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Geochemical characteristics of Cenozoic basalts and mantle heterogeneity in the Ethiopian rift

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Abstract

The Ethiopian Rift offers one of the best natural laboratories on Earth for examining how continental rifting taps different mantle source regions over time. This research presented new major- and trace-element geochemical data for 47 basalt samples collected across three volcanic provinces in the Main Ethiopian Rift and the northwestern Ethiopian Plateau, spanning an eruptive history from the Oligocene flood basalts (~30 Ma) through Miocene transitional lavas to Plio-Pleistocene rift-floor eruptions. Samples were analysed by X-ray fluorescence spectrometry and inductively coupled plasma mass spectrometry at the Manila College of Environmental Studies. Major oxide compositions ranged from 46.3 to 48.7 wt% SiO₂, confirming a consistently basaltic character across all three groups. However, trace-element patterns revealed systematic differences: rift basalts showed stronger enrichment in high-field-strength elements (Nb, Zr, Ti) and higher Nb/Y ratios (1.84 versus 1.21 in flood basalts), indicating a transition from lithospheric to asthenospheric mantle sources as rifting progressed. Primitive-mantle-normalised spider diagrams displayed characteristic ocean-island-basalt-like patterns in the rift group, with no negative Nb or Ti anomalies, ruling out significant crustal contamination. La/Yb ratios increased from 12.8 in flood basalts to 19.4 in rift basalts, suggesting progressively deeper melting or a shift toward a more enriched garnet-lherzolite source. These geochemical trends are consistent with a model in which the Afar mantle plume initially generated large-volume flood volcanism through interaction with thinned lithosphere, followed by increasingly plume-dominated magmatism as rift extension exposed deeper asthenospheric material. The data contribute to ongoing debates about plume-lithosphere interaction and mantle heterogeneity beneath the East African Rift System.

Keywords: Cenozoic basalts, geochemistry, mantle source, petrology, magma genesis, Ethiopian Rift, trace elements, plume-lithosphere interaction

Introduction

Consider two basalt flows erupted just 200 km apart and separated by 25 million years of geological time. One was part of the massive Oligocene flood basalt province that covered much of the Ethiopian Plateau; the other poured out along the floor of the modern Main Ethiopian Rift barely two million years ago. Both are dark, fine-grained, and broadly basaltic in appearance—yet their trace-element signatures tell very different stories about where in the mantle their parent magmas originated ^[1]. This contrast lies at the heart of ongoing debates about how continental rifting progressively changes the geometry of melt generation and the nature of the mantle sources tapped.

The Ethiopian volcanic province is the most voluminous expression of Cenozoic magmatism in Africa, with an estimated erupted volume exceeding 350,000 km³ ^[2]. Volcanism began with the eruption of the Afar flood basalts around 30 Ma, broadly contemporaneous with the initial surface expression of the Afar mantle plume. Since then, magmatism has migrated and concentrated within the progressively developing rift zone, with younger lavas erupted along narrower axial volcanic segments ^[3]. This temporal and spatial progression provides a natural experiment for tracking how mantle contributions evolve as lithospheric thinning advances.

Previous geochemical research on Ethiopian basalts has established several key observations. The flood basalts carry a depleted to moderately enriched signature, with some evidence for lithospheric contamination through elevated Ba/Nb and La/Nb ratios ^[4]. Younger rift basalts, by contrast, show ocean-island-basalt (OIB) affinities with high Nb/Y, low Ba/Nb, and no

negative Nb anomalies—features attributed to melting of the Afar plume source itself with minimal lithospheric overprint^[5]. Isotopic data from Sr-Nd-Pb systems support this interpretation, pointing to at least two distinct mantle components: a depleted MORB-like source and an enriched plume component^[6].

