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LITHOSPHERIC STRUCTURE BENEATH THE CRETACEOUS ORAPA KIMBERLITE FIELD, BOTSWANA: 4D LITHOSPHERE IMAGING USING GARNET INDICATOR MINERAL CHEMISTRY

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Introduction

The Orapa kimberlite province, located along the western margin of the Archaean Zimbabwe Craton in eastern Botswana, comprises 86 individual kimberlite occurrences and includes Debswana's well known Orapa, Lethlakane and Damtshaa mines (Fig. 1). Orapa AK1, also known as Orapa Mine, was the first kimberlite discovered in this province in 1967. The most recent kimberlite (i.e. Orapa-AK25) was discovered within the present-day Orapa Mine lease area (Fig. 1) in 2010. Covering an area of approximately 2,600 square kilometres along the southern shore of the Makgadigadi Basin, these kimberlites can be divided into several discrete cluster groups that include bodies of varying size (from in excess of 100 hectares to less than 0.5 hectares), mode of intrusion (e.g. pipes and dykes) and diamondiferous character (barren to in excess of 100 cpht). Ages of emplacement are Cretaceous and range from 111 Ma for Lethlakane-DK1 (Lethlakane Mine) to 85 Ma for Orapa-AK1, representing a protracted period of kimberlite magmatism lasting approximately 20 million years. Kimberlites were emplaced into Archaean basement gneisses (2,765 to 2,670 Ma) and Carboniferous to Jurassic-age Karoo sediments. The cover sequence is represented by Cainozoic Kalahari Group and Quaternary sediments.

Methodology

Major (n = ~137,000) and trace (n = 18,200) element analyses have been acquired for suites of concentrate garnets (major element data are also available for other mineral species – chrome spinel, chromian diopside and picro ilmenite) collected from **56** kimberlites in the Orapa field over the past 30 years of prospecting within this region (Fig. 1). These data have been petrogenetically classified (using the methodology described in Griffin *et al*., 2002) and pressure-temperature information calculated for each locality using: (i) the garnet nickel content to estimate temperature (after Griffin *et al*., 1989 and Canil, 1999); and (ii) the garnet Cr_2O_3 content to estimate pressure (after Ryan *et al*., 1996 – P_{Cr} and Grütter *et al*., 2006 – P_{min38}). The forsterite (Fo) content of the olivine with which each of the peridotitic garnets was likely to have equilibrated has been determined using the method outlined by Gaul (2000). Linear geotherms for each locality have been compiled assuming a mantle potential temperature of approximately 1350 °C at the base of the sub-continental lithospheric mantle (SCLM) and are expressed as lines of equal lithospheric thickness on the pressure-temperature (P-T) diagrams (after Hatton, 2007; 2008 – a method developed at De Beers). The resulting palaeo-geotherms, defined using the locus of the highest pressure peridotitic (low-Ca harzburgitic) garnets at any given temperature, have been used to construct idealised SCLM profiles (after Griffin *et al*., 2002) – a northern section from AK15 to BK14 and a south-eastern section from AK3 to DK1 (Fig. 1). Various chemical parameters (e.g. TiO_2, Y and Zr in garnet and calculated olivine Fo content) have been interpolated between kimberlites using the inverse distance weighted (IDW) method (with a search ellipsoid configuration of 10 x 10 x 20 kilometres) in order to construct a three-dimensional model of the chemical variation of the sampled garnet-bearing lithologies within the SCLM. Cross sections show that different lithospheric domains, defined by varying proportions of the implied rock types, olivine composition, and garnet minor and trace element composition, exist within the restricted Orapa area. In some cases it is clear that the lithospheric character changes significantly over short distances (on the order of several kilometres). The systematic variation of garnet variety, garnet composition (e.g. TiO_2, Zr, Y and the rare earth elements) and olivine Fo content in the associated peridotite show that the mantle may be significantly heterogeneous on this scale.

