1 Implications for mineralisation?

The trace element systematics of the ALG have important implications for mineralisation that may have developed within the ALG or associated intrusions. There are two main resources that may be of relevance: intrusion-hosted sulphide Ni-Cu ± platinum group elements (PGE; Stock & Beckwith, 2026) and supergene deposits of immobile elements such as Al_2O_3 or V (Eyles, 1952). Melt derived from a more enriched mantle source would have elevated concentrations of PGE, Al_2O_3 and V. As a result, the LBF and W-UBF (and associated intrusions) are more likely to be prospective for both igneous Ni-Cu-PGE and supergene Al_2O_3 and V deposits than the bulk of the E-UBF east of the Portrush Fault.

Additionally, mineralisation of PGE is strongly controlled by their chalcophile character and typically requires segregation of an immiscible sulphide liquid as a prerequisite. Crustal assimilation is frequently invoked as a trigger for sulphide saturation (e.g., Lightfoot & Keays, 2005). This study highlights that La/Nd and Ba/Zr appear to be robust proxies for crustal assimilation in basalts from across the BIPIIP and that that assimilation is more prevalent in the LBF. These elements are readily analysed by XRF including by handheld instruments, potentially making this a practical and cost-effective prospecting tool in flood basalts and layered mafic intrusions.

5.4 Origin of interbasaltic period magmatism

5.4.1 Tardree Rhyolite Complex

Compared to ALG basalts, TRC samples show limited evidence for crustal assimilation. They have low concentrations of Ba and Rb relative to ALG basalts and to other silicic magmas in the NAIP. In SE Antrim near Tardree, a series of intermediate lavas occur sporadically within the upper part of the LBF and define a trend linking LBF basalts and TRC rhyolites (Lyle & Thompson, 1983). Moreover, petrological modelling is able to reproduce these trends and TRC compositions through extensive fractional crystallisation alone (Fig. 3). This is supported by Sr isotope data which show that TRC samples have ratios only very slightly elevated from LBF and UBF basalts (0.707 cf. ~0.703; Wallace et al., 1994).

These observations suggest that the TRC formed through extensive fractional crystallisation with relatively limited crustal assimilation from a parental magma that may have resembled LBF basalts. Lyle (1985b) interpreted the silicic rocks of the TRC and intermediate flows collectively as the final fractionation products of a waning magmatic system during the last stages of LBF emplacement. Rhyolites are also reported in a few other localities in Antrim (Meighan et al., 1984) and have been recovered in drill holes suggesting that such conditions may have characterised the Antrim magmatic system more widely at this time.

5.4.2 Causeway Tholeiite Formation

In contrast to the TRC which was emplaced as one of the final events of the LBF sequence, the CTF is underlain by thick laterites developed in the upper flows of the LBF (Port na Spaniagh Member) and is itself lateritised in its upper part (Ballylagan Member), although not to the same thickness (Lyle & Preston, 1993).

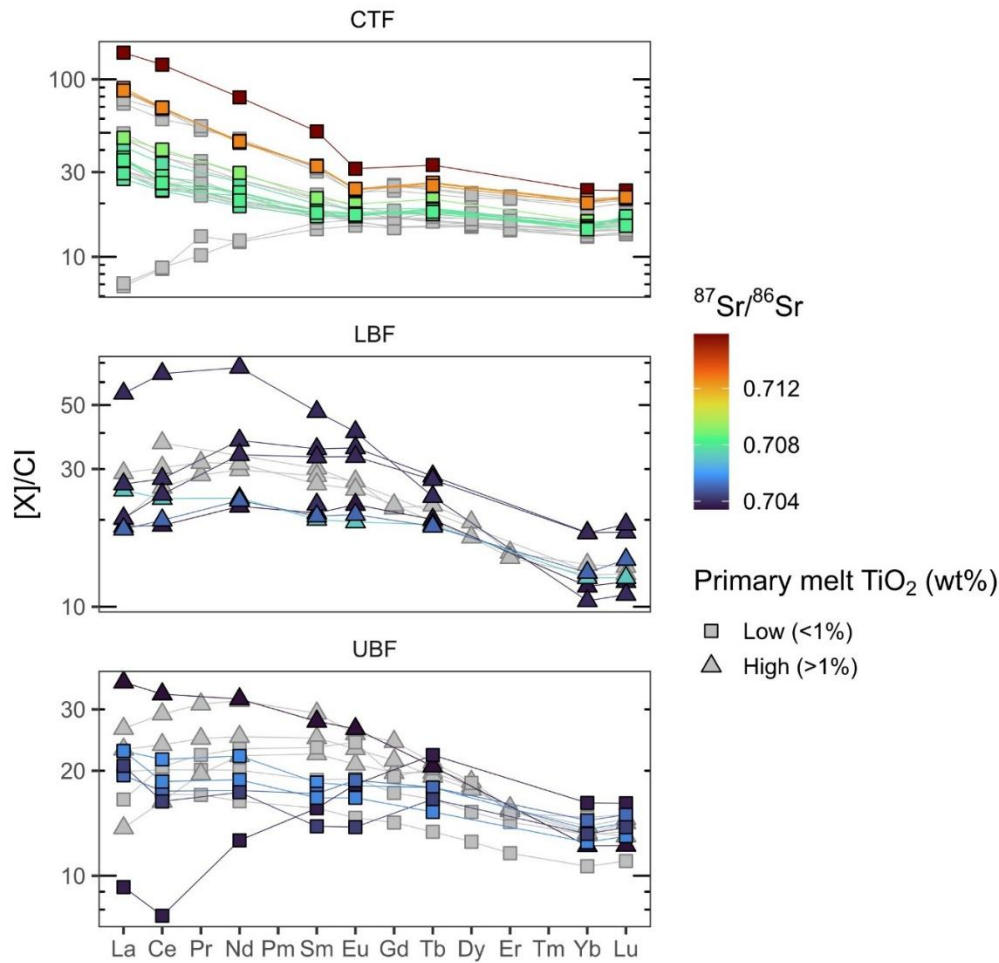


Figure 13 – chondrite-normalised rare-earth element diagram for ALG samples from GEOROC (DIGIS Team, 2023), colour coded by $^{87}\text{Sr}/^{86}\text{Sr}$. **A:** CTF. **B:** LBF. **C:** UBF. Low and high TiO_2 samples are plotted as squares and triangles, respectively. Samples without $^{87}\text{Sr}/^{86}\text{Sr}$ data are shown in grey.

The CTF shows three principal chemical distinctions from the LBF and UBF: First, it has flat MREE-HREE profiles which may show either LREE enrichment or depletion. This has been taken to indicate that it formed by shallow melting, entirely within the spinel stability field (Barrat & Nesbitt, 1996). Second, it shows even lower $\text{TiO}_2^{\text{primary}}$ than either LBF or UBF. Third, it shows major, trace and isotopic evidence of significant crustal assimilation with $^{87}\text{Sr}/^{86}\text{Sr}$ extending to the most radiogenic values observed in the ALG (Fig. 13; Barrat & Nesbitt, 1996; Wallace et al., 1994). Unlike LBF and UBF, $^{87}\text{Sr}/^{86}\text{Sr}$ correlates strongly with SiO_2 as well as incompatible trace elements such as Zr, indicating combined assimilation fractional crystallisation (AFC; Barrat & Nesbitt, 1996).

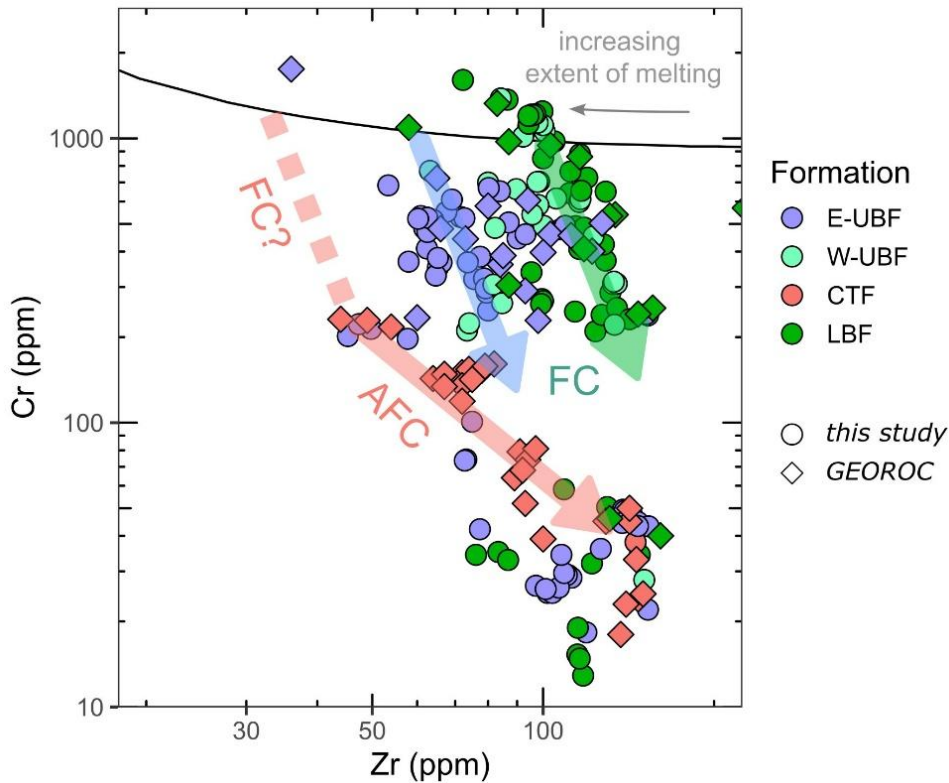


Figure 14 – Cr versus Zr showing distinct differentiation trends of CTF, E-UBF and LBF/W-UBF. Melting trend from (Pearce, 1982).

Despite significant contamination, the tholeiitic character of the primary melts is apparent from elements such as Cr and Ti, little affected by crustal contamination. Plotted as Cr vs Zr, the CTF follows a distinct trend to LBF or E-UBF, suggesting an additional input of Zr to the melt through AFC (Fig. 14). Projecting this back to an uncontaminated primary magma indicates a melt with substantially lower Zr than UBF or LBF indicating formation through a higher degree of melting. A transition to shallower melting than the earlier LBF suggests some process must have thinned the lithosphere prior to formation of the CTF.

Similar to the UBF, LREE enrichment in the CTF appear to be the result of crustal assimilation and correlates strongly with Sr isotopes (Fig. 13), while less contaminated samples show pronounced LREE depletion. Combined with the lack of HREE depletion this suggests shallow melting of a depleted source subsequently modified in most samples by a large degree of crustal assimilation in the upper crust. This is supported by uniformly low OPAM pressures indicating stalling of melts in the upper crust (see Section 5.2.1 above). This may explain why the CTF shows a greater degree of assimilation and an AFC trend not seen in LBF or UBF lavas.

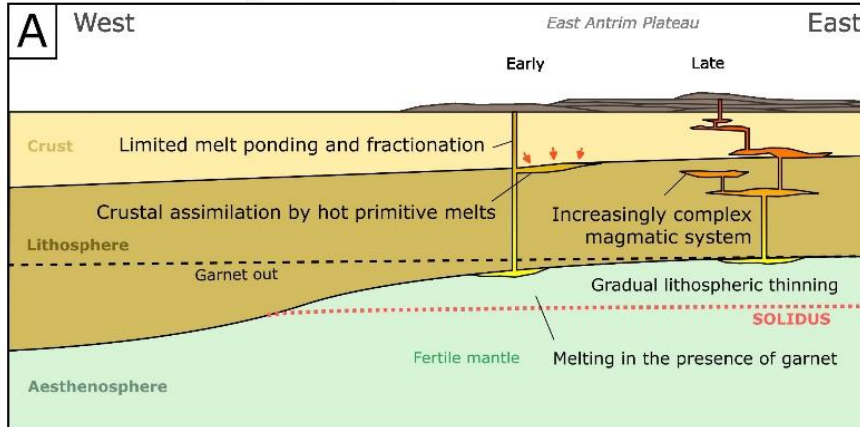
5.4.3 Magmatism during a near-hiatus

Although the precise modes of formation for CTF and TRC are slightly different there are notable commonalities. Both are relatively small volume and restricted in area of exposure. Further, both require prolonged upper crustal residence times to allow for extensive fractionation ($\pm$ assimilation). Together with the lack of voluminous volcanism during the interbasaltic period, these observations indicate small bodies of magma fractionating in the upper crust with little input of fresh primitive melt. Ultimately this indicates that melt flux was low across most of the area during the interbasaltic period, as also evidenced by the development of thick laterites, with important consequences for geodynamic interpretations.

