Os isotope and PGE evidence for modification of cratonic lithosphere: A study of peridotites from the Premier mine, Kaapvaal Craton, SA

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The Kaapvaal subcontinental lithospheric mantle (SCLM) is mainly Archaean in age (Pearson et al, 2003) and formed as residua from partial melting. It is characterised by depletion in basaltic melt components, but contains high silica and incompatible trace element contents indicative of a complex melt-fluid enrichment history (Kelemen et al, 1998; Simon et al, 2007). Tomographic studies (Fig. 1) have established that Kaapvaal SCLM forms a thick buoyant lithospheric root except for a region where a marked seismic anomaly coincides with the region of a major magmatic activity that formed the Bushveld Province at 2.05Ga. This study of mantle xenoliths from the Premier kimberlite aims to establish the effect of this major magmatic event on the SCLM with a study of mantle xenoliths from the Premier kimberlite pipe that erupted through the centre of the seismic anomaly. The specific goal is to determine if new SCLM was formed at 2.05Ga or if there was a major modification of the existing SCLM.

Geophysics

The uppermost mantle beneath the Bushveld Province is characterised by low P+S waves velocities compared to rest of the Kaapvaal Craton (Fig.1). Bushveld activity in the Proterozoic may have produced new depleted mantle or fertilised the existing SCLM. Both processes would produce relative iron enrichment and hence reduce seismic velocities relative to extensively melt depleted Archaean SCLM. From an examination of 110 xenoliths and previous studies (Danchin et al, 1979) the average composition and mineral modes of Premier xenoliths was calculated. Compared to average Kaapvaal composition (Pearson et al. 2003) this composition is 3% richer in clinopyroxene and 2% richer in garnet, which is sufficient to explain the 0.5% difference observed in present-day seismic velocities.

Major and trace elements

The Premier xenolith suite contains two peridotite populations (Fig. 2.). The first is typical of depleted low-T peridotites from the Kaapvaal Craton and has an average olivine of Mg# 92.4, identical to that seen in the Kaapvaal crtaon and globally (Bernstein et al., 2006; Pearson & Wittig, 2008). The second Premier peridotite group has a more fertile composition, with olivine Mg# =90.6-91.3 (Fig.2)

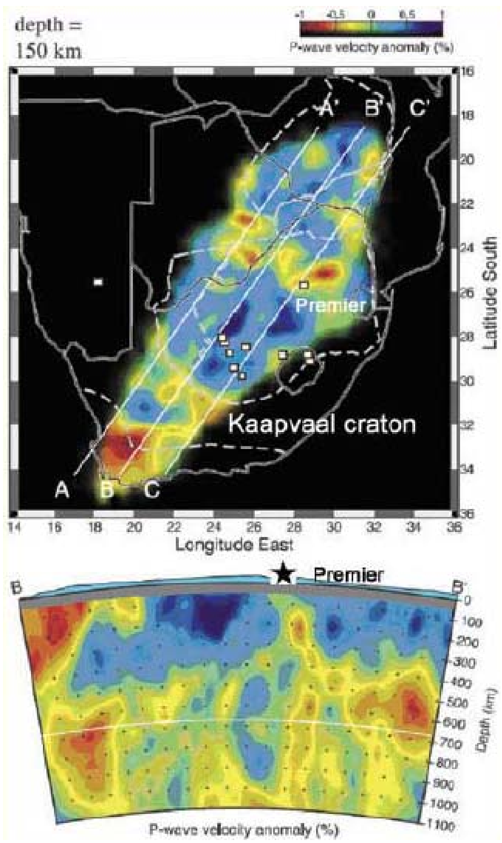


Fig.1 Map of velocities perturbations at 150 km depth and cross section along Kaapvaal Craton BB' profile (James et al., 2004).