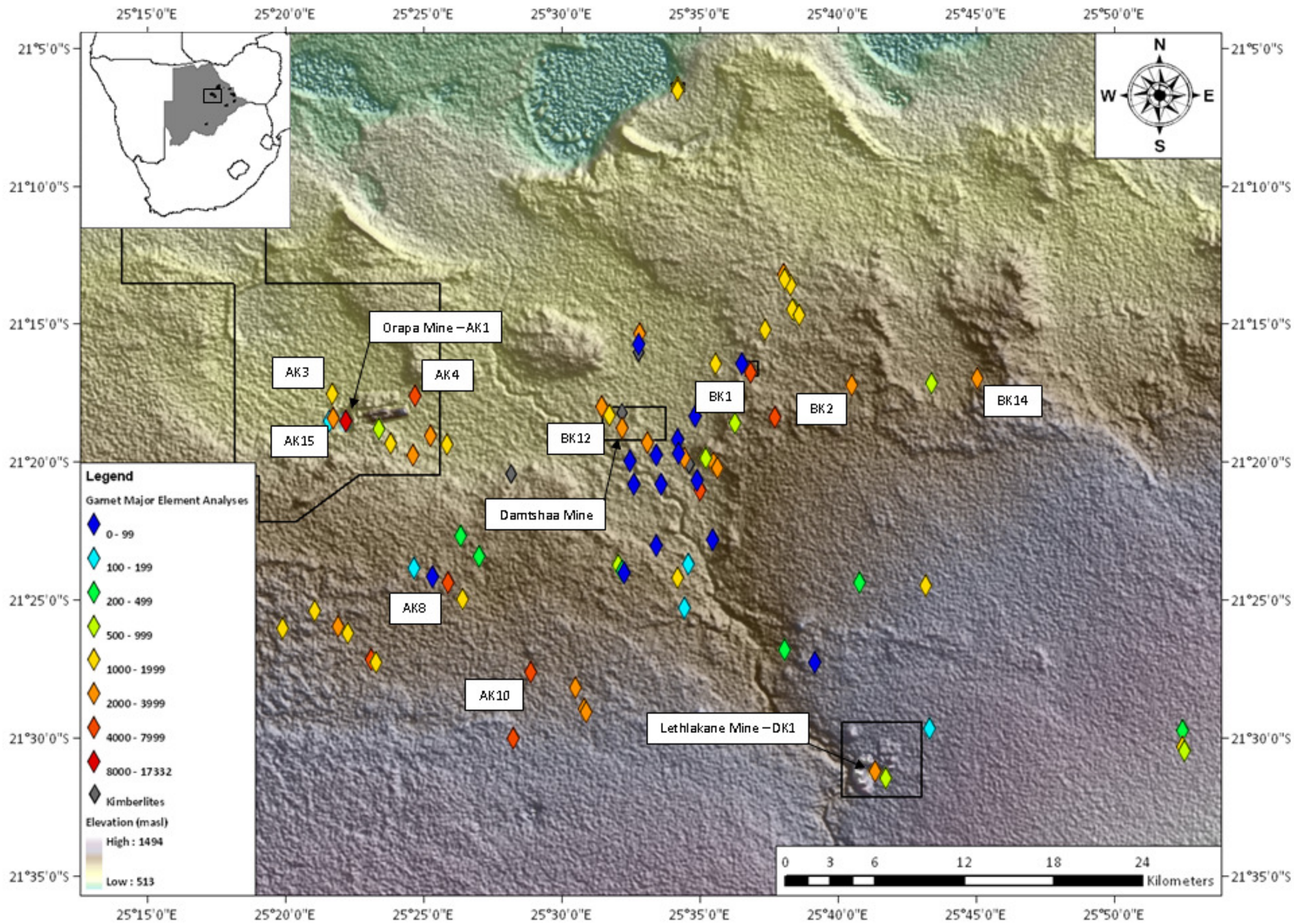

Figure 1: Locality map showing the Orapa kimberlite field and present-day Debswana mine lease areas (black polygons) in eastern Botswana (see inset). The data coverage per kimberlite, in terms of garnet major element analyses, is indicated by the coloured symbology. The low-lying region to the north represents the present-day southern shoreline of the Makgadikgadi Basin.

Results

Compilation of the ~17,800 *peridotitic* garnet trace element analyses collected from the 56 kimberlites highlights the relative scarcity of low-calcium harzburgitic to dunitic garnets (~1.5 %; note that the *total* harzburgitic component – low-Ca and Ca-harzburgite – accounts for approximately 20 % of the garnet dataset) and abundance of lherzolitic compositions (Fig. 2). The combined dataset does reveal some interesting (and useful) trends that are fundamental to attempting to estimate lithosphere thickness and 'image' the lithosphere with any degree of confidence.

