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Magmatic expressions of the Mesoproterozoic Midcontinent Rift and consequences for sampling diamonds – ultramafic lamprophyres from the Superior craton

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Introduction

The 1.1 Ga Midcontinent Rift is one of the best-preserved examples of a failed rift system. It left behind a 3000 km long belt of volcanic and sedimentary rocks with upwards of 2,000,000 km^3 of volcanic rocks, associated with the Keweenawan Large Igneous Province (Elling et al. 2020). Magmatic activity within the rift occurred over a period of ≥ 30 million years, causing a major tectonothermal imprint on the subcontinental lithospheric mantle beneath the southern Superior craton (Grütter 2009; Smit et al. 2014; Stachel et al. 2018). Whether the Midcontinent Rift formed passively, through extensional processes, or actively, through the arrival of the Keweenawan plume, remains contentious (Nicholson and Shirey 1990; Rooney et al. 2022; Brzozowski et al. 2023). The southern Superior craton is host to Mesoproterozoic ultramafic lamprophyres (UMLs) which erupted during the incipient stages of rift development. These early erupting rocks provide essential information on the source and initiation of rift activity. In this study, we present the first U-Pb perovskite geochronology of several UML bodies, along with whole-rock and mineral chemistry, tracer isotopes and detailed petrography to determine the timing and duration of emplacement, mantle source characteristics, and petrogenetic history relative to the evolution of the Midcontinent Rift. We also use the mineral chemical data to better characterise the phase chemistry of UMLs in general.

Petrography and Mineralogy

Thirty-seven UML samples were collected by Canabrava Diamond Corp. from outcrop and ice-rafted boulders along the Kapuskasing structural zone – a 500 km long east-verging thrust fault which exposes a 20 km cross-section of the crust, uplifted at about 1.9 Ga (Percival et al. 2012). Twenty of the freshest UML samples were selected for further analysis. They all have broadly similar mineralogy, classifying as aillikites, with olivine and phlogopite phenocrysts set in a groundmass of clinopyroxene, apatite, phlogopite, spinel, perovskite, and carbonate. Spinel is abundant throughout the samples, classifying as chromite, magnetite, and magnesian Ti-magnetite. Spinel compositions are distinctly less enriched in Mg than spinel in kimberlites, but zoning trends broadly overlap and extend the global UML data (Figure 1a). Phlogopites are Fe- and Ti-rich and Ba-poor (<3.5 wt.% BaO) in comparison to phlogopite in kimberlite (Figure 1b). Clinopyroxene compositions classify as Fe-rich diopside, with a minor to moderate esseneite ($CaFe^{3+}AlSiO_6$) component, consistent with clinopyroxene in global UMLs. Olivine displays a large range in grain size and shape, with molar 100Mg/(Mg+Fe) ranging from 78-94, overlapping with olivine in global UML, kimberlite, carbonate-rich olivine lamproite, and olivine lamproite.

