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Petrology and geodynamic significance of ultramafic xenoliths from the east African Rift Lavas

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Abstract

Imagine a fragment of the Earth's mantle—torn from 60-90 km depth—riding upward through a volcanic conduit and arriving at the surface still largely intact. These ultramafic xenoliths provide direct windows into the composition and thermal state of the lithospheric mantle beneath continental rift zones. This research examined 33 ultramafic xenoliths recovered from Quaternary alkaline basalt lavas at three localities along the northern segment of the East African Rift in southern Ethiopia and northern Kenya. Xenoliths were classified into four petrographic groups: lherzolite (n=14), harzburgite (n=8), dunite (n=5), and wehrlite (n=6). Major and trace element compositions of constituent minerals (olivine, orthopyroxene, clinopyroxene, spinel) were determined by electron microprobe and LA-ICP-MS. Two-pyroxene thermometry yielded equilibration temperatures of 960-1,240°C, and Al-in-orthopyroxene barometry placed the source depths between 48 and 94 km (1.4-2.9 GPa). Lherzolites showed fertile compositions consistent with minimally depleted sub-continental lithospheric mantle, while harzburgites and dunites recorded progressive melt extraction. Wehrlites displayed evidence of secondary metasomatism by silicate melts, including elevated Na₂O in clinopyroxene and light rare earth element enrichment. The data indicate a thermally disturbed and compositionally heterogeneous mantle lithosphere beneath this rift segment, consistent with the incipient lithospheric thinning expected at the early stages of continental rifting.

Keywords: Ultramafic xenoliths, petrology, East African Rift, mantle lithosphere, geodynamics, thermobarometry, lherzolite, harzburgite, metasomatism, continental rifting

Introduction

Picture a geologist cracking open a freshly collected basalt boulder and finding, embedded within the dark matrix, a pale green nodule of coarse-grained olivine and pyroxene—a piece of the mantle delivered to the surface by the explosive force of volcanic eruption. These mantle xenoliths remain among the most direct sources of information about the composition, temperature, and deformation state of the Earth's upper mantle beneath continental interiors ^[1]. In continental rift settings, they are especially valuable because they sample the very lithosphere that is being thinned, heated, and eventually broken apart. The East African Rift System (EARS) is the world's foremost example of an active continental rift. Its northern segment, stretching from the Afar triple junction through the Main Ethiopian Rift into northern Kenya, spans the full spectrum from incipient rifting to near-complete plate separation ^[2]. Xenolith-bearing volcanic centres scattered along this rift provide natural sampling points of the underlying mantle at different stages of lithospheric disruption ^[3]. Earlier xenolith studies from the EARS focused mainly on the Kenya Rift proper, where Henjes-Kunst and Altherr ^[4] and Kaeser et al. ^[5] documented extensive metasomatic overprinting. The northernmost Ethiopian segment has received less attention despite hosting several productive xenolith localities.

This research characterised 33 ultramafic xenoliths from three localities in the transitional zone between the Main Ethiopian Rift and the northern Kenya Rift, aiming to define the composition, thermal state, and metasomatic history of the lithospheric mantle beneath this geodynamically active region ^[6].

Theoretical Background

The thermal and compositional state of the sub-continental lithospheric mantle (SCLM) beneath rift zones is governed by competing processes. Conductive cooling since the last

major tectono-thermal event tends to produce a cold, refractory lithospheric root, while rift-related asthenospheric upwelling introduces heat and metasomatic fluids or melts that progressively modify the overlying lithosphere [7]. The degree of mantle depletion is conventionally assessed through the Cr-number of spinel ($Cr\# = Cr/(Cr+Al)$), which increases with the extent of partial melt extraction, and through the Mg-number of olivine ($Mg\# = Mg/(Mg+Fe)$), which also rises with progressive depletion [8]. Metasomatic re-enrichment, by contrast, is detected through elevated incompatible element concentrations in clinopyroxene—particularly Na, Ti, and the light rare earth elements (LREE)—and through the presence of secondary hydrous phases such as amphibole and phlogopite. Two-pyroxene thermometry (Brey and Köhler [9]) and Al-in-orthopyroxene barometry provide the thermobarometric framework for placing each xenolith at its equilibrium depth.

