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The origin of Camp Alpha megacrysts and their relationship to kimberlite magmatism - Liberia, West African Craton

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Introduction

Kimberlite megacrysts are large (>10mm) single mineral crystals and intergrowths of garnet, clinopyroxene, ilmenite, olivine, phlogopite, orthopyroxene, and/or zircon. The suite is divided into two populations (1) Cr-poor, which are poor in Cr and Mg and rich in Fe and Ti relative to peridotite minerals and (2) Cr-rich, which have Mg- and Cr-rich and Fe- and Ti-poor compositions closer to those of peridotitic minerals. There are, however megacrysts intermediate between Cr-poor and Cr-rich suites and compositional thresholds between the two vary in different studies (e.g., Kopylova et al., 2009). Equilibration pressures and temperatures (P-T) indicate that most megacrysts form between 3 to 7.5 GPa at 600 to 1450 °C (e.g., Nkere et al., 2021) and many megacrysts have isotopic ages that are close to those of the host kimberlite (e.g., Kopylova et al., 2009). However, controversy still surrounds their origin as well as the nature of their parental magma and by extension, the relationship between megacryst minerals and their host kimberlites. Current petrogenetic models for megacrysts generally fall within 3 categories: (1) that megacrysts are magmatic and crystallized from a melt that was present either very shortly prior to, or at the time of kimberlite eruption, although the composition of the melt varies, e.g., alkaline picritic/basaltic, kimberlitic or proto-kimberlitic melt (e.g., Nowell et al., 2004). (2) That megacrysts formed through progressive metasomatism of lithospheric wall-rock by a metasomatic melt with a kimberlite-like composition at a low melt-rock ratio (e.g., Kopylova et al., 2009). (3) That megacrysts formed through a combination of fractional crystallization of melt at a high melt-rock ratio as well as assimilation and/or metasomatic melt-lithosphere interactions with proto-kimberlite melt at a low melt-rock ratio (e.g., Nkere et al., 2021). Here, we present data for 418 garnets, clinopyroxenes, orthopyroxenes, ilmenites and clinopyroxene-ilmenite intergrowths from the Camp Alpha kimberlites in Liberia, with the main focus on developing a robust petrogenetic model to reconcile the first extensive in-situ major, trace and isotopic compositions of megacrysts from the West African Craton.

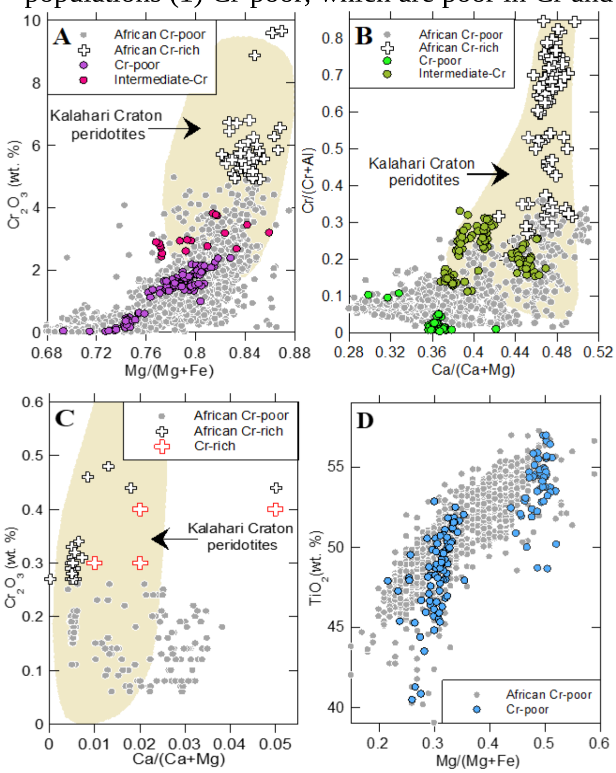

Figure 1: (a) garnet (b) clinopyroxene (c) orthopyroxene (d) ilmenite megacryst compositions

