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Ar-Ar Dating of the Nephelinite-to-Basanite Transition at Etinde and Mount Cameroon (Cameroon Volcanic Line, West Africa) Provides Insights Into the Origin of Intraplate Magmatism

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Key Points:

- New $^{40}Ar/^{39}Ar$ ages, and mineral and whole-rock geochemical data are presented for Etinde and Mount Cameroon of the Cameroon Volcanic Line
- Etinde mafic nephelinites pre-date Mount Cameroon basanite by 0.45 Ma, and geochemical data show that the magmas share the same mantle source
- The temporal progression from nephelinite to basanite reflects increasing degrees of melting of an enriched melt source region

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Intraplate magmatism is widespread in continental and oceanic domains. Some occurrences, such as Hawai'i, fit the predictions of the mantle-plume hypothesis well. However, many occurrences require alternative explanations. The Cameroon volcanic line (CVL) in West Africa is one of the most voluminous and long-lived non-plume intraplate magmatic provinces, providing an ideal location for testing alternative intraplate magma-generation hypotheses. Two CVL volcanoes, Etinde and Mount Cameroon, located on the African continental margin are composed mostly of nephelinite and basanite, respectively. We present 12 new Ar-Ar dates and show that the Etinde mafic nephelinites (0.572 ± 0.032 and 0.5152 ± 0.0073 Ma) predate the Mount Cameroon basanites (0.442 ± 0.014 Ma to present). Basanite samples from Etinde had much younger ages (0.113 ± 0.019 and 0.073 ± 0.011 Ma) and likely originated in the Mount Cameroon magmatic system. Indistinguishable radiogenic isotope ratios and similar primitive-mantle-normalized incompatible-element patterns indicate that the magmas feeding the two volcanoes share the same mantle source. The temporal progression from nephelinite (Etinde) to basanite (Mount Cameroon and minor, late eruptions on Etinde) is marked by a reduction in La/Yb and an increase in SiO_2 content in the most mafic magmas. These features are consistent with the progressive melting of a common carbonate-enriched mantle source in which the proportion of carbonate in the melt declined with increasing melt fraction. We propose that the carbonate-enriched mantle flowed outwards from beneath Africa and decompressed as it encountered a thinner lithosphere at the continent-ocean boundary, leading to magmatism at Etinde and Mount Cameroon.

Plain Language Summary Our paper provides 12 new age dates as well as new whole-rock and mineral-specific geochemical data for two volcanoes, Etinde and Mount Cameroon, of the Cameroon Volcanic Line. Samples from Etinde comprise nephelinite (more enriched) and basanite (less enriched), whereas samples from Mount Cameroon are exclusively basanite (less enriched). Our data show that Etinde mafic nephelinite samples erupted 0.45 Ma before basanites from Etinde and Mount Cameroon. Etinde and Mount Cameroon basanites overlap in age and composition, allowing us to infer that the same magma erupted via the Etinde and Mount Cameroon plumbing systems. The fact that the most enriched samples, the Etinde mafic nephelinites, erupted earliest indicate that these initial Etinde samples represent the first small-degree partial melts of an enriched source region in this part of the CVL. Signs of this enriched source region enrichment were diluted by larger-degree partial melting at the time of basanite magma genesis, 0.45 Ma later. Our findings support a new model for intraplate magmatic settings which lacks evidence for a mantle plume, which relies on the presence of an enriched source region. Therefore, our manuscript could be of significance to researchers globally.

1. Introduction

No single mechanism can explain all intraplate magmatism. Time-progressive oceanic (e.g., Hawai'i and the Emperor Seamounts) and continental (e.g., Yellowstone and the Snake River Plain) volcanic trails are readily explained by deep-mantle plumes, but some (arguably most) occurrences lack evidence in support of a plume origin (e.g., Fitton, 2007; Kirstein et al., 2023). Unequivocally plume-related hotspots (e.g., Hawai'i, Réunion, Galapagos) are generally dominated by subalkali to mildly alkali basalt, whereas the others are usually more

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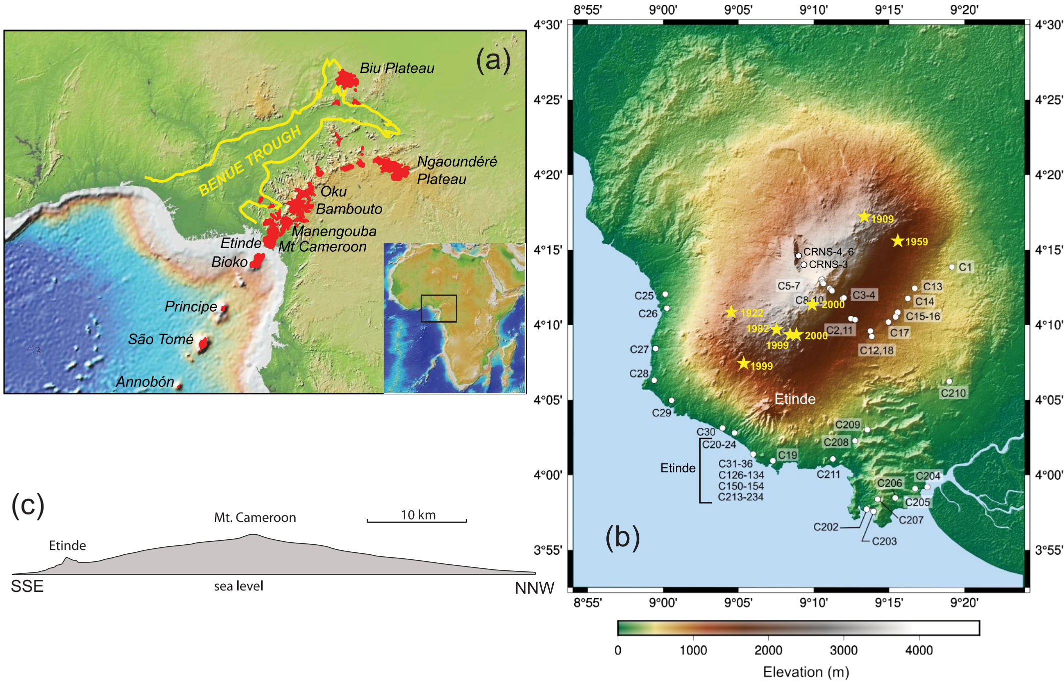

Figure 1. (a) Map of part of West Africa with volcanic rocks of the Cameroon line marked in red and the amagmatic early Cretaceous Benue Trough outlined in yellow. Location within the African continent shown by inset. Information on the ages of the volcanic and plutonic centers forming the Cameroon volcanic line is given in Njome and De Wit (2014). (b) Relief map of Mount Cameroon and Etinde showing sample localities (white circles) and the location of historic eruption sites (yellow stars; locations from Favalli et al., 2012). (c) A true-scale topographic profile through the summits of Etinde and Mount Cameroon.

silica-undersaturated (alkali basalt, basanite, nephelinite, and melilitite) (Kirstein et al., 2023) and require alternative, non-plume explanations.

The Cameroon volcanic line (CVL) in West Africa is "an enigmatic intraplate magmatic province that defies common dynamic models of melt generation and volcanic activity on Earth" (Milelli et al., 2012). It consists of a 1,700-km-long chain of volcanoes that extends from the island of Annobón in the Atlantic Ocean across the continental margin and into the interior of Africa (Figure 1). The individual volcanic centers are voluminous and show no age progression (Adams, 2022; Fitton, 1987; Njome & De Wit, 2014). Magmatism started at about 65 Ma and continues to the present with the currently active Mount Cameroon at the center of the line.