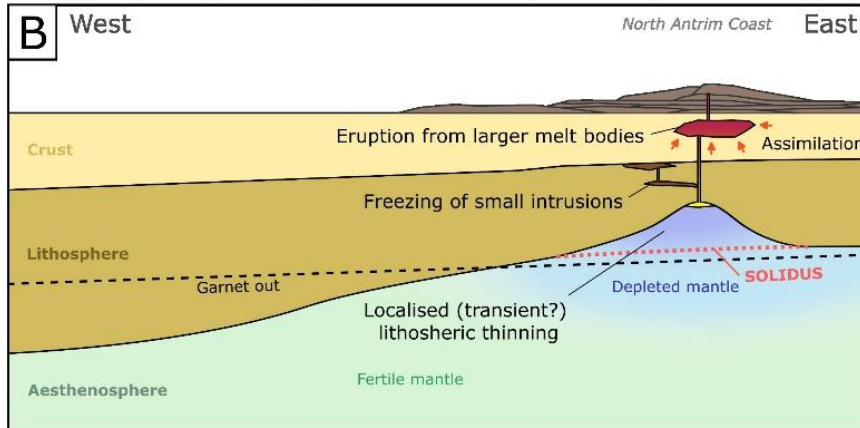
5.5 Geodynamic interpretation and the significance of alkali to tholeiitic transitions

Trace element systematics strongly suggest that LBF/W-UBF, CTF and E-UBF were formed by melting of different mantle sources and at different pressures (Figs. 6g, 10). LBF/W-UBF have high TiO_2 , convex up REE profiles and high Nd/Y indicative of melting in the presence of garnet (Fig. 9). CTF and E-UBF meanwhile have low TiO_2 and Nd/Y with flat MREE to HREE arising from melting predominantly in the spinel stability field. Similar temporal transitions from deep to shallower melting have been recognised in Skye and Mull and have been interpreted as representing lithospheric thinning due to stretching and/or thermal erosion by the plume (Ellam, 1992; Kerr, 1994). To explain the shallow melting which appears to characterise the Antrim tholeiites, lithospheric thinning of around 10–15 km must be invoked (Barrat & Nesbitt, 1996; Kerr, 1994). However, this is inconsistent with the maximum tectonically recorded extension (England, 1992) and the uplift recorded by the subsidence history of the area (Brodie & White, 1995; Saunders et al., 1997). The UBF presents a further problem for this view as it contains high Ti lavas with a distinct deep garnet melting signature, predominantly west of the Portrush and Bann Valley faults, but occasionally within the E-UBF succession too (Barrat & Nesbitt, 1996). Alkalic magmas of similar affinity occur in late dykes and cone sheets on Mull (Kerr et al., 1999) and Skye (Thompson & Morrison, 1988). Interpreted purely in terms of lithospheric thickness, the transition back to deep melting would suggest substantial rethickening of the lithosphere following tholeiite magmatism. Some rethickening could occur through underplating which is thought to have totalled 2–5 km across much of the BIPI (Brodie & White, 1995). However, this cannot account for the co-existence of both deep and shallow melting signatures in the W-UBF and E-UBF, respectively.

Lower Basalt Formation (~61.6-61 Ma)



Interbasaltic period / Causeway Tholeiite Formation (~61-60 Ma)



Upper Basalt Formation (~60-59 Ma)

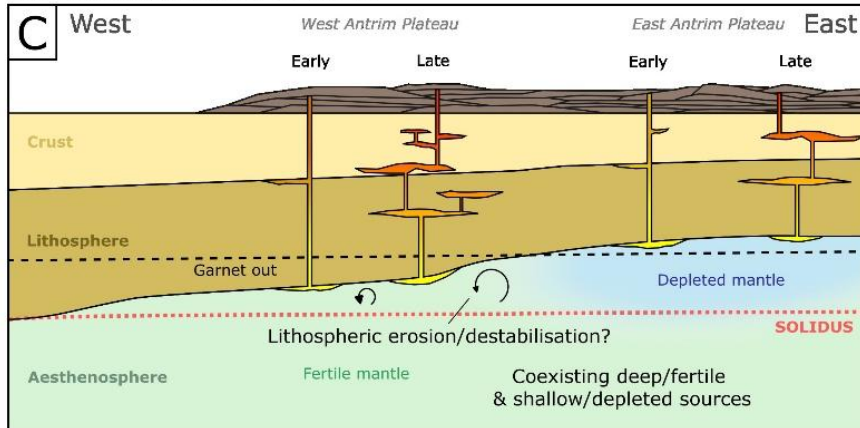


Figure 15 – schematic cartoon depicting petrogenetic model for the ALG. **A:** magmatism to form the LBF concentrated in the east of the plateau with progressive development of crustal magma plumbing. **B:** CTF magmatism controlled by localised lithospheric topography and low mantle T_p resulting in restricted melting without garnet presence. **C:** resurgent mantle T_p results in magmatism in east and west, the latter possible initiated by lithospheric erosion or instability. Prior melt depletion results in adjacent zones of fertile and depleted mantle. Timescales are approximate, based on the geochronology of Cooper et al. (2026) and laterite formation timing estimated by Hill et al. (2000).

Various alternative explanations have been advanced to explain alkali to tholeiite transitions. One suggestion is that tholeiitic melts are formed beneath areas of thinned lithosphere NW of Scotland such as the Rockall Trough and underwent substantial lateral movement along dykes to their eruptive centres (Hole et al., 2015; White, 1992a, 1992b). Although dyke swarms associated with the NAIP indeed propagate laterally for 100s km (Morrison et al., 2026), this theory cannot explain the temporal transition to tholeiitic melts and would require local cessation of transitional/alkali melt production such that distally-sourced tholeiitic melts dominated. Moreover, it is inconsistent with the distinct regionality of magmatism within the BIPIP (and the NAIP more broadly) wherein the lava sequences at Mull, Skye and Antrim all show clear distinctions in their primary melt compositions, arising from source and/or melting process variations (Figs. 6, 13; Morrison et al., 1997; Saunders et al., 1997). These differences strongly argue against widespread lateral transport of erupted magmas which should equally distribute or homogenise any spatial variation. Magnetic fabric evidence from the McKenzie giant dyke swarms suggests, instead, that melt transport is dominantly vertical within the central region of melt production, becoming lateral only more distally (Ernst & Baragar, 1992). This is also supported by the density of dykes around igneous centres in the BIPIP which become sparser radially outwards, strongly suggesting these centres formed above the melt which fed them (Anderson et al., 2016; Cooper et al., 2012; Kerr et al., 1999). This is not to say that significant lateral transport of melt along dykes cannot occur, but it appears unlikely to have been a significant source of *extrusive* BIPIP lavas.

Variation in pressures of melting recorded by melt compositions could also result from changes in the depth from which melts are extracted. This would imply that melts with a strong garnet signature represent well mixed averages of the entire melting column while more tholeiitic melts were extracted only from the upper part of the column. However, it is unclear why the efficiency of melt pooling should vary temporally. More importantly, the trace element systematics of the E-UBF and CTF indicate they cannot be formed by variable extents of melting of the same source but require sources that are depleted relative to that which supplied the LBF (Figs. 6, 10, 11). Similar objections were raised by Kerr et al. (1999) who instead suggested that the Central Mull Tholeiite was generated beneath *locally* thinned lithosphere.

Thinning could result from localised lithospheric stretching and/or thermal erosion by the plume concentrated in the areas of greatest melt flux (Davies, 1994). Indeed, Bonadio et al. (2025) have recently demonstrated that the lithosphere is systematically thinner (by <30 km) in the circum-Irish sea region where the majority of BIPIP

magmatism was concentrated, compared to amagmatic areas; this is inferred to have been driven or enhanced by plume erosion. Notably pronounced thinning is indicated beneath the eastern Antrim plateau, which diminishes towards the west where the W-UBF was erupted.

This strongly suggests that thinning of the lithosphere both results from and enhances magmatic flux, driving a feedback loop such that eruption of the LBF was accompanied by thinning under much of the eastern Antrim Plateau where volcanism was concentrated. Such a mechanism could have interacted with incipient rifting to enhance developing inhomogeneities in lithospheric thinning. During the interbasaltic period, volcanism was concentrated in a small area and may correspond to particularly thin lithosphere, resulting in spatially restricted formation of the CTF. Localised thinned lithosphere, the Rathlin Trough, is known to exist just to the north of the Antrim Coast and has been previously suggested as the locus of melting for CTF melting (Lyle & Preston, 1993).

During eruption of the UBF, areas of thicker and thinner lithosphere coexisted in the west and east respectively, with the boundary defined approximately by the Portrush and Bann Valley faults (Fig. 15c). Melting beneath these regions then resulted in deep, smaller fraction and shallower, depleted, higher fraction melts, feeding eruptions of the W-UBF and E-UBF, respectively. The onset of W-UBF volcanism may have been driven by gravitational destabilisation of thicker lithosphere to the west resulting in upwelling of fertile aesthenospheric mantle, possibly enhanced by eastwards mantle flow (e.g., Ballmer et al., 2015; Gernon et al., 2023).

The paucity of high Ti lava compositions in the E-UBF suggests limited lateral transport of magmas; either transport in dykes was predominantly vertical, or the Portrush Fault presented an effective impermeable barrier to ascending magmas. Those few samples with high Ti compositions reported from the E-UBF could be attributed to very limited lateral movement of magmas from nearby areas of thicker lithosphere. Alternatively, these and the late alkali magmas of Mull and Skye may have resulted from a deepening solidus during the final waning of stages of Phase 1 NAIP magmatism (Barrat & Nesbitt, 1996).

This model provides an explanation for the correlation between depletion (e.g. $\text{TiO}_2^{\text{primary}}$) and shallow depth of melting (Nd/Y) in ALG samples (Figs. 9, 10). If localised lithospheric thinning was related to magmatic flux (either through thermal erosion or extension and dyke propagation) then areas with the thinnest lithosphere would be associated with the most depleted residual mantle. Nd/Y shows a continuous up-

section evolution in primitive samples suggesting that both LBF and E-UBF compositions record a steady process of lithospheric thinning (Fig. 5e). That said, there is a lack of progression in $\text{TiO}_2^{\text{primary}}$ though the emplacement of the LBF which suggests some additional factor is required to fully explain the depleted sources for E-UBF and CTF. It could be that these simply represent mantle domains with variable depletion which is unrelated to extraction of the LBF (e.g. Permian magmatism; Morrison et al., 1997; Thompson & Morrison, 1988). Alternatively, removal of latent heat from melting to form the LBF may have required a period of thermal re-equilibration before remelting was possible. A further possibility is that earlier, more enriched compositions might result from influence of sub-continental lithospheric mantle while later depleted melts arise from upwelling depleted asthenosphere during incipient rifting; such a temporal progression has been suggested on the basis of PGE systematics in Irish Paleogene dyke swarms (Morrison et al., 2026). That said, the extent to which lavas and dykes respectively record local/distal mantle melting remains uncertain.

5.5.1 Interbasaltic period quiescence: record of a pulsing plume?

A final notable feature of ALG magmatism is the near-hiatus between LBF and UBF and subsequent resurgence. Trace element systematics and spatial relationships between the different eruptive units of the BIPIP indicate localised lithospheric thinning resulted in alkali to tholeiitic transitions at each eruptive centre. However, under constant mantle T_p this should not generate a volcanic hiatus.

Across BIPIP successions the areal extent of alkaline successions is generally larger than that of the overlying tholeiites. Despite their significant thickness, flows of the Central Mull Tholeiite occupy a restricted area within the central complex (Emeleus and Bell, 2005). Similarly, dykes of the Preshal Mhor type are closely spatially associated with the zone of maximum crustal dilation in Skye, though they constitute the majority of the dyke swarms there (Mattey et al., 1977). Under steady state mantle T_p , production of transitional/alkali melts should continue over a wide area, with tholeiites forming only a small proportion of the overall succession, occurring interfingering with the transitional/alkali flows. Indeed, the occurrence of rare tholeiitic melts in the upper part of the Skye Main Series (the Fairy Bridge type, Saunders et al., 1997) may represent such a scenario.