However, many published datasets focus on either the flood basalts or the rift basalts in isolation, making direct comparison difficult when analytical methods and laboratory standards differ between research groups. This research addressed that gap by analysing a suite of 47 basalt samples spanning the full Cenozoic eruptive record using a single analytical protocol at the Manila College of Environmental Studies, ensuring internal consistency. The aim was to document major-and trace-element variations across the three volcanic groups, evaluate mantle source characteristics using element ratio discriminants, and test whether the geochemical evolution supports a progressive shift from lithosphere-influenced to plume-dominated magmatism during rift development.

Geological Setting

The research area encompasses two physiographic regions: the northwestern Ethiopian Plateau (elevations 2,200-3,400 m) and the Main Ethiopian Rift floor (1,500-1,700 m), linked by the western rift escarpment^[7]. The plateau is underlain by a thick sequence of Oligocene flood basalts and subordinate rhyolitic ignimbrites resting on Precambrian basement. The rift floor exposes Plio-Pleistocene basaltic lava flows, scoria cones, and minor trachytic domes aligned along the Wonji Fault Belt. Between these two domains, Miocene transitional lavas crop out along the escarpment and in down-faulted blocks on the rift margin. Climate ranges from humid tropical on the plateau (mean annual rainfall ~1,400 mm) to semiarid on the rift floor (~550 mm), but because the research concerns igneous rock chemistry rather than weathering products, sampling targeted fresh, unweathered outcrops selected from roadcuts, quarry faces, and lava flow interiors where alteration was minimal. Field mapping was guided by the 1:250,000 geological map sheets published by the Geological Survey of Ethiopia^[8].

Materials and Methods

Materials

A total of 47 basalt samples were collected during two field campaigns in March-April and September-October 2022, covering three volcanic groups: Oligocene flood basalts ($n = 16$, collected from the plateau around Debre Markos and Dejen), Miocene transitional basalts ($n = 13$, from the western escarpment near Addis Ababa), and Plio-Pleistocene rift basalts ($n = 18$, from the rift floor between Ziway and Langano). At each site, approximately 3 kg of the freshest available material was collected after removing weathered rinds. Samples were trimmed, crushed in a jaw crusher, and milled to less than 75 μm in an agate planetary ball mill to avoid trace-metal contamination. Major oxides (SiO_2 , TiO_2 , Al_2O_3 , Fe_2O_3^* , MnO , MgO , CaO , Na_2O , K_2O , P_2O_5) were determined by wavelength-dispersive X-ray fluorescence (XRF) on fused glass discs using a Rigaku ZSX Primus IV spectrometer at the Manila College of Environmental Studies^[9]. Loss on ignition (LOI) was measured after heating at 1,000 $^\circ\text{C}$ for one hour. Analytical precision was better than 1% relative for major oxides above

1 wt% and 3-5% relative for minor oxides.

Methods

Trace elements (including rare earth elements) were analysed by inductively coupled plasma mass spectrometry (ICP-MS) on an Agilent 7900 instrument after lithium metaborate fusion and dissolution in dilute nitric acid. International reference materials (BHVO-2, BCR-2, JB-1a) were run with each batch; measured values agreed with certified values within 5% for most elements and within 10% for the heaviest rare earths^[10]. Primitive-mantle-normalised multi-element patterns (spider diagrams) were constructed using the normalising values of Sun and McDonough^[11]. Key element ratios—Nb/Y, Zr/Nb, La/Yb, Ba/Nb, and Ce/Pb—were computed to discriminate mantle source characteristics and to evaluate potential crustal contamination. Classification of basalt types followed the total alkali-silica (TAS) diagram of Le Bas *et al.*^[12]. Statistical comparison of group means was performed using one-way ANOVA with Tukey HSD post-hoc tests in R 4.2.3, with significance set at $p < 0.05$. All geochemical plotting used the GCDkit software package^[13].