The similarity in chemical and isotopic composition between mafic rocks in the oceanic and continental sectors of the CVL (Fitton & Dunlop, 1985; Halliday et al., 1988, 1990) requires a sub-lithospheric mantle source for the magmatism. A seismic experiment carried out by Reusch et al. (2011) showed that the mantle transition zone beneath the CVL and adjacent areas has a uniform thickness similar to the global average, implying that any thermal anomaly in the upper mantle beneath the CVL must be confined to the asthenosphere. The numerous models proposed to explain the CVL have been reviewed by Adams (2022).

Remarkably, the CVL has a contemporaneous and compositionally indistinguishable, mirror-image intraplate volcanic province on the exact conjugate margin in north-east Brazil (NEB), comprising the oceanic Fernando de Noronha archipelago, and the continental Mecejana volcanic field and Macau-Queimadas volcanic lineament (Guimarães et al., 2020). Magmatic activity in the two provinces started 40–50 Myr after continental separation. The lack of age progression in the location of volcanism in either province, and low $^{3}He/^{4}He$ in basalt samples from the CVL (2.1–8.6 Ra; Barfod et al., 1999; Aka et al., 2004) are difficult to reconcile with a plume origin (Guimarães et al., 2020). Furthermore, mantle potential temperatures inferred from seismic velocities identify the CVL as one of several "cold hotspots" (Baö et al., 2022) with temperatures indistinguishable from those beneath mid-ocean ridges. Taken together, these observations effectively rule out the involvement of mantle plumes in CVL and NEB magmatism.

This poses the question of how to sustain voluminous intraplate magmatism over extended periods (>65 Myr in the case of the CVL) in the absence of plumes or lithospheric extension. The melt zones beneath the two provinces must be continuously fed over long periods, and since we can rule out feeding the melt zones from below via plumes, the supply of enriched mantle most likely flowed in horizontally. Guimarães et al. (2020) proposed a model for CVL and NEB magmatism that involves the slow, pervasive enrichment of continental lithospheric mantle through the addition of carbonate-rich melt. Lithospheric mantle is thickened by compression during supercontinent assembly and then slowly re-equilibrates thermally as it heats up by conduction and the decay of radioisotopes, thereby becoming part of the asthenosphere. The enriched asthenosphere is held in place by buoyancy until the supercontinent breaks up and the continental fragments rift away from each other. Mobile enriched mantle then flows outwards between cratonic blocks, rather like an upside-down river system, decompresses beneath thinner parts of the lithosphere, and partially melts. The process can potentially supply carbonate- and incompatible-element-enriched mantle source material for intraplate magmatism for long periods following supercontinent break-up.

The Guimarães et al. (2020) model predicts the formation of enriched, highly silica-undersaturated magmas (e.g., nephelinite) due to the influence of carbonate during initial melting and, with increasing degrees of melting, the generation of larger volumes of less-undersaturated melt (e.g., basanite). Evidence for volatile-induced enrichment of the Cameroon line mantle source is plentiful. The presence of haüyne and nosean phenocrysts in the more evolved Etinde nephelinites shows that the magmas contained high concentrations of sulfur and chlorine (Baldwin et al., 2025). Furthermore, Suh et al. (2008) found exceptionally high concentrations of CO_2, H_2O, S, Cl, and F in olivine-hosted melt inclusions from Mount Cameroon, and the 1,986 Lake Nyos disaster also attests to the abundance of CO_2 in the Cameroon line magmas (Aka et al., 2001). The presence of CO_2 in silica-undersaturated alkaline melts expands the stability field of pyroxene and destabilizes olivine; as a result, there are also potential petrographic indicators of such a volatile-enriched source.

Here we investigate the temporal relationship between the highly incompatible-element-enriched nephelinites and basanites that form Etinde and Mount Cameroon with the aim of providing greater insight into the origin of intraplate magmatism generally. These two volcanoes are located on the Cameroon coast at the center of the CVL (Figure 1a). With six recorded eruptions in the 20th Century, Mount Cameroon is one of the most active volcanoes in Africa (Favalli et al., 2012). It rises from sea level to a height of 4,040 m and is composed of basanite, tephrite and trachybasalt lava flows (Figure 2) interbedded with tephra (Suh et al., 2003). Etinde forms a separate 1,713 m peak on the SW flanks of Mount Cameroon (Figures 1b and 1c) and is enveloped by younger lava flows from Mount Cameroon on its NW, NE and SE sides. It is composed of nephelinites with extreme enrichment in incompatible elements and basanites (Figure 2). Although previous studies have addressed the petrographic and geochemical relationship between Mount Cameroon and Etinde (Fitton, 1987; Halliday et al., 1990; Nkoumbou et al., 1995), their geochronological relationship was unclear prior to the present study. K-Ar dating suggested ages up to 2.83 ± 0.11 Ma for Mount Cameroon (Aka et al., 2004; Wandji et al., 2009), and between 0.1 and 0.65 Ma for Etinde (Aka et al., 2004; Fitton & Dunlop, 1985; Nkoumbou et al., 1995). However, K-Ar age determinations are vulnerable to violations of initial conditions and closed system criteria, namely the potential presence of excess ^{40}Ar at the time of formation, and potential for subsequent unrecognized open system argon loss. Because these features can give apparent ages that are, respectively, too high or too low, K-Ar ages may not only be inaccurate, but they cannot easily be used as limiting ages. Hence, a key question that we address in this paper is what is the true age relationship between Mount Cameroon and Etinde. Did Etinde predate Mount Cameroon, as suggested by the morphology of the two volcanoes, or did the two volcanic centers erupt contemporaneously? If the former, then the volcanic system could be tapping magmas generated by increasing degrees of melting of a common carbonate-enriched mantle source. If the latter, then the system must be tapping discrete domains in a heterogeneous mantle source. We also present supporting major- and trace-element compositions for our suite of Etinde and Mount Cameroon rock samples, and electron microprobe data for olivine phenocrysts in samples of Etinde nephelinite and basanite to aid interpretation. These data are given in Table S1.

2. Methods

All samples analyzed for major- and trace-element compositions were collected from Cameroon and prepared and analyzed by X-Ray Fluorescence (XRF) spectrometry at the University of Edinburgh; the analyses are given in Table S1. Analyses of lava samples from historic eruptions of Mount Cameroon have previously been published

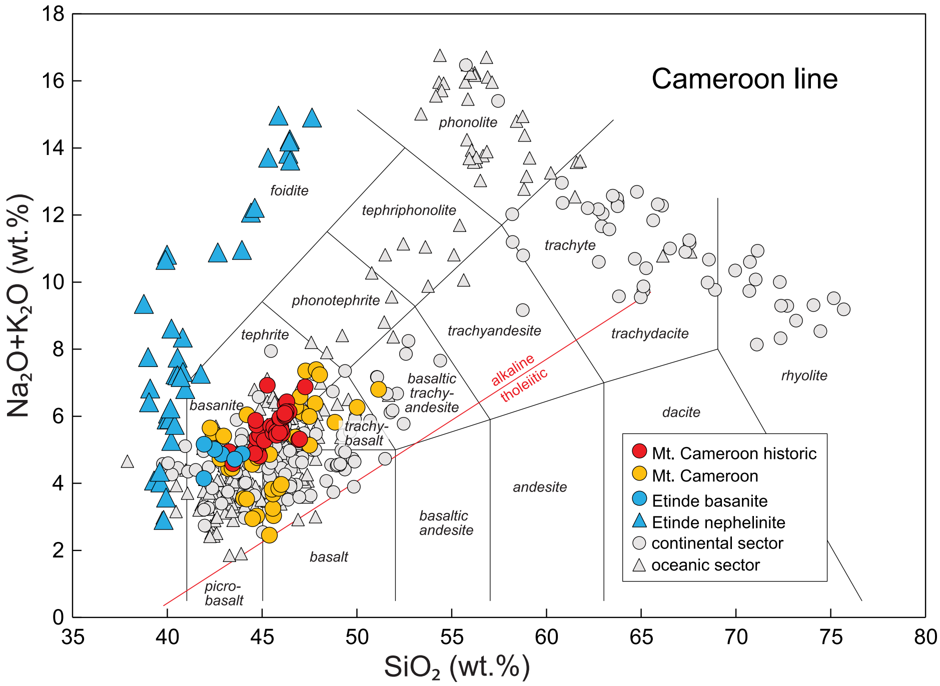

Figure 2. A plot of total alkalis against silica (after Le Bas et al., 1986) showing the composition of lava flows from Etinde and Mount Cameroon analyzed in this study, compared with the composition of rocks from the continental and oceanic sectors of the Cameroon line as a whole (Fitton, 1987). The composition of mafic lava flows in the oceanic and continental sectors of the Cameroon volcanic line is notably similar. The line separating Hawaiian tholeiitic and alkaline basalts is from Macdonald and Katsura (1964).