However, the occurrence of a distinct interval in all the main BIPIP successions where tholeiites dominate and alkali basalts are mostly absent suggests a regional interval with low melt productivity from areas of thicker lithosphere. This implies a transient decrease in mantle potential temperature during this interval which would result in a

shallowing of the solidus, restricting melt production only to areas of thinner lithosphere (Fig. 15b). Resurgent magmatism then accompanied a return to higher temperatures and resulted in formation of the W-UBF and E-UBF.

These results are consistent with T_p estimates from olivine-spinel thermometry and olivine-addition methods which demonstrate (1) similar average temperatures during formation of both LBF and UBF, as well as (2) significant ($<120^\circ\text{C}$) variation in mantle T_p during formation of LBF indicating unstable or oscillatory dynamics (Carter et al., 2024). Likewise, on the basis of recent U-Pb geochronology, LBF and UBF have been suggested to represent two pulses of plume magmatism that can be widely recognised across the NAIP (Cooper et al., 2026). Pulsatory behaviour in mantle plumes has been demonstrated from several other studies and continues in the modern Iceland plume, resulting in V-shaped ridge formation along the Reykjanes Ridge (Liu et al., 2023; Parnell-Turner et al., 2014; Pearman et al., 2026; Spice et al., 2016; Taylor et al., 2020). A waning magmatic system was invoked in early studies to explain the development of intermediate lavas towards top of the LBF, culminating in the interbasaltic period (Lyle, 1985b; Lyle & Thompson, 1983). Furthermore, a similar chemostratigraphic sequence to that in Antrim has recently been described from the Faroe Islands (Millett et al., 2020). There, a transition from alkali to tholeiitic melts and development of a regional hiatus have been attributed to a combination of transient mantle cooling and lithospheric thinning. This suggests that such events may have common in the history of the ancestral Iceland plume and have played an important role in the petrogenesis of the NAIP and other LIPs.

6 Conclusions

New high-quality major and trace element data have been acquired on 168 samples from the Antrim Lava Group (ALG), the largest onshore exposure of the BIPIIP. Combined with previous published ALG analyses and a large compilation of BIPIIP basalts, these data clarify the complex petrogenesis of the ALG which have been understudied compared to similar successions in Scotland. Through comparison with Mull and Skye, results allow reconstruction of crustal, lithospheric and mantle controls on magmatism in the early NAIP:

- Both main lava units (LBF, UBF) show evidence for an evolving crustal magmatic system with two cycles of increasing fractionation with time, indicating increased magma residence time and progressive development in the complexity of melt plumbing.

- The degree of crustal assimilation can be determined from La/Nd or Ba/Zr ratios which closely correlate with radiogenic isotope ratios. Crustal assimilation decreased through the emplacement of both LBF and UBF. These appear to reflect two cycles characterised by depletion of fusible components from country rock surrounding a maturing transcrustal magma system.
- These cycles are separated by a marked hiatus in volcanism during which only the spatially restricted CTF and TRC were erupted. This hiatus was long enough to allow for significant cooling of the crust, resetting processes controlling major and trace element cyclicity.
- Economically relevant parameters including source fertility and degree of crustal assimilation can be determined using trace elements which are readily analysed by XRF (e.g. Ti₈, La/Nd) and represent a promising prospecting tool within the BIPIP.
- Trace elements in E-UBF, LBF and CTF cannot be reconciled with melting of a single source, either to different extents or under different pressures. Instead, they require distinct sources characterised by variable melt depletion, most likely associated with extraction of the LBF. Moreover, during eruption of the UBF, distinct magmatic systems fed by deep/fertile and shallow/depleted melts coexisted in west and east of the Antrim Plateau respectively.
- Alkali to tholeiitic transitions, common in many continental large igneous provinces can be explained by a model of localised, and potentially transient, lithospheric thinning. This model can reconcile several distinct aspects of magmatism in Antrim which earlier studies have struggled to explain, and provides a framework in which the petrogenesis of similar successions in the BIPIP and other large igneous provinces may be understood.
- The near hiatus in Antrim magmatism requires an interval of low mantle T_p and may be regionally related to the predominance of tholeiites in the upper parts of Mull and Skye successions. This and similar inferences from across the NAIP suggest that unstable or pulsatory dynamics are common features of plume-driven magmatism.

Data availability statement

All new geochemical data generated for this study will be available from the DIGIS Geochemical Data Repository upon completion of peer-review (Carter et al., 2026).

Data from core samples were published by Carter et al. (2024; <https://doi.org/10.1016/j.epsl.2024.118903>). Literature data for Antrim and Hebridean centres are available from the GEOROC repository (<https://georoc.eu/>).

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References

- Amstutz, F. M., Stock, M. J., Smith, V. C., Isaia, R., Vitale, S., Carter, E. J., & Natale, J. (2025). Volcano-tectonic controls on magmatic evolution at Campi Flegrei, Italy: Insights from thermodynamic modelling. *Journal of Petrology*, egaf068. <https://doi.org/10.1093/petrology/egaf068>
- Anderson, H., Walsh, J., & Cooper, M. (2016). Faults, intrusions and flood basalts: The Cenozoic structure of the north of Ireland. In M. E. Young (Ed.), *Unearthed: Impacts of the Tellus surveys of the north of Ireland*. Royal Irish Academy. <https://doi.org/10.3318/978-1-908996-88-6.ch14>
- Arndt, N. T., & Christensen, U. (1992). The role of lithospheric mantle in continental flood volcanism: Thermal and geochemical constraints. *Journal of Geophysical Research: Solid Earth*, 97(B7), 10967–10981. <https://doi.org/10.1029/92JB00564>
- Asimow, P. D., Hirschmann, M. M., & Stolper, E. M. (2001). Calculation of Peridotite Partial Melting from Thermodynamic Models of Minerals and Melts, IV. Adiabatic Decompression and the Composition and Mean Properties of Mid-ocean Ridge Basalts. *Journal of Petrology*, 42(5), 963–998. <https://doi.org/10.1093/petrology/42.5.963>
- 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: A description of parts of sheets 43, 44, 51, and 52 of the geological map*. HM Stationery Office. <https://pubs.bgs.ac.uk/publications.html?pubID=B01951>

- Baker, J. A. (2000). Resolving Crustal and Mantle Contributions to Continental Flood Volcanism, Yemen; Constraints from Mineral Oxygen Isotope Data. *Journal of Petrology*, 41(12), 1805–1820. <https://doi.org/10.1093/petrology/41.12.1805>
- Ballmer, M. D., Conrad, C. P., Smith, E. I., & Johnsen, R. (2015). Intraplate volcanism at the edges of the Colorado Plateau sustained by a combination of triggered edge-driven convection and shear-driven upwelling. *Geochemistry, Geophysics, Geosystems*, 16(2), 366–379. <https://doi.org/10.1002/2014GC005641>
- Barrat, J. A., & Nesbitt, R. W. (1996). Geochemistry of the Tertiary Volcanism of Northern Ireland. *Chemical Geology*, 129, 15–38.
- Baxter, R. J. M., MacLennan, J., Neave, D. A., & Thordarson, T. (2023). Depth of Magma Storage Under Iceland Controlled by Magma Fluxes. *Geochemistry, Geophysics, Geosystems*, 24(7), e2022GC010811. <https://doi.org/10.1029/2022GC010811>
- Beresford-Browne, A., Jolley, D., Millett, J., Stevenson, C., Watt, S., Raine, R., & Carter, E. (2024). Depositional system and plant ecosystem responses to long-term low tempo volcanism, the Interbasaltic Formation, Antrim Lava Group. *Geological Society, London, Special Publications*, 547(1), SP547-2023–2075. <https://doi.org/10.1144/SP547-2023-75>
- Black, B. A., Karlstrom, L., & Mather, T. A. (2021). The life cycle of large igneous provinces. *Nature Reviews Earth & Environment*, 2(12), 840–857. <https://doi.org/10.1038/s43017-021-00221-4>
- Bonadio, R., Lebedev, S., Chew, D., Xu, Y., Fullea, J., & Meier, T. (2025). Volcanism and long-term seismicity controlled by plume-induced plate thinning. *Nature Communications*, 16(1), 7837. <https://doi.org/10.1038/s41467-025-62967-5>
- Brodie, J., & White, N. (1995). The link between sedimentary basin inversion and igneous underplating. *Geological Society, London, Special Publications*, 88(1), 21–38. <https://doi.org/10.1144/GSL.SP.1995.088.01.03>
- Brown, E. L., & Leshner, C. E. (2016). REEBBOX PRO: A forward model simulating melting of thermally and lithologically variable upwelling mantle. *Geochemistry, Geophysics, Geosystems*, 17(10), 3929–3968. <https://doi.org/10.1002/2016GC006579>
- Carter, E. J., Stock, M. J., Beresford-Browne, A., Cooper, M. R., Raine, R., & Fereyrolles, A. (2024). Volcanic tempo driven by rapid fluctuations in mantle temperature during large igneous province emplacement. *Earth and Planetary Science Letters*, 644, 118903. <https://doi.org/10.1016/j.epsl.2024.118903>
- Carter, E. J., Stock, M. J., Beresford-Browne, A., Talbot, H., & Cooper, M. R. (2026). *Bulk rock major and trace element data (WD-XRF) from quarries and cliff sections in*

- the Antrim Lava Group, Northern Ireland* [Dataset]. GFZ Data Services.
<https://doi.org/10.5880/digis.2026.010>
- Cooper, M. R. (2004). Mantle plumes, ocean spreading and the North Atlantic Igneous Province, Palaeogene extrusive igneous rocks, Northern Ireland. In *The geology of Northern Ireland-our natural foundation*. Geological Survey of Northern Ireland.
https://earthwise.bgs.ac.uk/index.php/Mantle_plumes,_ocean_spreading_and_the_North_Atlantic_Igneous_Province,_Palaeogene_extrusive_igneous_rocks,_Northern_Ireland
- 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*, 169(1), 29–36. <https://doi.org/10.1144/0016-76492010-182>
- Cooper, M. R., Tapster, S., & Condon, D. (2020). *Feeling the pulse? New high resolution U-Pb zircon geochronological constraints for the Northern Ireland sector of the North Atlantic Igneous Province* (EGU2020-8464). Copernicus Meetings. EGU2020. <https://doi.org/10.5194/egusphere-egu2020-8464>
- Cooper, M. R., Tapster, S., & Condon, D. J. (2026). Feeling the pulse? Paleogene chronostratigraphy of Northern Ireland and the north of Ireland temporally coupled to the North Atlantic Igneous Province. *Geology*.
<https://doi.org/10.1130/G54157.1>
- Cox, K. G., & Hawkesworth, C. J. (1985). Geochemical Stratigraphy of the Deccan Traps at Mahabaleshwar, Western Ghats, India, with Implications for Open System Magmatic Processes. *Journal of Petrology*, 26(2), 355–377.
<https://doi.org/10.1093/petrology/26.2.355>
- Danyushevsky, L. V. (2001). The effect of small amounts of H₂O on crystallisation of mid-ocean ridge and backarc basin magmas. *Journal of Volcanology and Geothermal Research*, 110(3–4), 265–280. [https://doi.org/10.1016/S0377-0273\(01\)00213-X](https://doi.org/10.1016/S0377-0273(01)00213-X)
- Danyushevsky, L. V., & Plechov, P. (2011). Petrolog3: Integrated software for modeling crystallization processes. *Geochemistry, Geophysics, Geosystems*, 12(7).
<https://doi.org/10.1029/2011GC003516>
- Davies, G. F. (1994). Thermomechanical erosion of the lithosphere by mantle plumes. *Journal of Geophysical Research: Solid Earth*, 99(B8), 15709–15722.
<https://doi.org/10.1029/94JB00119>