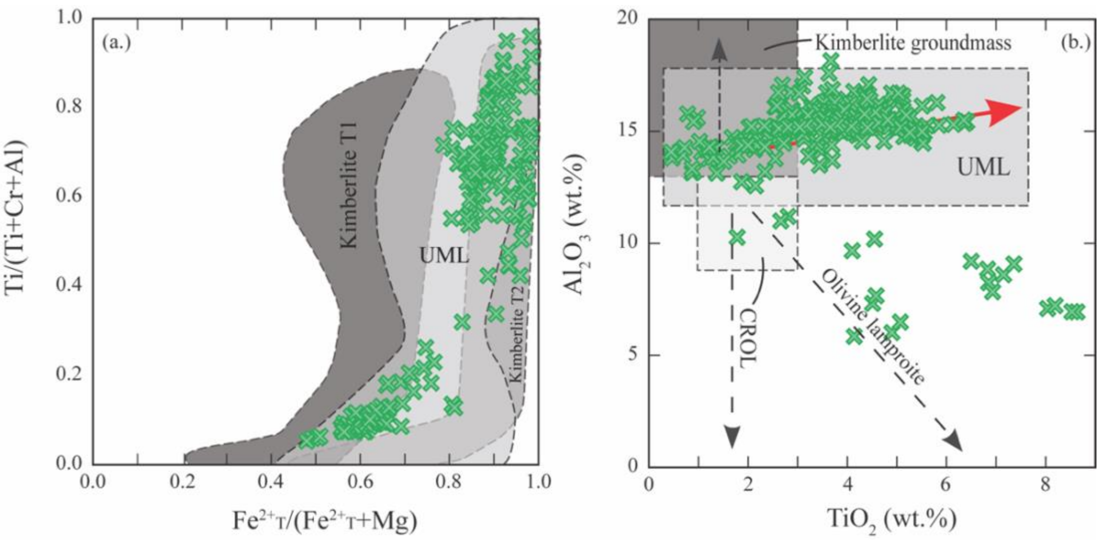

Figure 1: (a.) Reduced spinel bivariate plot of Ti/(Ti+Cr+Al) versus $Fe^{2+}_{tot}/(Fe^{2+}_{tot}+Mg)$ for Kapuskasing UMLs (green), with fields for global kimberlite spinel Trend 1 and Trend 2, and global UML data after (Kjarsgaard et al. 2022). (b.) Bivariate plot of Al_2O_3 (wt.%) versus TiO_2 (wt.%) for phlogopite from the Kapuskasing UMLs (green). Fields and compositional trends of global kimberlite, UML, carbonate-rich olivine lamproite (CROL), and olivine lamproite are shown. Modified after (Kjarsgaard et al. 2022).

Results and Discussion

Similar to global UML, whole-rock compositions of the Kapuskasing UMLs are characterised by high TiO_2 (2-7 wt.%), CaO (5-20 wt.%), and $Fe_2O_3^{total}$ (11-24 wt.%), and low MgO (10-33 wt.%), in comparison to global kimberlites. Compositional trends suggest variable interplay between primary magmatic fractionation/accumulation and crustal contamination. Primitive mantle normalized incompatible element diagrams and key inter-element ratios (La/Nb, Ba/Nb, Th/Nb, and Ce/Pb) are characteristic of global UMLs, and their overlap with kimberlites and ocean island basalts suggest broadly similar convecting mantle sources.

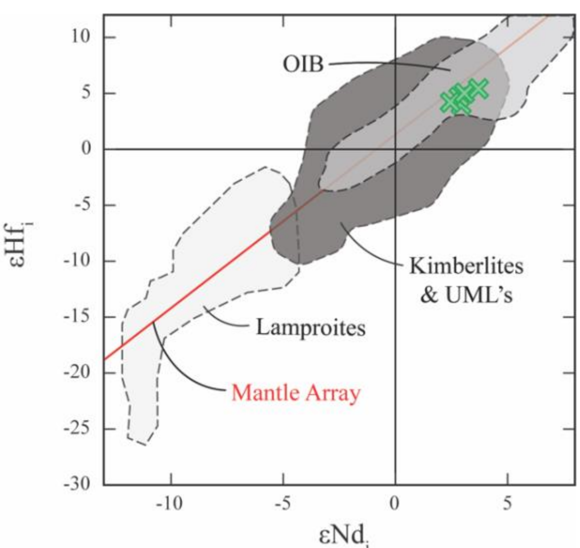

Figure 2: εHf_i versus εNd_i of Kapuskasing UMLs (green) with fields for global kimberlites and UMLs, lamproites, and ocean island basalt (OIB) (after Pearson et al. 2019). Nd-Hf mantle array is taken from Vervoort et al. (2011).

In-situ LA-ICP-MS U-Pb perovskite analyses of seven Kapuskasing UML samples confirm their Mesoproterozoic age, with emplacement between 1158 and 1121 Ma. Co-crystallising clinopyroxene was analysed to determine the common Pb isotope composition of the rocks, which showed excellent agreement with the two-stage average crustal Pb evolution model of Stacey and Kramers (1975). Sr, Nd, and Hf tracer isotopes were obtained on whole-rock fractions from five UMLs which showed minimal signs of crustal contamination. The Kapuskasing UML samples have relatively restricted, overlapping $^{87}Sr/^{86}Sr_i$, ranging from 0.70228 – 0.70297 and indicating a relatively unradiogenic source signature. Initial εNd values define a narrow range from +2.6 to +3.7 and εHf_i values range from +4.0 to +5.4 (Figure 2), which plot along the mantle array of Vervoort et al. (2011). The homogeneous range in Sr-Nd-Hf isotopes overlaps with ocean island basalts and global UML and kimberlite data, with very limited signs of lithospheric or crustal contamination/alteration. Our data unequivocally demonstrate a mildly depleted convecting mantle source during early rift initiation, similar in nature to Phanerozoic UML and kimberlites.

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