by Fitton et al. (1983), Suh et al. (2003, 2005) and Njome et al. (2008). Major element concentrations were measured on fused glass discs and trace element concentrations on pressed-powder pellets. Samples were analyzed using a Philips PW2404 wavelength-dispersive sequential X-ray spectrometer fitted with a Rh-anode end-window X-ray tube. A full description of the XRF techniques, including accuracy and precision estimates and values of international geochemical reference standards obtained in the Edinburgh laboratory, is given in Fitton et al. (1998).

Olivine composition was determined using a Cameca SX-100 electron microprobe at the University of Edinburgh. Analyses were performed using a 5 μm beam and an accelerating voltage of 15 kV. A beam current of 6 nA was used for major elements and 100 nA for minor elements. The following standards were utilized for calibration: jadeite for Na, spinel for Mg and Al, wollastonite for Si and Ca, synthetic fayalite for Fe, Durango apatite for P, rutile for Ti, and pure metals for Mn, Cr and Ni. Elements were analyzed in the following order: Na, Mg, Al, Si, Ca, Fe, Ca, P, Ti, Mn, P, Ti. Cameca software, PeakSight, was used to process the data after collection, and analyses with poor totals (outside the range 98%–101%) were not included in the final data set (Table S1). The 2σ standard deviation for minor elements in olivine was Ni, 185 ppm; Mn, 175 ppm; Ca, 130 ppm; Ti, 50 ppm and Na, 30 ppm.

Ages were measured by $^{40}Ar/^{39}Ar$ dating on carefully separated groundmass material using sample preparation methods outlined by Siegburg et al. (2018). Samples and neutron flux monitors were placed in wells within aluminum discs and stacked in quartz tubes with the relative positions of wells precisely measured for later reconstruction of neutron flux gradients. The sample package was irradiated in the Oregon State University reactor, Cd-shielded facility. Alder Creek sanidine (1.1891 ± 0.0008 Ma; Niespolo et al., 2017) was used to monitor ^{39}Ar production and establish neutron flux values (J) for the samples. For all samples except CRNS 03, −04 and −06, gas was extracted via step-heating using a mid-infrared (10.6 μm) CO_2 laser with a non-Gaussian, uniform energy profile and a 3.5 mm beam diameter. The samples were housed in a doubly pumped ZnS-window laser cell and loaded into a copper planchette containing four 2.6 cm^2 square wells. For the remaining samples (CRNS 03, −04 and −06), gas was extracted using an all-metal resistively heated furnace with multi-step heating

Table 1
Ar-Ar Results From Groundmass Material From a Range of Mafic Samples From Etinde and Mount Cameroon and a Felsic Nephelinite Sample From Etinde (C232)

Sample	Rock type	Accepted age (Ma)	±2σ	Type	Composite or single
Etinde					
C150	nephelinite (mafic)	0.5152	0.0073	plateau	comp
C225	nephelinite (mafic)	0.572	0.032	plateau	comp
C232	nephelinite (felsic)	0.4288	0.0050	plateau	comp
C151	basanite	0.113	0.019	plateau	single
C223	basanite	0.073	0.011	plateau	comp
Mount Cameroon					
C203	basanite	0.442	0.014	plateau	comp
C204	basanite	0.230	0.016	plateau	single
C206	basanite	0.127	0.016	isochron	comp
C211	basanite	0.053	0.012	isochron	comp
CRNS-3	basanite	0.0033	0.0025	isochron	single
CRNS-4	basanite	0.2029	0.0045	plateau	single
CRNS-6	basanite	0.1600	0.0040	plateau	single

Note. The accepted ages, either plateau or isochron, composite (comp) or single analysis, are those discussed in the text which were selected based on the stated acceptance criteria. See Table S1 for details.

schedules ranging from ∼700 to 1,500°C. Following extraction, liberated argon was purified of active gases, for example, CO_2, H_2O, H_2, N_2, CH_4, using three Zr-Al getters: one at 16°C and two at 400°C. Data were collected on a Thermo instruments ARGUS VI (laser) or ARGUS V (furnace) multi-collector mass spectrometer using a variable sensitivity Faraday collector array in static collection (non-peak hopping) mode (Mark et al., 2009). Time-intensity data were regressed to t_0 with second-order polynomial fits to the data. Blank corrections employed the average value and standard deviation of multiple blank bracketing and interspersed with the sample and air standard runs. Mass discrimination was monitored on a daily basis, both between and within sample runs by comparison to running-average values of an air standard. All data are blank-, interference- and mass-discrimination corrected using the MassSpec software package (MassSpec Version 8.251, authored by Al Deino, Berkeley Geochronology Center). Decay constants and corrections are after Renne et al. (2011). Isochron and plateau ages were calculated for each sample (Table 1). Plateau age criteria for acceptance was as follows: (a) The ages of at least 5 steps on a plateau release diagram are indistinguishable within 2σ uncertainty; (b) The accepted plateau steps form an isochron on a correlation diagram; (c) The trapped component on a correlation diagram is indistinguishable from air, $^{40}Ar/^{36}Ar_{ATM} = 298.56 \pm 0.62$, within 2σ uncertainty; (d) The dispersion of data points on the isochron and plateau diagrams are comparable to the expected analytical scatter, for example, MSWD is close to 1, and (e) The isochron and plateau ages are indistinguishable within 2σ uncertainty. All age uncertainties quoted herein are given at 2σ. Further details on the methodology and raw data are provided in Table S1.

3. Mount Cameroon and Etinde

The lower south–west slopes of Mount Cameroon receive an annual rainfall of around 10 m and so Etinde is enveloped in dense rainforest to the summit, and rock exposure is very limited and subject to deep tropical weathering. However, unaltered rock samples with a wide range of compositions were collected from boulders in two major streams draining the south–west side of Etinde (Figure 1b). These Etinde samples comprise highly undersaturated rock types (Figure 2), ranging from olivine nephelinite and basanite, through olivine-free haüyne-phyric nephelinite, to felsic leucite-nosean-nephelinite (Baldwin et al., 2025; Fitton, 1987; Nkoumbou et al., 1995). An ijolite xenolith (C234), included within a nephelinite sample, may represent the cumulate mineral assemblage from the evolving Etinde magma. Although we have no stratigraphic control on our Etinde rock samples, the boulders all originated on the deeply eroded south–west slopes of the volcano and therefore represent

