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The genesis and evolution of subcontinental lithospheric mantle beneath Botswana and N. South Africa.

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Introduction

The processes that led to the formation and stabilisation of sub continental lithospheric mantle (SCLM) remain a matter of debate (e.g., Pearson & Wittig, 2014; Aulbach et al., 2017). Resolving this question is required to determine how the SCLM is subsequently modified over time and to establish possible links between specific events within the mantle and diamond formation. This project reports on a project designed to obtain an integrated view of the SCLM beneath the north-west portion of the Kalahari Cration. The region was chosen specifically to assess the effects of amalgamation of the Kaapvaal and Zimbabwe Cratons and the subsequent formation of the Meso-Palaeoproterozic Magondi-Gweta and Choma-Kaloma Terranes. Over the last decade peridotite xenoliths have been sampled from open pits and drill cores from the Jwaneng, Orapa and Letlhakane (Botswana ~92 Ma) and Venetia (Limpopo Mobile Belt, northern South Africa ~530 Ma) diamond mines with the aim of determining the timing and processes responsible for the formation and subsequent modification of the SCLM. Samples were subjected to detailed petrological studies and selected samples to whole rock major and trace element and Re-Os isotope analysis and mineral major and trace element and coupled Sr-Nd-Hf isotope analysis.

Results & Discussion

Lithological abundances were quantified from the observation of 400 to > 1000 xenoliths at each location. Garnet lherzolite (clinopyroxene visible in hand specimen) dominate all assemblages with variable abundance of harzburgites and dunites (10-20%) and subordinate amounts of pyroxenites-websterites (<10%) and metasomites dominantly formed of amphibole and/or phlogopite (<5%). With the notable exception of Letlhakane, the preservation state of xenoliths recovered from open pits is poor with olivine only locally preserved. It is, however, possible to determine the original modal mineralogy. Xenoliths recovered from drill cores from up to 1200 m below the surface generally have much better preservation such that mineral zonation can be evaluated by electron microprobe.

As reported from elsewhere in the Kalahari Craton, high temperature harzburgites and lherzolites (T>1150°C), are usually deformed and have olivine with forsterite contents (Fo) between 88-92. In contrast low temperature garnet harzburgites/lherzolites (T<1150°C), have Fo between 92-93.5. Based on olivine abundance and composition the majority of the SCLM appears to have undergone extensive melt depletion: 30-50%. The xenoltih suites from the different mines record different degrees of Si/orthopyroxene enrichment with for example Letlhakane having up to 40% orthopyroxene (Fig. 1). There are, however, significant regional variations recorded in the degree of Si-enrichment but as yet no consistent variation with depth among the low temperature peridotites.

Calculated whole rock trace element contents of low temperature peridotites, such as low HREE, coupled with the high Fo olivine imply the low temperature harzburgites/lherzolites originated as residua formed by up to 50% predominantly in the absence of garnet. This conclusion contrasts with the widespread occurrence of clinopyroxene +/- amphibole and/or phlogopite, phases that record trace element enrichment. The majority of the clinopyroxene, amphibole and phlogopite in the garnet lherzolites is not in trace element and Nd-Hf isotope equilibrium with coexisting garnet implying metasomatic addition shortly before eruption of the host kimberlite with coupled Nd-Hf isotope ratios implying the involvement of metasomatic melts comparable to the host kimberlites. The exception to this observation are websterites and wehrlites that have coupled Nd-Hf isotope systematics indicating formation in the Proterozoic. The majority of the low temperature peridotites with petrographic evidence of significant clinopyroxene, amphibole and phlogopite addition have a within plate signature trace element signature (e.g., low La/Nb, Th/Nb) associated with clinopyroxene addition. Harzburgitic samples, in contrast, locally preserve a clear subduction related metasomatic signature (e.g., high La/Nb, Th/Nb).

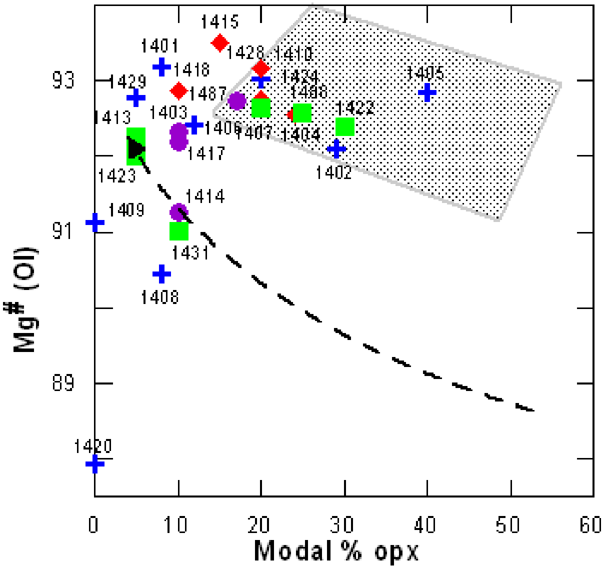

Figure 1: Olivine Mg# versus modal orthopyroxene content for Letlhakane samples. Black arrow is oceanic melting trend; grey field represents typical Kaapvaal xenoliths assuming 100 % olivine and opx assemblages (Boyd, 1989). SiO_2 enrichment leads to orthopyroxene addition, i.e. points move to the right of the oceanic melting trend. Blue cross: garnet free peridotites, Red diamond: garnet harzburgites, Green square: garnet lherzolites, Purple circle; amphibole garnet lherzolites.