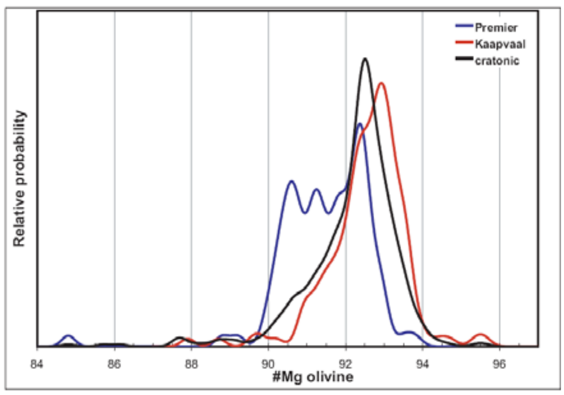


Fig.2 Probability distribution of #Mg olivine for Premier and Kaapvaal craton (Pearson & Wittig, 2008).

The amount of melt extraction from a peridotite can be estimated from the #Mg of olivine (Bernstein et al., 2006). Based on this approach the two Premier peridotite suites experienced approximately 20 and >30% melting respectively.

Major elements are not strong indicators of melting depth in metasomatised cratonic peridotites. Considering FeO-MgO systematics (Fig. 3a) scatter in FeO data is partly caused by orthopyroxene addition typical of Kaapvaal craton (Lee, 2006). The addition of opx lowers the bulk FeO without strongly affecting the MgO while olivine Mg numbers remain relatively unaffected because of the high Mg number of the added orthopyroxene. Premier samples spread towards higher pressure melting curves (Fig.3a). Mg-Al systematics (Fig. 3b) are less effect from opx, but cpx or garnet addition will lead to higher inferred melting pressures. Nonetheless, most sample record less than 30% melting at around 2 to 3GPa (Fig.3b).

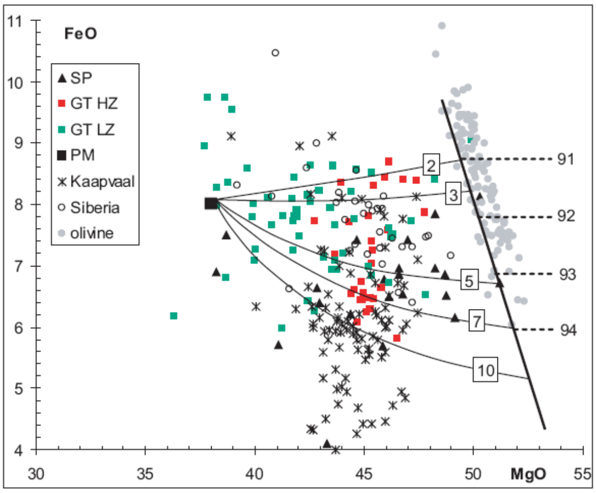
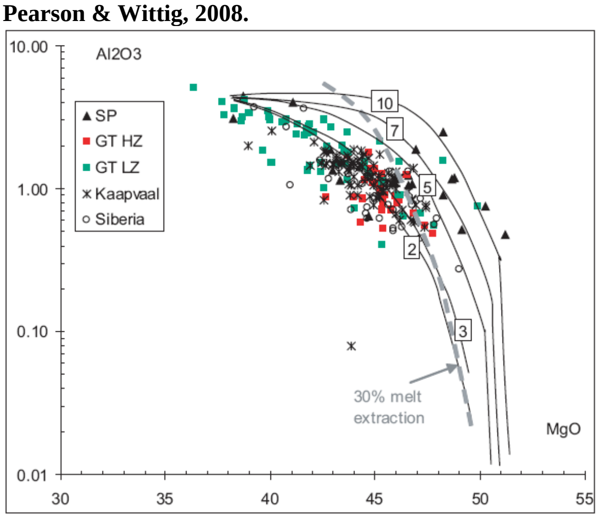


Fig.3 a & b: Bulk rock in wt% MgO versus FeO and Al_2O_3 for Premier peridotites. Solid black lines are the fractional melting trajectories for different pressures (2, 3, 5, 7, 10GPa) taken from Herzberg, 2004. In figure 3b, melt extraction equiline of 30% (larger extent of melting on ont the right of this line). Kaapvaal and Siberia whole rock analytical data sources are from the compilation of Pearson & Wittig, 2008.