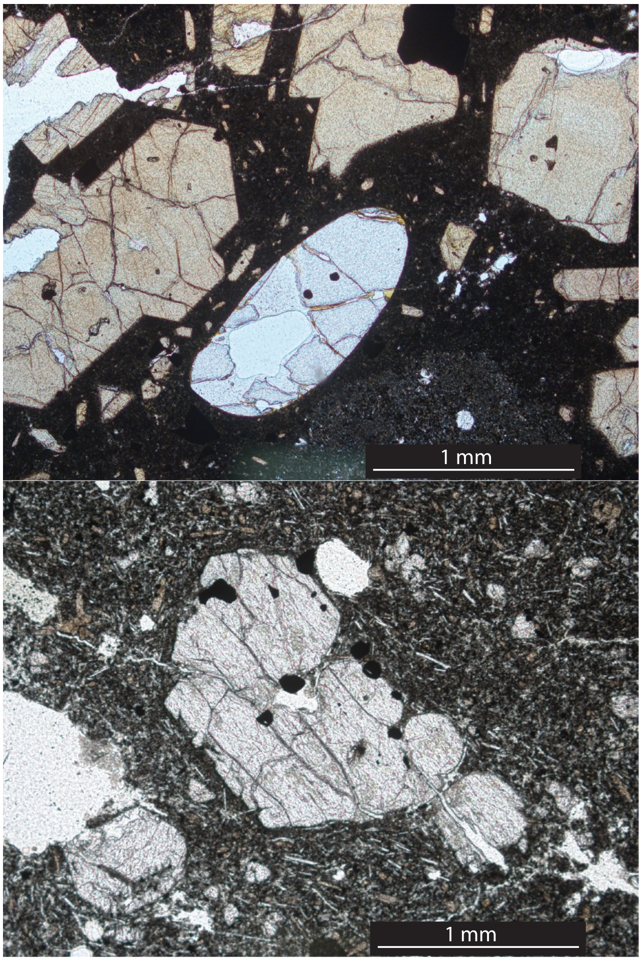

Figure 3. Photomicrographs of olivine nephelinite C225 (top) and basanite C222 (bottom) from Etinde. Images are taken with plane-polarized light. Note the rounded olivine (colorless) and euhedral titanaugite (brownish) phenocrysts in the nephelinite, and the euhedral olivine phenocrysts and groundmass plagioclase laths in the basanite.

a range of ages and include samples of all of the rock types shown on the geological sketch map of Etinde presented by Nkoumbou et al. (1995) and Ntoumbé et al. (2016).

The higher slopes of Mount Cameroon rise above the rainforest and are more accessible for sampling. A suite of lava-flow samples was collected from the drier south–east slopes and summit region, and from lava flows that reached the coast either side of Etinde (Figure 1b). These include samples from all the historic eruptions from 1922 to 2000. Lava flows that could predate the main volcanic edifice (C202-C211; Figure 1b) were sampled from the deeply dissected terrain to the south–east and supplemented with three samples (CRNS 03, −04 and −06) of lava exposed in a deep gully created by landsliding on the upper north-west flank of the volcano (Figure 1b).

The suite of mafic lava samples collected from Etinde is divided into two groups, olivine nephelinite and basanite (Figure 2), and is petrographically distinguished by the presence of groundmass plagioclase in the latter (Figure 3). Both groups contain olivine phenocrysts, but these have different morphologies in nephelinites (rounded) and basanites (euhedral) (Figure 3).

The extreme composition of the Etinde nephelinites in comparison to the Etinde and Mount Cameroon basanites, and the other CVL rocks is clearly seen on a total alkali—silica (TAS) diagram (Figure 2). The Etinde basanite samples plot within, but at the low-silica side of, the field of Mount Cameroon basanites (Figure 2). The distinction between the Etinde nephelinites and basanites, and the similarity between the latter and the basanites of Mount Cameroon, is also clear on the plots of CaO versus MgO and Zr versus SiO_2 (Figure 4).

Despite the clear difference in alkalinity shown on the TAS diagram (Figure 2), the Etinde and Mount Cameroon rocks have similar primitive-mantle-normalized incompatible element patterns (Figure 5) and indistinguishable Sr-, Nd- and Pb-isotope ratios (Halliday et al., 1990) (Figure 6). As would be expected, the Etinde olivine nephelinites are slightly more enriched than the basanites of Etinde and Mount Cameroon, but the coherence between the various rock samples suggests that the whole suite of mafic magmas was derived by variable degrees of melting of a common, enriched mantle source. In order to establish the relative ages of the nephelinite and basanite magmatism, we have dated two mafic nephelinite (C150, 225), one felsic nephelinite (C232), and two basanite (C151, 223) samples from Etinde, four basanite samples (C203, 204, 206 and 211) collected to the south–east of Mount Cameroon, and three basanite samples (CRNS-3, -4 and -6) from the north-west flank of Mount Cameroon.

4. Ar-Ar Ages of Etinde and Mount Cameroon

Accepted Ar-Ar ages for the 12 dated samples are given in Table 1; all age uncertainties are given at the 2σ level. Three samples (CRNS-x) were analyzed on an ARGUS V mass spectrometer equipped with a double-vacuum resistance furnace (Mark et al., 2009). The remaining samples (Cxxx) were analyzed using an ARGUS VI mass spectrometer operating in faraday-only mode coupled with a CO_2 laser extraction system. See Table S1 for full details of results, acceptance criteria, raw data and methods, and Supporting Information S1 for data plots of all runs.

All but two samples have coherent plateau ages that satisfy acceptance criteria, including isochron ages that are indistinguishable at 2σ and trapped component compositions that are coincident with atmosphere. For samples that were replicated, an error-weighted composite plateau and isochron age and uncertainty were calculated using all accepted steps from both experiments, producing resolvable increases in age precision. The composite calculations are justified as each sample shows replicate age results that are indistinguishable at 2σ.

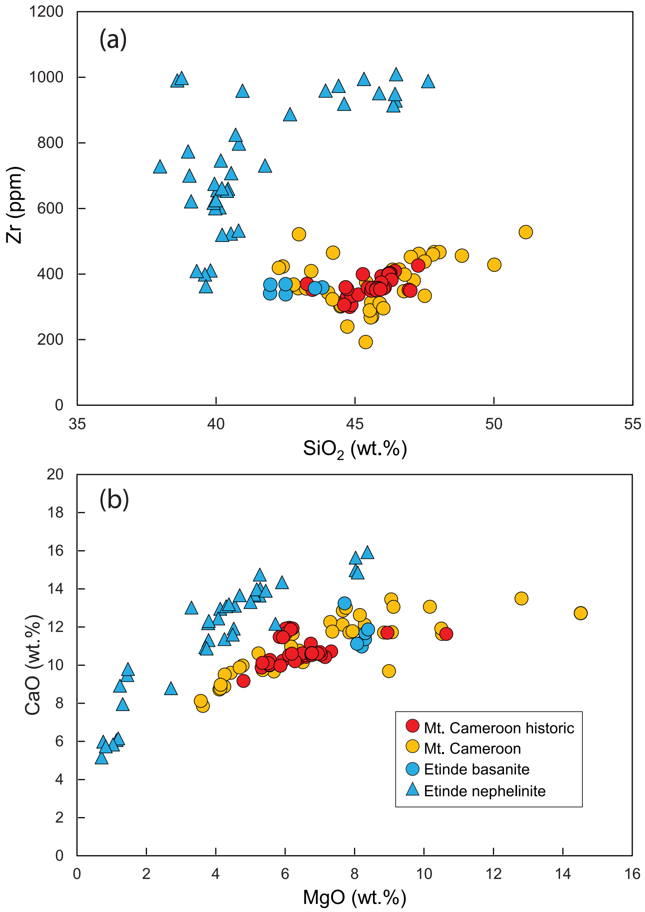

Figure 4. Plots of (a) Zr versus SiO_2 and (b) CaO versus MgO for the volcanic rocks of Etinde (blue) and Mount Cameroon (orange and red). Note that the Etinde basanites (blue circles) plot with the Mount Cameroon samples.