Results

All ilmenites, a majority of garnets and clinopyroxene are Cr-poor, showing a wide range of compositions and exhibiting tight, well-defined trends on major and incompatible trace element variation diagrams, similar to previously reported Cr-poor megacrysts worldwide (e.g., Orapa; Figs. 1 & 2). Many clinopyroxenes and a few garnets are transitional between Cr-poor and Cr-rich. They are characterized by highly evolved compositions that scatter or cluster on major and incompatible trace element variation diagrams. It is important to note that there are no Cr-rich garnet or clinopyroxene megacrysts equivalent to those from southern/central Africa. Orthopyroxenes are Cr-rich, exhibiting a wide range of highly scattered compositions and decoupling of HFSE. Single mineral thermobarometry indicates that clinopyroxenes equilibrated between 946 to 1444 °C at 4.3 to 8.4 GPa, while garnets have temperatures ranging between 783°C and 1381°C. The primitive Cr-poor megacrysts display higher P-T in contrast to more evolved intermediate megacrysts. All garnets and clinopyroxenes exhibit smooth and uniform convex upwards chondrite-normalized REE patterns, while orthopyroxene have sinusoidal REE patterns with strong enrichment in LREE and depletion in the MREE. Clinopyroxene Sr isotope signatures are relatively un-radiogenic in contrast to clinopyroxene megacrysts worldwide and the Camp Alpha kimberlites, but overlap with that of primitive groundmass perovskite in the host kimberlites (fig.2d).

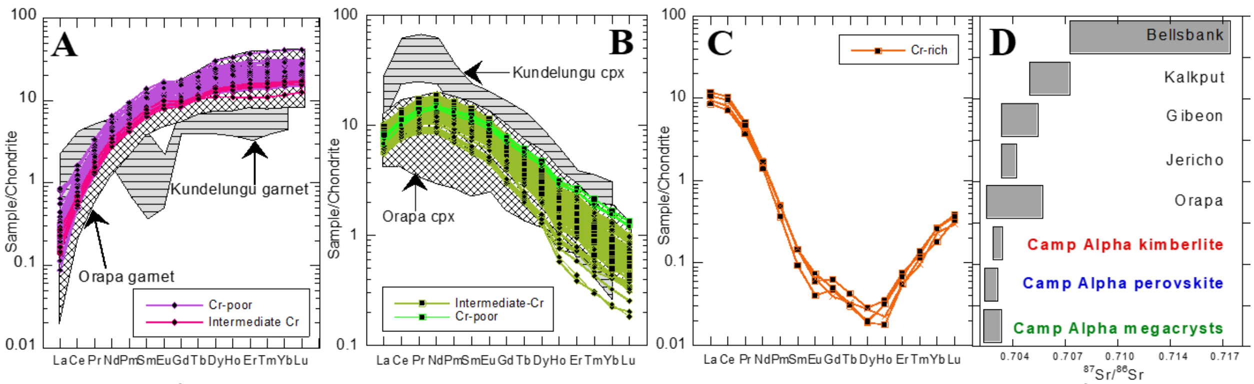

Figure 2: REE for (a) garnets, (b) clinopyroxene and (c) orthopyroxene. (d) Sr isotope compositions for Camp Alpha clinopyroxene megacrysts in contrast to kimberlite bulk rock, perovskite and clinopyroxene megacrysts worldwide. Literature data is from Davies et al. (2001), Kopylova et al. (2009), Nkere et al. (2021) and Pivin et al. (2009).