Most importantly, the low-Ca harzburgitic garnets define a maximum P_{min38} pressure threshold (after Grütter *et al.*, 2006) of 53 to 54 kilobars, notable given that over 17,000 peridotitic garnets have been used to establish this constraint. Satisfying the conditions required by Grütter *et al*. (2006) to reliably estimate a maximum pressure constraint, lithosphere thickness (or lithosphere-asthenosphere boundary depth) may be estimated considering the assumptions set out in Hatton (2007 & 2008). An in-depth examination of the P-T data for each individual kimberlite (not discussed here) dataset reveals that only eight of the 56 datasets within the Orapa kimberlite field yield maximum lithosphere thickness constraints consistent with the combined data. The arrow mark on the garnet P-T diagram in Fig. 2 indicates that this *empirical* best fit exists between 220 and 230 kilometres (noting that only eight outliers were generated). Under these conditions the graphite-diamond transition is constrained at less than 800 °C and approximately 37 kilobars.

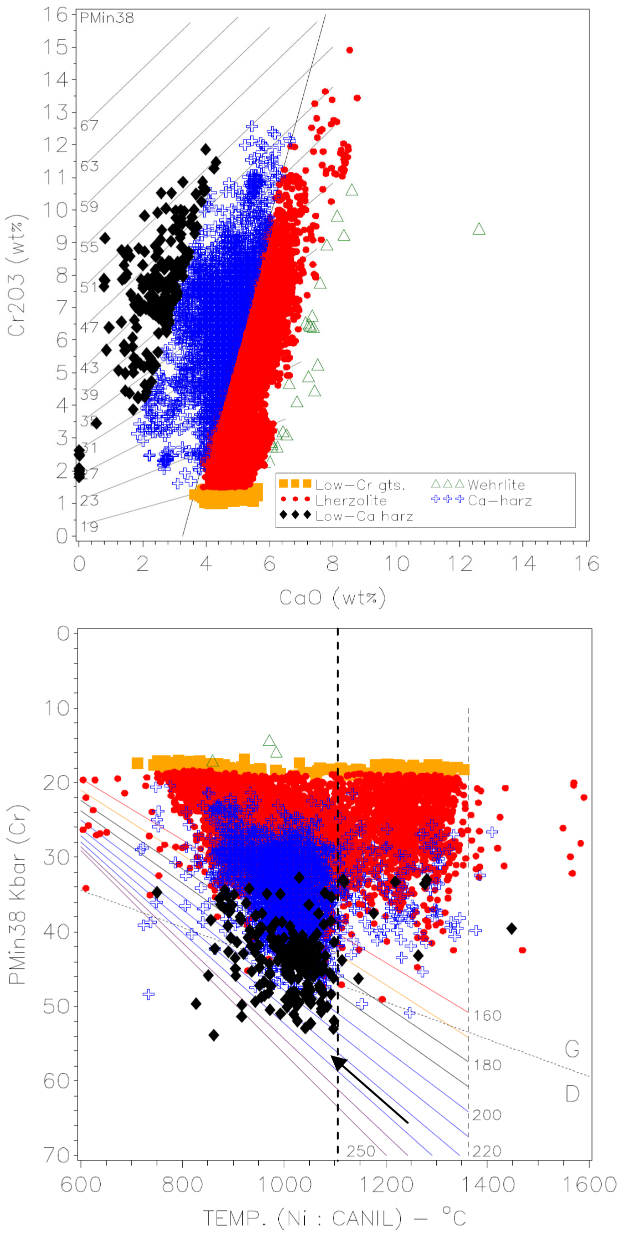

Figure 2: Trace element data (n = 17,813) for *peridotitic* garnets (i.e. > 1.0 weight percent Cr_2O_3) collected from 56 occurrences within the Orapa-kimberlite field (Fig. 1) shown in Cr-Ca compositional space (top). The compositional classification (see legend) is after Griffin *et* al. (2002). The P_{min38} isobars are after Grütter *et al*. (2006) These data are translated into P-T space (bottom) using the Canil (1999) Ni-in-garnet thermometer and Grütter *et al*'s (2006) empirical Cr-in-garnet barometer. The reference geotherms are after Hatton (2007; 2008). The graphite-diamond transition is after Kennedy and Kennedy (1976). The LAB is indicated by the arrow mark at between 220 and 230 kilometres following the assumptions of Hatton (2007, 2008).