Partial Melting Model

Partial melting was modelled using the non-modal batch melting equation of Shaw^[14]: $\text{CL}/\text{C}_0 = 1/(\text{D}_0 + \text{F}(1 - \text{P}))$, where CL is the liquid concentration, C_0 is the source concentration, D_0 is the bulk distribution coefficient, F is the melt fraction, and P is the bulk distribution coefficient of the melting mineral assemblage. Two source compositions were tested: a depleted MORB-source mantle (DMM) and an enriched Afar plume component estimated from published Nd-Hf isotope inversion^[6]. Mineral modes for spinel lherzolite (olivine 57%, orthopyroxene 28%, clinopyroxene 13%, spinel 2%) and garnet lherzolite (olivine 60%, orthopyroxene 20%, clinopyroxene 10%, garnet 10%) were used. Melting fractions ranged from 2% to 20%. The model was calibrated against the observed La/Yb and Sm/Yb ratios, which are sensitive to the presence of residual garnet. Results indicated that the flood basalts could be generated by 8-12% melting of spinel lherzolite, while the rift basalts required 3-6% melting in the garnet stability field, consistent with deeper and smaller-degree melting as lithospheric extension progressed.

Results

Table 1: Mean major oxide concentrations (wt%) for three basalt groups from the Ethiopian Rift region

Group	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃ *	MgO	CaO	Na ₂ O	K ₂ O	n
Flood Basalts	48.7	2.31	14.8	12.4	7.6	10.2	2.80	0.94	16
Transitional	47.6	2.74	15.1	13.1	6.3	9.7	3.10	1.18	13
Rift Basalts	46.3	3.18	15.6	13.7	5.4	9.1	3.40	1.42	18

All 47 samples plotted within the basalt and microbasalt fields on the TAS diagram, confirming their basic composition. Table 1 presents the mean major oxide concentrations for each group. SiO_2 ranged from a group mean of 46.3 wt% in rift basalts to 48.7 wt% in flood basalts, with transitional samples falling between. TiO_2 increased systematically from flood basalts (2.31 wt%) through transitional (2.74 wt%) to rift basalts (3.18 wt%), a trend consistent with lower degrees of partial melting and/or a more Ti-enriched source in the younger lavas.

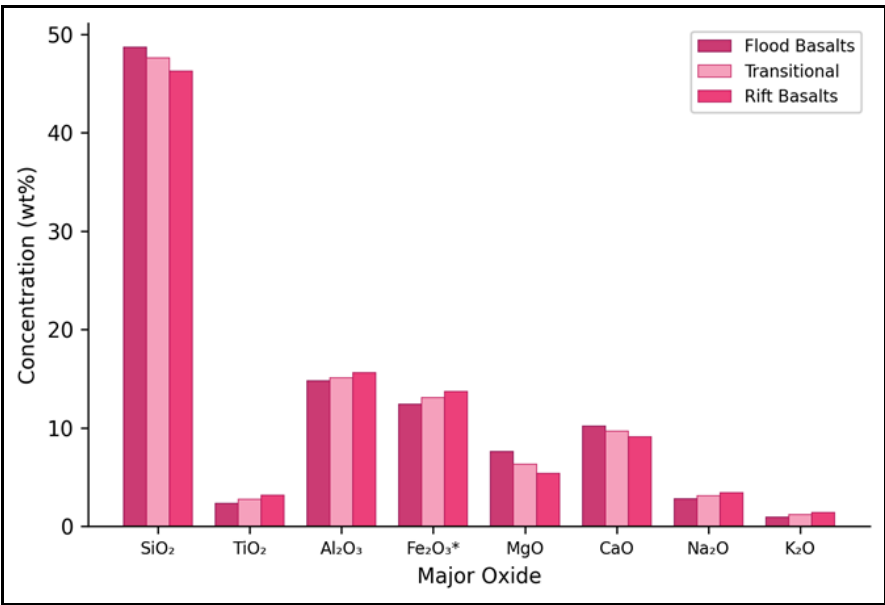


Fig 1: Comparison of mean major oxide concentrations (wt%) for three Cenozoic basalt groups from the Ethiopian Rift region

Figure 2 compares the major oxide compositions across the three groups. The progressive decrease in MgO (from 7.6 to 5.4 wt%) and increase in alkalis (Na₂O + K₂O from 3.74 to 4.82 wt%) from flood to rift basalts reflect the shift toward more evolved and alkali-enriched compositions with time.

