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Constraining the chemical and thermal structure of the Kaapvaal Craton subcontinental lithospheric mantle using kimberlite-indicator-mineral geochemistry

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Introduction

Garnet is the most utilized kimberlite indicator mineral (KIM) in diamond exploration owing to its widespread occurrence and large compositional variations that are strongly correlated with the extent of melt depletion, metasomatism and diamond occurrence. But garnet barometers are not considered generally reliable because they underestimate pressures when garnet is not in equilibrium with Cr-spinel (Ryan et al., 1996, Grütter et al., 2006). The coexistence of Cr-spinel and garnet is not easily determined from garnet composition alone. As a result, Grütter et al., (2006) proposed an equation for the graphite-diamond-constraint (GDC: $Cr_2O_3 \geq 5 + 0.94 * CaO$), where garnets plotting above this line are assumed to be (1) Cr-saturated, (2) within the diamond stability field and (3) applicable to thermobarometry. The Fitplot program iteratively calculates paleogeotherms specific to a locality, based on the P-T data and crustal and mantle properties of a particular locality (Mather et al., 2011). Since we are interested in the thermal structure of the SCLM, we prefer to use regression-based thermobarometric formulations rather than those assuming current surface heat flow because these reflect only the present thermal structure of the lithosphere (Mather et al., 2011). We use the combination: T_{Sud21} (Sudholz et al., 2021) - P_{Cr} (Ryan et al., 1996).

Following on from the work conducted by Kobussen et al. (2009), we use KIMs exhumed by Group II and Group I kimberlites from the Barkly West, Finsch Group and the Kimberley clusters in South Africa (termed "greater Barkly West"). We use novel and quantitative methods to investigate the chemical and thermal structure of the SCLM beneath the study area (e.g., k-intervals). K-intervals are a series of zones parallel to the GDC, defined by the equation:$Cr_2O_3 \geq k + 0.94 * CaO$, where k ranges from -4 to 8, in increments of 2 (Figure 1a&b), which we use to assess the Cr-saturation of garnets, in order to identify those best suited for garnet-based single mineral thermobarometry. We evaluate the precision and accuracy of the T_{Sud21} - P_{Cr} thermobarometer by comparing it with the BKN90 (Brey et al., 1990) mantle xenolith thermobarometer.

Results

Our analysis is based on a total of 7,923 and 4,670 garnet analyses from Group II and Group I kimberlites, respectively in the greater Barkly West cluster. In the Group II population, peridotitic garnets are composed of 53.81% G9, 23.34% G10 , and 1.86% G12 types (Grütter et al., 2004). In the Group I population, peridotitic garnets are composed of 69.36% G9, 14.30% G10 and 0.13% G12 types, suggesting that Group I-derived garnets are more calcic, on average than those derived from Group II kimberlites (Figure 1b). High-Cr (i.e.,plotting at $k \geq 4$) garnets make up 13.61% and 1.56% of the Group II and Group I peridotitic garnet populations, respectively (Figure 1e & d). Note that only high-Cr garnets with T_{Sud21} between 700 and 1200°C are used to calculate paleogeotherms.

All P-T plots indicate that high-Cr garnets equilibrated at $T_{Sud21} \leq 1200$°C and and $P_{Cr} \geq 45\ kbar$ (Figure 1c and d). The P_{Cr} –T_{Sud21} combination yields relatively cool palaeogeotherms for both Group II and Group I kimberlites, leading to overlapping lithosphere-asthenosphere-boundary (LAB) estimates of 203±14 and 196±11 km, respectively. Both paleogeotherms are similar to that determined for the P_{BKN90} –T_{BKN90} array of Finsch mantle xenoliths (Fig. 1c). In contrast, Group I mantle xenoliths estimate a hotter paleogeotherm (Figure 1d and Table 1). Intermediate Cr garnets (i.e., $0 < k < 4$) make up most of the garnet population (Figure 1c&d) and they exhibit the widest distribution in both temperature and CaO contents.