Moderately incompatible elements such as Yb or Lu are less sensitive to modal- and kimberlite-metasomatism. These elements also record extensive degrees of melting at pressure mostly below 3GPa (Pearson & Wittig, 2008, Fig. 4), consistent with peridotites from most of other cratons (Wittig et al., this volume).

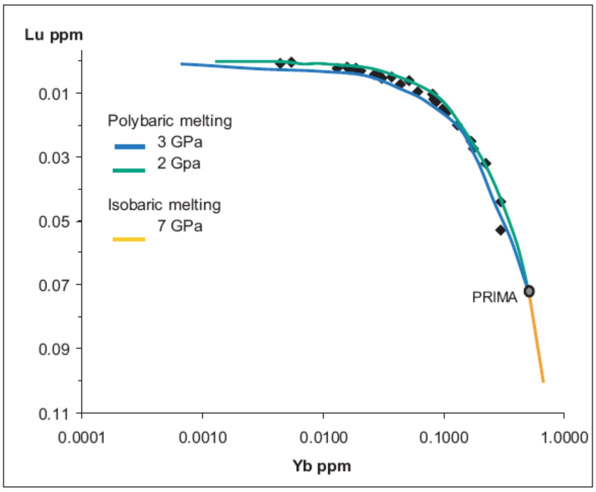


Fig.4 : Whole rock Lu versus Yb for Premier suite. Curves shows polybaric fractional melting beginning at 2 & 3GPa and isobaric melting at 7GPa (after Pearson & Wittig 2008).

PGE and Re-Os data

As with major and trace elements, the Premier peridotites can be split into 2 main groups on the basis of their PGE systematics (Fig.5a&b). Group A is characterised by low Pd, Pt concentrations and fractionation between I-PGEs (Os, Ir, Ru) and P-PGE (Pt, Pd). This group is comparable to the majority of samples derived from the Kaapvaal and other Archaean cratons (Pearson et al. 2004; Wittig et al., this volume). The other groups B-M, have relatively unfractionated PGE patterns. Groups B+M represent 60% of Premier xenoliths.

Subgroup M is very similar to group B but records greater sulphide contents and higher Pd and Re, most likely due to metasomatism.

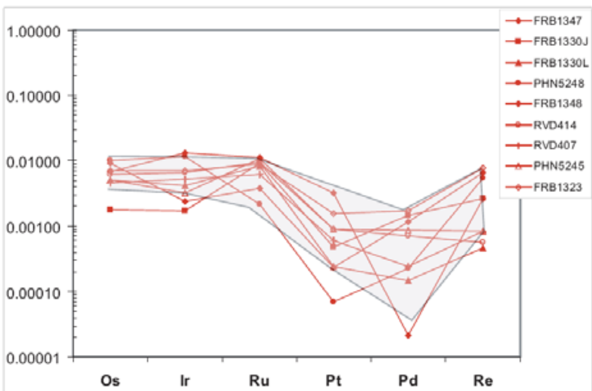


Fig.5a Whole rock chondrite normalised PGE patterns for Group A Premier peridotites. Chondrites values from McDonough and Sun, 1995. Kaapvaal grey field from Lesotho peridotites (Pearson et al., 2004).

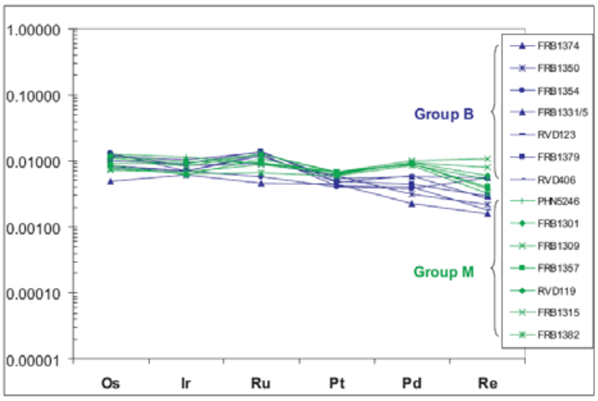


Fig.5a Same as 5a for Group B-M Premier peridotites.