- DIGIS Team. (2023). 2023-12-
WSTPOX_NORTH_ATLANTIC_IGNEOUS_PROVINCE_OR_NAIP.csv. In *GEOROC
Compilation: Continental Flood Basalts* (Version V9). GRO.data.
<https://doi.org/10.25625/WSTPOX/PVS1VS>
- Ellam, R. M. (1992). Lithospheric thickness as a control on basalt geochemistry.
Geology, 20(2), 153–156. [https://doi.org/10.1130/0091-
7613\(1992\)020<0153:LTAACO>2.3.CO;2](https://doi.org/10.1130/0091-7613(1992)020<0153:LTAACO>2.3.CO;2)
- Ellam, R. M., & Stuart, F. M. (2000). The sub-lithospheric source of North Atlantic
basalts: Evidence for, and significance of, a common end-member. *Journal of
Petrology*, 41(7), 919–932. <https://doi.org/10.1093/petrology/41.7.919>
- Emeleus, C. H., & Bell, B. R. (2005). *British regional geology: The Palaeogene volcanic
districts of Scotland* (Fourth edition). British Geological Survey Nottingham.
[https://earthwise.bgs.ac.uk/index.php/British_regional_geology:_The_Palaeogen
e_volcanic_districts_of_Scotland](https://earthwise.bgs.ac.uk/index.php/British_regional_geology:_The_Palaeogen
e_volcanic_districts_of_Scotland)
- England, R. W. (1992). The role of Palaeocene magmatism in the tectonic evolution of
the Sea of the Hebrides Basin: Implications for basin evolution on the NW
Seaboard. *Geological Society, London, Special Publications*, 62(1), 163–174.
<https://doi.org/10.1144/GSL.SP.1992.062.01.15>
- Ernst, R. E., & Baragar, W. R. A. (1992). Evidence from magnetic fabric for the flow
pattern of magma in the Mackenzie giant radiating dyke swarm. *Nature*,
356(6369), Article 6369. <https://doi.org/10.1038/356511a0>
- Ernst, R. E., Bond, D. P. G., Zhang, S.-H., Buchan, K. L., Grasby, S. E., Youbi, N., El Bilali,
H., Bekker, A., & Doucet, L. S. (2021). Large Igneous Province Record Through
Time and Implications for Secular Environmental Changes and Geological Time-
Scale Boundaries. In *Large Igneous Provinces* (pp. 1–26). American Geophysical
Union (AGU). <https://doi.org/10.1002/9781119507444.ch1>
- Eyles, V. A. (1952). *The Composition and Origin of the Antrim Laterites and Bauxites With
Mineral Determinations by X-ray Methods*. HM Stationery Office.
<https://pubs.bgs.ac.uk/publications.html?pubID=B02147>
- Feigenson, M. D., Hofmann, A. W., & Spera, F. J. (1983). Case studies on the origin of
basalt. *Contributions to Mineralogy and Petrology*, 84(4), 390–405.
<https://doi.org/10.1007/BF01160290>
- Fitton, J. G., Saunders, A. D., Norry, M. J., Hardarson, B. S., & Taylor, R. N. (1997).
Thermal and chemical structure of the Iceland plume. *Earth and Planetary
Science Letters*, 153(3–4), 197–208. [https://doi.org/10.1016/s0012-
821x\(97\)00170-2](https://doi.org/10.1016/s0012-821x(97)00170-2)

- Gale, A., Dalton, C. A., Langmuir, C. H., Su, Y., & Schilling, J. G. (2013). The mean composition of ocean ridge basalts. *Geochemistry, Geophysics, Geosystems*, 14(3), 489–518. <https://doi.org/10.1029/2012GC004334>
- Ganino, C., & Arndt, N. T. (2009). Climate changes caused by degassing of sediments during the emplacement of large igneous provinces. *Geology*, 37(4), 323–326. <https://doi.org/10.1130/G25325A.1>
- Gernon, T. M., Jones, S. M., Brune, S., Hincks, T. K., Palmer, M. R., Schumacher, J. C., Primiceri, R. M., Field, M., Griffin, W. L., O'Reilly, S. Y., Keir, D., Spencer, C. J., Merdith, A. S., & Glerum, A. (2023). Rift-induced disruption of cratonic keels drives kimberlite volcanism. *Nature*, 620(7973), Article 7973. <https://doi.org/10.1038/s41586-023-06193-3>
- Gleeson, M. L. M., Gibson, S. A., & Stock, M. J. (2020). Upper Mantle Mush Zones beneath Low Melt Flux Ocean Island Volcanoes: Insights from Isla Floreana, Galápagos. *Journal of Petrology*, 61(11–12), egaa094. <https://doi.org/10.1093/petrology/egaa094>
- Harðardóttir, S., Matthews, S., Halldórsson, S. A., & Jackson, M. G. (2022). Spatial distribution and geochemical characterization of Icelandic mantle end-members: Implications for plume geometry and melting processes. *Chemical Geology*, 604, 120930. <https://doi.org/10.1016/j.chemgeo.2022.120930>
- Harker, A. (1904). *The Tertiary igneous rocks of Skye*. HM Stationery Office.
- Herzberg, C., & O'Hara, M. J. (2002). Plume-Associated Ultramafic Magmas of Phanerozoic Age. *Journal of Petrology*, 43(10), 1857–1883. <https://doi.org/10.1093/petrology/43.10.1857>
- Higgins, O., & Stock, M. J. (2024). A New Calibration of the OPAM Thermobarometer for Anhydrous and Hydrous Mafic Systems. *Journal of Petrology*, 65(5), egae043. <https://doi.org/10.1093/petrology/egae043>
- Hill, I. G., Worden, R. H., & Meighan, I. G. (2000). Geochemical evolution of a palaeolaterite: The Interbasaltic formation, Northern Ireland. *Chemical Geology*, 166(1–2), 65–84. [https://doi.org/10.1016/S0009-2541\(99\)00179-5](https://doi.org/10.1016/S0009-2541(99)00179-5)
- Hole, M. J. (2018). Mineralogical and geochemical evidence for polybaric fractional crystallization of continental flood basalts and implications for identification of peridotite and pyroxenite source lithologies. *Earth-Science Reviews*, 176(May 2017), 51–67. <https://doi.org/10.1016/j.earscirev.2017.09.014>
- Hole, M. J., & Millett, J. M. (2016). Controls of mantle potential temperature and lithospheric thickness on magmatism in the North Atlantic igneous province. *Journal of Petrology*, 57(2), 1–20. <https://doi.org/10.1093/petrology/egw014>

- Hole, M. J., Millett, J. M., Rogers, N. W., & Jolley, D. W. (2015). Rifting and mafic magmatism in the hebridean basins. *Journal of the Geological Society*, 172(2), 218–236. <https://doi.org/10.1144/jgs2014-100>
- Hole, M. J., & Natland, J. H. (2020). Magmatism in the North Atlantic Igneous Province; mantle temperatures, rifting and geodynamics. *Earth-Science Reviews*, 206(February 2019), 102794. <https://doi.org/10.1016/j.earscirev.2019.02.011>
- Hughes, H. S. R., McDonald, I., & Kerr, A. C. (2014). Platinum-group element signatures in the North Atlantic Igneous Province: Implications for mantle controls on metal budgets during continental breakup. *Lithos*, 233, 89–110. <https://doi.org/10.1016/j.lithos.2015.05.005>
- Huppert, H. E., Stephen, R., & Sparks, J. (1985). Cooling and contamination of mafic and ultramafic magmas during ascent through continental crust. *Earth and Planetary Science Letters*, 74(4), 371–386.
- Jellinek, A. M., & DePaolo, D. J. (2003). A model for the origin of large silicic magma chambers: Precursors of caldera-forming eruptions. *Bulletin of Volcanology*, 65(5), 363–381. <https://doi.org/10.1007/s00445-003-0277-y>
- Jones, M. T., Stokke, E. W., Rooney, A. D., Frieling, J., Pogge von Strandmann, P. A. E., Wilson, D. J., Svensen, H. H., Planke, S., Adatte, T., Thibault, N., Vickers, M. L., Mather, T. A., Tegner, C., Zuchuat, V., & Schultz, B. P. (2023). Tracing North Atlantic volcanism and seaway connectivity across the Paleocene–Eocene Thermal Maximum (PETM). *Climate of the Past*, 19(8), 1623–1652. <https://doi.org/10.5194/cp-19-1623-2023>
- Jones, S. M., Hoggett, M., Greene, S. E., & Dunkley Jones, T. (2019). Large Igneous Province thermogenic greenhouse gas flux could have initiated Paleocene–Eocene Thermal Maximum climate change. *Nature Communications*, 10(1), Article 1. <https://doi.org/10.1038/s41467-019-12957-1>
- Karlstrom, L., & Richards, M. (2011). On the evolution of large ultramafic magma chambers and timescales for flood basalt eruptions. *Journal of Geophysical Research: Solid Earth*, 116(B8). <https://doi.org/10.1029/2010JB008159>
- Kent, R. W., & Fitton, J. G. (2000). Mantle sources and melting dynamics in the British Palaeogene igneous province. *Journal of Petrology*, 41(7), 1023–1040. <https://doi.org/10.1093/petrology/41.7.1023>
- Kerr, A. C. (1994). Lithospheric thinning during the evolution of continental large igneous provinces: A case study from the North Atlantic Tertiary province. *Geology*, 22(11), 1027–1030. [https://doi.org/10.1130/0091-7613\(1994\)022<1027:LTDTEO>2.3.CO;2](https://doi.org/10.1130/0091-7613(1994)022<1027:LTDTEO>2.3.CO;2)

- Kerr, A. C. (1995). The geochemistry of the Mull-Morvern Tertiary lava succession, NW Scotland: An assessment of mantle sources during plume-related volcanism. *Chemical Geology*, 122(1), 43–58. [https://doi.org/10.1016/0009-2541\(95\)00009-B](https://doi.org/10.1016/0009-2541(95)00009-B)
- Kerr, A. C., Kent, R. W., Thomson, B. A., Seedhouse, J. K., & Donaldson, C. H. (1999). Geochemical evolution of the Tertiary Mull volcano, western Scotland. *Journal of Petrology*, 40(6), 873–908. <https://doi.org/10.1093/petroj/40.6.873>
- Klein, E. M., & Langmuir, C. H. (1987). Global correlations of ocean ridge basalt chemistry with axial depth and crustal thickness. *Journal of Geophysical Research: Solid Earth*, 92(B8), 8089–8115. <https://doi.org/10.1029/JB092iB08p08089>
- Koppers, A. A. P., Becker, T. W., Jackson, M. G., Konrad, K., Müller, R. D., Romanowicz, B., Steinberger, B., & Whittaker, J. M. (2021). Mantle plumes and their role in Earth processes. *Nature Reviews Earth and Environment*, 2(6), 382–401. <https://doi.org/10.1038/s43017-021-00168-6>
- Kress, V. C., & Carmichael, I. S. E. (1988). Stoichiometry of the iron oxidation reaction in silicate melts. *American Mineralogist*, 73(11–12), 1267–1274.
- Kushiro, I., Yoder Jr., H. S., & Mysen, B. O. (1976). Viscosities of basalt and andesite melts at high pressures. *Journal of Geophysical Research (1896-1977)*, 81(35), 6351–6356. <https://doi.org/10.1029/JB081i035p06351>
- Lightfoot, P. C., & Keays, R. R. (2005). Siderophile and Chalcophile Metal Variations in Flood Basalts from the Siberian Trap, Noril'sk Region: Implications for the Origin of the Ni-Cu-PGE Sulfide Ores. *Economic Geology*, 100(3), 439–462. <https://doi.org/10.2113/gsecongeo.100.3.439>
- Liu, H., Leng, W., Wang, W., & Zheng, Y. (2023). Deciphering the deep Earth heterogeneities from the temperature fluctuation of mantle plumes. *Earth and Planetary Science Letters*, 618, 118275. <https://doi.org/10.1016/j.epsl.2023.118275>
- Lyle, P. (1980). A Petrological and Geochemical Study of the Tertiary Basaltic Rocks of Northeast Ireland. *Journal of Earth Sciences Royal Dublin Society*, 2(2), 137–152.
- Lyle, P. (1985a). The Geochemistry and Petrology of Tertiary Basalts from the Binevenagh Area , County Londonderry. *Irish Journal of Earth Sciences*, 7(1), 59–64.
- Lyle, P. (1985b). The petrogenesis of the Tertiary basaltic and intermediate lavas of northeast Ireland. *Scottish Journal of Geology*, 21(1), 71–84. <https://doi.org/10.1144/sjg21010071>