Discussion

The geochemical features of Camp Alpha megacrysts are indicative of a dynamic open-system crystallization process. They are predominantly Cr-poor and are characterised by large compositional ranges and smooth variation trends, features that are indicative of fractional crystallization from an evolving magma undergoing extensive differentiation at a high melt/rock ratio and at high P-T conditions. However, a portion of the magacrysts have more evolved compositions that are intermediate between Cr-poor and Cr-rich varieties. They lack clear variation trends and are enriched in incompatible trace elements. In addition, all orthopyroxenes are Cr-rich, having highly eratic and scattered major and trace element variations, as well as sinusoidal REE patterns. These details suggest a transition of the crystallisation enviroment from a high to lower melt/rock ratio and the assimilation of metasomatized peridotite wall-rock at moderate P-T conditions which increases differentiation of the megacryst parental magma. Single mineral thermobarometry indicates that the Cr-poor and intermediate-Cr megacrysts equilibrated at high and moderate P-T conditions, respectively, falling near the 40 mW/m^2 geotherm (fig. 3). Their intersection with the mantle adiabat corresponds to a lithospheric thickness of 207±10 km, in close agreement with 220 km thickness from the xenocryst geotherm of the nieghbouring Koidu kimberlite (146 Ma) (Smit et al., 2016). Melt compositions in equilibrium with the megacrysts, calculated using high-pressure partition coefficients between minerals and kimberlite melts, are nearly identical, indicating co-crystallization of the megacrysts (fig. 3). The calculated melts have trace element compositions similar to the host Camp Alpha kimberlite and in addition, the megacrysts have Sr isotope data that strongly correlate to those of both the host kimberlite and groundmass perovskite. This suggests crystallization from primitive melts with kimberlite-like trace element compositions and thus indicative of a genetic link between megacrysts and the host kimberlite (e.g., Nkere et al., 2021). We propose a model for the origin of Camp Alpha megacrysts in which Cr-poor megacrysts are generated by fractional crystallization at high temperatures from a large body of silicate-carbonate proto-kimberlite melt toward the base of the lithosphere. This occurs at an initially high melt/rock ratio, resulting in the large proportion of Cr-poor megacrysts in the suite. As the melt propagates and ascends though the lithosphere, the crystallization environment evolves to a low

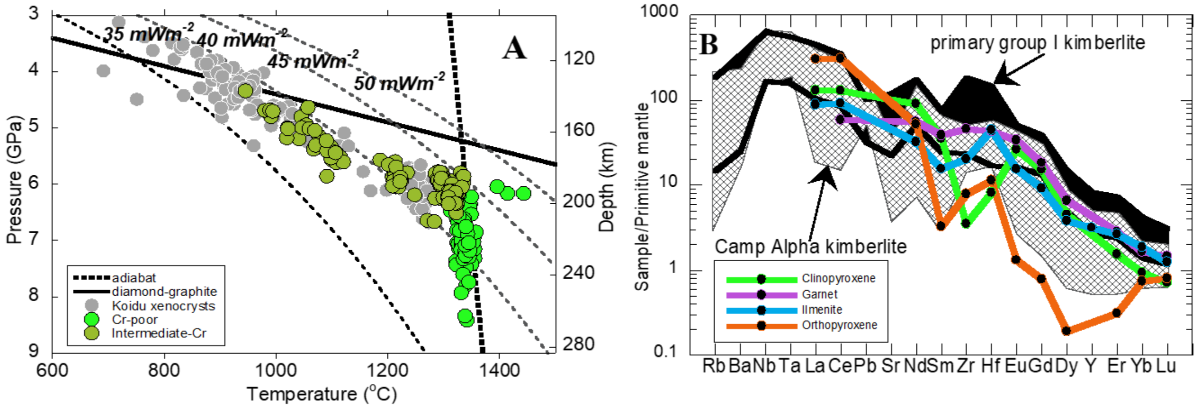

Figure 3: (a) Camp Alpha clinopyroxene P-T calculated using the geothermobarometer of Nimis & Taylor (2000). (b) Mean trace element patterns of melt in equilibrium with garnet, clinopyroxene, orthopyroxene and ilmenite megacrysts from Camp Alpha modelled using partition coefficient in kimberlitic systems (Fujimaki et al. 1984).

melt/rock ratio and metasomatic interaction with and/or assimilation of the surrounding lithosphere gradually dominates the crystallisation environment, further modifying the melt composition. As a consequence, the more evolved, low temperature megacrysts have compositions transitional between Cr-poor and Cr-rich. The Cr-rich orthopyroxene crystallised at very low melt/rock ratio and high degrees of metasomatic interaction and/or assimilation of the lithosphere. The fact that (except for orthopyroxene) there are no true Cr-rich megacrysts implies that at Camp Alpha, there was 1) a large sized magma body ≈100–120 km in total vertical extent, based on clinopyroxene barometry. And/or 2) Melt networks did not extend to sufficiently shallow depths to encounter measomitised peridotite that is easy to assimilate (e.g., Nkere et al., 2021).

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