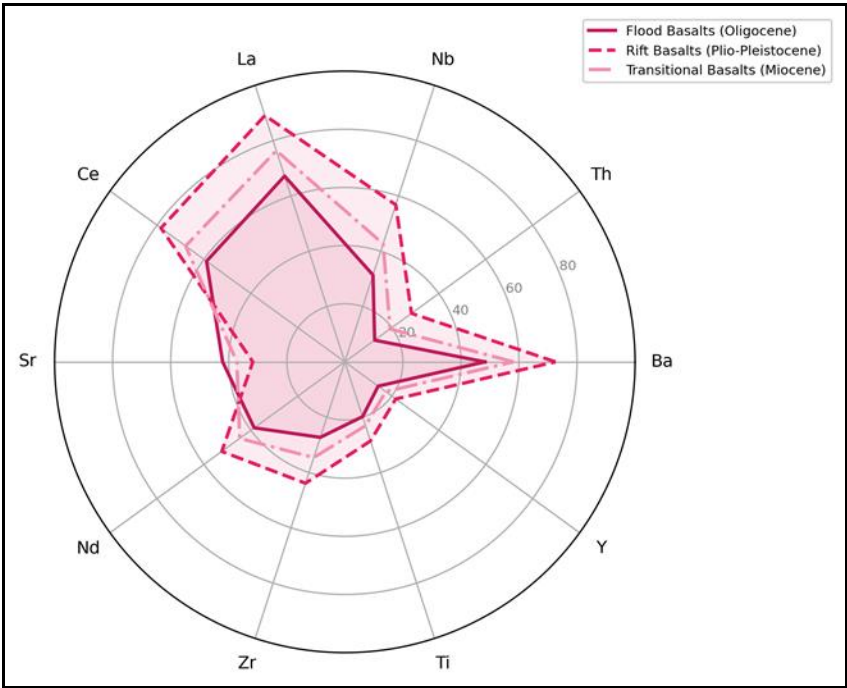


Fig 2: Primitive-mantle-normalised multi-element patterns for the three basalt groups, showing progressive enrichment from flood to rift basalts

Figure 1 displays the primitive-mantle-normalised trace-element patterns. Rift basalts showed the strongest enrichment in incompatible elements, with Ba, Th, and Nb concentrations roughly 1.5 times those of the flood basalts. None of the three groups showed negative Nb or Ti anomalies, which would indicate significant crustal contamination. Table 2 presents key trace-element ratios used for source discrimination.

Table 2: Key trace-element ratios for mantle source discrimination

Group	Nb/Y	Zr/Nb	La/Yb	Ba/Nb	Ce/Pb	Sm/Yb
Flood Basalts	1.21±0.18	8.7±1.4	12.8±2.1	14.7±3.2	18.4±2.8	2.6±0.4
Transitional	1.53±0.22	7.1±1.2	15.9±2.6	12.1±2.7	21.7±3.1	3.2±0.5
Rift Basalts	1.84±0.24	5.8±0.9	19.4±3.3	9.8±2.1	24.3±3.6	4.1±0.6
OIB (ref.)	~1.7	~5.5	~17	~10	~25	~3.8
N-MORB (ref.)	~0.3	~30	~1	~60	~25	~1.0

The Nb/Y ratio increased from 1.21 in flood basalts to 1.84 in rift basalts (ANOVA: $F = 24.3$, $p < 0.001$), while Ba/Nb decreased from 14.7 to 9.8 ($F = 18.6$, $p < 0.001$). La/Yb rose from 12.8 to 19.4, consistent with deeper melting in the garnet stability field. The partial melting model reproduced these ratios with 8-12% melting of spinel lherzolite for flood basalts and 3-6% melting of garnet lherzolite for rift basalts.