Sample C206 (both aliquots) shows trapped component compositions that are supra-atmospheric ($^{40}Ar/^{36}Ar > 298.56 \pm 0.62\ 2\sigma$) and saddle-shaped spectra suggesting the presence of excess ^{40}Ar. For this reason, we take the composite isochron analysis as the best age estimate. We note, however, that the isochron and plateau ages for individual aliquots are indistinguishable, suggesting that the overall effect of excess argon is minor.

One aliquot (B) of sample C211 has a short plateau (46.5%^{39}Ar), in part due to an analytical error that released too much gas in a single early step. We therefore conservatively take the composite isochron analysis (and its larger uncertainty) as the best estimate of the emplacement age. As with sample C206, we note that the isochron and plateau ages (individual and composite) are indistinguishable at 2σ, The seven Mount Cameroon samples range in age from 0.442 ± 0.014 to 0.0033 ± 0.0025 Ma, and the five from Etinde from 0.572 ± 0.032 Ma to 0.073 ± 0.011 Ma (Table 1). The Etinde dates fall into two distinct age-groups: nephelinites C150, C225 and C232 (mid-Pleistocene, 0.5152 ± 0.0073, 0.572 ± 0.032 and 0.4288 ± 0.0050 Ma, respectively) are much older than Etinde basanites C151 and C223 (upper Pleistocene, 0.113 ± 0.019 and 0.073 ± 0.011 Ma, respectively). The Etinde mafic nephelinites pre-date the oldest Mount Cameroon basanite by approximately 70 ky, while the younger Etinde samples (basanite) erupted contemporaneously with lavas from Mount Cameroon. The felsic nephelinite (C232) represents the youngest dated nephelinite eruption on Etinde (0.4288 ± 0.0050 Ma) and overlaps slightly with the oldest dated Mount Cameroon basanite lava flow (0.442 ± 0.014 Ma).

The two older mafic Etinde samples (C150, C225) are both entirely feldspar-free nephelinites with abundant titanaugite phenocrysts and occasional olivine phenocrysts that are strongly resorbed with rounded edges (Figure 3). By contrast, the younger Etinde samples (<0.1130 Ma) are basanites with groundmass plagioclase and abundant euhedral olivine phenocrysts (Figure 3). Given the clear petrographic differences between the two age groups at Etinde, it is likely that the other (undated) mafic Etinde nephelinite samples (C134 and C214) are older than the undated basanite samples (C219, C220, C221 and C222). The Etinde basanites are compositionally (Figure 2) and petrographically similar to the Mount Cameroon basanites. We therefore

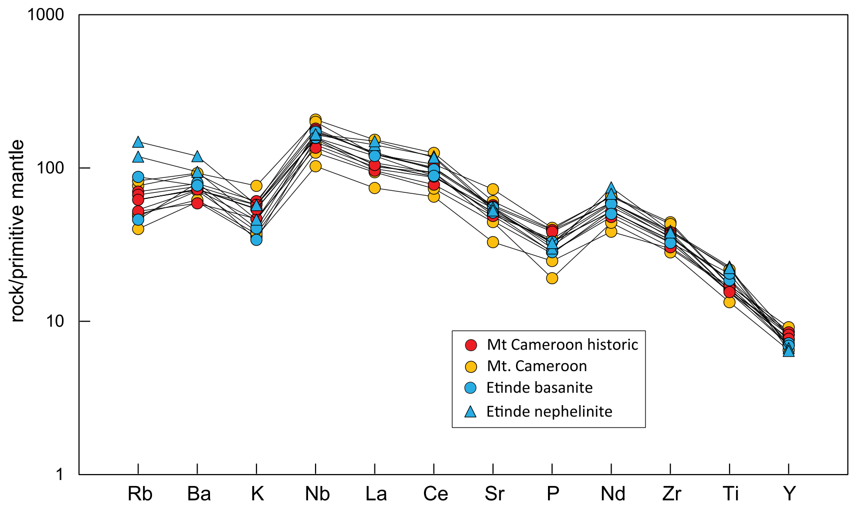

Figure 5. Incompatible trace element concentrations, normalized to primitive mantle values (McDonough & Sun, 1995), in all mafic Ar-dated and historic lava samples. The felsic nephelinite (C232) is not included.

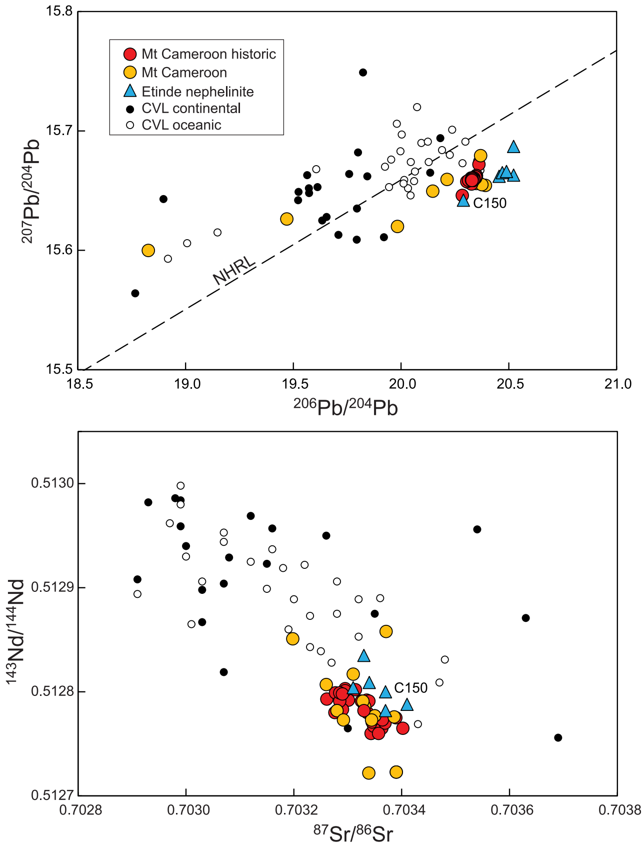

Figure 6. Isotopic data for Mount Cameroon, Etinde and the rest of the Cameroon volcanic line (CVL) (from Halliday et al., 1988, 1990; Tsafack et al., 2009; Wandji et al., 2009; Yokoyama et al., 2007) show that mafic volcanic rocks from the CVL oceanic and continental sectors are isotopically indistinguishable, implying a common, sub-lithospheric, mantle source. Lava samples from Mount Cameroon and Etinde are also isotopically indistinguishable from each other. Small adjustments were made to the Yokoyama et al. (2007) $^{87}Sr/^{86}Sr$ (+0.000082) and $^{206}Pb/^{207}Pb$ (−0.077) data for consistency with the Halliday et al. (1988) data, based on their respective values for the 1,959 and 1,982 basanite. Sample C150 from Etinde is an olivine nephelinite; the remaining Etinde samples are olivine-free intermediates and felsic nephelinites. NHRL is the Northern Hemisphere reference line from Hart (1984).

conclude that the eruption of the nephelinite flows that form the bulk of Etinde predates the basanite volcanism that built Mount Cameroon and formed some later flows on the south–west flank of Etinde.

5. Olivine Composition

The major element compositions of cores and rims of olivine phenocrysts from two Etinde nephelinites and four Etinde basanites were also measured (Table S1). Selected results are shown in Figure 7, together with published data from Mount Cameroon (Ngwa et al., 2020). The olivines are clearly not mantle-derived xenocrysts, based on their elevated Ca, Ti, and Al contents. The calculated forsterite range is from Fo_{71} to Fo_{85} (Figure 7), lower than mantle values (Fo > 89) but within the range of olivine measured from Mount Cameroon (Ngwa et al., 2020) and from ocean island basalts (Kirstein et al., 2023). There is a much broader range in forsterite content in olivines from the Etinde basanites (71.1–85.6 molecular per cent) compared with olivines from the Etinde nephelinites (82.8–84.6). Olivines from nephelinite contain more calcium (2,800–3,400 ppm) and less nickel (520–780 ppm) at the same Fo content than those from the basanites (Ca: 1,800–2,700 ppm; Ni: 1,090–1,940) (Figure 7). There is a large decrease in nickel with decreasing Fo content across the basanitic suite (1,940 ppm–285 ppm) (Figure 7). The Fe/Mn ratio is similar in both suites ranging from 55 to 81.