Closer examination of the garnet P-T diagram (bottom panel in Fig. 2) reveals a distinct truncation of the harzburgitic component at approximately 1,100 °C (dashed line in Fig. 2) highlighting the prevalence of more depleted peridotitic lithologies at shallower depth. Lherzolite is prevalent throughout the temperature range from < 800 °C and extending to the inferred lithosphere-asthenosphere boundary (LAB) at approximately 1,350 °C.

The projection of each individual garnet from each kimberlite concentrate sample onto the 220-kilometer palaeo-geotherm produces unique garnet sampling profiles for each kimberlite as shown in Figure 3. Note that it is assumed, given the relatively small area of the SCLM that has been sampled by the Orapa kimberlites (approximately 1,200 square kilometres) and subsequently imaged as part of this study, that the LAB or lithosphere thickness is consistent across the region. The profiles shown in Figure 3 are for two traverses across the kimberlite field (E-W: AK15 to BK14 and NW-SE: AK3 to DK1) and show that in most cases, sampling of garnet-bearing lithologies is generally shallow, but within the diamond stability field. The BK1, BK2 and AK1 samples appear to be dominated by harzburgite while data from AK4, AK8 and DK1 indicate entrainment of deep-seated TiO_2-enriched garnet-bearing rocks (green symbology in the idealised sampling profiles in Fig. 3). The sampling profile for AK3 reveals a pronounced and dominant lherzolitic component at a shallower depth that is consistent with entrainment within the graphite stability field and resultant sub-economic grade.

The interpolation of various chemical parameters (TiO_2 in garnet is shown here) between samples (or kimberlites) highlights small-scale variations in the composition of the garnets recovered and is only possible with large, spatially representative datasets. For example, the region of the SCLM sampled by AK8 and AK10 (bottom panel in Fig. 3) is conspicuous, indicating possible local enrichment, at least with respect to garnet titanium content close to the inferred LAB. The relatively fine-scale interpolation (at 10 x 10 x 20 kilometres) reveals a 'chemical high' where the SCLM appears to be relatively more enriched in TiO_2 relative to the northern traverse and may indicate a local thermal perturbation at the base of the lithosphere in this region. Economic deposits such as AK1, BK1, BK2 and DK1, however, consistently indicate entrainment of low-TiO_2 (< 0.5 weight percent TiO_2), garnet-bearing lithologies at relatively shallow depth (160 kilometres) and the presence of harzburgitic lithologies.