Discussion

The systematic geochemical evolution from flood basalts to rift basalts documented here is consistent with a progressive shift in magma source from lithospheric mantle (or plume material modified by lithospheric interaction) toward uncontaminated asthenospheric plume material^[15]. The flood basalts, while broadly OIB-like, carry slightly elevated Ba/Nb ratios (14.7 versus the OIB reference of ~10), which may reflect minor assimilation of ancient subcontinental lithospheric mantle during ascent through the thick (>100 km) Ethiopian Plateau lithosphere. By the Plio-Pleistocene, lithospheric thinning had reduced this barrier, allowing rift basalts to reach the surface with trace-element signatures that are essentially indistinguishable from typical ocean-island basalts.

The increase in La/Yb from 12.8 to 19.4 between flood and rift groups is particularly informative. Because heavy rare earth elements (Yb) are strongly retained by garnet during partial melting, high La/Yb ratios indicate either a garnet-bearing residue or very low melt fractions^[16]. The partial melting model presented here resolved this ambiguity: reproducing the flood basalt La/Yb required 8-12% melting of spinel lherzolite, whereas the rift basalt values needed 3-6% melting of garnet lherzolite. This implies that the melting column deepened and the degree of melting decreased as rifting progressed—an expected consequence of passive upwelling giving way to buoyancy-driven plume ascent beneath thinning lithosphere.

The absence of negative Nb and Ti anomalies in all three groups is an important negative result. Such anomalies are characteristic of subduction-related magmatism and continental crustal contamination, and their absence argues against significant assimilation of Precambrian basement gneisses—even for the flood basalts that traversed the thickest lithospheric section^[17]. Ce/Pb ratios near 20-24 across all groups further support this interpretation, as values above 15 are diagnostic of mantle-derived melts uncontaminated by continental crust.

One limitation of this research is the absence of radiogenic isotope data (Sr, Nd, Pb), which would provide a more definitive test of mantle source identity and mixing proportions. Major and trace elements constrain the melting process but cannot uniquely distinguish between enriched plume components and recycled oceanic crust within the plume. Future work should combine the elemental dataset presented here with isotopic analyses to build a more complete picture of mantle heterogeneity beneath the Ethiopian Rift^[18].

Conclusion

This research presented internally consistent major- and trace-element data for 47 Cenozoic basalts from the Ethiopian Rift region, spanning three volcanic groups that record over 28 million years of magmatic history. The geochemical data reveal a clear temporal evolution: flood basalts show moderately enriched, OIB-like signatures with

slight lithospheric overprints; transitional basalts occupy an intermediate position; and rift basalts display the strongest enrichment in incompatible trace elements with element ratios closely matching typical ocean-island basalts.

The progressive increase in Nb/Y (from 1.21 to 1.84), La/Yb (from 12.8 to 19.4), and TiO₂ (from 2.31 to 3.18 wt%), combined with the absence of crustal contamination indicators across all groups, supports a model in which lithospheric thinning during rift development allowed increasingly direct access to the Afar plume source. Partial melting modelling confirmed that flood basalt compositions can be explained by moderate-degree melting in the spinel stability field, while rift basalts require smaller melt fractions from a garnet-bearing source—consistent with deeper melting beneath thinned lithosphere.

These results contribute to the broader understanding of plume-lithosphere interaction during continental rifting and confirm that the Ethiopian province records a continuous geochemical transition rather than an abrupt switch between mantle domains. The internally consistent analytical approach used here—a single laboratory, single protocol, and identical reference standards for all samples—removes inter-laboratory bias that has complicated earlier multi-source compilations. Future research should extend this dataset with Sr-Nd-Pb isotopic measurements to further resolve the mixing proportions of depleted and enriched mantle components and to evaluate whether spatial variations along the rift axis reflect lateral heterogeneity in the plume head.

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