The limited published Mount Cameroon olivine data (Ngwa et al., 2020) extend to higher Fo contents and show similar Ti, Ca, Ni and Mn values (Figure 7). The observed increase in Ca and Mn with decreasing Fo content in olivines from the basanites is consistent with olivine fractionation. The low Ni content of olivine in the two nephelinite samples (Figure 7a) is due to a correspondingly low Ni content in the host rocks. Allowing for the Ni content of the small proportion of olivine phenocrysts, the olivine and bulk-rock Ni data imply $D^{ol/liq}$ of 13–15 in the basanites and nephelinites, values in line with those determined experimentally by Förster et al. (2018) in alkali-rich mafic liquids. Similarly, the high Ca content of the olivine phenocrysts in the nephelinites compared with those in the basanites (Figure 7c) reflects differences in their whole-rock Ca contents.

6. Discussion

6.1. Chronology

Our new Ar data (Table 1) clearly show that the Etinde mafic nephelinites predate the earliest Mount Cameroon basanites. The two Etinde olivine-nephelinite samples gave ages of 0.5152 ± 0.0073 and 0.572 ± 0.032 Ma, respectively, consistent with a single K-Ar isochron age of 0.65 ± 0.2 Ma from an Etinde nephelinite sample reported by Nkoumbou et al. (1995). The oldest Mount Cameroon basanite sample, collected from the deeply dissected terrain to the south–east of the volcanic edifice, is dated at 0.442 ± 0.014 Ma; the age of the other Mount Cameroon samples ranges from 0.230 ± 0.016 Ma to the present day. Three of the six compositionally and petrographically distinct basanite samples that were included with the nephelinite samples collected from Etinde have ages ranging from 0.113 ± 0.019 to 0.073 ± 0.011 Ma, within the age range of basanites from Mount Cameroon. These ages are markedly younger than the K-Ar ages reported by Wandji et al. (2009).

Figure 8 shows a schematic of the measured age relationship of the two volcanoes and the inferred differences in their respective magma plumbing systems. The lava flows of the older volcano Etinde range in composition from olivine-poor mafic nephelinite, through olivine-free intermediate nephelinite, to felsic nephelinite (Esch, 1901; Fitton, 1987; Nkoumbou et al., 1995; Ntoumbé et al., 2016; Figure 2), implying the operation of fractional crystallization in a large magma reservoir (Figure 8a). A sample of felsic nephelinite (C232) gave an age that overlapped with the onset of Mount Cameroon basanite magmatism (Figure 8b) and may represent the emptying

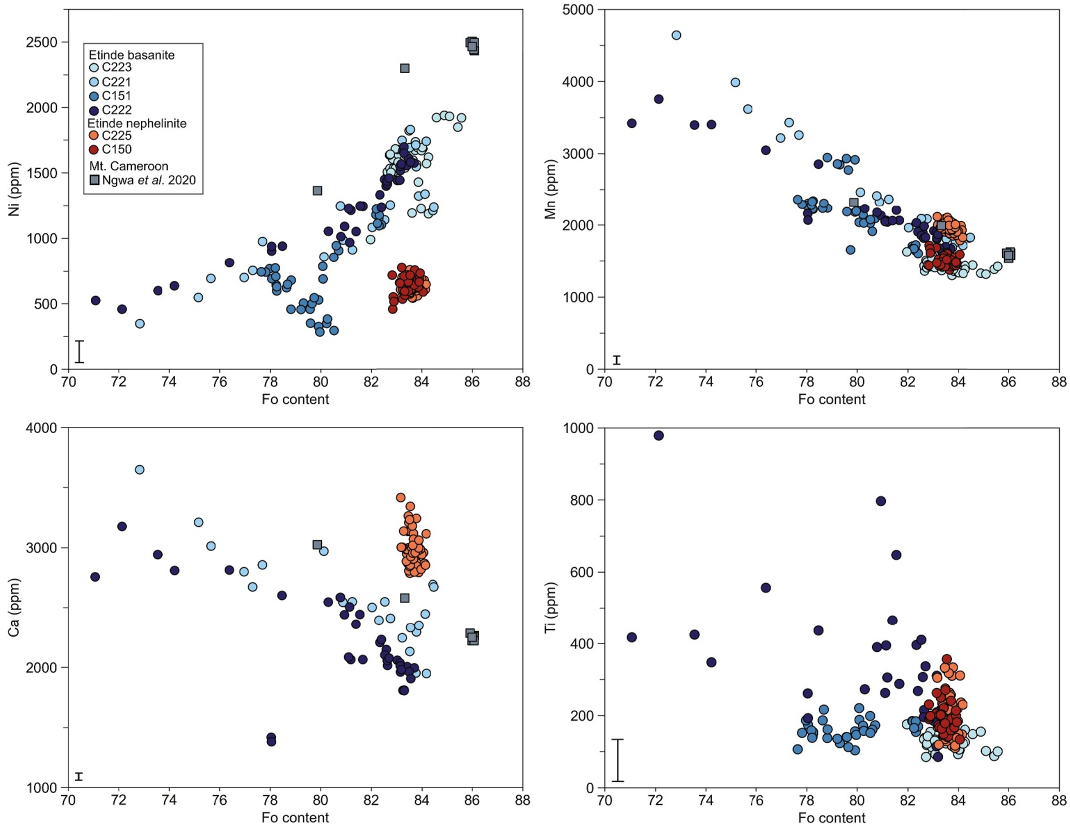

Figure 7. Ni, Mn, Ca and Ti content of olivine phenocrysts plotted against the molecular forsterite content of olivine phenocrysts in Etinde basanites (blue) and nephelinites (red/orange). Mount Cameroon data, included for comparison, are from Ngwa et al. (2020). The markedly lower Ni and higher Ca contents of the nephelinite olivine reflect differences in their respective host-rock Ni and Ca contents. The vertical bars show 2σ error, for Fo content 2σ error it is less than the size of the symbols.

of an evolved magma from the reservoir at a late stage in its evolution. The change in magma composition from nephelinite to basanite at ∼0.45 Ma was accompanied by an increase in magma production. Mount Cameroon lavas are entirely mafic and restricted in composition to basanite and trachybasalt, implying a higher magma-flux rate and storage in small, short-lived reservoirs (Figure 8c).

Our new chronology for Etinde and Mount Cameroon is based on the first Ar-Ar ages from these volcanoes and differs significantly from previous K-Ar ages (Aka et al., 2004; Fitton & Dunlop, 1985; Nkoumbou et al., 1995; Tsafack et al., 2009; Wandji et al., 2009). The oldest age we obtained for Mount Cameroon (0.44 Ma) is considerably younger than the 2.83 Ma K-Ar age obtained by Wandji et al. (2009). This raises the question of whether a volcano as large as Mount Cameroon could be built in <0.5 Myr. Suh et al. (2003) estimated the total volume of the volcano to be ∼1,200 km^3 and the total volume of lava erupted in the last century to be ∼10^8 m^3 or 10^6 m^3 per year. At this current rate, it would take 1.2 Myr to build Mount Cameroon to its present size, but a large proportion of the magma produced will be retained as intrusions within the volcanic edifice rather than erupted on the surface. Also, it is likely that the magma effusion rate will decline as the volcano grows (e.g., Roman & Jaupart, 2014). This being so, our conclusion that Mount Cameroon took <0.5 Myr to form is reasonable. If the 2.83 Ma K-Ar age obtained by Wandji et al. (2009) is correct, then the current eruption rate must be considerably higher than the average rate over the life of the volcano.