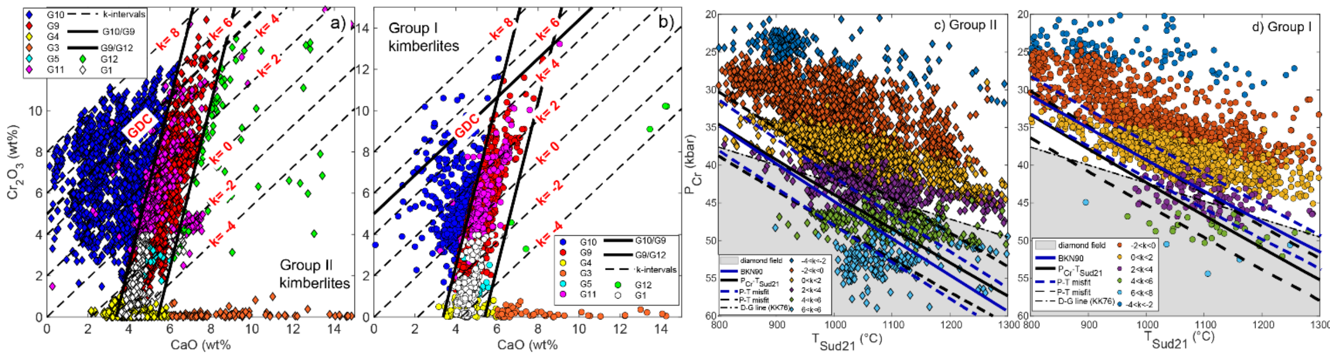

Figure 1. CaO vs. Cr_2O_3 (a – b) and T_{Sud21} vs. P_{Cr} (c – d) diagrams of garnets exhumed by Group II and Group I kimberlites from the Greater Barkly West cluster. K-intervals are shown by dashed lines parallel to the GDC on the CaO–Cr_2O_3 plot. Data points in panels c & d are color-coded based on ther k-intevals. The Fitplot paleogeotherm (black solid line) is calculated using the P-T arrays of only the high-Cr garnets (i.e., $k \geq 4$). The BKN90 geotherm (blue solid line) is based on lherzolitic mantle xenoliths.

Table 1: Fitplot program output parameters from high-Cr garnet-based paleogeotherms in Figure 1c&d.

P-T combination	LAB (km)	P-T misfit (°C)	Host Type	Sample Type
P_{Cr}-T_{Sud21}	203±14	88.8	Group II	xenocryst
BKN90	211±10	65.4	Group II	xenolith
P_{Cr}-T_{Sud21}	196±11	66.2	Group I	xenocryst
BKN90	175±12	56.7	Group I	xenolith

LAB: Lithosphere-Asthenosphere-Boundary depth. P-T misfit: measure of how well the P-T data fits the calculated geotherm.

Discussion

The presence of a significantly larger proportion of high-Cr, CaO-poor and HREE-depleted garnets exhumed by Group II relative to Group I kimberlites suggests that a more depleted SCLM was sampled by Group II kimberlites, which appears to have been relatively little affected by Mesozoic metasomatism (Kobussen et al., 2009). P_{Cr} –T_{Sud21} arrays of high-Cr garnets from both kimberlite groups yield relatively cool palaeogeotherms with overlapping LAB depth estimates. We agree with the hypothesis of Lazarov et al. (2009) that the geotherm of the SCLM sampled by Group II kimberlites represents essentially steady-state conditions. Bell et al. (2003) suggested that Group I palaeogeotherms are transient geotherms. However, this study and that of Nimis et al., (2020) both determined cool palaeogeotherms for xenoliths/xenocrysts exhumed by Group I kimberlites. Thus, with the use of high-Cr garnets, we obtain Group I palaeogeotherms that appear to be representative of steady-state conditions, whereas the Group I xenolith geotherm is a transient geotherm, likely affected by Group I-related metasomatism. High-Cr garnets are interpreted to be remnants of the SCLM that has not been detectably affected by Mesozoic metasomatism, irrepective of kimberlite group.

The rarity of high-Cr garnets in Group I kimberlites reflect the relatively pervasive modification of the SCLM into more lherzolitic compositions. Additionally, garnets falling within individual k-intervals display similar major and trace elements characteristics and behaviour, suggesting that it is the Cr_2O_3 contents of the garnets that largely controls element exchange, as previously suggested by Lazarov et al. (2012). Therefore, in addition to evaluating Cr-saturation, k-intervals can be used to investigate the metasomatic overprinting in garnets. Intermediate Cr garnets reveal evidence of CaO-enrichment and exhibit near-sobaric heating in Figures 1c&d, which implies that the infiltrating melts were responsible for both chemical and thermal modification of the SCLM. Kobussen et al. (2009) showed that the SCLM exhumed by Group II and Group I kimberlites had interacted with compositionally different metasomatizing agents (i.e., hydrous, K-rich and CO_2 & SiO_2-rich melts, respectively), resulting in two distinct styles of metasomatism on the lithosphere of the Kaapvaal Craton and its southwestern periphery. According to Kobussen et al. (2009), Group II-related metasomatism proceeded without heating the SCLM, whereas Group I-related metasomatism was accompanied by significant heating of the the SCLM. Although we agree with Kobussen et al. (2009) in that there are two distinct metasomatic agents involved, our results reveal that the SCLM exhumed by Group II kimberlites has also experienced heating, but to a smaller extent than that exhumed by Group I kimberlites.

Conclusions

1. Irrespective of garnet compositions (i.e., G10 or G9), high-Cr garnets exhibit little chemical evidence of young (i.e., Mesozoic) metasomatic overprinting, and are most likely to be Cr-saturated, and are therefore the most reliable on which to base temperature and pressure estimates and paleogeotherms.
2. Both Group II and Group I kimberlite magmatism were associated with metasomatic events that resulted in different extents of heating of the SCLM, the extent of thermal perturbation appears to be related to the metasomatizing agent.
3. Both P_{Cr}–T_{Sud21} formulations yield results comparable with the Group II mantle xenoliths P-T array, which shows that k-intervals filter for samples reliable for estimating palaeogeotherms.

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