- Lyle, P. (1988). The Geochemistry, Petrology and Volcanology of the Tertiary Lava Succession of the Binevenagh-Benbraddagh Area of County Londonderry. *Irish Journal of Earth Sciences*, 9(2), 141–151. <https://doi.org/10.2307/30002481>
- Lyle, P. (2000). The eruption environment of multi-tiered columnar basalt lava flows. *Journal of the Geological Society*, 157(4), 715–722. <https://doi.org/10.1144/jgs.157.4.715>
- Lyle, P. (2001). Phase Relationships within the Causeway Tholeiite Member of the Tertiary Antrim Lava Group. *Irish Journal of Earth Sciences*, 19, 37–41.
- Lyle, P., & Patton, D. J. S. (1989). The Petrography and Geochemistry of the Upper Basalt Formation of the Antrim Lava Group in Northeast Ireland. *Irish Journal of Earth Sciences*, 10(1), 33–41.
- Lyle, P., & Preston, J. (1993). Geochemistry and volcanology of the Tertiary basalts of the Giant's Causeway area, Northern Ireland. *Journal of the Geological Society*, 150(1), 109–120. <https://doi.org/10.1144/gsjgs.150.1.0109>
- Lyle, P., & Thompson, S. J. (1983). The classification and chemistry of the Tertiary intermediate lavas of Northeast Ireland. *Scottish Journal of Geology*, 19(1), 17–27.
- Mattey, D. P., Gibson, I. L., Marriner, G. F., & Thompson, R. N. (1977). The diagnostic geochemistry, relative abundance, and spatial distribution of high-calcium, low-alkali olivine tholeiite dykes in the Lower Tertiary regional swarm of the Isle of Skye, NW Scotland. *Mineralogical Magazine*, 41(318), 273–285. <https://doi.org/10.1180/minmag.1977.041.318.16>
- Matthews, S., Shorttle, O., & MacLennan, J. (2016). The temperature of the Icelandic mantle from olivine-spinel aluminum exchange thermometry. *Geochemistry, Geophysics, Geosystems*, 17(11), 4725–4752. <https://doi.org/10.1002/2016GC006497>
- McDonough, W. F., & Sun, S. -s. (1995). The composition of the Earth. *Chemical Geology*, 120(3–4), 223–253. [https://doi.org/10.1016/0009-2541\(94\)00140-4](https://doi.org/10.1016/0009-2541(94)00140-4)
- Meade, F. C., Troll, V. R., Ellam, R. M., Freda, C., Font, L., Donaldson, C. H., & Klonowska, I. (2014). Bimodal magmatism produced by progressively inhibited crustal assimilation. *Nature Communications*, 5(May). <https://doi.org/10.1038/ncomms5199>
- Meighan, I. G., Gibson, D., & Hood, D. N. (1984). Some aspects of Tertiary acid magmatism in NE Ireland. *Mineralogical Magazine*, 48(348), 351–363. <https://doi.org/10.1180/minmag.1984.048.348.05>

- Millett, J. M., Hole, M. J., Jolley, D. W., Passey, S. R., & Rossetti, L. (2020). Transient mantle cooling linked to regional volcanic shut-down and early rifting in the North Atlantic Igneous Province. *Bulletin of Volcanology*, 82(8), 61.
<https://doi.org/10.1007/s00445-020-01401-8>
- Millett, J. M., Jolley, D. W., Hole, M. J., Augland, L., Pugsley, J. H., McLeod, G. W., & Planke, S. (2024). High-precision UPb zircon dating of explosive volcanism in an early bi-modal volcano-sedimentary sequence from the Isle of Mull, North Atlantic Igneous Province. *Lithos*, 107729.
<https://doi.org/10.1016/j.lithos.2024.107729>
- Morrison, A. O., Stock, M. J., Cooper, M. R., Andersen, J. C. Ø., Hughes, H. S. R., Carter, E. J., Beckwith, J., McDonald, I., Kerr, A. C., & Mohr, P. (2026). Platinum-group element systematics in the North Atlantic Igneous Province: New insights from Northern Irish and Irish magmatism. *Lithos*, 542–543, 108725.
<https://doi.org/10.1016/j.lithos.2026.108725>
- Morrison, M. A., Thompson, R. N., Gibson, I. L., Marriner, G. F., O'Hara, M. J., & Pankhurst, R. J. (1997). Lateral chemical heterogeneity in the Palaeocene upper mantle beneath the Scottish Hebrides. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 297(1431), 229–244. <https://doi.org/10.1098/rsta.1980.0212>
- Neave, D. A., Namur, O., Shorttle, O., & Holtz, F. (2019). Magmatic evolution biases basaltic records of mantle chemistry towards melts from recycled sources. *Earth and Planetary Science Letters*, 520, 199–211.
<https://doi.org/10.1016/j.epsl.2019.06.003>
- O'Driscoll, B., Emeleus, C. H., Donaldson, C. H., & Daly, J. S. (2010). Cr-spinel Seam Petrogenesis in the Rum Layered Suite, NW Scotland: Cumulate Assimilation and in situ Crystallization in a Deforming Crystal Mush. *Journal of Petrology*, 51(6), 1171–1201. <https://doi.org/10.1093/petrology/egq013>
- Old, R. A. (1975). The age and field relationships of the Tardree Tertiary rhyolite complex, County Antrim, Northern Ireland. *Bulletin of the Geological Survey of Great Britain*, 51, 21–40.
- Parnell-Turner, R., White, N., Henstock, T., Murton, B., MacLennan, J., & Jones, S. M. (2014). A continuous 55-million-year record of transient mantle plume activity beneath Iceland. *Nature Geoscience*, 7(12), Article 12.
<https://doi.org/10.1038/ngeo2281>
- Patterson, E. . M. ., Mitchell, W. . A. ., & Swaine, D. . J. . (1955). The Tertiary Volcanic Succession in the Western Part of the Antrim Plateau. *Proceedings of the Royal*

- Irish Academy. Section B : Biological , Geological, and Chemical Science*, 57, 155–178. <https://doi.org/10.2307/20518846>
- Pearce, J. (1982). Trace Element Characteristics of Lavas from Destructive Plate Boundaries. In *Orogenic Andesites* (pp. 525–548).
- Pearman, C., Tien, C.-Y., White, N., MacLennan, J., Murton, B., Gibson, S., Day, J., & Parnell-Turner, R. (2026). Collapse and resurgence of the Iceland mantle plume. *Nature Communications*, 17(1), 4104. <https://doi.org/10.1038/s41467-026-71618-2>
- Peate, D. W., Peate, I. U., Rowe, M. C., Thompson, J. M., & Kerr, A. C. (2012). Petrogenesis of High-MgO Lavas of the Lower Mull Plateau Group, Scotland: Insights from Melt Inclusions. *Journal of Petrology*, 53(9), 1867–1886. <https://doi.org/10.1093/petrology/egs036>
- Pedersen, G. B. M., Belart, J. M. C., Óskarsson, B. V., Gudmundsson, M. T., Gies, N., Högnadóttir, T., Hjartardóttir, Á. R., Pinel, V., Berthier, E., Dürig, T., Reynolds, H. I., Hamilton, C. W., Valsson, G., Einarsson, P., Ben-Yehosua, D., Gunnarsson, A., & Oddsson, B. (2022). Volume, Effusion Rate, and Lava Transport During the 2021 Fagradalsfjall Eruption: Results From Near Real-Time Photogrammetric Monitoring. *Geophysical Research Letters*, 49(13), e2021GL097125. <https://doi.org/10.1029/2021GL097125>
- R Core Team. (2021). *R: A Language and Environment for Statistical Computing* [Computer software]. R Foundation for Statistical Computing. <https://www.R-project.org/>
- Salters, V. J. M., & Stracke, A. (2004). Composition of the depleted mantle. *Geochemistry, Geophysics, Geosystems*, 5(5). <https://doi.org/10.1029/2003GC000597>
- Saunders, A. D., Fitton, J. G., Kerr, A. C., Norry, M. J., & Kent, R. W. (1997). The North Atlantic Igneous Province. In *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism. Geophysical Monograph 100* (pp. 45–93). American Geophysical Union. <https://doi.org/10.1029/GM100p0045>
- Scarrow, J. H., Curran, J. M., & Kerr, A. C. (2000). Major Element Records of Variable Plume Involvement in the North Atlantic Province Tertiary Flood Basalts. *Journal of Petrology*, 41(7), 1155–1176. <https://doi.org/10.1093/petrology/41.7.1155>
- Shorttle, O., & MacLennan, J. (2011). Compositional trends of Icelandic basalts: Implications for short-length scale lithological heterogeneity in mantle plumes. *Geochemistry, Geophysics, Geosystems*, 12(11). <https://doi.org/10.1029/2011GC003748>

- Shorttle, O., MacLennan, J., & Lambart, S. (2014). Quantifying lithological variability in the mantle. *Earth and Planetary Science Letters*, 395, 24–40.
<https://doi.org/10.1016/j.epsl.2014.03.040>
- Silverman, B. W. (1986). The kernel method for univariate data. In *Density estimation for statistics and data analysis* (pp. 34–74). Springer.
- Simms, M. J. (2021). Subsidence, not erosion: Revisiting the emplacement environment of the Giant's Causeway, Northern Ireland. *Proceedings of the Geologists' Association*, 132(5), 537–548. <https://doi.org/10.1016/j.pgeola.2021.07.001>
- Spice, H. E., Fitton, J. G., & Kirstein, L. A. (2016). Temperature fluctuation of the Iceland mantle plume through time. *Geochemistry, Geophysics, Geosystems*, 17(2), 243–254. <https://doi.org/10.1002/2015GC006059>
- Stock, M., & Beckwith, J. (2026). *Orthomagmatic Ni-Cu-Au-PGE mineralisation in Ireland and Northern Ireland: A review of historic exploration and future prospectivity*. <https://eartharxiv.org/repository/view/13001/>
- Stracke, A., Hofmann, A. W., & Hart, S. R. (2005). FOZO, HIMU, and the rest of the mantle zoo. *Geochemistry, Geophysics, Geosystems*, 6(5).
<https://doi.org/10.1029/2004GC000824>
- Taylor, R. N., Davila-Harris, P., Branney, M. J., Ruth Farley, E. M., Gernon, T. M., & Palmer, M. R. (2020). Dynamics of a chemically pulsing mantle plume. *Earth and Planetary Science Letters*, 537, 116182.
<https://doi.org/10.1016/j.epsl.2020.116182>
- Thompson, R. N., Dickin, A. P., Gibson, I. L., & Morrison, M. A. (1982). Elemental fingerprints of isotopic contamination of hebridean Palaeocene mantle-derived magmas by archaean sial. *Contributions to Mineralogy and Petrology*, 79(2), 159–168. <https://doi.org/10.1007/BF01132885>
- Thompson, R. N., & Morrison, M. A. (1988). Asthenospheric and lower-lithospheric mantle contributions to continental extensional magmatism: An example from the British Tertiary Province. *Chemical Geology*, 68(1), 1–15.
[https://doi.org/10.1016/0009-2541\(88\)90082-4](https://doi.org/10.1016/0009-2541(88)90082-4)
- Thompson, R. N., Morrison, M. A., Dickin, A. P., Gibson, I. L., & Harmon, R. S. (1986). Two contrasting styles of interaction between basic magmas and continental crust in the British Tertiary Volcanic Province. *Journal of Geophysical Research: Solid Earth*, 91(B6), 5985–5997. <https://doi.org/10.1029/JB091iB06p05985>
- Toplis, M. J. (2005). The thermodynamics of iron and magnesium partitioning between olivine and liquid: Criteria for assessing and predicting equilibrium in natural and

