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Effects of melt depletion and metasomatism on U-Th-Pb behavior in cratonic mantle

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Introduction

Cratons often result from large and ancient melting events. Information of these past events is recorded in peridotites of cratonic roots, which are sampled and brought to surface by kimberlitic eruptions that rapidly traverse this thick lithosphere. The roots of the Kaapvaal craton represent the residue of large Archean melting events that presumably left them barren of sulfide minerals and depleted in incompatible trace elements (i.e., LREE, U, Th, Pb), priming them for subsequent metasomatic overprint by hydrous fluids, silicate melts and kimberlite magmas (e.g., Simon et al. 2007). This study aims to quantify the time-integrated change in U-Th-Pb distribution and contents between the minerals that compose the mantle roots

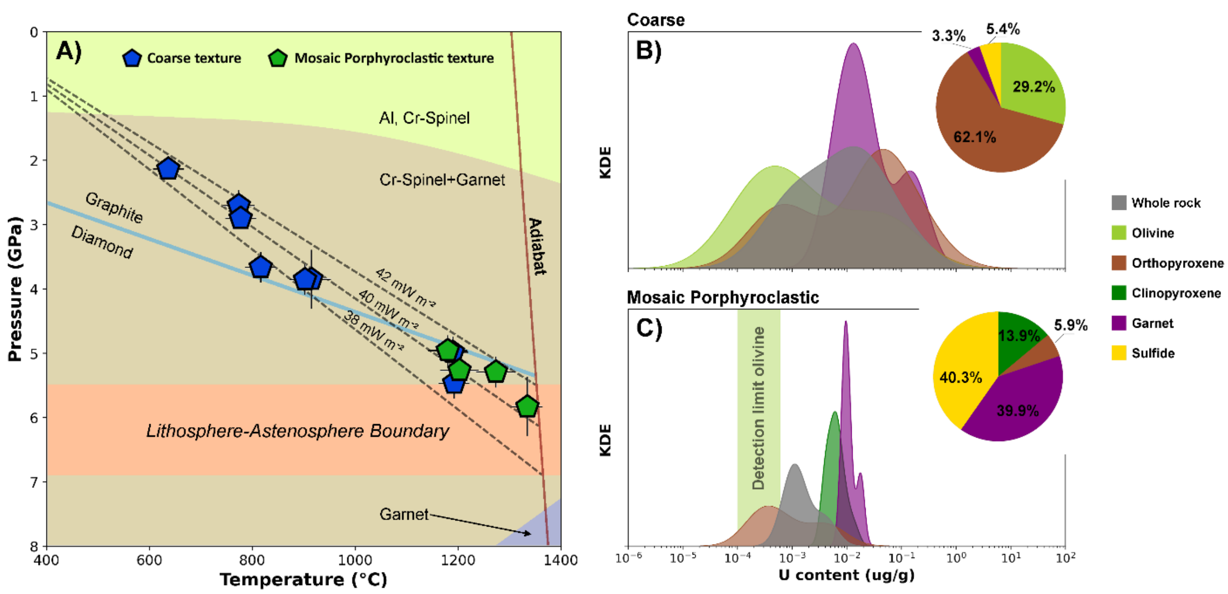

Fig. 1. A) Pressure-temperature estimates for the studied xenoliths from iterative solutions of the Al-in ol and Ca-in opx thermometers and the Cr-in grt and Al exchange grt-opx barometers or projecting into the 40 mW/m^2 geotherm using the PTEXL Excel sheet (further details on the methods used in Stachel 2022), grouped by textural characteristics. Errorbars represent 2σ of P-T estimates. Kernel density plots of the U content in the primary silicate phases and the respective reconstructed whole rock, and pie chart of U budget in primary silicate phases and sulfide (assuming the same sulfide modal abundance and U content for all xenoliths, based on the observation in a single mosaic porphyroclastic xenolith) estimate for the studied **B)** coarse and **C)** mosaic porphyroclastic Jagersfontein peridotites.

of the Kaapvaal craton, from their original depleted compositions to the posterior metasomatic overprint. Further constraining the abundance of heat-producing elements such as U-Th (and their decay product Pb) will improve our understanding of the evolution of the thermal state and thickness of the craton.

Results

Twelve peridotitic xenoliths from the Jagersfontein kimberlite in South Africa were investigated for their petrographic textures, major and trace element contents. Major element compositions were determined by EPMA analyses and trace element concentrations by LA-ICP-MS. Modal abundances of the primary mineralogy were estimated from 2D surface area calculations in each thin section, and posteriorly employed to calculate from mineral mass fractions (i.e., weighted averages of modal abundance and mineral density) the reconstructed bulk rock compositions.

The samples can be classified into two groups based on their textures and P-T estimates (Fig. 1A): i) coarse spinel to garnet harzburgites at pressures of 2.0-5.5 GPa and temperatures of 650-1200 °C, and ii) mosaic porphyroclastic garnet lherzolites and garnet harzburgites in the P-T range of 5-6 GPa and 1200-1350 °C. According to batch melt extraction models of Walter (2003), coarse samples experienced large melting degrees of >40%, and show enrichments in SiO_2, as evidenced by addition of orthopyroxene and a lower modal abundance of olivine at a constantly high Mg# range (92.5-93.5). Silicate minerals exhibit LREE enrichment, with most of the garnets showing sinusoidal patterns. HREE element concentrations are low, consistent with the large melt depletion. Peridotites with a mosaic porphyroclastic texture follow a decompression melting trend and show a simple LREE depletion pattern in garnet with relatively high HREE concentrations, typical of a lower melt depletion of 30%, and potentially limited metasomatism.

