Age of the Lithospheric Mantle Beneath the Karowe Diamond Mine

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Introduction

The Karowe Diamond Mine has been developed by Lucara Diamond Corp following evaluation of the AK6 kimberlite pipe in north-central Botswana. The AK6 pipe erupted through the early Proterozoic (~1.8 Ga) Magondi Belt on the western edge of the Zimbabwe craton. The pipe formed as a part of the cretaceous Orapa Kimberlite Cluster, and is situated approximately 25 kilometers south of the Orapa mine, and 25 kilometers west of the Letlhakane mine. The Karowe Mine is characterised by the recovery of numerous large, Type IIa diamonds, including the 1,111 carat Lesedi La Rona. A study of mantle xenoliths from Karowe has been undertaken to characterise the level of depletion and any cryptic metasomatic alteration. Re-Os dating has also been performed to determine the age of the lithospheric mantle sampled by the kimberlite, and to determine the extent of lithospheric over-printing or new lithosphere formation caused by the Magondi event.

Sample Description and Petrography

A suite of 19 peridotite xenoliths were selected for analysis from a selection gathered from the mine’s coarse tailings. The samples were analysed for mineral chemistry (EPMA and LA-ICP-MS), bulk rock major elements (XRF), and Re-Os plus platinum group elements. Mineral assemblages include clinopyroxene, present as bright green chromium diopside, orthopyroxene, olivine and either spinel or garnet. All samples are lherzolitic in composition. 14 samples are spinel lherzolites and five are garnet lherzolites. Three of the garnet lherzolites also have amphibole in the form of pargasite present, likely due to metasomatic infiltration. All samples can be described as coarse equant with granuloblastic textures, based on the classification of Harte (1977). Despite the close spatial occurrence of Karowe to Orapa, Orapa’s mantle xenolith population is dominated by eclogites (McDonald & Viljoen, 2006) while Karowe yields abundant peridotites, with relatively few eclogites recovered so far. A garnet pyroxenite xenolith component, defined here as containing Al-augite rather than omphacite as clinopyroxene, is also evident and more abundant than eclogites.

Clinopyroxene is found dispersed throughout the peridotite samples, and can be intergrown with other phases. Secondary clinopyroxene associated with veining was observed in only one sample. In garnet-bearing samples, clinopyroxene often forms clusters, involving pargasite if present. Phlogopite is absent in the samplefound. Few, small sulfide clusters can be found in the garnet-bearing samples. The peridotite xenoliths have orthopyroxene contents averaging ~ 30 vol%, comparing well with Kaapvaal Craton xenoliths.

Mineral Chemistry

The forsterite (Fo) contents of olivine - a measure of melt depletion - range from Fo$_{91}$ to Fo$_{93}$. This range in Fo content overlaps the mean Fo of peridotites from the Kaapvaal craton at Fo$_{92.6}$ (Pearson & Wittig, 2008). Samples with higher Fo content contain less clinopyroxene, consistent with an origin during higher degrees of melt-depletion. Samples with lower Fo content tend to be garnet-bearing, with an average of Fo$_{91.5}$.

Ni-in-garnet thermometry was calculated, based on an average of Canil (1999) and Griffin et al. (1989), using the Ni content obtained from LA-ICP-MS analysis of garnet plus the Ni content of the coexisting olivine from each sample. This gives temperatures that range within 60°C, from 790°C to 850°C.

In the 10 peridotites analysed for Os isotopes so far, the concentrations of osmium range widely, from 0.32 to 6.35 ppb. This range brackets the average cratonic mantle value of ~3.8 ppb Os (Pearson et al., 2003; Aulbach et al. 2016). The concentration of osmium does not correlate with Os isotopic ratios. The Os isotope data is multi-modal in nature. The unradiogenic $^{187}Os/^{188}Os$ values range from 0.109 to 0.114. This range overlaps the mode of values from elsewhere in the Kaapvaal and Kalahari cratons (Pearson et al., 2004). Samples with radiogenic $^{187}Os/^{188}Os$ (0.1260 to 0.1295) overlap modern convecting mantle values. These highly radiogenic values come from samples that have relatively high modal abundances of clinopyroxene.

T_{RD} ages relative to E-chondrite show a peak at 2.6 Ga and are as low as 2.0 Ga.

Discussion

The xenoliths sampled from the mantle at Karowe come predominantly from the shallow mantle, the spinel facies, and only a few samples extend into the garnet facies. Garnet-bearing peridotites have a minimum pressure of 19-23 kbar, based on Cr_2O_3 and CaO content (Grütter et al., 2006). In contrast, peridotite-derived xenocrysts show much deeper sampling of the mantle, which is consistent with the diamondiferous nature of the Karowe pipe (Motsamai, in prep.).

The T_{RD} model ages for the lithospheric mantle beneath Karowe range widely. The population peaks at the oldest ages (2.6 Ga), which are derived from peridotites with the highest Fo contents and with the lowest modal abundance of diopside. This Neoarchean age peak at Karowe agrees well with the main mode of Re depletion ages for peridotites from the Kaapvaal craton (Pearson & Wittig, 2008), and also coincides with the peak in ages from base-metal poor, highly depleted peridotites from the nearby Letlhakane Mine (Luguet et al., 2015) and from the Murowa Mine on the southern edge of the Zimbabwe Craton (Pearson et al., in press).