- experimental systems. *Contributions to Mineralogy and Petrology*, 149(1), 22–39.
<https://doi.org/10.1007/s00410-004-0629-4>
- Wallace, J. M., Ellam, R. M., Meighan, I. G., Lyle, P., & Rogers, N. W. (1994). Sr isotope data for the Tertiary lavas of Northern Ireland: Evidence for open system petrogenesis. *Journal of the Geological Society*, 151(5), 869–877.
<https://doi.org/10.1144/gsjgs.151.5.0869>
- Wang, Z.-Z., & Liu, S.-A. (2021). Evolution of Intraplate Alkaline to Tholeiitic Basalts via Interaction Between Carbonated Melt and Lithospheric Mantle. *Journal of Petrology*, 62(4), egab025. <https://doi.org/10.1093/petrology/egab025>
- White, R. S. (1992a). Crustal structure and magmatism of North Atlantic continental margins. *Journal of the Geological Society*, 149(5), 841–854.
<https://doi.org/10.1144/gsjgs.149.5.0841>
- White, R. S. (1992b). Magmatism during and after continental break-up. *Geological Society, London, Special Publications*, 68(1), 1–16.
<https://doi.org/10.1144/GSL.SP.1992.068.01.01>
- White, R. S., & McKenzie, D. (1995). Mantle plumes and flood basalts. *Journal of Geophysical Research*, 100(B9). <https://doi.org/10.1029/95jb01585>
- White, R. S., Mckenzie, D., & O’Nions, K. (1992). Oceanic Crustal Thickness From Seismic Measurements and Rare Earth Element Inversions. *Journal of Geophysical Research*, 97(B13), 19,683-19,715.
- Wilkinson, C. M., Ganerød, M., Hendriks, B. W. H., & Eide, E. A. (2017). Compilation and appraisal of geochronological data from the North Atlantic Igneous Province (NAIP). *Geological Society Special Publication*, 447(1), 69–103.
<https://doi.org/10.1144/SP447.10>

Supplementary Figures

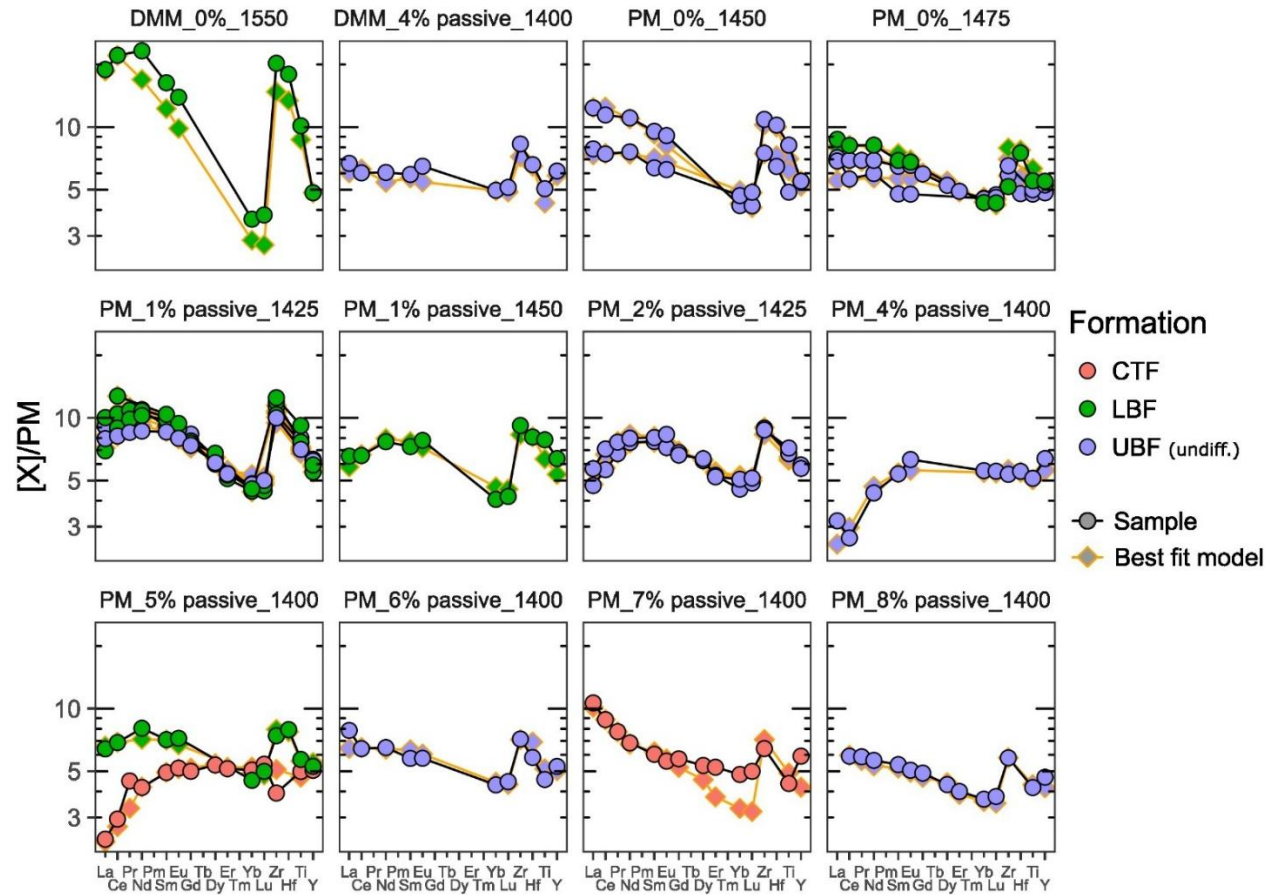


Figure S1 – sample data and best fit modelling melt compositions (see Section 3.5) compared for literature ALG data from GEOROC (DIGIS Team, 2023). Samples are shown with black outlines and modelled melt compositions with orange outlines. The mantle source, degree of depletion and T_p of the best fit model run is shown above each panel.

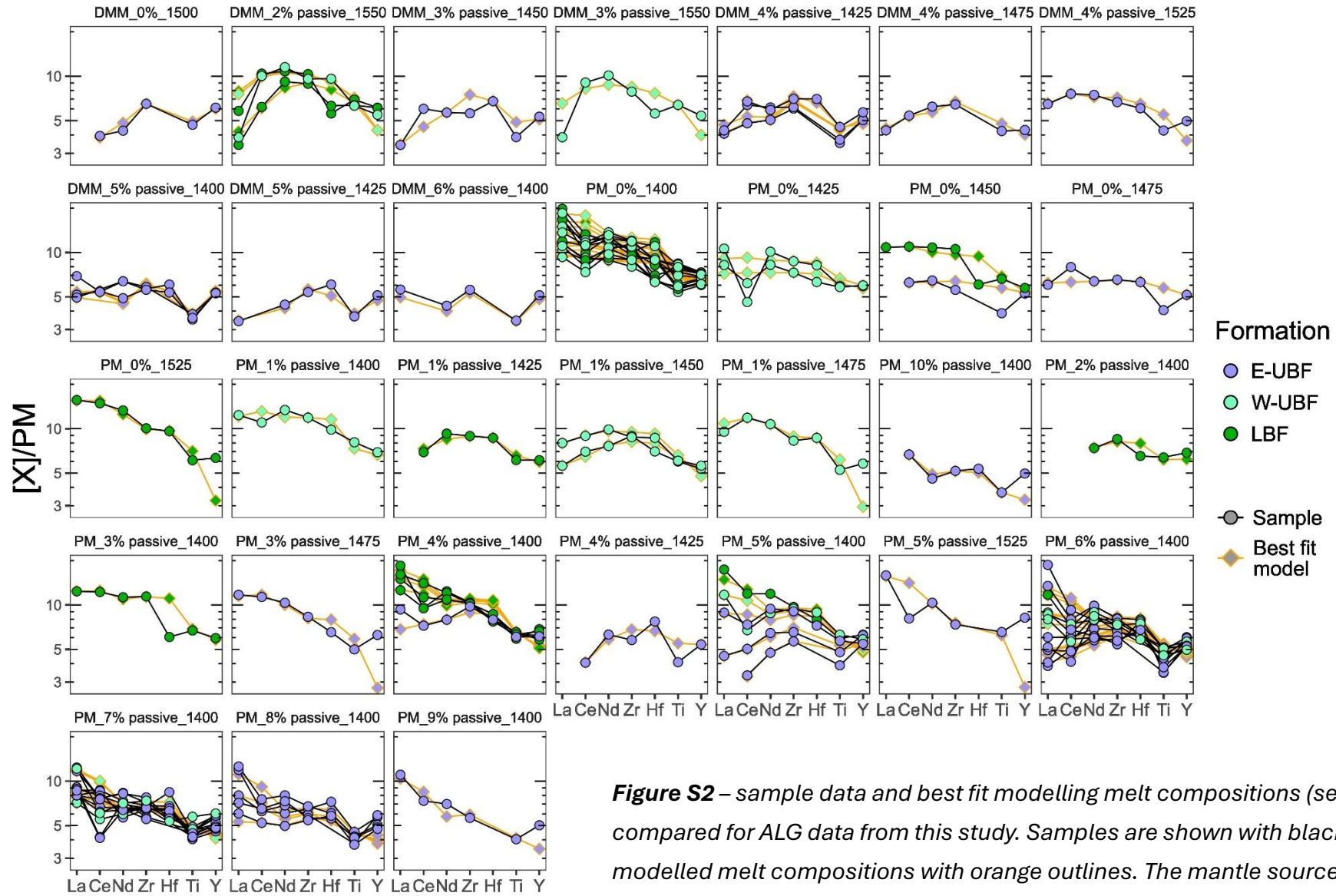


Figure S2 – sample data and best fit modelling melt compositions (see Section 3.5) compared for ALG data from this study. Samples are shown with black outlines and modelled melt compositions with orange outlines. The mantle source, degree of depletion and T_p of the best fit model run is shown above each panel.

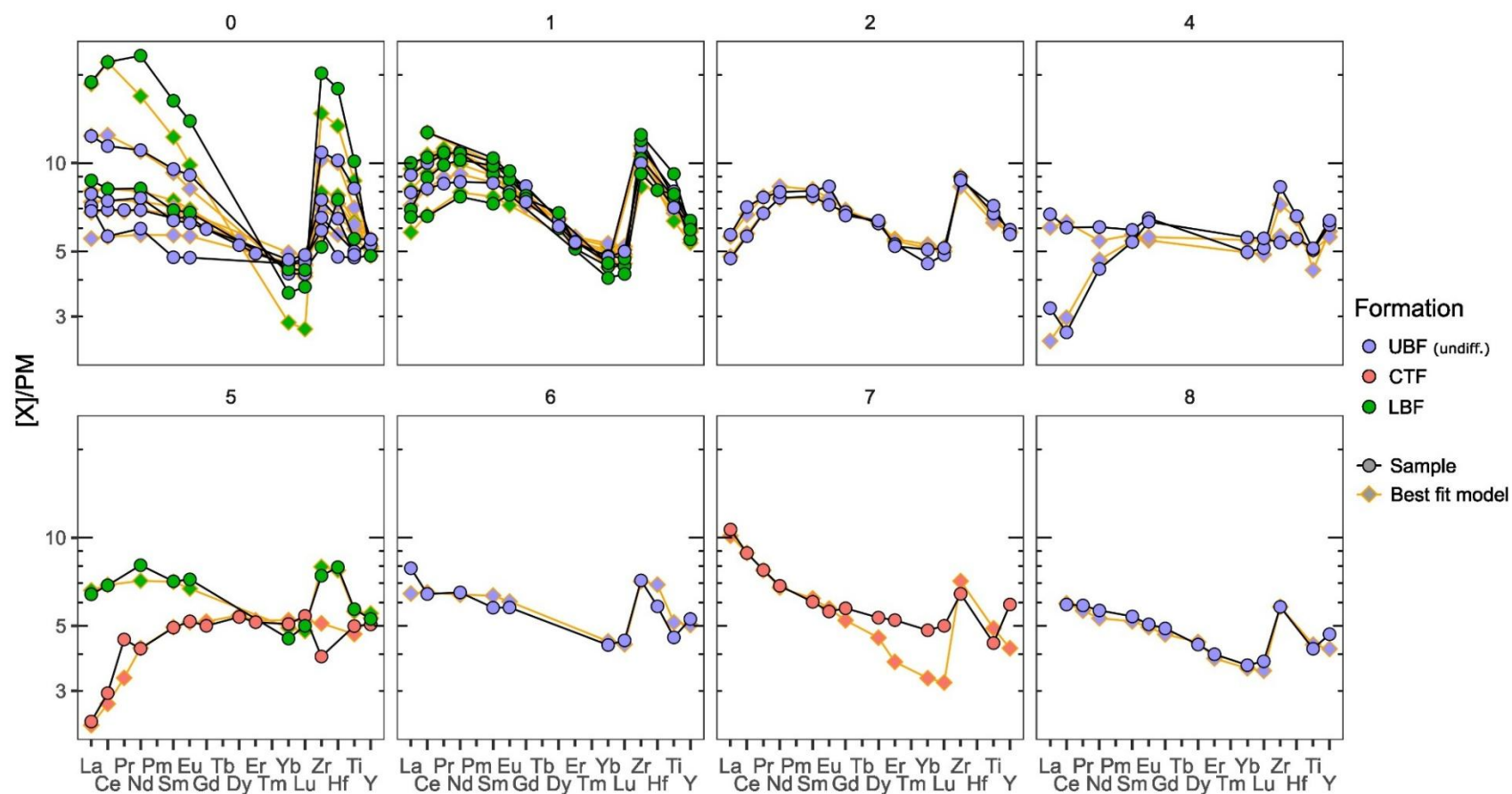


Figure S3 – ALG sample data and best fit modelling melt compositions from GEOROC as in Figure S1 subdivided by degree of source depletion. Samples are shown with black outlines and modelled melt compositions with orange outlines. The degree of depletion (in %) of the best fit model run is shown above each panel.