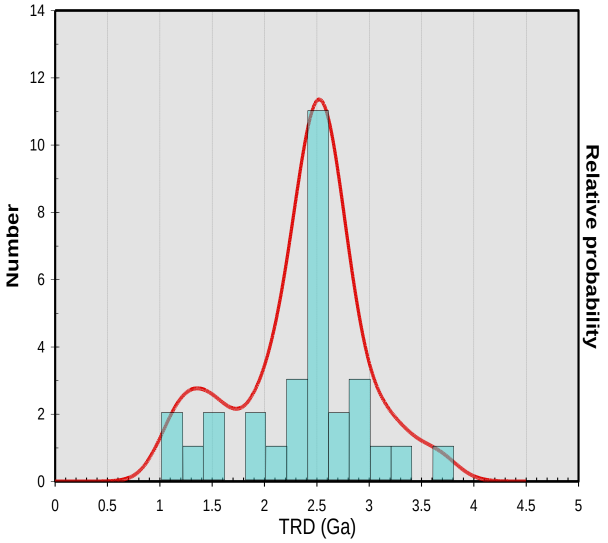

Figure 2: Relative probability plots for rhenium depletion ages of all analysed samples, including Carlson, 1999 (n=30). An error of 0.2 Ga is used for calculation of the Gaussian probability curve for all rhenium depletion ages.

Os isotope whole rock data were performed on samples across the region. Rhenium depletion ages range from 1 to 3 Ga with the majority in the region of 2.5-2.7 Ga implying major melt depletion of the peridotitic precursors associated with stabilisation/amalgamation of the craton and Limpopo Belt formation. A finding comparable to previously reported data (e.g., Irvine et al. 2001; Luguet et al., 2015). Major differences between mantle depletion and Re depletion ages, however, imply that many samples have undergone significant redistribution of Re and/or Os. This process is best illustrated in the 530 Ma Venetian suite, which is characterised by significant Si-enrichment. Samples without petrographic and geochemical evidence of clinopyroxene addition immediately prior kimberlite eruption record a coherent isochronous relationship that defines an age of 3.28 ± 0.17 Ga, an age indistinguishable from the mantle depletion ages of the samples but significantly older than T_{RD} ages (van der Meer at al. in press; Fig. 2). Samples defining the “isochron” are derived from ~50 to ~170 km depth, suggesting coeval melt depletion of the majority of the Venetia lithospheric mantle column. Remaining samples have elevated Re/Os due to Re addition during kimberlite magmatism but have otherwise undergone a similar evolution as the samples that define the “isochron” and have overlapping $^{187}Os/^{188}Os$ at eruption age: $^{187}Os/^{188}Os_{EA}$. A subset of samples have low Os concentrations, unradiogenic $^{187}Os/^{188}Os_{EA}$ and were effectively Re-free prior to kimberlite magmatism. The combination of Re-Os mobility, preservation of an isochronous relationship, place firm constraints on the formation and subsequent evolution of Venetia lithosphere. Melt depletion and remobilisation of Re and Os must have occurred within error of the 3.28 Ga mean T_{MA} age, potentially related to Si-enrichment. Perhaps most importantly, the refractory peridotites contain significant Re despite recording >40 % melt extraction suggesting that melting does not remove all Re from peridotites and that T_{RD} ages can significantly underestimate the time of melt depletion. The overlap of the ~2.6 Ga T_{RD} ages with the time of Limpopo Orogeny is therefore interpreted as purely fortuitous and has no geological significance.

Throughout the region Nd-Hf-Sr isotope relationships recorded by minerals in the peridotites are highly variable. Harzburgitic samples preserve evidence of initial Archaean depletion (εHf > 300) followed by metasomatism that produced LREE enrichment in the late Archaean, mid and late Proterozoic. These events were followed by widespread clinopyroxene, amphibole and phlogopite formation, in some cases associated with kimberlite related magmatism. Clinopyroxene, amphibole, phlogopite and garnet are often in, or close to, isotopic equilibrium at the time of kimberlite eruption with initial ratios that imply equilibration with the host kimberlites or related magmas. In contrast, websterites and pyroxenites record evidence of late Proterozoic formation yielding relatively coherent Hf and Os T_{MA} ages. In summary, the regional SCLM records evidence of melting/metasomatic events at ~3.2, >2.0, ~1.5 and 1.0 Ga, ages that coincide with diamond formation and can be linked to regional tectono-magmatic events (Richardson et al 2004; Koornneef et al., 2016; Timmerman et al. 2017).

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