6.2. Petrology and the Evidence for a Carbonate Enriched Source

Olivine phenocrysts are present only in the most mafic (MgO ∼8 wt.%) Etinde nephelinites and are usually rounded and partly resorbed in contrast to basanites, which contain abundant euhedral olivine phenocrysts (Figure 3). The resorption of olivine phenocrysts by reaction with liquid during fractional crystallization of

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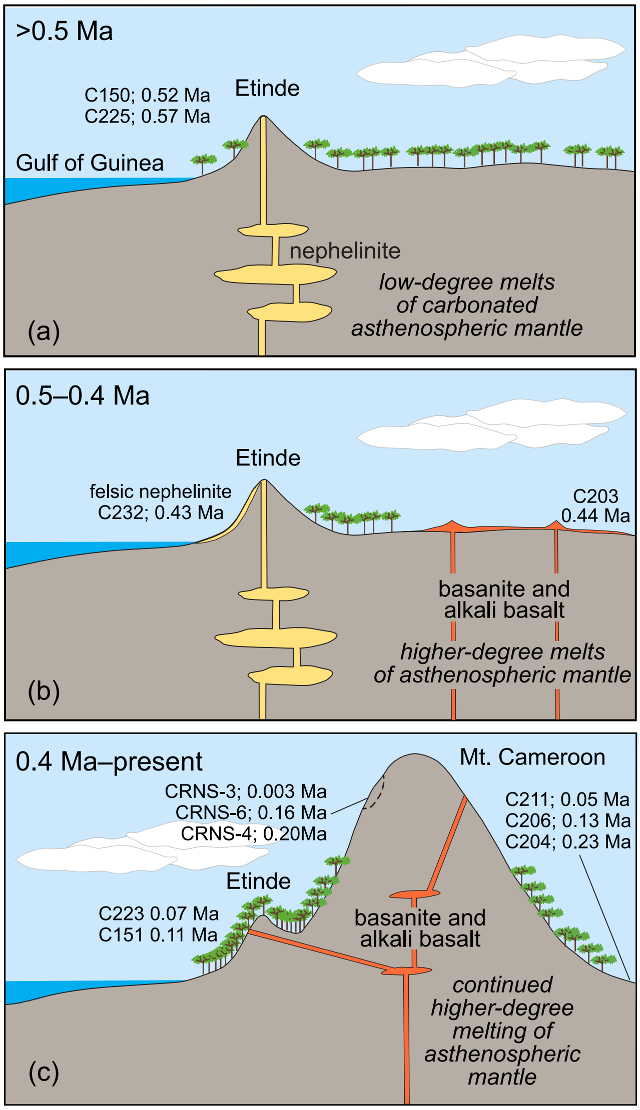

Figure 8. Schematic diagrams showing the development of the Etinde and Mount Cameroon volcanoes. Etinde is built of nephelinite lavas that erupted mostly before ~0.5 Ma (a), although a felsic nephelinite sample gave a younger age (b). A marked increase in magma production after ~0.45 Ma resulted in the eruption of basanite lavas that form the adjacent and much larger Mt. Cameroon (c). Some of the Mt. Cameroon basanite magma erupted on the flanks of Etinde. The Etinde and Mount Cameroon magmas share a common carbonated mantle source.

nephelinite magma is a common observation (Le Bas, 1987). This is most likely due to the effects of increasing CO_2 content in the evolving magma, which shifts the olivine-clinopyroxene cotectic toward olivine (Fraser, 2005; Le Bas, 1987), thereby causing olivine phenocrysts to dissolve and leaving clinopyroxene (titanaugite) as a phenocryst phase.

Olivine phenocrysts in the Etinde nephelinites have a higher CaO content (average 0.42 wt.%) than those in the basanites (0.33 wt.%; Figure 7), reflecting the higher CaO in the nephelinites (average 15.4 wt.%) compared with the basanites (11.7 wt.%). Figure 9 shows the clear distinction between the nephelinites and basanites on a plot of CaO/(CaO + MgO) against SiO_2. The most mafic (lowest SiO_2) nephelinites and basanites define a trend of decreasing CaO/(CaO + MgO) with increasing SiO_2, a trend parallel to that in liquids produced in 3 GPa melting experiments of carbonated peridotite (Dasgupta et al., 2007; Hirose, 1997). Both sets of experiments used the peridotite composition KLB-1 with 2.5 wt.% CO_2 added. In the Hirose (1997) experiments, CO_2 was added as 5 wt.% magnesite, whereas Dasgupta et al. (2007) added CO_2 as a mixture of carbonates with the same Ca:Mg:Fe:Na:K ratio as KLB-1. The two sets of experiments produced essentially identical results, with CaO/(CaO + MgO) falling and SiO_2 increasing with increasing degree of melting (Figure 9). A similar trend was reported by Foley et al. (2009) in melting experiments on phlogopite peridotite in the presence of CO_2 and H_2O. It is now well established that the presence of CO_2 increases silica-undersaturation in mantle melts and that magmas ranging in composition from melilitite through nephelinite to basanite can be produced by increasing degrees of melting of carbonated peridotite (see Yaxley et al., 2019 for a review).

The liquids produced by Hirose (1997) and Dasgupta et al. (2007) represent primary magma with 20–29 wt.% MgO, which accounts for the lower CaO/(CaO + MgO) in the melting trend compared with the least evolved nephelinites and basanites, which have around 8 wt.% MgO (Figure 4b). Fractional crystallization of olivine would raise CaO/(CaO + MgO) with only a small change in SiO_2 (Figure 9). The sub-horizontal trends in the nephelinite and basanite data are due to subsequent low-pressure fractional crystallization dominated by titanaugite. Figure 9 shows the composition of an Etinde ijolite xenolith (C234) composed of titanaugite zoned to aegirine-augite, magnetite, perovskite, nepheline, biotite and titanite, which probably represents the crystallizing assemblage (cumulate) driving fractional crystallization in the Etinde nephelinite magma suite.

6.3. Geochemistry and Melting of a Common (Carbonated) Mantle Source

Rock samples from Etinde and Mount Cameroon have similar primitive-mantle-normalized incompatible element patterns (Figure 5) and are isotopically indistinguishable (Halliday et al., 1990; Figure 6), suggesting that they share a common mantle source. The inverse correlation between CaO/(CaO + MgO) and SiO_2 in the least fractionated nephelinites and basanites (Figure 9) provides evidence that this source was carbonated peridotite, as proposed by Guimarães et al. (2020). We conclude that the Etinde and Mount Cameroon volcanoes were fed by magma generated by decompression of carbonated asthenospheric mantle that flowed outwards from beneath Africa and encountered thinner lithosphere at the continent-ocean boundary. High $\delta^{34}S$ in the intermediate and felsic nephelinites from Etinde suggest that some of the volatile-element enrichment in the mantle source was due to ancient subduction (Baldwin et al., 2025). The temporal progression from nephelinite (Etinde) to basanite (Mount Cameroon and Etinde) reflects increasing degrees of melting. This can be seen clearly on a plot of La/Yb (which falls with increasing degree of melting) against SiO_2 (an inverse indicator of carbonate involvement). The negative correlation