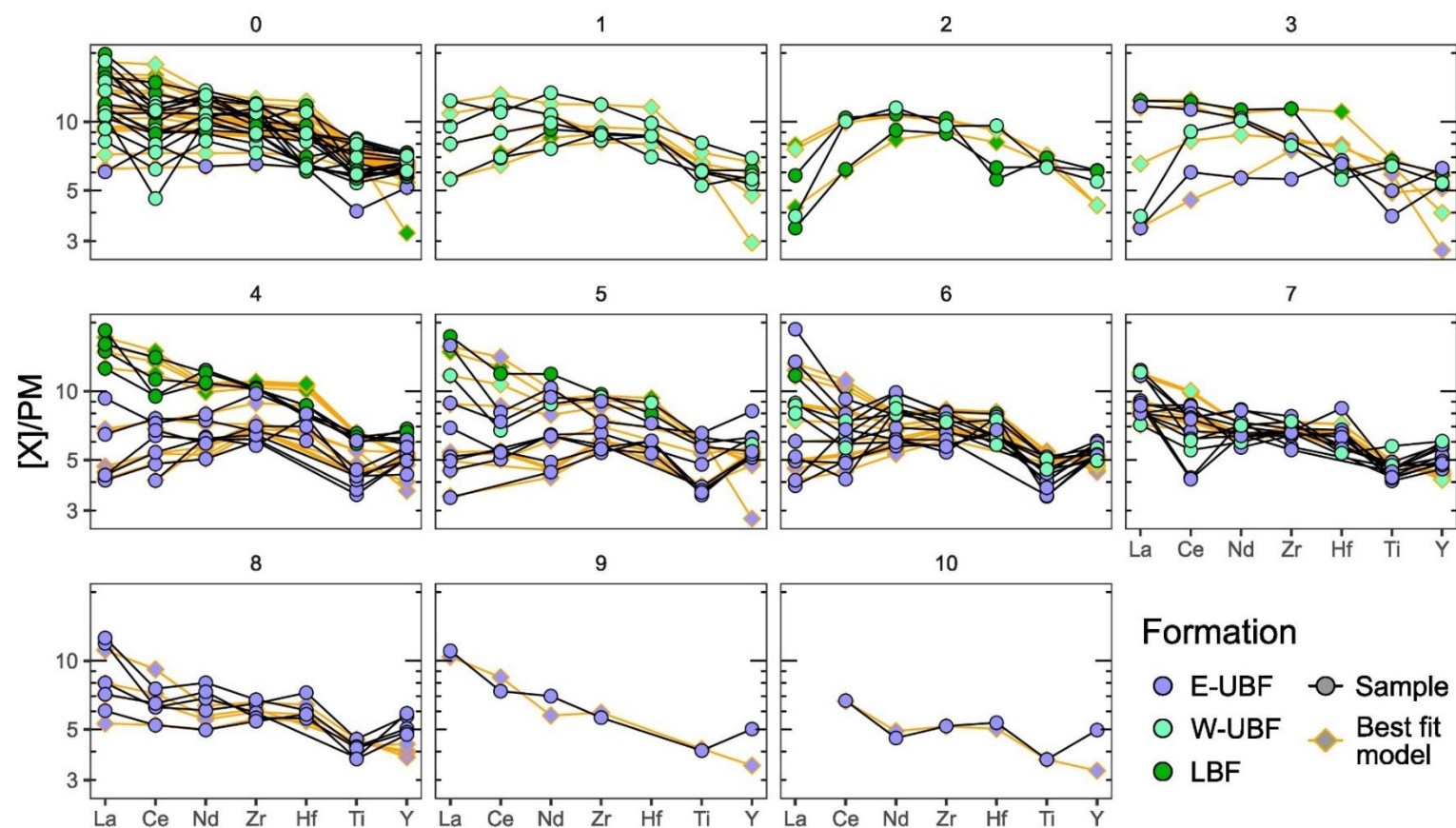


Figure S4 - ALG sample data and best fit modelling melt compositions from this study as in Figure S2 subdivided by degree of source depletion. Samples are shown with black outlines and modelled melt compositions with orange outlines. The degree of depletion (in %) of the best fit model run is shown above each panel.

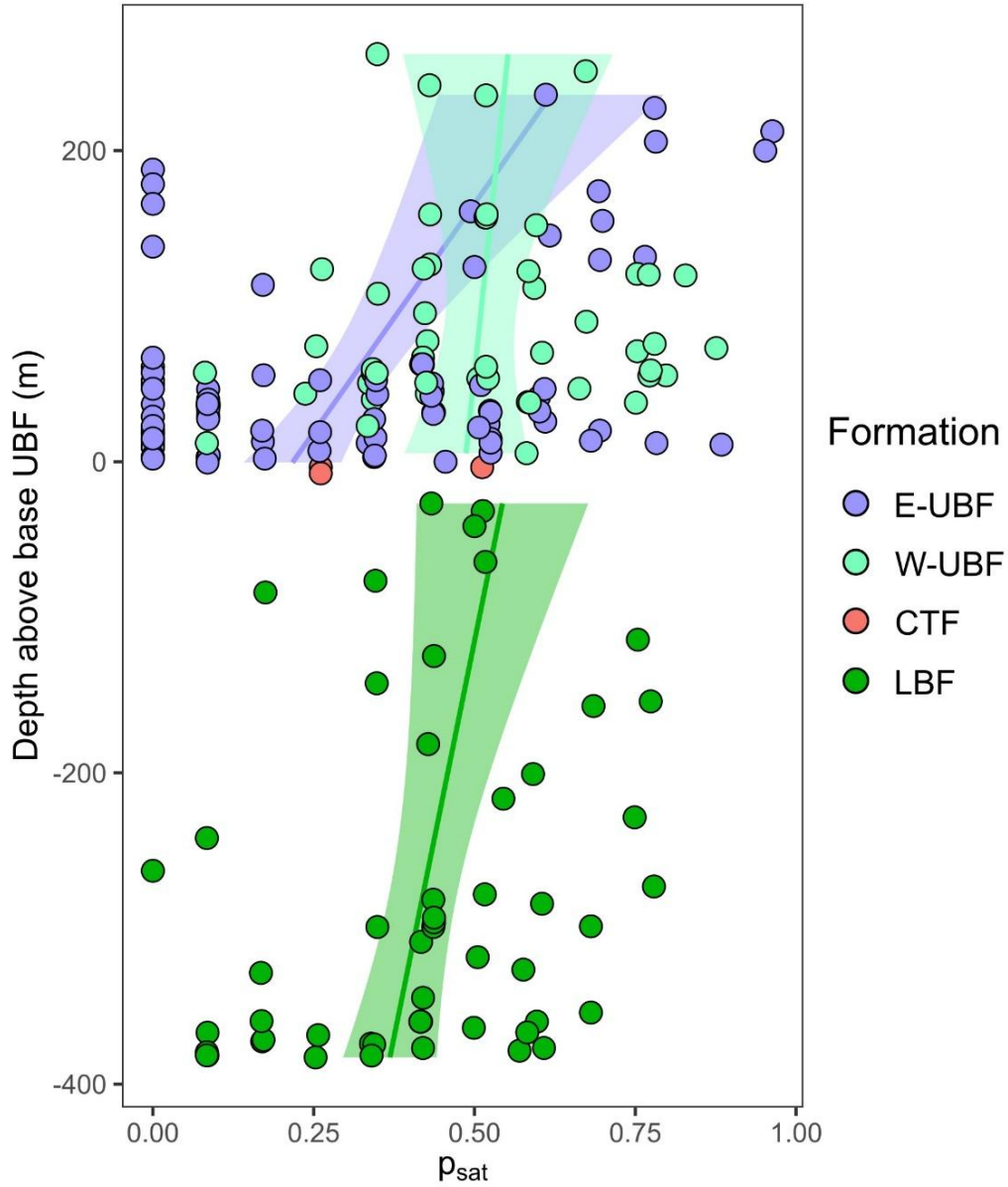


Figure S5 – stratigraphic variation in the probability of three-phase saturation (p_{sat}) predicted by the algorithm of Higgins & Stock (2024). All samples are plotted here; only those with $p_{sat} > 0.5$ are used for pressure determination. For each formation a linear regression to the data is fitted.

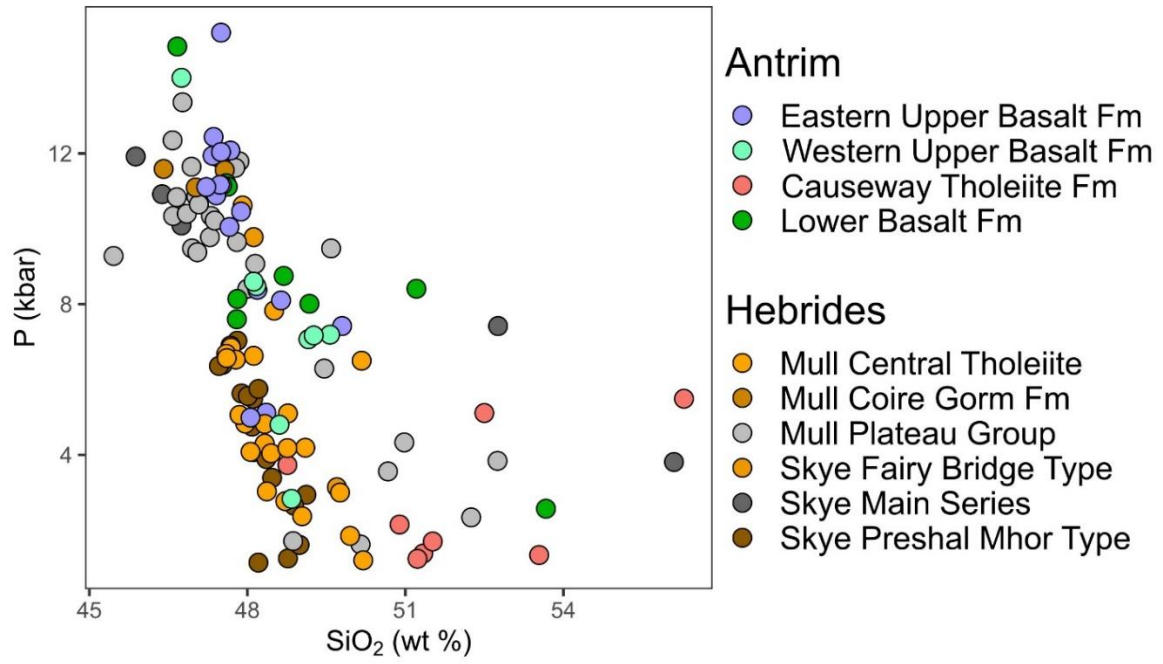


Figure S6 – negative correlation of pressure of melt equilibration with magmatic differentiation (SiO₂) for Antrim Lava Group (ALG) and Hebrides data from this study and GEOROC (DIGIS Team, 2023). Only samples with $p_{sat} > 0.5$ are plotted.