Re depletion ages are presented for Premier and a compilation of Kaapvaal samples in Fig. 6. The Premier xenoliths define two age populations. One yields Archaean ages between 2.5 and 3.4Ga while the second clusters at 2.1Ga, the age of the Bushveld event.

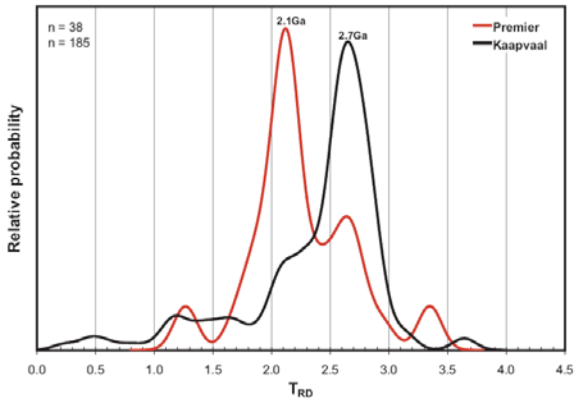


Fig.6 T_{RD} age distribution for Premier samples (in red) and Kaapvaal peridotites (in black, compilation from Pearson & Wittig, 2008). T_{RD} are calculated using the initial ratio corrected to the age of eruption which is 1180Ma for Premier.

These data establish that the SCLM sampled by the Premier kimberlite is of mixed origin. Some peridotitic lithosphere remains from the original generation of the Kaapvaal craton in the Archean, likely associated with suduction (Simon et al. 2007; Pearson & Wittig, 2008). The majority of the lithosphere sampled by the kimberlite appears to have formed in association with the Bushveld Province magmatism.

The clustering and homogeneity of T_{RD} ages from the fertile group around 2.05Ga is likely a result of new melt depletion than from the addition of metasomatic sulphides. This is confirmed by differences in major elements and mineral chemistry.

A large combined P-T and Os isotope dataset allow us to examine the variation of SCLM age with depth (Fig 7). Os model ages are variable for spinel facies and for the deepest samples which have P>6GPa and T>1300°C (T_{RD} 3.3 and 1.2Ga). In contrast, low temperature garnet peridotites and spinel-garnet facies only have T_{RD} ages around 2.1Ga.

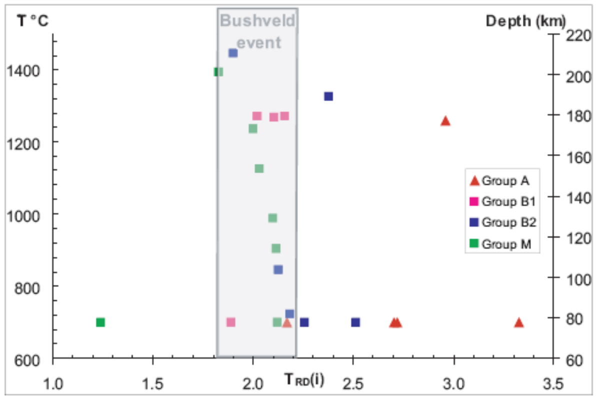


Fig.7 Re depletion ages (T_{RD}) versus temperature of equilibration. Temperatures and pressures were calculated using standard geothermobarometry methods. Combined P-T calculations are not possible for spinel lithologies hence P-T was arbitrarly fixed at 700°C and 2GPa.

Premier peridotites clearly record the same Archaean history as the rest of Kaapvaal with high degrees of melting in shallow environment. However, the main suite is dominated by SCLM formation at 2Ga, associated with the Bushveld magmatic event that has caused replacement of part of the existing lithospheric mantle.

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