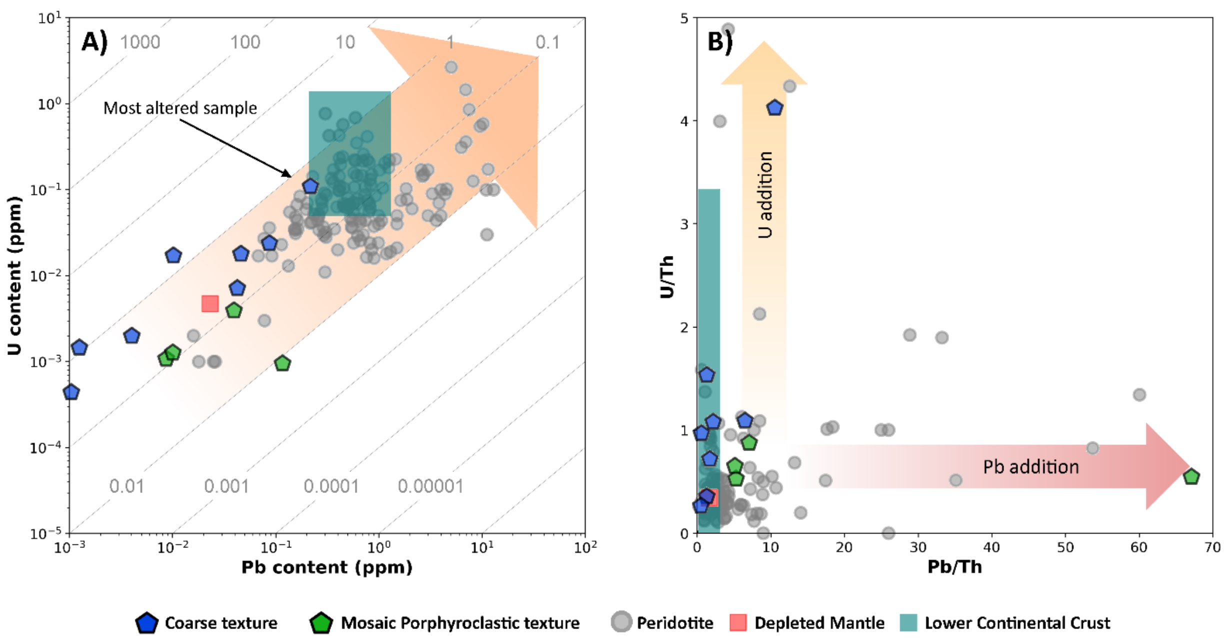

Fig. 2. A) Bulk rock U and Pb contents in peridotites and other cratonic xenoliths. Background arrow highlights the direction of increasing U and Pb towards lower continental crust, at a constant U/Pb ratio. Literature data is from the PetDB and GEOROC databases (Lehnert et al. 2000). **B)** U/Th vs Pb/Th ratios in Jagersfontein peridotites and other cratonic xenoliths. Estimates for depleted mantle from Salters and Stracke (2004), and lower continental crust from Rudnick and Gao (2003).

As expected of residues of large melting events, the contents of the incompatible elements U-Th-Pb are low and rarely exceed 0.5 ppm in the primary silicate phases (olivine, orthopyroxene, clinopyroxene and garnet), with clinopyroxene and garnet frequently showing the highest contents in these elements (Fig. 1B and C). Sulfides could constitute an important sink for U-Th-Pb in the cratonic roots, despite their scarcity (only found in one xenolith here) and low modal abundance (<0.17%). Without determining the provenance of the sulfides in the xenoliths (i.e., primary or metasomatic), their proportion in the U-Th-Pb total budget can only be considered a maximum estimation. Preliminary $^{207}Pb/^{206}Pb$ ratios of sulfides measured by LA-ICPMS record a common Pb isotope composition most typical of either a late metasomatic addition or re-equilibration with the host around the kimberlite eruption age, suggesting it is not a primary sulfide.

Most whole rock analyses from previous studies are based on analyses of bulk rock powder. Here we reconstructed whole rock trace element contents from in-situ mineral analyses and modal abundances, thus excluding secondary phases, alterations to serpentine, and interstitial melt. The discrepancy between our relatively low U-Th-Pb concentrations and typically higher literature values (Fig. 2A) can be explained by infiltration of low-degree melts rich in incompatible elements (McIntyre et al. 2021). When U and Pb are compared with a fluid immobile element (Th), U/Th and Pb/Th ratios of our peridotites fall within literature values, although most of the studied peridotites exhibit similar U/Th ratios (<1.5), mosaic porphyroclastic samples have experienced an overall addition of Pb (Fig. 2B).

Conclusion and Outlook

The data show a clear tendency towards lower U concentrations at greater depth in coarse samples and lower U/Pb ratios due to Pb addition in mosaic porphyroclastic samples. Despite the large melt depletion recorded in coarse samples, they have more variable U-Th-Pb concentrations at higher U/Pb ratios, likely as a result of different degrees of both modal and cryptic metasomatism. This indicates that depth and metasomatism may play more dominant roles in controlling the U-Th-Pb budgets than melting. Ongoing deconvolution models into melt depletion and metasomatism parameters coupled to the U-Th-Pb contents and distribution in the two textural groups will further constrain the behaviour of U-Th-Pb during these processes, better define partition coefficients, and improve our understanding of fluid and melt metasomatism in cratonic roots. Infiltrations by magmas (e.g. kimberlites) into the lithospheric mantle locally increase the heat-producing element concentrations of the wall rock, thereby heating and weakening the cratonic root.

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