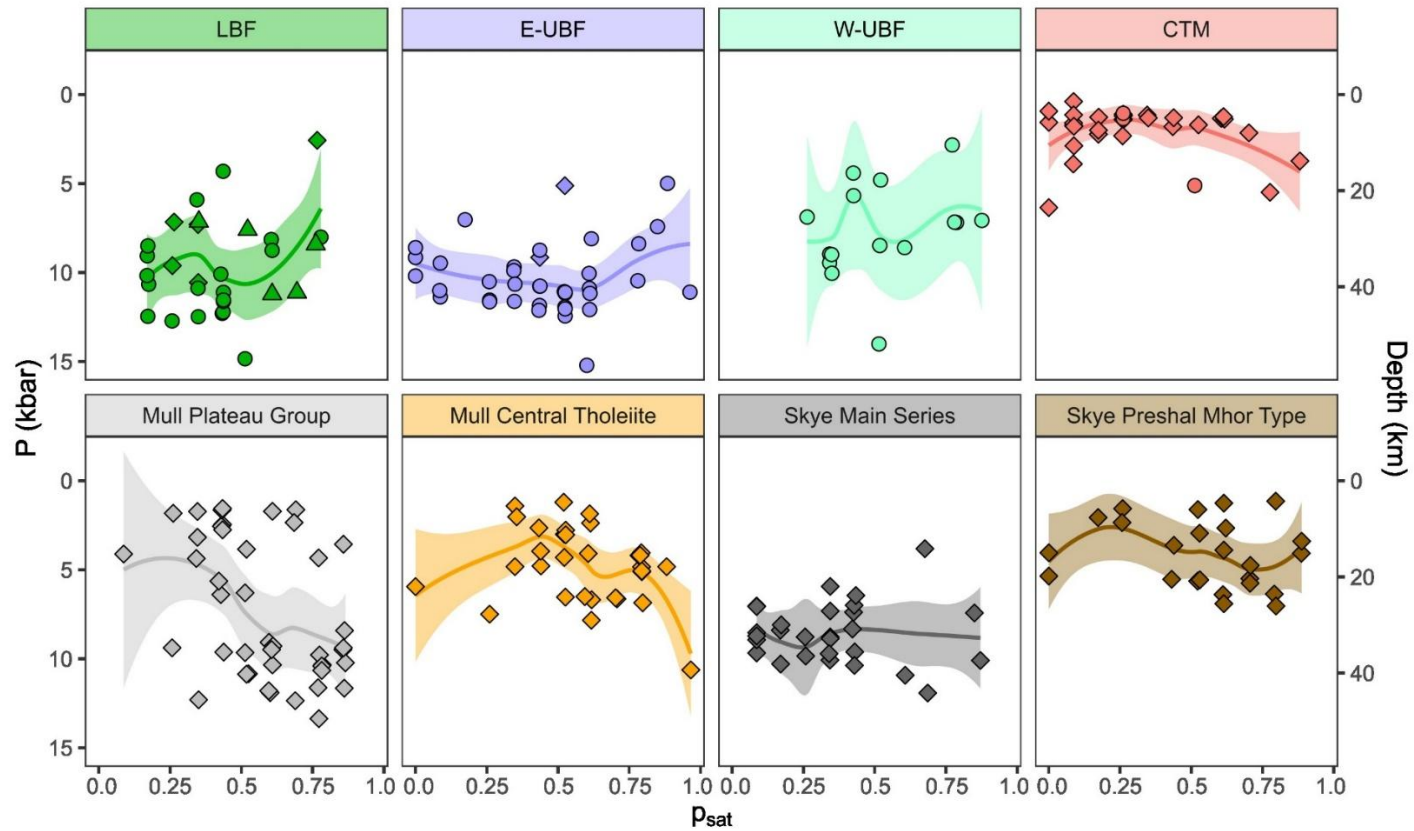


Figure S6 – variation in pressure of equilibration plotted against probability of three-phase saturation (p_{sat}) for Antrim Lava Group (ALG) and Hebrides data from this study and GEOROC (DIGIS Team, 2023) showing lack of systematic variation. A loess fit to the data and 1 sigma confidence envelope are plotted for each formation. Approximate depths have been calculated assuming a pressure gradient of 0.27 kbar/km.

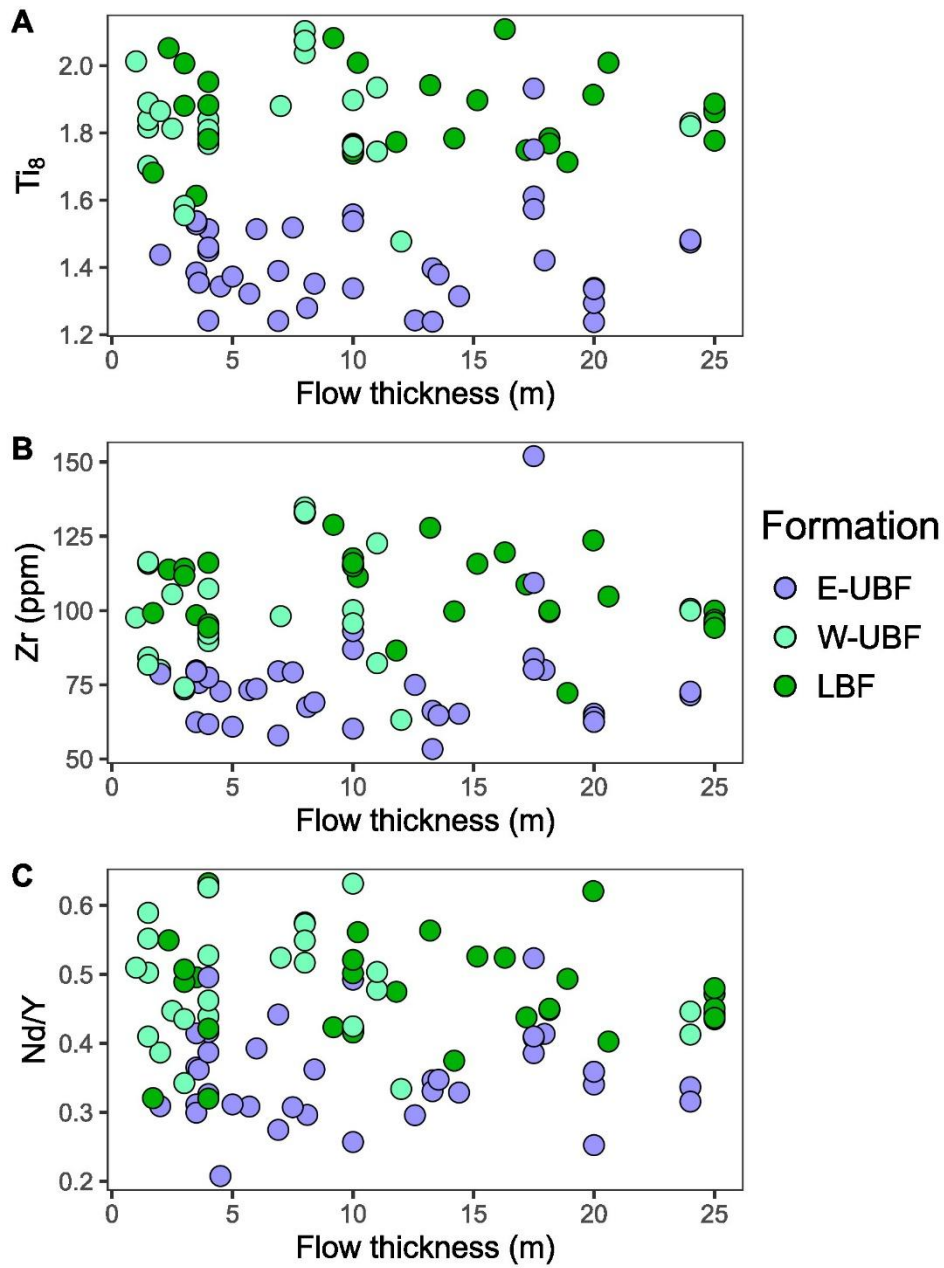


Figure S7 – Ti_8 , Zr and Nd/Y plotted against flow thickness for primitive fresh ALG samples ($MgO > 8$ wt%, $LOI < 5$ wt%)

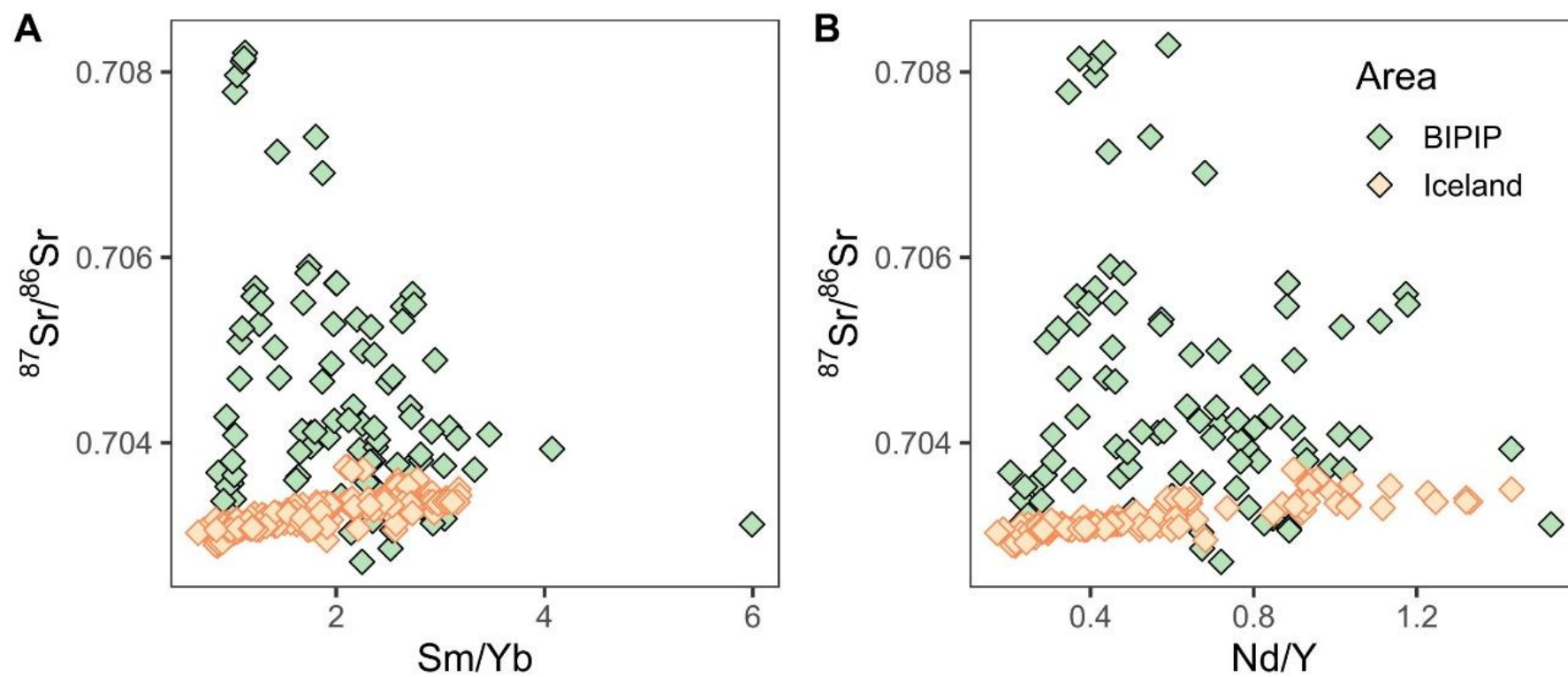


Figure S8 – Sm/Yb and Nd/Y versus $^{87}\text{Sr}/^{86}\text{Sr}$ showing lack of correlation for BIPIP samples. BIPIP data ($45\% < \text{SiO}_2 < 52\%$) from GEOROC (DIGIS Team, 2023). Iceland data ($6\% < \text{MgO} < 14\%$) from compilation of (Harðardóttir et al., 2022).