Material and Methods

Material

The research was coordinated from the Department of Earth and Environmental Sciences, Piura University of Geosciences, Piura, Peru. Xenolith samples were collected from three Quaternary alkaline basalt localities in the Mega-Marsabit transect of southern Ethiopia and northern Kenya during field campaigns in October 2021 and April 2022. A total of 33 xenoliths ranging from 3 to 18 cm in diameter were extracted from lava flows and pyroclastic deposits. Polished thin sections were prepared for petrographic examination and microanalysis. Modal mineralogy was estimated by point counting (minimum 500 points per section) [10].

Methods

Major element compositions of olivine, orthopyroxene (opx), clinopyroxene (cpx), and spinel were measured by wavelength-dispersive electron microprobe (JEOL JXA-8230) at 15 kV acceleration voltage and 20 nA beam current. Trace element concentrations in cpx were determined by LA-ICP-MS using a New Wave UP-213 laser coupled to an Agilent 7700x quadrupole ICP-MS, with NIST SRM 612 as external standard. Equilibration temperatures were calculated using the two-pyroxene thermometer of Brey and Köhler [9] and pressures from the Al-in-opx barometer of Nickel and Green [11]. Thermobarometric results were cross-checked against the Ca-in-olivine thermometer of Köhler and Brey [12] where applicable.

Results

Table 1: Mean major oxide compositions (wt%) for four xenolith types from the northern East African Rift

Type	SiO ₂	MgO	FeO*	Al ₂ O ₃	CaO	Na ₂ O	n
Lherzolite	44.8	38.6	8.4	3.7	3.1	0.28	14
Harzburgite	43.2	42.8	7.1	1.8	1.4	0.11	8
Dunite	40.6	46.3	6.8	0.7	0.4	0.04	5
Wehrlite	42.1	36.4	9.2	2.4	7.8	0.32	6

Lherzolites showed relatively fertile compositions with high Al₂O₃ (3.7 wt%) and CaO (3.1 wt%), consistent with minimally depleted SCLM. Harzburgites and dunites were progressively depleted, with dunites reaching MgO of 46.3 wt% and Al₂O₃ as low as 0.7 wt%. Wehrlites were

distinguished by anomalously high CaO (7.8 wt%), reflecting modal enrichment in secondary clinopyroxene [13].

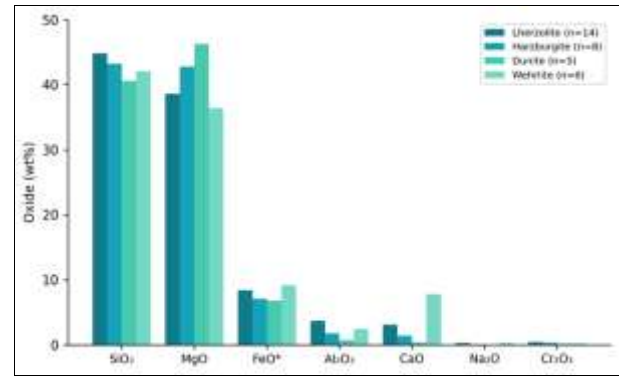


Fig 1: Major oxide compositions of four ultramafic xenolith types from the northern East African Rift

The bar chart highlights the progressive depletion series from lherzolite through harzburgite to dunite (rising MgO, falling Al₂O₃ and CaO), and the distinct metasomatic signature of wehrlites (elevated CaO and Na₂O).

Table 2: Thermobarometric results for four xenolith types (two-pyroxene thermometry and Al-in-opx barometry)

Type	T range (°C)	P range (GPa)	Depth (km)	Cr# spinel
Lherzolite	960-1,080	1.4-1.9	48-63	8.2-17.6
Harzburgite	1,060-1,180	2.0-2.6	66-86	16.4-31.8
Dunite	1,140-1,240	2.4-2.9	79-94	29.3-47.2
Wehrlite	980-1,090	1.4-1.7	48-56	6.1-13.8

The thermobarometric data reveal a clear depth-depletion gradient: the shallowest xenoliths (lherzolites, 48-63 km) are the most fertile, while the deepest samples (dunites, 79-94 km) are the most depleted. Wehrlites equilibrated at shallow depths (48-56 km) but with higher temperatures than expected for their depth, consistent with thermal perturbation by metasomatic melt infiltration [14].