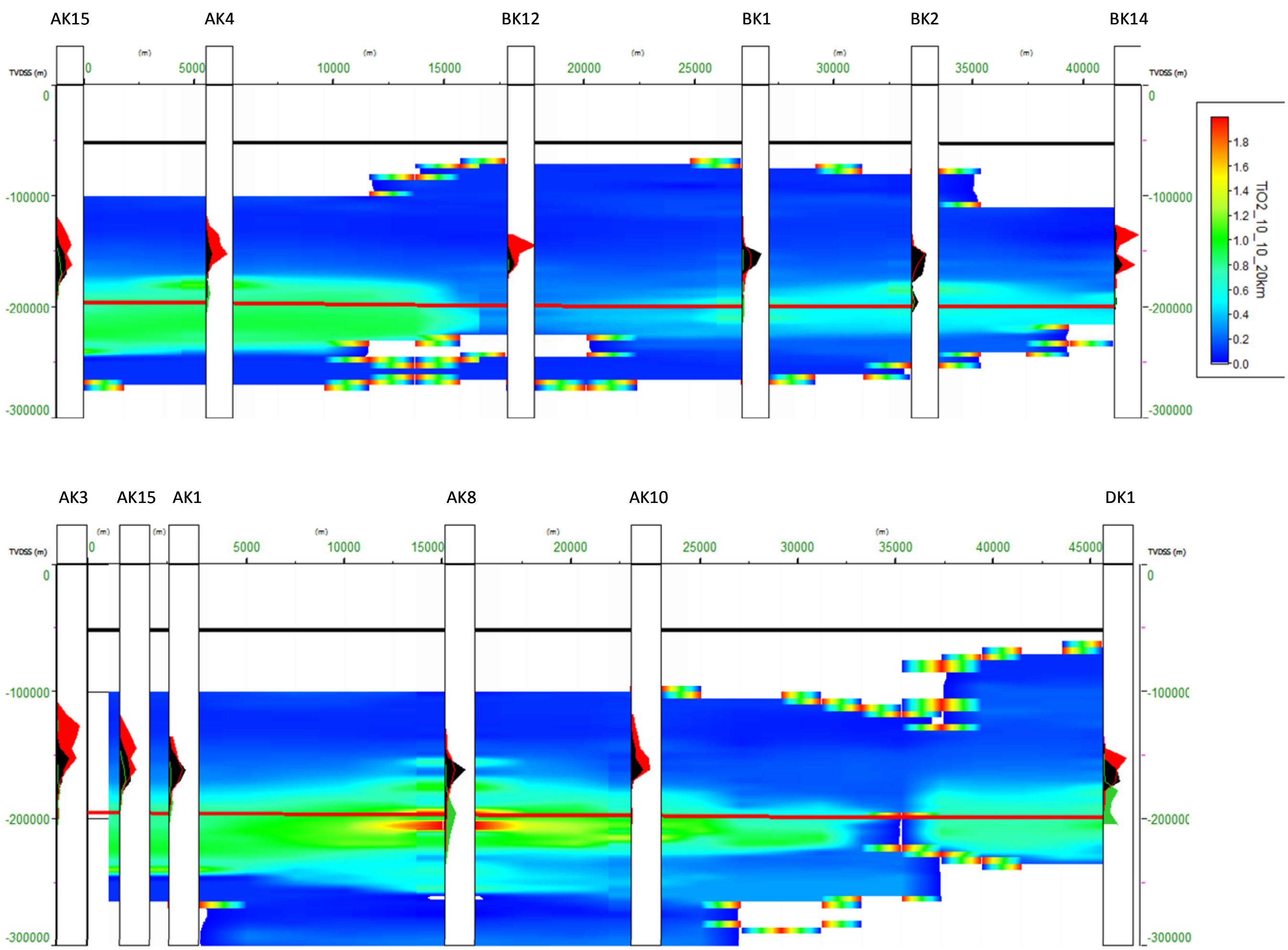

Figure 3: Idealised mantle sampling profiles for the garnet-bearing portions of the SCLM as sampled by individual Orapa kimberlites (red = lherzolite; black = harzburgite; green = Ti-rich lherzolite). The profiles are shown against the backdrop of the interpolated garnet titanium content (expressed in weight percent TiO_2). A search ellipsoid with dimensions 10 x 10 x 20 (X, Y, Z) kilometres was used for the inverse distance weighted interpolation of the data. The units for the vertical and horizontal axes are expressed in metres. The Moho discontinuity is indicated by the solid black line at approximately 50 kilometers' depth. The solid red line represents the 200-kilometer reference LAB constraint.

Conclusions

1. High-pressure harzburgitic to dunitic garnets (low-Ca harzburgitic) are relatively scarce in Orapa kimberlite concentrate samples, but represent pronounced features in the idealised sampling profiles of the high interest, economic deposits such as AK1, BK1, BK2 and DK1 (Fig. 3). The recovery of these garnets, necessitated by large, spatially representative concentrate samples, represents a fundamental input to the successful application of xenocryst data to lithosphere thickness estimation and SCLM imaging.

2. Only eight kimberlites (out of a total of 86 that constitute the Orapa kimberlite field), including AK1 (Orapa Mine), yield garnet P-T arrays that consistently indicate a maximum LAB depth constraint of between 220 and 230 kilometres.

3. With reliance on the high-pressure, low-calcium harzburgitic garnets (i.e. low-Ca harzburgite indicated in Fig. 2) and in accordance with the methodology set out by Grütter *et al.* (2006), the palaeo-geotherm or lithosphere thickness *can* be determined from xenocryst samples using established P-T techniques.

4. Three dimensional modelling (interpolation) of various chemical parameters including calculated forsterite content of *assumed* co-existing olivine (not shown) and titanium-in-garnet indicates relatively homogeneous and depleted lithospheric sections down to 180 kilometres. This is defined, in general, as the lowermost limit of low-TiO_2 (i.e. < 0.5 weight percent) garnets in the SCLM sections presented in Fig. 2. *However*, the high density of data collected from the Orapa kimberlite field successfully resolves sub-domains (especially around AK8 and to a lesser extent AK10 – Fig. 3) where mantle enrichment/re-enrichment is pronounced as evidenced by significantly higher TiO_2-in-garnet (up to 1.8 weight percent TiO_2) and lower olivine forsterite content (not shown) at much shallower levels (160 kilometres) within the SCLM.

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