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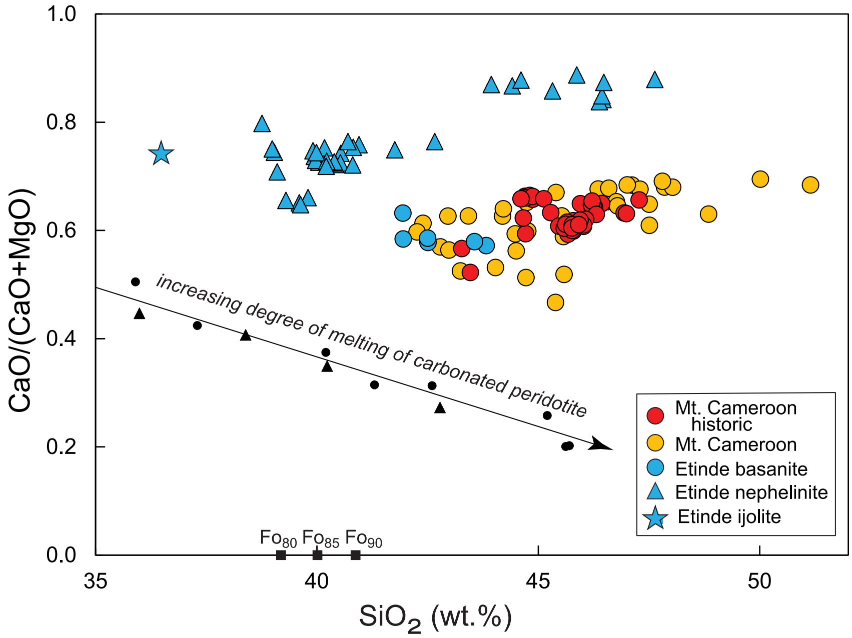

Figure 9. The nephelinites and basanites from Etinde and Mount Cameroon are separated clearly on a plot of CaO/(CaO + MgO) against SiO_2. The composition of liquids produced in 3 GPa melting experiments on carbonated peridotite are from Hirose (1997, black triangles) and Dasgupta et al. (2007, black circles). Black squares show the composition of olivine with 80, 85 and 90 mol.% forsterite. Note that the most primitive (lowest SiO_2) Etinde and Mount Cameroon samples define a parallel trend to that defined by the melts from carbonated peridotite (black arrow).

between La/Yb and silica content in mafic rocks from Etinde and Mount Cameroon (Figure 10) shows the effects of increasing melt fraction accompanied by falling carbonate fraction. The first, small-degree melts represented by the Etinde nephelinites are dominated by carbonate from the mantle source (high La/Yb, low silica). The later Mount Cameroon basanites, formed by more advanced melting (lower La/Yb), will contain a smaller proportion of carbonate (higher silica) because this was extracted from the mantle source to form the nephelinites.

6.4. Nephelinite to Basanite Transition

A transition from nephelinite to basanite is not an uncommon occurrence in intraplate magmatic provinces and is usually interpreted as being due to progressive melting of lithospheric peridotite containing amphibole-rich veins (e.g., Francis & Ludden, 1990; Pilet et al., 2008). A similar explanation has been proposed by Minissale et al. (2022) for the simultaneous eruption of melilite nephelinite and basanite magma at, respectively, the Nyiragongo and Nyamuragira volcanoes in the Virunga volcanic province in the western branch of the East African Rift. In each of these examples, the derivation of nephelinite and basanite magma from different lithospheric mantle lithologies is supported by differences in radiogenic-isotope ratios and incompatible-element patterns, but this is not the case with Etinde and Mount Cameroon (Figures 5 and 6). The striking similarity in composition of mafic lava flows in the oceanic and continental sectors of the CVL (Figures 2 and 6) shows that these must share a similar mantle source and therefore cannot have been produced by in situ melting of the lithospheric mantle (Fitton & Dunlop, 1985). Our new Ar dates for the Etinde and Mount Cameroon volcanoes, coupled with our petrographic and geochemical data, suggest that the earliest Etinde magmas sample an initial, low-degree partial melt of a carbonated source. Later, Mount Cameroon magmas, some of which are also erupted via Etinde, sample a higher degree of melting, which dilutes the enrichment in the source region. These new findings provide critical evidence that supports the Guimarães et al. (2020) model for the origin of magmatism in this intraplate setting, a model also applicable more broadly to other systems.

7. Conclusions

Etinde and Mount Cameroon are two volcanoes located on the African continental margin in the center of the CVL. New Ar-Ar age dates (Table 1) show that the mafic nephelinites that form most of Etinde predate the

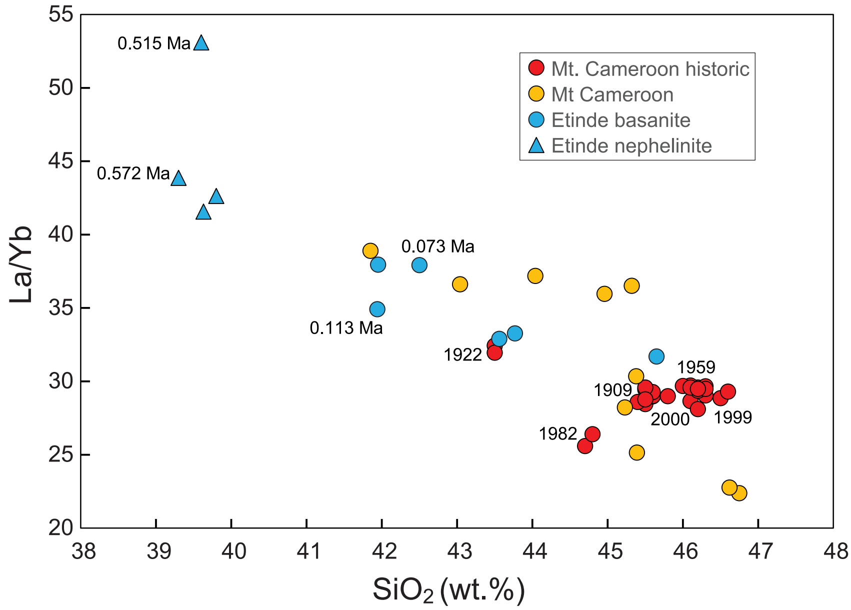

Figure 10. A plot of La/Yb against silica showing the temporal progression from Etinde nephelinite (low silica, high La/Yb) to Mount Cameroon basanite (higher silica, lower La/Yb) due to increasing degree of melting of a common, carbonate-enriched, mantle source. First, low-degree melts (Etinde) will be dominated by carbonate, while higher-degree melts (Mount Cameroon) will be less influenced by carbonate. Etinde data from Baldwin (2025a, 2025b); Mount Cameroon data from Yokoyama et al. (2007), Tsafack et al. (2009) and Wandji et al. (2009). The ages of our Etinde samples and the dates of historic eruptions of Mount Cameroon are indicated.

basanite lava flows of the adjacent and much larger Mount Cameroon, the only currently active volcano on the CVL. The transition from nephelinite-to basanite magmatism occurred at ~0.45 Ma. Incompatible element and radiogenic isotope data show that parental magmas feeding the two volcanoes share a common mantle source. Their respective mafic lava flows define a trend of decreasing CaO/(CaO + MgO) with increasing SiO_2 that can best be explained by progressive melting of a carbonated mantle source. Etinde nephelinite magmas were produced by an initial small-degree of partial melting, and this is reflected in the high concentration of incompatible elements in the erupted nephelinite lavas. The transition from Etinde nephelinite to Mount Cameroon basanite was accompanied by slightly lower concentrations of the more incompatible elements (Figures 5 and 10). Some of this later basanite magma erupted on the flanks of Etinde (Figure 8). The melt source most likely originated as a carbonate-enriched subcontinental lithospheric mantle that was converted to the asthenosphere following supercontinent assembly and then mobilized following continental breakup as proposed by Guimarães et al. (2020). The outward flow and channeling of the carbonated-enriched asthenosphere provides a plausible explanation for prolonged intraplate magmatism in the absence of mantle plumes.

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Data Availability Statement

All data used in this study are openly available via digital repositories. The data on which this study is based are available in Baldwin (2025a).

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