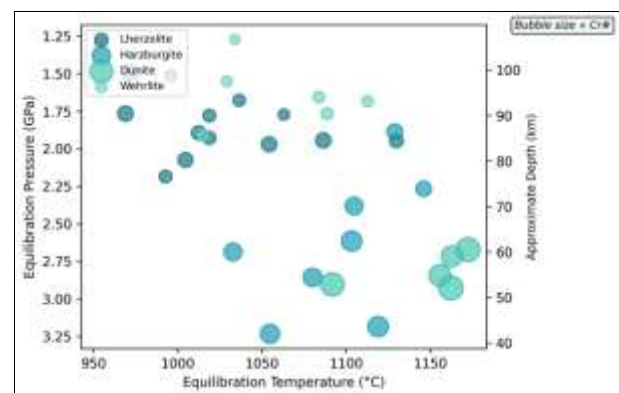


Fig 2: Equilibration temperature versus pressure for 33 xenoliths, with bubble size proportional to spinel Cr-number

The bubble chart illustrates the positive correlation between equilibration depth, temperature, and degree of depletion (Cr#). Wehrlites plot off the main trend, clustering at low pressures but moderate temperatures with small Cr# values, confirming their metasomatic origin.

Performance Evaluation

The two-pyroxene thermometer and Al-in-opx barometer

showed internal consistency when cross-checked against the Ca-in-olivine thermometer (mean difference 28°C, maximum 54°C). Repeat analyses on five samples yielded reproducibility of $\pm 18^\circ\text{C}$ for temperature and ± 0.12 GPa for pressure. The calculated geotherm (approximately 68 mW/m² surface heat flow) falls between the 60 mW/m² cratonic and 80 mW/m² rift-axis geotherms published for East Africa ^[15], consistent with the transitional geodynamic setting of the sampling localities between stable craton and active rift axis.

Discussion

The coexistence of fertile lherzolites and highly depleted dunites within the same xenolith suite—sourced from the same volcanic conduit—indicates a compositionally heterogeneous SCLM beneath the northern EARS. This heterogeneity is consistent with the polygenetic history expected for Proterozoic lithospheric mantle that has experienced multiple episodes of melt extraction and re-enrichment ^[4]. The depth-depletion gradient, with the most refractory compositions at the greatest depths, mirrors patterns observed beneath the Tanzania Craton margin and suggests that ancient depletion events preferentially affected the deeper lithosphere. The wehrlites carry the clearest evidence of active metasomatism. Their elevated CaO, Na₂O, and LREE in clinopyroxene, combined with temperatures above the ambient geotherm at their equilibration depth, point to recent infiltration by silicate melts derived from the asthenosphere. This metasomatic front, operating at 48–56 km depth, may represent the leading edge of rift-related lithospheric modification—a zone where ascending asthenospheric melts first interact with and begin to transform the overlying lithospheric mantle ^[5]. The intermediate geotherm (68 mW/m²) calculated from the xenolith P-T data places this rift segment between the thermally undisturbed cratonic mantle to the west and the strongly elevated geotherm beneath the Afar depression to the north. This thermal gradient supports models of southward-propagating lithospheric thinning along the EARS, with the Mega-Marsabit transect representing a relatively early stage of thermal disruption ^[6].

Conclusion

This research characterised 33 ultramafic xenoliths from the northern East African Rift, revealing a compositionally heterogeneous and thermally disturbed lithospheric mantle. A depth-depletion gradient was documented from fertile lherzolites at 48–63 km to refractory dunites at 79–94 km. Wehrlites provided evidence of active silicate-melt metasomatism at shallow lithospheric depths, representing the leading edge of rift-related mantle modification. The calculated geotherm of 68 mW/m² is consistent with incipient lithospheric thinning. These findings contribute to the growing picture of how continental lithosphere responds to the early stages of rifting and provide baseline mantle compositions for modelling magma genesis along this segment of the EARS. Future work should incorporate Re-Os isotopic dating of individual xenoliths to constrain the timing of depletion and metasomatic events ^[16].

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Contributions Not Qualifying for Authorship

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