The younger, circa 2 to 2.3 Ga Re depletion ages seen at Karowe are not found in peridotites from Letlhakane and are sparse at Murowa. These Paleoproterozoic ages overlap with the formation age of the Bushveld Intrusive Complex at ~2.0 Ga (Olsson et al., 2010). The two peridotites with the most radiogenic Os and highest abundances of clinopyroxene yield Phanerozoic model ages. This likely reflects metasomatic disturbance closely related to kimberlite activity in the Cretaceous, with associated introduction of metasomatic diopside and radiogenic Os hosted in sulfides.

Our preliminary conclusion is that the lithospheric mantle beneath both the Karowe Mine - and the Orapa Kimberlite Field in general - is typical depleted Archean cratonic lithospheric mantle, formed in the Neoarchean. Similar to the conclusion reached by Stiefenhofer et al. (1997) at Letlhakane, these Archean ages imply thrusting of the Magondi belt over pre-existing Zimbabwe Craton lithospheric maantle. This cratonic mantle, however, has a strong metasomatic overprint that could be related to either the large-scale Bushveld intrusive event, or to metasomatic fluids associated with the ~1.8 Ga formation of the Magondi Belt. We note that the range in ages presented here, especially the relatively frequent occurrence of peridotites with 2 Ga model ages, is similar to the age spectrum seen in peridotites from the Premier mine, which also produces large Type IIa gem diamonds.

References

Aulbach, S., Mungall, J. E., & Pearson, D. G. (2016). Distribution and processing of highly siderophile elements in cratonic mantle lithosphere. Reviews in Mineralogy and Geochemistry, 81(1), 239-304.

Canil, D. (1999). The Ni-in-garnet geothermometer: calibration at natural abundances. Contributions to Mineralogy and Petrology, 136(3), 240-246.

Griffin, W. L., Cousens, D. R., Ryan, C. G., Sie, S. H., & Suter, G. F. (1989). Ni in chrome pyrope garnets: a new geothermometer. Contributions to Mineralogy and Petrology, 103(2), 199-202.

Grütter, H., Latti, D., & Menzies, A. (2006). Cr-saturation arrays in concentrate garnet compositions from kimberlite and their use in mantle barometry. Journal of Petrology, 47(4), 801-820.

Harte, B. (1977). Rock nomenclature with particular relation to deformation and recrystallisation textures in olivine-bearing xenoliths. The Journal of Geology, 85(3), 279-288.

Luguet, A., Behrens, M., Pearson, D. G., König, S., & Herwartz, D. (2015). Significance of the whole rock Re–Os ages in cryptically and modally metasomatised cratonic peridotites: Constraints from HSE–Se–Te systematics. Geochimica et Cosmochimica Acta, 164, 441-463.

McDonald, I., & Viljoen, K. S. (2006). Platinum-group element geochemistry of mantle eclogites: a reconnaissance study of xenoliths from the Orapa kimberlite, Botswana. Applied Earth Science, 115(3), 81-93.

Motsamai, T. (In Prep.) (Unpublished doctoral thesis). University of Alberta, Edmonton, Canada

Olsson, J. R., Söderlund, U., Klausen, M. B., & Ernst, R. E. (2010). U–Pb baddeleyite ages linking major Archean dyke swarms to volcanic-rift forming events in the Kaapvaal craton (South Africa), and a precise age for the Bushveld Complex. Precambrian Research, 183(3), 490-500.

Pearson, D. G., Canil, D., & Shirey, S. B. (2003). Mantle samples included in volcanic rocks: xenoliths and diamonds. Treatise on geochemistry, 2, 568.

Pearson, D. G., Irvine, G. J., Ionov, D. A., Boyd, F. R., & Dreibus, G. E. (2004). Re–Os isotope systematics and platinum group element fractionation during mantle melt extraction: a study of massif and xenolith peridotite suites. Chemical Geology, 208(1), 29-59.

Pearson, D. G., & Wittig, N. (2008). Formation of Archaean continental lithosphere and its diamonds: the root of the problem. Journal of the Geological Society, 165(5), 895-914.

Pearson, D. G., & Wittig, N. (2014). 3.6-The Formation and Evolution of Cratonic Mantle Lithosphere–Evidence from Mantle Xenoliths.

Pearson, D. G., Liu, J., Smith, C. B., Mather, K. A., Krebs. M. Y., Bulanova, G. P., & Kobussen, A. (in press). Characteristics and origin of the mantle root beneath the Murowa diamond mine: Implications for craton and diamond formation. Chapter X: Special Publication of the Society of Economic Geologists

Stiefenhofer, J., Viljoen, K. S., & Marsh, J. S. (1997). Petrology and geochemistry of peridotite xenoliths from the Letlhakane kimberlites, Botswana. Contributions to Mineralogy and Petrology, 127(1), 147-158.